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(U) INVESTIGATION OF DECOMPOSITION CATALYSTS
FOR 98% HYDROGEN PEROXIDE

FINAL REPORT

Contract AF04(611)11208

T. C. F. Munday, L. R. Darbee, and J. C. McCormick

Technical Report AFRPL-TR-67-80

GROUP 4

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FOREWORD

This program was conducted under Contract AF04(611)11208 (Project 3148) by FMC Corporation, Princeton, New Jersey, for the Air Force Rocket Propulsion Laboratory, Edwards Air Force Base, California. The engineering tests were carried out under a subcontract by Walter Kidde and Company, Belleville, New Jersey. Lt. Ralph Fargnoli, USAF/RPCL, was the program monitor for the Air Force.

These investigations were carried out between December, 1965 and December, 1966 and the report submitted in January 1967. The program was administered by Dr. L. R. Darbee, Project Director for FMC, with Dr. T. C. F. Munday as principal investigator. Mr. J. C. McCormick served as rocket engineer and general consultant. The literature survey was conducted by Mr. P. L. Garwig. Assistance in data correlation was provided by Mr. W. C. DeKleine, Research Engineer.

The Walter Kidde Company subcontract was directed by Mr. K. A. Traynalis, with Mr. G. Reid as project manager. The project engineer was Mr. W. Green and the test engineer was Mr. R. Glaser.

This report is classified Confidential according to DD Form 254, Security Requirements Check List, dated 18 October 1965.

Classified information has been extracted from asterisked documents listed under References.

This technical report has been reviewed and is approved.

WILLIAM H. EBELKE, Colonel, USAF
Chief, Propellant Division

CONFIDENTIAL ABSTRACT

Heterogeneous decomposition catalysts for 98% H_2O_2 were evaluated in both laboratory and engineering tests. The laboratory program screened thirty-three metals and alloys and eighteen catalyst pellets for catalytic activity and thermal stability at the high ($\geqslant$1740°F) decomposition temperatures of 98% H_2O_2. Silver and silver-palladium alloy screens with samarium surface activations were the best catalysts, but only the silver-palladium catalyst exhibits the required thermal stability. Manganese, cobalt, lead, and barium oxides were also very active and thermally stable, but were not suitably incorporated into catalyst packs. The catalytic activity of the remaining materials was insufficient for rocket applications in the forms tested. Catalyst packs containing the silver-30% palladium catalyst screens were tested in 22 and 40 pound thrust motors and a 3/4" internal diameter gas generator. Inlet and chamber pressures and temperatures, flow rates, catalyst pack temperatures, thrusts, and starting responses were measured. Pack configurations were tested with and without silver or silver-5% palladium screens in the inlet section and with 40 or 20 mesh screens in the inlet and 20 or 14 mesh screens in the exhaust section. The silver-30% palladium catalyst gave good performance in gas generator tests up to 0.8 lb/sec flow rates and 1500 psia chamber pressures. The use of silver screens in the inlet section of the pack proved beneficial but packs containing only the silver-30% palladium screens also performed well. Packs as short as 7/8" in length operated smoothly at high loadings and with feed temperatures up to 140°F. Screens with greater open area than 20 mesh have been recommended to decrease the pressure drop across the catalyst. A preheat-type motor was successfully tested with motor and feed at 30°F. The results have been correlated to give the variation in catalyst pack pressure drop with changes in chamber pressure, pack loading, feed temperature, and pack length. Examples of design for application of the catalyst pack are given for thrust motors and gas generators.

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LIST OF ABBREVIATIONS AND SYMBOLS

Amp. - Ampere
Atn. - Atmospheres
B. C. - Bore center
C - Centigrade
C* - Characteristic exhaust velocity
C/A - Chromel-alumel
cc. - Cubic centimeter
CUC - Copper-constantan
Diam. - Diameter
Exh. - Exhaust
F - Thrust or Fahrenheit

H. C. - Hole center
ISP - Specific impulse
lb. - Pounds
max. - Maximum
Mil. - Milli
min. - Minutes
ml. - Milliliters
msec., MSec - Milliseconds

PC, Pc - Chamber pressure
PF - Pressure of feed
PI - Pressure at inlet
Press. - Pressure
PSI - Pounds per square inch
PSIA - Pounds per square inch absolute
psig - Pounds per square inch gage
PSIM - Pounds of 98% H_2O_2 per square inch of catalyst frontal area per minute

sec. - seconds

Δ - Change of

 # - Pounds

" - Inches

° - Degrees

SECTION I
INTRODUCTION

Hydrogen peroxide can be decomposed heterogeneously by passing over a catalyst. This decomposition results in release of heat and formation of the gaseous decomposition products, oxygen and steam.

Propulsion applications of hydrogen peroxide date back to World War II with the Walter submarine engine, the Messerschmidt ME163 fighter plane, and the infamous V-2 rocket. These systems employed 70 to 82% hydrogen peroxide with calcium permanganate-impregnated "stones". as a decomposition catalyst. These calcium permanganate "stones" were later used by the United States Army in the Redstone and Jupiter C missiles to burn 76% hydrogen peroxide.

Stabilized 70% hydrogen peroxide has also been employed since World War II by the United States Navy in torpedo applications. Lead dioxide was first used as a decomposition catalyst and later "Argent" (silver-plated iron) and "Irium" (cobalt-plated) screens were used. These catalysts have performed very satisfactorily and have the advantage that they are not readily poisoned by the heavily stabilized peroxide. They are not, however, suitable for 98% H_2O_2 decomposition due to the low melting point of the alloys used and the higher decomposition temperature of the high strength hydrogen peroxide.

In 1948, FMC undertook the development of new decomposition catalysts for 90% H_2O_2 to be used in submarine propulsion. Three successful catalyst systems were developed: one using silver, a second using a liquid sodium iodide system, and a third using fused powder (MnO_2-Cobalt). The sodium iodide and fused powder systems were operated in excess of ten hours.

The use of silver catalysts for the decomposition of 90% hydrogen peroxide was further developed as part of the Navy's super performance aircraft program in the late 1950's. The AR-2 H_2O_2 rocket engines developed under this program have since been adapted to the F-104 aircraft. Other systems which have successfully employed silver-screen catalysts include: the ROR (Reactor on Rotor) helicopter, the X-1 submarine, the Scout attitude control motors, the Mercury capsule, the SynCom Satellite, and NASA's Lunar space simulator. The above systems use samarium oxide-coated silver wire as the catalyst.

In an attempt to increase the effective surface area per unit volume, silver-plated screening has been used. A rough-electroplated silver screen has a very high surface-to-volume ratio and permits high flow rates. Flow of 85 pounds per minute per square inch of flow area have been demonstrated using 90% hydrogen peroxide.

Several materials have been employed for the base screens. These include cartridge brass (70% Cu - 30% Zn) and iron. Brass has the disadvantage that copper and silver form a eutectic melting at 1435° F which is only slightly above the decomposition temperature of 90% H_2O_2. In the case of iron it has been difficult to obtain an adherent plating. Catalyst screens with porous coatings have become rusty, inactive, and have caused high pressure drops. Platings therefore have been avoided except under special conditions.

In late 1947 the FMC Corporation made available to the Armed Services for the first time commercial quantities of 98% hydrogen peroxide. Ninety-eight percent hydrogen peroxide is an excellent oxidizer for many space applications, both in monopropellant and bipropellant systems because it is non-cryogenic, has high density, and can be used as a regenerative coolant. However, the high decomposition temperature of 98% H_2O_2 (1735° F at one atmosphere pressure, versus 1364° F for 90% H_2O_2) causes melting of the conventional silver-screen catalyst currently used to decompose the 90% H_2O_2. Under conditions of a regeneratively oxidant-cooled rocket engine, it may be desirable to have hydrogen peroxide feed temperatures as high at 300° F and chamber pressures of 3,000 psi. In this case the hydrogen peroxide decomposition temperature would then be approximately 2065° F. Silver, which is the most commonly used catalyst for 90% hydrogen peroxide, melts at 1760° F (at one atmosphere), and at lower temperatures in an oxygen atmosphere at high pressures. Therefore, high melting catalysts for 98% H_2O_2 need to be developed and evaluated.

Several silver alloys and other materials having melting points above the decomposition temperature of 98% H_2O_2 have been investigated as potential catalysts . The selection of materials which investigators tested was quite broad, including various surface activated cobalt, manganese, nickel, platinum, silver, copper, iron and palladium metals and alloys, usually employed in the form of wire screens. A large number of oxides and metal-metal oxide mixtures compacted under pressure to form pellets or perforated disks also were studied . Although some of the tests looked encouraging none of these materials was a suitable catalyst for 98% H_2O_2.

In 1964 and 1965 FMC investigated the development of a catalyst for 98% H_2O_2 which could be used in higher temperature and higher pressure systems. Tests with a variety of catalytic materials showed that silver-palladium alloys appeared the most promising. Silver-palladium alloy wire was then obtained and fabricated into screens to prepare catalyst packs with greater uniformity and controlled pressure drop. Engine tests were encouraging. With 98% H_2O_2 feed at room temperature, starting transients (to 90% maximum chamber pressure) as low as 58 milliseconds were obtained with a 70% silver-30% palladium alloy screen (mp 2120°F).

The investigation of 98% H_2O_2 decomposition was continued under Contract AF04(611)-11208, sponsored by the Air Force Rocket Propulsion Laboratory with the objective of the further development and evaluation of the silver-palladium catalysts and the screening of additional materials which could lead to new catalysts. The scope of this program included both laboratory screening and motor demonstration. (1-3)

During the initial phase, a review of the literature on heterogeneous catalytic decomposition of H_2O_2 was conducted. The literature search was issued as a separate report (4). The laboratory studies were divided between development of the silver-palladium catalyst and investigation of alternative catalysts. The silver-palladium catalyst had been shown to suffer some loss of catalytic activity upon being heated to the high temperatures of rocket motors. This effect was investigated. For alternative catalysts, both metal and alloy screens and catalyst pellets were examined.

The motor studies were devoted primarily to evaluation and development of catalyst packs based upon the silver-palladium catalyst. The basic types of catalyst pack configurations incorporating the silver-palladium catalyst were first tested in an initial motor screening program. The best configurations from these tests were then subjected to motor evaluations at high pressures and high pack loading, and with heated and cooled 98% H_2O_2 feed. Brief engineering tests were also carried out on catalyst pellets composed primarily of cobalt metal and manganese oxide.

SECTION II

LABORATORY SCREENING PROGRAM

Rocket applications of 98% H_2O_2 require decomposition catalysts which are not only catalytically active but also thermally stable. The thermal stability requirement is particularly important since the decomposition temperature of 98% H_2O_2 is nearly 400° F higher than that of 90% H_2O_2, which is currently in use. This means that the silver catalyst screen generally used for decomposing 90% H_2O_2 would melt when employed with 98% H_2O_2. However, a catalyst based on silver-palladium alloys does not melt and has been successfully tested in rocket motors.

The useful silver-palladium catalyst is a 70% silver-30% palladium alloy which, like the common silver catalyst, is coated with samarium oxide. This catalyst exhibits high activity for decomposing 98% H_2O_2, but was observed to be less active after being heated to the decomposition temperature of 98% H_2O_2. Therefore, laboratory studies were undertaken to investigate the nature of this activity loss and to seek appropriate modifications of the catalyst.

The laboratory program was also concerned with screening alternatives to the silver-palladium catalyst. This entailed testing a large number of metals and alloys, both with and without surface activation treatments. In addition, various catalyst pellets and compounds which could be used in catalyst pellets were investigated.

1. EXPERIMENTAL

a. Activity Test

This laboratory study was planned as a screening procedure for catalysts, to be followed shortly by the thrust motor test program at Walter Kidde and Company, Belleville, New Jersey. The motor tests included well-monitored measurements of the temperatures, pressures, flow rates, thrusts, and start transients for specific catalyst beds consisting of catalyst configurations suggested by the laboratory study. Consequently, a simple activity test like that used in previous studies was used in the laboratory program to evaluate the basic suitability of the laboratory-prepared catalysts. This test consisted of addition of the catalyst to a 10 ml. sample of 98% H_2O_2 contained in a 100 ml. graduate. In each test the time required for complete decomposition of the hydrogen peroxide was measured. Results of the tests were reported as ml. of 98% H_2O_2 decomposed per minute. If rapid, complete decomposition did not occur, or it was apparent this would not occur within ten minutes, only a qualitative description of the rate was recorded. In some cases the initial activity of the catalyst during the test was so low that the test was terminated within a minute or two. In other cases, bubbling from the catalytic surface indicated that complete decomposition would occur within several minutes and the test was allowed to go to completion.

b. The Silver-30% Palladium Catalyst

The screen used to evaluate the silver-30% palladium alloy catalyst was made of .014 inch diameter wire woven 20 by 20 mesh. Generally 1" diameter pieces of the screen were used for testing since the rocket motor screening tests were to use that size diameter catalyst pack.

The silver-30% palladium screens have been surface activated in several ways. One previously developed coating procedure for the silver palladium screens consisted of dipping the fresh screen in a 50% by volume solution of nitric acid containing a few percent each of Pd $(NO_3)_2$, $AgNO_3$, and $Sm(NO_3)_3$. The screen was then heated to 500° F and this dip-bake operation was carried out a total of three times.

A second coating procedure consisted of one dip in a HNO_3 solution containing only $AgNO_3$ and $Pd(NO_3)_2$, followed by heating to 500-600° F then 8 to 10 dips in a 10% by weight $Sm(NO_3)_3$ solution, followed by heating to 750-900° after each dip. This procedure appears in greater detail in Section III, Rocket Engine Tests (page 27) where it was used extensively for the catalyst screens employed in those tests.

Screens prepared by these procedures were used as standards for comparison with modified procedures. The modifications consisted of varying the number of solution and heating treatments and the components of the solutions. These variations are reported with the results where applicable.

Tests were also run on a number of reagent grade chemicals and several prepared compounds. Samples of .02 to .2 grams were tested for rough indications of catalytic activity. The test with 10 ml. of 98% H_2O_2 was used. Additional details on the preparation of of the compounds are reported in the results section.

c. Other Metal and Alloy Catalysts

The metals and alloys were generally spot-tested before more definitive tests with larger quantities of H_2O_2 were used. The spot test consisted merely of adding the metal or alloy to one drop of 98% H_2O_2 contained on a watch glass. The metals or alloys were either used (1) in untreated condition (i. e. surface affected only by exposure to the atmosphere) or (2) after purposely being covered with a thick oxide coating by heating in air in a resistance furnace. For the latter preparation, the samples were suspended on a platinum wire for three minutes in the temperature regulated furnace held at 2000° F.

For those materials which appear to be most active in the spot tests, more definitive tests were run with 10 ml. of 98% H_2O_2 as described previously. The time required for the sample to completely decompose the 10 ml. was measured and converted to ml/min for reporting and comparison with other tests.

d. Barium-Manganese Mixed Oxide Catalyst

Catalyst screens were also prepared by applying a coating to a support screen. The support screens were generally one inch in diameter and were either 14 or 20 mesh screen made from .014 inch diameter, alloyed wire containing 95% nickel-5% manganese by weight (Ni-5% Mn). Stainless steel screens of 14 mesh and .014 inch diameter wire were also used. The active components were contained in the coating which was applied to the support screens in the following manner.

A dry mixture of the desired coating chemicals was finely ground, dusted on the screen, and fused to the screen by heating. The dusting was accomplished by sprinkling the mixture onto the screen with a spatula. When an even covering of the screen had been achieved without plugging the open spaces of the screen, heat was applied. The screens were heated to between 1800 and 2500° F in an oxygen-hydrogen flame, 2100° in a gas-air flame, or 2000-2100° in a temperature-controlled resistance furnace. Two or three applications of the coating mixture were made to each side of the screen. These screens were also tested for catalytic activity by measuring the time required to decompose 10 ml. of 98% H_2O_2.

e. Pellet Catalysts

Specific details concerning the cobalt metal-manganese oxide catalyst pellet appear in the discussion of Motor Screening Tests, page 28. Further information on the commercial catalyst pellets tested has been collected in the discussion of results, page 22. Refractory magnesia pellets of 1/8" diameter were used to prepare impregnated pellets for testing. The magnesia pellets were soaked in solutions of various ions and fired at 1830°F after each solution treatment. Solutions containing calcium permanganate; barium and manganese nitrates; barium, manganese, and lead nitrates; vanadate ion; and molybdate ion were used to impregnate the magnesia. Three treatments were used with the calcium solution, two each with the barium solutions and one treatment for the last two solutions. The pellets were then spot tested for catalytic activity with one drop of 98% H_2O_2.

2. RESULTS OF THE LABORATORY TESTS

a. The Silver-30% Palladium Catalyst

(1) Deactivation by Heating

The investigation of the deactivation of the surface activated silver-30% palladium catalyst began with a search for the probable active component of the catalyst. The first test showed that the silver-30% palladium alloy itself was inactive (Sample 1, Table I). Attention then turned to investigation of the components of the surface coating in a search for the catalytically active substance. Possible coating components can be recognized by consideration of the coating procedures where the oxides Ag_2O, PdO, and Sm_2O_3 were believed to be formed at the surface of the screen. Therefore, separate samples of each of these oxides were prepared and tested for activity. As Table I shows, Ag_2O was very active, PdO moderately active, and Sm_2O_3 only slightly active.

The activity of numerous surface-coated, silver-30% palladium screens were then correlated with the activities of Ag_2O, PdO, and Sm_2O_3. The literature reports that Ag_2O and PdO decompose thermally at 320° and 1470°F, respectively. Thus screens prepared at low temperatures might be expected to show the high activity of Ag_2O, while screens heated to approximately 1470° would retain only the moderate activity of PdO. Screens heated considerably above 1470° would be expected to show very low activity. The tests roughly supported this suggestion, and representative results are given in Table I, Samples 5-8. The screens were heated by being suspended in a resistance furnace and the temperatures were measured with a chromel-alumel thermocouple.

TABLE I. SILVER-PALLADIUM CATALYST

Sample	Elements of Interest	Material	Solution Treatments	Treating Solutions	Baking Conditions	Decomposition Rate(ml/min.)	Observations
1	Ag, Pd	Ag-30% Pd, 1" screen	None	---	---	Not observable	
2	Ag	Ag_2O .1g	Precipitated with base, washed repeatedly, filtered, and dried	---	---	Very high	Violent decomposition, most Ag_2O was expelled from H_2O_2
3	Pd	PdO .02g	"	---	---	5	Smooth decomposition
4	Sm	Sm_2O_3 .25g	"	---	---	0.2	
5	Ag, Pd, Sm	Ag-30% Pd, 1" screen	3	HNO_3-$AgNO_3$-$Sm(NO_3)_3$	5 min. at 600°F	21	
6	"	Sample 5 reused after above test	None	---	7 hrs. at 600°F	24	
7	"	Sample 6 reused after above test	None	---	6 hrs. at 896°F	3	
8	"	Sample like 5 reused after similar test	None	---	1/2 hr. at 1760°F	0.3	
9	Ag	Ag_2SO_4 .2g	None, reagent grade chemical used	---	---	Negligible	
10	Ag	Ag_2S .2g	Precipitated with base, washed repeatedly, filtered, and dried	---	---	Negligible	
11	Ag	Ag_3PO_4 .2g	"	---	---	Negligible	

Very active screens were prepared by procedures that included heating for short periods at 315° and 480° F, where Ag_2O would be expected to decompose. Even extended heating at 600° (Sample 6) did not destroy this high activity, although extended heating at 900° (Sample 7) moderated the activity. These results suggest that Ag_2O was present in a mixed oxide layer or otherwise stabilized so that it was not thermally decomposed at the 320° decomposition temperature for simple Ag_2O. Therefore, a successful silver-30% palladium catalyst might result if a more thermally stable, mixed oxide coating were produced.

Since $AgNO_3$ was used in the treating procedure and this compound decomposes at 830° F, it could be argued that $AgNO_3$ rather than Ag_2O accounts for the observed behavior. However, this compound, as well as palladium nitrate, is soluble and its continued presence in the coating after repeated contact with H_2O_2 would not be expected. Repeated tests on highly active screens showed no tendency toward decreased activity unless the catalyst was heated as previously discussed.

Three silver compounds which have considerably higher thermal stability than Ag_2O or even $AgNO_3$ were tested as possible coating components (Samples 9-11). None of the compounds exhibited activity.

(2) Alternative Surface Activations

The above tests suggested that the thermal stability of the active Ag_2O component in the screen coating might be increased by proper choice of the other coating components. This could result if mixed oxides of silver and the other components were formed. Therefore, additional tests were carried out to study the effect of other coatings on the silver-30% palladium screens. These tests included coatings formed by heating screens that had been dipped into solutions containing manganese, chromium, cobalt, copper, cerium, and lead ions. Only lead and manganese showed high activity. Since it was later shown that these three ions formed active coatings regardless of what metal or alloy was used for the support screen, no activity contribution from the silver-palladium screen was indicated. The results of these tests are reported in Table II.

b. Other Metal and Alloy Catalysts

The heterogeneous catalytic activity of metals for decomposing H_2O_2 has generally been attributed to their oxides rather than to the metals themselves. Thus the problem of finding suitable metal screen catalysts for 98% H_2O_2 centers on metals whose oxides are active, thermally stable, and either adherent to the base metal or can be generated

TABLE II

ALTERNATIVE SURFACE ACTIVATIONS FOR THE SILVER-30% PALLADIUM CATALYST

Sample	Elements of Interest	Material	Treatments	Treating Solutions	Baking Conditions (°F in air)	Decomposition Rate(ml/min.)
1	Pd	Ag-30% Pd, 1"screen	5	HNO_3-Pd $(NO_3)_2$- $Sm(NO_3)_2$	10 min at 1290	4
2	Cr,Ag	Ag-30% Pd, 1"screen	2	HNO_3-$AgNO_3$- $Cr(NO_3)_3$	5 min. at 1290	Negligible
3	Cr,Ag	Ag-30% Pd, 1"screen	2	HNO_3-$AgNO_3$- $Co(NO_3)_2$	5 min. at 1290	Negligible
4	Cu,Ag	Ag-30% Pd, 1"screen	2	HNO_3-$AgNO_3$- $Cu(NO_3)_2$	5 min. at 1290	Negligible
5	Pb,Mn	Ag-30% Pd, 1"screen	5	$Pb(NO_3)_2$- $Mn(NO_3)_2$	10 min. at 1290	9
6	Ce	Ag-30% Pd, 1"screen	2	$(NH_4)Ce$ $(SO_4)_4$	5 min. at 1290	Negligible

from the base metal as required. Metal oxides and other chemical compounds which are catalytically active and thermally stable can also be incorporated into catalyst pellets or catalyst screen coatings. However, catalysts which are fabricated in the form of wire screens are known to form effective and predictable catalyst packs for decomposing H_2O_2. They can withstand high flow rates, pressures, and temperatures without breakdown and can give consistent results from one catalyst pack to another because of the uniform distribution of the catalyst.

(1) General Selection

The requirements for possibly useful metals and alloys can be outlined briefly as follows. For the largest section of the catalyst pack, the material should have a melting point above 2000°F in order to survive the high decomposition temperatures of 98% H_2O_2, particularly if the H_2O_2 feed is to be above room temperature (for example, 2066°F is the decomposition temperature if 300°F H_2O_2 feed and 3000 psi chamber pressure are used). The metal or alloy must also be sufficiently stable in oxidizing atmospheres to have extended usefulness in the presence of the decomposition products, oxygen and water vapor, at high temperatures.

Since the inlet section of the catalyst pack is cooled by the H_2O_2 flow, a small number of lower melting catalyst screens can be accommodated there. Thus, if a material which melts somewhat lower than 2000°F exhibits very high activity, it can be used in the inlet portion of the pack to give the motor good starting response.

The literature (4) shows that some heterogeneous catalytic activity exists for many elements. However, direct comparisons which designate which elements (oxides) are sufficiently active for consideration as H_2O_2 decomposition catalysts are lacking. It is known that manganese, cobalt, silver, and lead form the most active catalysts.

Silver is the most widely used catalyst for decomposing 90% H_2O_2. Various silver-palladium alloys, when properly coated with Sm_2O_3, have shown good activity for decomposing 98% H_2O_2. In this program mixtures of oxides of manganese, barium, lead and cobalt have also been found to be highly active (see part c, page 14). So far these have not been formed by oxidation of alloys of the metals themselves, but only as oxide coatings on inert support screens.

Of these four elements, manganese is very brittle and so cannot be drawn into wire. High manganese alloys are also brittle and have not been commercially developed (5). However, the use of such materials in the form of small pieces similar to catalyst pellets could be explored.

Barium has a low melting point (1310° F) and is reported to ignite in oxygen atmospheres at much lower temperatures (6). Alloys containing useful percentages ($>30\%$) of barium are uncommon and generally have low melting points.

The melting point of lead is far too low for use even in the relatively cool inlet section of the catalyst pack. Alloys containing significant percentages of lead will also have very low melting points. Nevertheless, the use of lead monoxide as a coating component remains of interest, since its melting point is 1630° F and it could be incorporated in higher melting oxide combinations.

Cobalt and its alloys are high melting and can be expected to give extended life in high temperature, oxidizing atmospheres. Further examination of these materials was particularly warranted.

(2) Test Results

The results for tests on a large number of metals and alloys are reported in Table III, divided roughly into groups based on the periodic table. Among the transition metals, manganese and cobalt exhibited the greatest activity, as expected. However, only surface oxidized manganese produced activity of the order needed for a catalyst pack (>10 ml/min), and the results were somewhat erratic (varying from 2 to 10 ml/min). Although cobalt has been successfully used as a major component in catalyst pellets, the surface oxidised, massive metal used in this test was not as active as the manganese. Nevertheless, since cobalt can be drawn into wire, its use in place of the much less active nickel-5% manganese as filler screens in the highest temperature zone of the pack might be beneficial.

The transition metal alloys were consistently rather inactive.

Among the platinum metals, palladium proved to be somewhat active. This warrants its use as an alloying agent to give thermal stability to silver, but is not sufficient to permit palladium to be used as a catalyst by itself.

TABLE III

COMPARATIVE H_2O_2 DECOMPOSITION BY METALS AND ALLOYS

	Sample	Metal or Alloy	Form	Calculated Area (in²)	Room Temp Activity[a]: Untreated	Room Temp Activity[a]: Oxidized (1000°F 5 min. or as noted)	Color Produced by Heating (1000°F)	Decomposition[b] Rate [illegible]
Transition Metals	1	Cr	Plate on steel	1/4	Very slow bubbling	None	Green-black	—
	2	[illegible]	Foil	1/2	Slow bubbling, then rapid decomposition with formation of [illegible]	Moderate bubbling, then rapid decomposition with formation of [illegible]	Yellow-white (removed) plus blue-black	Very low
	3	Mn	Electrolytic segment	[illegible]	Rapid, complete[c] decomposition	Rapid, complete decomposition	Brown	[illegible] (untreated)[c] [illegible] (oxidized) (2 min, 1000°F)
	4	Fe	Stainless screen	1/30	Very slow bubbling	(1300° - 10min) Very slow bubbling	Black	—
	5	Co	Flat section	1/8	Rapid bubbling	Rapid, complete decomposition	Black	Very low (untreated) low (oxidized, 5min. at 1000°F)
	6	Ni	Foil	1/4	Very slow bubbling	None	Green	—
Transition Metal Alloys	7	80 Ni-20 Cr Chromel	Wire	1/50	Very slow bubbling	Very slow bubbling	Green	—
	8	70 Ni-30Cr [illegible]	Wire	1/60	Very slow bubbling	Very slow bubbling	Green	—
	9	54 Fe-17Co-29Ni Kovar	Foil	1/16	None	Slow bubbling	Black	—
	10	53 Fe-[illegible]-33Ni [illegible]	Wire	1/40	Slow bubbling	Moderate bubbling [illegible]	Black	—
	11	[illegible]	Wire	1/3	Very slow bubbling	Very slow bubbling	—	—
	12	[illegible]	Wire	1/30	Very slow bubbling	Slow bubbling	Green	—
	13	90 [illegible]	Wire	1/5	Very slow bubbling	Very slow bubbling	—	—
	14	Ni-[illegible]	Wire	1.4	None	None	Black	—
	15	[illegible] Alumel	Wire	1/30	Very slow bubbling	Very slow bubbling	Black	—
	16	75 Cu-25Ni	Flat section	1/16	Very slow bubbling	—	—	—
	17	57 Cu-43Ni Constantan	Wire	1/70	Very slow bubbling	Slow bubbling	Black (wire disintegrated)	—
Platinum Metals	18	Rh	Wire	1/30	Very slow bubbling	Very slow bubbling	None	Very low
	19	Pd	Wire	1/30	Very slow bubbling	([illegible]°-3min)-Very slow bubbling	None	Very low (untreated) 0.3(samarium coated)
	20	Pt	Wire	1/30	Moderate bubbling	(1300°-5min) Moderate bubbling	None	Low (heated 5 min. 1300°)
Noble Metals	21	Cu	Wire	1/70	None	(1300°-5min)- None	Black	—
	22	Ag	Wire	1/2 1.4	Rapid, complete decomposition, [illegible]	—	—	5 (untreated) 30(samarium coated)
	23	Au	Foil	1/8	Slow bubbling	---	---	—
	24	Pb	Irregular	1/8	Rapid, complete decomposition with formation of yellow PbO on clean surface	Slow starting on[d] black PbO₂ surface; then rapid complete decomposition with formation of PbO	Black[d]	3.5(sudden start after two min; sample melted)
Platinum and Noble Metal Alloys	25	99 Ag-1Au	Wire	---	Rapid, complete decomposition	---	—	5 (untreated)
	26	95 Ag-5 Pd	Wire	1.4	Rapid, complete decomposition	—	—	30 (samarium coated)
	27	70 Ag-30 Pd	Wire	1.4	Very slow bubbling	(1100°) Moderate bubbling	Gray	30 (samarium coated)
	28	67 Ag-30 Pd-3 Au	Wire	1/8	Very slow bubbling	Very slow bubbling	—	Low(samarium coated)
	29	60 Ag-30Pd-10 Au	Wire	1/4	Very slow bubbling	Very slow bubbling	—	Low(samarium coated)
	30	[illegible] Pd-[illegible] Co	Wire	1/4	Slow bubbling	None	Blue-black	0.5(samarium coated)
	31	40 Pd-60 Cu	Wire	1/4	Slow bubbling	Very slow bubbling	Blue-black	—
	32	[illegible] Pd-[illegible]-30 Au	Wire	1/3	Slow bubbling	Very slow bubbling	Blue-black	2 (samarium coated)
	33	60 Pd-40 [illegible]	Wire	1/4	Moderate bubbling	Very slow bubbling	None	—

NOTES: [a]Contact of sample on one drop of 90% H_2O_2.

[b]Test used 10ml. of 90% H_2O_2 initially at 75°F. Surface treatments noted in parentheses; "samarium coated" refers to the standard surface treatment used for the silver-[illegible] palladium catalyst screens (page ___).

[c]Sample not heated; air oxidized.

Silver and lead were by far the most active elements among the remaining metals, as suggested by the literature. The low melting point of lead prohibits its use, as discussed previously.

Of the platinum and noble metal alloys, the high silver alloys were selected to explore possible improvements on the silver-30% palladium catalyst. The inclusion of gold as an alloy constituent was not found of value, though the test used was not sufficiently sensitive to distinguish between silver and silver-1% gold. Some activity was shown by palladium alloys with other elements than silver, but silver-30% palladium still appeared to be more active. The platinum-rhodium alloy suffered a decline in activity on being heated.

It should be recognised that the test with 10 ml. of H_2O_2 is essentially a test under flood conditions, as occurs in the inlet region of the catalyst pack during rocket motor operation. This test does not necessarily detect which catalysts will be most active for decomposing theheated H_2O_2 further into the pack or the remaining H_2O_2 vapor which occurs toward the exhaust end of the catalyst pack. Some of the materials tested might yet prove to be good high temperature decomposition catalysts. Screens of monel alloy, nickel, or nickel-5% manganese alloy have been used for the highest temperature zones of the pack, even though their activity under cool, flood conditions is negligible. The suggestion has been made that thermal decomposition in conjunction with such inert metal screens completes the H_2O_2 decomposition which is largely effected by active screens earlier in the pack (7). However, direct comparisons of different metals and alloys as fillers screens in the exhaust section of the packs have not been made.

Both the lead and molybdenum activities appeared to be dependent on the formation of their particular oxides, molybdenum trioxide and lead monoxide. These oxides were produced through oxidation of the metals or lower oxides by the H_2O_2. The dark colored, lower oxides were comparatively inactive.

c. Barium-Manganese Mixed Oxide Catalysts

(1) Screen Coatings

The attempts to modify the surface activation coating of the silver-30% palladium catalyst to stabilise silver oxide in the coating indicated the high activity of coatings containing oxides of lead and manganese. However, the activity of these materials was shown to be independent of the metal of the support screen by the use of nickel-5% manganese and stainless steel support screens as well as the silver-palladium screen. Further studies of various alternative catalysts which could exhibit the required thermal stability for decomposing 98% H_2O_2 were carried out. These tests revealed the high catalytic activity of barium-manganese mixed oxides, which are related to the calcium permanganate impregnated catalysts used for lower concentrations of H_2O_2 for many years.

Additional mixed oxide coatings of barium-manganese, manganese-lead, and lead-barium were then prepared by solution treatments and tested. The barium-manganese mixtures were the most active catalysts, but their activity decreased in subsequent tests and did not persist after heating to 2070°F (Table IV, Samples 1-4). Tests of the mixed oxide (Table IV, Sample 5) as an isolated compound rather than as a screen coating showed the mixture to be active after 2070° heating. This indicated that insufficient coating thickness was being obtained by the application of barium and manganese from solution, followed by baking. A thicker coating was then achieved by thermal decomposition of a dry, chemical mixture onto the screen. This screen (Table IV, Sample 6) showed continued high activity in spite of being heated to 2070°, but also showed non-adherence of the coating to the screen and therefore the useful life of the catalyst was limited.

(2) Coating Binders

Several tests to improve the bonding of the coating to the screen were carried out (Table IV Samples 7-10). First it was found that better adhesion resulted for nickel-5% manganese than for stainless steel support screens. Binder components were then added to the dry chemical mixture. The oxides Cu_2O or Al_2O_3 (containing some minor organic components) improved the adherence, but SiO_2 or $Zr(SO_4)_2$ did not help.

Other materials tested as possible binders are shown in Table V. For catalyst samples 1 to 4, different chemical sources of Ba, Mn, and Pb were used in the coating to see if these acted as binders. The materials used for samples 1 and 2 did not give adherent coatings. A uniform, adherent coating was obtained for sample 3, but very high temperatures were required to apply the coating and the activity of this sample diminished to a negligible level on the second test. Further development of this catalyst or of sample 4 could prove worthwhile.

The other binder materials were selected from a large group of stock chemicals whose melting or thermal decomposition behaviors were observed under the same conditions as those used to apply the coatings to the support screens. Chemicals which produced uniform coatings and did not fracture appreciably on heating were chosen

TABLE IV BARIUM-MANGANESE CATALYST

Sample	Elements of Interest	Material	Treatments	Treating Solutions	Baking Conditions	Decomposition Rate(ml/min.)	Observations
1	Ba,Mn	Stainless 3/4"screen	5	$Ba(NO_3)_2$- $Mn(NO_3)_2$	10 min.at 1300 F	9.5	Coating partly flaked from screen
2	Ba,Mn	Sample 1 after above test	None	---	---	2	Coating flaked from screen
3	Ba,Mn	Ni-5% Mn, 1"screen	5	$Ba(NO_3)_2$- $Mn(NO_3)_2$	10 min.at 1300 F	10	Coating thin but adherent; 4 subsequent tests gave rates of 5-10
4	Ba,Mn	Sample 3 after above 5 tests	1	---	10 min.at 1830° F	Negligible	Coating was flaked from screen by 1830° heating
5	Ba,Mn	Ba-Mn mixed oxide, ~.2g	$Ba(NO_3)_2$-$Mn(NO_3)_2$ solution evaporated to dryness	---	5 min.at 2050°	2	
6	Ba,Mn	Ni-5% Mn, 1"screen	Dry BaO-$MnSO_4 \cdot H_2O$ mixture baked on screen in flame	---	1/2 min.at 2100°	27	Coating not adherent; on 6 subsequent tests rate decreased slowly to 10
7	Ba,Mn,(Al)	Ni-5% Mn, 1"screen	Dry BaO-$MnSO_4 \cdot H_2O$-Al_2O_3 mixture baked on screen in flame	---	1/2 min.at 2100°	33	Coating partly adherent; rate reproduced on 5 subsequent tests
8	Ba,Mn,(Al)	Sample 7 after 6 tests	1	---	10 min.at 2100°	30	Rate reproduced on 9 subsequent tests
9	Ba,Mn,(Zr)	Ni-5% Mn, 1/2"screen	BaO-$MnSO_4 \cdot H_2O$ $Zr(SO_4)_2 \cdot 4H_2O$ mixture baked on screen in flame	---	1/2 min.at 2100°	2.5	Coating was non-adherent
10	Ba,Mn,(Si)	Ni-5% Mn, 1/2"screen	BaO-$MnSO_4 \cdot H_2O$ SiO_2 mixture baked on screen in flame	---	1/2 min.at 2100°	3.3	Coating was non-adherent

TABLE V

BINDERS FOR ACTIVE OXIDE COATINGS ON INACTIVE SUPPORT SCREENS

(Ni-5% Mn Support Screens)

Sample	Active Elements	Binders	Heat Treatment (~ Flame Temp.)	Observations	Decomposition* Rate (ml/min)
1	Ba	BaO	2000°F	Coating not adherent	5 (avg. of 2 tests)
2	Ba, Mn	BaO, $MnAc_2 \cdot 4H_2O$	2100°	Coating not glazed or adherent	-
			2280-2550°	Coating remained heterogeneous	5
3	Ba, Mn	BaO, $MnSO_4 \cdot H_2O$	2550°	Coating glazed	4, then very low on second test
4	Ba, Mn, Pb	PbO	2100°	Coating glazed	-
5	Ba, Mn, Pb	PbO, NaCl	2100°	Coating glazed	3
			2280-2550°	Coating not adherent	-
6	Mn	Cu_2O	2100°	Coating heterogeneous, not glazed	-
			> 2250° (mp Cu_2O)	Metallic luster	7
7	Ba, Mn	$Al_2O_3 \cdot 3H_2O$	2100	Coating not adherent, partly glazed	-
			2280-2550°	Coating dissipated	-
8	Ba, Mn	NaOH	2100°	Coating partly glazed	-
			2280-2550°	Coating flaked away	-
9	Ba, Pb	B_2C_3	2000°	Coating slightly soluble in H_2O	-

* Decomposition test used 10 ml of 98% H_2O_2 which was initially at 70°F.

for the tests shown in Table V. Boric oxide appeared to be the best binder.

More extensive investigations of the activity of mixed oxide catalysts containing B_2O_3 as a binder are reported in Table VI. Use of 33% B_2O_3 effectively eliminated the catalytic activity by diluting the active components. On the other hand, 2 1/2% B_2O_3 did not contribute enough adherence to the coating. Intermediate amounts of binder produced adherent, active coatings.

The B_2O_3 binder was employed in catalysts containing Ba, Co, Mn, and Pb oxides. (Samples 4 to 12, Table VI) Catalysts containing only one of these oxides with B_2O_3 were relatively inactive. Among catalysts containing two or more of the oxides, maximum activity resulted from the combination of barium, manganese, and lead oxides. Good activity was also obtained for the barium-manganese and barium-cobalt-lead catalysts.

Two samples(Samples 13-14, Table VI)which tested the effect of added SiO_2 and Na_2CO_3 did not show increased activity. The Na_2CO_3 did increase the porosity of the catalyst and resulted in better starting activity.

The remaining four catalysts listed in Table VI explored the preparation of the coating in an oxidizing rather than reducing flame. An increased activity depending on heat treatment of the catalyst under oxidizing conditions was not clearly indicated.

These last four samples proved useful in determining the activity of full-sized, 1" diameter screens and the effect of extended heating at high temperatures. Activities approaching that required ($\geqslant$ 10 ml/min) for the inlet portion of the catalyst bed were achieved, but results were not consistently that high. The temperature stability of the catalyst was clearly demonstrated. This combination of moderate activity and good temperature stability suggested possible application of the catalyst in the hot zones lower in the catalyst bed.

Since the B-Ba-Mn-Pb containing catalysts could be of interest for the hot zone of the catalyst bed, tests were carried out using H_2O_2 which had been heated to 120° F. As in the tests run at 70° F, the 10 ml of 98% H_2O_2 was placed in a 100 ml graduate. The graduate was lowered into a 600 ml beaker of water heated by a hot plate. The temperature of the H_2O_2 was measured by means of a chromel-alumel thermocouple and potentiometer. The time required for the 1 inch catalyst screens to completely decompose the 10 ml of H_2O_2 was measured and then converted to ml/min for listing in Table VII.

TABLE VI

MIXED OXIDE CATALYSTS EMPLOYING B_2O_3 BINDER. OXIDES COATED ON Ni-5% Mn SUPPORT SCREENS

Sample	Screen Diameter	% B_2O_3 (by weight)	Active Elements	Dry Mix Composition (by weight)	Heat Treatment (~ Flame Temp.)	Observations	Decomposition Rate* (ml/min)
1	1/3"	33	Ba, Mn	1/3 B_2O_3 -1/3 BaO- 1/3 $MnSO_4 \cdot H_2O$	2100°F	Coating glassy, adherent	Very low
2	1/3"	2 1/2	Ba, Mn	1/40 B_2O_3 - 1/2 BaO- 1/2 $MnSO_4 \cdot H_2O$	2200	H_2O_2 exposed brown powdery surface	4 (avg. of 3 tests)
3	1"	5	Ba, Mn	1/20 B_2O_3 - 1/2 BaO- 1/2 $MnSO_4 \cdot H_2O$	2070 (10 min in furnace)	Coating adherent	2
4	1/3"	20	Ba	1/5 B_2O_3 - 4/5 BaO	2100	Glazed olive coating was not adherent	~ 2
5	1/3"	20	Co	1/5 B_2O_3 - 4/5 Co oxide	2100	Adherent black, crusted coating	Very low
6	1/3"	20	Mn	1/5 B_2O_3 - 4/5 Mn oxide	2100	Adherent black, crusted coating	Very low
7	1/3"	20	Pb	1/5 B_2O_3 - 4/5 PbO	2100	Adherent black, smooth coating	Very low
8	1/3"	20	Co, Mn	1/5 B_2O_3 - 2/5 Co oxide 2/5 Mn oxide	2100	Adherent black, crusted coating	Very low
9	1"	20	Ba, Mn	1/5 B_2O_3 - 2/5 BaO- 2/5 $MnSO_4 \cdot H_2O$	2070 (10 min. in furnace)	Adherent coating	3
10	1/3"	25	Ba, Pb, Co	1/4 B_2O_3 - 1/4 BaO- 1/4 PbO- 1/4 Co oxide	2100	Adherent coating	5 (avg. of 4 tests)
11	1/3"	20	Co, Mn, Pb	1/5 B_2O_3 - 1/4 Co oxide 1/4 Mn oxide - 1/4 PbO	2100	Adherent, very irregular black coating	Very low
12	1/3"	20	Ba, Mn, Pb	1/5 B_2O_3 - 1/4 BaO- 1/4 PbO - 1/4 Mn oxide	2100 >2200	Adherent black irregular coating Adherent	5 (avg. of 3 tests) 6 (avg. of 4 tests)
13	1/3"	20	Ba, Mn, Pb	1/5 each of B_2O_3, BaO SiO_2, PbO, and $MnSO_4 \cdot H_2O$	2100	Coating not adherent	1,5,10
14	1/3"	2 1/2	Ba, Mn	1/40 B_2O_3-1/2 Na_2CO_3- 1/2 BaO - 1/2 $MnSO_4 \cdot H_2O$	>2200	Good initial activity	4 (avg. of 3 tests)
15	1"	20	Ba, Mn, Pb	1/5 B_2O_3 - 1/4 BaO - 1/4 PbO - 1/4 $MnSO_4 \cdot H_2O$	>2200 reducing flame	Minor flaking	6 (avg. of 4 tests)
16	1"	20	Ba, Mn, Pb	"	>2200 oxidizing flame 1140 (10 min. in furnace)	Minor flaking Minor flaking	9 (avg. of 8 tests) 9 (avg. of 3 tests)
17	1"	20	Ba, Mn, Pb	"	>2200 oxidizing flame 1140 (10 min. in furnace)	Coating adherent Screen brittle	2 (avg. of 2 tests) 11 (avg. of 5 tests)
18	1/3"	20	Ba Mn	1/5 B_2O_3 - 2/5 BaO- 2/5 $MnSO_4 \cdot H_2O$	>2200 oxidizing flame	Coating adherent	9

* Test used 10 ml of 90% H_2O_2 which was initially at 70°F.

TABLE VII

CATALYST ACTIVITIES IN 70° AND 120°F H_2O_2 (98%)

Sample	Catalyst	Condition	Decomposition Rate* with 70°C H_2O_2 (ml/min)	Decomposition Rate* with 120°F H_2O_2 (ml/min)
1	Ag-30%Pd	Active **	29	24
2	Ag-30%Pd	Heat deactivated	0.5	12
3	Ag-30%Pd	Heat deactivated	Inactive for > 11 min.	2
4	B-Ba-Mn-Pb on Ni-5%Mn	Heated to 2070°F for 10 min.	3	15
5	B-Ba-Mn-Pb on Ni-5%Mn	~ 1 min preparation at > 2100°	-	13
6	B-Ba-Mn-Pb on Ni-5%Mn	Heated in oxidizing flame	9	24
7	Ni-5%Mn	Untreated	-	Inactive for > 16 min.
8	Ni-5%Mn	Air oxidized at > 2100°	Inactive for > 10 min.	Inactive for > 7 min.

* Test used 10 ml of 98% H_2O_2 which was initially at 70°C or 120°F.

** The activation treatment is shown on Page 10.

As Table VII shows, the activity of the B-Ba-Mn-Pb catalyst compared favorably with the Ag-30% Pd catalyst for 120° H_2O_2. The active silver-palladium catalyst did not exhibit greater activity at the higher temperature than at room temperature. However, the B-Ba-Mn-Pb catalyst was significantly more active at 120° than at 70°. The B-Ba-Mn-Pb catalyst appeared far superior to the Ni-Mn screens commonly used as filler screens in the hot zone.

An attempt was made to prepare the barium manganese catalyst screen in sufficient quantity for a motor screening test. However, the screens continued to show inconsistent catalytic activity which was often very low. The variation in activity is attributed to the formation of different mixed oxides depending upon the ratio of barium and manganese oxides used and the temperature at which the coating was fired. Further study of these variables is required.

d. Pellet Catalysts

Catalyst pellets have the advantage of very high surface area when compared with metal screens. However, it is generally believed that pellets prepared by compaction and firing of powdered ingredients will be eroded and disintegrated under the high flow rates and high temperatures experienced in rocket motors. Nevertheless, pellets have been developed and successfully used in certain applications in the past. This part of the laboratory program was designed to explore further the possible application of pellet catalysts for 98% H_2O_2 decomposition.

(1) Cobalt Metal-Manganese Oxide Pellet

In an earlier program (8) a large number of compacted and fired catalyst pellets were prepared and tested. The principle active ingredients used were MnO_2 and cobalt metal. Various additional components were added to provide porosity and binding to the pellets. As a result of that program a pellet was developed which decomposed 98% H_2O_2 successfully for 222 minutes, including 12 cold starts, at a flow rate of 6. 5 pounds per square inch cross-section per minute. Laboratory studies on this pellet were not carried out in the current program, but the pellet was prepared in quantity and motor tested as part of the motor screening tests. Further details concerning the composition and preparation of the pellet are given on page 28.

(2) Commercial Pellets

A variety of available catalyst pellets were tested with 98% H_2O_2 and the results are shown in Table VIII. The pellets have been roughly grouped according to their manner of preparation by observation of their gross morphology. In some cases pellets listed as compressed powder pellets may have resulted from impregnation of extruded porous supports. In general, the decomposition rates produced were lower than those obtainable with catalyst screens. However, some compensation must be made for the fact that between 3 and 12 pellets would be used in place of one active catalyst screen, depending on the manner of packing the pellets in a pack for motor tests.

Disintegration of the compressed powder pellets appeared to be a significant problem even under the relatively mild conditions of the tests. The pellets which showed better activity in an untreated or non-fired condition could be considered for the cool inlet section of the catalyst pack. Of these, only the cobalt catalyst pellet (Sample 9) produced a very high decomposition rate, but this pellet had little physical strength. Additional tests would be required to show whether the moderate activity of the silver catalyst pellet (Sample 18) is of interest.

Those pellets which could be fired without failure were further tested for use in the hot section of the catalyst pack. Good activity resulted for the molybdenum sulfide pellet (Sample 5) but the pellet did not hold together. Only the copper chromite catalyst exhibited any cohesive strength, and its activity was low.

None of the obviously impregnated pellets were both physically strong and catalytically active. The last three materials listed were not expected to show much catalytic activity, as was found. They may prove useful as supports for impregnation with other active components.

Though none of the catalyst pellets as tested were considered useful in the present program, some of the chemical constituents have shown high activity. These materials may be of use as screen coating or impregnated pellet components.

TABLE VIII

H_2O_2 DECOMPOSITION BY COMMERCIAL CATALYST PELLETS

COMPRESSED POWDER PELLETS

Sample	Catalyst	Size (inches) Diam.	Length	Manufacturer	Spot Test Activity[1] Untreated	Fired (1000°F-[illegible] Minutes)	Effect of Firing (1000°F)	Decomposition[2] Rate (ml/min)
1	Titania	1/8	1/8	Harshaw	Moderate bubbling	None	Color from bisque to yellow	---
2	Vanadia	1/8	1/8	Harshaw	Slow bubbling; yellow solution formed	Rapid, complete decomposition	None	1.6, 1.9 (fired pellets used; disintegrated)
3	Chrome Alumina	1/8	1/8	Harshaw	Slow start, then violent fracture of pellet	Slow start, then violent fracture of pellet	None	Low (untreated pellet used; disintegrated)
4	Molybdena Alumina	1/8	1/8	Harshaw	Moderate bubbling	Rapid bubbling	None	---
5	Molybdenum Sulfide	1/8	1/8	Harshaw	Rapid complete decomposition	Rapid complete decomposition; vapor binding	Only small piece remained	Low (untreated pellet) 8.6 (fired pellet; disintegrated)
6	Tungsten	1/8	1/8	Harshaw	Very slow bubbling	Rapid bubbling	Color from yellow to white	---
7	Tungsten Nickel	1/8	1/8	Harshaw	Slow bubbling	Very slow bubbling	Color from blue to green	---
8	Iron	1/8	1/8	Harshaw	Slow bubbling; red solution formed	Rapid bubbling	None	---
9	Cobalt	1/8	1/8	Harshaw	Rapid complete decomposition; some pellet disintegration	Rapid bubbling	Pellet shrunk; color from black to purple	24 (untreated pellet used; disintegrated)
10	Nickel	1/8	1/8	Harshaw	None	Slow bubbling; pellet disintegrated to powder	Color from black to yellow	---
11	Copper chromite 42% CuO 43% Cr_2O_3 10% BaO	3/16	3/16	Harshaw	Moderate bubbling, then complete decomposition	Rapid complete decomposition	Pellet cracked; color from black to green	Low (untreated or fired)
12	Copper chromite 80% Cu 16% Cr_2O_3	1/8	1/8	Harshaw	Violent disintegration of pellet	Very slow bubbling	Shrunk	Low (untreated pellet; partly disintegrated)
13	Copper chromite 10% Cu	1/8	1/8	Harshaw	Slow bubbling, then violent complete decomposition	Rapid bubbling	Color from green to brown	---

IMPREGNATED PELLETS

Sample	Catalyst	Size (inches) Diam.	Length	Manufacturer	Spot Test Activity[1] Untreated	Fired	Effect of Firing (1000°F)	Decomposition[2] Rate (ml/min)
14	Palladium .2% Pd on silica	(4-8 mesh)		Grace	Slow bubbling	---	Support shattered	---
15	Palladium .5% Pd on granular carbon	(4-8 mesh)		Engelhard	Rapid, complete decomposition; vapor binding	---	Support oxidized	Low (untreated pellet; floated on H_2O_2)
16	Palladium .5% Pd on alumina	1/8	1/8	Engelhard	Rapid, complete decomposition; vapor binding	Moderate bubbling	Color from gray to black	Low (untreated)
17	Platinum	1/8	3/16	Houdry	Slow bubbling	Rapid, complete decomposition; pellet disintegrated to powder	Pellet cracked	---
18	Silver	1/8	3/16	Harshaw	Rapid, complete decomposition; vapor binding	Moderate bubbling	Color from gray to ivory	1.3 (untreated)

POSSIBLE SUPPORTS

Sample	Catalyst	Size (inches) Diam.	Length	Manufacturer	Spot Test Activity[1] Untreated	Fired	Effect of Firing (1000°F)	Decomposition[2] Rate (ml/min)
19	Molecular Sieve 5A	1/8	1/4	Linde	Rapid bubbling	None	None	---
20	Molecular Sieve 13X	1/8	1/4	Linde	Slow bubbling	None	Pellet expanded	---
21	Silicon Carbide	1/8	3/16	Harshaw	None	---	---	---

---

[1] Effect of sample on one drop of 98% H_2O_2.

[2] Used one pellet and 10 ml. 98% H_2O_2 initially at 70°F.

[redacted]

[redacted]

(3) Impregnated Pellets

Since difficulties were encountered with disintegration of catalyst pellets prepared as compacted and fired composites, the impregnation of refractory magnesia pellets was studied. Solutions containing calcium permanganate; barium and manganese nitrates; barium, manganese, and lead nitrates; vanadate ion; and molybdate ion were used to impregnate the magnesia. The pellets were then spot tested for catalytic activity with one drop of 98% H_2O_2. The calcium permanganate impregnated pellet showed only slow bubbling and the other four pellets had even less activity. Nevertheless, the materials impregnated into these pellets are known to be active. Further studies are required to explore the impregnation of magnesia and other pellet-type supports. Since various products of the impregnation-firing procedure are possible, knowledge of the effect of firing temperature and ratio of solution components is needed. The same situation has been encountered for mixed-oxide coatings on inert screen supports (page 21).

[redacted]

SECTION III

ROCKET ENGINE TESTS

The evaluation of the catalyst performance during actual motor operation was carried out under subcontract with the Walter Kidde and Company, Inc., Belleville, New Jersey. This part of the program had two basic purposes. The first of these involved motor screening tests on a variety of catalyst configurations and materials. These tests were designed to screen catalysts for possible use in the motor demonstration test program.

The motor demonstration tests included operation (a) at high chamber pressure and high throughput, (b) with high temperature H_2O_2 feed, (c) at a variety of chamber pressures and throughput conditions for correlation design information, (d) for extended time to measure catalyst life, and (e) with low temperature H_2O_2 feed.

1. INITIAL MOTOR SCREENING TESTS

Initial screening tests were performed to evaluate those catalysts which were found to be most active in the laboratory studies. The surface treated, 70% silver, 30% palladium by weight catalyst screens gave most encouraging performance in the laboratory phase, therefore, catalyst packs were designed and fabricated using these catalyst screens together with the common silver catalyst screens and 95% nickel-5% manganese filler screens.

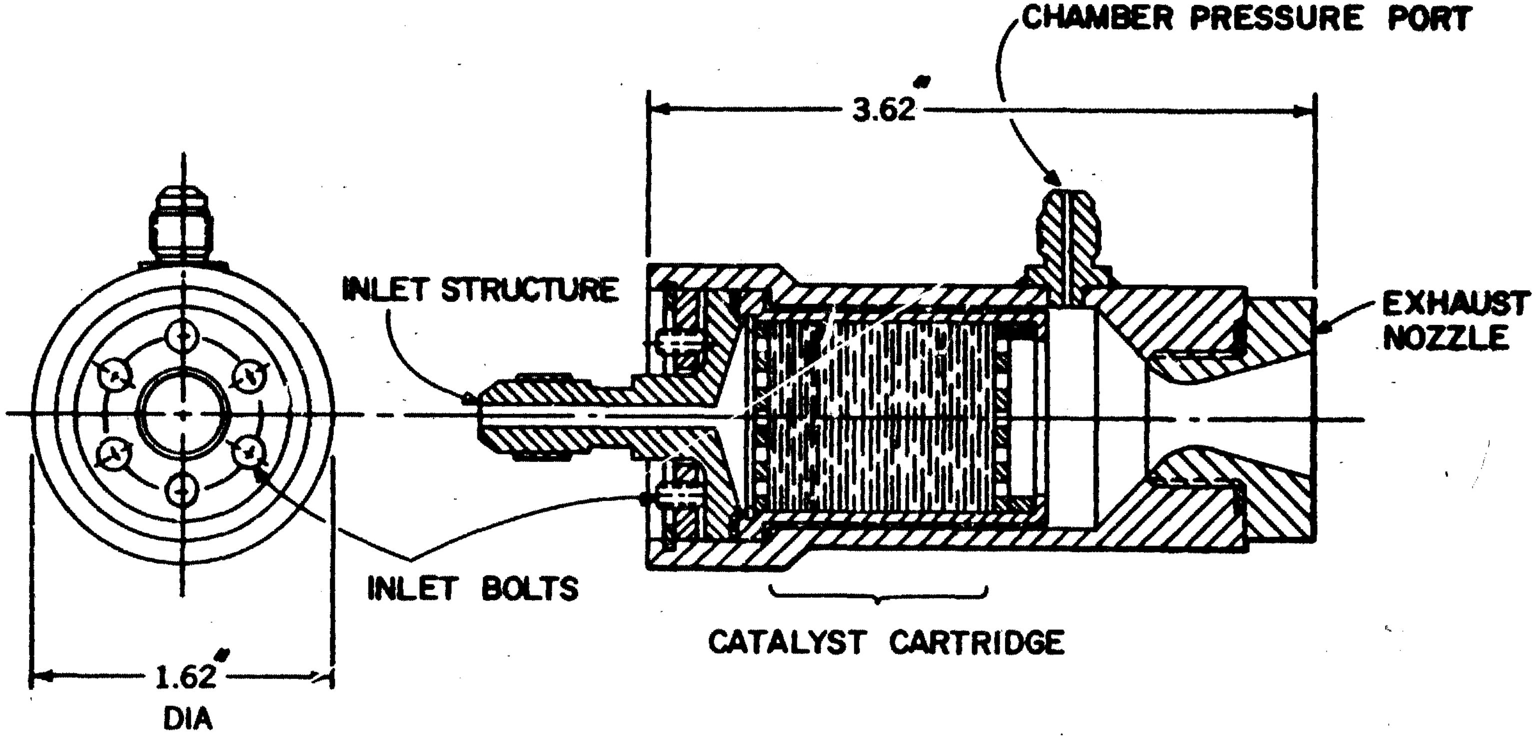
The catalyst screens were packed into cartridges and then sent to Walter Kidde and Company, Belleville, New Jersey, for testing in a 40 pound thrust motor. Pressure, temperature, thrust, initial startup, and other performance characteristics were recorded. At the completion of the motor tests, the cartridges were returned to FMC for laboratory measurements and testing of the catalyst screens.

In addition, a screening test was carried out with a catalyst pellet developed by FMC under an earlier program (8). The principle active ingredients of this pellet were MnO_2 and cobalt metal. Additional components were added to provide porosity and binding to the pellets.

a. Thrust Motor

The 40 lb. thrust motor used in these tests is shown in Figure 1. The inlet structure can be separated from the remainder of the motor by removal of the inlet bolts. This permits the catalyst cartridge to be withdrawn from the motor. The port for chamber pressure measurements is indicated on the figure. It enters the chamber between the end of the catalyst cartridge and the fitting for the exhaust nozzle. The exhaust nozzle is shown at the extreme right. It was not changed during the tests with this motor.

Figure 1



40# 98% H_2O_2 THRUST CHAMBER USED IN SCREENING TEST STUDIES

b. Catalyst Preparation

The silver-30% palladium 20 and 40 mesh catalyst screens were treated prior to use according to the procedure listed below.

A. Preparation of Screen

1. The screen was degreased in a vapor degreaser containing perchloroethylene.

2. The screen was then sandblasted with a 54 grit aluminum oxide at 60-80 psi.

B. Acid Treatment of Screen

1. A 1" square piece of 20 mesh, 0.014 mil, 70% Ag-30% Pd alloy, wire screen was dropped into 500 cc concentrated nitric acid and allowed to dissolve. The sandblasted screen was dipped into the nitric acid solution containing the dissolved screen and moved about in the liquid for approximately 30 seconds. It was then removed and allowed to drain as thoroughly as possible.

2. The screen was then placed in the oven at a temperature of 400° F for 20 minutes; upon its removal the screen was quite dark and rather heavily coated. It was then dipped a second time following the same procedure as above and again heated for 20 minutes at 400° F.

C. Samarium Nitrate Treatment of Screen

1. The screen was next immersed into a solution of 20% by weight of samarium nitrate until thoroughly wet, removed from the solution and allowed to drain thoroughly.

2. The material was then heated for 20 minutes for 720° F. This procedure was repeated until seven (7) dips and seven (7) heatings had been completed.

3. Since some areas of the screen openings were generally blocked, the screen was brushed with a stiff brush.

The silver catalyst screens used in this program were also cleaned, sandblasted, acid treated, and coated with samarium oxide. The nickel-5% manganese filler screens were used without further treatment. Both treated catalyst screens and untreated filler screens were punched to one inch diameter discs for use in the motor cartridge.

The catalyst pellets tested in the last of the initial motor screening tests were prepared by a procedure developed by FMC under an earlier program (8). The composition of this pellet, type 113, was as follows:

Cobalt	68.6 weight %
NaCl	17.1
MnO_2	5.9
Fe_2O_3	3.6
CuO	2.4
$Ca_3(BO_3)_2$	1.2
Na_2CO_3	1.2

The components were thoroughly mixed and then compressed at 50,000 psi into 1/8" diameter, 3/16" long pellets using an automatic pellet press. The pellets were then fired in air at 2100°F for 30 minutes in an electric furnace.

c. Catalyst Packing

The catalyst cartridge is shown in greater detail in Figures 2 and 3. The first step in loading the cartridge with catalyst screens was to place the retainer plate inside the shell flat against the lip at the bottom of the shell. Next the catalyst screens were added one-by-one on top of the retainer plate. Each screen was rotated somewhat from the orientation of the previous screen to provide a uniform distribution of catalyst within the cartridge. After one-third of the screens had been loaded, a 4" long, 1" diameter packing ram was inserted in the cartridge and the screens were compressed to 4000 psi on a laboratory bench press. The ram was removed and additional screens were added. The pack was again compressed to 4000 psi after 2/3 of the screens had been loaded into the cartridge. After all the screens were loaded, the anti-channel baffle and injection plate were placed above the catalyst screens. Then while the pack was compressed to 4000 psi with a packing ram only 1/2" in diameter, the snap ring was inserted into the slot just inside the front of the cartridge shell.

Figure 2

CATALYST PACK COMPONENT CONFIGURATION

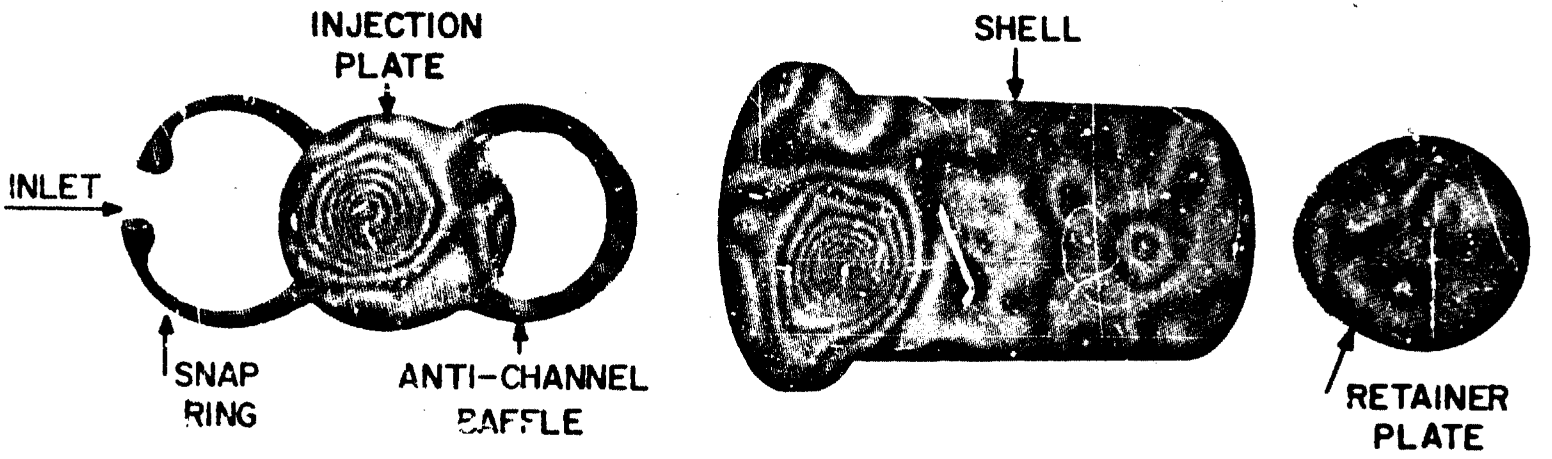
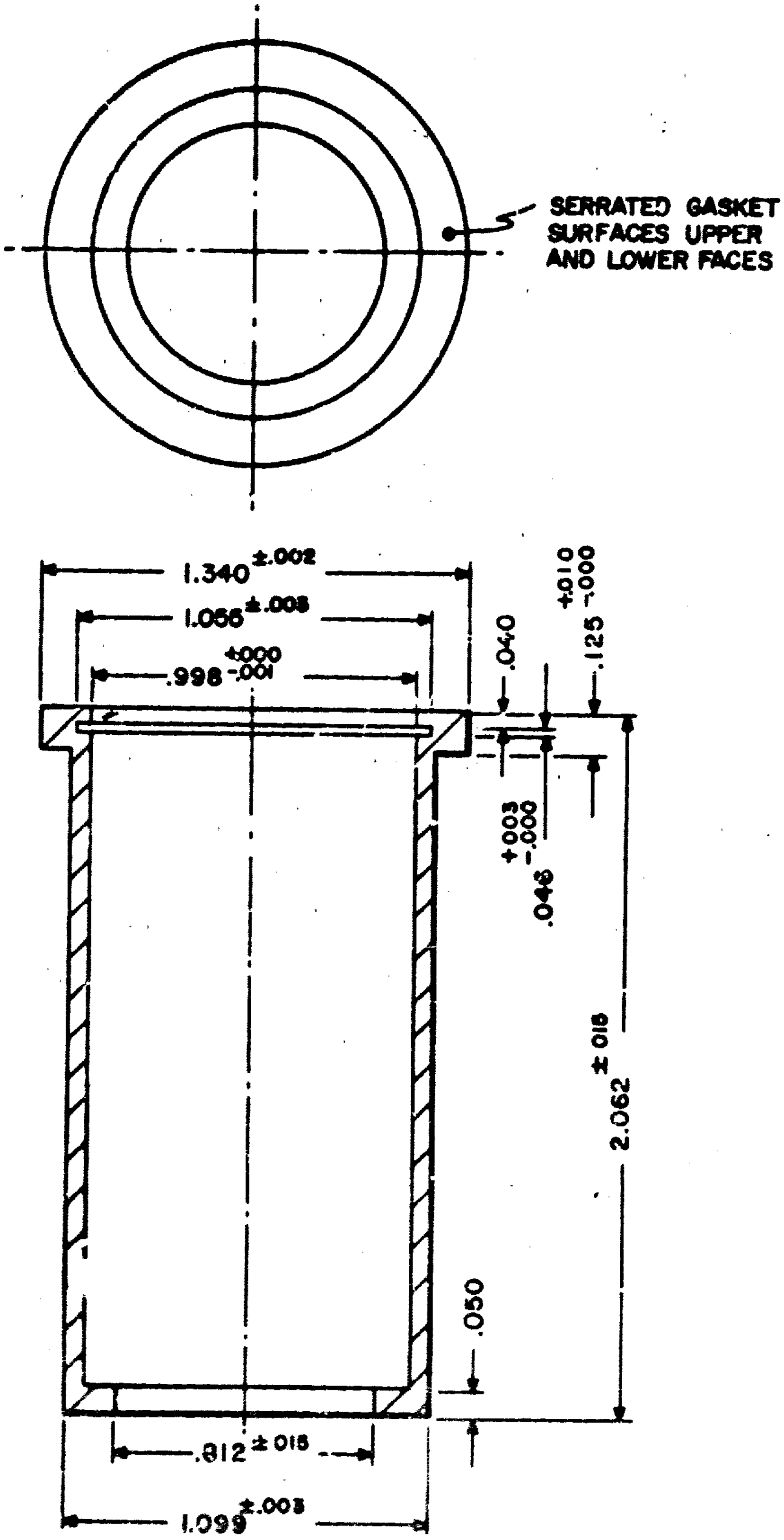


Figure 3

CATALYST CARTRIDGES USED IN THE CATALYST SCREENING TESTS



d. General Configuration Considerations

An important consideration in designing the catalyst packs is to properly relate the type of screens used to the temperature profile (9) that will be achieved in the motor. Previous motor tests with 98% H_2O_2 (7, 10) revealed that the inlet portion of the pack is relatively cool compared to the exhaust region during motor operation. In fact, the theoretical decomposition temperature is not reached until about 1/4" to 3/8" into the bed. If the catalyst pack operates properly, the remainder of the pack is heated to a rather uniform temperature, approximately the theoretical decomposition temperature of the 98% H_2O_2.

Because of this temperature profile it is possible to use very active but less thermally stable screens in the inlet region of the pack. By this means good starting characteristics can be achieved. However, it is critical that these screens be kept out of the regions in the pack subjected to the high temperatures, or screen melting will occur.

Previous FMC studies have shown that ten to sixteen 20 mesh silver screens can be used at the inlet of a catalyst pack for 98% H_2O_2. In fact, a pack prepared with sixteen, 20 mesh silver screens containing only inert screens below the silver resulted in full decomposition of the H_2O_2 on start-up.

In progressing through the pack the H_2O_2 soon reaches a high temperature. It is probable that a large variety of catalysts are sufficiently active to decompose the remaining heated H_2O_2 in this hot zone of the pack. On the other hand, it is essential that the catalysts maintain their physical properties at the high temperature. Thus the criterion of thermal stability seems more important than activity in the high temperature section of the pack.

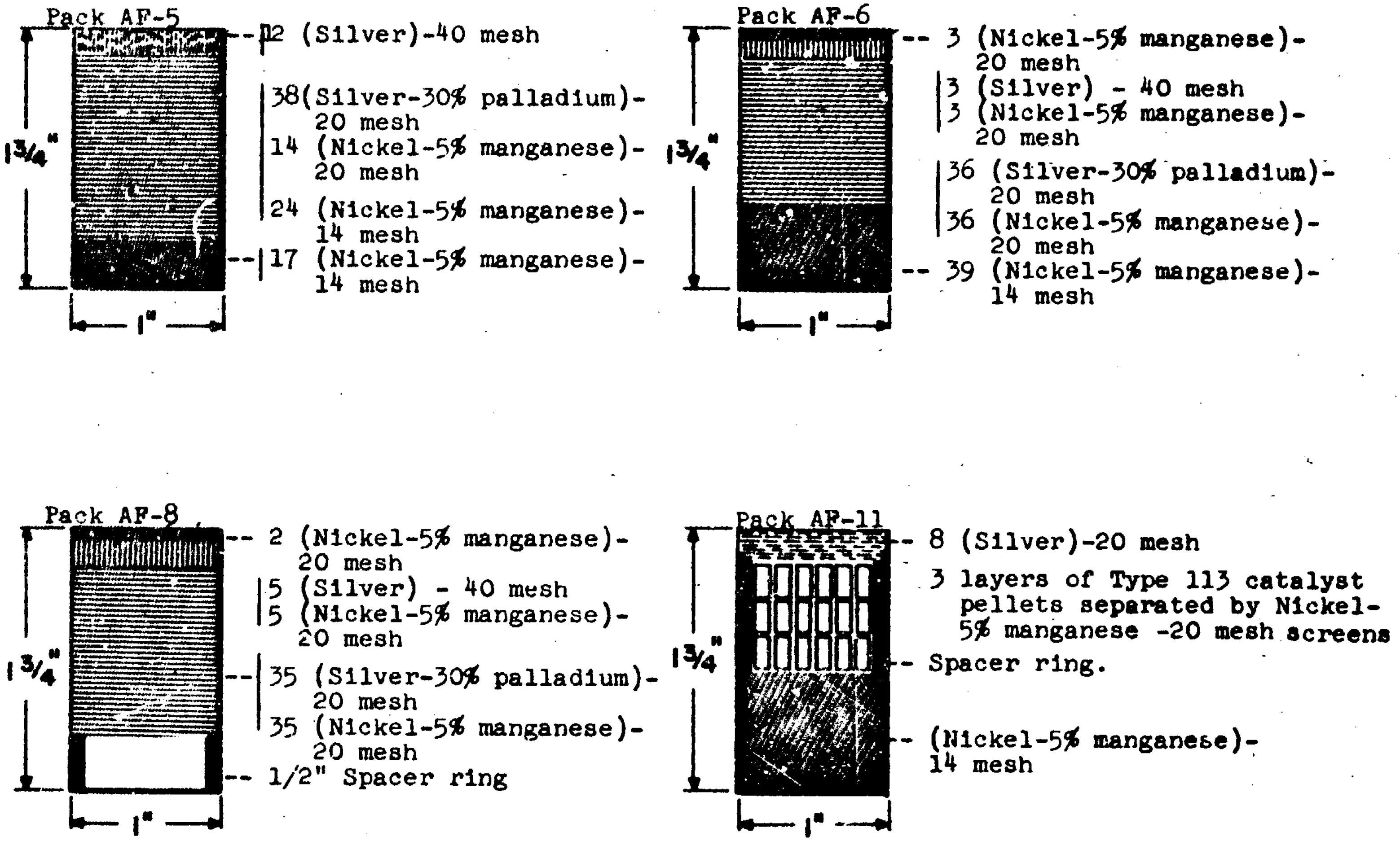
e. Catalyst Pack Configurations

The catalyst configurations of some representative catalyst packs used in the initial motor screening tests are shown in Figure 4. Packs AF-5 and AF-6 operated the best of the configurations tested. Pack AF-8 contained a spacer ring below the catalyst pack to allow a shorter pack without requiring a different motor cartridge.

Pack AF-11 also contained a spacer ring, which, in this case, protected the catalyst pellets from the 4000 psi pack compression. A total of 65 pellets were distributed among three layers. Nickel-5% manganese filler screens were used to separate the layers and thus maintain the pellet alignment during motor testing. Each pellet was 1/8" in diameter and 3/16" in length.

Figure 4

Representative Catalyst Pack Screen Configurations Used in Initial Motor Screening Tests



Note: Anti-channel baffle ring was placed after the first 15 screens in each pack.

A complete summary of all the catalyst pack configurations tested in the initial motor screening tests appears in Table IX. In the first column to the left appear the catalyst pack designations. The next eight columns indicate the numbers of each type of 1" diameter screens used in the catalyst packs. These columns are arranged in order from left to right so the inlet screens appear to the left and the exhaust end of the pack is at the right. The next column indicates the changes and re-use of catalyst screens for some of the packs. The last column gives the pack compression for each pack.

f. Test System

A schematic of the initial screening test system appears in Figure 5 . The 98% H_2O_2 for the test was contained in a 5 gallon tank shown to the left in the schematic. The feed pressure of the H_2O_2 was maintained by nitrogen gas which entered the top of the tank. The test was started by applying an electrical impulse to the remotely operated propellant valve. The feed, inlet, and chamber pressures were measured by transducers. A copper-constantan thermocouple was used to measure the inlet temperature and a chromel-alume thermocouple determined the chamber temperature.

The thrust motor was mounted on a cantilever-type load cell which enabled the measurement of thrust. The load cell was calibrated using weights placed on top of the motor. A quick disconnect was used to separate the H_2O_2 tank from the remainder of the system so it could be weighed before and after each steady state test. In this way the propellant flow during steady state operation was determined.

The test stand itself appears in Figure 6 . The motor is mounted to the end of the cantilevered frame which is fixed (toward the bottom of the picture) to the remainder of the dark-colored test stand. The load cell is contained within the test stand. The pressure transducers, thermocouples, and propellant valve are also indicated in the figure.

g. Test Procedure

All tests were conducted using FMC Corporation supplied 98% H_2O_2 which was filtered to 10 microns prior to introduction into the test system. The pressurant used was nitrogen gas, per MIL-BB-N-411B, Grade B, type 1, class 1 filtered to 10 microns prior to introduction into the test system.

The testing of the catalyst packs was performed in the following sequence using a static fuel pressure of 530 psig.

TABLE IX

SUMMARY OF CATALYST DATA FOR INITIAL MOTOR SCREENING TESTS

Catalyst Pack	Catalyst Screen Configuration (Inlet) Nickel 40 mesh	Silver 40 mesh	Silver 20 mesh	Silver-5% Palladium 40 mesh	Silver-5% Palladium 20 mesh	Silver-30% Palladium 20 mesh	Nickel-5% Manganese 20 mesh	Nickel-5% Manganese 14 mesh (Exhaust)	Catalyst Screen Sources and Changes	Pack Compression (psi)
AF-1	2	---	---	10	12	20[1]	22	11	New Pack	2500
AF-2	3	---	---	---	20	15[1]	16	26	New Pack	2500
AF-3	---	15	---	---	15	12[1]	---	87	AF-2 screens used	4300
AF-4	2	---	---	10	12	20[1]	22	47	Nickel-manganese added to AF-1	5200
AF-5	---	12	---	---	---	38[1]	14	41	New Pack	4800
AF-6	---	3[1]	---	---	---	36[1]	42[3]	39	New Pack	7200
AF-7	---	---	---	4	5	41[1]	41	24	New Pack	7000
AF-8	---	5[1]	---	---	---	35[1]	42[4]	---	New Pack	6400
AF-9	----	12	---	---	---	42[2]	23[4]	---	New Pack	5400
AF-10	---	12	---	---	---	38[1]	14	61	Silver-palladium and some nickel-manganese from AF-7, others new	4100
AF-11[5]	---	---	8	---	---	---	25	24	New Pack	3900

---

[1] Alternated with nickel-5% manganese filler screens.

[2] Interspaced with 21 nickel-5% manganese filler screens, one filler screen after each two catalyst screens.

[3] Three screens placed at front of pack.

[4] Two screens placed at front of pack.

[5] Also employed 65 pellets between the 20 mesh silver screens and the remainder of the pack. The pellets were 1/8" in diameter and 3/16" long.

Tests conducted by Walter Kidde Co.

Figure 5

SCHEMATIC OF COLD START TEST STAND

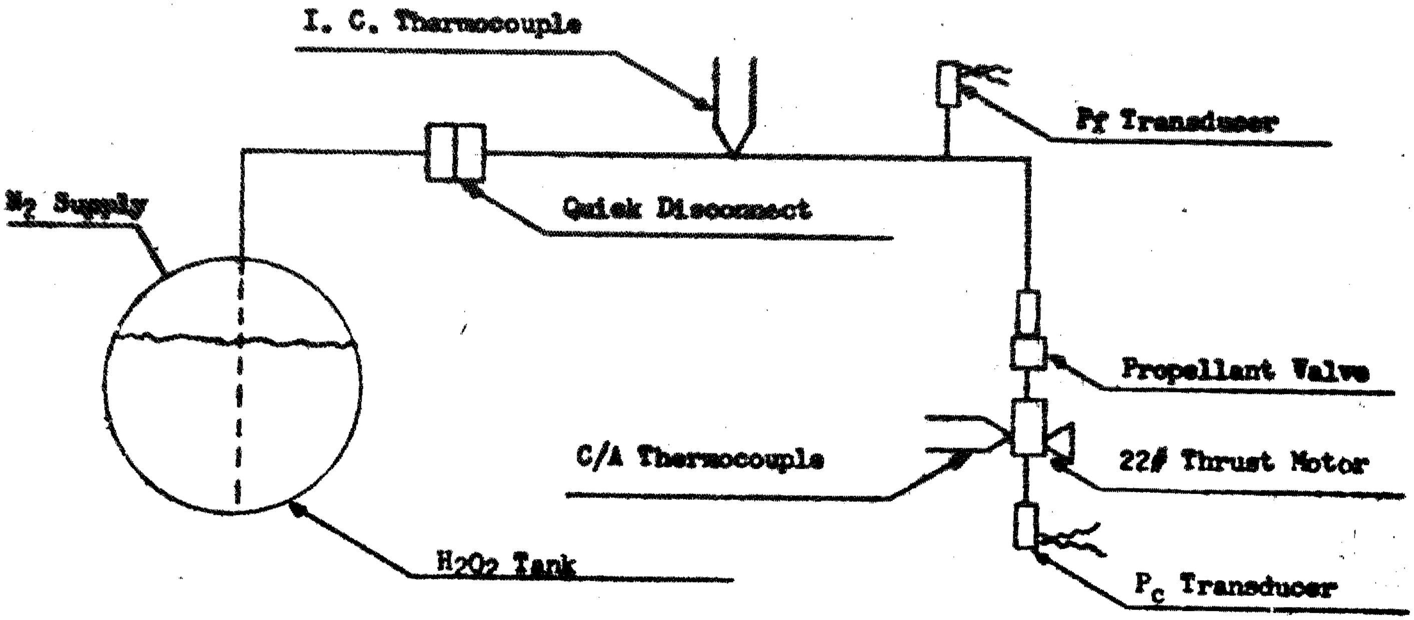
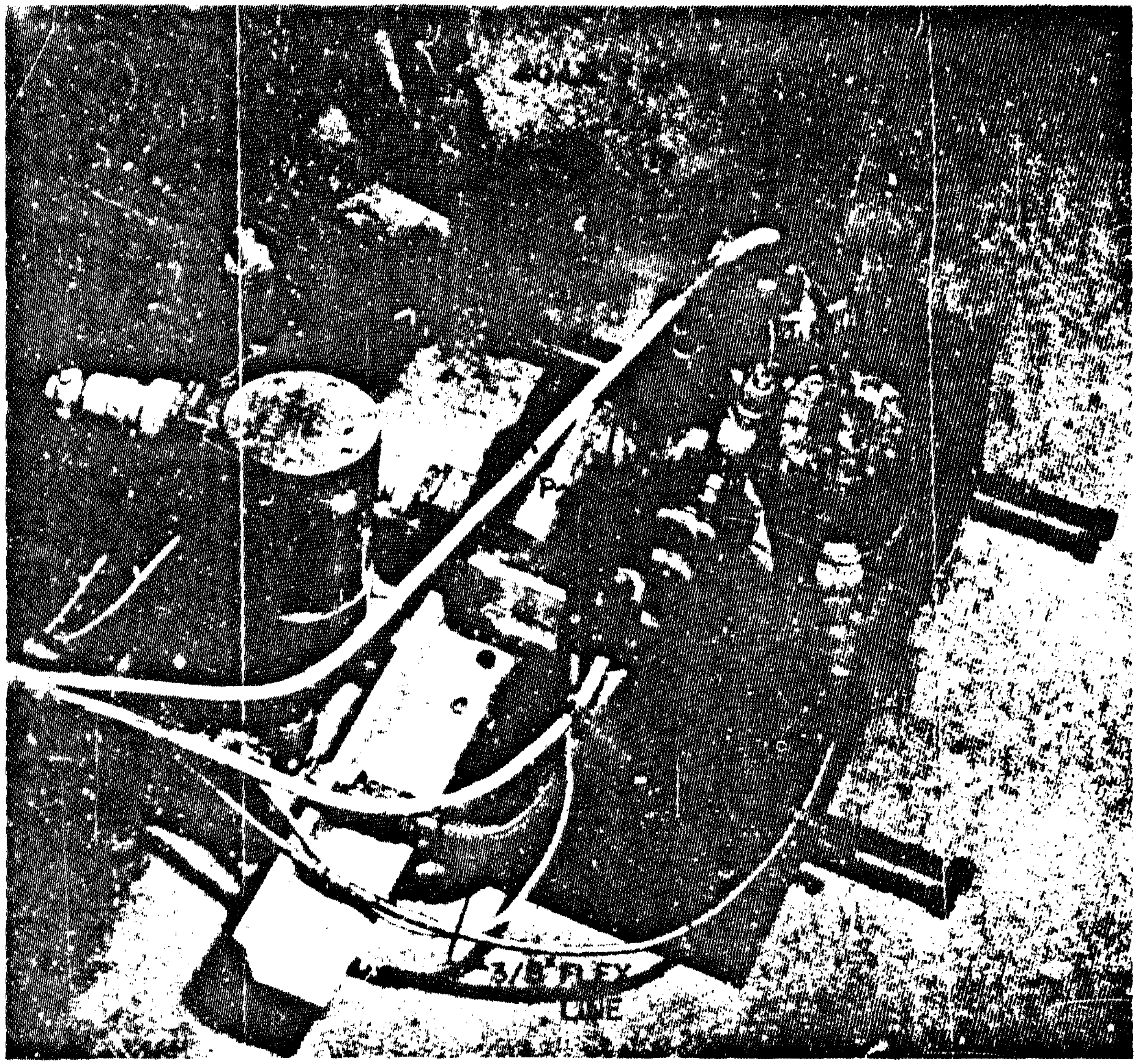


Figure 6



TEST STAND – INITIAL SCREENING
FMC 98 % H_2O_2 MOTOR TESTS
CONTRACT- AF04 (611)-11208 SUB NO.1

NOMENCLATURE

- P_1 - PROPELLANT INLET PRESSURE
- P_2 PROPELLANT PRESSURE MOTOR INLET
- P_3 CHAMBER PRESSURE
- T_1 PROPELLANT TEMP. MOTOR INLET
- T_2 CHAMBER TEMP.
- V_1 PROPELLANT VALVE
- LOAD CELL REGISTERS VERTICAL THRUST OF MOTOR, CALIBRATED USING WEIGHT ON TOP OF MOTOR.

1. The ambient temperature motor was pulsed three times at a pulse mode of 200 msec. on and three seconds off.
2. The motor was allowed to cool for ten minutes.
3. The motor was pulsed three hundred times at a pulse mode of 150 msec. on and 350 msec. off.
4. The fuel tank was then disconnected and weighed.
5. The fuel tank was reconnected and a 30 second steady state test was run. The fuel tank was then reweighed.
6. The motor was then allowed to cool to ambient temperature.
7. Steps 1 and 2 were repeated.
8. The motor was pulsed six times at a pulse mode of 150 msec. on and 350 msec. off.
9. Steps 6, 7, and 8 were repeated.
10. The motor was purged with nitrogen gas.

After the test of catalyst cartridge AF-1 resulted in extremely foggy exhaust, the test procedure described above was temporarily bypassed for preliminary testing of cartridge AF-2. This cartridge was tested at five different fuel pressures for five second steady state operations. Exhaust continued foggy with this cartridge and no data was recorded. The problem was traced to low catalyst pack compression and the described test procedure was resumed with cartridge AF-3.

The outputs of the test instruments were recorded with an oscillograph recorder at 8-10 inches per second paper speed as follows.

Chamber Pressure	300 psig
Motor Inlet Pressure	500 psig max.
Propellant Tank Pressure	600 psig
Thrust	40 lb. F
Propellant Temperature at Motor Inlet	+80°F ± 10°F
Valve Signal (Current)	1 Amp.

Instrument calibration was performed prior to each test using the above values as maxima at approximately four inches deflection.

h. Results of the Tests

The results for the initial motor screening tests are summarised in Table X. The pack numbers for the ten screen configurations and one pellet configuration are shown in the first column. The second column indicates the specific tests for which the data in the remaining columns is given: the first and third cycles of the 300 cycle portion of the test program, and the average of data taken at five different points during the steady stage tests. The specific impulse and the characteristic velocity of the exhaust gases (in feet per second) are represented by ISP and C* respectively.

Two columns to the right in the table show the time in milliseconds required to reach 10% and 90% of maximum chamber pressure at the start of the test and to decay to 90% and 10% at shutdown. These recorded start and shutdown responses are approximately 10 msec. greater than the true values. This has resulted because the line from the motor to the chamber pressure transducer was greater than minimum length (Figure 6), which causes a time lag in the measurement of chamber pressure. Remarks concerning the nature of the exhaust and the stability of motor operation appear in the last column.

Tables XXII to XXXI in the Appendix give more complete data for each initial screening test.

The three "warm-up" pulses constituted the first contact of the catalyst pack with 98% H_2O_2. The responses and decays of each pack for the first and third of these initial warm-up pulses are given in Tables XI and XII. Since the feed lines are not initially filled, the start transients recorded for the first pulse are greater than the actual motor response. The data for the second and third sets of warm-up pulses in the test procedure are also given. For tests AF-1 through AF-7, both the chamber pressure and thrust responses and decays are given. Only chamber pressure data is given for the remaining tests.

(1) Pack Compression

The first two packs (AF-1 and AF-2) produced foggy exhaust at startup indicative of incomplete decomposition due to loose packing of the screens in the catalyst pack. Loose screens allow the H_2O_2 to pass more directly through the catalyst pack, thus shortening the stay time in the pack and giving less total contact with catalyst surface. Both of these factors contribute to incomplete decomposition.

SUMMARY DATA SHEET COVERING THE INITIAL 98% H_2O_2 CATALYST SCREENING TESTS

TEST MOTOR, 1" BORE; THROAT DIAMETER 0.342 IN.

Pack No.	Test Seq.	Chamber Pres. psia	H_2O_2 Inlet Pres. psia	Cat. Pack Δ psi	H_2O_2 Inlet Temp. °F	Thrust 1 Atm. Exh.	H_2O_2 Flow lb/sec.	Pack Loading PSIM	ISP Sec.	Meas. C*	Start M Sec. 10%/90%	Decay M Sec. 90%/10%	Remarks
AF-1	1st cycle	265	361	96	75	29.7	---	---	---	---	54/90	14/54	Liquid spray
	3rd cycle	307	390	83	75	34.4	---	---	---	---	30/55	10/42	Cloudy
	30 sec. run	241	309	68	83	29.3	.408	31.2	71.8	1750	43/85	10/95	Exhaust slightly foggy
AF-2	1st cycle	N/A	N/A	---	---	---	---	---	---	---	---	---	Liquid spray
	3rd cycle	---	---	---	---	---	---	---	---	---	---	---	Started, but severe oscillations
AF-3	1st cycle	225	435	210	89	26.3	---	---	---	---	35/74	6/53	Liquid fog
	3rd cycle	259	438	204	88	25.8	---	---	---	---	14/23	8/53	Slight vapor
	30 sec. run	266	453	187	36	35.1	.241	18.4	---	3270	28/68	8/81	Clear exhaust, severe
AF-4	1st cycle	N/A	N/A	---	86	---	---	---	---	---	N/A	N/A	Liquid spray
	3rd cycle	204	439	235	86	24.3	---	---	---	---	21/50	3/41	Severe oscillations
	30 sec. run	244	457	213	86	33.4	.220	16.8	---	3286	30/68	4/69	Severe oscillations
AF-5	1st cycle	252	420	193	70	30.6	---	---	---	---	32/71	8/57	Slightly misty exhaust on start up
	3rd cycle	277	478	201	68	34.0	--	---	---	---	19/28	1/44	
	30 sec. run	295	464	169	67	36.7	.273	20.9	134.3	3201	30/72	4/52	Clear exhaust
AF-6	1st cycle	252	464	212	75	28.4	---	---	---	---	31/74	8/98	Slightly misty exhaust nozzle diam. 0.339
	3rd cycle	258	467	209	75	30.7	---	---	---	---	18/26	5/45	
	30 sec. run	290	476	186	75	35.5	.253	19.3	138.4	3322	37/74	5/70	Clear exhaust, good performance
AF-7	1st cycle	265	N/R	---	89	30.6	---	---	---	---	35/53	6/61	Wet cloud, nozzle diam. 0.339
	3rd cycle	279	N/R	---	90	32.6	---	---	---	---	18/40	5/42	Clear exhaust
	30 sec. run	303	474	171	92	36.4	.267	20.4	136.1	3289	39/76	51/65	Clear exhaust, good performance
AF-8	1st cycle	289	457	168	N/R	33.2	---	---	---	---	38/84	7/77	Nozzle diam 0.330
	3rd cycle	287	458	171	N/R	32.7	---	---	---	---	21/31	6/57	Slight instability at end
	30 sec. run	319	473	154	N/R	34.6	.267	20.4	129.5	3462	35/77	N/R	Stable test
AF-9	1st cycle	295	478	183	77	33.3	---	---	---	---	38/78	5/67	Oscillations, nozzle diam. 0.338
	3rd cycle	292	482	190	77	32.7	---	---	---	---	23/32	8/70	Oscillations
	30 sec. run	299	450	151	77	32.4	.261	19.9	124.3	3320	42/85	3/120	Oscillations
AF-10	1st cycle	222	413	191	70	27.4	---	---	---	---	39/81	7/52	Slightly misty, nozzle diam. 0.339
	3rd cycle	254	427	173	70	30.2	---	---	---	---	29/51	7/53	
	30 sec. run	292	464	172	70	33.5	.264	20.2	127.0	3205	37/80	4/58	Oscillations up to 10 sec.
AF-11	1st cycle	30	60	30	N/R	N/R	---	---	---	---	72/165	20/39	Foggy exhaust, nozzle diam. 0.339
	3rd cycle	111	167	56	N/R	N/R	---	---	---	---	32/53	13/88	Foggy exhaust
	30 sec. run	328	439	111	N/R	35.5	.297	22.7	123.0	3201	26/62	9/60	Pulsed to start, test stable.

Notes: PSIM , lbs. of propellant/inch² of catalyst frontal area/min.

The theoretical C* is 3340 for 75°F feed

N/A denotes no start.

N/R denotes not recorded.

Screen sequences in the catalyst packs are shown in Figure ______.

Tests conducted by Walter Kidde Co.

TABLE XI

98% H_2O_2 INITIAL SCREENING TESTS

Starting Behavior of Catalyst Packs AF-1 through AF-6

Cat. Pack No.	Cycle No.	Mil. Sec. to 90% Thrust Response	Mil. Sec. to 90% Chamber Response	Mil. Sec. for Thrust Decay to 10%	Mil. Sec. for Chamber Decay to 10%
AF-1	1	N/A	N/A	N/A	N/A
	3	56	60	34	38
	1	N/A	N/A	N/A	N/A
	3	45	46	42	42
	1	N/A	N/A	N/A	N/A
	3	25	49	41	54
AF-2	1	N/A	N/A	N/A	N/A
AF-3	1	N/A	N/A	N/A	N/A
	3	17	27	34	41
	1	N/A	N/A	N/A	N/A
	3	27	25	25	49
	1	N/A	N/A	N/A	N/A
	3	23	28	20	42
AF-4	1	N/A	N/A	N/A	N/A
	3	23	30	23	48
	1	N/R	N/R	N/R	N/R
	3	N/R	N/R	N/R	N/R
AF-5	1	115	104	44	79
	3	20	31	30	43
	1	70	97	24	49
	3	20	28	28	48
	1	134	137	10	39
	3	28	27	30	49
AF-6	1	229	220	112	120
	3	29	32	35	36
	1	88	100	22	45
	3	27	33	23	45
	1	128	132	23	49
	3	26	30	24	41

N/A - Denotes that the motor did not start.

N/R - Test discontinued because of severe oscillations.

TABLE XII

98% H_2O_2 INITIAL SCREENING TESTS

Starting Behavior of Catalyst Packs AF-7 through AF-11

Cat. Pack No.	Cycle No.	Mil. Sec. to 90% Thrust Response	Mil. Sec. to 90% Chamber Response	Mil. Sec. for Thrust Decay to 10%	Mil. Sec. for Chamber Decay to 10%
AF-7	1	N/A	N/A	N/A	N/A
	3	21	40	22	42
	1	140	160	36	85
	3	22	38	29	46
	1	N/A	N/A	N/A	N/A
	3	21	26	18	42
AF-8	1	---	221	---	98
	3	---	57	---	53
	1	---	N/A	---	N/A
	3	---	33	---	60
	1	---	N/A	---	N/A
	3	---	33	---	48
AF-9	1	---	N/A	---	N/A
	3	---	41	---	55
	1	---	87	---	62
	3	---	35	---	49
	1	---	139	---	53
	3	---	34	---	48
AF-10	1	---	N/A	---	N/A
	3	---	55	---	35
	1	---	N/A	---	N/A
	3	---	58	---	52
	1	---	N/A	---	N/A
	3	---	5	---	26
AF-11	1	---	N/A	---	N/A
	3	---	91	---	72
	1	---	210	---	82
	3	---	27	---	64
	1	---	N/A	---	N/A
	3	---	47	---	59

N/A - Denotes that the motor did not start.

Catalyst pack AF-1 was repacked as pack AF-4 with no change except the addition of Ni-5%Mn filler screens to the exhaust (hot zone) end of the pack. By this means the packing pressure required to load the pack into the cartridge was nearly doubled to 4100 pounds. As a result, AF-4 produced the clear exhaust associated with relatively complete decomposition of H_2O_2. The configuration of pack AF-2 was also packed at a much higher pressure (AF-3) and also yielded complete decomposition.

(2) Use of Low-Melting Screens

The configurations of packs AF-1 to AF-4 contained silver-5% palladium catalyst screens (Table IX). These screens have a melting point of 1780°F, which is about 20° higher than that of the silver screens, but still far lower than the silver-30% palladium screens (mp. 2120°F). Complete decomposition of the H_2O_2 feed was not achieved for packs AF-1 and AF-2, so an adequate test of the silver-5% palladium screens was not obtained. However, the catalyst packs in cartridges AF-3 and AF-4 both resulted in melting of some of the silver-5% palladium screens near the inlet of the pack. In view of the known catalyst pack temperature profiles it seemed probable that a 1/4" to 3/8" depth of lower melting screens such as silver or silver-5% palladium could be used in the inlet portion of the pack. However, the results with packs AF-3 and AF-4 indicated this region of lower temperatures is limited to about 1/8" at 20 psim pack loading.

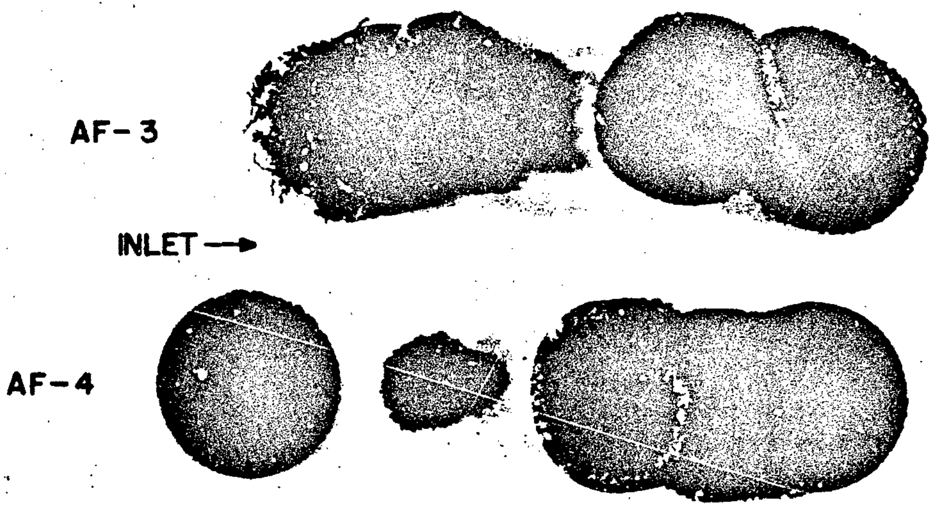
As the screens of packs AF-3 and AF-4 melted, the molten material was carried further down the pack. Distinct clogging of some areas occurred. Severe oscillations in the chamber pressure were observed and further tests on these packs were discontinued. Figure 7 shows the screens that were removed from catalyst packs AF-3 and AF-4. The screens have been separated to show clearly where the melting occurred. The damaged screens indicated that melting was most extensive where the H_2O_2 flow had been forced inward by the baffle ring.

(3) Best Catalyst Packs

Catalyst packs AF-5 and AF-6 (Figure 4) were prepared with fewer low-melting screens in the inlet section than packs AF-3 and AF-4. These packs resulted in the best performance of any of the initial motor screening tests. Basically the same configurations were found to give the best results in the high-pressure-high pack loading tests later in the program.

Figure 7

SCREENS FROM CATALYST PACKS AF-3 AND AF-4 AFTER MOTOR TESTS



SCREENS HAVE BEEN SEPARATED TO SHOW THE PORTIONS OF THE PACKS THAT MELTED

Catalyst pack AF-5 contained 13 pieces of 40 mesh silver catalyst screen at the pack inlet. This pack gave a clear exhaust on the first pulse. Starting transients are shown in Table XI. Because of the delay in filling the fuel lines, good transients on the first pulse are difficult to measure. Figure 8 shows the third pulse of the initial warm-up sequence for the AF-5 catalyst pack. Time reads from right to left on the figure. At the top of the page the initiation of the H_2O_2 flow is indicated by the valve signal and the valve voltage, which designate the instrumental signal to open the valve and the actual response of the valve. The thrust trace is shown with the points marked where the response of the motor reached 90% of maximum thrust at startup and where decay reached 10% at shutdown. The temperature, inlet pressure, and chamber pressure traces are also shown. Chamber pressure and thrust remained steady throughout the pulse.

The beginning and end of the 30 second steady state test for pack AF-5 are shown in Figure 9 . The notations on the figure are substantially the same as those on Figure 8 . The fuel and inlet pressure readings are not identical because of pressure drops resulting from valves the feed lines.

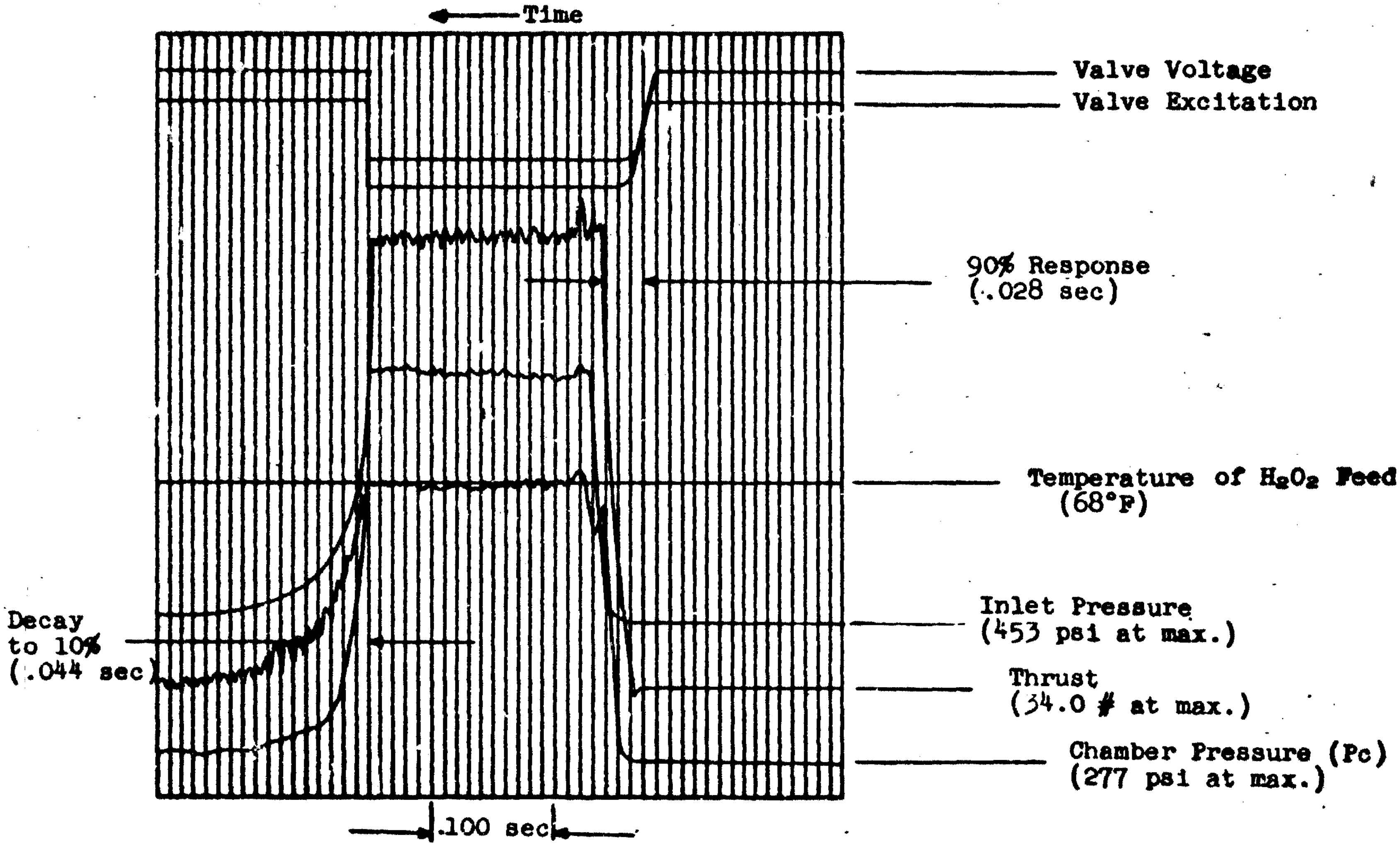
The specific impulse realized was 134. 3 sec at a chamber pressure of 295 psia, which was 96% of theoretical. Figure 10 shows the specific impulses of tests AF-5 through AF-10 and indicates the theoretical values by the dark line curve. The characteristic velocity (C*) for pack AF-5 averaged 3201 feet per second.

Figure 11 shows the first of three warm-up pulses prior to the first six cycle run on pack AF-5. This section of the test procedure occurred after the 300 cycle run and the 30 second steady-state test. Figure 12 gives the first two cycles of the second six cycle run, which concluded the test program for pack AF-5. The notations on these two figures are the same as those described previously. The actual reduced data for these tests are given in Table XXV in the Appendix.

Figure 13 shows the internal parts of pack AF-5 after the test. From the left appear the snap ring which held the pack in the cartridge, the injection plate, and an anti-channel baffle. Next appear the 40 mesh silver catalyst screens of the inlet section of the pack. Following are the 20 mesh,silver-30% palladium catalyst screens alternated with 20 mesh nickel-5% manganese filler screens. A second anti-channel baffle is also shown. To the right are the 20 and 14 mesh nickel-5% manganese filler screens which made up the exhaust section of the pack. The retainer plate which held the exhaust section in the cartridge appears at the right end. No damage of the screens was apparent.

FIGURE 8

THIRD WARM-UP PULSE WITH 98% H_2O_2 USING CATALYST PACK AF-5 IN 40# F UNIT



Tests conducted by Walter Kidde Co.

Figure 9

INITIAL SCREENING TEST AF-5
START AND SHUTDOWN OF 30 SECOND
STEADY STATE TEST WITH 67°F FEED
98.2% H_2O_2 AND 40 POUND THRUST MOTOR

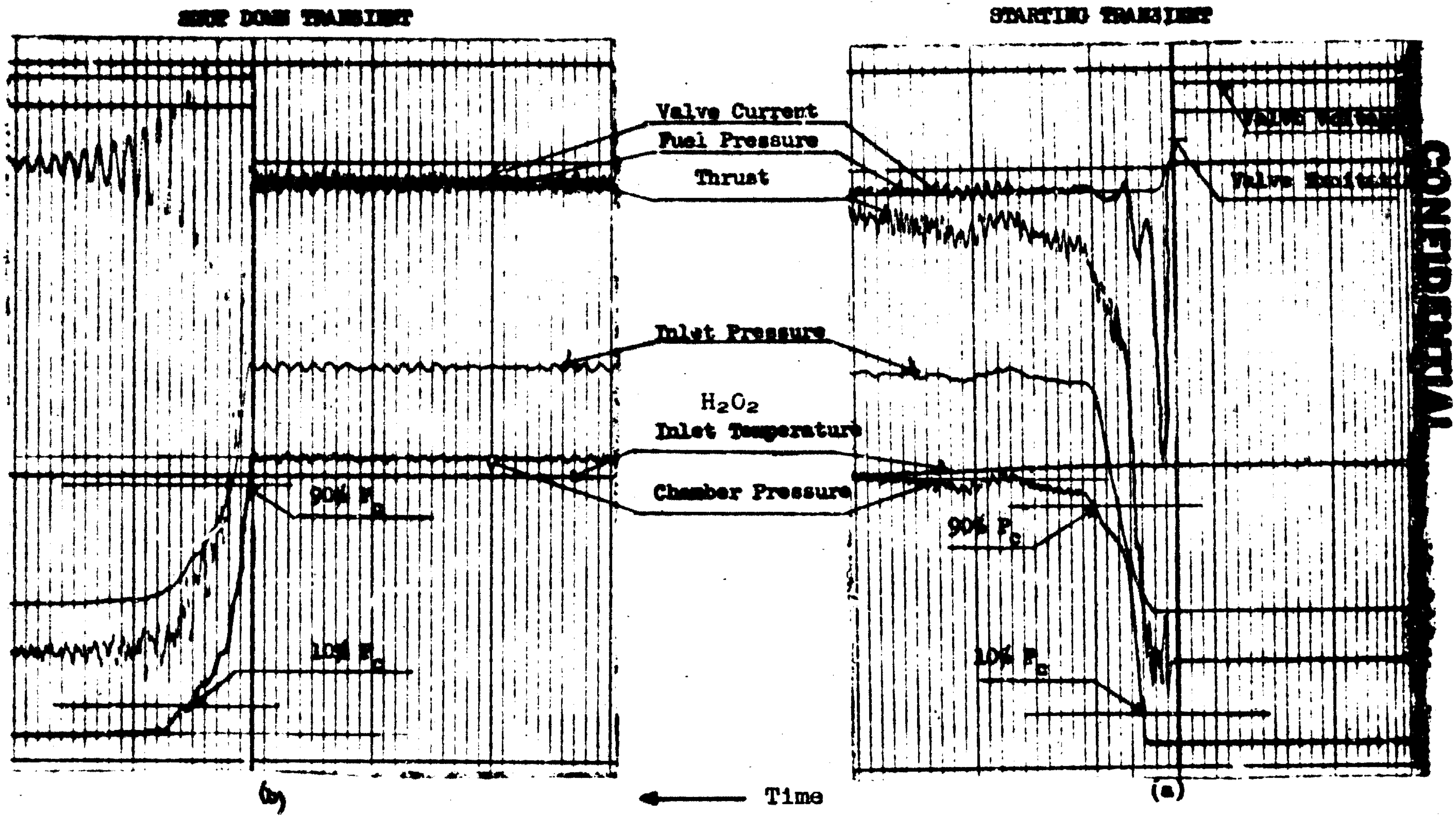


Figure 10

COMPARISON OF SPECIFIC IMPULSE REALIZED IN TEST RUNS AF-5 TO AF-11 WITH THEORETICAL VALUES

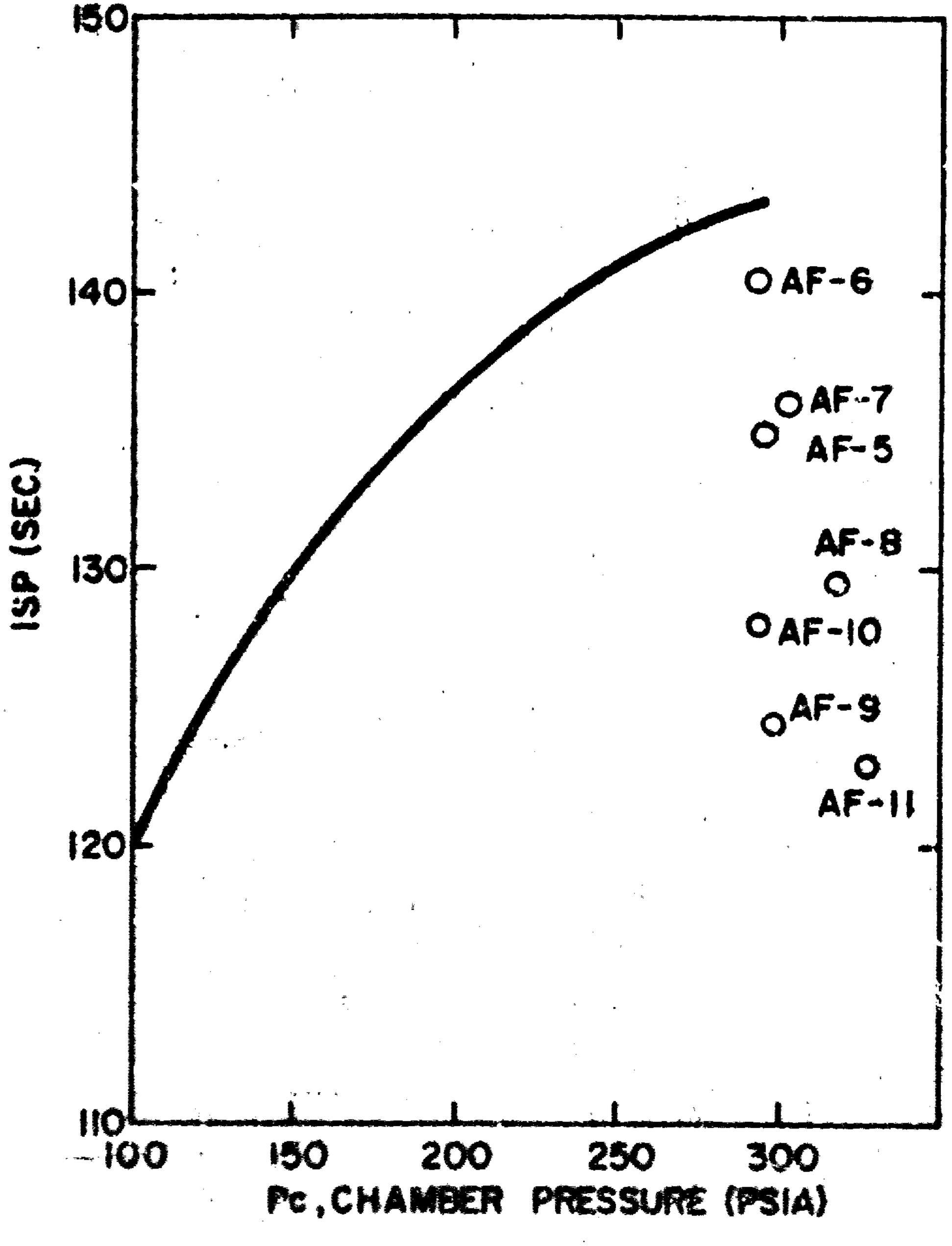


Figure 11

INITIAL SCREENING TEST AF-5
FIRST WARM-UP PULSE PRIOR
TO FIRST SIX CYCLE TEST
WITH 75°F FEED
98.2% H_2O_2 AND 40 POUND THRUST MOTOR

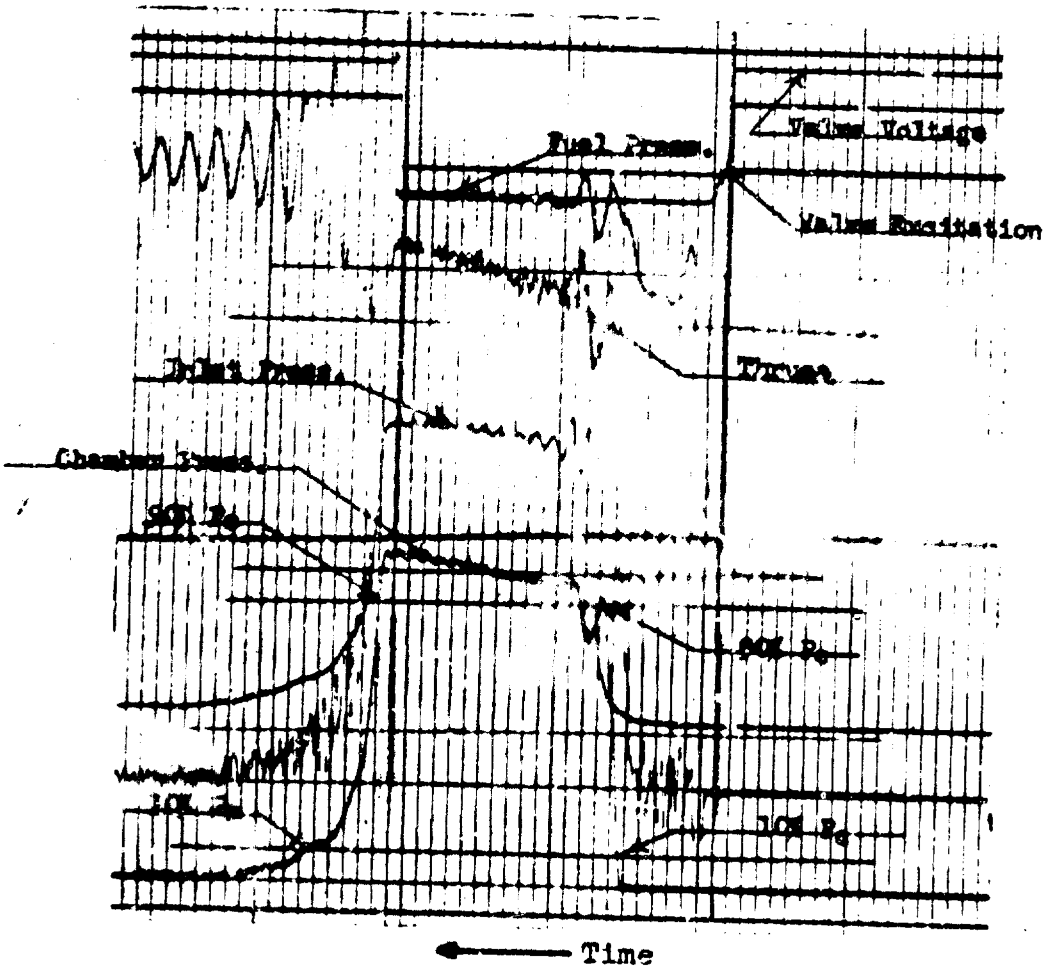


Figure 12

INITIAL SCREENING TEST AF-5
FIRST TWO PULSES OF SECOND
SIX CYCLE TEST WITH 73°F FEED
98.2% H_2O_2 AND 40 POUND THRUST MOTOR

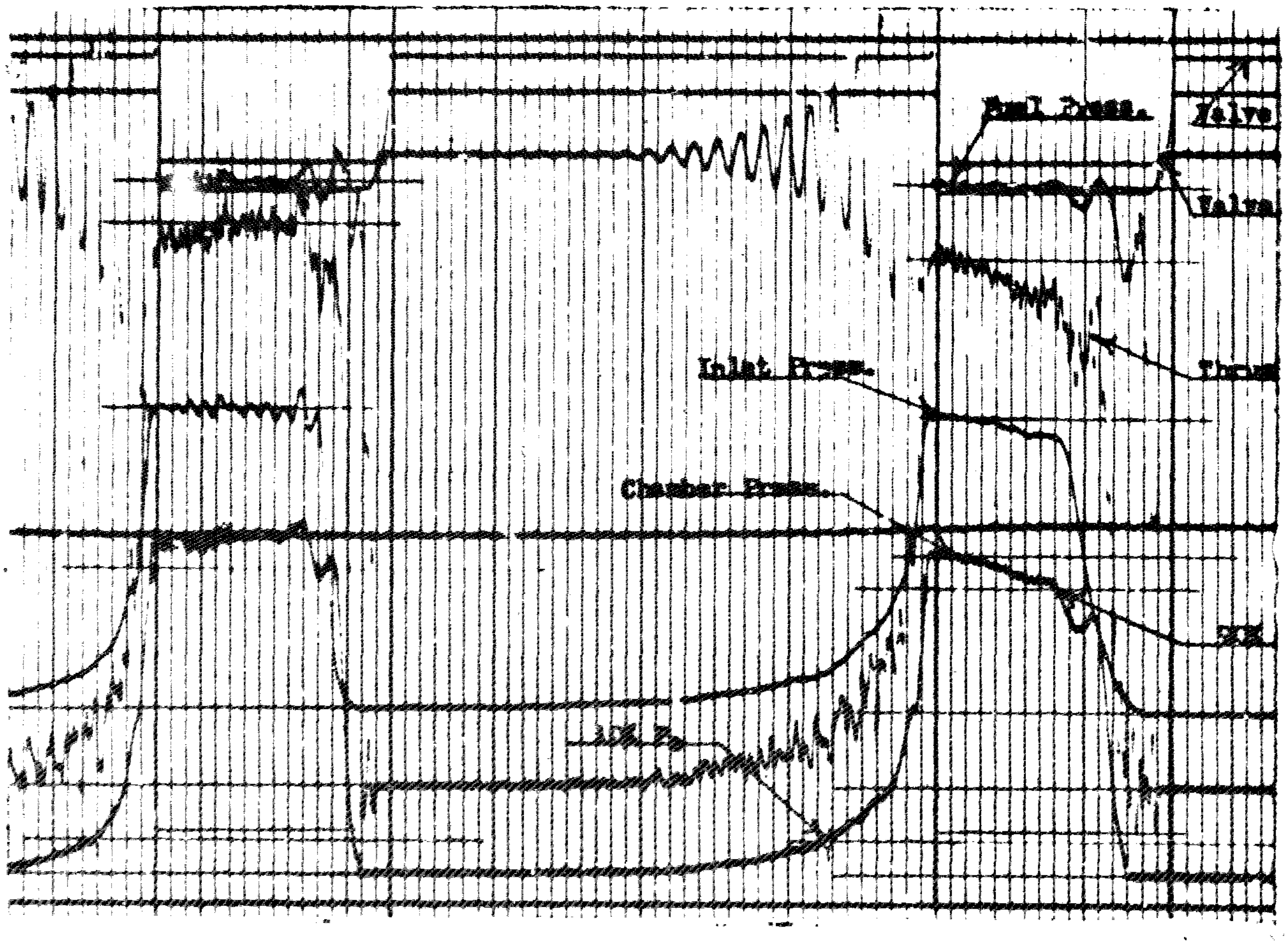
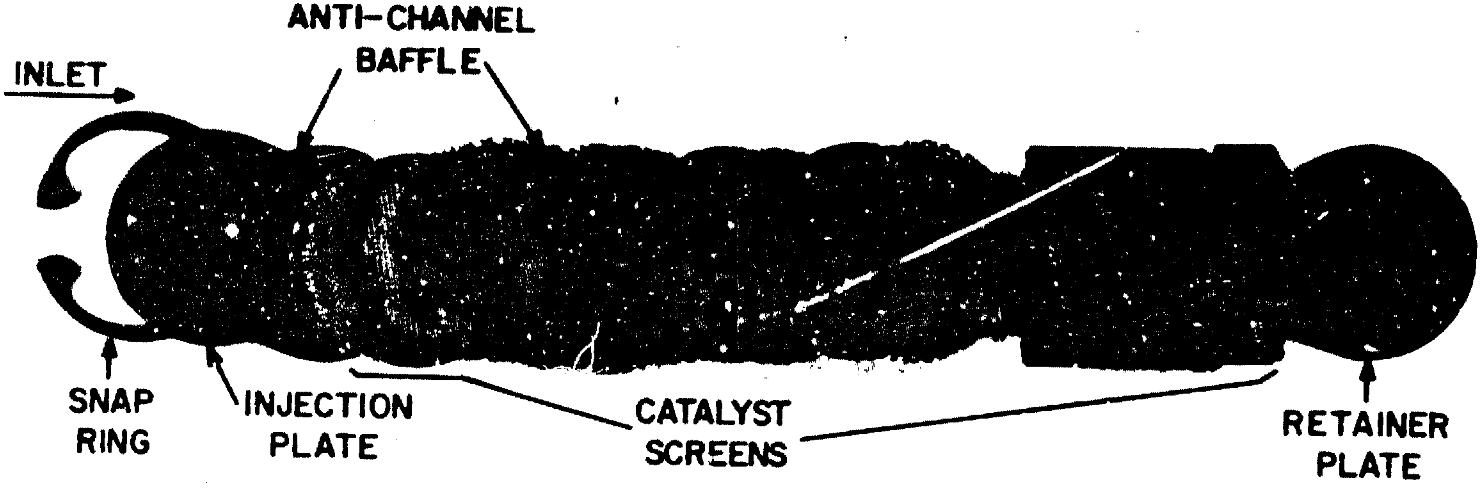


Figure 13

INTERNAL ELEMENTS OF CATALYST PACK AF-5
AFTER THE MOTOR TEST



Catalyst pack AF-6 contained 3 pieces of 40 mesh silver catalyst screen alternated with 20 mesh nickel-5% manganese screens at the pack inlet. The initial pulse was relatively weak. Subsequent pulses were strong and steady. Figure 14 shows the third initial warm-up pulse of the AF-6 catalyst pack. Following are the beginning and end of the 30 second steady-state test, the first of three warm-up pulses prior to the first six cycle run, and the first two cycles of the second six cycle test (Figures 15, 16, and 17.). All AF-6 test traces correspond to the traces given for AF-5 and described above. The specific impulse realized was 138.4 sec. at a chamber pressure of 290 psia. This is 98% of the theoretical value. The characteristic velocity (C*) was 3320.

Figure 18 shows the internal parts of catalyst pack AF-6 after the test. Details similar to those described above for Figure 13 are shown. No evidence of screen damage was apparent.

Tests on packs AF-5 and AF-6 showed that the silver screens in the inlet of the pack gave sufficient activity to insure a dry engine start, when used in combination with the silver-30% palladium alloy screens located lower in the pack. Both the performance data and inspection of the packs after the tests confirmed that at this fuel temperature, chamber pressure and pack loading the silver screens were not damaged.

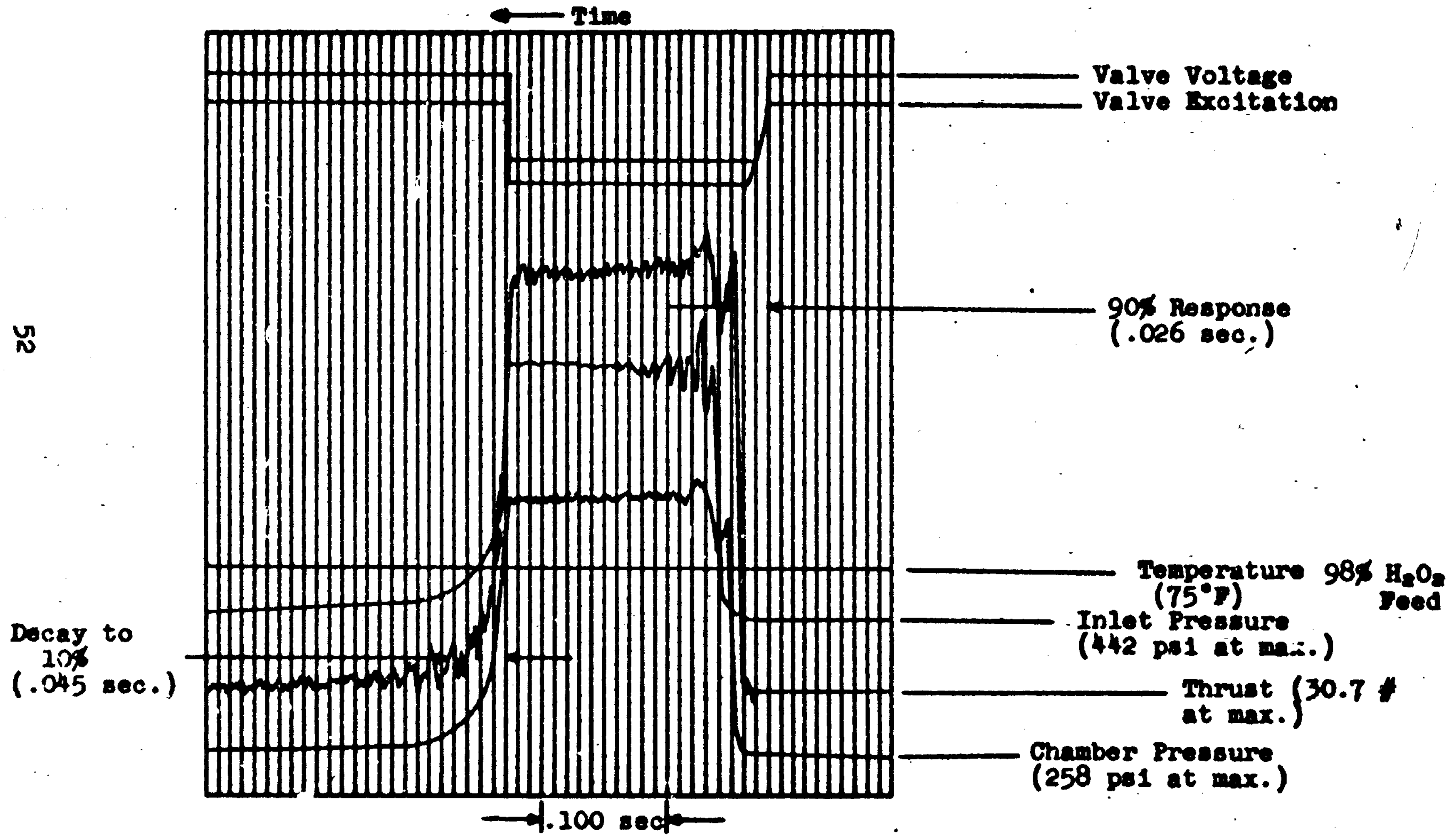
The effect of motor operation on the activity of selected screens from packs AF-4, 5, and 6 is shown in Table XIII. The activity of both the silver and silver-30% palladium alloy screens is lower after use in the motor. The silver-30% palladium screens in the lower (hotter) portion of the bed are less active than those closer to the inlet. The nickel-5% manganese screens which showed essentially no activity before the motor tests showed reasonably high activity after the test, especially when tested with 50° C H_2O_2. This probably represents carry-over of active catalyst material from the screens above.

(4) Silver Versus Silver-5% Palladium Screens

Catalyst pack AF-7 incorporated silver-5% palladium alloy screens in the cooler inlet section of the pack. No silver screens were used. The first pulse resulted in a misty spray, while the second pulse provided a good start. The specific impulse realized was 136.1 secs. or 95% of theoretical at a chamber pressure of 302 psia. The characteristic velocity was 3280. This data shows that pack AF-7 was comparable to AF-5 and AF-6 in general performance. However, the starting behavior as shown in Tables XI and XII, was inferior to AF-5 and AF-6. This shows the greater activity which silver catalyst screens have in comparison to the silver-5% palladium screens. Nevertheless, since the general performance was quite good, the silver-5% palladium can be used in motors employing programmed starts (10).

Figure 14

THIRD PULSE WITH 98% H_2O_2 USING CATALYST PACK AF-6 IN 40# F UNIT



Tests conducted by Walter Kidde Co.

Figure 15

INITIAL SCREENING TEST AF-6
START AND SHUTDOWN OF 30 SECOND
STEADY STATE TEST WITH 75°F FEED
98.2% H_2O_2 AND 40 POUND THRUST MOTOR

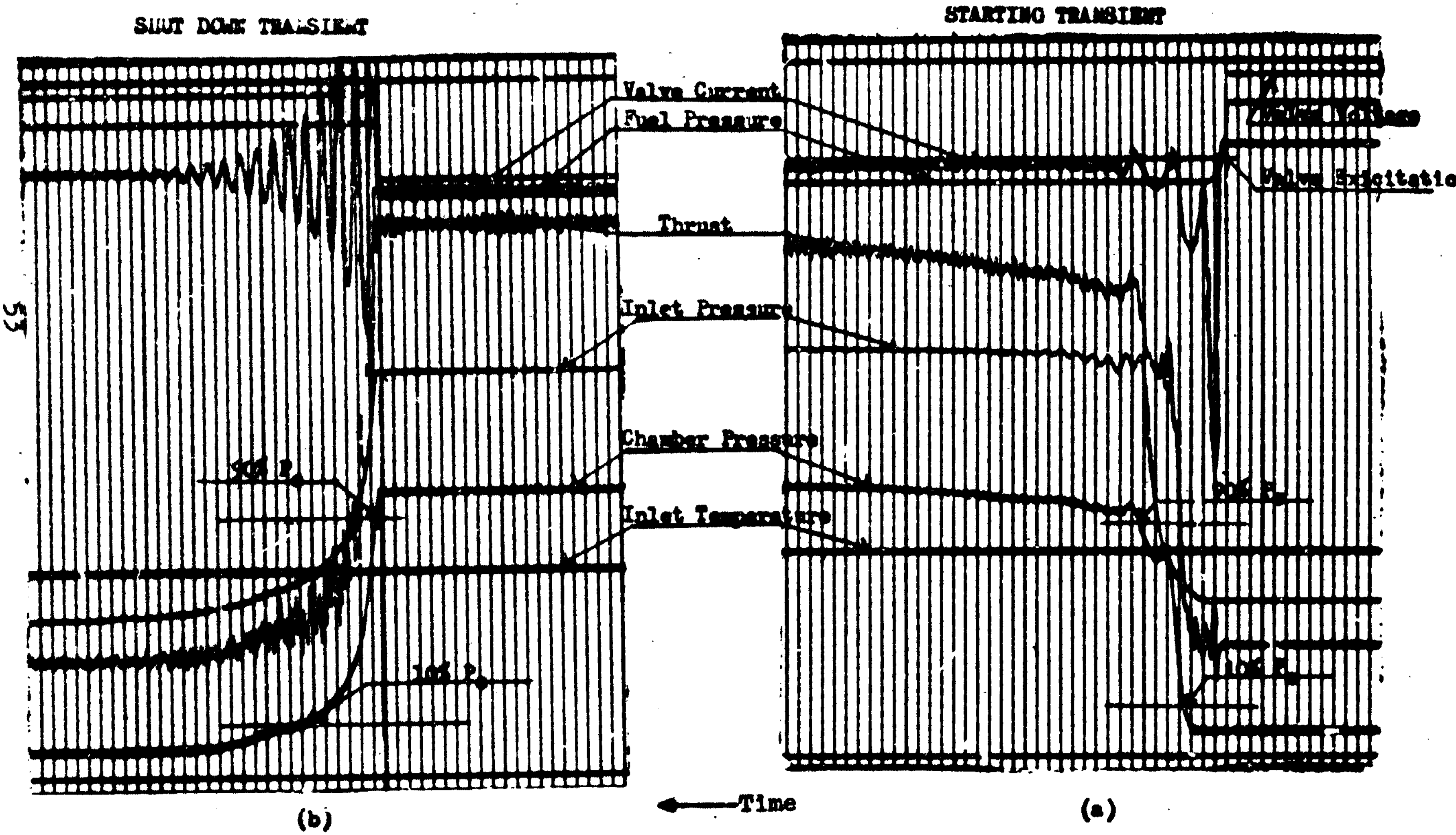


Figure 16

INITIAL SCREENING TEST AF-6
FIRST WARM-UP PULSE PRIOR
TO FIRST SIX CYCLE TEST
WITH 74°F FEED
98.2% H_2O_2 AND 40 POUND THRUST MOTOR

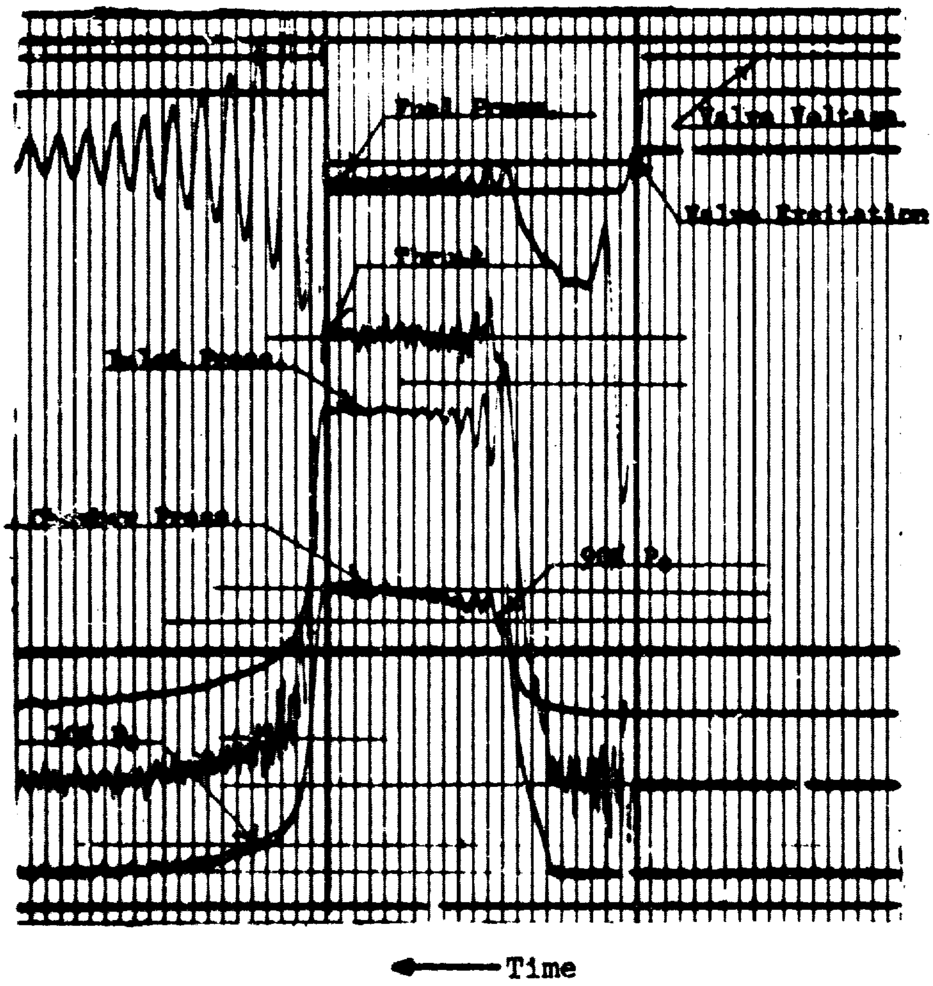


Figure 17

INITIAL SCREENING TEST AF-6
FIRST TWO PULSES OF SECOND
SIX CYCLE TEST WITH 74°F FEED
98.2% H_2O_2 AND 40 POUND THRUST MOTOR

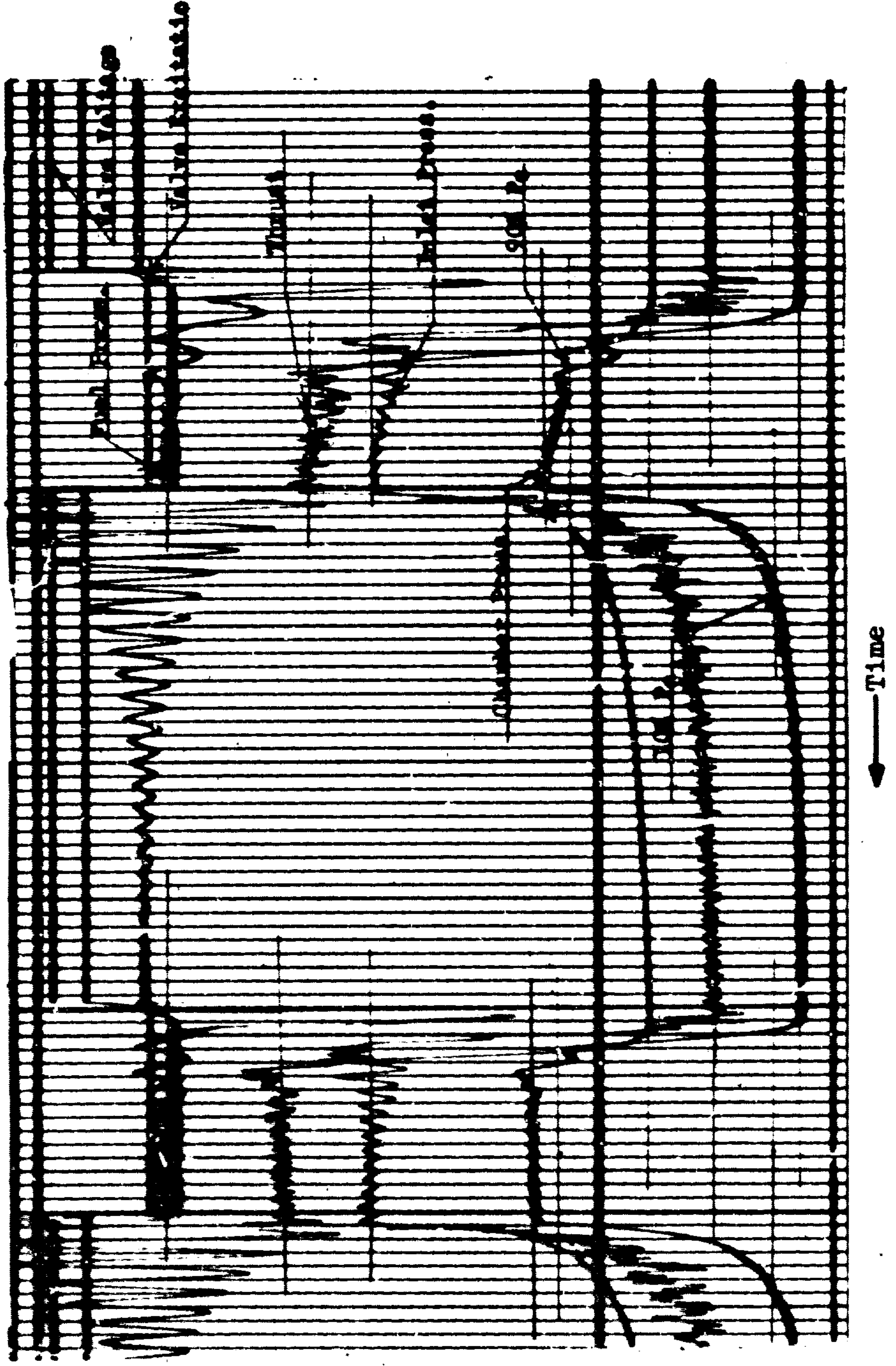


Figure 18

INTERNAL ELEMENT OF CATALYST PACK AF-6
AFTER THE MOTOR TEST

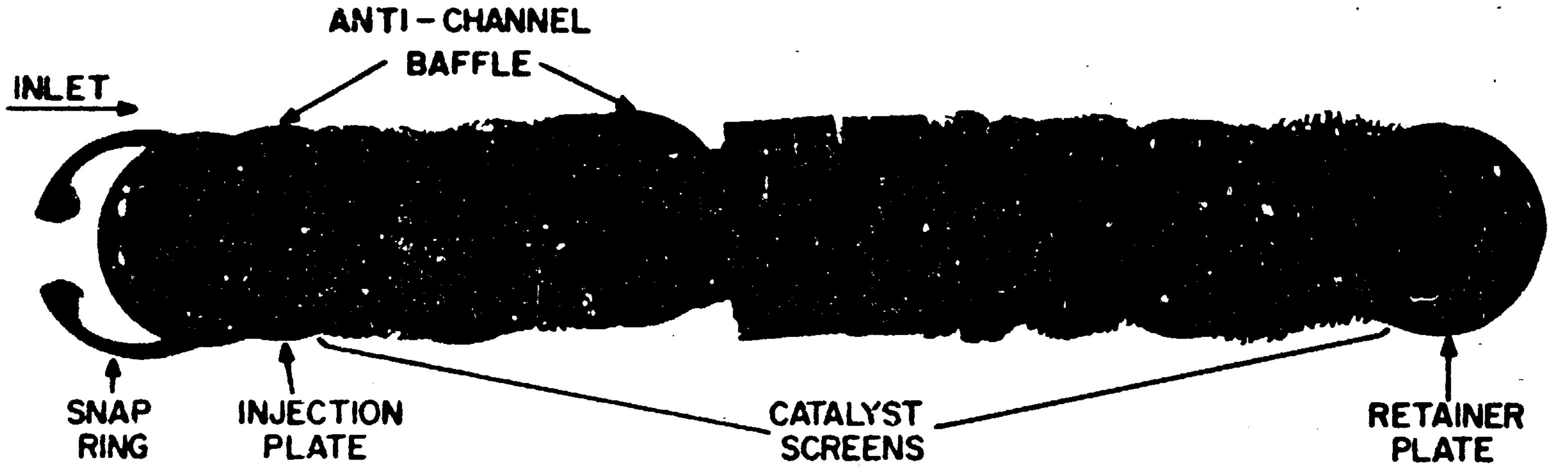


TABLE XIII

EFFECT OF MOTOR OPERATION UPON CATALYST ACTIVITY

Catalyst Pack Number	Catalyst* Type	Typical Decomposition* rate for unused Catalyst (ml/min)	Screen Position in Pack	Decomposition Rate* after Motor Tests (ml/min)
AP-4	Ni-5%Mn	~ 0	69th(last)Ni-5%Mn	5 (70° H_2O_2)
AP-5	Silver	30	First Silver	10
	Ag-30%Pd 20 mesh	30	First Ag-30%Pd 20 mesh	11
			37th Ag-30%Pd 20 mesh	10
			38th(last)Ag-30%Pd 20 mesh	4
	Ni-5%Mn	~ 0	54th Ni-5%Mn	7 (50° H_2O_2)
			55th(last)Ni-5%Mn	10 (50° H_2O_2)
		~0 (surface oxidized at 1100°C in air)		
		~0 (surface oxidized at 1100°C in air, 50° H_2O_2 used)		
AP-6	Ag-30%Pd 20 mesh	30	First Ag-30%Pd 20 mesh	13
			34th Ag-30%Pd 20 mesh	9
			35th Ag-30%Pd 20 mesh	3
			36th(last) Ag-30%Pd 20 mesh	3
	Ni-5%Mn	~ 0	81st(last) Ni-5%Mn	10 (50° H_2O_2)

* Test used 10 ml of 98% H_2O_2 which was initially at 20°C except where noted.

(5) Short Packs

Though packs AF-5 through AF-7 operated quite well, the pressure drop across the packs was between 170 and 200 psi. This is at the upper limit of the desired range and partially represents a needless loss of efficiency in motor operation. Therefore, two catalyst packs were designed and tested to attempt to lower the pressure drop.

The pressure drop can be reduced in several ways, all of which amount to reducing the obstructions to the flow of H_2O_2 and decomposition products. These include using shorter catalyst packs and decreasing the mesh size (increasing the open area) of the screens in the pack. Since packs AF-5 to AF-7 all contained a reasonable number of relatively inactive nickel-5% manganese screens at the exhaust end of the packs, it was decided to shorten the packs from 1-3/4 to 1-1/4 inches by elimination of this section. In order to do this and still use the same cartridge as for previous tests, a ring spacer was designed to fit within the catalyst pack, the spacer took up the pressure used to pack the screens into the cartridge, while leaving the central area free from interference with the flow.

Catalyst packs AF-8 and AF-9 were packed as shown in Table IX and tested using the shorter pack length. The screen configurations were chosen to correspond roughly with those of packs AF-6 and AF-5 respectively. In each case one baffle was inserted between the injection plate and the top of the pack and a second baffle was placed after the first 15 screens of the pack.

The summarized results for packs AF-8 and AF-9 are shown in Tables XXVIII and XXIX. The starting behavior, as given above in Table XII and noted in the Remarks column of Tables XXVIII and XXIX, indicates that these packs were inferior to AF-5 and AF-6. The specific impulses achieved were only 90% and 86% of theoretical, respectively, compared wity 96 to 98% for AF-5 and AF-6. Somewhat lower pressure drops were produced for AF-8 and AF-9, but the general performance was low. Later results during the high pressure-high pack loading tests indicated that lower pressure drops can be attained without impairing performance by a combination of shorter packs with larger open area screens in both inlet and exhaust sections of the packs.

(6) Injection Plate Variation

The injection plate placed at the inlet end of the catalyst pack serves both to hold the catalyst screens tightly in the cartridge and to distribute the H_2O_2 flow across the full area of the catalyst pack. The plate used for packs AF-1 to AF-9 contained 19 holes of 1/8 inch diameter.

Examination of the first few screens of those catalyst packs after motor testing showed color patterns indicating the H_2O_2 flow that resulted from the injection plate. The patterns suggested that the injection plate did cause uniform flow through all of the 19 holes, but that the parts of the first few catalyst screens which were not exposed by the holes were poorly utilized. Therefore, an injection plate containing 44 holes of about 1/32 inch diameter was obtained. This plate has only about 6% open area compared to about 39% for the previous plate discounting the area blocked by the baffle. However, it was expected that the increased number of sites where H_2O_2 contacts the highly active inlet screens would provide better use of those catalysts.

Catalyst pack AF-10, as shown in Table IX, was prepared using the new injection plate. The screen configuration was chosen to match that of pack AF-5. An additional number of inactive nickel-5% manganese screens were required to attain the required packing pressure. This was probably the result of re-use of the silver-30% palladium screens, which allowed them to pack more tightly the second time. The silver-30% palladium screens were tested before re-use and found to have activities of 10 ml. /min. or better. This is comparable to the activities measured for silver-30% palladium screens which have run successfully in packs AF-5 to AF-7.

The results for pack AF-10 are given in Tables X and XII and in the Appendix, Table XXX. The starting response of the pack was poor. This can be traced to the re-use of the silver-30% palladium screens, which do suffer some decrease in activity upon being tested in the motor. The characteristic exhaust gas velocity (C*) was good but the specific impulse was low.

The pressure drop across the catalyst pack (ΔP) was about the same as that for AF-5, though the additional filler screens in pack AF-10 would tend to increase the ΔP. This suggests that the liquid-gas boundary during motor operation was located farther from the inlet in pack AF-10 than in AF-5, leaving both packs with approximately the same number of screens in the gas phase where most of the pressure drop occurs. The longer liquid phase region is attributed to the increased injection velocity which resulted from the smaller open area of the injection plate and correspondingly increased pressure drop across the plate. Increased injection velocity probably resulted in greater penetration of the H_2O_2 feed into the inlet section of the catalyst pack before high percentage decomposition was achieved. This indicates that the44 holes of the AF-10 injection plate should be drilled out at least until the 39% open area of previously used injection plates is reached.

The pressure oscillations observed during both pulse and steady-state operation may also have been connected with the increased injection velocity, if preheating and then sudden decomposition of the H_2O_2 were caused. The motor operation became stable after ten seconds of the steady-state test, suggesting that perhaps the flow at that point became sufficient to flood the inlet region of the catalyst pack and give smooth decomposition.

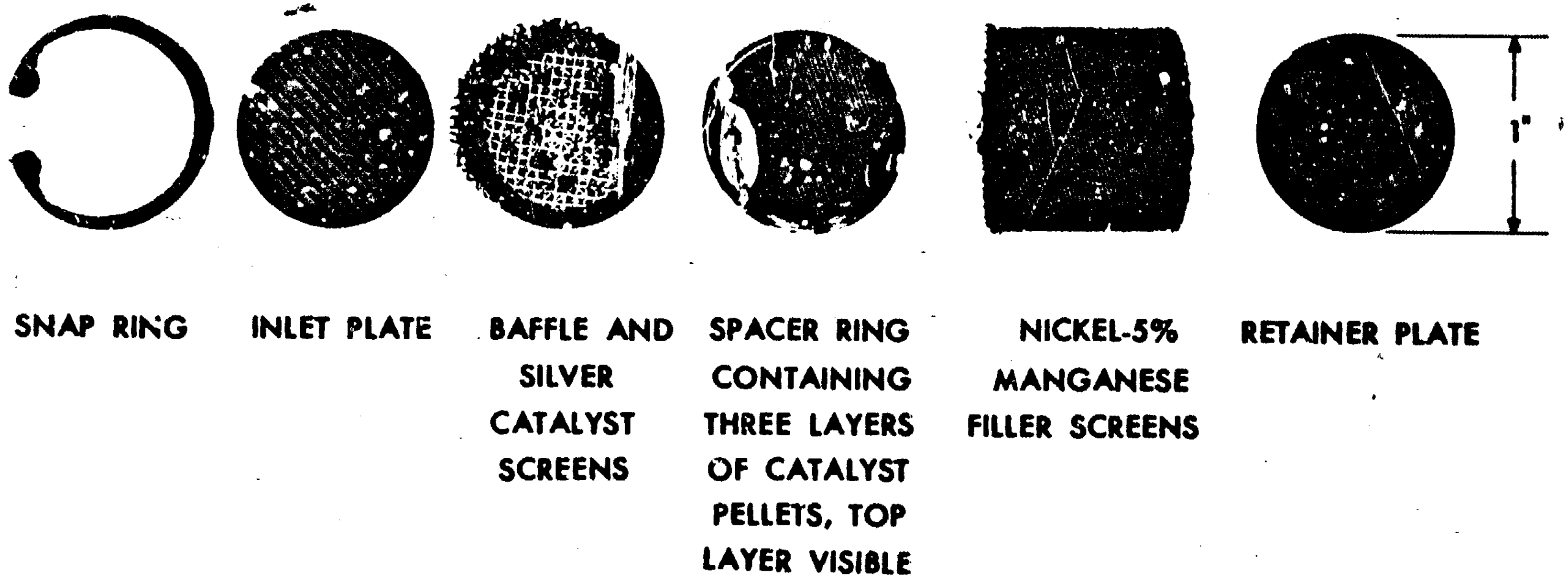
(7) Pellet Catalyst Pack

The configuration of the pellet catalyst pack, AF-11, has been given in Table IX and shown in Figure 4. Pack AF-11 also appears in Figure 19, which shows the sections of the pellet catalyst pack AF-11 disassembled for inspection after firing. The snap ring, inlet plate, and retainer plate used were identical to those used in tests with the screen catalysts. Eight 20 mesh silver screens were packed in the inlet section up to the anti-channel baffle. The pellets are shown packed within the spacer ring to prevent crushing of the pellets when the packing pressure was applied. The compressed set of nickel-5% manganese filler screens was in the exhaust end of the pack just upstream from the retainer plate. As is clear in the figure, the pellets did not show mechanical breakdown. Some minor patterns can be seen in the top layer of pellets. These patterns were caused by the pressure of neighboring screens which was not sustained by the spacer ring during pack compression. However, the damage to the pellets was not serious.

The results for pack AF-11 (Table X) showed mixed performance. The starting response of the pack (Table XI) was poor and the specific impulse was low. However, the characteristic exhaust velocity (C*) was high and the motor operation was smooth. Also, the pressure drop across the pack was considerably lower than for the packs composed entirely of screens. These results, together with the mechanical strength exhibited by the pellets, suggest that further studies should be made, both in the laboratory and in motor tests. Laboratory studies should concentrate on increasing the activity of the catalyst to improve the starting characteristics of the pack. Motor tests at high pressure and high pack loading are required to demonstrate the structural strength of the pellets under those conditions.

Figure 19

DETAIL OF PELLET CATALYST PACK AFTER INITIAL SCREENING TEST AF-11



2. ADVANCED MOTOR DEMONSTRATION TESTS

a. High Pressure-High Pack Loading Tests with Ambient Temperature 98% H_2O_2 Feed

The catalyst packs used in these tests were the configurations of silver-30% palladium catalysts identical to AF-5 and AF-6 used in the screening program. These consisted of a short inlet section of silver catalyst screens, followed by a longer section of silver-30% palladium catalyst screens and an exhaust section of nickel-5% manganese filler screens. The catalyst packs were evaluated under high pressure high throughput conditions in the chamber shown in Figure 20.

(1) Test Chamber and Chamber Configuration

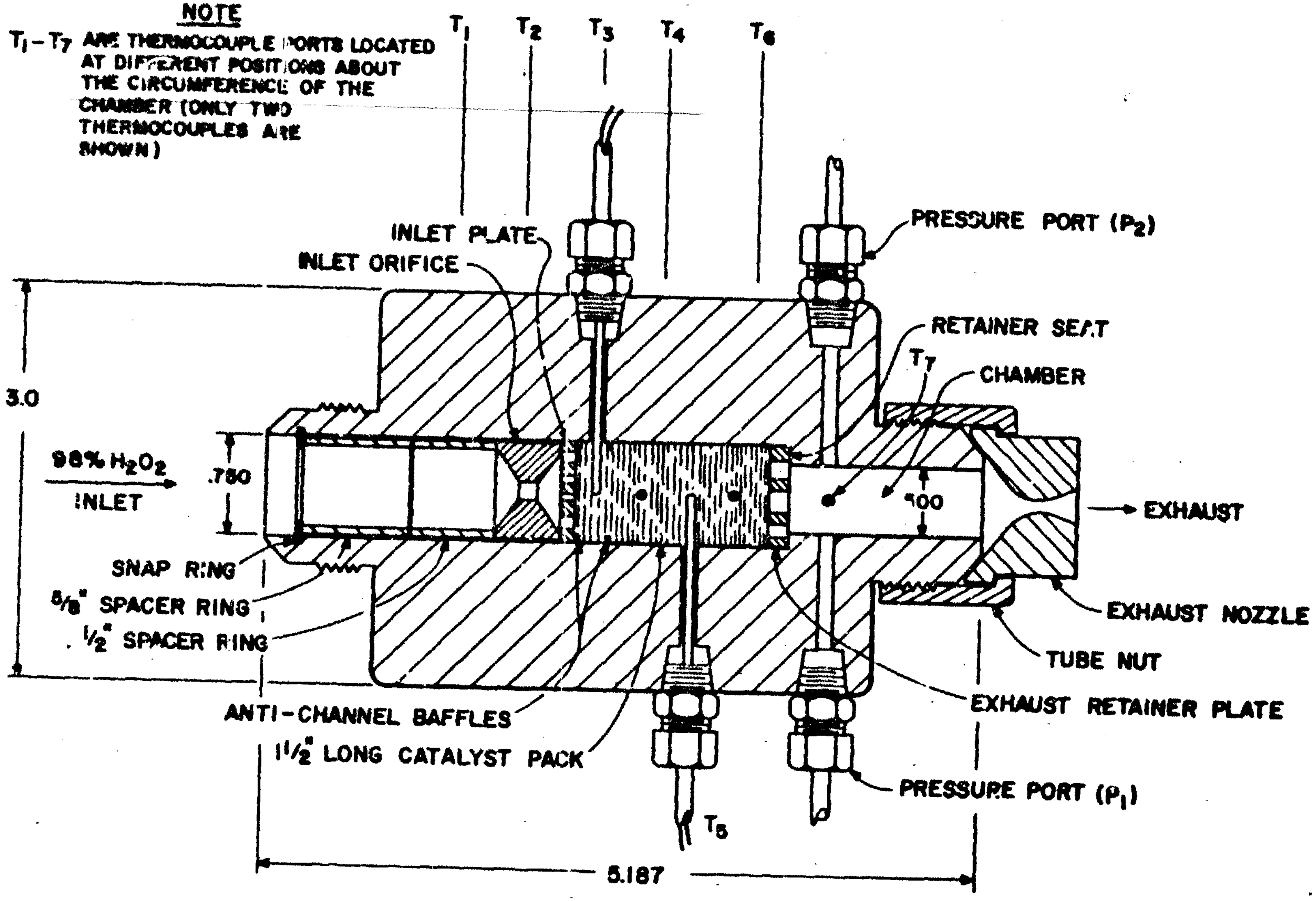
The Test Chamber (Figure 20) was fabricated from three inch diameter stock of stainless steel No. 347. The chamber contained seven thermocouple ports identified in the picture at T_1 through T_7. These were spaced in a spiral rotation about the diameter of the chamber. The thermocouples were chromel-alumel protected by inconel sheaths. Two additional ports numbered P_1 and P_2 appear in the exhaust section of the chamber and were used for chamber pressure measurements.

The catalyst pack and associated parts were held in the 3/4" diameter hole of the chamber between the retainer seat and the snap ring. Just inside the snap ring were two or more spacer rings. These spacer rings served to allow the use of various lengths of catalyst pack. The spacer rings were 1/16" in thickness. Directly after the spacer rings is the inlet orifice, followed by the inlet plate, the catalyst pack, and the exhaust retainer plate. Details concerning the inlet orificies, the inlet and retainer plates, and the exhaust nozzles are shown in Figures 21 through 23.

Six different orificies were used in the test program. These are indicated in Figure 21. The first of these, type A, was of the straight-through center-hole variety. The remaining five contained a number of holes of different diameters and located in different patterns.

Figure 20

TEST CHAMBER FOR HIGH PRESSURE-HIGH PACK LOADING TESTS

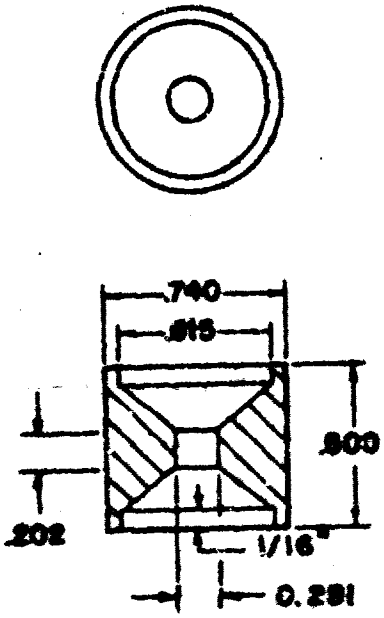


NOTE
T_1-T_7 ARE THERMOCOUPLE PORTS LOCATED AT DIFFERENT POSITIONS ABOUT THE CIRCUMFERENCE OF THE CHAMBER (ONLY TWO THERMOCOUPLES ARE SHOWN)

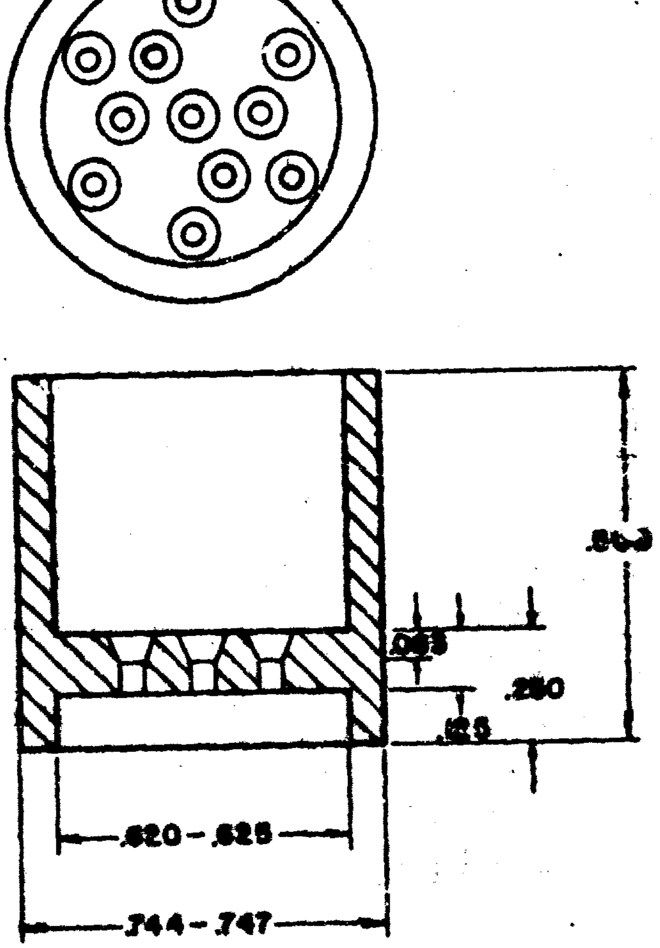
Figure 21

INLET ORIFICES FOR HIGH PRESSURE-HIGH LOADING TESTS WITH 3/4" DIAMETER CHAMBER

Type	Holes Number	 Diameter (inches)	Pattern
A	1	0.281	centered
B	11	3/64	6 on 7/16" H.C. 4 on 3/16" H.C. 1 centered
C	13	3/64	8 on 7/16" H.C. 4 on 3/16" H.C. 1 centered
D	10	3/64	6 on 7/16"H.C. 3 on 1/4" H.C. 1 centered
E	10	1/16	Same as Type D
F	10	1/32	6 on 7/16" H.C. 3 on 1/8" H.C. 1 centered



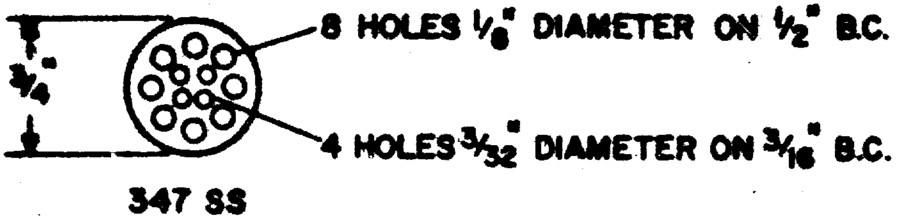
Type A



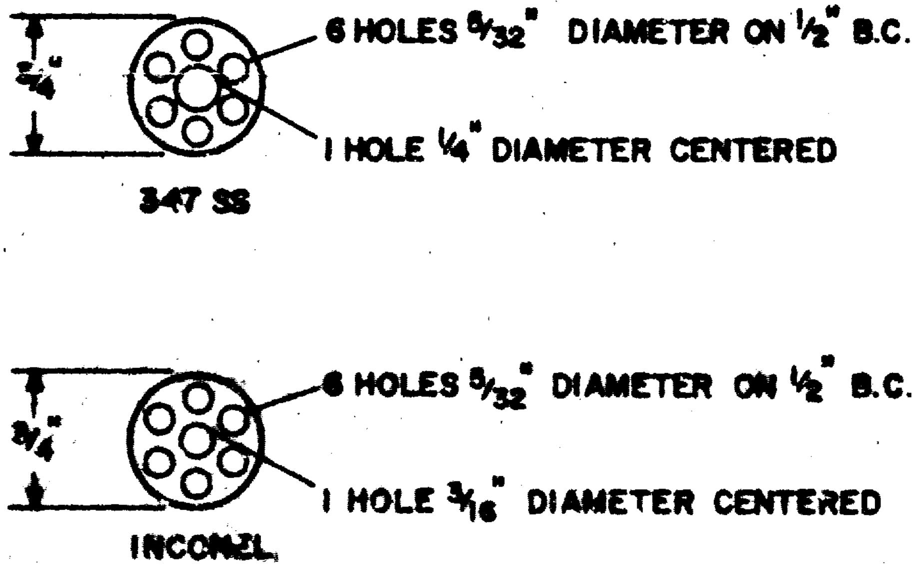
Type B-F

Figure 22

INLET AND RETAINER PLATES FOR HIGH PRESSURE-HIGH LOADING TESTS WITH 3/4" DIAMETER CHAMBER



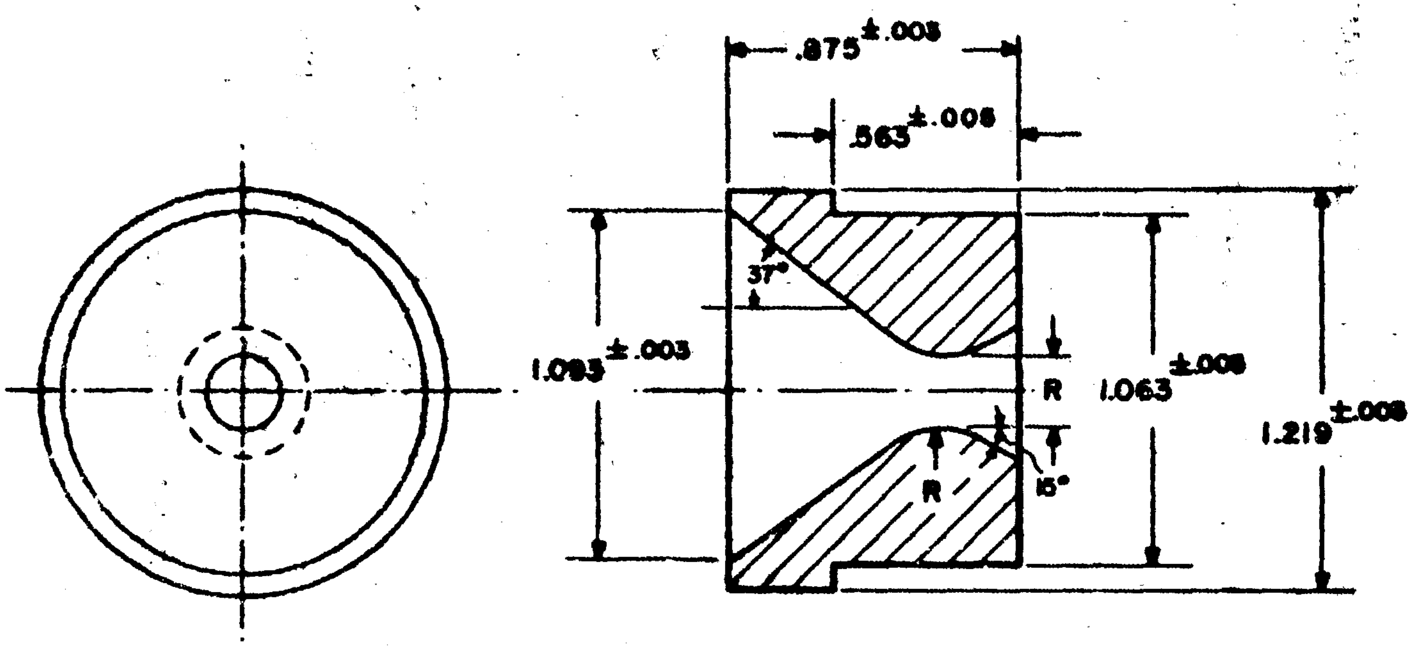
INLET PLATE



EXHAUST PLATES

Figure 23

EXHAUST NOZZLES FOR HIGH PRESSURE-HIGH LOADING TESTS WITH 3/4" DIAMETER CHAMBER



R (INCHES)
.138
.163
.198
.253
.283
.299

Figure 22 shows the inlet and retainer plates used in the test. All plates were 1/8" in thickness. The failure of exhaust plates made from 347 stainless steel necessitated the fabrication of an exhaust plate made from inconel as shown at the very bottom. The inconel plate was used in the last half of the high pressure high-loading tests.

Details for the exhaust nozzles are shown in Figure 23. All were constructed from 347 stainless steel. A tube nut was employed to hold the nozzles to the test chamber.

(2) Catalyst Packing

For each test the catalyst screens were handpacked in the chamber and then compressed with the hydraulic bench press to 4000 psi. The first step of the packing operation was to locate the exhaust retainer plate at the bottom of the 3/4" diameter hole in the test chamber, making certain that the retainer plate lay flush against the retainer seat. As in the initial screening tests, the screens were then placed individually into the chamber. Each screen was rotated somewhat from the position of the previous screen to provide an even distribution of catalyst throughout the pack. After 1/3 of the catalyst screens had been loaded into the chamber, a 3/4" diameter packing ram was inserted into the inlet end of the chamber and the screens were compressed on the bench press to 4000 psi. The pack was again compressed after 2/3 of the catalyst screens had been packed into the chamber. After all the screens had been packed, the anti-channel baffle, inlet plate, inlet orifice, spacers and snap ring were inserted above the catalyst pack. A 1/2" diameter packing ram was used for the final compression. It passed inside the snap ring and spacer rings and bore upon the inlet orifice. After 4000 psi compression was exerted upon the plates, catalyst pack and orifice, the snap ring was seated in a groove in the upper inlet part of chamber.

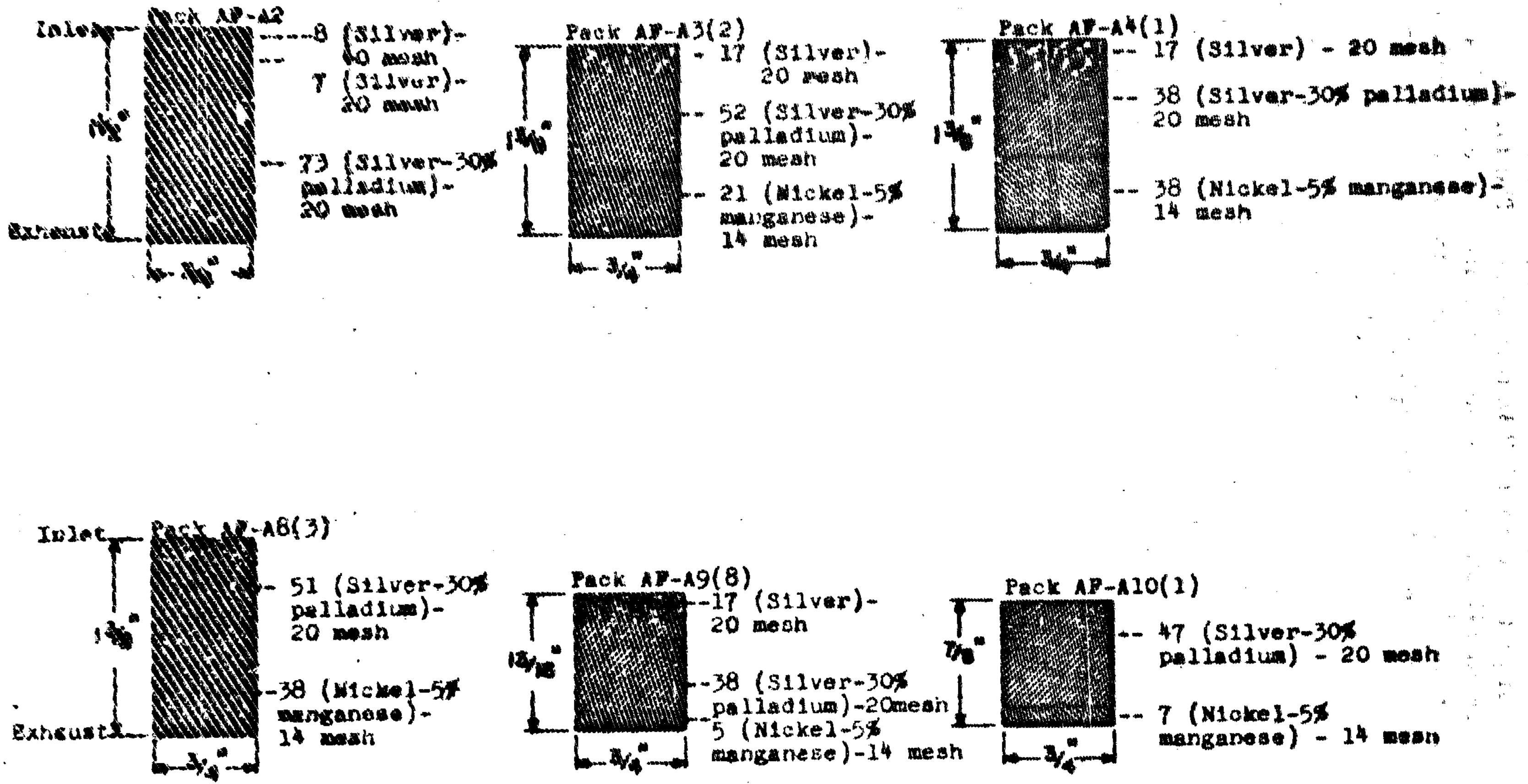
The choice and arrangement of test chamber configuration, including catalyst pack, retainer plates, baffles, orifices, and ring spacers varied somewhat from test to test. Depending on the length of the pack used and its desired location along the length of the chamber different ring spacers located in different positions were required. Additional baffles were also included for some of the tests.

(3) Catalyst Pack Configurations

The basic catalyst pack configurations used in these tests are shown in Figure 24. Each catalyst pack loaded into the test chamber was given a number from AF-A1 through AF-A10. The tests on each catalyst pack are indicated by numbers in parentheses following the pack number. In some cases, minor changes were made in the catalyst pack without changing the basic catalyst pack number.

Figure 24

BASIC CATALYST PACK SCREEN CONFIGURATIONS USED IN HIGH PRESSURE-HIGH LOADING TESTS



Note: Anti-channel baffle ring was placed after the first 14 screens in each pack

Catalyst packs AF-A1 and AF-A5 thru AF-A7 are not shown in the figure since they are roughly identical to the packs shown. However, a complete listing of the catalyst pack configurations appears in Table XIV. In the table, column six indicates the minor changes made in the catalyst packs and also the source of screens which were re-used, particularly toward the end of the program. Column seven indicates the compression applied in order to pack the catalyst into the test chamber. Column eight shows where inlet spacers were added to the inlet region of the catalyst chamber to take up extra space which is commonly left after a pack has been tested. Column ten indicates the distance from the first screen of the catalyst pack to the retainer seat of the chamber. This is not identical with the pack length since spacer rings were often placed beneath the catalyst pack in order to locate the pack properly with respect to the thermocouple port openings.

(4) Test System

The high pressure test chamber was mounted on a test stand as shown from two different views in Figures 25 and 26. A schematic of the test system is shown in Figure 27. The water jacketed 15 gallon storage tank contained the 98% H_2O_2 for the test. Sheathed copper-constantine thermocouples entered the tank at the top and bottom so temperatures of both the liquid and vapor could be monitored. A line for high pressure N_2 gas entered the top of the tank through a 10µ filter Fuel pressure could be regulated by adjusting the N_2 pressure. The tank was equipped with a pressure relief valve at the top and an emergency dump valve at the bottom. A steam line, which coiled inside the water jacket but did not contact the H_2O_2-containing wall directly, allowed the H_2O_2 to be safely heated in the storage tank.

Prior to the test, the nitrogen gas line was removed and the storage tank filled with 98% H_2O_2 through the same tank port. The H_2O_2 was filtered through a different 10µ filter than the nitrogen filter shown on the schematic. Nitrogen pressure was required to force the H_2O_2 through the filter. During tank filling, the fill vent valve was opened.

During a test, the H_2O_2 was allowed to flow through the test chamber by opening the two propellant valves. Pressure transducers measured the inlet and chamber pressures. Flow was monitored by the pottermeter. The outputs of the transducers, pottermeter, and thermocouples were recorded on an oscillograph recorder.

A check valve was included in the H_2O_2 feed line to prevent any possible malfunction at the test chamber from sending contaminants back to the H_2O_2 storage tank.

After each test the test chamber was purged with nitrogen This served both to cool the chamber and to dry any moisture remaining in the catalyst pack or test chamber.

TABLE XIV

SUMMARY OF CATALYST DATA FOR HIGH PRESSURE-HIGH PACK LOADING TESTS WITH 98% H_2O_2

Catalyst Pack(test)	Catalyst Screen Configuration: Silver 40 mesh	Silver 20 mesh	Silver-30% Palladium 20 mesh	Nickel-5% Manganese 14 mesh	Catalyst Screen Sources and Changes	Pack Compression (psi)	Inlet[1] Spacers added	Pack Length (inches)	Pack[2] Location (inches)	Observations Concerning Catalyst
AP-A1(1to3)	8	7	38	78	New pack	9000	No	1-1/2	1-5/8	Compressed too much
AP-A2(1)	8	7	73	---	New pack	4300	---	1-1/2	2-1/16	More open area needed
AP-A3(1)	8	7	52	21	New pack	4300	---	1-3/8	1-3/4	Spitting caused by 40 mesh.
AP-A3(2)	---	17	52	21	10 new silver used with AP-A3(1)	2000	Yes	1-3/8	1-3/4	
AP-A4(1)	---	17	38	38	New pack	4300	---	1-3/8	1-3/4	
AP-A4(2to7)	---	17	38	38	Pack AP-A4(1) used	---	No	1-3/8	1-3/4	Localized silver melting
AP-A4(8)	---	17	38	38	Silver of AP-A4(7) replaced[3]	2000	---	1-3/8	1-3/4	
AP-A4(9to12)	---	17	38	38	Pack AP-A4(8) used	---	Yes[4]	1-3/8	1-3/4	
AP-A5(1)	3	8	30	56	New pack	4850	---	1-3/8	1-3/4	
AP-A5(2)	---	11	30	56	3 new silver used with AP-A5(1)	2000	---	1-3/8	1-3/4	
AP-A6(1)	---	17	38	59	New pack	4000	---	1-5/8	1-3/4	
AP-A7(1)	---	---	55	38	New pack	4000	---	1-3/8	1-3/4	First start good, later starts slower
AP-A7(2)	---	---	55	38	Pack AP-A7(1) used	---	No	1-3/8	1-3/4	
AP-A8(1)	---	---	51	38	New pack	4000	---	1-3/8	1-3/4	First start good, later starts slower
AP-A8(2and3)	---	---	51	38	Pack AP-A8(1) used	---	Yes[5]	1-3/8	2-5/8	
AP-A8(4to6)	---	---	51	38	Pack AP-A8 (3) used	---	Yes	1-3/8	1- 1	Poor starts
AP-A9(1)	---	17	38	38	Last 58 screens of AP-A8 (6) used; others new	4000	---	1-3/8	1-3/4	Compressed too much
AP-A9(2to4)	---	17	38	38	Pack AP-A9(1) used	---	No	1-3/8	1-3/4	Compressed too much
AP-A9(5)	---	17	38	38	Silver-palladium from AP-A2, A3, and A9; other screens new	4000	---	1-3/8	1-3/4	
AP-A9(6and7)	---	17	38	38	Pack AP-A9 (5) used	---	No	1-3/8	1-3/4	
AP-A9(8)	---	17	38	5	Nickel-manganese removed from AP-A9 (7)	---	No	15/16	1-13/16	
AP-A10(1to3)	---	---	47	7	Compressed groups of silver-palladium from AP-A5 and AP-A6; nickel-manganese from AP-A6	---	No	7/8	1-3/4	Slower starts than packs containing silver screens

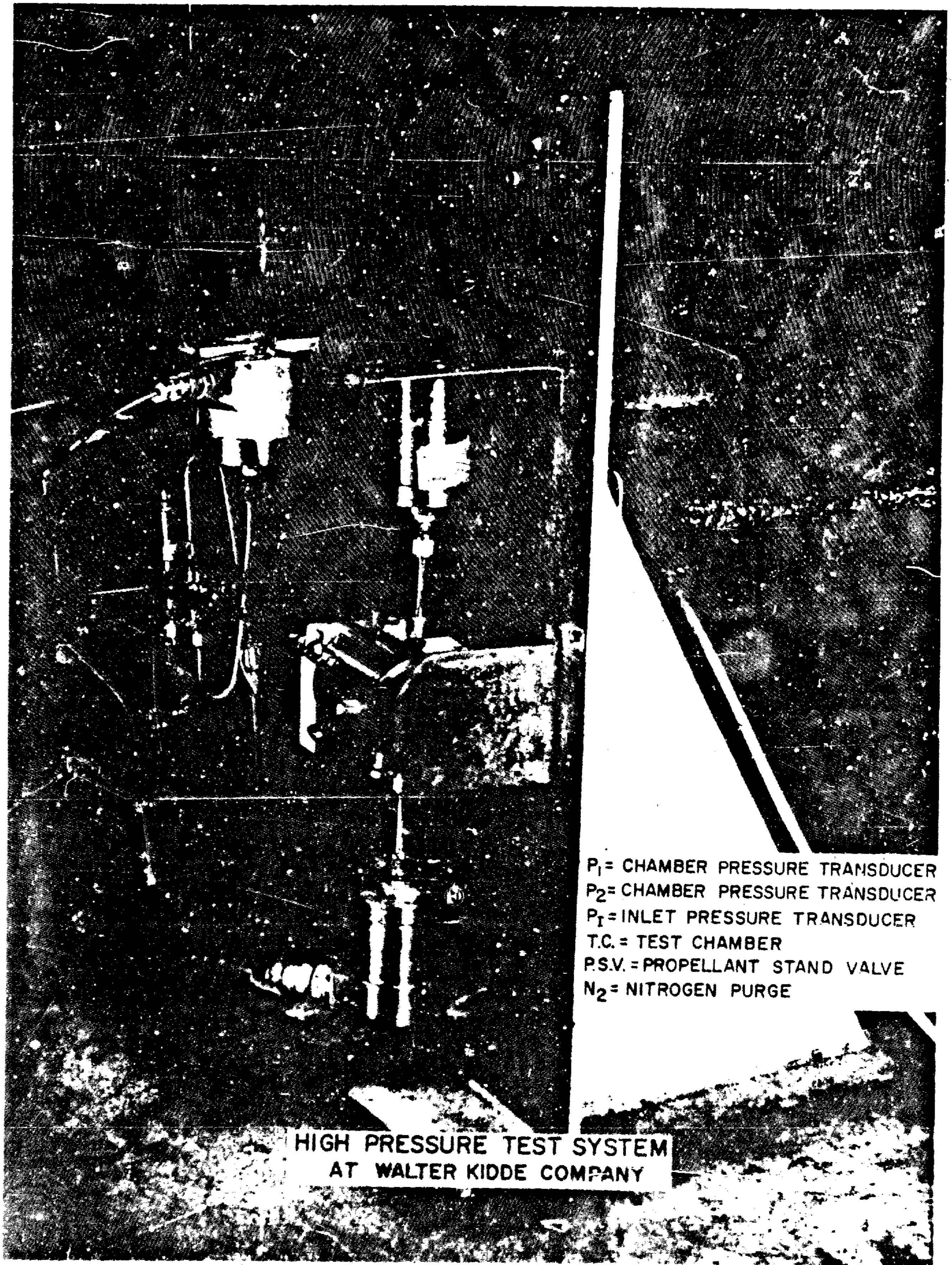
1. Pack tightened by addition of spacers to inlet region to eliminate void space produced above catalyst pack by previous test.
2. Distance that first screen at pack inlet was upstream from retainer seat of chamber.
3. Two 14 mesh and one 20 mesh nickel-5% manganese screens placed at inlet of pack.
4. Before test AP-A4(9) only.
5. Before test AP-A8 (2) only.

Figure 25

P_1 = CHAMBER PRESSURE TRANSDUCER
P_2 = CHAMBER PRESSURE TRANSDUCER
P_I = INLET PRESSURE TRANSDUCER
T.C. = TEST CHAMBER
P.V. = PROPELLANT VALVE
P.S.V. = PROPELLANT STAND VALVE
F.M. = FLOW METER
P.T. = H_2O_2 TANK
N_2 = NITROGEN PURGE

HIGH PRESSURE TEST STAND
AT WALTER KIDDE COMPANY

Figure 26

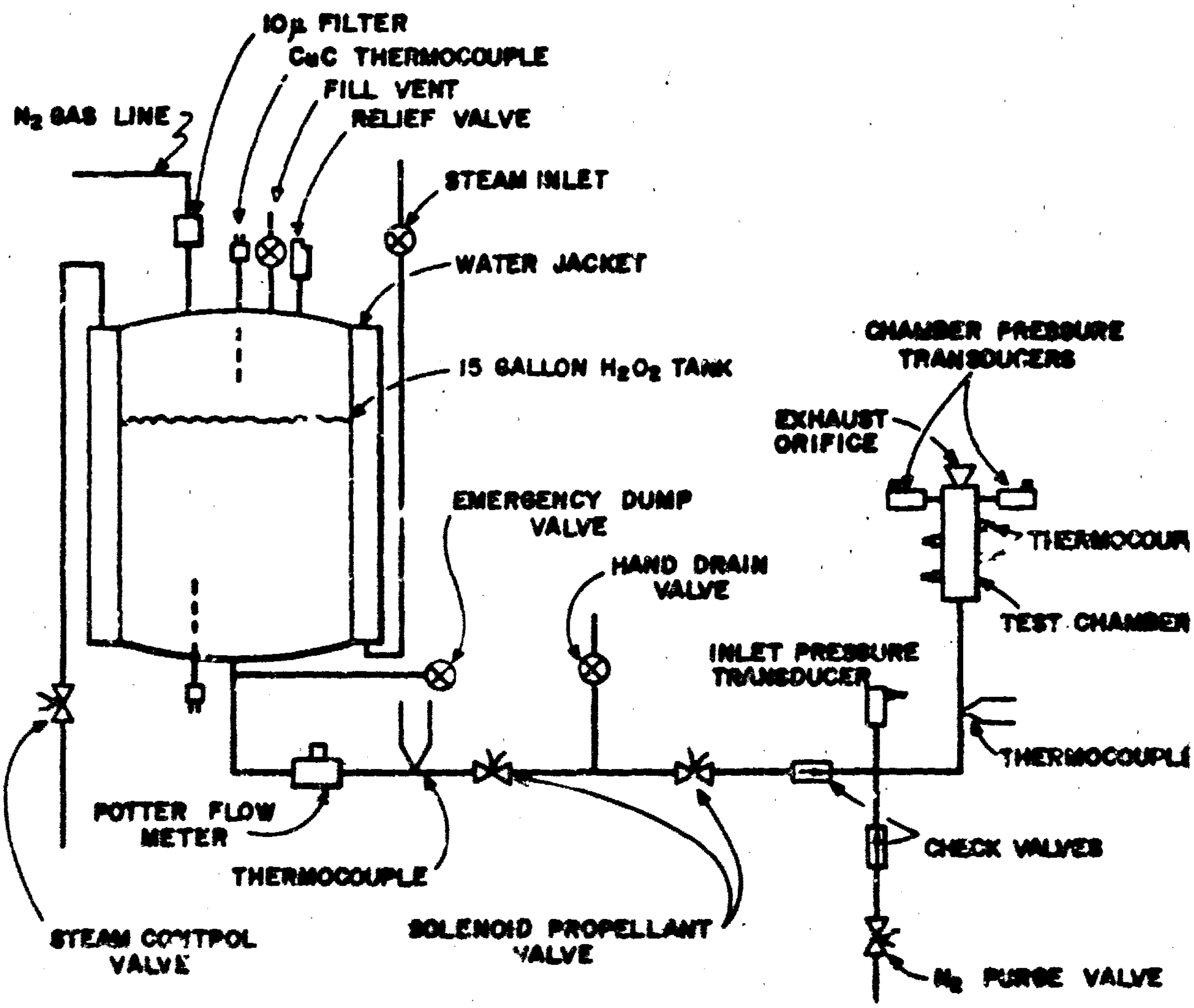


P_1 = CHAMBER PRESSURE TRANSDUCER
P_2 = CHAMBER PRESSURE TRANSDUCER
P_I = INLET PRESSURE TRANSDUCER
T.C. = TEST CHAMBER
P.S.V. = PROPELLANT STAND VALVE
N_2 = NITROGEN PURGE

HIGH PRESSURE TEST SYSTEM
AT WALTER KIDDE COMPANY

Figure 27

SCHEMATIC OF HIGH PRESSURE TEST SYSTEM



The emergency dump line and the drain valve both emptied to a drain. A large water flow was kept running into the drain during the tests and upon emptying the storage tank at the conclusion of testing on any one day. This provided for dilution of discarded H_2O_2. As a safety precaution, H_2O_2 was not left in the storage tank overnight.

(5) Test Procedure

The tests were conducted using FMC supplied 98% H_2O_2 which was filtered to 10 microns prior to introduction into the test system. The pressurant used was nitrogen gas, per MIL-BB-N-411B, Grade B, type 1, class 1 filtered to 10 microns prior to introduction into the test system.

The tests were performed in the following manner: The feed pressure was set between 200 and 400 psig. The propellant feed valve was manually actuated to fire the test chamber three times at approximately 200 msec on and 2 seconds off.

The test chamber was then fired steady-state at a fuel pressure between 200 and 400 psig. After the chamber was started, the feed pressure was immediately increased to its maximum setting between 1000 and 2000 psig. These settings were determined approximately with Bourdon tube pressure gages. Each test was run for a minimum of 30 seconds with the exception of tests numbered AF-A8 (1, 5 and 6) and AF-A10(3) which were terminated due to instability. At the conclusion of the test, the motor was purged with nitrogen to remove remaining traces of water.

All tests were recorded on an oscillograph at a paper speed of 8-10 in/sec. The following parameters were recorded:

Parameter	
Chamber pressure	0 - 2000 psia
Inlet Pressure	0 - 2000 psia
Propellant Tank Pressure	0 - 2000 psia
Inlet Temperature	50°F - 150°F
Catalyst Bed Temperatures	70°F - 2400°F
Exhaust Temperature	70°F - 2400°F
Propellant Flow	0 - 1.5 lb/sec.

An electrical calibration was taken and recorded prior to running the test and at the completion of each test. This calibration served to indicate any change in the electrical characteristics of the recording system during the test. The pressure transducers were calibrated within 24 hours of the beginning of the test against a standard, high accuracy Bourdon gage reserved for calibration. Thermocouples for temperature measurements were calibrated with a potentiometer.

(6) Results of the Tests

A general summary of the results of these tests is given in Table XV and complete data are shown in the appendex Tables XXXII - LIII. Column three of the table gives data on the inlet orifices. The orifice type refers to that shown previously in Figure 21. The other orifice data concerns the number of holes and the size of each hole in the orifice. The remaining columns (other than the observations at the extreme right) concern data for the point of maximum loading during the test. For example, the first column gives the number of seconds into the test at which maximum loading occurred.

A progression of improvements were produced during the test series. These involved interrelated factors which reduced the pressure drop across the catalyst pack, increased the throughput, and achieved C* values at high percentages of theoretical. Table XVI shows progress achieved in reduction of the pressure drop. In the second column are the pressure drops across the catalyst pack recorded when the throughput reached its maximum during the test, as shown in the third column. The throughputs are given in pounds per square inch frontal area of the catalyst chamber per minute.

Catalyst packs containing both silver and silver-30% palladium or only silver-30% palladium catalyst screens were successfully tested with 50 to 140°F H_2O_2 feed and loading rates through 110 PSIM. Packs as short as 7/8" operated effectively with programed starts. Data generated gave information that could prove useful in the design of screen-type catalyst packs for use with 98% H_2O_2.

(a) Pack Compression

The first two catalyst packs evaluated showed the effect of pack compression on motor operation. Pack AF-A1 was inadvertantly compressed to approximately 9000 psi. This resulted in a very high pressure drop across the pack and correspondingly large pressure oscillations. Pack AF-A2 was compressed at the customary 4000 psi level and smooth performance was achieved.

During motor operation additional compression is produced. The catalyst screens expand due to the high decomposition temperatures (1740-1800°F). This expansion causes the pack to be

TABLE XV

SUMMARY OF DATA FOR HIGH PRESSURE-HIGH PACK LOADING TESTS WITH 98% H_2O_2

			Data for Point of Maximum Loading During the Test[1]												
Catalyst Pack(test)	Exhaust Orifice Diameter in inches	Inlet[2] Orifice Type, Holes, & Diam. (inches)	Time of Reading (sec.)	Chamber Pressure (psia)	H_2O_2 Inlet Pressure (psia)	Pressure drop (psi)	Thermocouple Temperatures in Catalyst Pack[3] T2(°F)	T4(°F)	T5(°F)	T1(°F)	Inlet Temp. (°F)	98% H_2O_2 Flow (lb/sec)	c* ft/sec	Theo. c* (per cent)	Observations Concerning Motor Operation
APA1(1)	0.253	A 1 .082	—												Motor unstable for entire test
APA1(2)	0.253	B 11 3/64	—												Motor unstable for entire test
APA1(3)	0.253	B 11 3/64	—												Motor unstable for entire test
APA2(1)	0.253	C 11 3/64	25	892	1763	874	1660[4]	1730	1000	———	59	.476	3030	91.1	Stable at high pressure.
APA3(1)	0.253	B 11 3/64	35	1851	1853	642	1085	1700	1700	1720	60	.638	3174	95.5	Slight instability present
APA3(2)	0.253	B 11 3/64	40	1845	1857	518	958	1360	1497	1600	56	.655	3065	92.7	Test stable.
APA4(1)	0.253	B 11 3/64	40	1384	1886	502	980	1690	1745	1845	61	.703	3187	96.0	Test stable.
APA4(2)	0.253	B 11 3/64	40	1350	1878	528	———	———	———	———	65	.719	3036	91.6	Test stable.
APA4(3)	0.138	B 10 3/64	40	1813	1895	82	———	———	———	———	69.5	.257	3318	102	Motor unstable at high pressure.
APA4(4)	0.138	B 10 3/64	41	1538	1609	71	———	———	———	———	68.5	.253	3180	96.0	Motor unstable at high pressure.
APA4(5)	0.163	B 11 1/64	44	1474	1615	141	1340	1745	1860	———	74	.301	3290	99.1	Instability present from 0 to 40 sec.
APA4(6)	0.163	B 10 1/64	—												Motor unstable for entire test.
APA4(7)	0.180	F 10 1/64	—												Motor unstable for entire test.
APA4(8)	0.163	F 10 1/32	—												Motor unstable for entire test.
APA4(9)	0.163	B 10 1/16	—												Motor unstable for entire test.
APA4(10)	0.253	B 11 3/64	—												Test identical to AP-A4(1) and stable. Data not reduced (system checkout).
APA4(11)	0.253	B 11 3/64	38	1405	1881	776	718	728	1739	1940	~150	.479	3838	108	Motor exploded.
APA5(1)	0.253	B 11 3/64	—												Motor unstable for entire test.
APA5(2)	0.253	B 11 3/64	38	1846	1784	538	1383	1690	1765	1850	58	.815	2481	75.0	Leakage noted at inlet fitting.
APA6(1)	0.163	F 10 1/32	—												Motor unstable for entire test.
APA7(1)	0.163	F 10 1/32	—												Motor unstable for entire test, instability not severe.
APA7(2)	0.163	F 10 1/32	—												Test terminated because of instability, retainer plate failed.
APA8(1)	0.163	F 10 1/32													Test terminated at 20 seconds ΔP value excessive
APA8(2)	0.163	F 10 1/32	—												Motor unstable for entire test.
APA8(3)	0.253	F 10 1/32	30	1430	1847	415	1015	———	———	———	64	.785	3197	96.8	Motor became unstable after 35 sec.
APA8(4)	0.163	F 10 1/32	—												Motor unstable for entire test.
APA8(5)	0.163	None used	—												Test terminated; motor highly unstable.
APA8(6)	0.253	B 11 3/64	—												Test unstable; incomplete decomposition observed.
APA9(1)	0.253	B 11 3/64	30	1130	1931	801	———	———	———	———	62	.570	3209	96.6	Test stable.
APA9(2)	0.253	B 11 3/64	45	1073	1912	839	475	1730	———	1745	61	.543	3199	96.3	Test stable.
APA9(3)	0.283	B 11 3/64	44	898	1910	1018	415	1730	———	1740	61	.570	3170	95.4	Test stable.
APA9(4)	0.299	B 11 3/64	48	791	1914	1123	415	1780	———	1735	58	.583	3068	92.5	Slight leakage noted at thermocouple.
APA9(5)	0.253	B 11 3/64	30	1363	1843	480	1100	1690	———	1730	56	.691	3193	96.3	Test stable.
APA9(6)	0.283	B 11 3/64	30	1249	1851	602	1350	1672	———	1730	56	.783	3215	97.4	Test stable.
APA9(7)	0.299	B 11 3/64	20	1137	1821	684	1360	1670	———	1725	56	.810	3174	95.7	Test stable.
APA9(8)	0.253	B 11 3/64	10	1506	1910	404	1005	1680	———	1730	56	.741	3290	99.2	Test stable.
APA10(1)	0.253	B 11 3/64	99.5	1206	1375	169	430	1750	———	1650	54	.598	3265	98.6	Test stable.
APA10(2)	0.253	B 11 3/64	10	1140	1440	300	1445	1775	———	1760	68	.565	3066	97.3	Test stable.
APA10(3)	0.253	B 11 3/64	—												Test terminated; motor highly unstable. Pressure rise occurred in H_2O_2 tank.

[1] Complete data for stable tests is given in the Appendix.

[2] See page   for details of inlet orifices.

[3] See Appendix for location of thermocouples in each catalyst pack.

[4] T_2 reading was 1100°F.

TABLE XVI

PROGRESS IN REDUCTION OF PRESSURE DROP (ΔP)

Pack (Test)	ΔP(psi)	Through-put (PSIM)	Reason for Lower ΔP
AP-A2(1)	809	65	--
AP-A3(1,2)	611	90	Substitution of 14 for 20 mesh screens.
AP-A4(1)	502	95.4	Further substitution of 14 for 20 mesh screens
AP-A8(3)	415	98	Lower catalyst activity moving liquid front toward exhaust
AP-A9(8)	404	101	Shorter pack length
AP-A10(1)	170	80	Lower catalyst activity moving liquid front toward exhaust and shorter pack length

compressed above 4000 psi, since the outside dimensions of the catalyst pack are restricted by the chamber. Upon motor shutdown the catalyst pack cools and shrinks so the pack length decreases. After each motor test a 1/32 to 1/16" space is thus left above the catalyst pack, and it appears that the pack will be loose during the following test. In reality however, the heat and consequent expansion of the pack will make the pack tight again during testing.

In tests AF-A8 (1 to 6), the void space left above the catalyst pack by pack expansion and shrinkage was filled several times through the use of additional inlet section spacers. Part of pack AF-A8 was incorporated directly into pack AF-A9 which was again compressed to 4000 psi. As a result of the repeated additional compression, the pressure drop across the catalyst pack was significantly increased. Tests 1 and 2 on pack AF-A9 recorded pressure drops of 840 and 810 psi at 74 and 78 PSIM, respectively. An identical pack configuration, AF-A4, had produced a pressure drop of only 404 psi at 76 PSIM. (Test 1).

When these high pressure drops were observed, pack AF-A9 was prepared for tests 5 to 7 by repacking loose screens of the same configuration to 4000 psi. The consequent reduction of pressure drop to AF-A4 (Tests 1 and 2) levels is apparent in the summary table (Table XV). Thereafter care was exerted to allow 1/32 to 1/16" slack in loading into the chamber any pack which had previously been compressed to 4000 psi and had not since been separated into loose screens. No further large pressure-drop increases were noted for packs AF-A9(8) or AF-A10.

(b) Screen Mesh Size

The first three catalyst packs were prepared with eight 40 mesh silver catalyst screens at the inlet end of the pack. These screens were used since they give an increased amount of catalyst surface when compared with the 20 mesh silver screens. However, there was some occassional minor instability apparently associated with liquid spitting during high loading tests where the 40 mesh screens were employed. This was attributed to liquid blocking by the 40 mesh screens. Substitution of 20 mesh silver catalyst screens for the 40 mesh screens eliminated this form of instability and smooth operation was achieved.

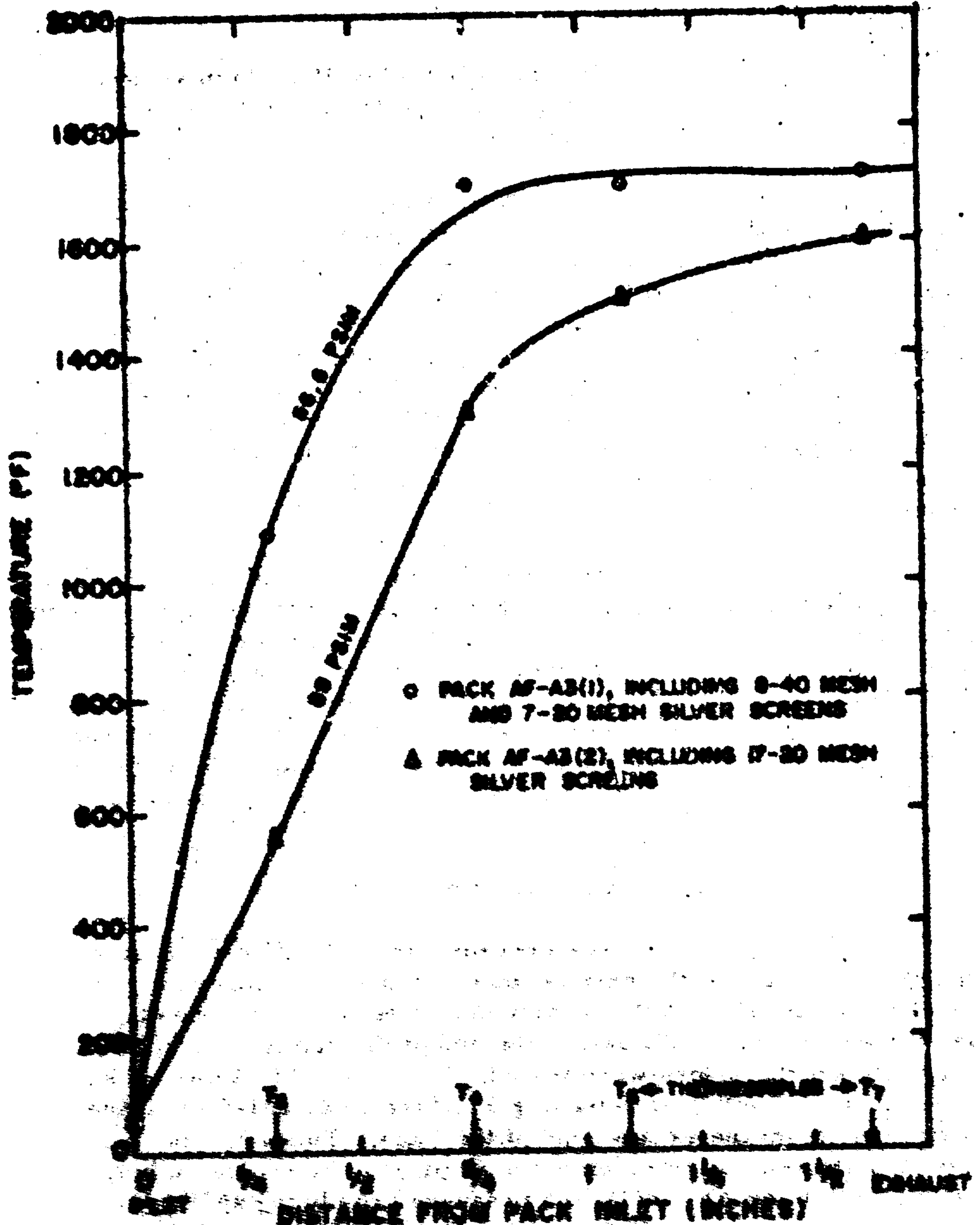
The effect of the increased activity of 40 mesh castalyst screens is shown by the temperature profiles for tests 1 and 2 on pack AF-A3 (Figure 28). Substitution of 20 mesh for the 40 mesh silver screens for test 2 resulted in the liquid front moving down the pack.

One of the several changes made to reduce the pressure drop across the catalyst pack was the substitution of 14 mesh (58% open area) nickel-5% manganese filler screens for 20 mesh (52% open area) silver-30% palladium catalyst screens at the exhaust end of the

Figure 23

TEMPERATURE PROFILES FOR HIGH PRESSURE–HIGH LOADING TESTS WITH $\frac{5}{8}$" DIAMETER CHAMBER CATALYST PACKS WITH AND WITHOUT 40 MESH SILVER CATALYST SCREENS

TESTS USED 0.265" EXHAUST ORIFICE, $1\frac{5}{8}$" PACK LENGTH



pack. Progressive substitution from pack AF-A2 to AF-A4 produced successively lower pressure drops (Figure 29) and at the same time led to improved performance. The size of the pressure drop reduction was less from AF-A3 to AF-A4 than from AF-A2 to AF-A3, indicating that the limit of this substitution was being approached. While some further reduction might be possible by other means, the use of silver-30% palladium catalyst screens with lower mesh size (more open area) than 20 mesh seems to be warranted

(c) Silver: Silver-30% Palladium versus All Silver-30% Palladium Pack Configurations

The silver catalyst screen is known to have better catalytic activity than the silver-30% palladium catalyst. Therefore, a short section of silver screens was used at the inlet end of most of the catalyst packs tested in this program. However, due to the increased catalytic activity concentrated at the front of such packs, the liquid front during motor operation remains nearer the inlet than for packs containing only silver-30% palladium catalysts screens. This effect can be seen in the temperature profiles shown in Figure 30 for packs AF-A9(8) (containing silver and silver-30% palladium catalyst screens) and AF-A10(1) (containing only silver-30% palladium catalyst screens).

The pressure drop of a catalyst pack depends in large measure on the length of pack which the decomposition gases must pass through. Thus, if the liquid front is located farther from the inlet, the gas phase region is comparatively shorter and the pressure drop lower (for constant length packs). For this reason the pressure drop of pack AF-A8(3) (containing silver-30% palladium but no silver) was lower than AF-A4 (silver-30% palladium and silver) and AF-A10 (only silver-30% palladium)was lower than AF-A9(8) (silver-30% palladium and silver).

(d) Pack Length

The pressure drop was also reduced by decreasing the length of the catalyst pack. Since the temperature measurements consistently showed that nearly complete H_2O_2 decomposition (~1740°F) was reached well before the end of the catalyst pack, two significantly shorter packs were tested. The first, AF-A9(6), was prepared from AF-A9(7) by removing 33 of the 38 nickel-5% maganese filler screens from the exhaust end of the pack. This left a pack 15/16" long, which showed an improvement over previously evaluated longer packs (AF-A9(5) and AF-A4(1), the pressure drop being approximately 400 psi at 1500 psia chamber pressure and 100 PSIM throughput.

Figure 29

HIGH PRESSURE - HIGH LOADING TESTS WITH $\frac{3}{4}$" DIAMETER CHAMBER

REDUCTION OF PRESSURE DROP ACROSS CATALYST PACK
BY SUBSTITUTION OF 14 MESH FOR 20 MESH SCREENS

14 MESH SCREEN = 58% OPEN AREA
20 MESH SCREEN = 52% OPEN AREA

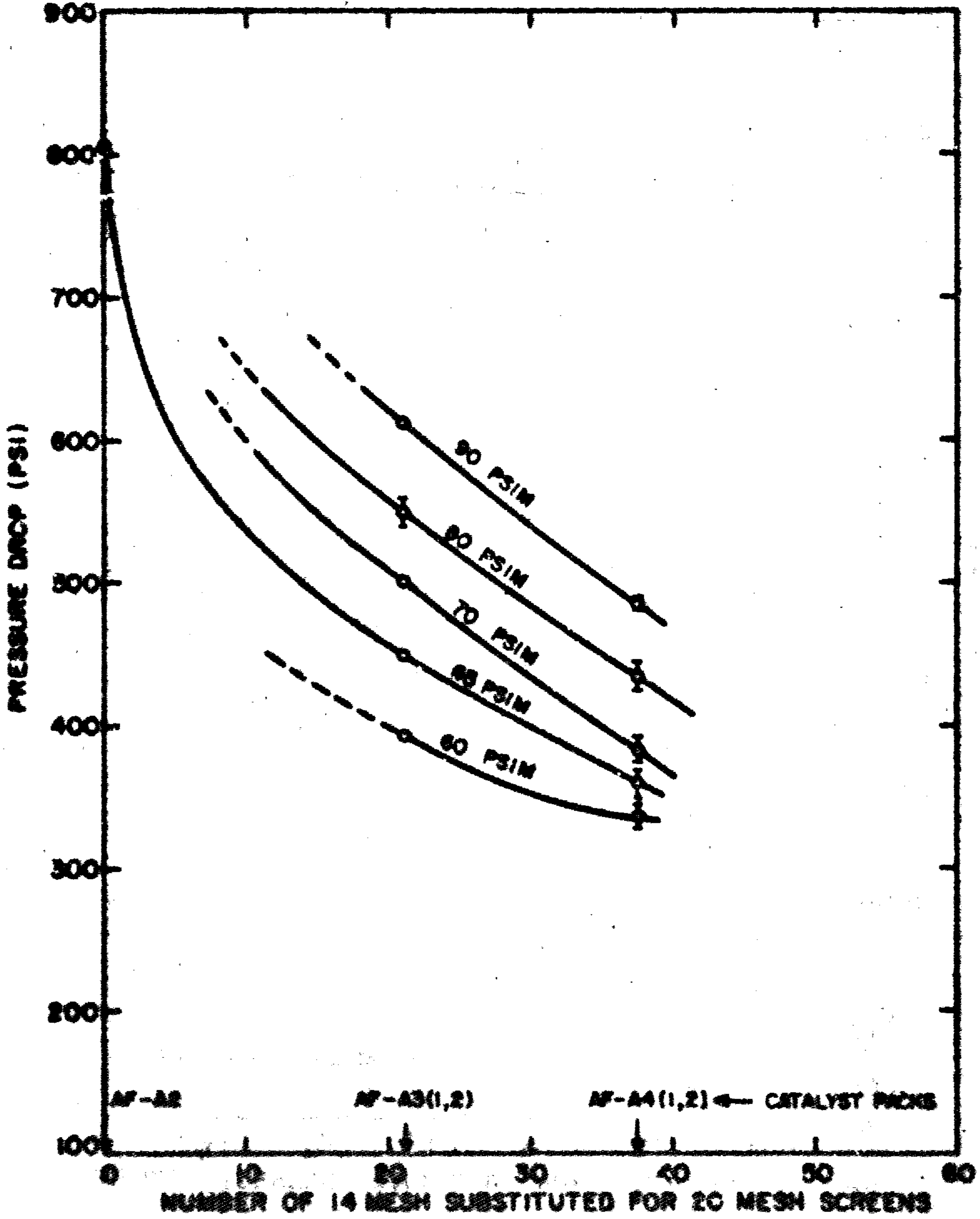
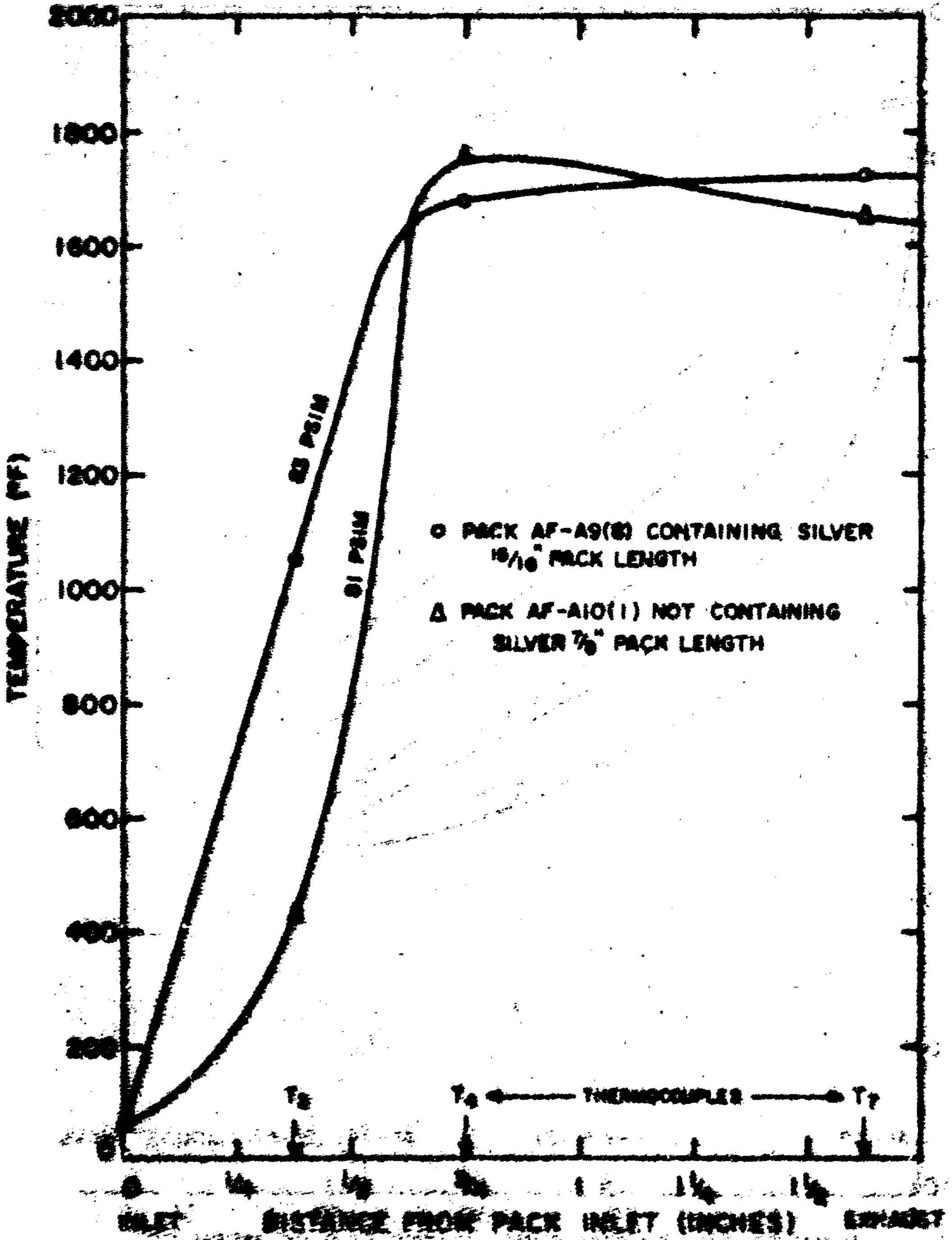


Figure 30

TEMPERATURE PROFILES FOR HIGH PRESSURE—HIGH LOADING TESTS WITH 3/4" DIAMETER CHAMBER: CATALYST PACKS WITH AND WITHOUT SILVER CATALYST SCREENS

TESTS USED 0.283" EXHAUST ORIFICE



The temperature profiles for tests AF-A4(1), AF-A9(5), and AF-A9(8) are given in Figure 31. Good reproducibility was exhibited for tests AF-A4(11) and AF-A9(5) which used identical catalyst configurations. The figure also indicates that the temperature profiles and thus the location of the liquid front was not affected by the shortening of pack AF-A9(8).

Pack AF-A10(1) was 7/8" in length. This pack contained 47 silver-30% palladium catalyst screens and 7 nickel-5% manganese filler screens. No 20 mesh silver catalyst screens were employed. The pack produced an even lower pressure drop, ~170 psi 80 PSIM and 1206 psia chamber pressure, versus ~408 psi at 84 PSIM and 1506 psia chamber pressure for Pack AF-A8. These two packs were similar in that they did not contain silver screens.

Figure 32 shows the pressure drop reductions realized by shortening the silver-and non-silver-containing packs. The values for pack AF-A8(3) are probably high due to additional pack compression as discussed in section (a) (Pack Compression) above. In view of the temperature profiles for packs AF-A9(8) (Figure 31) and AF-A10(1) (Figure 30) a further reduction of pack length and corresponding decrease in pressure drop may be possible.

The liquid front of pack AF-A9(8) containing both silver and silver-30% palladium catalyst screens was shown to be nearer the inlet that in a similar length, all silver-30% palladium pack (AF-A10) (see section (c) above). Therefore, it is likely that the length of AF-A9(8) could be decreased proportionately more than AF-A10. This could lead to nearly equal pressure drops for the two packs.

(e) Alternation of Catalyst and Filler Screens

In catalyst pack AF-A1 the silver-30% palladium catalyst screens were alternated with nickel-5% manganese filler screens. This packing arrangement was not used in later packs because maximum concentration of catalytic surface toward the inlet end of the pack was desired. There was no indication of screen matting problems except in those cases where the pack was tightened after each test. Alternation of the silver and silver-30% palladium screens with inert screens has been recommended for packs of greater than one inch in diameter to increase their structural strength. This alternation is presently giving satisfactory results in high pressure (4000 psi) tests under AF Contract AF04(611)10785(10).

Figure 31

TEMPERATURE PROFILES FOR
HIGH PRESSURE – HIGH LOADING TESTS WITH 3/4" DIAMETER CHAMBER
REPRODUCIBILITY AND THE EFFECT OF SHORT CATALYST PACKS
THE PACKS WERE IDENTICAL EXCEPT THAT AF-A9(8) WAS
SHORTENED BY REMOVAL OF FILLER SCREENS
ALL TESTS USED 0.253" EXHAUST ORIFICE

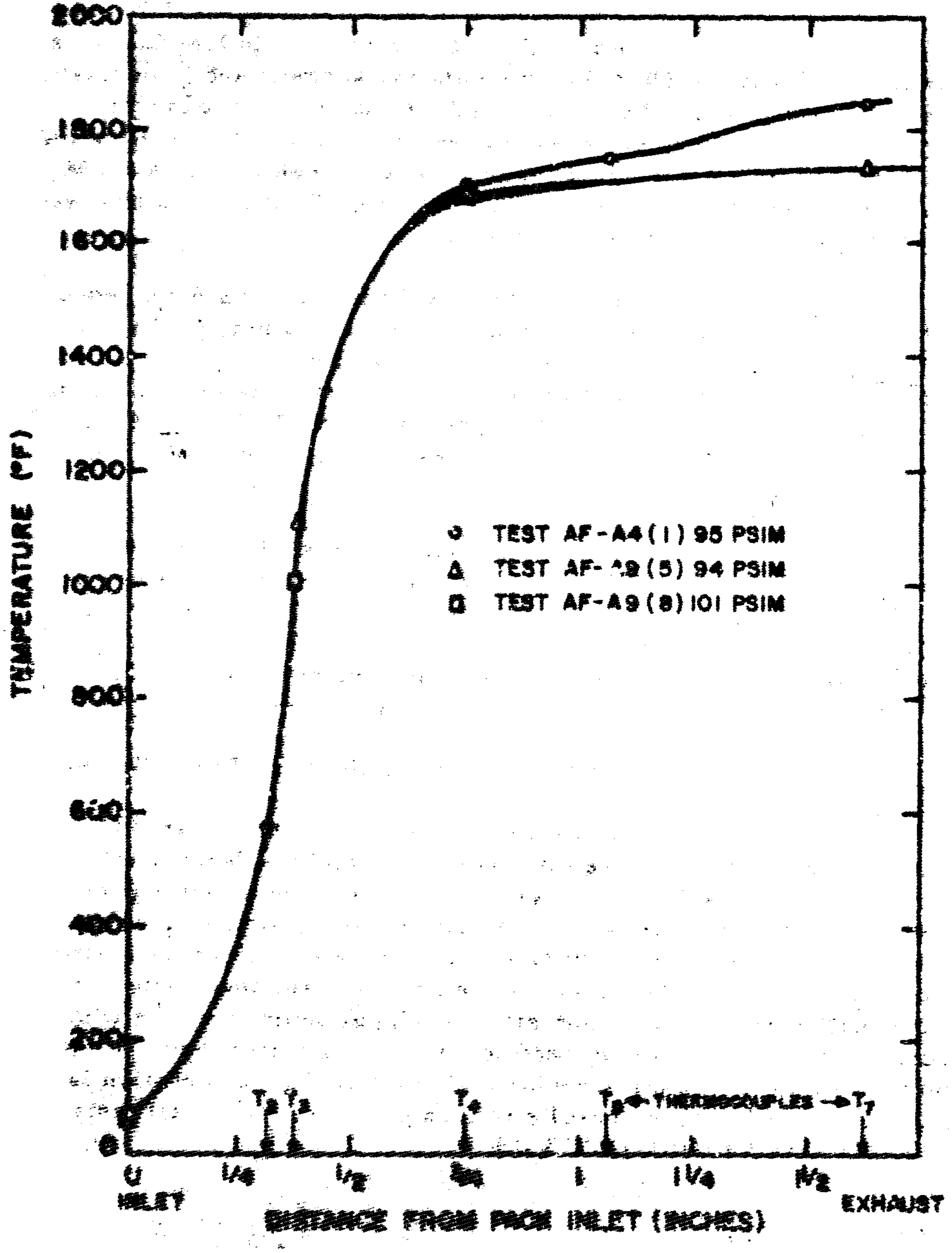
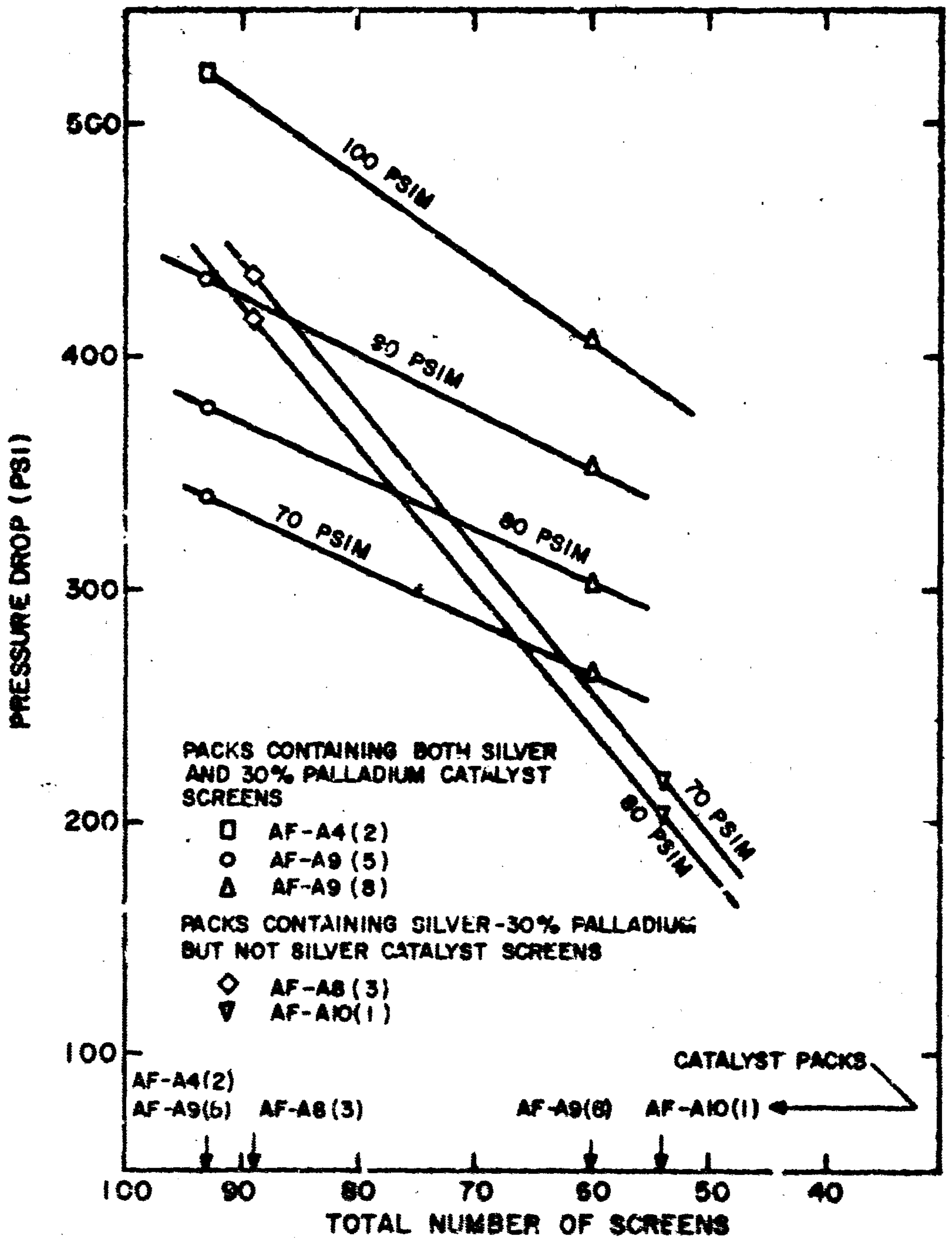


Figure 32

HIGH PRESSURE-HIGH LOADING TESTS WITH $\frac{3}{4}$" DIAMETER CHAMBER
REDUCTION OF PRESSURE DROP ACROSS CATALYST PACK
BY DECREASE IN PACK LENGTH
ALL TESTS WITH 0.253" EXHAUST ORIFICE



(f) Pressure Oscillations

The high pressure-high pack loading test program included a number of correlation tests whose purpose was to produce data for design of rocket motors and other applications of the catalyst pack. These correlation data tests were originally planned to be run at low pack loading rates of 20 to 40 PSIM. However, the tests at these flow rates were consistantly disrupted by oscillations in the chamber and inlet pressure. As indicated previously, some useful data was accumulated at low loading rates for pack AF-A4, tests 3 to 5. Nevertheless, the oscillations were often severe and could not be completely eliminated. High pack loading tests were not affected.

A number of changes were made in the test chamber configuration to try to control or eliminate the oscillations. The first three AF-A4 tests (3 to 5) at low loading produced oscillations at the start which decreased to smooth operation for the latter part of the test. This tendency to smooth out as the flow increased was not continued in test AF-A4(6). Since AF-A4 tests 1 and 2 had been smooth at high loading rates, a larger diameter nozzle was used for AF-A4 test 7, but without improvement. An inlet orifice with a pressure drop of 70-80 psi at 100 PSIM was tried in test AF-A4(8). Next the void space between the inlet orifice and the front of the catalyst pack was eliminated for test AF-A4(9). Thus the lower rim of the orifice was cut off and it was set directly on the pack without an inlet plate in between.

After the above changes had been tried without success, test AF-A4(10) was run with the original 70-80 psi inlet orifice and exhaust nozzle combination, and the smooth operation of tests AF-A4 (1 and 2) was reproduced. This result indicated that the oscillations were not due to a progressive deterioration of the catalytic activity of the catalyst pack.

Additional modifications of the test chamber configuration were tested as remedies for the low loading, pressure oscillations. Pack AF-A6 showed that lengthening the pack was not beneficial. Very tight baffles before and after the inlet orifice and within the catalyst pack were used in tests with Pack AF-A8 and all subsequent packs and proved unrewarding. For test AF-A9(2) the catalyst pack was located just after the snap ring at the very inlet end of the chamber. This was done to test the suggestion that incoming H_2O_2 was heated by carry-back of heat from lower in the chamber, and thus premature decomposition and oscillations were produced. This also failed to correct the problem.

In test 4 with Pack AF-A8 the thermocouple ports T_1 to T_6 were completaly covered by a sleeve to eliminate any possible organpipe effect of the void spaces. Lastly, the inlet orifice was removed for test AF-A8(5), leaving only the inlet plate before the catalyst pack. None of these various changes were effective in eliminating the oscillations. The oscillations were uniformly of low frequencies, between 40 and 170 cycles per second. High amplitudes of the order of 800 psi out of a possible 1500 were sometimes reached.

As the gas generator used in these tests was designed for 5000 psi service and required ease of catalyst removal, the chamber inlet configuration was not optimum. The variable flow operation limited the desirability of using a cavitating venturi. Trim orifices were employed and proved beneficial in the high flow tests.

(g) Best Catalyst Packs

Figure 33 shows the best two catalyst packs tested during the program. Pack AF-A9(8) reached a maximum throughput of 101 PSIM, chamber pressure of 1506 psia, and pressure drop of 404 psi. Pack AF-A10(1) showed a pressure drop of only 170 psi at 80 PSIM throughput and 1206 psia chamber pressure. The figure shows the chamber configuration parts in order from the inlet on the left to the exhaust at the right. with pack AF-A10 inserted at the proper location. The holes where the thermocouples were inserted to the center of the packs appear in the picture. A more detailed and enlarged view of pack AF-A9(8) appears in Figure 34. As is apparent in the figures, no visible damage was suffered by either pack during the tests.

Figure 35 shows the smooth steady state operation of Pack AF-A9(8) at 101 PSIM loading, 1506 psia chamber pressure, and 99.2% C^*. In the figure Pc_1 and Pc_2 are the chamber pressure traces and T_3, T_6, and T_7 are the temperature readings from the thermocouples. The positions of the various traces were a function of the selection of deflection range for each input, and so do not appear to indicate their actual relative values.

Figure 36 shows the start of test AF-A10(1). Of particular interest is the rapid rise in temperature to steady state values shown by thermocouple traces T_3, T_6, and T_7. The T_7 reading is actually higher than T_6, though the opposite appears true on the trace due to scaling factors. Pc_1 and Pc_2 are again the chamber pressure values.

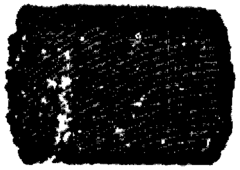
(h) Value of Temperature Measurements

Perhaps the most important measurements made during these tests were the temperatures determined for various locations within the catalyst pack. The effect of various alterations to the

Figure 33

BEST CATALYST AND CHAMBER CONFIGURATION AFTER HIGH PRESSURE-HIGH LOADING TESTS

CATALYST PACK AF-A9(B)



CHAMBER CONFIGURATION AND CATALYST PACK AF-A10

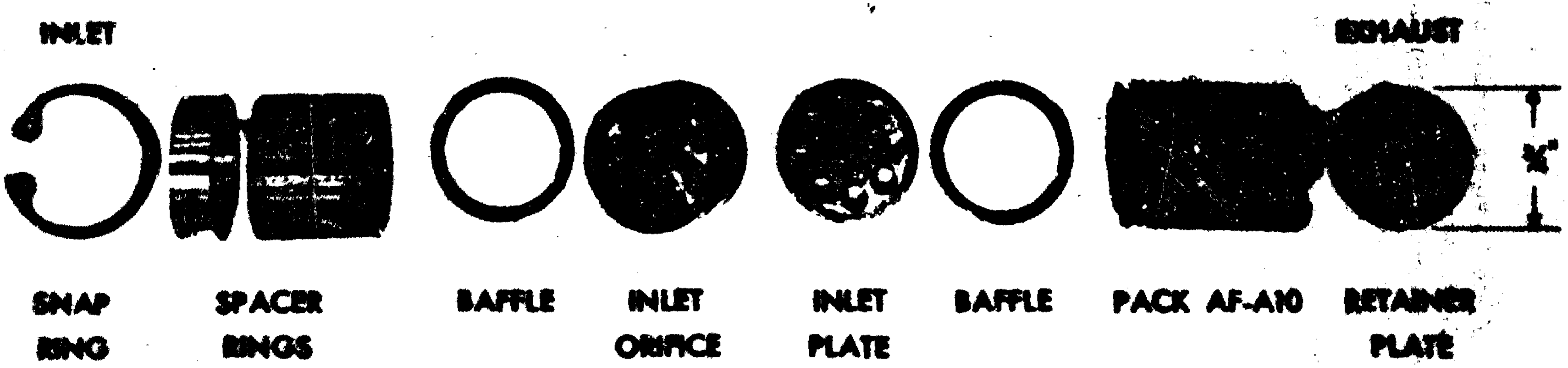


Figure 34

DETAIL OF CATALYST PACK AF-A9(8) AFTER HIGH PRESSURE-HIGH PACK LOADING TESTS

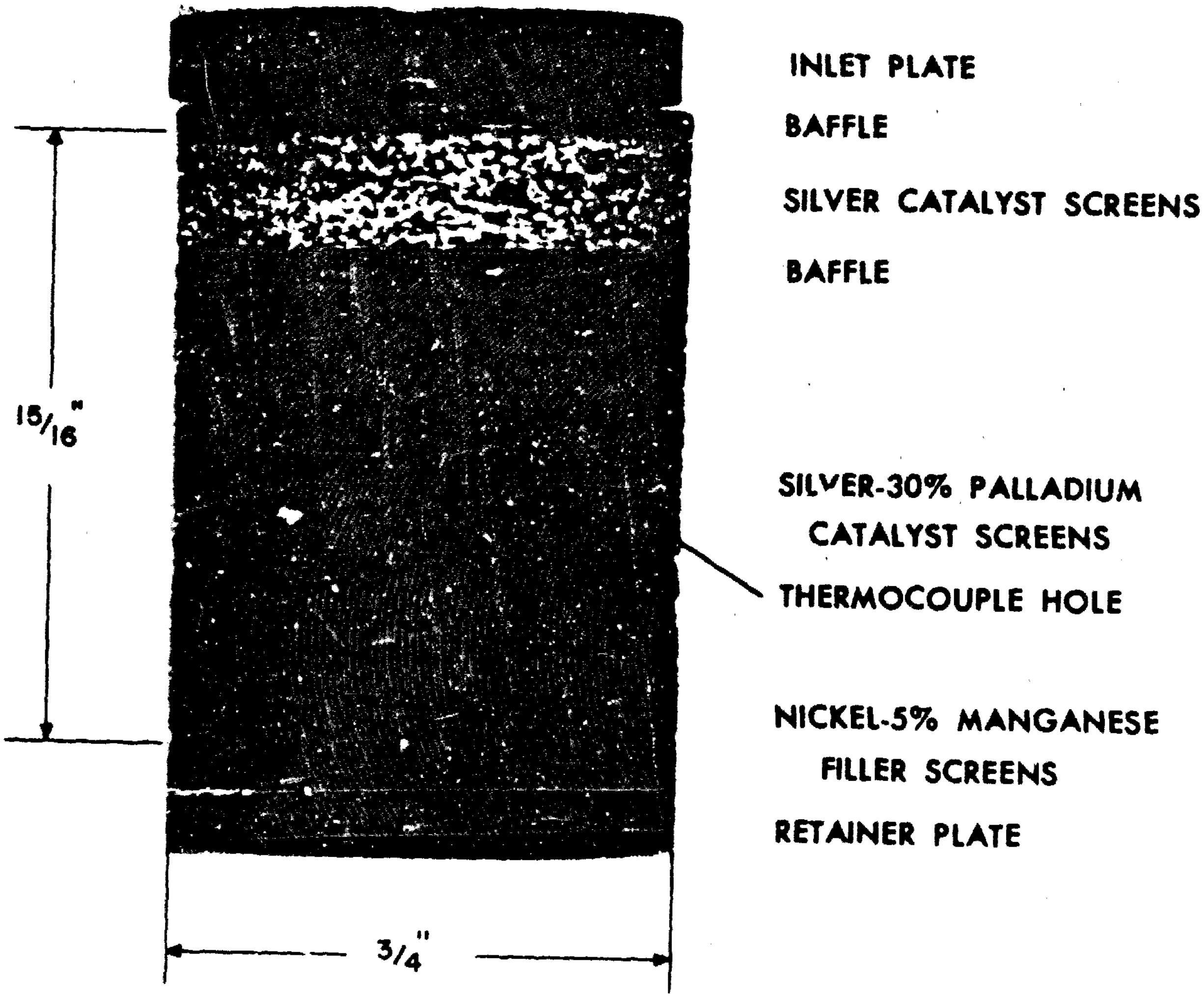


Figure 35

HIGH PRESSURE-HIGH PACK LOADING TEST WITH 98% H_2O_2
TEST AF-A9(8), STEADY STATE AT 10 SECONDS
3/4" DIAMETER TEST CHAMBER AND 56°F FEED

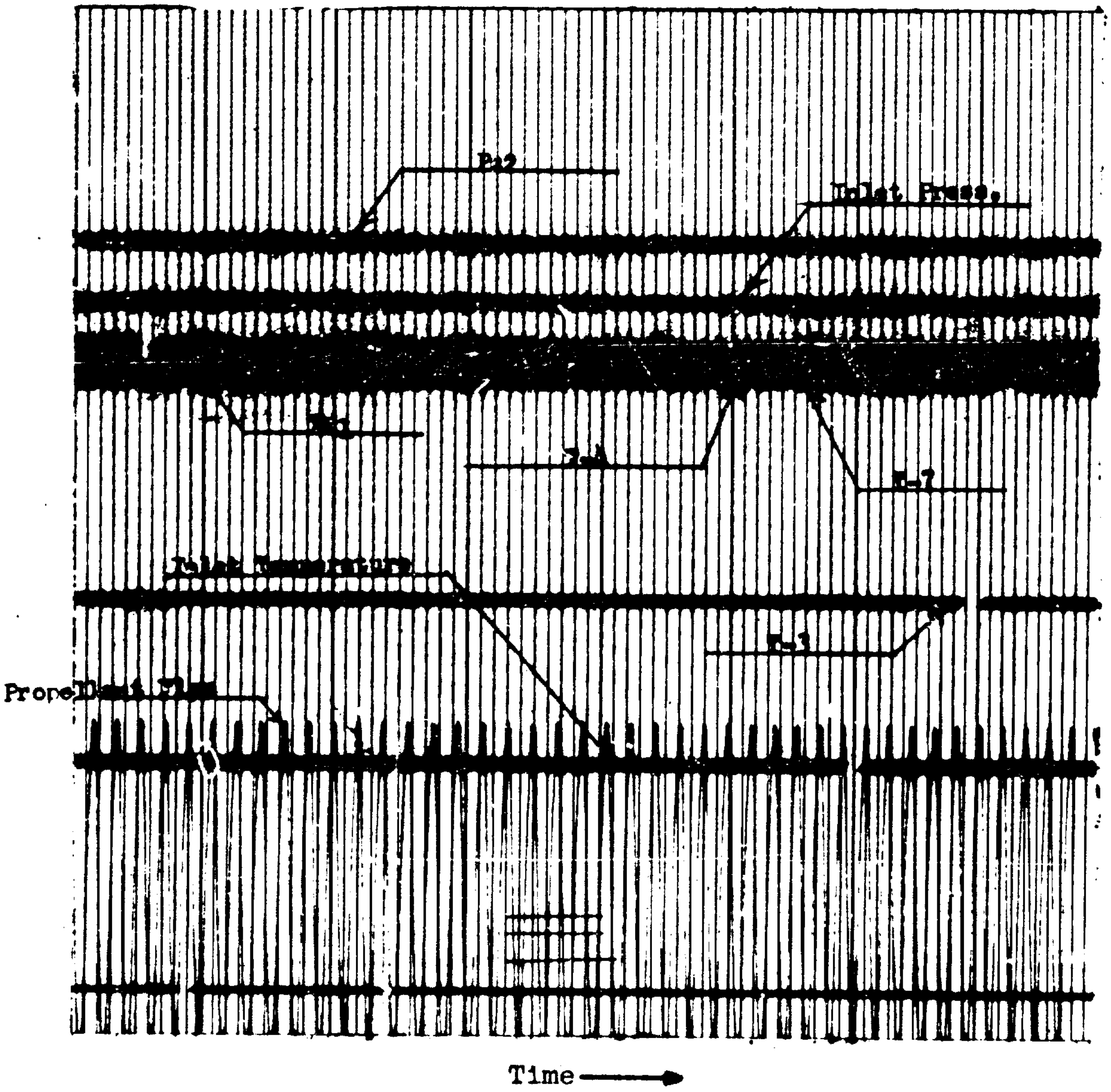
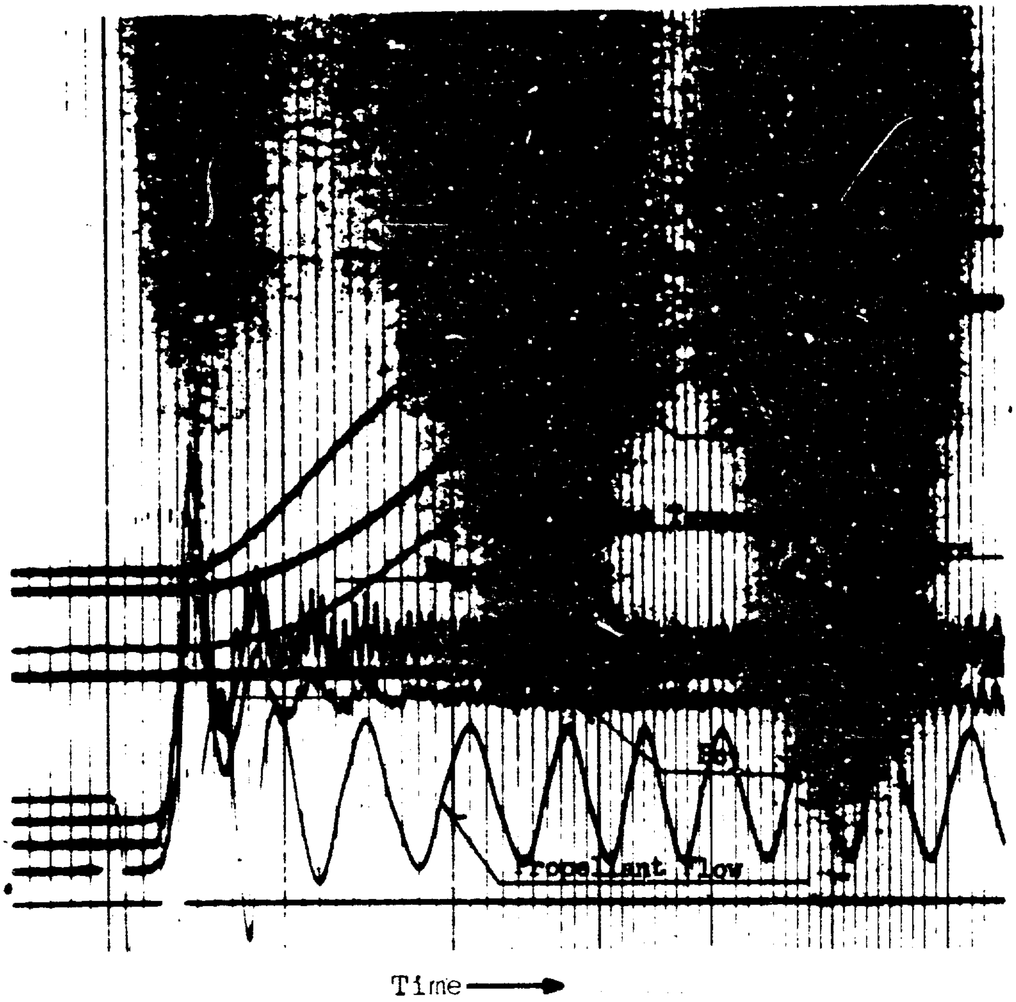


Figure 36

HIGH PRESSURE-HIGH PACK LOADING TEST WITH 98% H_2O_2
TEST AF-A10(1), START OF STEADY-STATE
AFTER THREE WARM-UP CYCLES
3/4" DIAMETER TEST CHAMBER AND 54°F FEED



catalyst pack was indicated clearly when temperature values were used in conjunction with the usual information concerning pressure and flowrates.

Temperature changes were especially valuable in showing the reduced catalytic activity which resulted when 20 mesh rather than 40 mesh silver screens were used in the inlet section of the catalyst pack and when no silver screens at all were used in the pack. The temperatures also indicated that removing 14 mesh nickel manganese screens from the exhaust section of the pack did not change the operation of the remainder of the pack. These points have been discussed in detail in previous parts of the report.

A typical example of the use of temperature data is given in Figure 37. The figure shows the temperature shifts which occurred 3/8" from the inlet end of the catalyst pack as the throughput was increased. Thus the movement of the liquid front is clearly indicated. Also its location within the catalyst pack has been determined for a particular small range of pack loadings. Data are given for three tests on the same catalyst pack with differenct diameter exhaust orifices. The temperature change at 3/4" into the pack for one of the tests is also given in the figure. This shows the rather constant temperatures obtained for those parts of the pack which remained continuously in the gas phase.

The temperature measurements were also used in evaluating the tests with heated H_2O_2 feed. The movement of the liquid front toward the inlet can again be determined. In that case, however, the movement results from increased feed temperature rather than changes of pack loading. Further discussion of that test appears in section b, page 95.

(i) Catalyst Life and Erosion

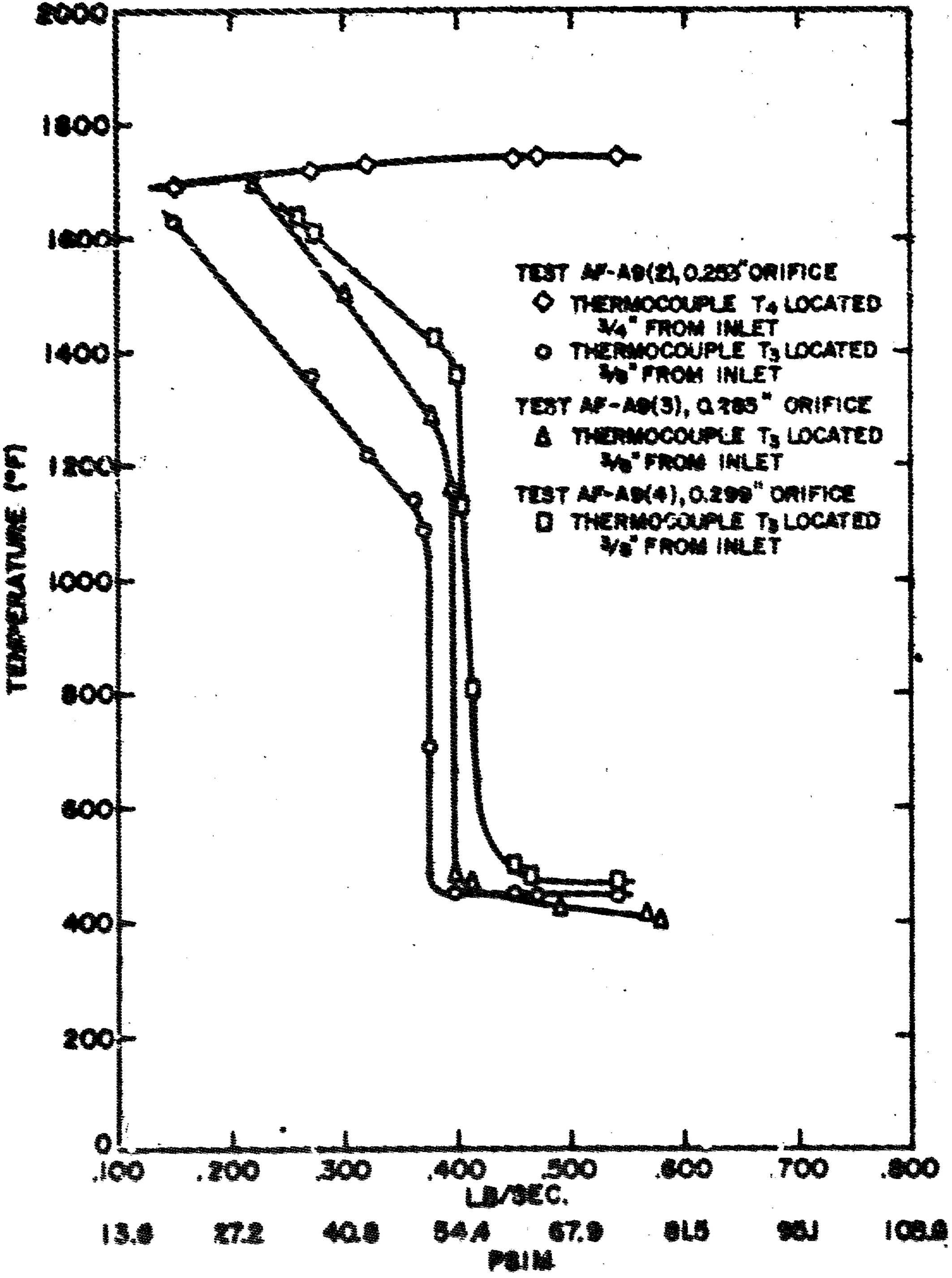
The changes in weight and catalytic activity which resulted from extended testing of the catalyst have been measured and evaluated. The results of these studies for the high pressure-high pack loading tests, heated H_2O_2 feed tests, and low temperature tests have been reported in the Life Tests section (page 104).

b. High Pressure-High Pack Loading Tests with Elevated Temperature 98% H_2O_2 Feed.

These tests were planned to evaluate the effect of heated 98% H_2O_2 upon the silver-30% palladium catalyst at high pack loading rates and pressures simulating the startup conditions of a rocket engine regeneratively cooled with 98% H_2O_2. The tests were carried out using the same test chamber as that employed for the high pressure-high pack

Figure 37

HIGH PRESSURE-HIGH LOADING TESTS WITH 3/4" DIAMETER CHAMBER
SHIFT OF CATALYST TEMPERATURE WITH INCREASED LOADING
TESTS AF-A9(2-4), 98.4% H_2O_2 FEED AT 80°F



loading tests with ambient temperature H_2O_2 feed. The catalyst packs tested were AF-A4 (Test $_{11}$) and AF-A10 (Test 2). The screen configuration (Table XIV), chamber configuration (Table XV), and test results (Table XV) have been tabulated and described earlier in this report. The test system was also the same as that used previously and is shown in Figure 25, 26, and 27 and described in the text on page 69.

(1) Test Procedure

The two high pressure-high pack loading tests with heated 98% H_2O_2 feed used the same test procedure and recording of test data as reported on page 74, with two modifications. Two modifications involved the heating of the H_2O_2 before the test and the cooling of the H_2O_2 after the completion of the test.

First the nitrogen gas pressure above the H_2O_2 in the feed tank was increased to 200-400 psi. Then the steam flow through a coil within the water jacket around the H_2O_2 storage tank was turned on to raise the H_2O_2 temperature. Over a period of one hour, the steam was turned on for several periods of 10 to 30 seconds to heat the H_2O_2 to 160-170°F. The liquid and vapor temperatures in the H_2O_2 tank and the water temperature in the jacket were carefully monitored as the H_2O_2 temperature was increased. A check was also maintained on the nitrogen pressure in the H_2O_2 tank, since H_2O_2 decomposition from non-passive sites within the tank would cause an abnormal rise in the pressure above the H_2O_2.

At the conclusion of the test, nitrogen pressure over the H_2O_2 in the tank was maintained at 200-400 psi while tank and H_2O_2 temperatur was reduced by flowing cold water through the water jacket around the tank.

(2) Results of the Tests

Test AF-A4(11) was conducted with elevated temperature 98% H_2O_2 feed in the neighborhood of 150°F. Smooth operation was achieved for most of the test. However, the pressure drop across the catalyst pack increased steadily during the test, reaching 900 psi near the end. Also, the oscillograph trace showed minor disturbances in the pressure reading beginning at 17 seconds into the test and sharp but isolated spikes beginning at 36 seconds. At 42 seconds a failure of the chamber inlet fittings occurred and the test was terminated.

Since the catalyst pack and retainer plate were not recovered, some doubt existed concerning the cause of the failure. However, shortly thereafter test AF-A7(2) with ambient feed produced a structural failure in the 347 stainless retainer plate. In this case, the distorted plate and catalyst pack were recovered still lodged within the exhaust nozzle. These results indicated clearly that test AF-A4(11) had also suffered a retainer plate failure. An inconel plate was used in subsequent tests and no further failures occurred.

Pack AF-A4 contained 17 relatively low-melting silver catalyst screens in the inlet region. Since the pack was not recovered it is not known whether these screens melted during the test. The other pack (AF-A10) which was tested with heated H_2O_2 feed did not contain any silver screens. Thus the question of possible melting of such screens in tests with heated feed remains open.

The smooth operation of test AF-A10(2) with 140°F H_2O_2 feed is shown in Figure 38, giving the recorded trace at 50 seconds into the test. The two chamber pressure measurement are designated by Pc_1 and Pc_2. Temperature readings are shown at T_3, and T_4, both within the catalyst pack, and T_7 the chamber temperature.

Figure 39 shows the increase in the realized 98% H_2O_2 decomposition gas temperature versus in the feed temperature for test AF-A10(2). The feed temperature increase from 66 to 140°F resulted in a rise of decomposition gas temperature from 1760 to 1865°F at thermocouple T_4 in the lower section of the catalyst pack. This is a 1.41°F increase in decomposition gas temperature per 1°F rise in 98% H_2O_2 feed temperature. The 1.41 value closely approaches the theoretical value of 1.442. Figure 40 shows a graph of the theoretical change of decomposition gas temperature with feed temperature for 98% H_2O_2.

The temperature profiles achieved in test AF-A10(2) are shown in Figure 41 for two different feed temperatures. As shown in the figure, the T_7 chamber temperatures are somewhat lower than the T_4 values, but this is a common phenomena attributed to heat losses to the motor. Thus the T_4 values are more representative of the actual decomposition temperatures obtained.

Catalyst pack pressure drop increased approximately 150-200 psi during the high temperature feed tests. This resulted because the liquid front moved toward the inlet as the H_2O_2 feed temperature increased during the test (Figure 41), resulting in a longer gas phase section. This again points out the need for catalyst screens with increased open area.

The theoretical characteristics velocity of exhaust gases (C*) varies with 98% H_2O_2 feed temperature as shown in Figure 42. Test AF-A10(2) produced measured C* values which reached above 98% of theoretical for 121°F feed temperature, but then

Figure 38

HIGH PRESSURE-HIGH PACK LOADING TEST WITH 98% H_2O_2
TEST AF-A10(2), STEADY STATE AT 50 SECONDS
3/4" DIAMETER TEST CHAMBER AND 140°F FEED

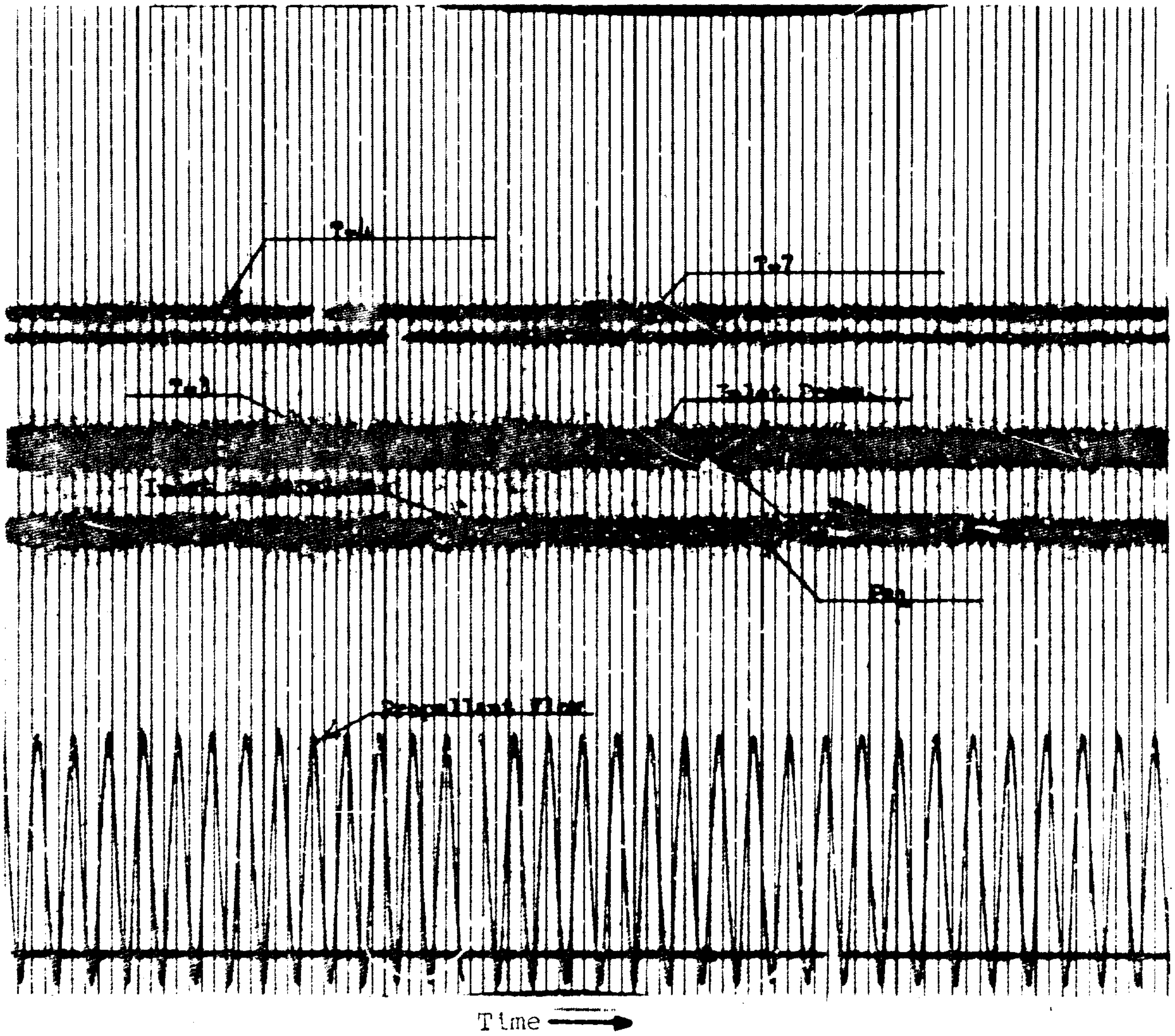


Figure 39

CHAMBER TEMPERATURE VERSUS 98% H_2O_2 FEED TEMPERATURE
HIGH PRESSURE-HIGH LOADING TEST WITH 3/4" DIAMETER CHAMBER
TEST AF-AIO(2), PACK LENGTH 7/8"

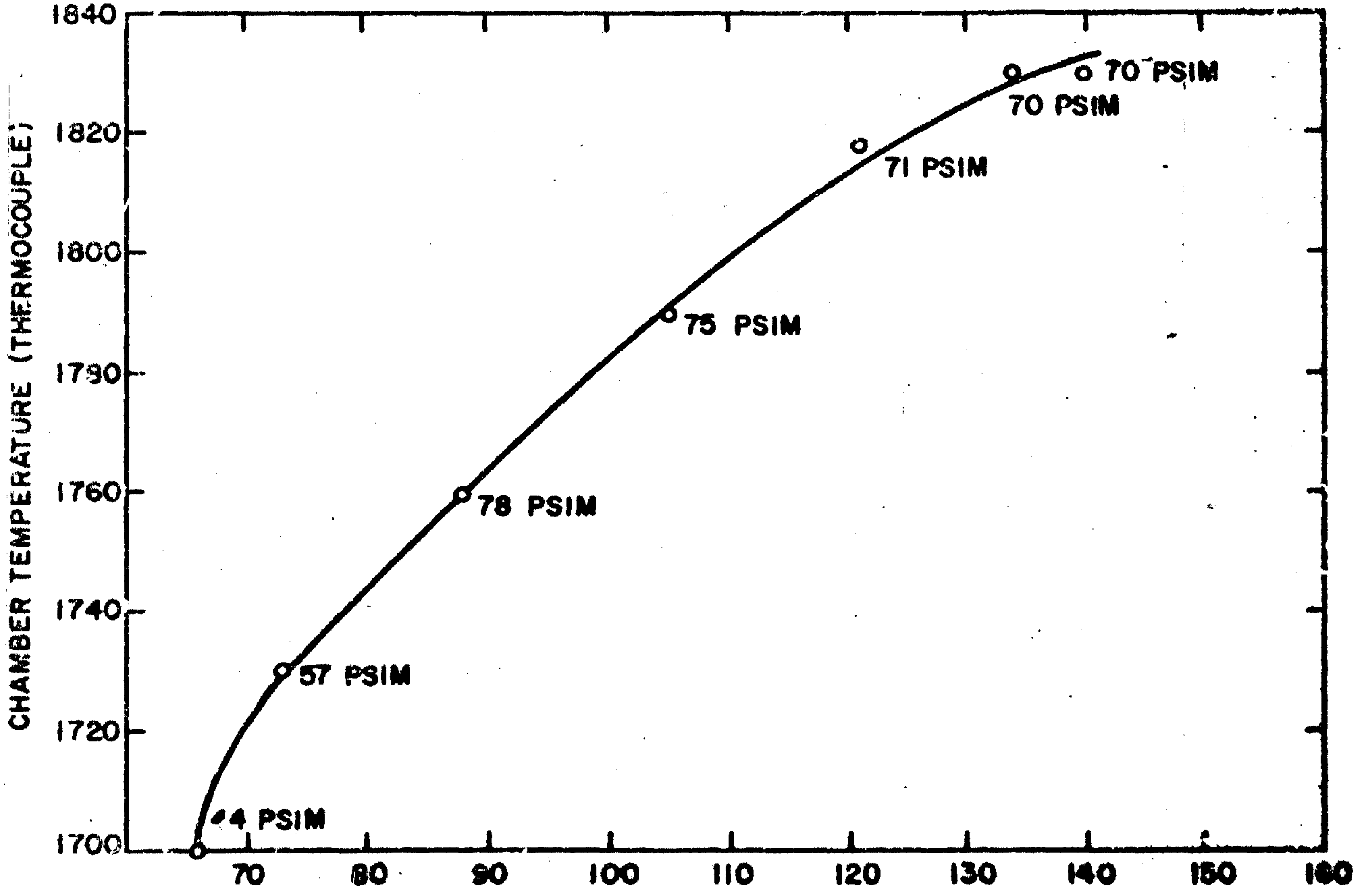
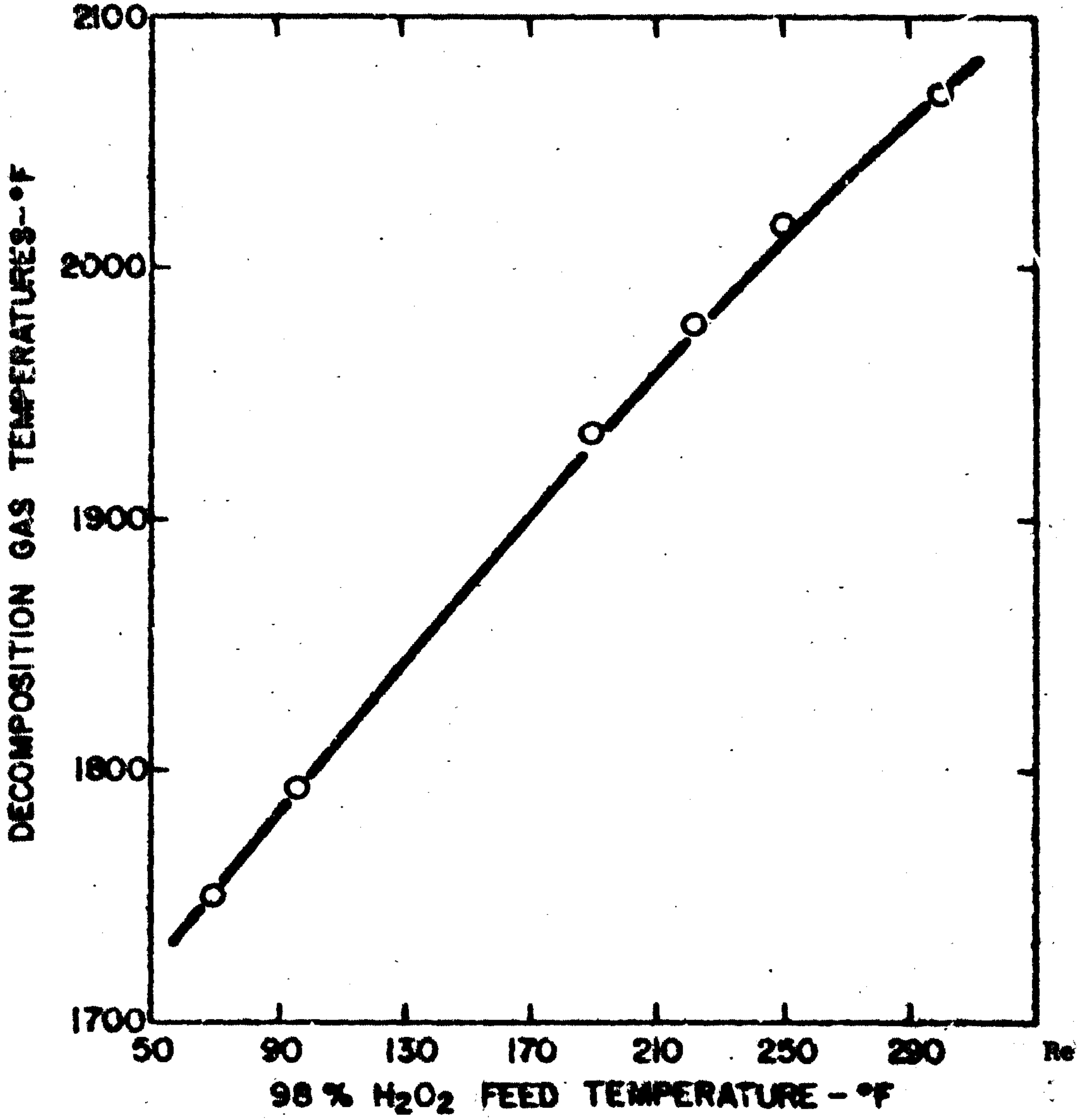


Figure 40

DECOMPOSITION GAS TEMPERATURE OF 98% H_2O_2 AT VARIOUS FEED TEMPERATURES AND 1200 - PSIA



Ref.(11)-FMC Corp.

Figure 41

TEMPERATURE PROFILES WITH HEATED 98% H_2O_2 FEED
HIGH PRESSURE-HIGH LOADING TEST WITH 3/4" DIAMETER CHAMBER
TEST AF-A10(2) EXHAUST ORIFICE 0.253"

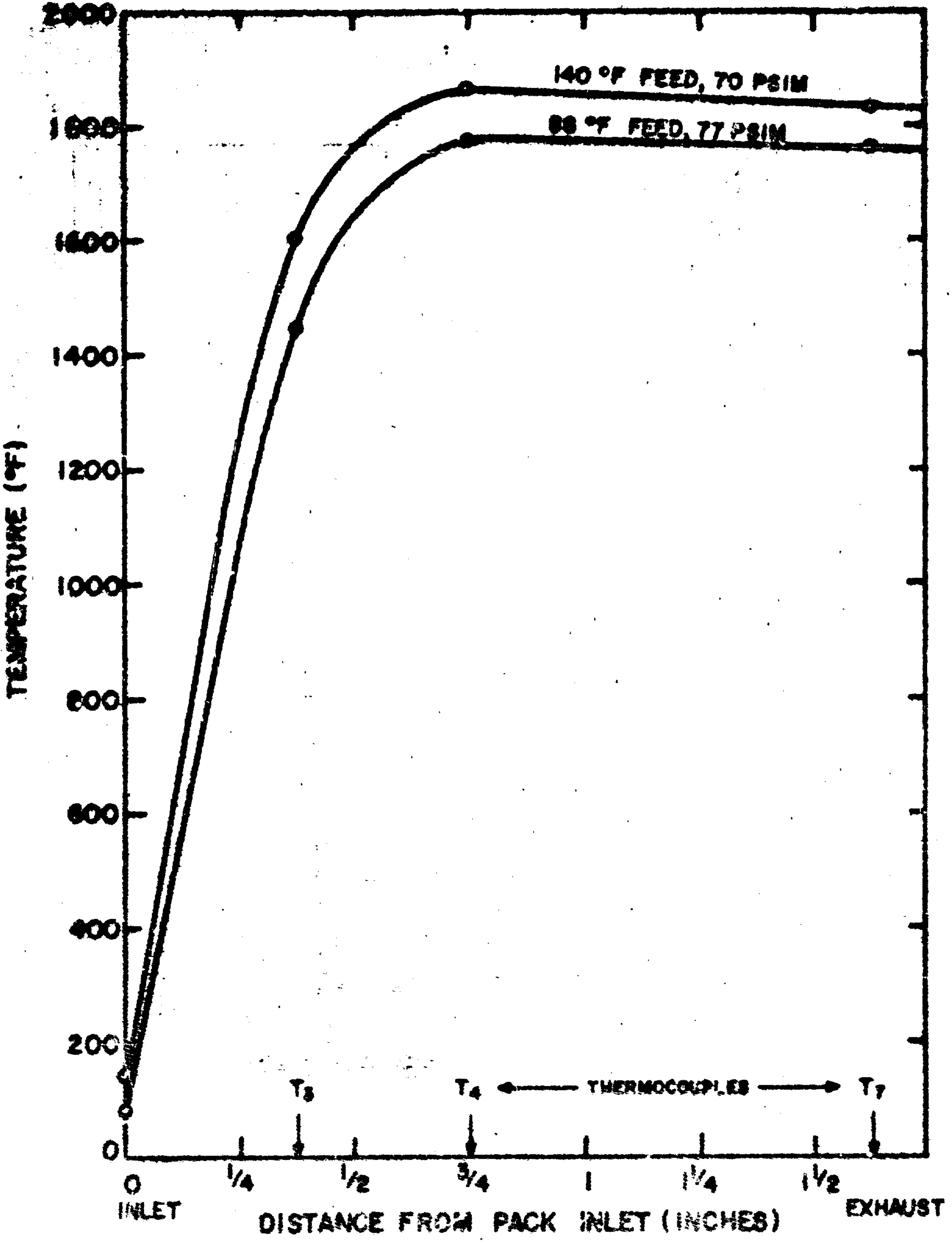
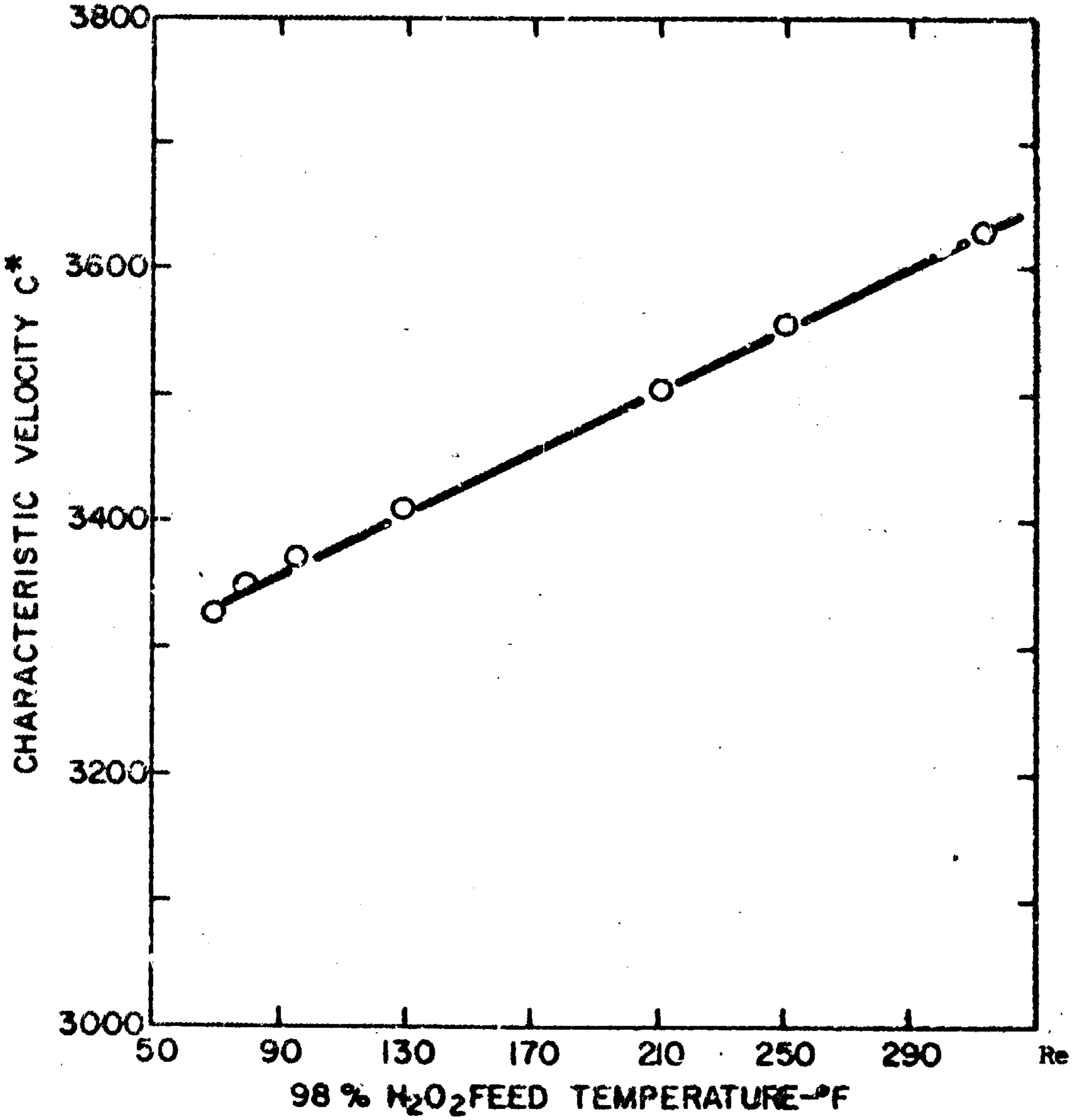


Figure 42

CHARACTERISTIC VELOCITY C* FOR 98% H_2O_2
AT VARIOUS FEED TEMPERATURES AND 1200 - PSI.



Ref. (11)-FMC Corp.

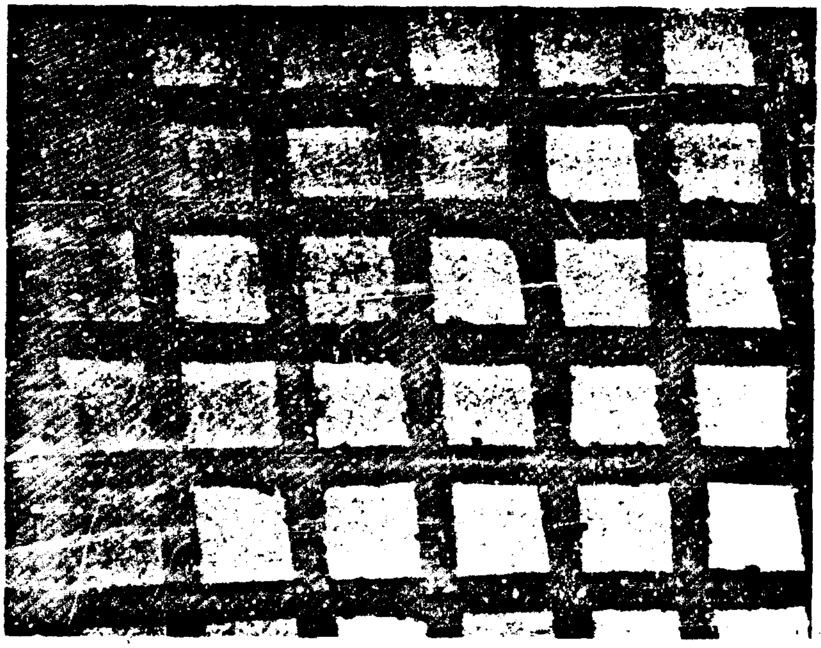
dropped off to 92% as the feed temperature rose to 140 . This can be traced to the corresponding increase in pressure drop across the catalyst pack as noted above.

Tests were also planned with 200°F and 250°F 98% H_2O_2; however, an increased gassing rate in the feed tank occurred during propellant heating above 170-180°F. Contract termination prevented feed tank repassivation due to unavailable time.

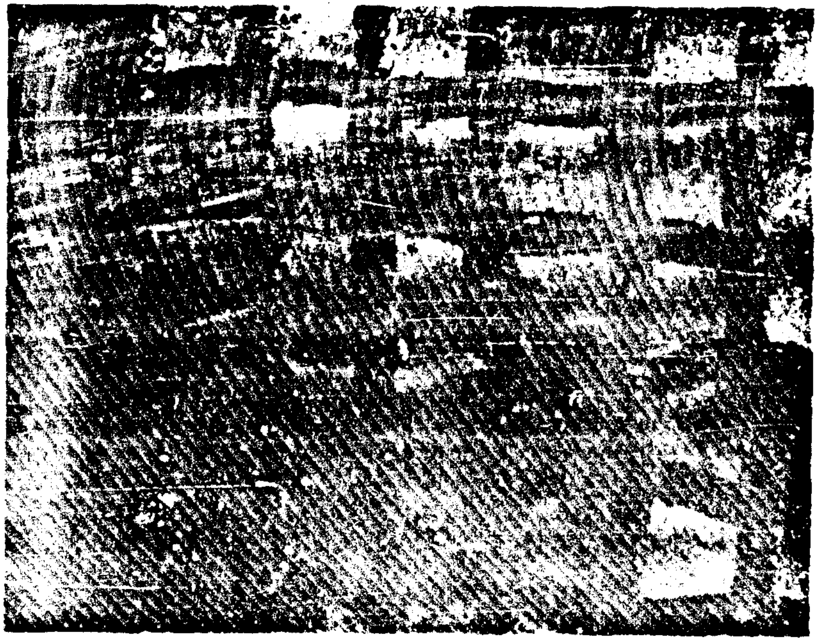
The silver-30% palladium catalyst screen has a theoretical melting point of 2120°F which is well above the decompositon temperature (2012°F) of 98% H_2O_2 at a feed temperature of 250°F. Silver-30% palladium catalyst screens (20 and 40 mesh) were previously evaluated (10) with 251°F 98% H_2O_2 and were not damaged by the 2025°F decomposition gases (Figures 43 and 44). These tests show that the screens are suitable for use in regeneratively cooled engines employing 98% hydrogen peroxide as the coolant

Figure 43

PHOTOMICROGRAPHS OF SILVER-30% PALLADIUM CATALYST SCREENS USED WITH 251°F 98% H_2O_2 FEED



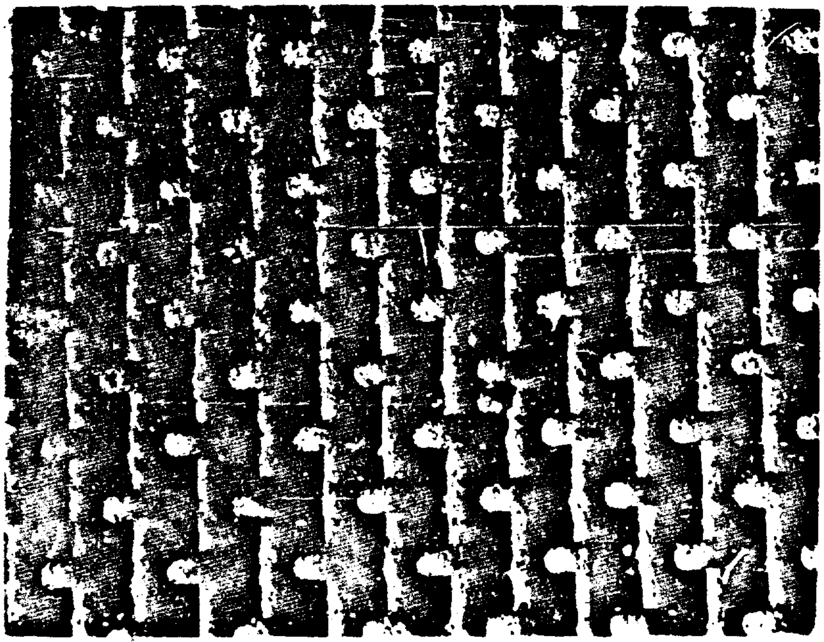
New 20 Mesh Screen (14X)



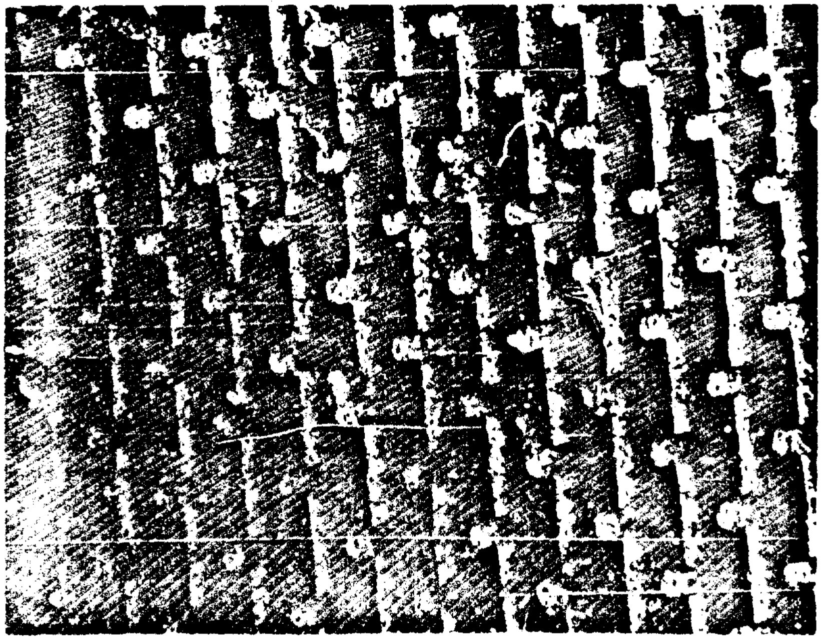
Used 20 Mesh Screen (14X)
(Deformation Due to Excessive Packing Pressure)

Figure 44

PHOTOMICROGRAPHS OF SILVER-30% PALLADIUM CATALYST SCREENS USED WITH 251°F 98% H_2O_2 FEED



New 40 Mesh Screen (14X)



Used 40 Mesh Screen (14X)

c. Life Tests

Extended testing was carried out on packs AF-A4 and AF-A8, AF-A9, and AF-A10. During the eleven tests on pack AF-A4, slightly more than 8 minutes run time was accumulated. This pack was lost at the end of test 11 due to failure of the retainer plate, so analysis of the catalyst screens after the tests was not possible. However, the results for test AF-A4(10) after 7 minutes run time essentially reproduced the results of AF-A4 tests 1 and 2, and were carried out with the same inlet orifice and exhaust nozzle. This indicates that the catalyst was still operating properly.

Approximately three minutes test time was accumulated on pack AF-A8. This pack exhibited a greater decline in starting capability than the other tests, which is attributed to the lack of silver screens in the inlet of the pack.

Pack AF-A9(8) was still giving good starts and performance at the termination of testing. The silver screens contained in the inlet of this pack account for the continued starting capability. Pack AF-A10, again without silver, showed a decline in start response. The testing on this pack included about one minute with elevated temperature H_2O_2 feed which reached 140° F. No particular effects on either the screen appearance or screen activity related to the heated feed were observed.

The activity of selected silver-30% palladium screens after motor testing is shown in Table XVII. The activities were determined by the standard flood test with 10 ml. of 98% H_2O_2 as outlined on page 4 . The results show that more significant activity loss occurred for these tests than for the initial motor screening tests (Table XIII). Either the high pack loading or the extended test time compared to the initial screening tests could be the cause of the added decrease in activity. In each case, screens located in the hotter regions farther from the inlet suffered greater activity losses. This concurs with the findings of the laboratory program, which showed that activity loss was a direct function of the temperature.

For several packs the screens were weighed before and after being motor tested. For the silver-30% palladium screens, weight losses up to 4% of the total screen weight were commonly found. However, during compression of either silver or silver-30% palladium catalyst screens into a cartridge or chamber, the samarium oxide coating is always crushed where the screens cross and a fine powder is produced. This causes a weight loss of the same magnitude, whether or not the screens are actually subjected to a motor test. Thus the weight measurements were not able to detect a change due specifically to motor operation.

TABLE XVII

EFFECT OF MOTOR OPERATION UPON CATALYST ACTIVITY OF SILVER-30% PALLADIUM SCREENS

Catalyst Pack	Position of Screen Among Ag-30% Pd Screens (numbered from inlet)	Total Test Time (min.)	Decomposition Rate After Motor Tests (ml/min)*		
			First Test	Second Test	Third Test
S/N 002	5th	1 1/2	15	---	---
	10th	1 1/2	1	---	---
AF-A5(2)	10th	1 1/2	~0	---	---
AF-A8(6)	5th	3	~0	---	---
	25th	3	~0	~0	---
AF-A9(8)	2nd	4 1/2	1	14	16
	15th	4 1/2	~0	---	---
AF-A10(3)	20th	3	1.5	20	---
	40th	3	~0	---	---

*Test used 10 ml. of 98% H_2O_2 which was initially at 20°C. The unused silver-30% palladium catalyst screens commonly show a decomposition rate of ~30 ml./min.

The nickel-5% manganese filler screens are not coated so no weight is lost because of pack compression. These screens generally showed a weight gain of up to 1% due to oxidation of the screen surface during motor operation.

d. Data Correlation and Engineering Design Information

A series of data correlation tests were planned as part of the high pressure-high pack loading motor test program. These tests were performed to produce data which can be extrapolated over a wide range of conditions to aid in design of rocket motors and other applications of the catalyst pack. Therefore seven of the high pressure-high pack loading tests were carried out with the same catalyst configuration (Type of AF-A4, Figure 24). The results of these tests have been examined in detail.

A modification of configuration type AF-A4 at the end of the program led to improved performance (AF-A9(8)). However, the modification involved only the removal of filler screens from the exhaust section of the pack. Thus a good indication of the performance of the improved pack over a range of operating conditions can be gained from the results correlated for the longer pack, type AF-A4.

The remaining of the two best pack configurations (AF-A10) tried during the program was not tested extensively. The correlated data for type AF-A4 will still serve as a guide for predicting the performance of AF-10, though perhaps not quite so well as for AF-A9(8). The correlated data can also be used approximately for other catalyst configurations similar to those studied in this program.

(1) Data Consistency

Data from the seven tests which employed the same catalyst configuration (type AF-A4) are shown in Figures 45 to 51. Similar plots for the two best configurations are given in Figures 52 and 53. The figures show the change of pack loading rate with change in chamber pressure. Lines for 95 and 99% theoretical C* (characteristic exhaust velocity) are shown on the figures for comparison. Some of the points which appear out of line in the figures were measured at moments of rapid change in flow rate, which probably caused inaccuracies in the determination of flow. This is the case particularly for two points of test AF-A9(5) and one point each from tests AF-A91(8) andAF-A10(1). Otherwise, the figures show that the data remained consistently at 95 to 99% of theoretical C* for most of the tests. The slopes of the data exhibit a smooth transition in performance as the exhaust nozzle size was increased from 0. 138 to 0. 299 inches diameter. Good agreement was obtained for the four tests (AF-A4(1), AF-A9 (5 and 8), and AF-A10(1)) which employed the same 0. 253 inch diameter nozzle, though catalyst packs AF-A9(8) and AF-A10(1) were short packs and AF-A10(1) did not contain silver catalyst screens. These results show that significant pressure leakage did not occur and that pressure and pack loading instrumentation was functioning properly. Thus the data appears to be satisfactory for use in motor and orifice design.

Figure 45

HIGH PRESSURE-HIGH PACK LOADING TESTS WITH 97.5% H_2O_2 AND 3/4" DIAMETER CHAMBER: PACK LOADING VERSUS CHAMBER PRESSURE TEST AF-A4(1) WITH 0.253" ORIFICE AND 61°F FEED

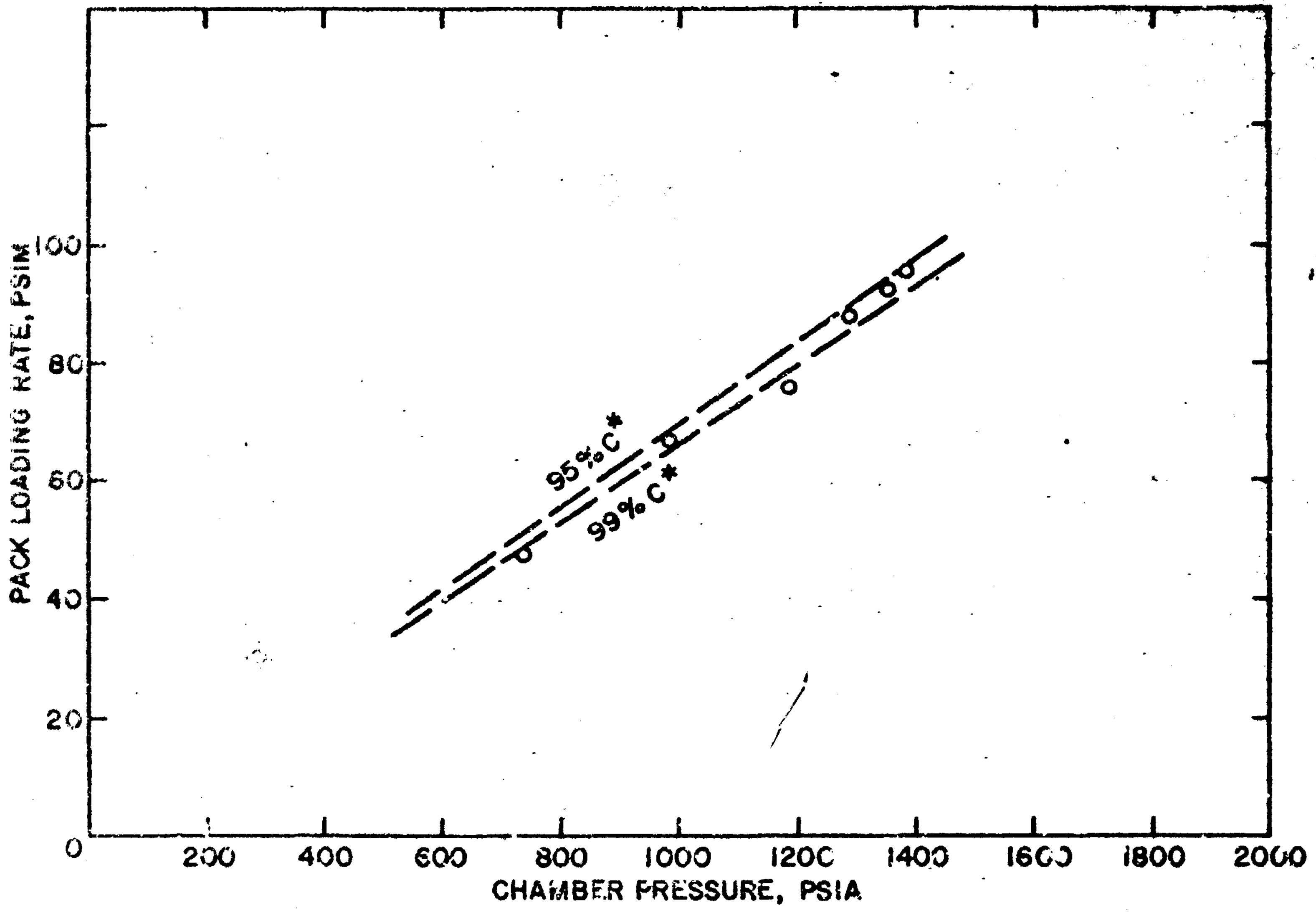


Figure 46

HIGH PRESSURE-HIGH PACK LOADING TESTS WITH 97.6% H_2O_2 AND 3/4" DIAMETER CHAMBER: PACK LOADING VERSUS CHAMBER PRESSURE TEST AF-A4(3) WITH 0.138" ORIFICE AND 65°F FEED

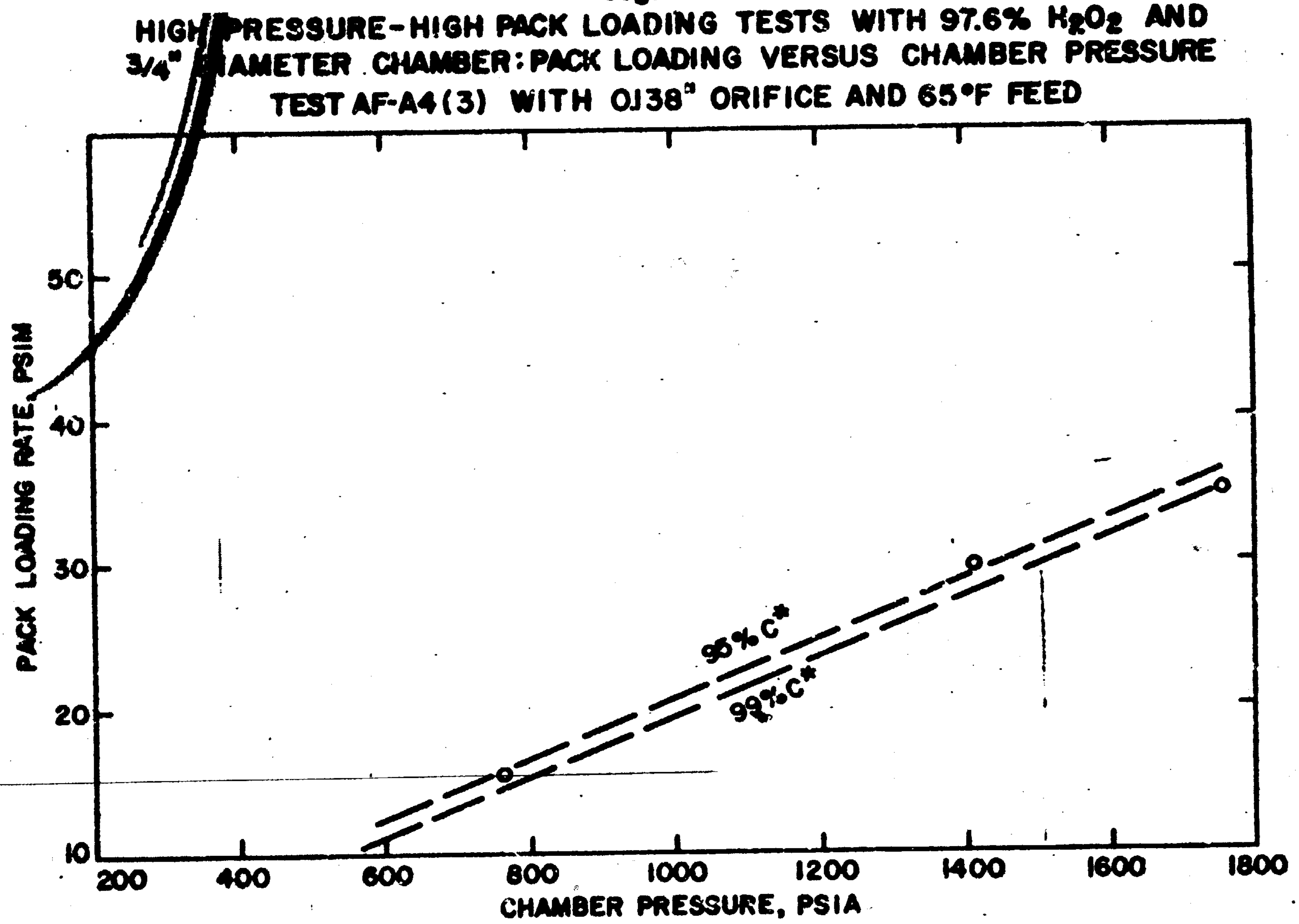


Figure 47

HIGH PRESSURE-HIGH PACK LOADING TESTS WITH 97.6% H_2O_2 AND 3/4" DIAMETER CHAMBER: PACK LOADING VERSUS CHAMBER PRESSURE TEST AF-A4(4) WITH 0.138" ORIFICE AND 69°F FEED

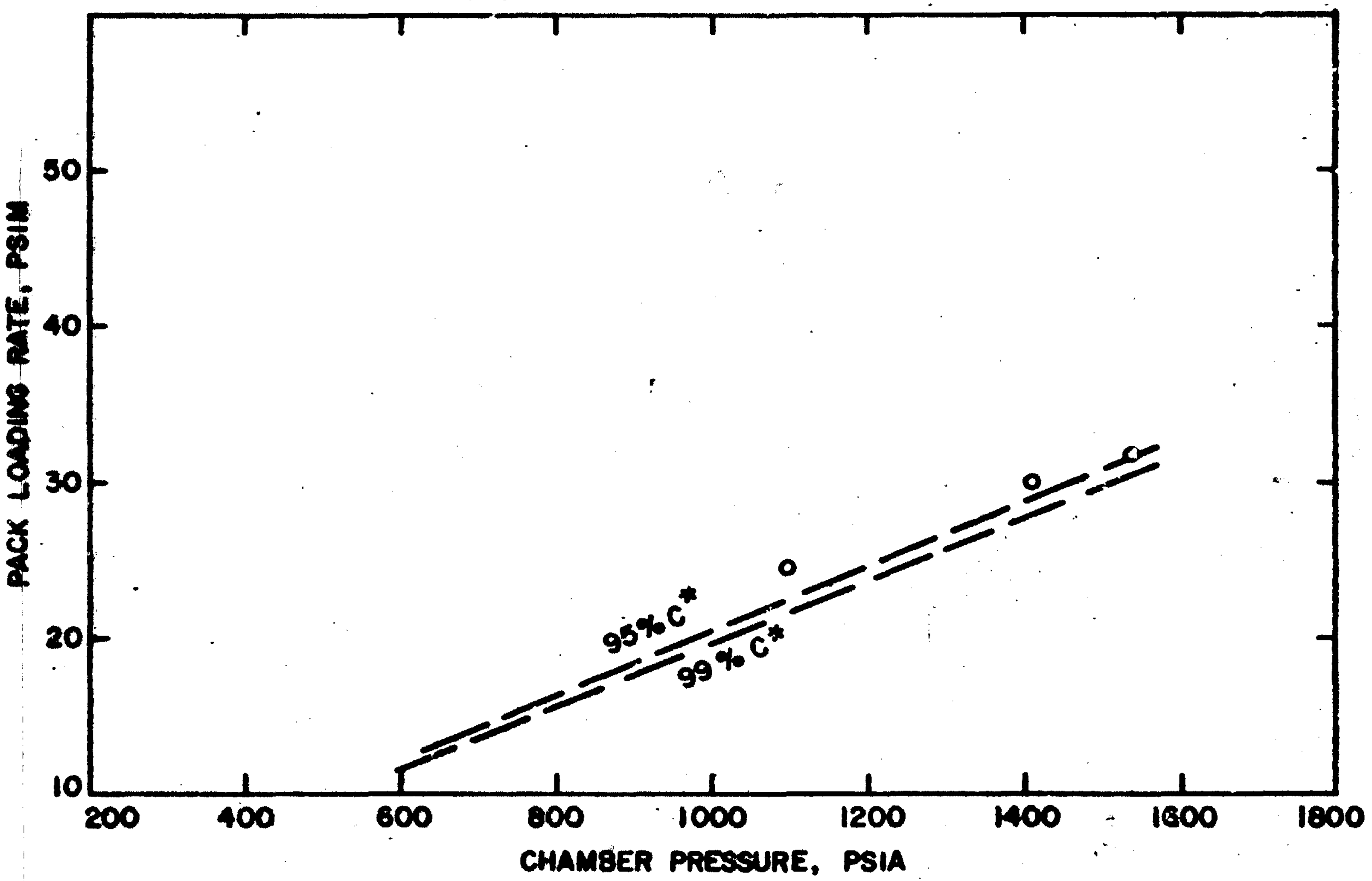


Figure 48

HIGH PRESSURE-HIGH PACK LOADING TESTS WITH 97.5% H_2O_2 AND 3/4" DIAMETER CHAMBER: PACK LOADING VERSUS CHAMBER PRESSURE TEST AF-A4(5) WITH 0.163" ORIFICE AND 74°F FEED

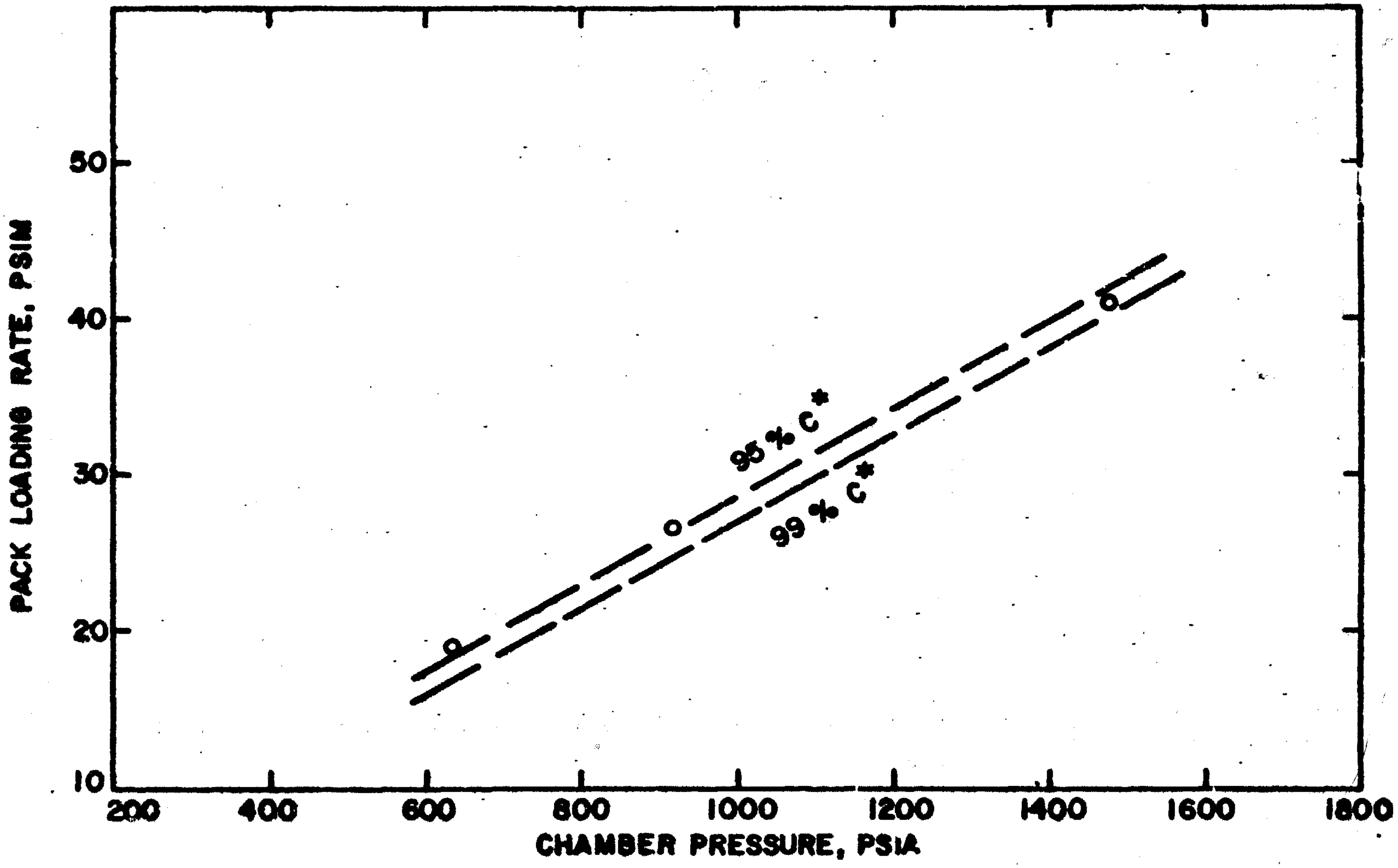


Figure 49

HIGH PRESSURE-HIGH PACK LOADING TESTS WITH 98.4% H_2O_2 AND 3/4" DIAMETER CHAMBER: PACK LOADING VERSUS CHAMBER PRESSURE TEST AF-A9(5) WITH 0.253" ORIFICE AND 56°F FEED

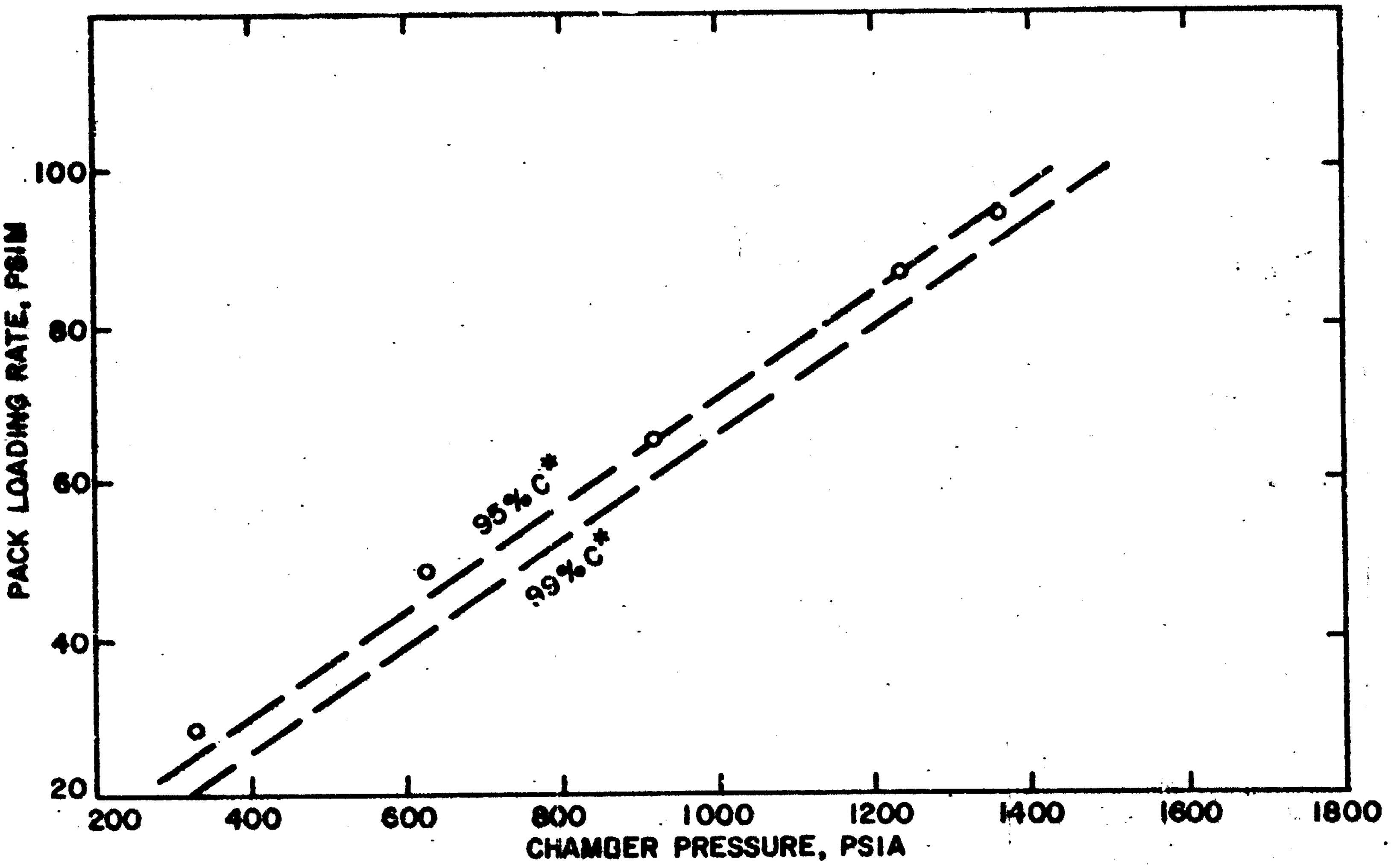


Figure 50

HIGH PRESSURE-HIGH PACK LOADING TESTS WITH 98% H_2O_2 A. 3/4" DIAMETER CHAMBER: PACK LOADING VERSUS CHAMBER PRESSURE TEST AF-A9(6) WITH 0.283" ORIFICE AND 56°F FEED

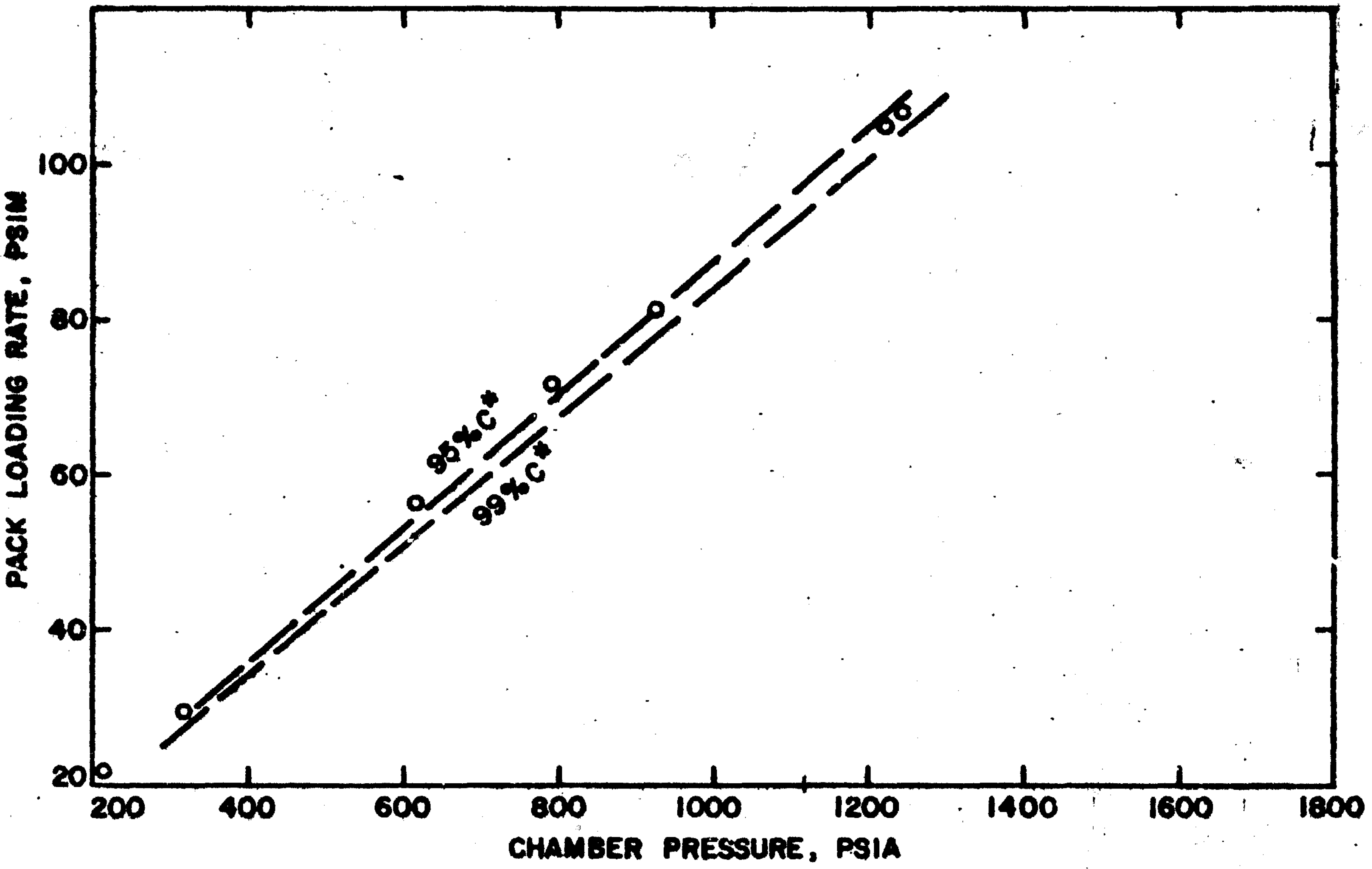


Figure 51

HIGH PRESSURE-HIGH PACK LOADING TESTS WITH 98% H_2O_2 AND 3/4" DIAMETER CHAMBER: PACK LOADING VERSUS CHAMBER PRESSURE TEST AF-A9 (7) WITH 0.299" ORIFICE AND 57°F FEED

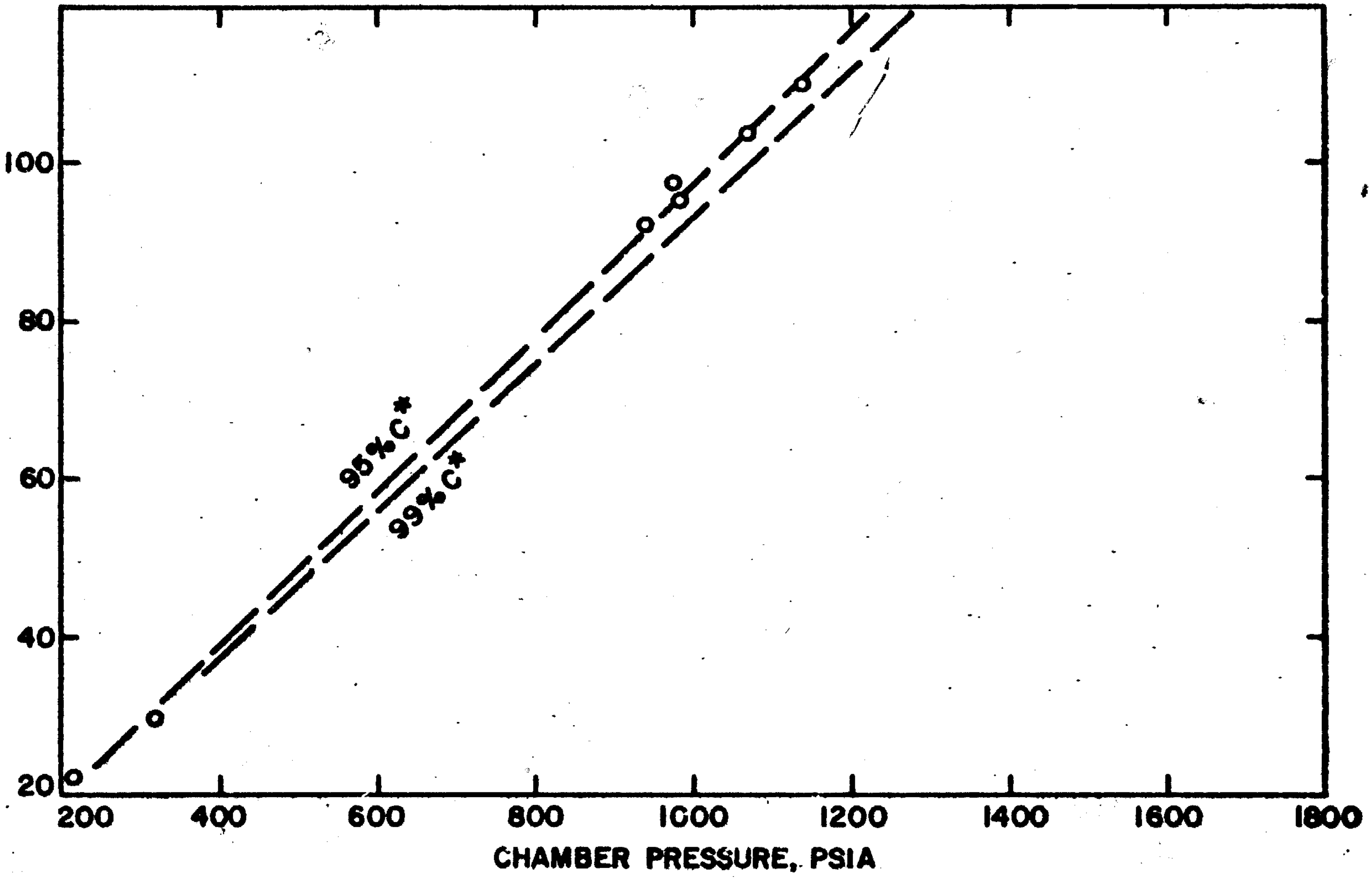


Figure 52

HIGH PRESSURE-HIGH PACK LOADING TESTS WITH 98% H_2O_2 AND 3/4" DIAMETER CHAMBER: PACK LOADING VERSUS CHAMBER PRESSURE
TEST AF-A9 (8) WITH 0.253" ORIFICE AND 56°F FEED

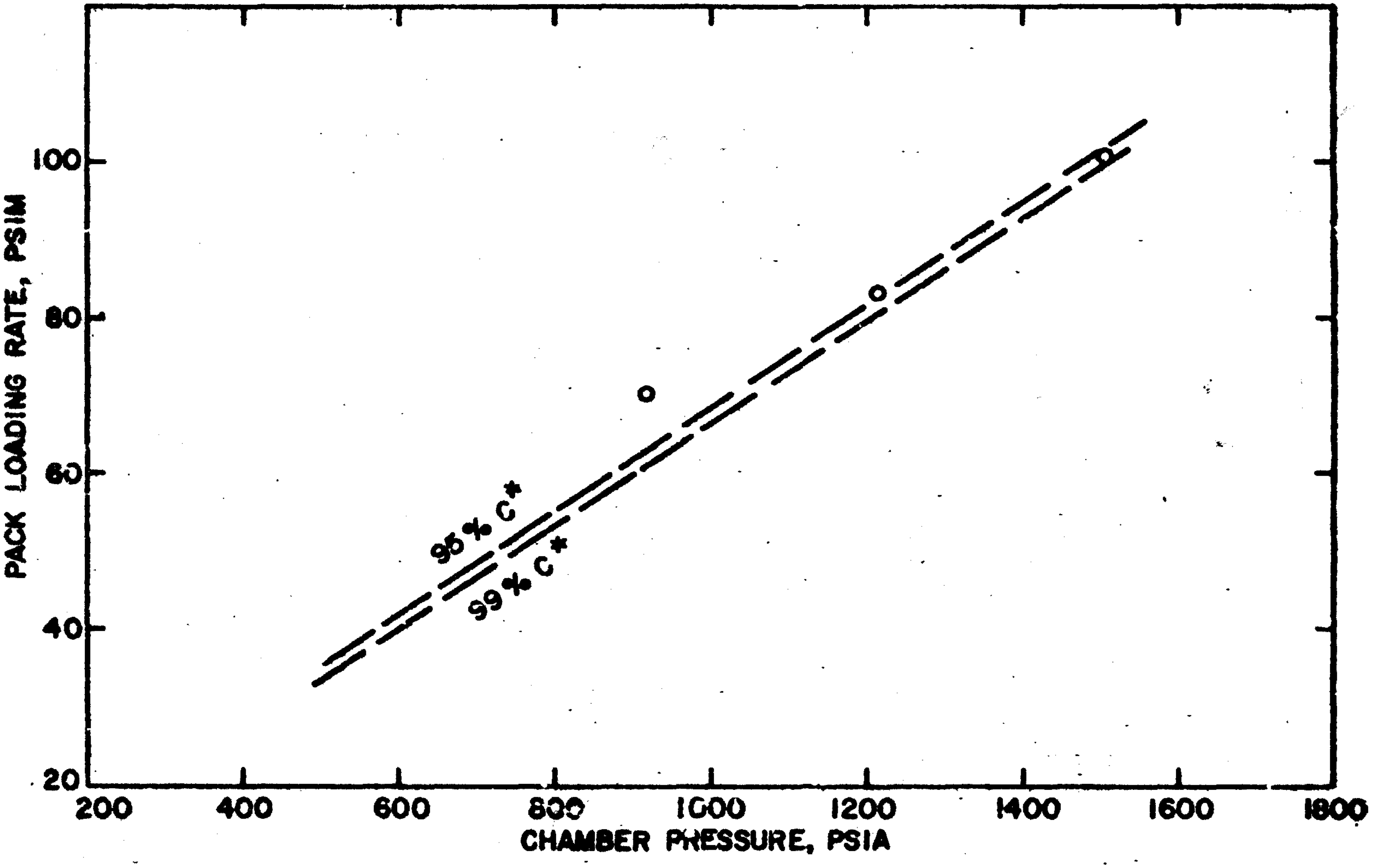
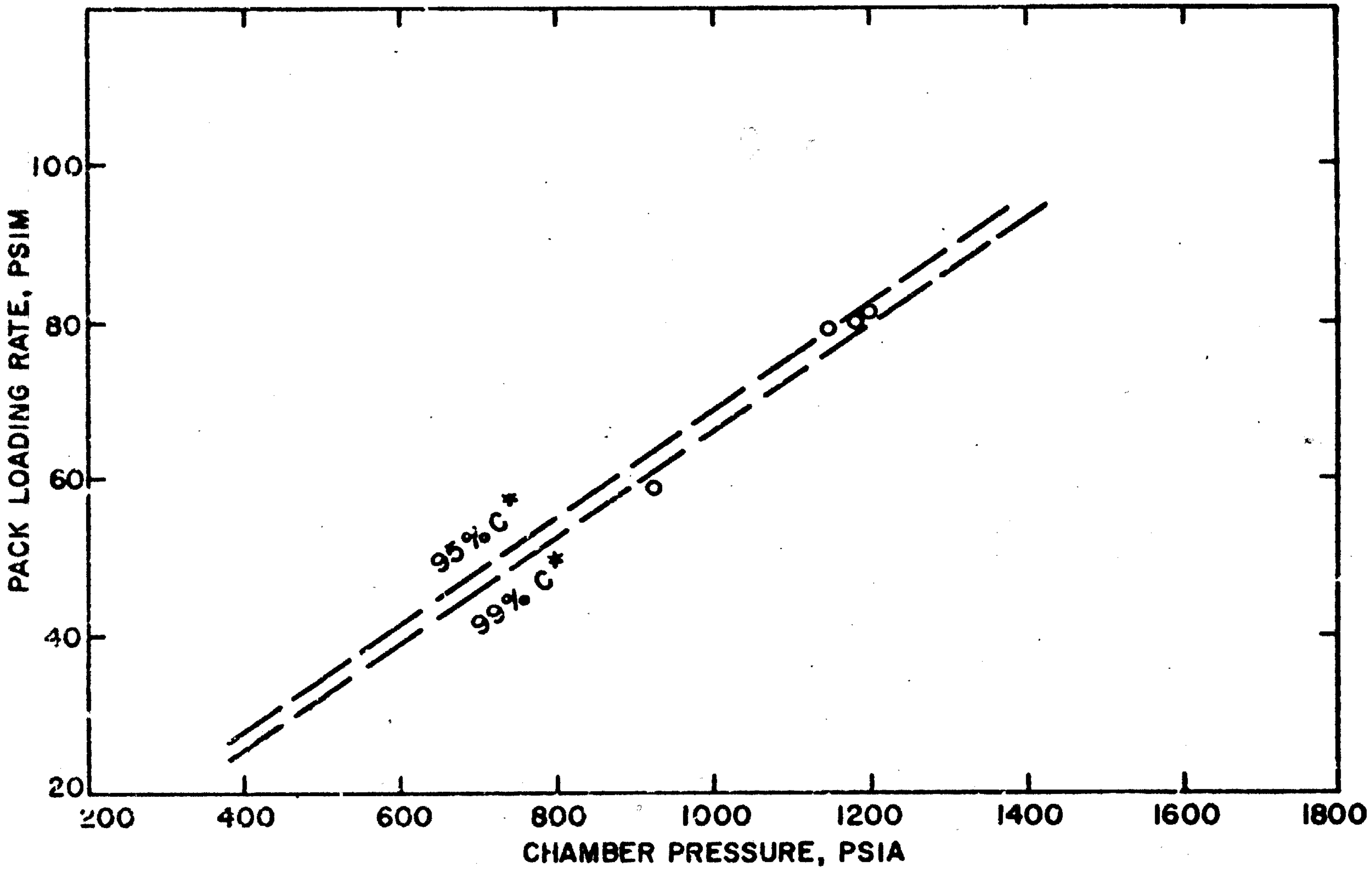


Figure 53

HIGH PRESSURE-HIGH PACK LOADING TESTS WITH 98% H_2O_2 AND 3/4" DIAMETER CHAMBER: PACK LOADING VERSUS CHAMBER PRESSURE TEST AF-A10(1) WITH 0.253" ORIFICE AND 55°F FEED



(2) Correlation

The relationship between the pressure drop across the catalyst pack and the chamber pressure, pack loading, and pack length are of interest for design of catalyst packs and motor systems. Most of the pressure drop can be shown to occur in the gas phase region of the pack. Reference to fluid-flow equations suggests that the pressure drop (ΔP) for the decomposition gases in this region should be directly proportional to the square of the pack loading (G) and inversely proportioned to the first power of the chamber pressure (Pc). A development (10) on this basis has susggested that the pressure drop is also directly proportional to the first power of the feed temperature (T) and to the square of the catalyst pack length (L), as

$$\frac{\Delta P_2}{\Delta P_1} = \left(\frac{Pc_1}{Pc_2}\right)^1 \left(\frac{G_2}{G_1}\right)^2 \left(\frac{T_2}{T_1}\right)^1 \left(\frac{L_2}{L_1}\right)^2$$

(a) Pressure Drop and Chamber Pressure

The data for catalyst pack configuration type AF-A4 was plotted to show the relationship between ΔP and Pc. The pack length was constant for the seven type AF-A4 tests and the feed temperature was nearly constant. The data have been plotted for roughly constant values of pack loading. In agreement with the above equation, a good correlation was obtained on a log-log plot as shown in Figure 54. This plot gives a slope of .85, which corresponds to

$$\log \Delta P = -.85 \log Pc + C_1$$

where C can be calculated from the data for each specific pack loading, but is not a simple function of the loading. The equation may be used in the form

$$\frac{\Delta P_2}{\Delta P_1} = \left(\frac{Pc_1}{Pc_2}\right)^{.85}$$

for constant pack loading G when one ΔP and one Pc are known. The pressur drop is shown to decrease with increasing chamber pressure. This is attributed to the decrease in specific volume of the decomposition gases as the pressure is increased, as shown in Figure 55.

(b) Pressure Drop and Pack Loading

The data for ΔP and pack loading (G) at constant Pc, T, and L were plotted on both logarithmic or linear scales (Figures 56 and 57). The logarithmic relationship gives

$$\frac{\Delta P_2}{\Delta P_1} = \left(\frac{G_2}{G_1}\right)^{1.34}$$

Figure 54

HIGH PRESSURE-HIGH PACK LOADING TESTS WITH 98% H_2O_2 AND $\frac{3}{4}$" DIAMETER CHAMBER: CORRELATION OF CATALYST PACK PRESSURE DROP WITH CHAMBER PRESSURE
CATALYST PACKS AF-A4(1,3-5) AND AF-A9(5-7)
WITH IDENTICAL CONFIGURATIONS

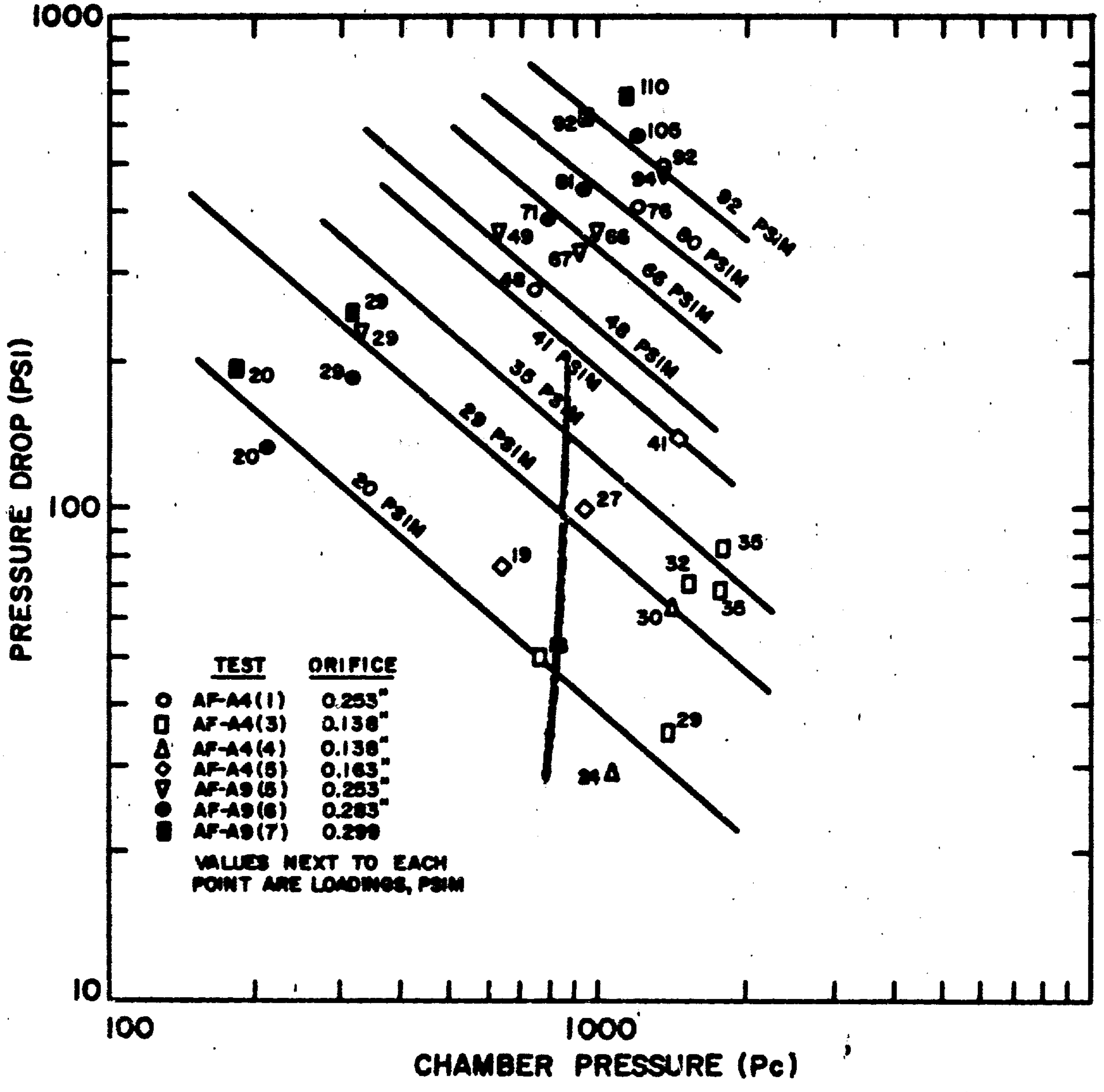
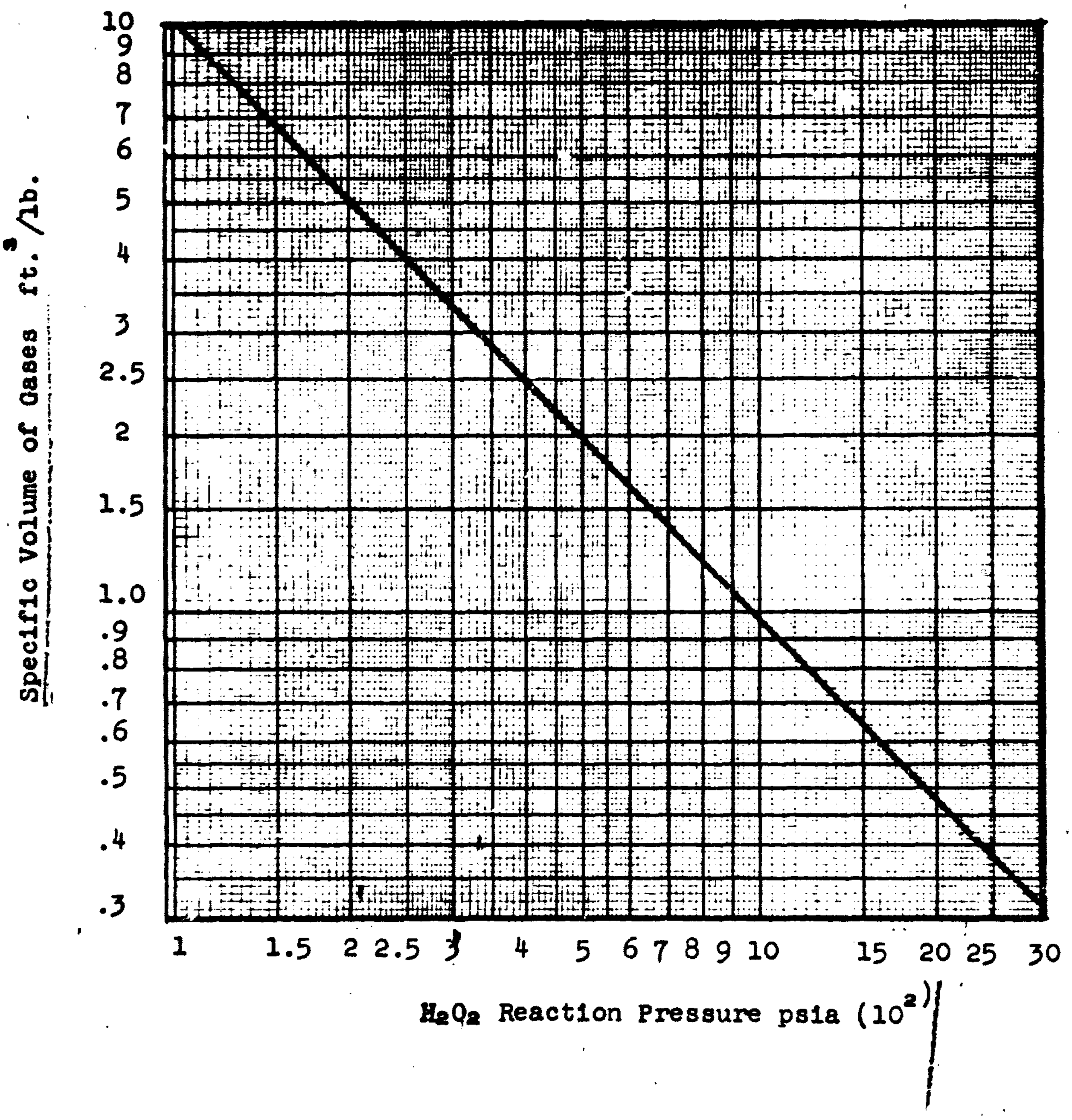


Figure 55

Specific Volume of the Decomposition Gases of 98% H_2O_2 at Various Pressures



Ref: BuMines
PX-3-107/14

Figure 56

HIGH PRESSURE – HIGH PACK LOADING TESTS WITH 98% H_2O_2 AND ¾" DIAMETER CHAMBER: VARIATION OF CATALYST PACK PRESSURE DROP WITH PACK LOADING; CATALYST PACKS AF-A4(1,3-5) AND AF-A9(5-7) WITH IDENTICAL CONFIGURATION

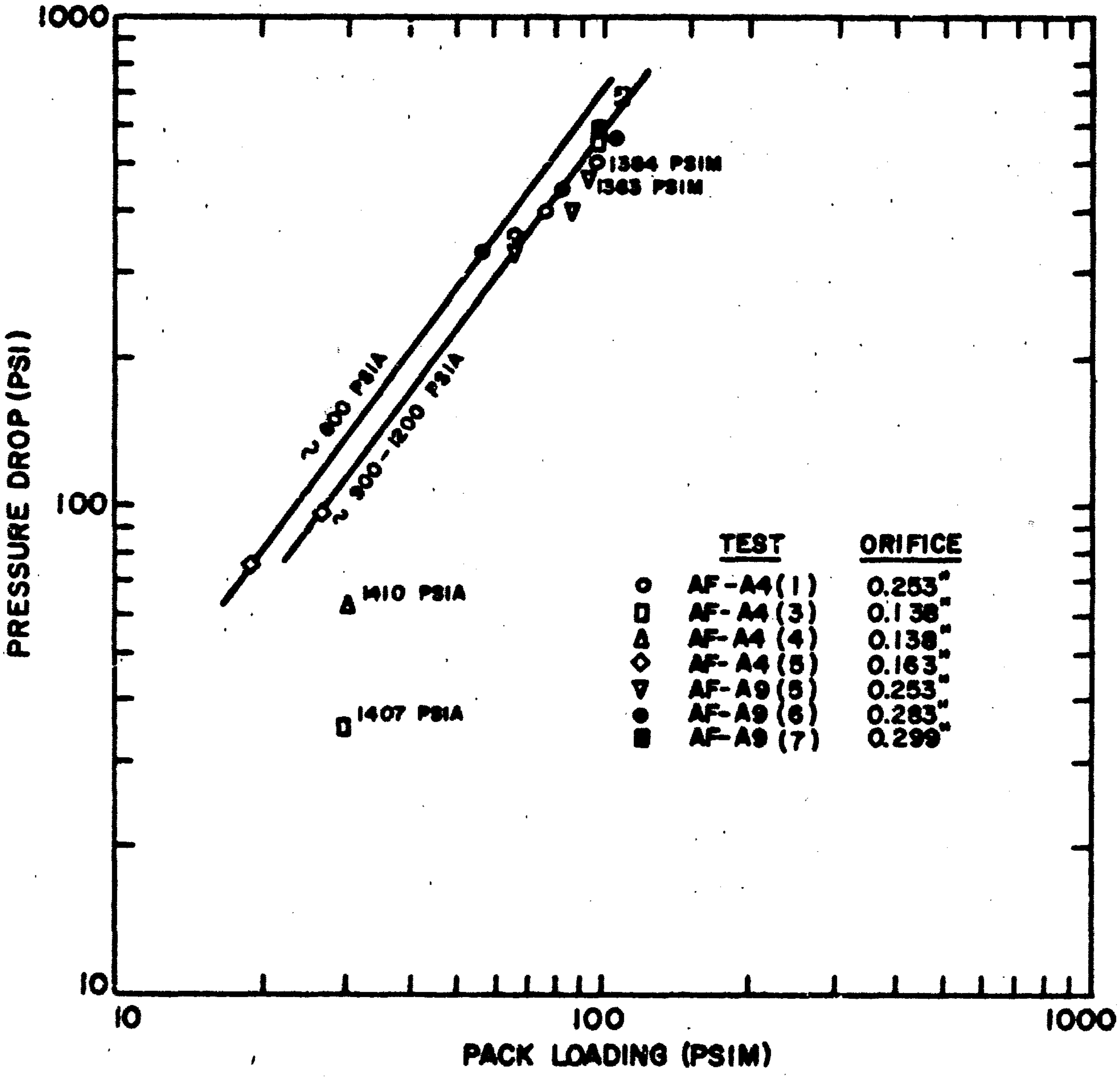
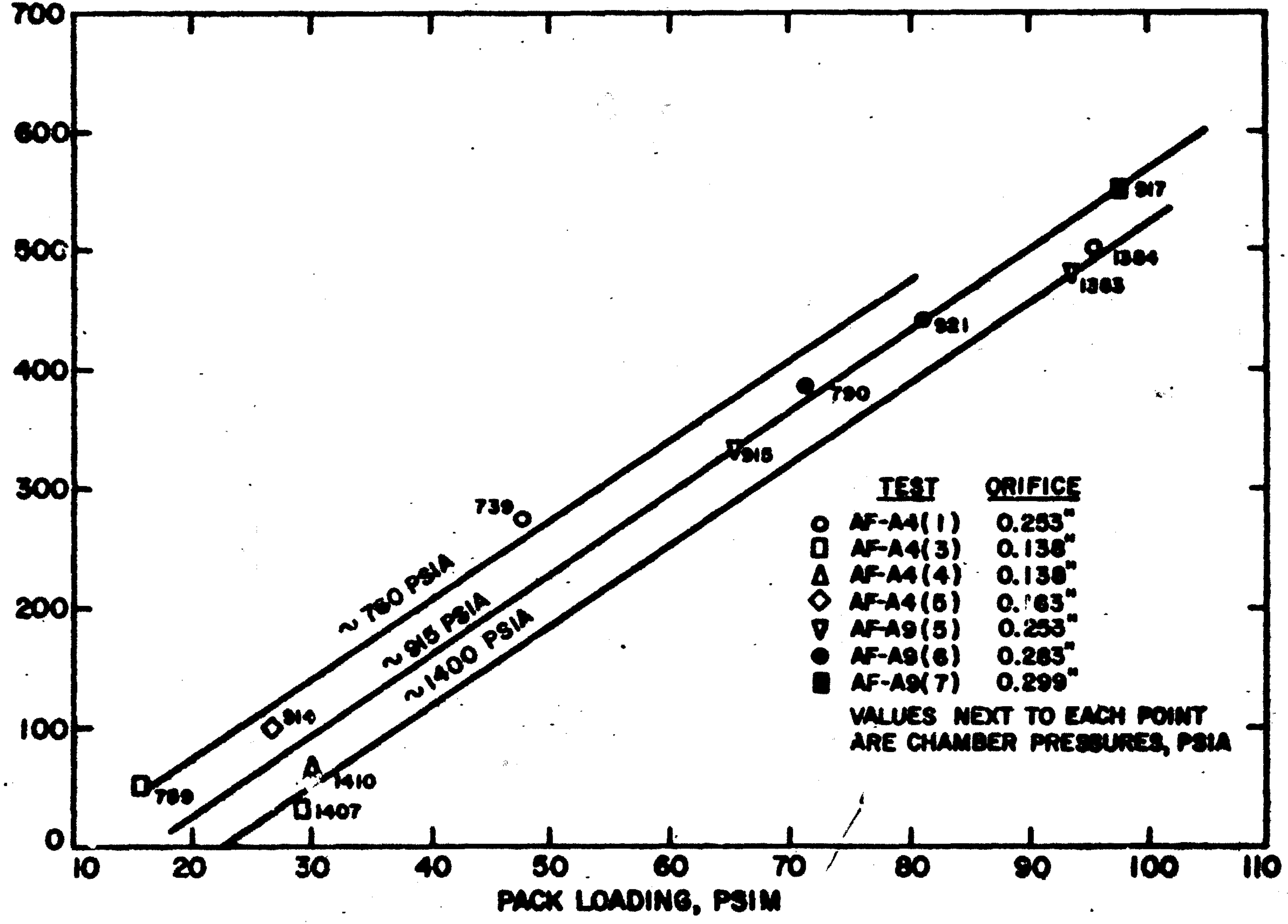


Figure 57

HIGH PRESSURE-HIGH PACK LOADING TESTS WITH 98% H_2O_2 AND $\frac{3}{4}$" DIAMETER TEST CHAMBER: CATALYST PACK PRESSURE DROP VERSUS PACK LOADING AT CONSTANT CHAMBER PRESSURE
ALL TESTS WITH THE SAME CATALYST CONFIGURATION



for constant Pc, while the linear plot gives

$$\Delta P = 6.8\ G + C_2$$
or
$$\Delta P_2 - \Delta P_1 = 6.8\ (G_2 - G_1).$$

for constant Pc.

(c) Pressure Drop and Feed Temperature

The variation of ΔP with feed temperature has been graphed for the type AF-A10 configuration pack (Figure 58). The equation of the line drawn is

$$\Delta P = 2.22\ T + 93$$
or
$$\Delta P_2 - \Delta P_1 = 2.22\ (T_2 - T_1).$$

This equation is only approximate since the data on which it is based are not strictly for constant chamber pressure and constant pack loading. The results for a log-log plot of this data (Figure 59) provide a poorer fit which corresponds roughly to the equation

$$\log \Delta P = .81 \log T + C_3$$
or
$$\frac{\Delta P_2}{\Delta P_1} = \left(\frac{T_2}{T_1}\right)^{.81}$$

However, this form of the data correlation can be incorporated with the other results in a general equation of the original type.

(d) Pressure Drop and Pack Length

The variation of ΔP with pack length is plotted in Figure 60 for type AF-A4 packs. The screen configuration of pack AF-A9(8) was different only in the number of nickel-5% manganese filler screens contained in the exhaust end of the pack. All three packs were compressed at 4,000 psi and used the 0.253 exhaust orifice. The feed temperature was also nearly constant. The lines on the figure were drawn for approximately equal pack loadings and chamber pressures.

$$\Delta P = 193\ L + C_4$$
or
$$\Delta P_2 - \Delta P_1 = 193\ (L_2 - L_1)$$

for constant Pc, T and G. A log-log plot in this case yields a range of possible exponents and so is unsatisfactory.

Figure 58

HIGH PRESSURE-HIGH PACK LOADING TESTS WITH 98% H_2O_2 AND 3/4" DIAMETER CHAMBER: VARIATION IN PRESSURE DROP WITH H_2O_2 FEED TEMPERATURE

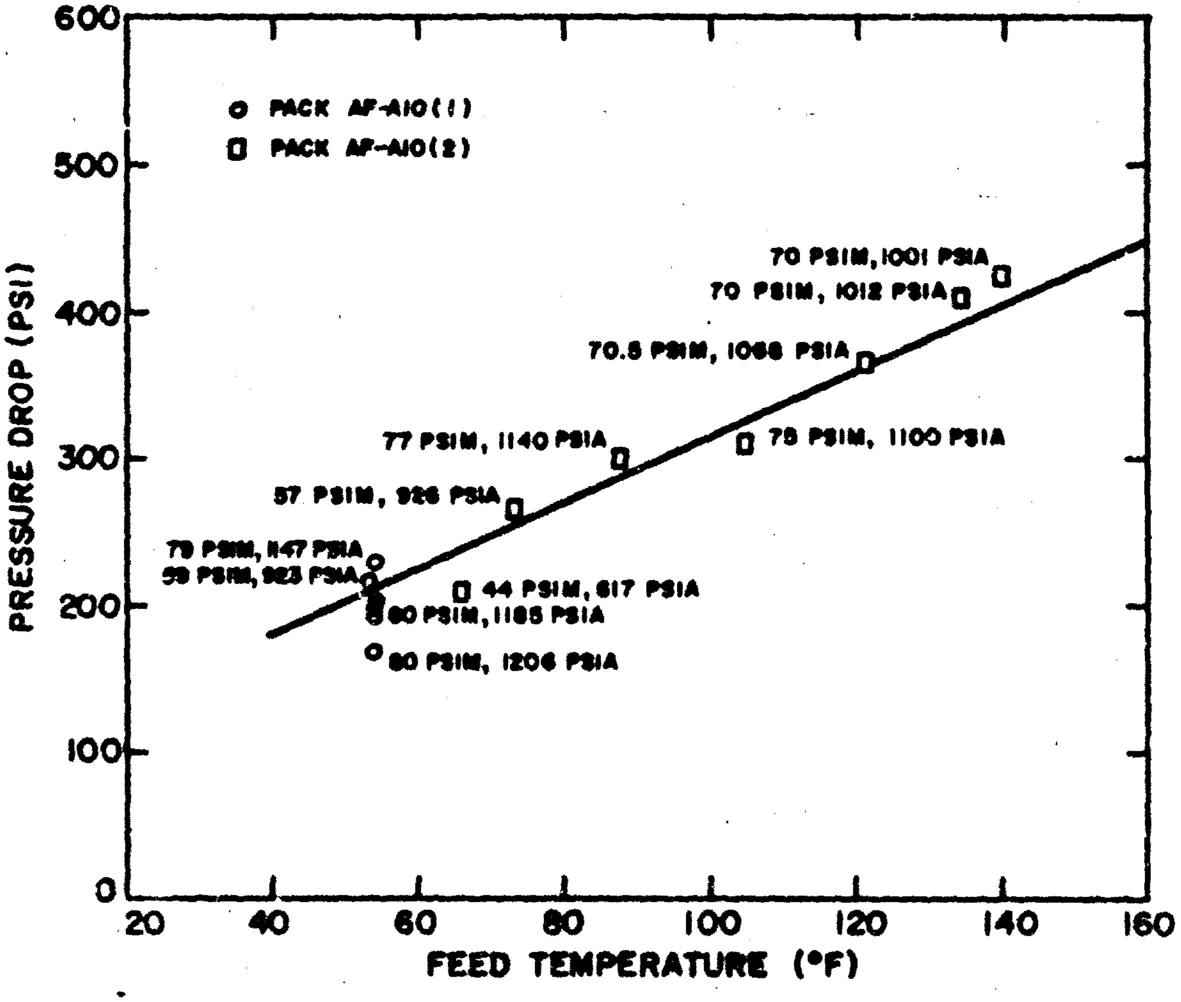


Figure 59

HIGH PRESSURE-HIGH PACK LOADING TESTS WITH 98% H_2O_2 AND
3/16" DIAMETER CHAMBER: VARIATION OF PRESSURE DROP
WITH FEED TEMPERATURE PACK AF-A10(2)

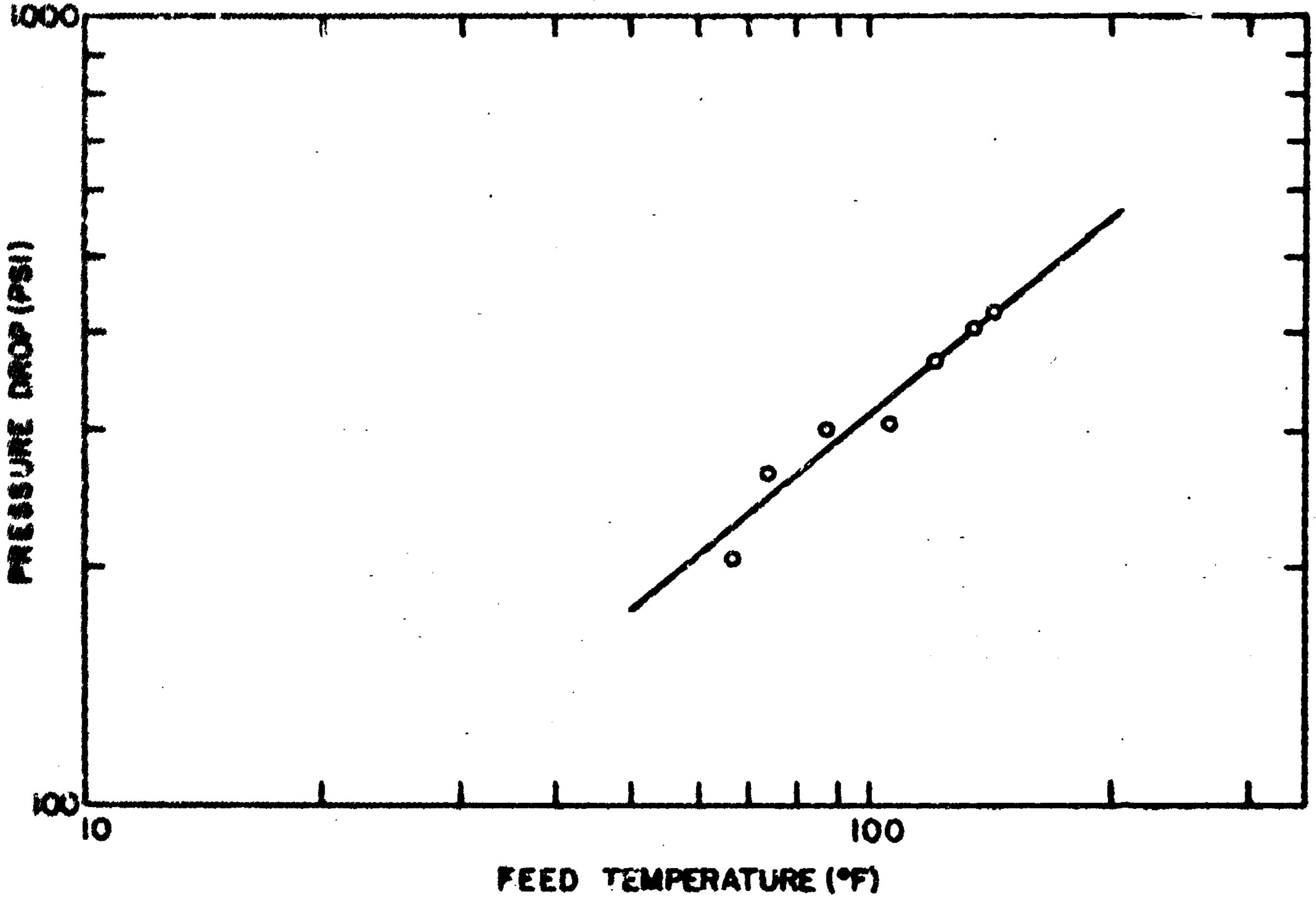
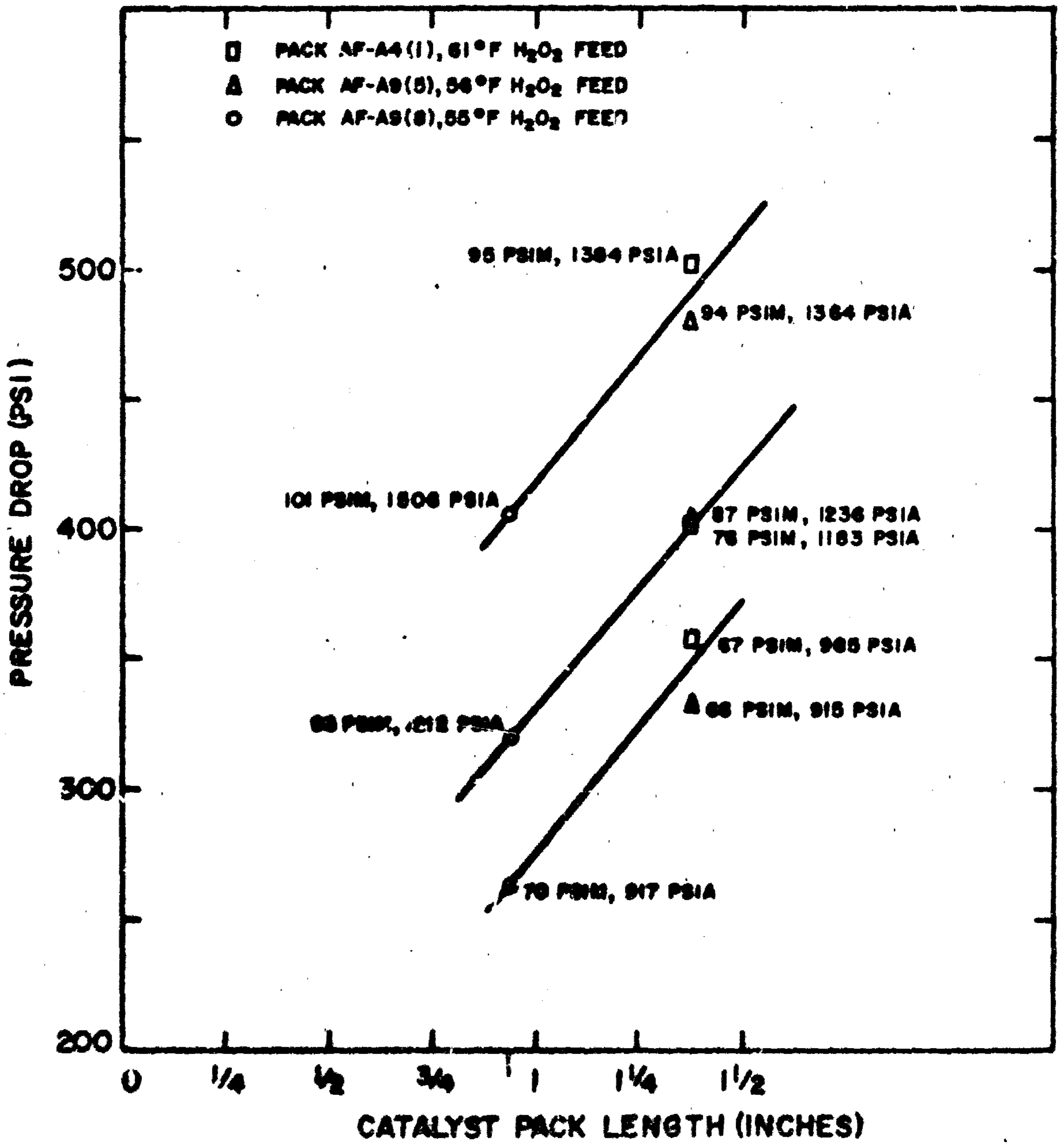


Figure 60

HIGH PRESSURE-HIGH PACK LOADING TESTS WITH 98% H_2O_2 AND 3/4" DIAMETER CHAMBER: VARIATION OF PRESSURE DROP WITH CATALYST PACK LENGTH; IDENTICAL CATALYST CONFIGURATION WITH 0.253" ORIFICE



(e) Combined Correlation and Examples

Though the logarithmic relationships between pressure drop and pack loading or feed temperature do not give definitive results, the following combined equation may be given for the data of this test program.

$$\frac{\Delta P_2}{\Delta P_1} = \left(\frac{Pc_1}{Pc_2}\right)^{.85} \left(\frac{G_2}{G_1}\right)^{1.34} \left(\frac{T_2}{T_1}\right)^{.81}$$

However, the separate equations for ΔP variations with pack loading and feed temperature will provide better results for pack configuration type AF-A4.

The use of the equations for predicting changes in pressure drop with chamber pressure and pack loading for catalyst configuration type AF-A4 can be illustrated as follows. Find the ΔP at 97.5 psim pack loading and 917 psia chamber pressure, given that the ΔP is 227 psi at 29 psim and 327 psia.

$$\frac{\Delta P_2}{\Delta P_1} = \left(\frac{Pc_1}{Pc_2}\right)^{.85} \left(\frac{G_2}{G_1}\right)^{1.34}$$

$$\Delta P_2 = 227 \left(\frac{327}{917}\right)^{.85} \left(\frac{97.5}{29}\right)^{1.34}$$

$$= 530 \text{ psi}$$

The given starting data are from test AF-A9(5) and the result gives reasonable agreement with the 554 psi ΔP found at 97.5 psim and 917 psia in test AF-A9(7)

For a second example, find the ΔP at 81 psim and 921 psia for a type AF-A4 pack which has ΔP equal to 62 psi at 30 psim and 1410 psia (pack AF-A4(4)).

$$\Delta P_2 = 62 \left(\frac{1410}{921}\right)^{.85} \left(\frac{81}{30}\right)^{1.34}$$

$$= 336 \text{ psi}$$

This result compares with an actual value of 443 psi found at 81 psim and 921 psia in test AF-A9(6). This second example shows the spread of results which can be obtained for this correlation equation. The scatter of the high psia chamber pressure values marked on Figure 56 suggests difficulty with the logarithmic correlation.

An improved result for the data of the second example is produced by using the linear rather than the logarithmic relationship between ΔP and G.

$$\Delta P_2 = \Delta P_1 \left(\frac{Pc_1}{Pc_2}\right)^{.85}$$

$$= 62 \left(\frac{1410}{921}\right)^{.85}$$

$$= 89 \text{ psi}$$

$$\Delta P_3 = \Delta P_2 + 6.8 \, (G_2 - G_1)$$

$$= 89 + 6.8 \, (81-30)$$

$$= 423 \text{ psi}$$

This value compares favorably with the measured ΔP of 443 psi. This suggests that

$$\Delta P_2 = \Delta P_1 \left(\frac{Pc_1}{Pc_2}\right)^{.85} + 6.8 \, (G_2 - G_1)$$

is a better representation of the data gathered in this program.

For determination of the variation of pressure drop with feed temperature and pack length, the best results will be obtained by using the linear equations:

$$\Delta P_2 = 2.22 \, (T_2 - T_1) + \Delta P_1$$

$$\Delta P_2 = 193 \, (L_2 - L_1) + \Delta P_1$$

Since these equations are derived from only one test which varied feed temperature and only two tests for different lengths of catalyst packs, the correlations expressed must be considered approximate.

(3) Catalyst Pack Applications

The two basic types of applications of the 98% H_2O_2 catalyst pack are gas generators and thrust motors. The following two examples demonstrate the usual calculations required to incorporate the catalyst pack into the total design.

(a) Gas Generator

Determine the diameter of a catalyst pack for use with 98% H_2O_2 in a gas generator having a power output of 1000 H. P. at 50% efficiency and 1500 psia chamber pressure. First the flow rate of 98% H_2O_2 must be found as follows.

$$98\%\ H_2O_2 \text{ flow rate} = \frac{\text{Theoretical flow rate}}{\text{Turbine efficiency}}$$

The theoretical flow rate can be selected from Figure 61. If a different horsepower generator were required, the appropriate modification to data from Figure 61 could be made, using the equation given at the top of the figure. For the problem at hand

$$98\%\ H_2O_2 \text{ flow rate} = \frac{1.4 \text{ lbs./sec.}}{50\% \text{ eff.}} = 2.8 \text{ lbs./sec.}$$

Now the catalyst pack cross-sectional area can be determined for a selected pack loading rate, chosen in this case to be 20 psim.

$$\begin{aligned}\text{Pack frontal area in square inches} &= \frac{(\text{Flow rate in lbs. sec})(60 \text{ sec/min})}{(\text{Loading in lbs./in.}^2\text{/min.})}\\ &= \frac{(2.8)(60)}{20}\\ &= 8.4 \text{ in.}^2\end{aligned}$$

Then the pack diameter is easily obtained.

$$\text{Diameter} = \left(\frac{(4)(\text{Frontal area})}{\pi}\right)^{1/2} = 3.28 \text{ in.}$$

The recommended catalyst configuration is type AF-A9(8) given on page
The screens should be compressed at 4000 psi for a pack length of 15/16"

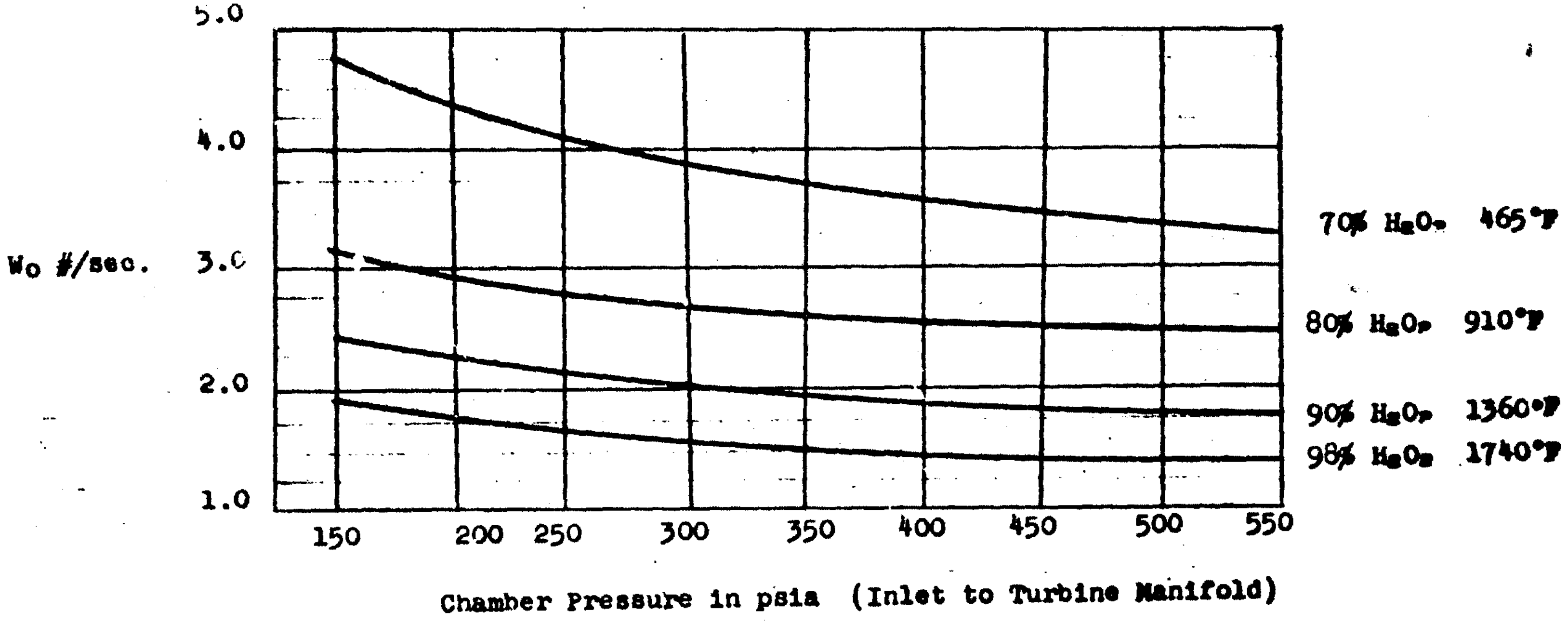
(b) Thrust Motor

Design a 40 lb. thrust motor to operate with 98% H_2O_2 at 100,000 feet altitude with a chamber pressure of 300 psia. The following information is given or available from the indicated figures.

Figure 61

THEORETICAL H_2O_2 FLOW IN LBS./SEC. PER 1000 HP

$$W_o = \frac{(1000\ \text{HP})\ (550\ \text{Ft.-Lbs/Sec. HP})}{(778\ \text{Ft. Lb./BTU})\ (H_1 - H_2\ \text{BTU/Lb.})}$$



Ref. - Bu. of Mines Report PX-3-107/14 A.J.K./J.C.M.

Thrust (F) = 40 lbs.

Chamber Pressure (Pc) = 300 psia

Altitude = 100,000 ft.

Theoretical Specific Impulse (ISP) (Figure 62) = 192 sec.

Characteristic Exhaust Velocity of Gases (C*) for 98% H_2O_2 Feed Temperature of 70° F (Figure 42) = 3330 ft./sec.

Thrust Coefficient (C_F) (Figure 63) = 1.85

Efficiency of Catalyst and Nozzle = .96

Gravitational Constant (g) = 32.2 ft./sec.^{2}

The catalyst efficiency has been taken at 99% and the nozzle efficiency at 97% to give the listed combined efficiency of 96%.

First the required flow rate (W) is calculated

$$98\%\ H_2O_2\text{ flow rate} = \frac{\text{Thrust}}{(\text{Efficiency})(\text{Specific Impulse})}$$

$$W = \frac{40}{(.96)(192)} = .217\text{ lbs/sec.}$$

Next the required area of the nozzle throat (A_t) is found.

$$C* = \frac{gAtPc}{W}$$

or

$$At = \frac{C*W}{gPc}$$

$$= \frac{(333)(.217)}{(32.2)(300)}$$

$$= .0748\text{ in.}^2$$

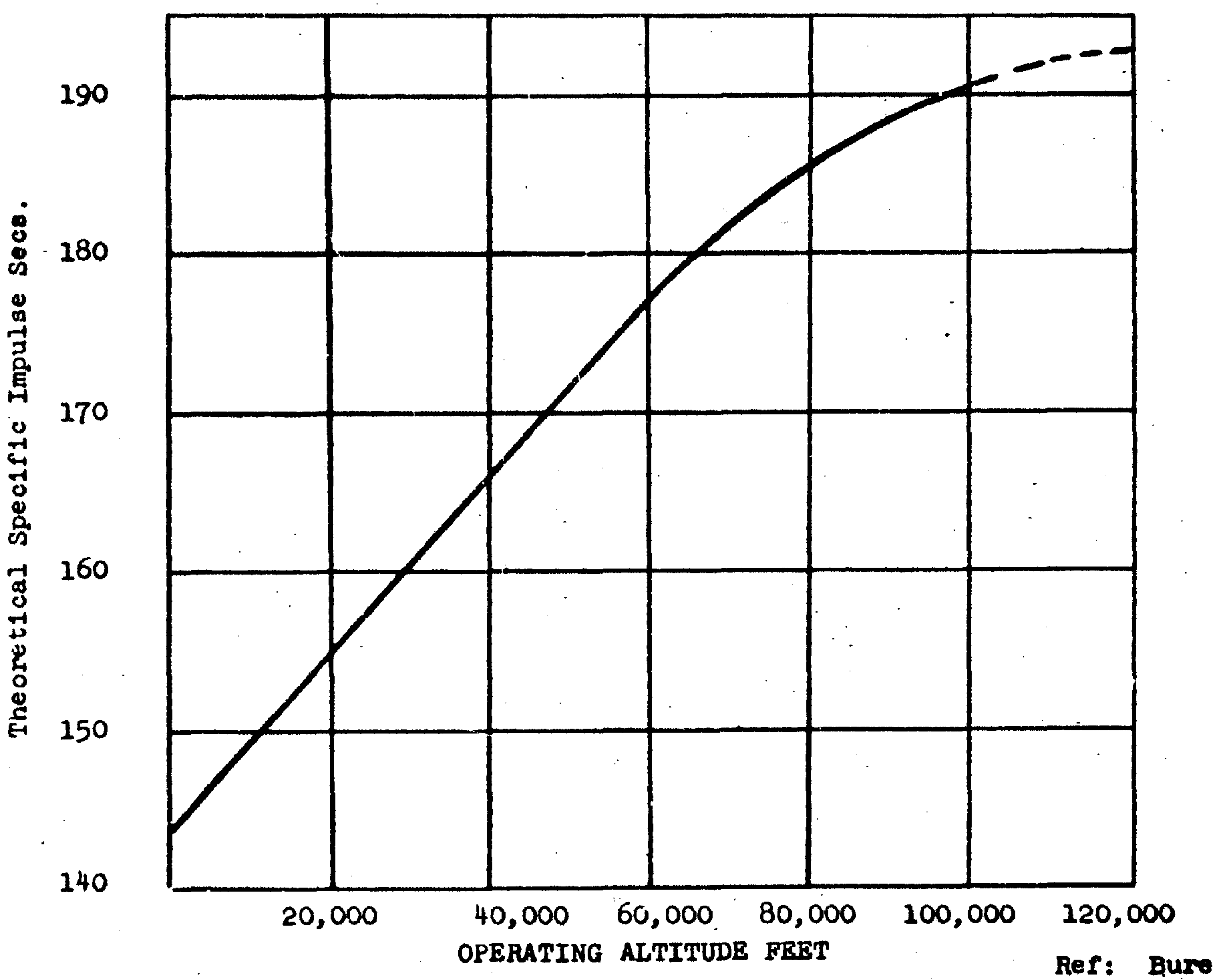
The diameter of the throat can be found from the area as before.

$$\text{Diameter} = \left(\frac{(4)(.0748)}{\pi}\right)^{1/2} = .309\text{ in.}$$

Figure 62

IDEAL SPECIFIC IMPULSE Isp. SEC. Vs ALTITUDE FOR 98% HYDROGEN PEROXIDE

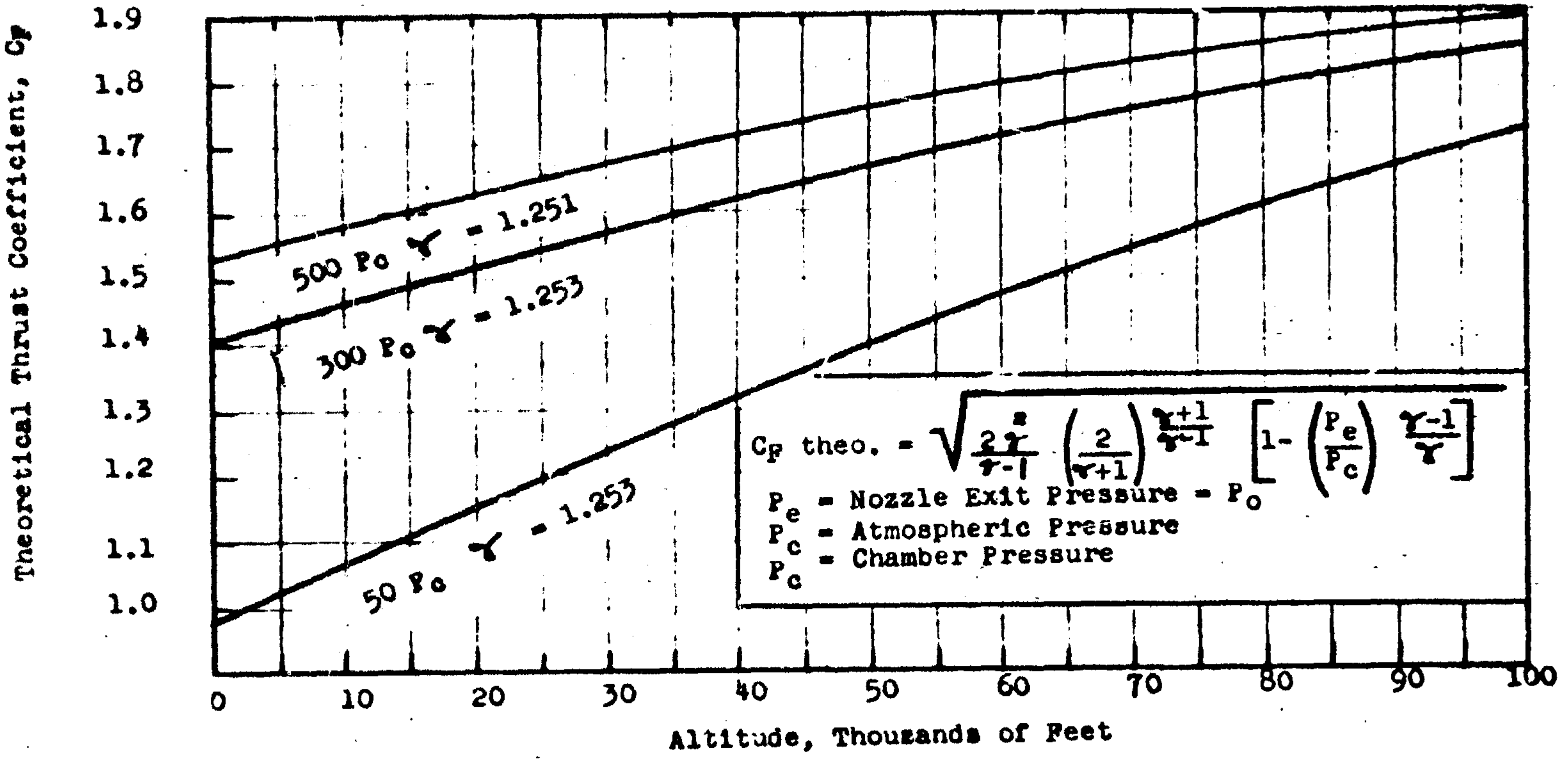
OPTIMUM EXPANSION AT Pc - 300 PSIA



Ref: Bureau of
Mines Report
PX-3-107/14

Figure 63

THEORETICAL THRUST COEFFICIENT (C_f) VS ALTITUDE FOR 98% H_2O_2
OPTIMUM EXPANSION



$$C_F \text{ theo.} = \sqrt{\frac{2\gamma^2}{\gamma-1}\left(\frac{2}{\gamma+1}\right)^{\frac{\gamma+1}{\gamma-1}}\left[1-\left(\frac{P_e}{P_c}\right)^{\frac{\gamma-1}{\gamma}}\right]}$$

P_e = Nozzle Exit Pressure = P_o
P_c = Atmospheric Pressure
P_c = Chamber Pressure

Ref. - Bureau of Mines Report PX-3-107/14
FMC Corporation - JMC

Lastly, the efficiency of the designed system can be found to check the suitability of the design. To do this the C_F value based on the designed nozzle sizing is determined.

$$F = C_F A_t Pc$$

or

$$C_F = \frac{F}{At\ Pc}$$

$$= \frac{40}{(.0748)(300)} = 1.78$$

This value is then compared with the theoretical C_F.

$$\text{Percent of theoretical} = \frac{1.78}{1.85} = 96\%$$

Thus the nozzle sizing is satisfactory and the motor will give high performance.

The catalyst design can now be selected for the above thrust motor. The preheat design to be discussed beginning on page 135 (Figure 64) is recommended due to its high reliability. The diameter of the catalyst scroll to be used is determined as follows. The equations for pack frontal area and pack diameter have been given on page 128 and the flow rate for the thrust motor calculated above to be .217 lb/sec. The pack loading rate is chosen to be 15 psim.

$$\text{Frontal area} = \frac{(.217)(60)}{15} = .87 \text{ in.}^2$$

$$\text{Pack diameter} = \left(\frac{(4)(.87)}{\pi}\right)^{1/2} = 1.05 \text{ in.}$$

The recommended preheat scroll diameter is 0.8 times the diameter of the main catalyst section.

$$\text{Scroll (O. D.)} = (0.8)(1.05) = .84 \text{ in.}$$

The length of the main catalyst section is recommended to be 1.125 inches and the scroll height should be designed for 30 ft/sec. fluid velocity.

(c) General Design Suggestions

Some suggestions concerning the general design of thrust motors and gas generators for 98% H_2O_2 can be enumerated as follows:

1. Use a minimum free volume above the injector plate.
2. Use two anti-channel baffles, one under the injector plate, one 15 screens down the pack. Baffle interference .001 to .004 inches. Baffle material - Inconel X.
3. Correct for the H_2O_2 fluid inlet line velocity by using a reduced open area at the center section (1.25 x inlet tube I.D.) of the injector plate.
4. Design the injector plate to give uniform catalyst loading with minimum pressure drop.
5. Use a 50 psi ΔP trim orifice or a cavitating venturi in the H_2O_2 feed line at the chamber inlet.
6. Use 347 SS material for gas generator or thrust motors. When the pressure housing O.D. exceeds 3 inches, Inconel 718 or other high stress steel non-oxidizing materials may be used.
7. Use 1300 to 1400°F metal temperatures when determining wall thicknesses in preheat thrust motors and gas generators.
8. Support plates should be Inconel X or Inconel 718 material. Rib design supports are weight saving, thus, recommended in larger gas generators and thrust motors.

e. Low Temperature Tests

These tests were carried out to determine the performance of the silver: silver-30% palladium catalyst under low temperature conditions. The initial starting behavior was measured with the 98% H_2O_2 feed, the motor test system, and the catalyst pack cooled to below 30° F. Subsequent starts with low temperature feed and warm motor and catalyst were also measured. In addition, the steady-state performance of the catalyst with low temperature feed was tested. For comparison, a second identical catalyst and motor were tested, and both catalysts were then subjected to ambient temperature tests.

(1) Preheat Motor

Two 22 pound thrust preheat motors were employed, S/N 001 and S/N 002. The preheat-type hydrogen peroxide powered thrust motor was developed by FMC Corporation under a NASA contract and is presently used on the Scout missile. This motor design was selected because it has demonstrated excellent low starting properties with Becco 90% H_2O_2. (12).

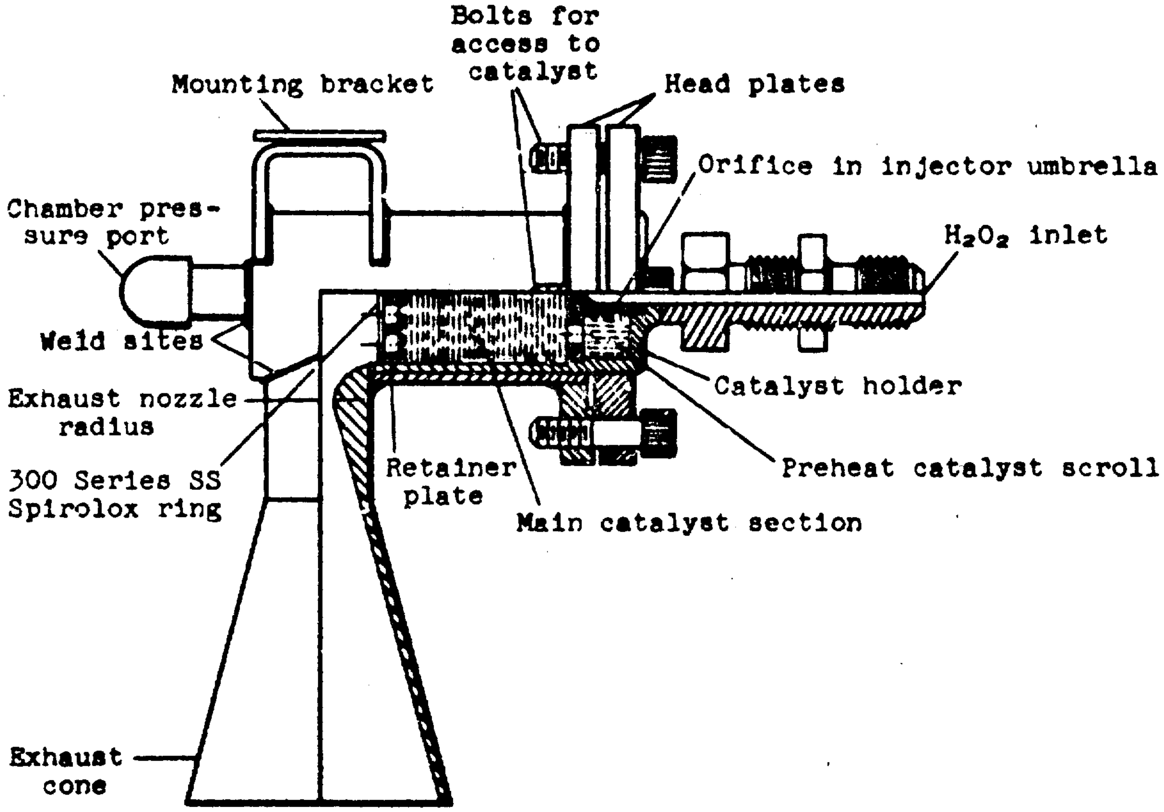
The test motor design is shown by Figure 64. The lower right-hand portion of the motor is shown in cross section, while the remainder is an external view. In this type motor, the H_2O_2 enters the inlet pipe from the right and passes at a right angle through orifices in the injector umbrella and into a "preheat" catalyst scroll. The H_2O_2 partially decomposes and makes another 90° turn and then passes axially through the main catalyst pack. These changes in the direction of flow increase the H_2O_2 stay time in the catalyst pack and result in better low temperature starting.

To the left in the figure appears the entry for chamber pressure measurements. Also shown are the mounting bracket, exhaust nozzle radius and cone, and the darkened sites where parts of the motor were welded together. The figure shows the bolts and head plates which permit access to the catalyst pack. The catalyst screens themselves are held within the catalyst holder by the injector umbrella retainer plate, and spiralox ring. These component parts are shown in greater detail in Figure 65. To the left appears the catalyst holder with cavities for the preheat scroll and main catalyst. At the right is the injection umbrella which holds ~~the~~ preheat scroll and fits inside the preheat scroll cavity of the catalyst holder. The retainer plate appears at the bottom right.

Figure 64

22# THRUST PREHEAT MOTOR USED TO DECOMPOSE 98% H_2O_2

IN THE LOW TEMPERATURE STARTING TESTS

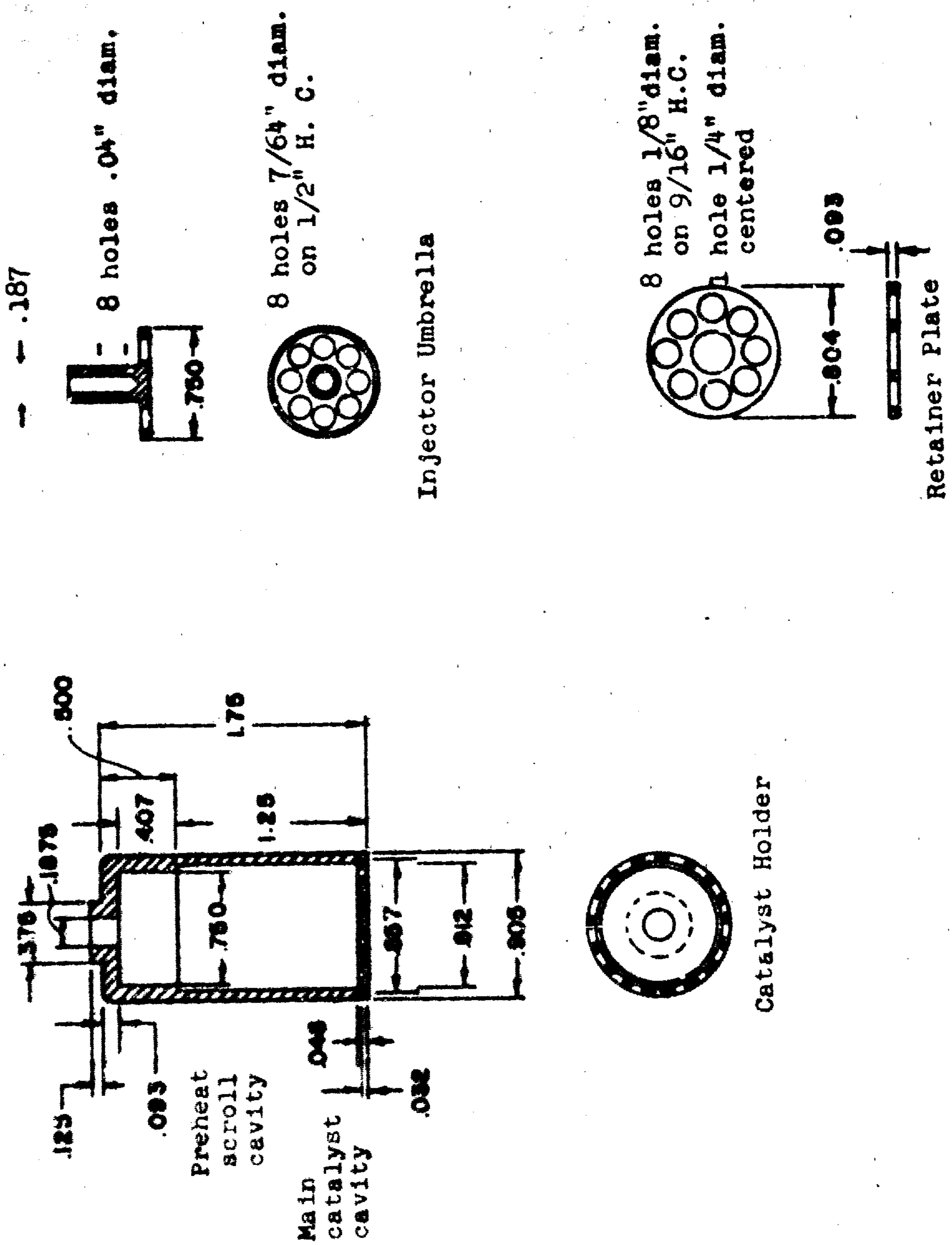


Note: 1. Chamber 347 SS except for bolts and head seal gasket

2. Full scale

Figure 65

COMPONENT PARTS FOR THE 22# THRUST MOTOR USED TO DECOMPOSE 98% H_2O_2 IN THE LOW TEMPERATURE TESTS



(2) Catalyst Configuration and Packing

The catalyst configuration used for both low-temperature test packs is shown in Figure 66. The preheat scroll catalyst screen was wound around the inlet tube of the injector umbrealla, beginning with a 6" length of silver screen, continuing with 6" of silver-5% palladium screen, and ending with 12" of silver-30% palladium screen. The injector umbrella was then inserted within the catalyst holder and the main catalyst section screens were added. The main section of the pack was compressed to 4000 psi and then the retainer plate and Spirolox ring were inserted.

(3) Test System

The 22 pound thrust preheat motor was mounted on a test stand as shown in Figure 67. The entire system was surrounded by an insulated box so the temperature could be uniformly reduced. The 98% H_2O_2 feed tank (5 gal.), the propellant valve, and the chamber pressure transducer can also be seen. The feed pressure transducer is not shown but appears in the schematic of Figure 68 as Pf. A chromel-alumel thermocouple was used to monitor the surface temperature on the outside of the chamber, and an iron-constantan thermocouple measured the H_2O_2 feed temperature. A quick disconnect allowed the H_2O_2 feed tank to be separated for weighing before and after the steady-state tests so propellant flow could be determined. The schematic also shows the nitrogen gas fuel pressurant supply (per MIL-BB-N-411B, Grade B, type 1, class 1 filter to 10 microns prior to introduction into the test system).

(4) Test Procedure

All tests were conducted using FMC supplied 98% H_2O_2 which was filtered to 10 microns prior to introduction into the test system. As in the earlier tests, the pressures and temperatures were recorded on an oscillograph recorder.

The test system and 98% H_2O_2 were cooled in the insulated box with dry ice. Several hours were allowed for all parts of the system to reach temperature. This initial temperature was 25°F for motor S/N 002 and 30°F for motor S/N 001. The motors were then tested as follows using a feed pressure of 530 psig.

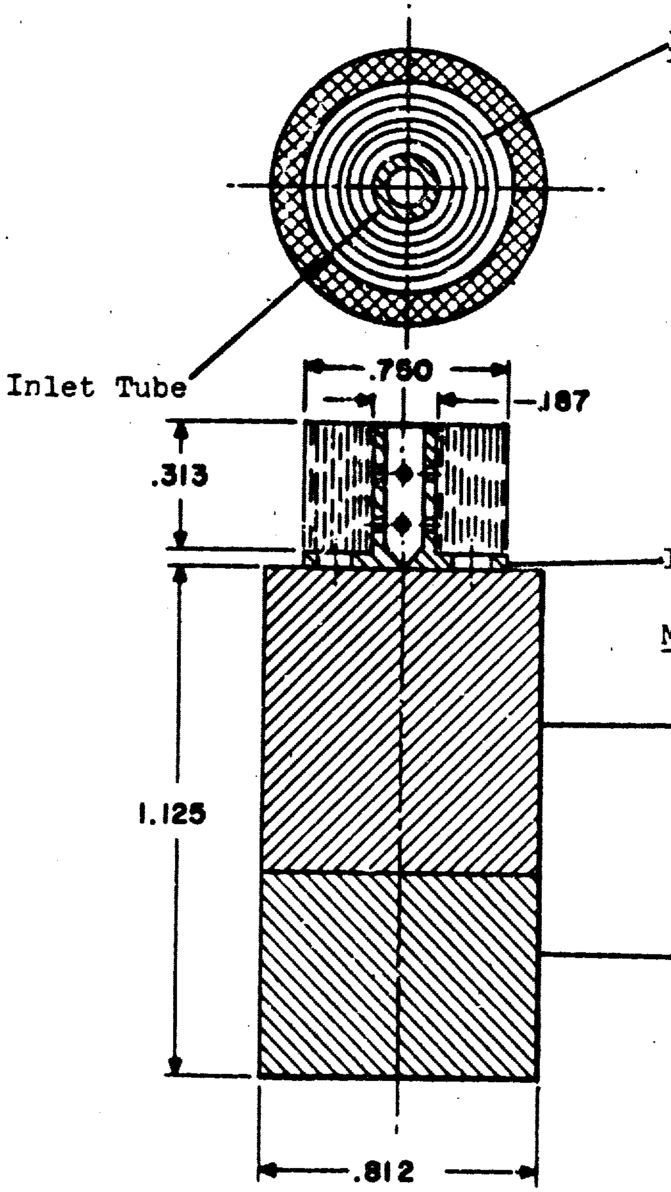
(1) The motor was pulsed three times at a pulse mode of 150 msec. on and 3 seconds off.

Figure 66

Catalyst Pack Used for the Low Temperature Starting

Tests with 98% Hydrogen Peroxide

Test Motor - 22# Thrust Preheat



Preheat Catalyst Scroll

(given from center outward) 6" of 40 mesh silver, 6" of 40 mesh silver-5% palladium, and 12" 40 mesh silver-30% palladium catalyst screen

Injector Umbrella

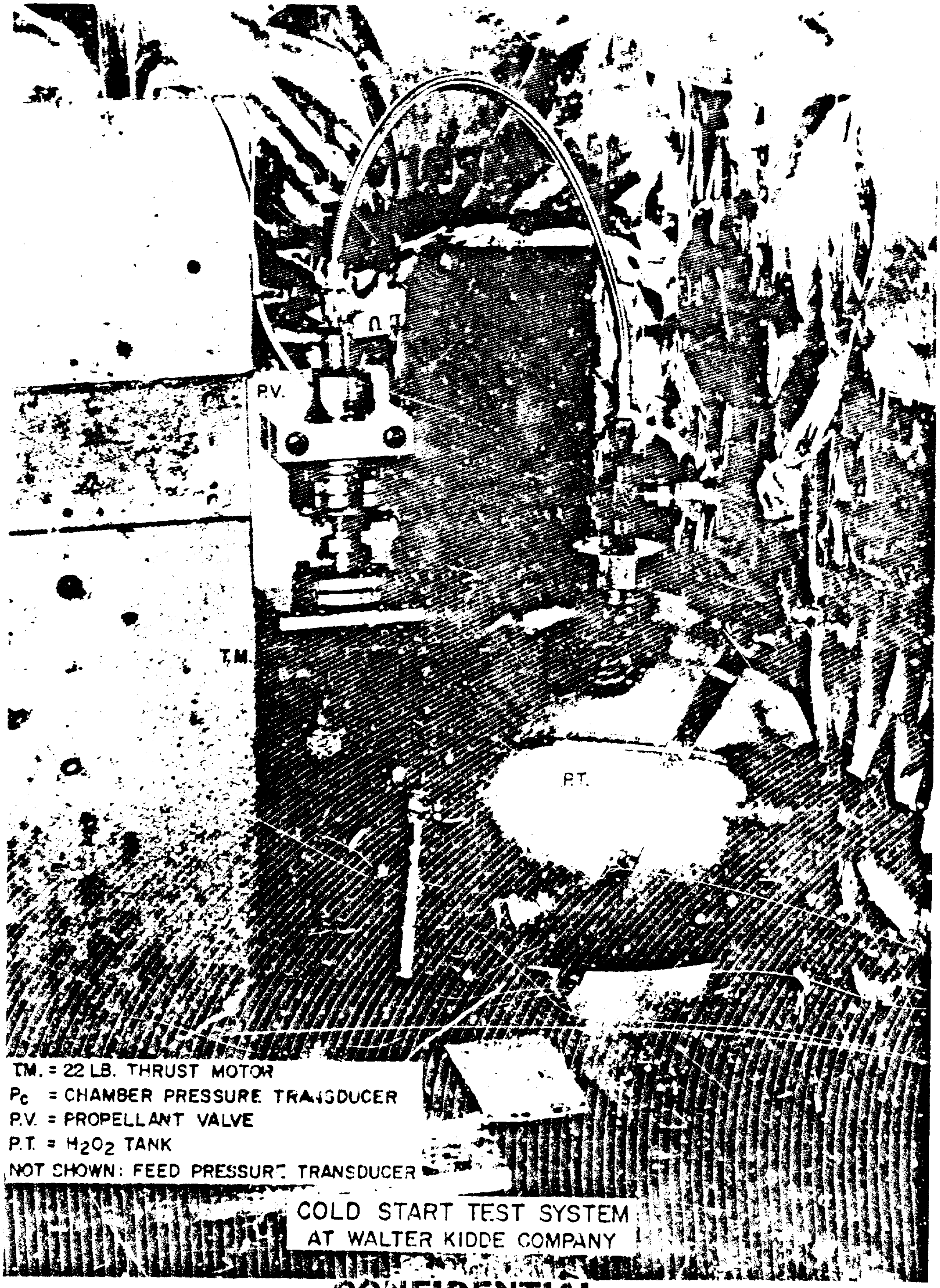
Main Catalyst Section

36 pcs. 20 mesh silver-30% palladium screens

21 pcs. 14 mesh-5% manganese screens

Pack Main Section at 4000 psi.

Figure 67

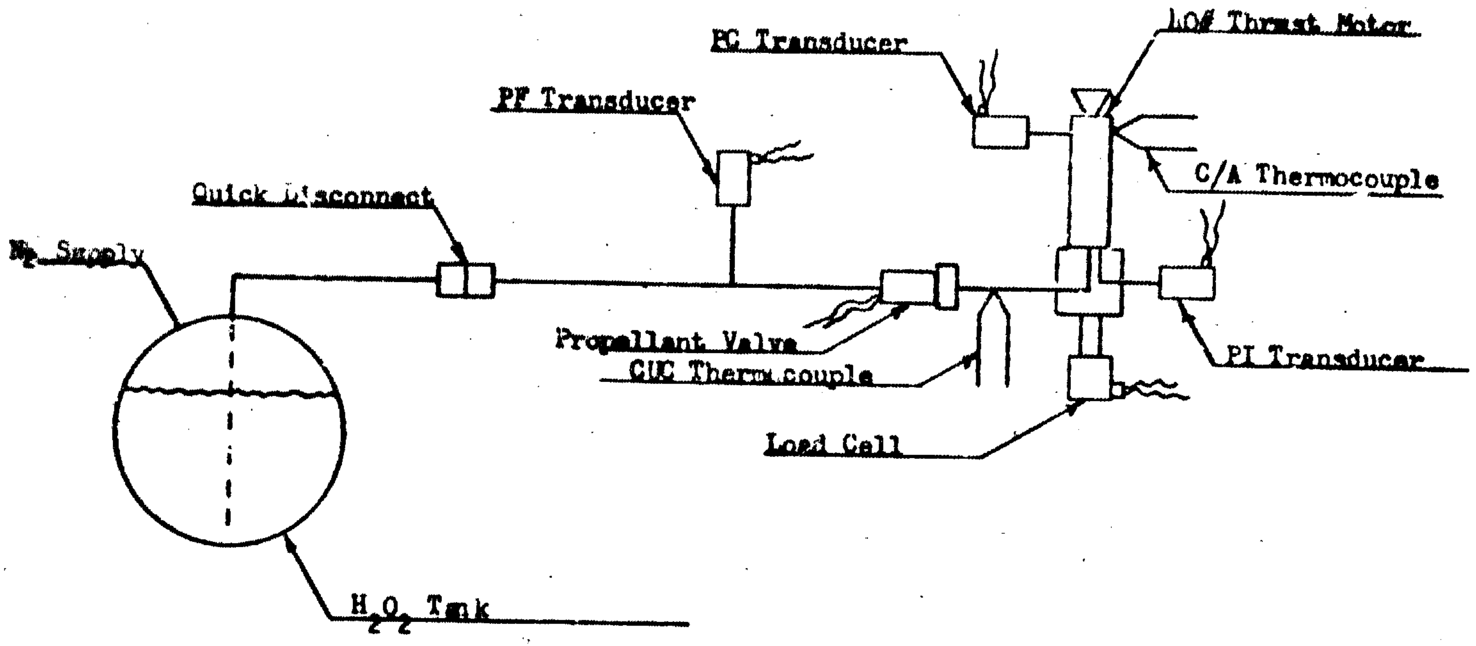


T.M. = 22 LB. THRUST MOTOR
P_c = CHAMBER PRESSURE TRANSDUCER
P.V. = PROPELLANT VALVE
P.T. = H_2O_2 TANK
NOT SHOWN: FEED PRESSURE TRANSDUCER

COLD START TEST SYSTEM
AT WALTER KIDDE COMPANY

Figure 68

SCHEMATIC OF INITIAL SCREENING TEST STAND



(2) Upon initiation of the following 300 cycle sequence for motor S/N 002, no firing occurred because the 98% H_2O_2 had frozen at 25°F. Motor S/N 002 was then allowed to soak at 30°F for a period of one hour before it was restarted, while motor S/N 001 was allowed only 10 minutes at 30°F prior to restart.

(3) The motors were then pulsed 300 times at a pulse mode of 150 msec. on and 350 msec. off.

(4) The fuel tank was disconnected and weighed.

(5) The fuel tank was reconnected and a 30 second steady-state test was run.

(6) The fuel tank was then disconnected and reweighed.

Both motors and the fuel system were removed from the environmental chamber and allowed to reach ambient temperature. An ambient correlation test was then performed on each motor using the same fuel system and the same feed pressure settings. The ambient tests were performed in the following sequence:

(1) The motor was pulsed three times at a pulse mode of 150 msec. on and 3 seconds off.

(2) The motor was allowed to cool for ten minutes.

(3) The motor was pulsed ten times at a pulse mode of 150 msec. on and 350 msec. off.

(4) The motor was fired continuously for ten seconds (steady-state).

(5) Results of the Tests

(a) Motor S/N 002

The first low temperature starting test employed +25°F 98% H_2O_2 and +25°F motor (S/N 002). Figures 69, 70, and 71 show the first, second, and third pulses for motor S/N 002. The symbols used to identify the traces on the figures have the same meaning as those described previously (page 45). The first pulse showed no significant pressure rise. The second and third pulses were rapid with 30 and 25 msec. to 90% of attained chamber pressure (PC).

Figure 69

LOW TEMPERATURE TEST
FIRST PULSE WITH 25°F FEED
98.1% H_2O_2 AND 22 POUND THRUST MOTOR S/N 002

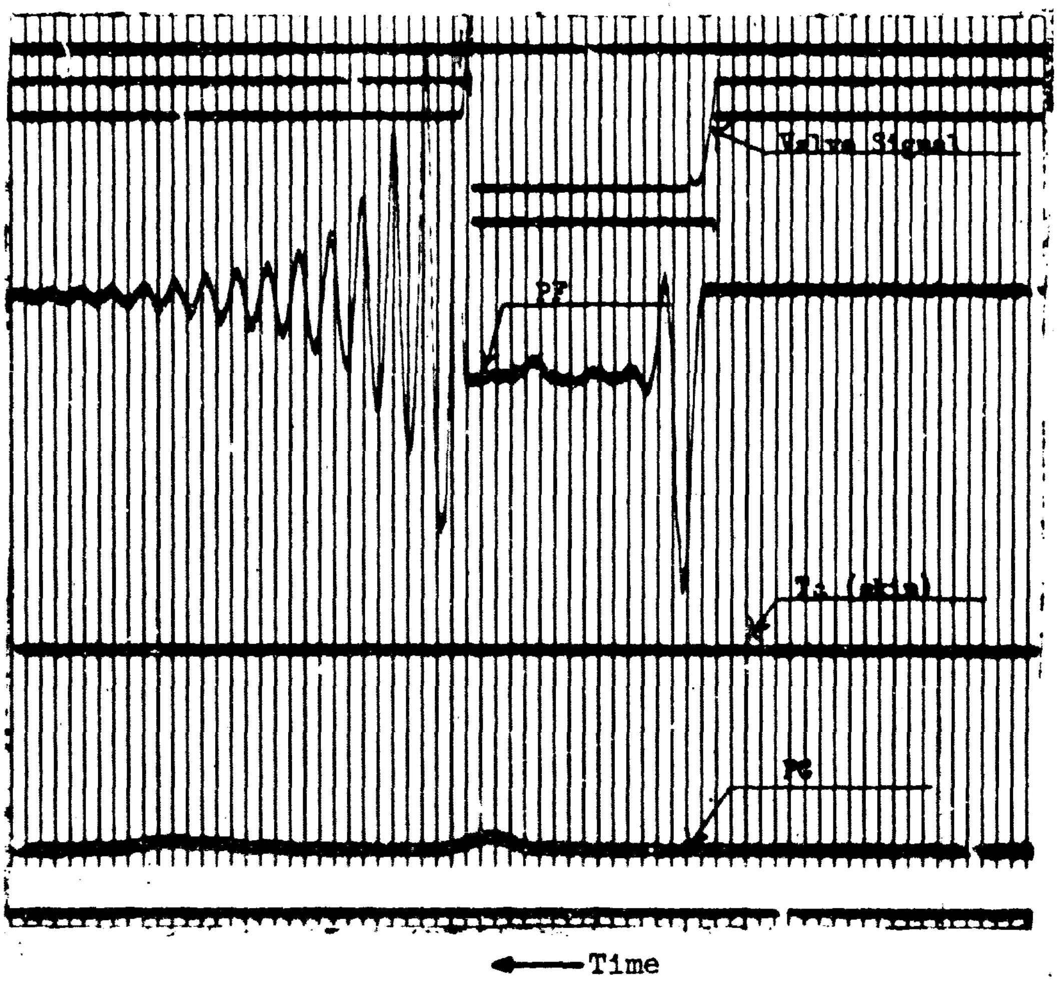
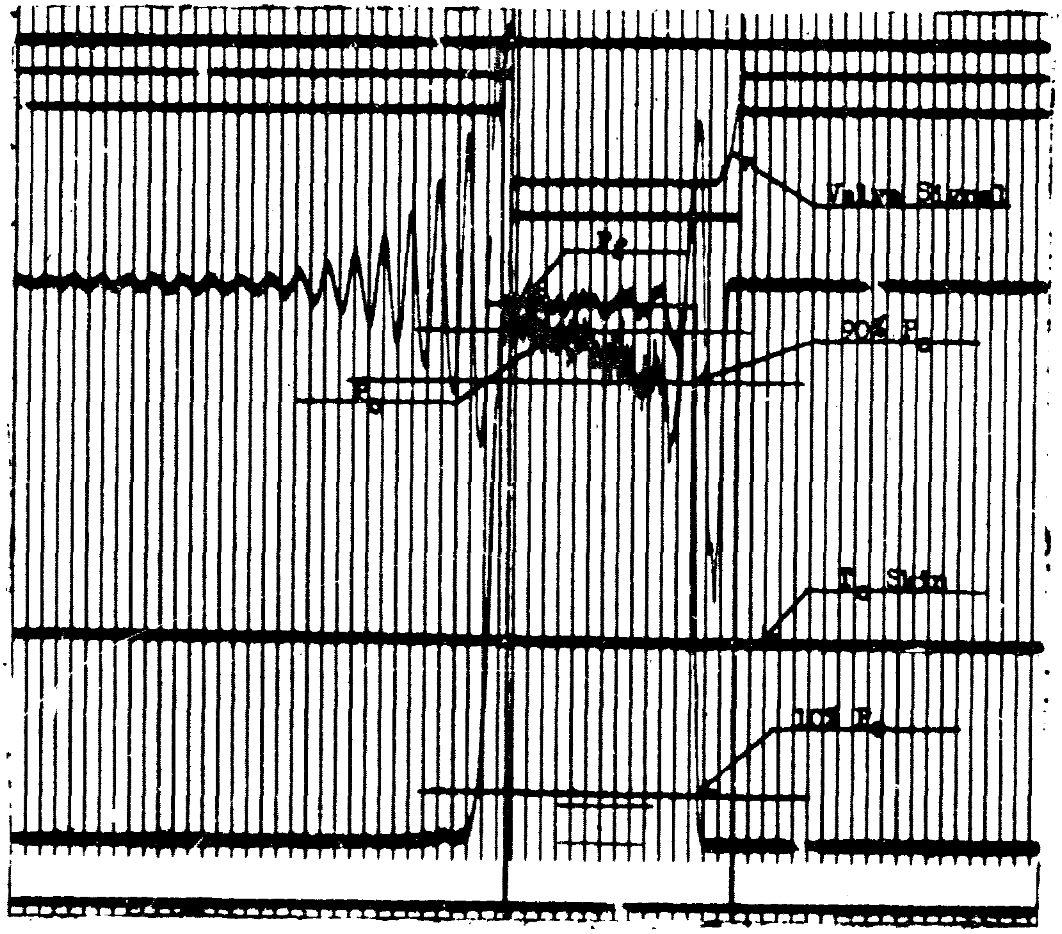


Figure 70

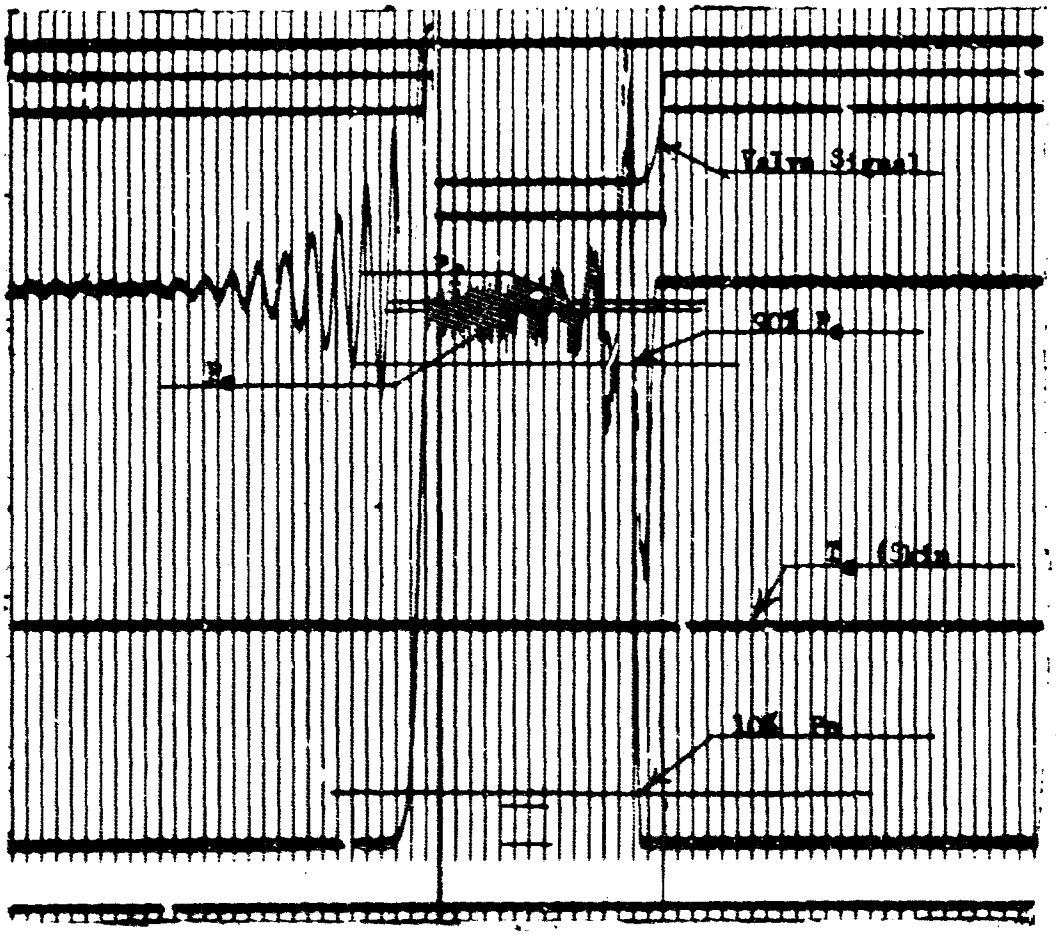
LOW TEMPERATURE TEST
SECOND PULSE WITH 25°F FEED
98.1% H_2O_2 AND 22 POUND THRUST MOTOR S/N 002



← Time

Figure 71

LOW TEMPERATURE TEST
THIRD PULSE WITH 25°F FEED
98.1% H_2O_2 AND 22 POUND THRUST MOTOR S/N 002



← Time

The H_2O_2 froze in the feed line following the third pulse, which was evident when there was no H_2O_2 flow at the initiation of the 300 cycle sequence. The 98% H_2O_2 was then warmed to 30°F and the 300 pulses were carried out. Figure 72 shows the first two cycles of the 300 cycle sequence. Due to the long wait between the first 3 pulses and the start of the 300 cycle sequence, the motor was again cold, as for the first pulse. This accounts for the lack of response for the first of the 300 cycles, when compared to the response of motor S/N 001 which was still warm at this point. Response time in cycles 2 to 300 for S/N 002 averaged 16-20 msec. to 90% Pc (valve delay time 8-10 msec.). Decay times averaged 18-25 msec. to 10% Pc. Catalyst pack pressure drop was approximately 200 psi, including 20-30 psi due to the valve.

The 30 second steady-state run was carried out to determine engine efficiency. Measured C* was 3367 ft/sec. which shows high motor performance, 99% of theoretical with the 30°F H_2O_2 feed. Figure 73 shows that pressure oscillations were experienced. No orifices were employed in the H_2O_2 feed line and the oscillations could be eliminated by use of a trim orifice or venturi at the inlet to the chamber.

The low temperature test results for motor S/N 002 are given in Table XVIII. In the first column to the left appear the three basic sequences of the test program. Column two shows the cycle within the sequence or the second of the steady state for which data appears in the remaining columns: chamber pressure, pressure of the H_2O_2 feed, pressure drop (ΔP) across the catalyst pack, temperature of the H_2O_2 feed, temperature on the outside of the chamber wall, and the start and decay transients for 10 and 90% of realized chamber pressure.

Following the low temperature tests, the motor was subjected to ambient temperature calibration tests. Starts were rapid and pulses were sharp. The first start transient with 54°F 98.1% H_2O_2 was 104 msec. to 90% chamber pressure (Figure 74). Pulse transients varied from 16 to 27 msec. for 90% Pc for the remaining starts (Figures 75, 76, and 77). Thus the results show that the initial start for motor S/N 002 was significantly better at 54°F than at 25°F, but that additional starts with a 25°F 98% H_2O_2 feed but a warm motor were essentially the same as those for 54°F H_2O_2 feed.

The 10 second steady-state test at ambient temperatures (Figure 78) again exhibited pressure oscillations, confirming that they were not peculiar to the low temperature operation of the motor. The pressure drop across the catalyst pack was roughly the same as that obtained at low temperature, again including a 20-30 psi value ΔP.

Figure 72

LOW TEMPERATURE TEST
FIRST TWO PULSES OF 300
CYCLE TEST WITH 32°F FEED
98.1% H_2O_2 AND 22 POUND THRUST MOTOR S/N 002

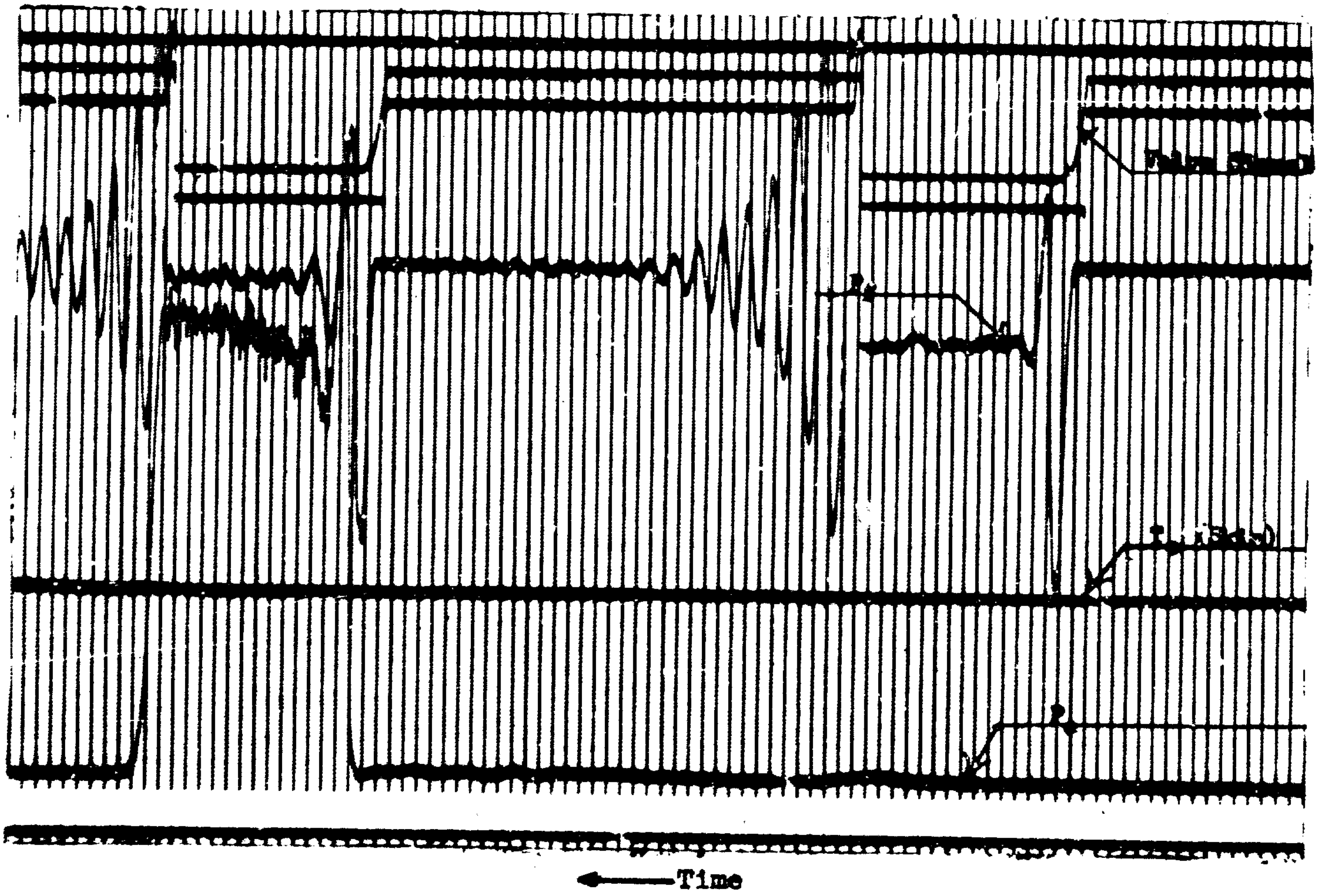


Figure 73

LOW TEMPERATURE TEST
START OF STEADY STATE TEST WITH 30°F FEED
98.1% H_2O_2 AND 22 POUND THRUST MOTOR S/N002

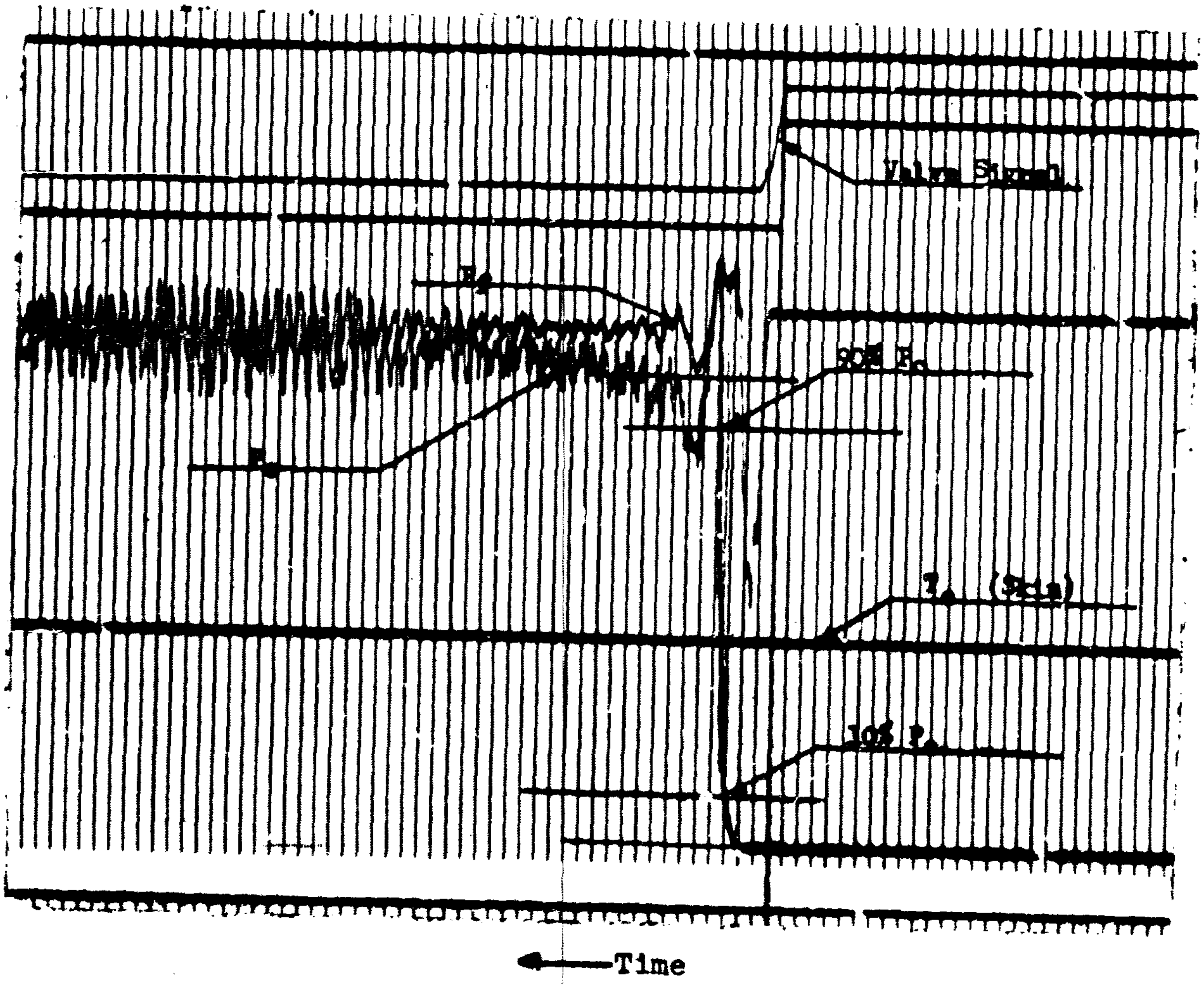


TABLE XVIII

LOW TEMPERATURE TESTS WITH MOTOR S/N 002

H_2O_2 Concentration - 98.1%
Throat Diameter - .2875 inches

Test Sequence	Cycle Number	Chamber Pressure (PSIA)	H_2O_2 Feed Pressure (PSIA)	ΔP (PSI)	Feed H_2O_2 Temp. (°F)	Outer Wall of Chamber (°F)	Transients[a] Response 10%	Response 90%	Decay 90%	Decay 10%
3 Cycle Warm-up	1	N/A	---	---	25	---	---	---	---	---
	2	296	507	211		33	25	29	9	25
	3	308	510	202		90	16	20	8	19
300 Cycles	1[b]	N/A	---	---	32	---	---	---	---	---
	3	302	597	205		55	24	26	8	20
	6	308	512	204		95	17	17	7	18
	10	313	510	197		200	17	18	6	18
	50	312	510	198		1043	15	18	7	21
	100	315	513	198		1125	14	19	9	26
	150	315	513	198		1175	13	16	8	25
	200	312	508	196		1165	11	17	8	23
	250	313	510	197		1160	12	19	9	25
	300	315	513	198		1160	12	20	7	22
30 Second[c] Steady-State	Second 1[d]	298	499	201	30	115	30	39	---	---
	5	305	499	194		580	---	---	---	---
	10	306	495	189		845	---	---	---	---
	15	307	497	190		970	---	---	---	---
	20	311	497	186		1015	---	---	---	---
	25	312	497	185		1030	---	---	---	---
	30	315	497	182		1030	---	---	11	33
	AVG.	309	497	188		---	---	---	---	---

Notes: N/A - Denotes failure to start.
a - Given in msec. for the designated percentages of chamber pressure; valve delay approximately 10 msec.
b - Motor cooled for one hour prior to restart.
c - Flow for steady-state test was .1918lb/sec. C* was 3367 ft./sec.
d - Not included in average.

Tests Conducted by Walter Kidde Co.

Figure 74

AMBIENT TEMPERATURE TEST
FIRST PULSE WITH 54°F FEED
98.1% H_2O_2 AND 22 POUND THRUST MOTOR S/N 002

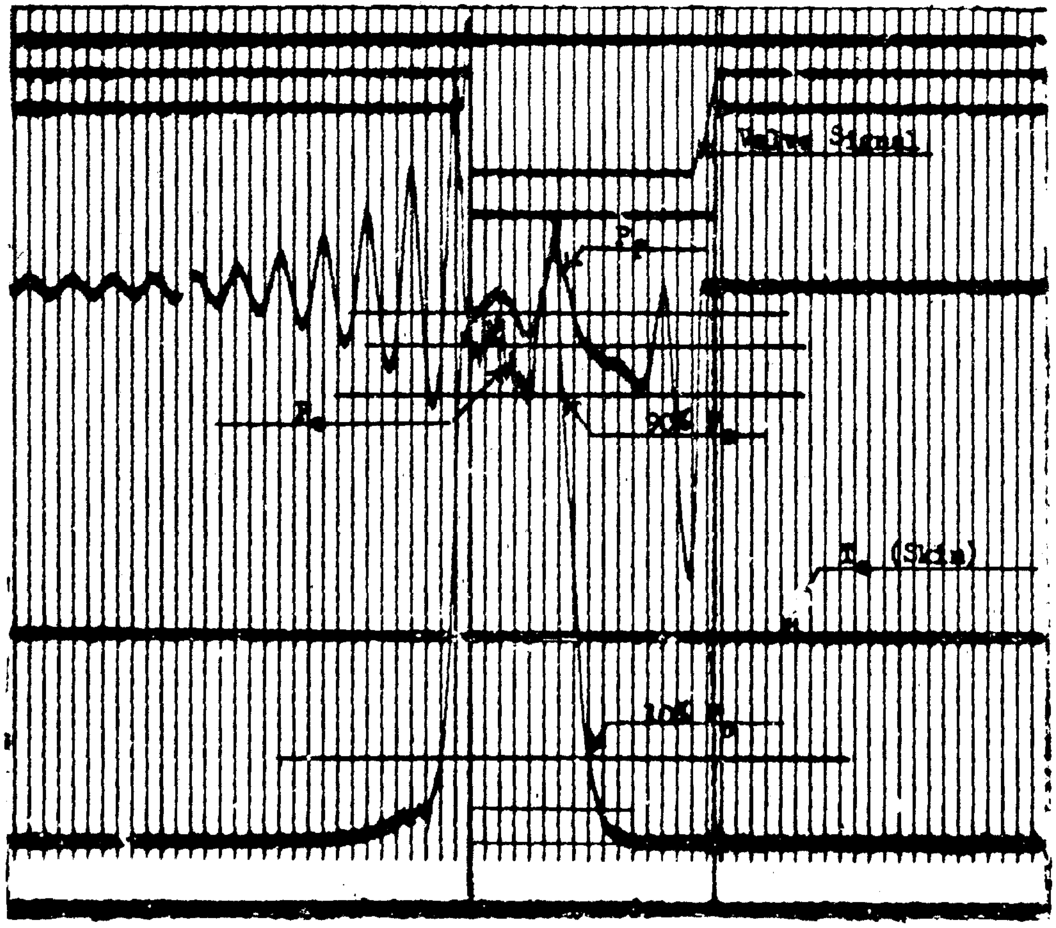


Figure 75

AMBIENT TEMPERATURE TEST
SECOND PULSE WITH 54°F FEED
98.1% H_2O_2 AND 22 POUND THRUST MOTOR S/N 002

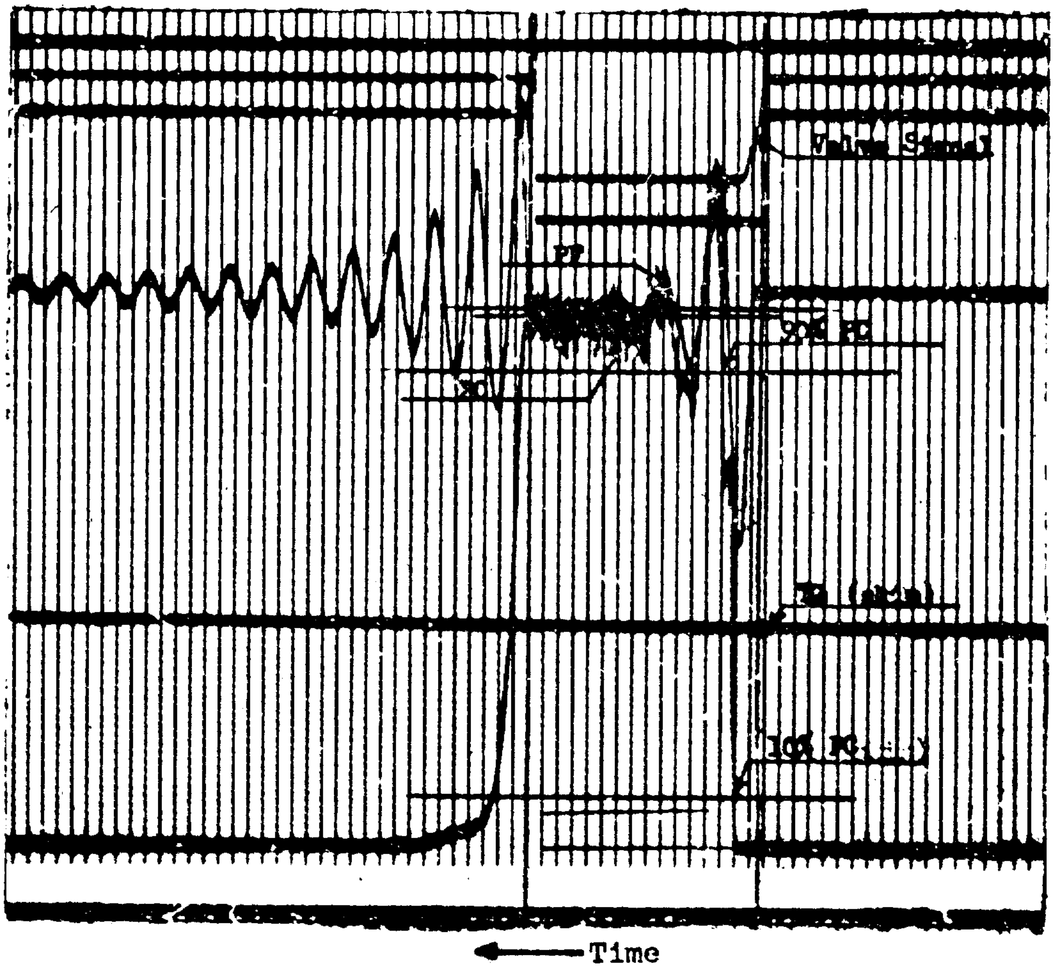


Figure 76

AMBIENT TEMPERATURE TEST
THIRD PULSE WITH 54°F FEED
98.1% H_2O_2 AND 22 POUND THRUST MOTOR S/N 002

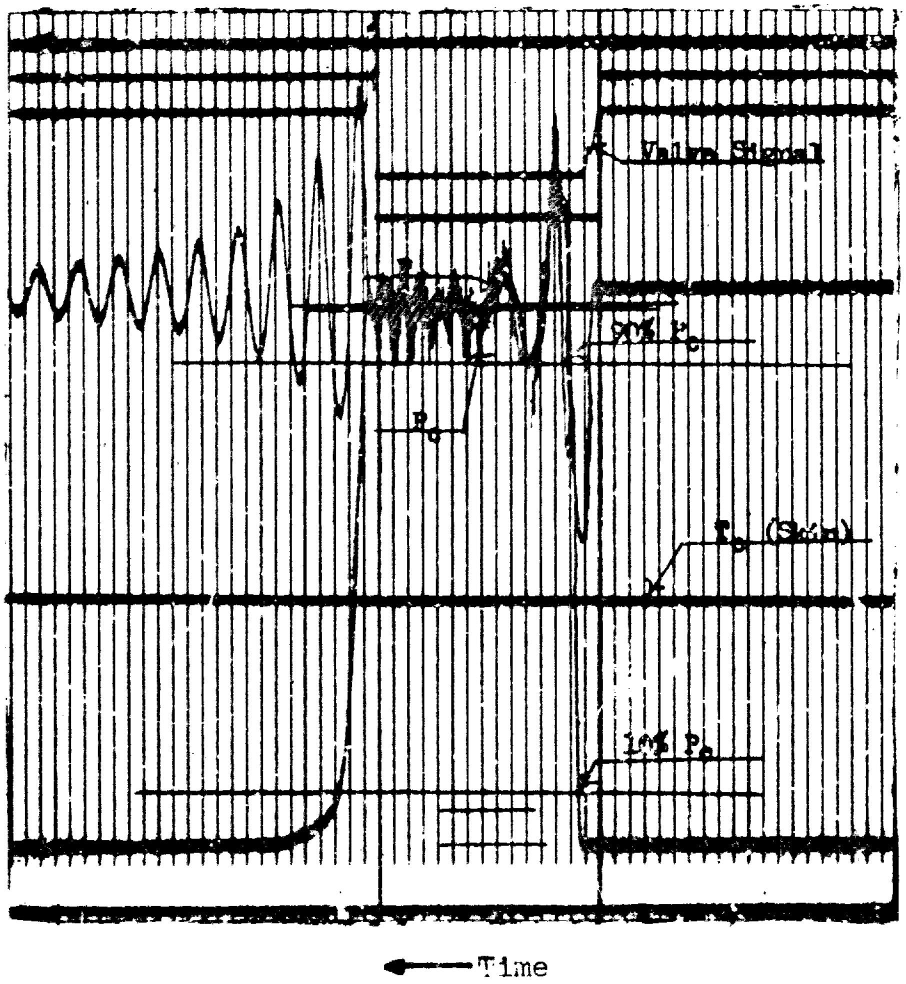


Figure 77

AMBIENT TEMPERATURE TEST
FIRST TWO PULSES OF TEN CYCLE TEST WITH 55°F FEED
98.1% H_2O_2 AND 22 POUND THRUST MOTOR S/N 002

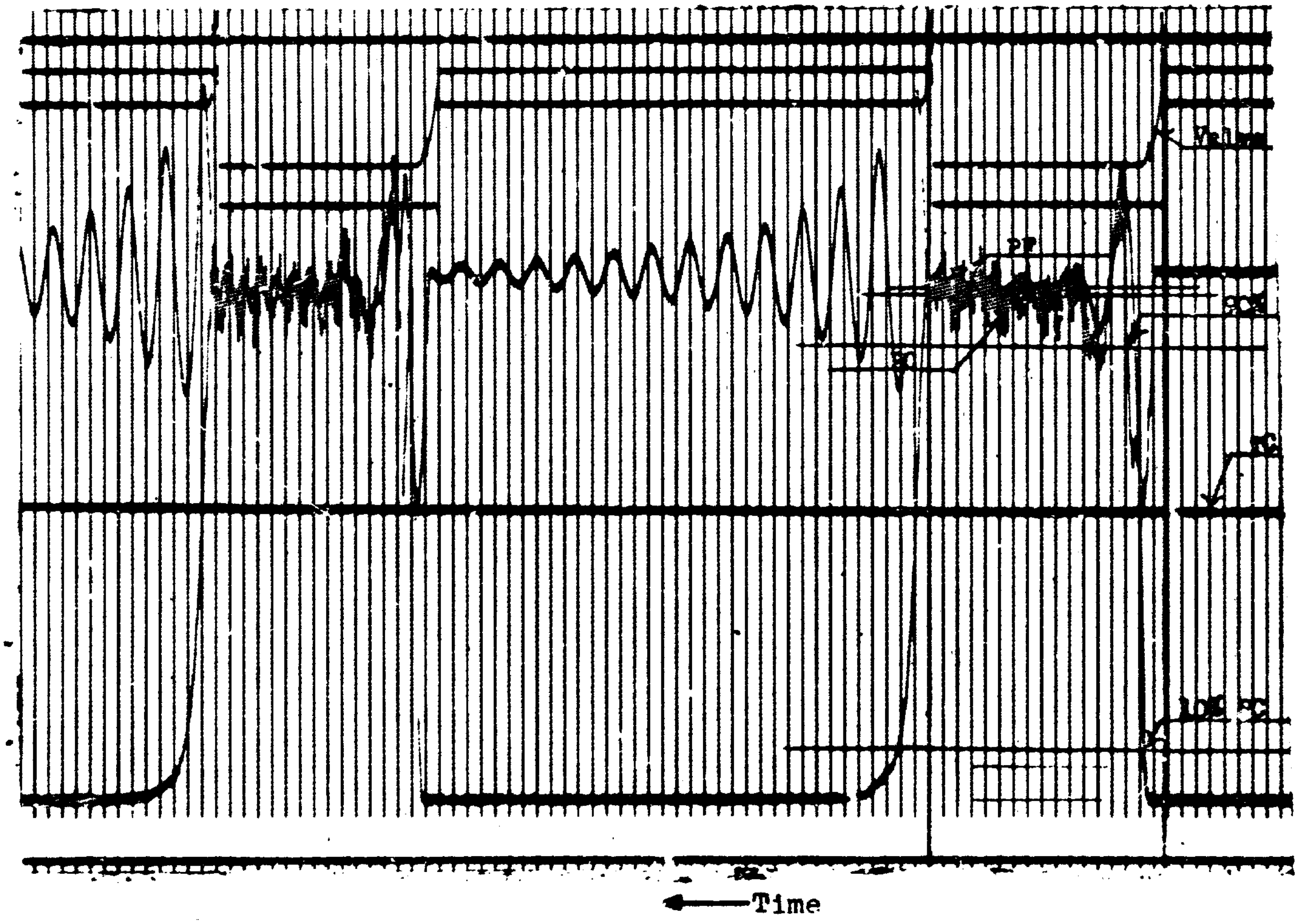
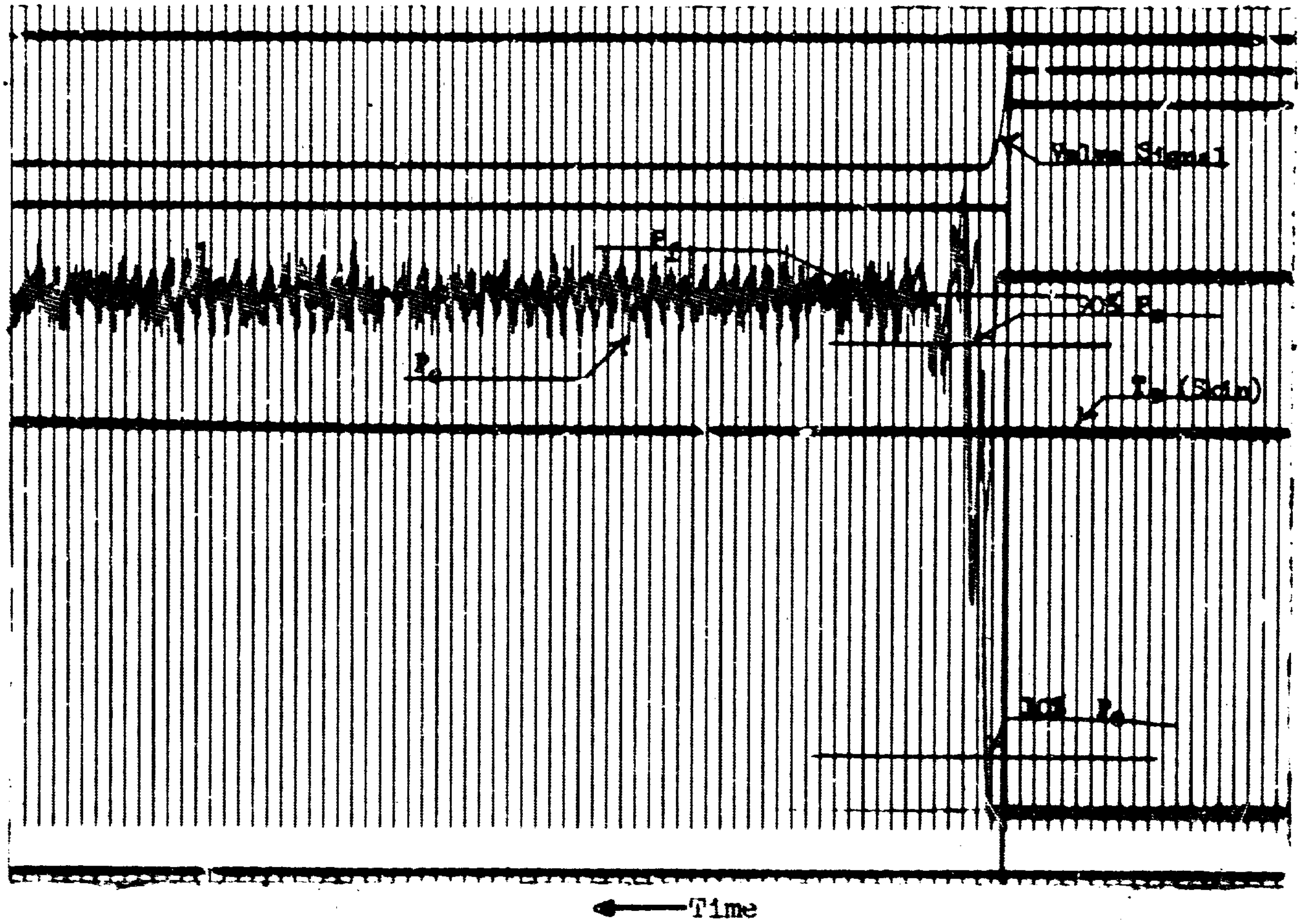


Figure 78

AMBIENT TEMPERATURE TEST
START OF STEADY STATE WITH 58°F FEED
98.1% H_2O_2 AND 22 POUND THRUST MOTOR S/N 002



The ambient temperature results for motor S/N 002 are shown in Table XIX. The same data have been reported as for the low temperature tests (page 149).

(b) Motor S/N 001

A similar set of tests with preheat motor S/N 001 produced results comparable to those obtained with S/N 002. Figures 79, 80, and 81 show the first, second and third cold start pulses. The first pulse again showed no significant pressure rise while the second and third pulse starts were rapid at 30 and 25 msec. to 90% Pc.

The 300 cycle pulse sequence was then initiated before the motor had had time to cool completely. Thus the first of the 300 pulses (Figure 82) gave a good response, whereas motor S/N 002 did not. Response times for the remaining pulses averaged 17 to 25 msec. to 90% Pc and 21 to 28 msec. to 10% Pc decay. Catalyst pack ΔP averaged 230 to 240 psi including the 20-30 psi pressure drop across the valve.

The 30 second steady-state test produced a measured C* of 3190 ft./sec. which is 97% of theoretical. Figure 83 shows the initial start transient. As in tests with S/N 002, pressure oscillations were experienced which could be eliminated by the use of a trim orifice or venturi in the feed line.

The results of the low temperature tests with motor S/N 001 are given in Table XX.

The results of the ambient temperature calibration tests with S/N 001 were also similar to those for S/N 002. The initial start with 54° F 98.1% H_2O_2 was 149 msec. to 90% Pc. (Figure 84), and transients averaged 24 and 19 msec. in cycles 2 and 3 (Figures 85 and 86). Start transients for the ten pulse sequence averaged 17-25 msec. to 90% Pc, while decay rates were 26-29 msec. to 10% of Pc, (Figure 87). The 10 second steady-state test (Figure 88) showed chamber pressure oscillations much the same as with low temperature feed. Table XXI gives the ambient temperature test results for S/N 001.

TABLE XIX

AMBIENT CORRELATION TEST PERFORMED AFTER LOW TEMPERATURE TEST WITH MOTOR S/N 002

H_2O_2 Concentration - 98.1%
Throat Diameter - .2875 inches

Test Sequence	Cycle Number	Chamber Pressure (PSIA)	H_2O_2 Feed Pressure (PSIA)	ΔP PSI	Feed H_2O_2 Temp. (°F)	Outer Wall of Chamber (°F)	Transients[a]			
							Response		Decay	
							10%	90%	90%	10%
3 Cycle Warm-up	1	293	505	212	54	70	86	104	9	27
	2	312	514	202		125	18	27	9	31
	3	313	514	201		210	16	26	9	27
10 Cycles	1	314	514	200	55	410	17	27	8	25
	3	314	508	194		460	12	16	10	26
	6	316	512	196		580	16	19	9	23
	10	321	514	193		770	12	17	10	28
10 Second Steady-State	Second									
	1	314	505	191	58	810	12	20	---	---
	5	321	508	187		1190	---	---	---	---
	10	322	512	190		1310	---	---	8	23
	AVG.	319	508	189		---	---	---	---	---

Note: a - Given in msec. for the designated percentages of chamber pressure; valve delay approximately 10 msec.

Tests Conducted by Walter Kidde Co.

Figure 79

LOW TEMPERATURE TEST
FIRST PULSE WITH 30°F FEED
98.1% H_2O_2 AND 22 POUND THRUST MOTOR S/N 001

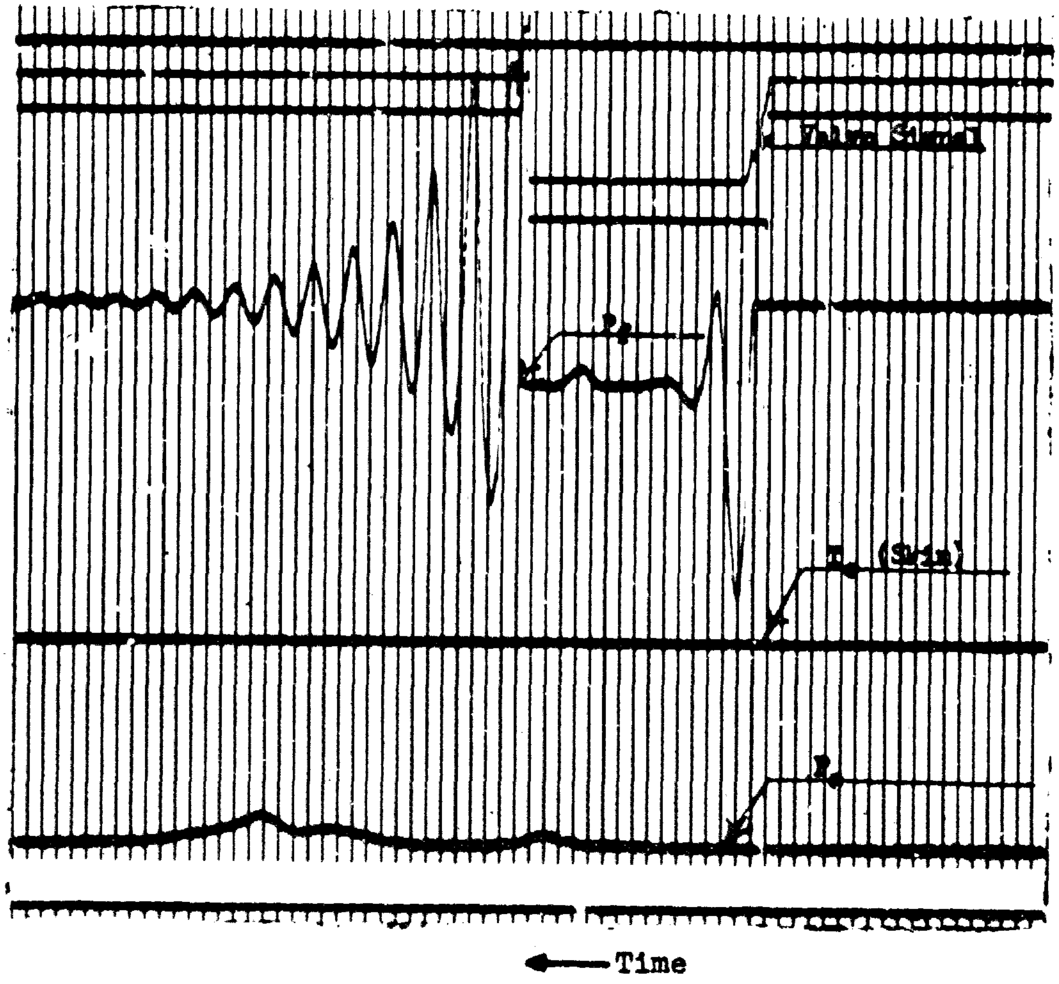


Figure 80

LOW TEMPERATURE TEST
SECOND PULSE WITH 30°F FEED
98.1% H_2O_2 AND 22 POUND THRUST MOTOR S/N 001

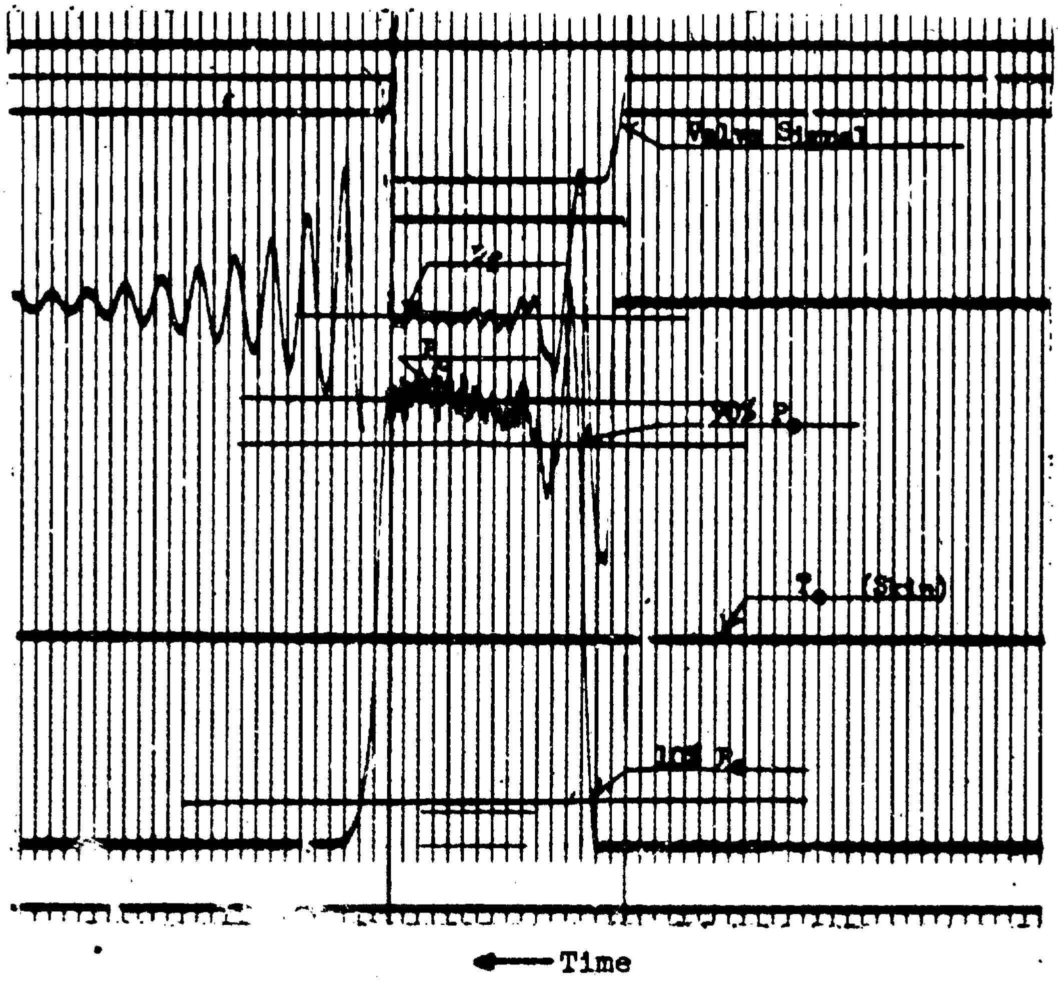


Figure 81

LOW TEMPERATURE TEST
THIRD PULSE WITH 30°F FEED
98.1% H_2O_2 AND 22 POUND THRUST MOTOR S/N 001

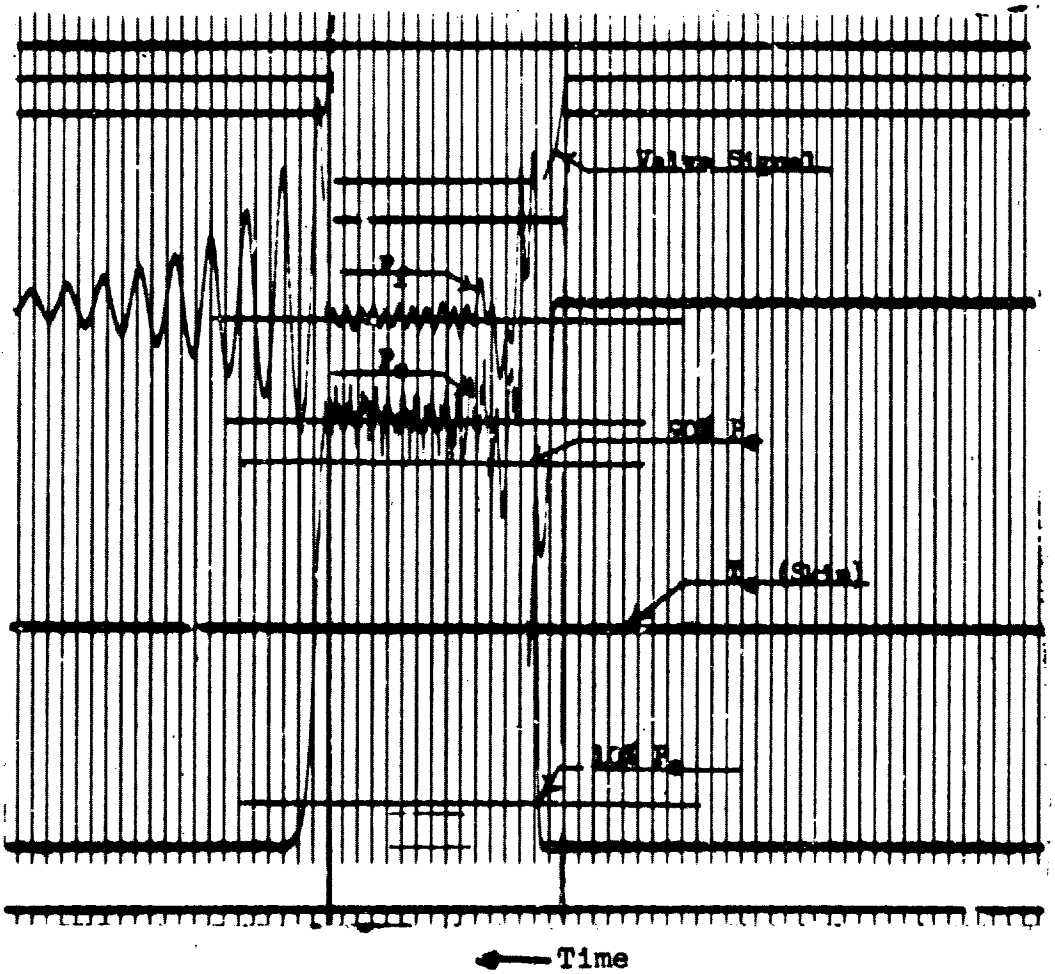


Figure 82

LOW TEMPERATURE TEST
FIRST TWO PULSES OF 300 CYCLE TEST WITH 30°F FEED
98.1% H_2O_2 AND 22 POUND THRUST MOTOR S/N 001

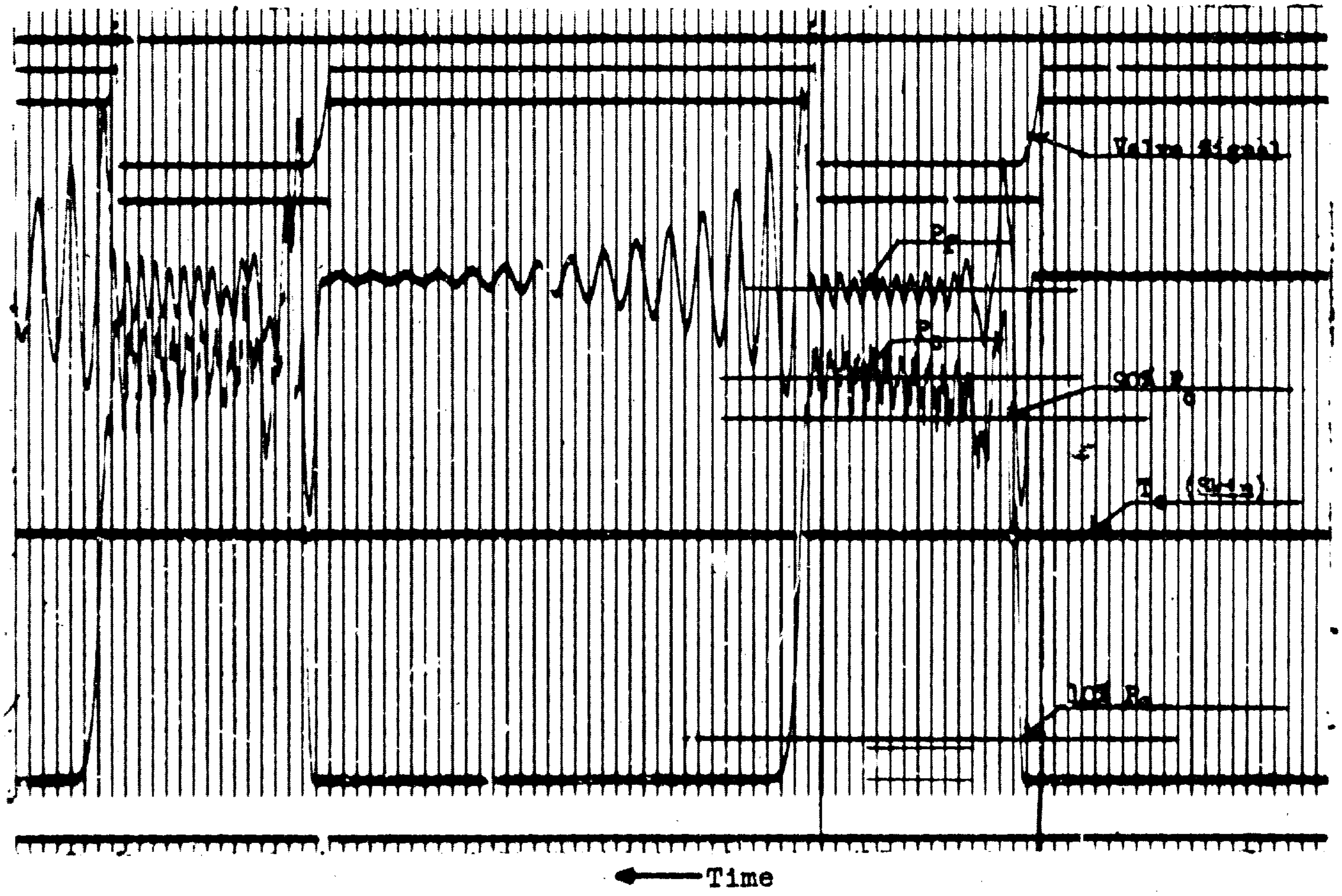


Figure 83

LOW TEMPERATURE TEST
START OF STEADY STATE WITH 30.5°F FEED
98.1% H_2O_2 AND 22 POUND THRUST MOTOR S/N 001

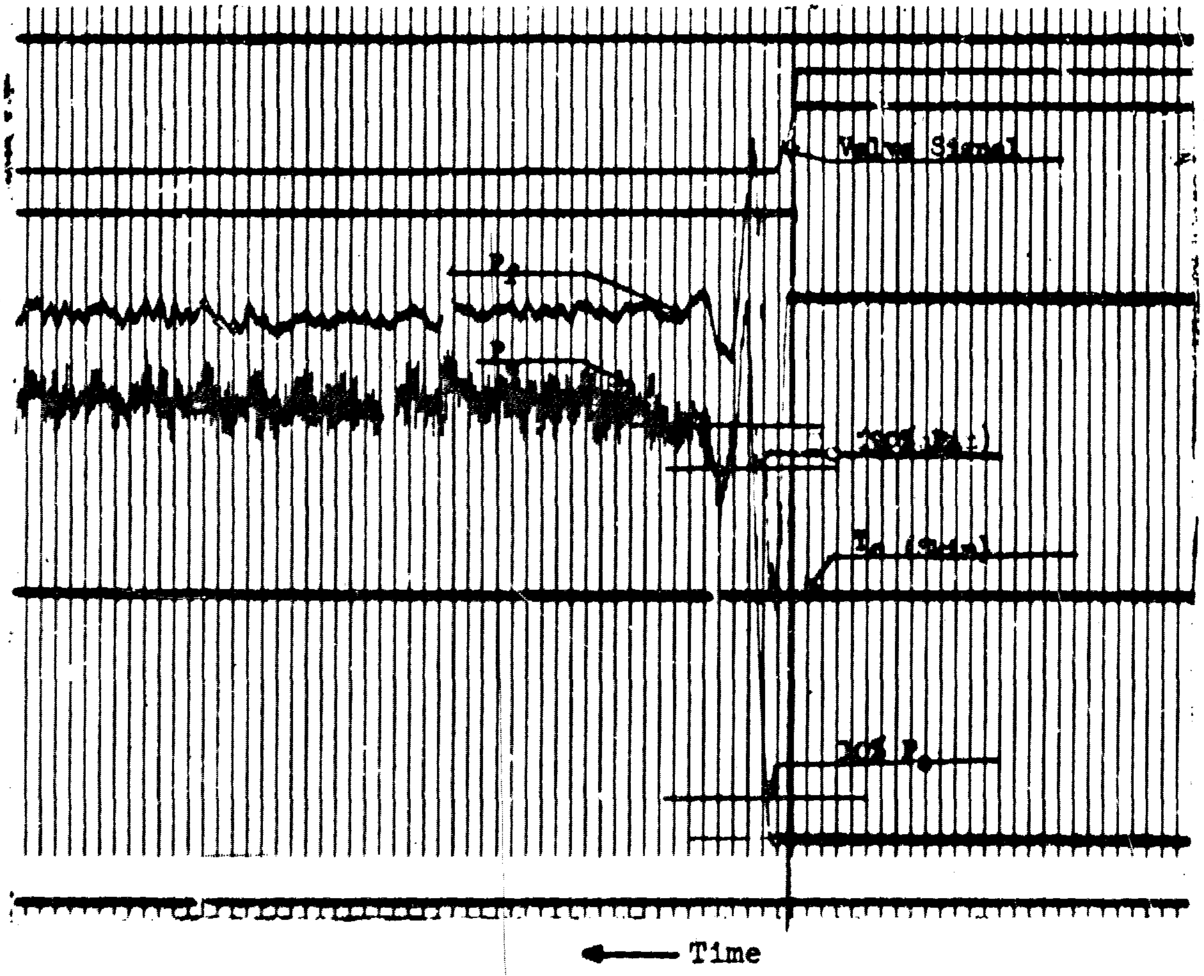


TABLE XX

LOW TEMPERATURE TESTS WITH MOTOR S/N 001

H_2O_2 Concentration - 98.1%
Throat Diameter - .3025 inches

Test Sequence	Cycle Number	Chamber Pressure (PSIA)	H_2O_2 Feed Pressure (PSIA)	ΔP PSI	Feed H_2O_2 Temp. (°F)	Outer Wall of Chamber (°F)	Transients[a]			
							Response		Decay	
							10%	90%	90%	10%
3 Cycle Warm-up	1	N/A	---	---	30°					
	2	267	510	243		70	21	30	8	22
	3	255	510	255		110	17	25	8	18
300 Cycles	1	258	510	252	30°	270	14	25	9	22
	3	262	506	244		290	14	19	7	21
	6	268	500	232		370	12	18	8	23
	10	267	508	243		510	14	17	9	23
	50	270	506	236		1105	15	21	9	26
	100	271	510	239		1179	13	19	10	28
	150	270	508	238		1175	13	19	8	27
	200	269	510	241		1179	12	18	10	27
	250	271	508	237		1182	12	17	9	28
	300	268	510	242		1179	12	22	9	28
30 Second[b] Steady-State	Second									
	1[c]	262	500	238	30.5	253	19	28	---	---
	5	268	502	234		760	---	---	---	---
	10	270	497	227		1015	---	---	---	---
	15	270	500	230		1130	---	---	---	---
	20	270	502	232		1175	---	---	---	---
	25	271	500	229		1179	---	---	---	---
	30	271	500	229		1200	---	---	---	---
	AVG.	270	500	230		---	---	---	9	28

Notes: N/A - Denotes failure to start.
a - Given in msec. for the designated percentages of chamber pressure; valve delay approximately 10 msec.
b - Flow for steady-state test was .195
lb/sec. C* was 3190 ft./sec.
c - Not included in average.

Tests Conducted by Walter Kidde Co.

Figure 84

AMBIENT TEMPERATURE TEST
FIRST PULSE WITH 54°F FEED
98.1 % H_2O_2 AND 22 POUND THRUST MOTOR S/N 001

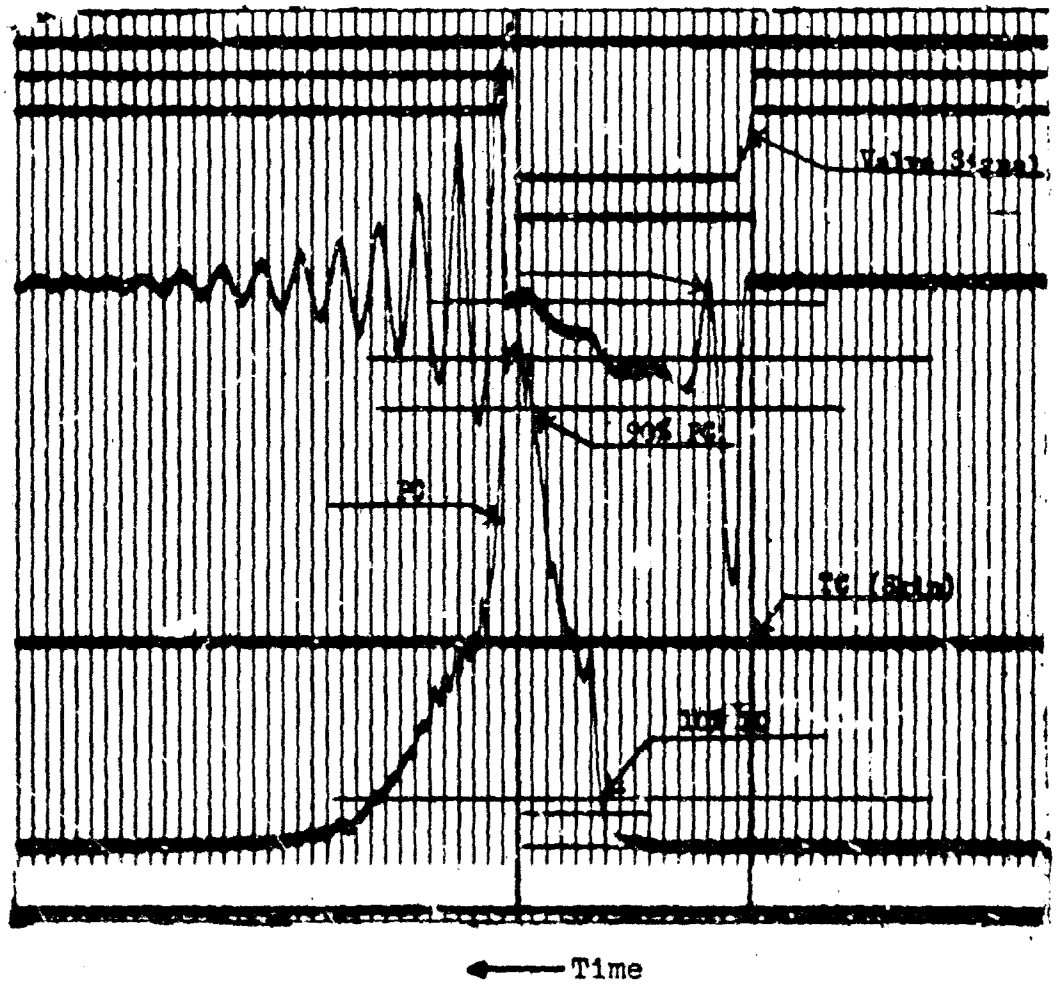


Figure 85

AMBIENT TEMPERATURE TEST
SECOND PULSE WITH 54°F FEED
98.1% H_2O_2 AND 22 POUND THRUST MOTOR S/N 001

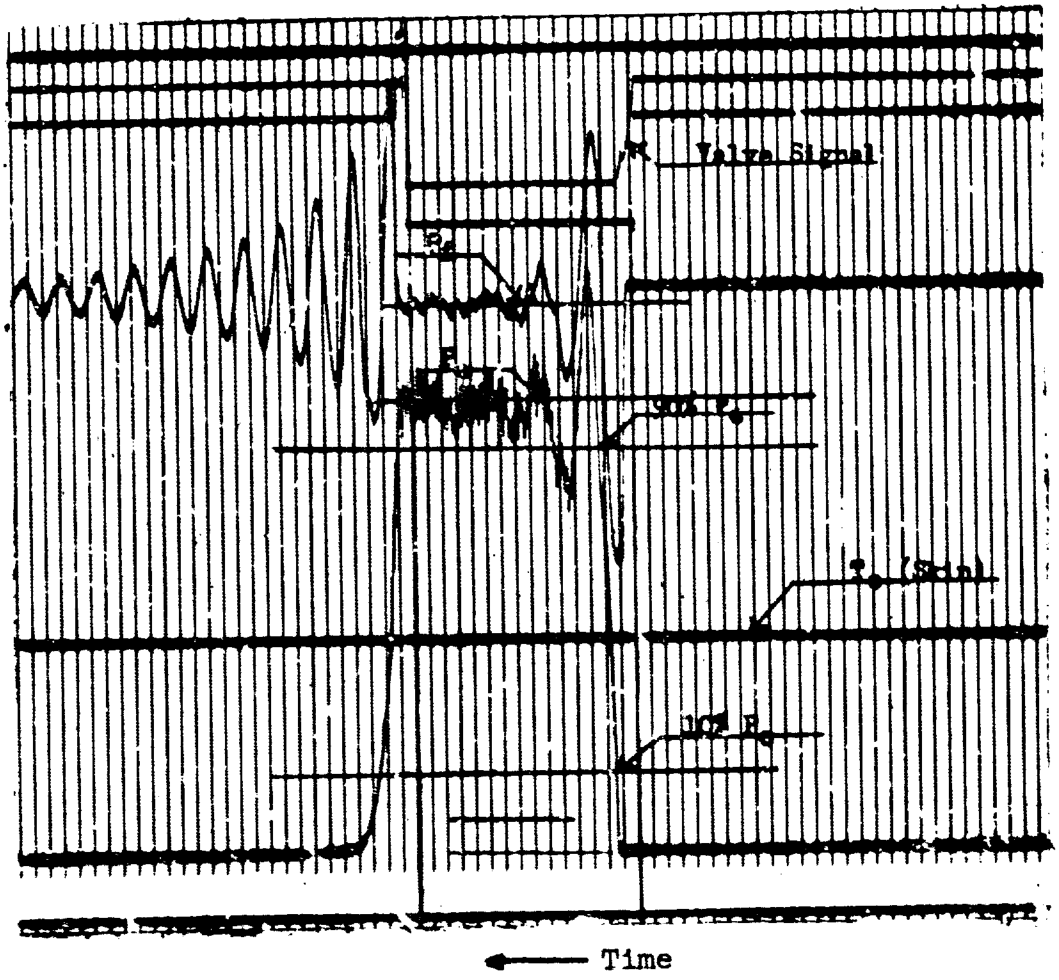


Figure 86

AMBIENT TEMPERATURE TEST
THIRD PULSE WITH 54 °F FEED
98.1% H_2O_2 AND 22 POUND THRUST MOTOR S/N 001

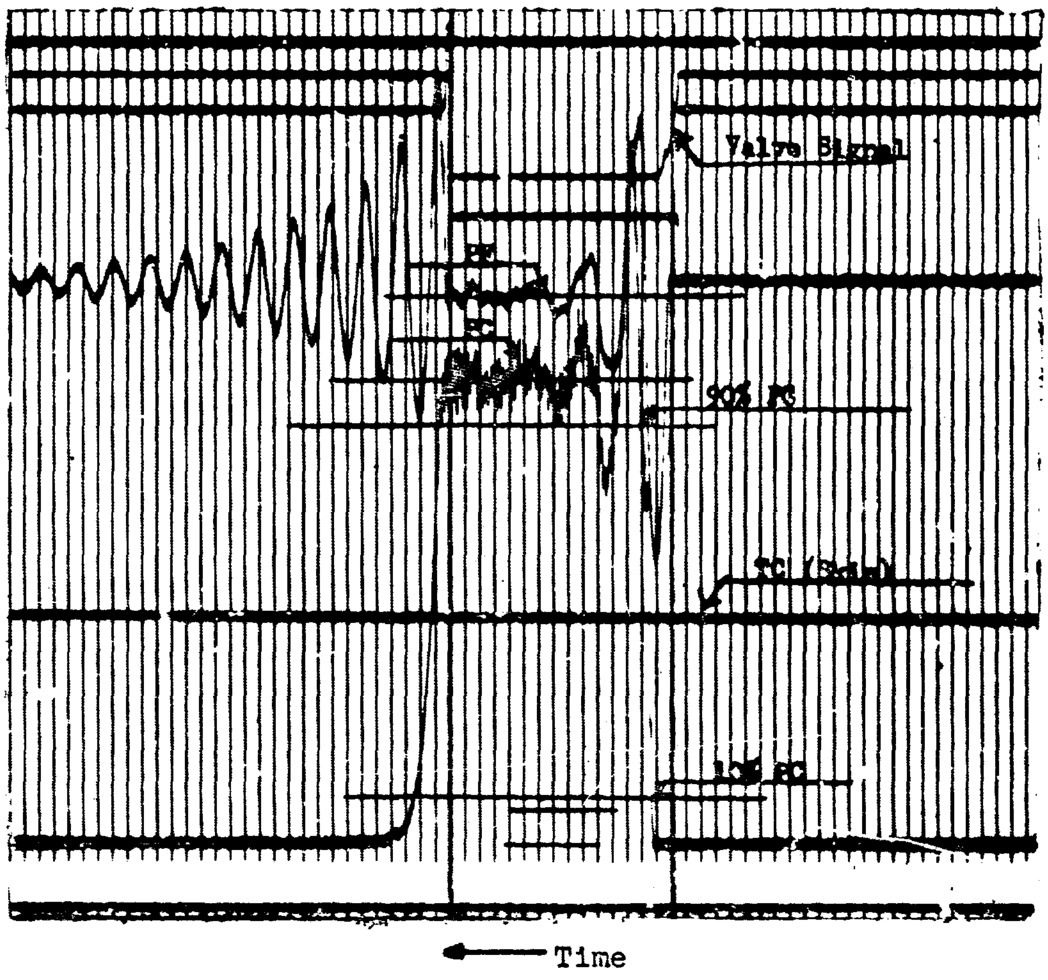


Figure 87

AMBIENT TEMPERATURE TEST
FIRST TWO PULSES OF TEN CYCLE TEST WITH 55°F FEED
98.1% H_2O_2 AND 22 POUND THRUST MOTOR S/N 001

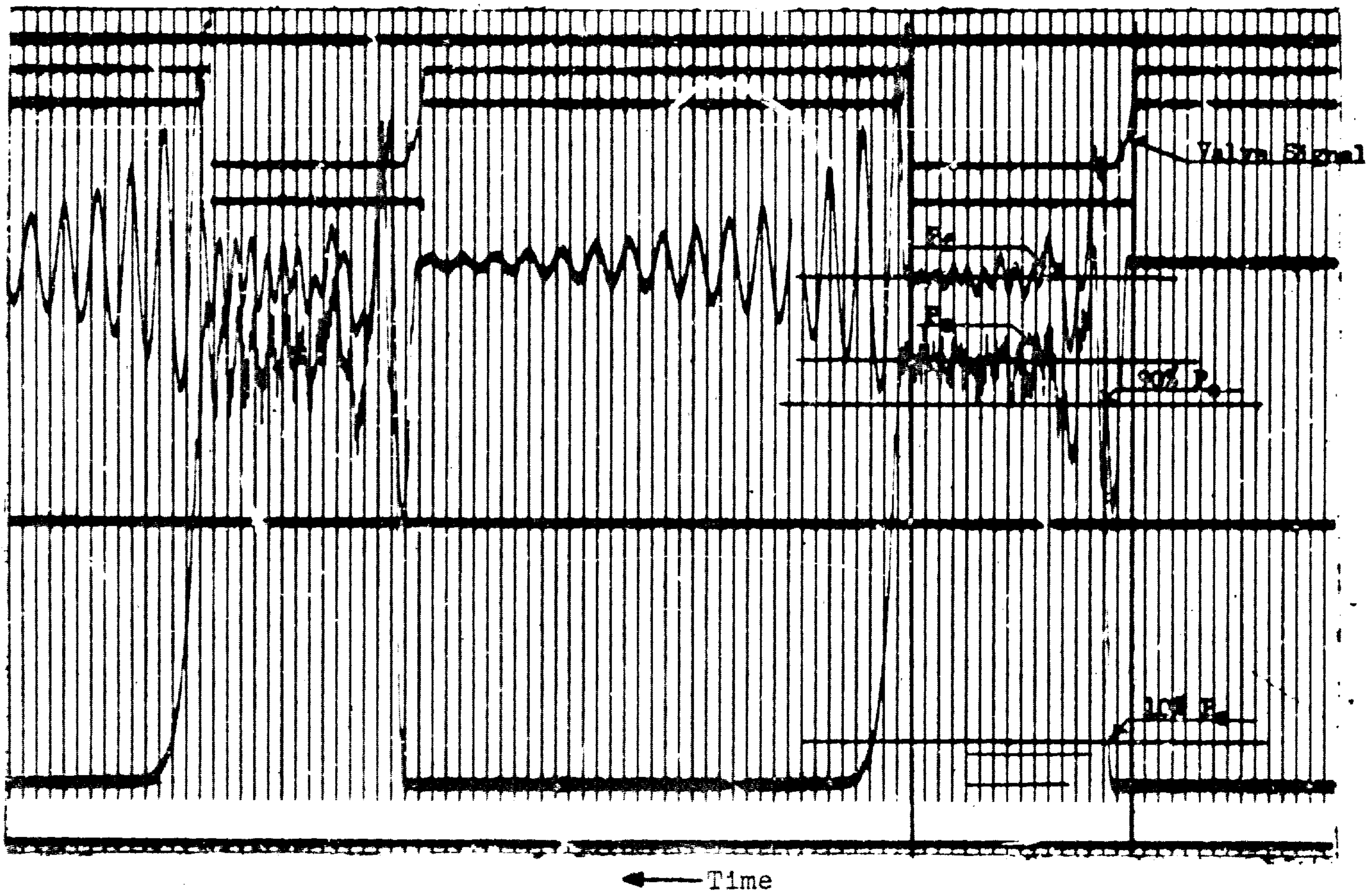


Figure 88

AMBIENT TEMPERATURE TEST
START OF STEADY STATE WITH 57°F FEED
98.1% H_2O_2 AND 22 POUND THRUST MOTOR S/N 001

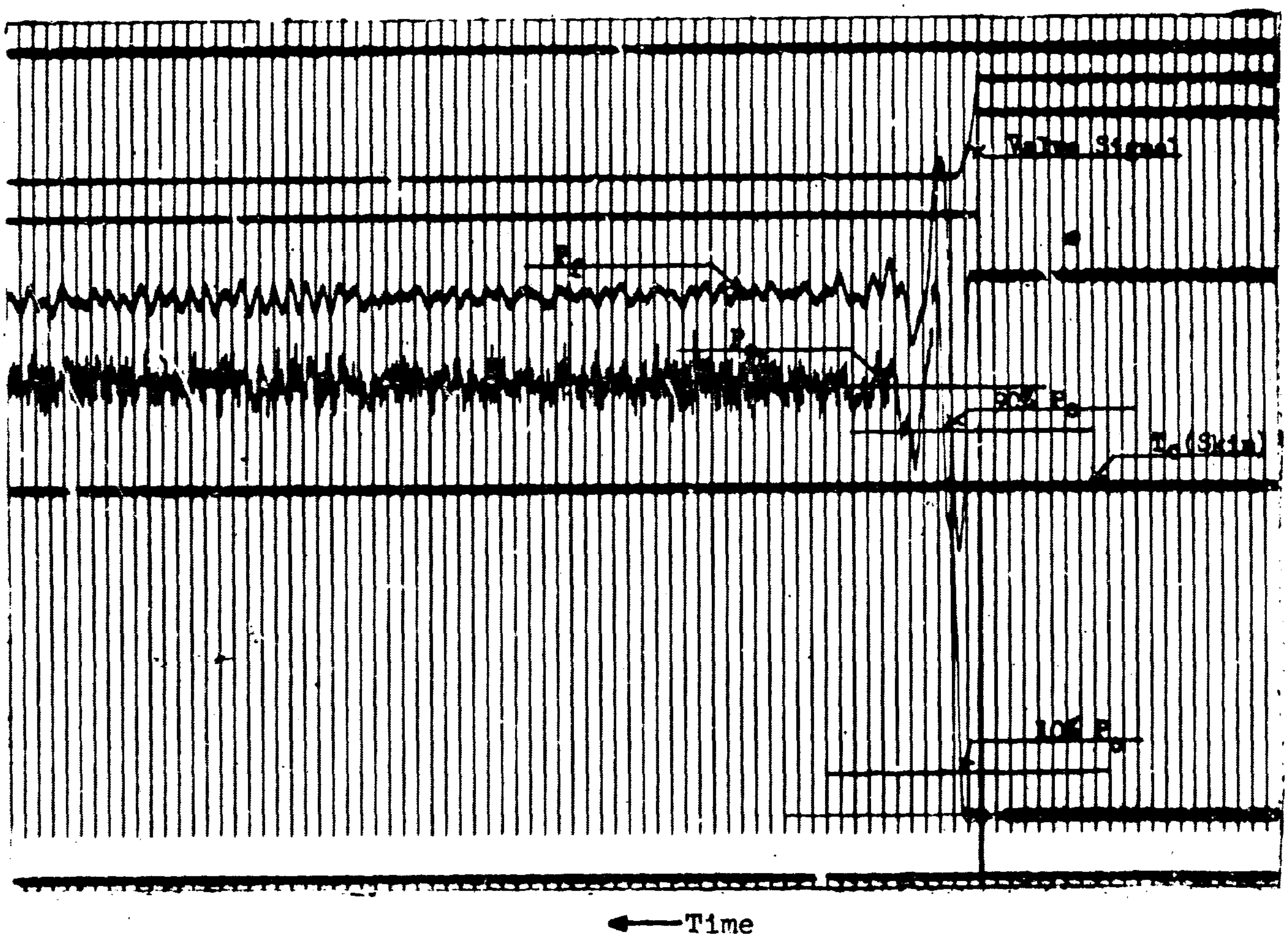


TABLE XXI

AMBIENT CORRELATION TEST PERFORMED AFTER LOW TEMPERATURE TEST WITH MOTOR S/N 001

H_2O_2 Concentration - 98.1%

Throat Diameter - .3025 inches

Test Sequence	Cycle Number	Chamber Pressure (PSIA)	H_2O_2 Feed Pressure (PSIA)	ΔP PSI	Feed H_2O_2 Temp. (°F)	Outer Wall of Chamber (°F)	Transients[a] Response 10%	Transients[a] Response 90%	Transients[a] Decay 90%	Transients[a] Decay 10%
3 Cycle Warm-up	1	287	522	235	54	55	103	149	8	94
	2	268	524	256		90	16	24	9	24
	3	275	526	251		140	16	19	10	25
10 Cycles	1	272	524	252	55	333	16	25	10	29
	3	271	522	251		350	14	19	9	28
	6	271	528	257		400	15	19	7	28
	10	274	522	248		485	14	17	8	26
10 Second Steady-state	Second									
	1	273	520	247	57	575	15	27	---	---
	5	274	520	246		840	---	---	---	---
	10	278	520	242		1020	---	---	10	30
	AVG	275	520	245		---	---	---	---	---

Note; a - Given in msec. for the designated percentages of chamber pressure; valve delay approximately 10 msec.

Tests Conducted by Walter Kidde Co.

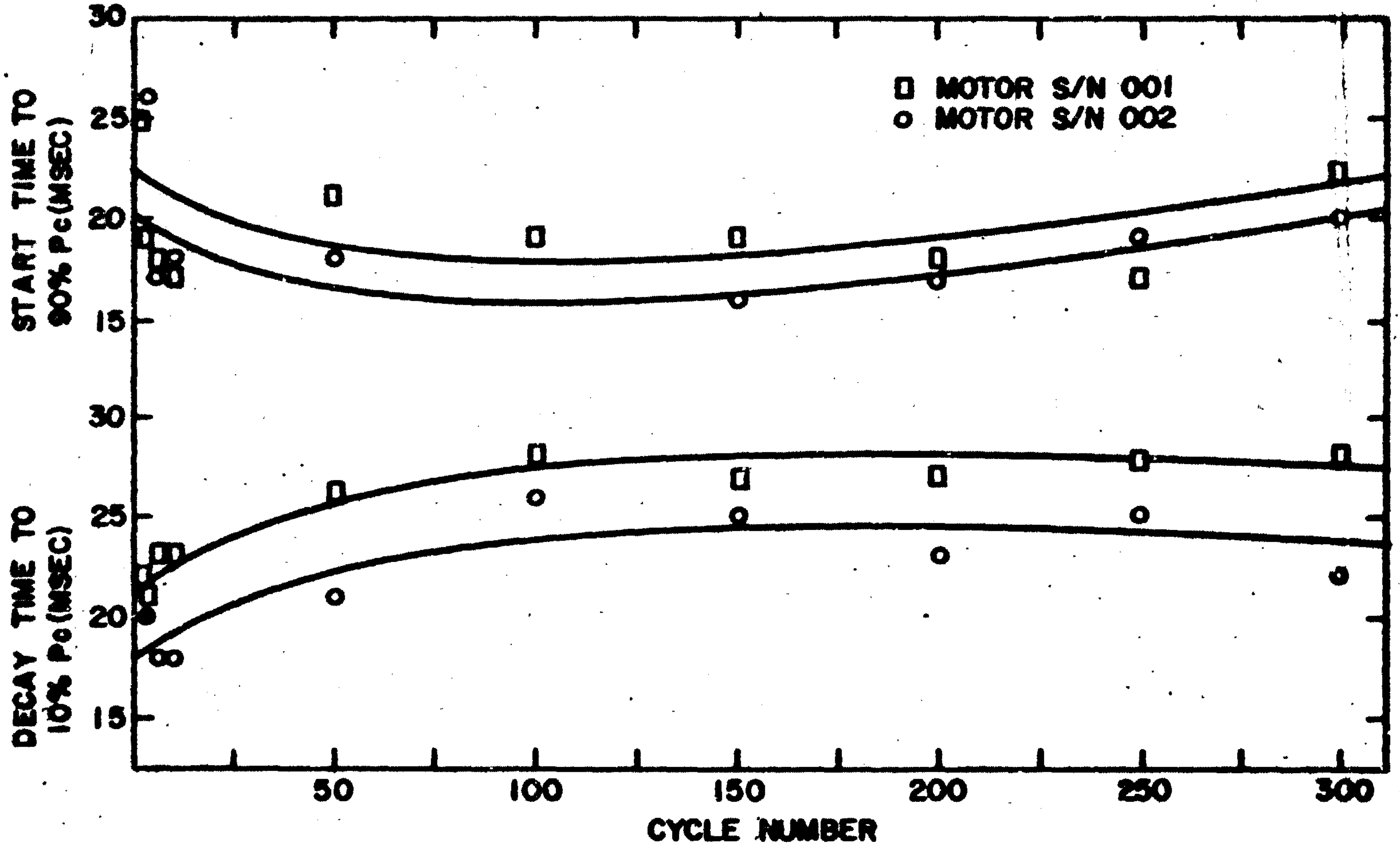
(c) Conclusions

Both preheat motors showed encouraging cold start capability. Figure 89 shows the comparison for the two motors of start and decay transients during the 300 cycle sequence using +30°F 98% H_2O_2 feed. There is good reproducibility in response times between the two motors. A general comparison of results obtained both at ambient and at lower temperatures indicates that there is little difference in starting characteristics with the exception of the first cold pulse. Catalyst packΔP averaged near 200 psi, which can be reduced further by using screens which have increased open area. The pressure drop through motor S/N 001 was somewhat higher than that experienced with motor S/N 002. This was probably due to a slight variation in catalyst packing procedure. On the whole, these tests demonstrate the feasibility of cold starting 98% H_2O_2 motors.

Pressure oscillations were noticable in all the tests with the preheat motors. Previous tests carried out by FMC Corporation and the Walter Kidde Company with the 98% H_2O_2 preheat motors showed minimum pressure oscillations. It was found that smooth motor operation could be obtained with chamber-to-feed system isolation through the use of trim orifices or venturi.

Figure 89

LOW TEMPERATURE TESTS WITH 30°F 98.1% H_2O_2 FEED: START AND DECAY TIMES FOR 300 CYCLE SEQUENCE 22#F MOTOR WITH 10 MSEC VALVE DECAY



SECTION IV

CONCLUSIONS AND RECOMMENDATIONS

The laboratory program showed that the silver and silver-palladium catalysts were the most active. The activity of the silver-palladium catalyst was found to decline upon exposure to high temperatures. However, in actual thrust motor tests, the catalyst effectively decomposed 98% H_2O_2 at high pressures and high pack loadings. Apparently only motor startup was affected by the loss of activity. Additional laboratory studies of the heat deactivation should be concerned with possible complex oxides containing silver which have higher thermal stability than those produced at the surface of the silver-palladium catalyst. Alloys which can form the more stable complex oxides should then be explored.

Although thirty other metals and alloys and eighteen catalyst pellets were studied in the laboratory, further development is required before any of these alternative catalysts could be used in catalyst packs. The best candidates for additional work include oxides of manganese, cobalt, barium, and lead. In particular, the formation of ternary oxides such as those containing manganese and barium should be investigated to determine which phases are catalytically most active and what the temperature range of stability is for each.

The thrust motor and gas generator tests demonstrate good performance for catalyst packs based on the silver-30% palladium catalyst screen. The initial startup response was rapid. The decrease in starting capability found in subsequent starts did not occur for packs which contained silver catalyst screens in the inlet section of the pack. In either case, the packs performed well at high pack loading and chamber pressure.

The initial starting response of the catalyst pack when both it and the 98% H_2O_2 feed were at 30. F was slower than at ambient temperatures. However, additional starts with the 30. F feed and a warm test motor were rapid. This indicates the feasibility of using the pack at low temperature conditions, particularly with programmed starts.

The pressure drop across the catalyst pack was successfully lowered by shortening the pack and using larger open area filler screens in the exhaust section of the pack. It is recommended that larger open area catalyst screens also be tested to achieve further reduction of the pressure drop.

Currently, stabilisers are not added to the commercially produced 98% H_2O_2. However for some applications of the catalyst pack, it may be desirable to use 98% H_2O_2 which has been stabilised by the inclusion of additives. Previous studies have shown that certain stabilisers poison the silver catalyst commonly used with 90% H_2O_2 thus rendering the pack ineffective. These stabilisers may also poison the silver-30% palladium catalyst. Therefore, it is recommended that silver-30% palladium catalyst packs be tested with 98% H_2O_2 feeds to which different known stabilisers have been added.

SECTION V

APPENDIXES

1. INITIAL MOTOR SCREENING TEST DATA

The following tables, XXII through XXXI, give the complete test data on catalyst packs AF-1 through AF-11 tested in the 40 pound thrust motor.

TABLE XXII

98% H_2O_2 INITIAL SCREENING TESTS CATALYST PACK NO. AF-1, THROAT DIAMETER 0.342 in.

Test Date 1966	Test Seq.	Chamber Pres. psia	H_2O_2 Inlet Pres. psia	Cat Pack Δ psi	H_2O_2 Inlet Temp. °F	Thrust 1 Atm. Exh.	ISP Sec.	Meas C*	Start M Sec. 10%/90%	Decay M Sec. 90%/10%	Remarks
	300 Cycles										
4-29	Cycle No 1	265	361	96	75	29.7			54/90	14/54	Exhaust foggy on the first three cycles
	3	307	390	83		34.4			30/55	10/42	
	6	313	398	85		35.8			28/53	6/45	
	10	320	401	91		36.6			26/49	6/41	Exhaust clear during the balance of the 300 cycles
	50	329	407	78		38.0			28/50	7/62	
	100	329	407	78		37.4			25/49	7/66	
	150	329	401	72		37.4			26/50	6/60	
	200	331	404	73		37.4			23/49	10/53	
	250	331	407	76		37.2			27/56	3/60	
	300	327	410	83		36.9			25/50	3/61	
	Average	318	399	81		36.1					
5-2	30 Second Steady State Second No.										
	1	223	297	74	83	25.7	63.0	2293			Exhaust foggy throughout steady state run
	10	240	308	68		28.5			43/85	10/95	
	15	240	308	68		28.8					
	20	242	310	68		29.6					
	25	240	305	65		29.6					
	30	242	313	71		29.9					
	Average	241	309	68		29.3					
5-2	6 Cycles										
	1	N/A	N/A	N/A	82	N/A			N/A	N/A	Raw fuel ejected
	2	199	274	75		23.2			25/59	9/57	Foggy exhaust
	3	270	365	95		31.9			22/47	8/43	Foggy exhaust
	4	299	385	86		35.2			23/45	8/46	Exhaust clear for last three cycles
	5	308	398	90		36.4			20/31	10/48	
	6	311	398	87		37.2			18/28	9/49	
	Average	277	364	87		32.8					
5-2	6 Cycles										
	1	127	183	56	83	13.6			65/140	10/65	Exhaust wet & foggy
	2	243	334	91		29.0			22/43	10/51	Exhaust foggy
	3	294	382	88		34.9			20/41	3/43	Exhaust misty
	4	315	409	94		37.8			19/40	10/51	Exhaust clear on last three cyles
	5	317	415	98		38.1			20/40	4/94	
	6	320	420	100		38.5			20/40	4/48	
	Average	269	332	88		32.0					

N/A - Denotes that motor did not start.

Tests conducted by Walter Kidde Co.

TABLE XXVII

98% H_2O_2 INITIAL SCREENING TESTS CATALYST PACK NO. AP-3, THROAT DIAMETER 0.342 in.

Test Date 1966	Test Seq.	Chamber Pres. psia	H_2O_2 Inlet Pres psia	Cat Pack Δ psi	H_2O_2 Inlet Temp. °F	Thrust 1 Atm. Exh.	ISP Sec.	Meas. C*	Start M Sec. 10%/90%	Decay M Sec. 90%/10%	Remarks
	300 Cycles										
5-11	Cycle No. 1	225	435	210	89.4	23.6			35/74	6/53	
	3	259	463	204	87.8	25.8			14/23	8/53	
	6	272	457	185	87.8	31.2			15/24	10/50	
	10	N/A									
	50	N/A									Severe oscillation therefore reduction of data not possible
	100	N/A									
	150	N/A									
	200	N/A									
	250	N/A									
	300	N/A									
	Average	252	452	200	88.3	26.9					
5-11	30 Second Steady										Max.Chamber Temp. 1700°F
	*State Second No.										
	1	264	463	199	87.8	31.3					
	10	267	452	185	86	33.6					
	15	265	452	187	86	34.4			28/63	8/81	
	20	266	452	186	86	35.6					
	25	266	455	189	86	36.1		3270			Max.Chamber Temp. 1720°F
	30	265	455	190	86	35.8					
	Average	266	453	187	86	35.1					
5-11	6 Cycles										
	1	227	444	217	88	24.1			29/72	9/50	
	2	N/A									
	3	N/A									
	4	N/A									Severe oscillation
	5	N/A									
	6	N/A									Max.Chamber Temp. 1185°F
	Average										
5-11	6 Cycles										
	1	224	427	223	88.5	25.0			40/75	7/55	
	2	N/A									
	3	N/A									
	4	N/A									Severe oscillation
	5	N/A									
	6	N/A									
	Average										Max.Chamber Temp. 1485°F

N/A - no data possible due to severe oscillations. * First reading not included in the average.

Tests conducted by Walter Kidde Co.

TABLE XXIV

98% H_2O_2 INITIAL SCREENING TEST CATALYST PACK NO. AP-4, THROAT DIAMETER 0.342 in.

Test Date 1966	Test Seq.	Chamber Pres. psia	H_2O_2 Inlet Pres. psia	Pack Δ psi	H_2O_2 Inlet Temp. °F	Thrust 1 Atm. Exh.	ISP Sec.	Meas. C*	Start M Sec. 10%/90%	Start M. Sec. 90%/10%	Remarks
	300 Cycles										
5-13	Cycle No. 1	N/A	N/A	N/A	88	N/A					Motor did not fire
	3	204	459	235	86	24.3			21/50	3/41	Wet exhaust
	6	225	452	227	86	N/A			17/32	2/43	Exhaust clear
	10	229	461	232	86	N/A			11/21	10/57	Severe oscillation
	50	242	459	217	86	N/A			11/20	9/53	throughout 300 cycle
	100	N/A									run
	150	N/A									
	200	N/A									
	250	N/A									
	300	N/A									Max Chamber Temp. 1700°F
	Average										
5-13	30 Second Steady										
	*State Second No.										
	1	238	457	219	86	27.6					Misty exhaust
	10	243	457	214		N/A					Severe oscillation
	15	245	457	212		32.2					from 6 sec. on
	20	244	457	213		33.3			30/68	4/69	Max.Chamber Temp. 1700°F
	25	244	457	213		32.6					Exhaust clear after 1st
	30	245	457	212		34.3					1/4 sec. approx
	Average	244	457	213		33.4		3286			
	6 Cycles										
	1	N/A									
	2										
	3										
	4										
	5										
	6										
	Average										
	6 Cycles										
	1	N/A									
	2										
	3										
	4										
	5										
	6										
	Average										

* First reading not included in the average. N/A - no data possible due to severe oscillations or no start.

Tests conducted by Walter Kidde Co.

TABLE XXV

98% H_2O_2 INITIAL SCREENING TESTS CATALYST PACK No. AP-5, THROAT DIAMETER 0.342 in.

Test Date 1966	Test Seq.	Chamber Pres. psia	H_2O_2 Inlet Pres. psia	Cat Pack Δ psi	H_2O_2 Inlet Temp. °F	Thrust 1 Atm. Exh.	ISP Sec.	Meas. C*	Start M Sec. 10%/90%	Decay M Sec. 90%/10%	Remarks
5-25	300 Cycles										
	Cycle No. 1	252	445	193	70	30.6			32/71	8/57	1st cycle exhaust had slight mist
	3	277	478	201	68	34.0			19/28	1/44	
	6	286	467	181	67	35.2			15/24	3/41	
	10	289	473	184	67	35.8			15/22	4/43	
	50	295	475	180	56	37.4			14/22	3/39	
	100	295	473	178	66	37.6			13/23	5/38	Max.Chamber Temp. 1720°F
	150	295	478	183	66	37.4			17/25	7/75	
	200	291	470	179	66	37.3			16/25	6/[illegible]	
	250	289	475	186	64	37.3			13/23	5/42	
	300	286	470	184	63	37.4			14/19	4/40	
	Average	286	470	184	-	36.0					
5-25	30 Second Steady *State Second No.										
	1	293	473	180	67	35.7					Clear exhaust on start
	10	296	464	168	66	36.6					
	15	295	464	169	67	35.7					
	20	296	467	171	67	36.8	134.8	3201			Max. Chamber Temp. 1740°F
	25	295	464	169	67	36.8			30/72	[illegible]/52	
	30	295	461	166	67	36.6					
	Average	295	464	169	-	36.7					
5-25	6 Cycles										
	1	277	465	188	75	33.2			35/8[illegible]	3/77	Exhaust slightly foggy on first cycle
	2	289	468	179	71	34.9			30/73	4/43	
	3	284	473	189	70	34.4			19/25	5/44	
	4	286	479	193	70	34.9			19/25	4/37	
	5	290	479	189	70	35.0			19/25	3/42	
	6	289	476	187	70	35.1			19/25	4/44	
	Average	286	473	187	-	34.6					
5-25	6 Cycles										
	1	275	467	192	75	33.2			28/72	6/70	
	2	290	475	185	71	35.2			22/35	5/40	
	3	283	473	190	73	34.3			19/25	3/37	Max.Chamber Temp. 895°F
	4	287	479	192	72	34.9			18/24	3/37	
	5	286	479	193	71	35.0			18/25	2/45	
	6	289	473	184	70	35.1			17/24	5/42	
	Average	284	474	190		34.6					

* First reading not included in the average.

Tests conducted by Walter Kidde Co.

TABLE XXVI

98% H_2O_2 INITIAL SCREENING TESTS CATALYST PACK NO. AF-6, THROAT DIAMETER 0.339 in.

Test Date 1966	Test Seq.	Chamber Pres. psia	H_2O_2 Inlet Pres. psia	Cat Pack Δ psi	H_2O_2 Inlet Temp. °F	Thrust 1 Atm. Exh.	ISP Sec.	Meas. C*	Start M Sec. 10%/90%	Decay M Sec. 90%/10%	Remarks
5-26	300 Cycles										
	Cycle No. 1	252	464	212	75	28.4			31/74	8/98	1st cycle slight fog in exhaust
	3	258	467	209	75	30.7			18/26	5/45	
	6	268	472	204	75	31.5			20/25	4/41	
	10	274	472	198	75	32.6			17/23	4/43	
	50	277	472	195	75	33.6			17/22	4/41	
	100	277	469	192	75	33.5			15/26	4/37	
	150	275	469	194	75	33.9			14/20	4/35	
	200	277	469	192	74	33.8			14/20	5/39	
	250	275	472	197	74	33.5			14/21	4/38	
	300	275	469	194	74	33.6			14/22	4/36	
	Average	271	470	199	75	32.5			14/22	4/36	
5-26	30 Second Steady State Second No.										
	1	282	480	198	74	32.9					
	10	290	477	187	75	34.8					Clear exhaust at start
	15	288	475	187	75	34.7					
	20	290	475	185	75	34.9					
	25	290	477	187	75	35.3					
	30	290	477	187	75	35.5					
5-26	Average	290	476	186	75	35.0	140.3	332C	37/74	5/70	
	6 Cycles										
	1	254	474	220	74	28.8			39/78	5/94	Slight mist in exhaus on first cycle
	2	269	471	202	74	30.4			23/48	3/59	
	3	266	477	211	74	30.2			19/28	4/53	
	4	265	471	206	74	30.3			14/22	7/49	
	5	266	474	206	74	30.6			18/26	4/41	
	6	268	474	206	74	31.1			14/22	8/30	
	Average	265	474	209	74	30.2					
5-26	6 Cycles										
	1	249	461	212	74	27.7			35/73	4/80	1st cycle slight fog
	2	261	461	200	74	29.8			22/44	3/59	
	3	260	469	209	74	29.8			21/25	7/50	
	4	261	471	200	74	30.2			19/24	4/38	
	5	266	471	205	74	30.6			18/21	7/40	
	6	268	471	203	74	30.9			17/20	5/38	
	Average	261	467	206	74	29.8					

Total Run Time - 78.6 sec.

Test Conducted by Walter Kidde Co.

TABLE XXVII

98% H_2O_2 INITIAL SCREENING TESTS CATALYST PACK NO. AF-7, THROAT DIAMETER 0.339 in.

Test Date 1966	Test Seq.	Chamber Pres. psia	H_2O_2 Inlet Pres. psia	Cat Pack Δ psi	H_2O_2 Inlet Temp. °F	Thrust 1 Atm. Exh.	ISP Sec.	Meas. C*	Start M Sec. 10%/90%	Decay M Sec. 90%/10%	Remarks
	300 Cycles										
	Cycle No. 1	265	N/A	N/A	89.0	30.6			39/53	6/61	1st cycle slight
	3	279	N/A	N/A	90.0	32.6			18/40	5/42	Fog in exhaust
	6	285	N/A	N/A	92.0	33.9			16/35	7/23	
	10	289	N/A	N/A	92.5	34.7			15/33	6/30	
	50	299	N/A	N/A	93.5	35.6			18/21	6/32	
	100	296	477	181	94.0	35.5			15/27	5/40	
	150	288	477	189	93.5	34.8			15/22	5/29	Max.Chamber Temp. 1580°F
	200	285	477	192	93.5	34.4			13/20	6/33	
	250	280	480	200	93.5	43.9			13/21	4/39	
	300	279	489	210	93.0	34.3			13/21	4/40	
	Average	285	480	195	92.5	34.0					
	30 Second Steady State Second No.										
	1	298	483	185	92.4	34.2					Slight mist on start
	10	304	475	171		36.2					exhaust
	15	304	475	171		36.2					
	20	302	472	170		36.4	136.3	3280	39/76	51/65	Max.Chamber Temp. 1640°F
	25	302	472	170		36.6					
	30	301	475	174		36.6					
	Average	305	474	171		36.4					
	6 Cycles										
	1	276	480	204	95	31.5			36/78	6/83	1st cycle slight
	2	277	472	195		32.1			21/42	6/50	Mist in exhaust
	3	280	483	203		32.1			16/23	5/46	
	4	280	486	206		32.6			15/21	8/52	
	5	279	494	215		32.8			15/19	5/39	
	6	282	492	210		32.6			16/22	4/40	
	Average	279	485	206		32.3					
	6 Cycles										
	1	274	475	201	71	31.3			38/77	9/76	1st cycle slight
	2	279	475	196		32.6			21/44	8/50	Fog in exhaust
	3	280	480	200		32.9			19/33	7/44	
	4	280	486	206		32.9			18/26	5/45	Max.Chamber Temp.1200°F
	5	282	492	210		33.0			17/25	5/49	
	6	283	489	206		33.0			15/24	6/42	
	Average	280	483	203		32.6					

Tests conducted by Walter Kidde Co.

TABLE XXV.II

98% H_2O_2 INITIAL SCREENING TESTS, CATALYST PACK NO. AF-8, THROAT DIAMETER 0.338 in.

Test Date 1966	Test. Seq.	Chamber Pres. psia	H_2O_2 Inlet Pres. psia	Cat. Pack Δ psi	H_2O_2 Inlet Temp. °F	Thrust 1 Atm. Exhaust lbs.	ISP sec.	Meas. C*	Start M Sec. 10%/90%	Decay M Sec. 90%/10%	Remarks
6-16	300 Cycles										
	Cycle No. 1	289	457	168	*	33.2			38/84	7/77	First two cycles good. Third cycle began oscillations.
	3	287	458	171		32.7			21/31	6 57	
	6	290	457	167		32.7			22/31	7/56	
	10	297	451	160		32.7			18/26	5/62	
	50	302	466	164		33.0			19/27	8/47	
	100	298	458	160		33.7			20/25	7/41	
	150	295	462	167		33.5			17/21	6/46	
	200	295	457	162		33.0			15/23	7/50	
	250	292	458	166		33.5			18/25	4/45	
	300	295	457	162		33.4			17/26	7/53	Max. chamber temp. 1535°F.
	Average	294	459	165		33.1					
6-16	30 Second Steady State										
	Second No.1	317	478	161		33.7					No oscillations
	10	319	474	155		34.5					
	15	317	474	157		34.5					
	20	321	474	153		34.7					
	24	319	471	152		34.7					
	27	319	474	155		34.8					
	Average	319	473	154		34.6	129.62	3450	35/77	*/*	Max. chamber temp. 1550°F.
6-16	6 Cycles										
	1	297	456	159		35.0			62/103	7/59	First cycle had slow start. Oscillations in 3rd-6th cycles.
	2	300	474	174		35.6			20/30	6/51	
	3	297	485	188		36.7			20/29	5/43	
	4	294	485	191		35.1			19/30	6/52	
	5	297	482	185		35.1			18/26	6/50	
	6	299	489	190		35.5			19/27	6/53	Max. chamber temp. 1370°F.
	Average	297	479	182		35.5					
6-16	6 Cycles										
	1	311	471	160		36.0			58/168	5/49	First cycle foggy and had slow start.
	2	296	478	182		35.6			14/22	7/50	
	3	302	486	184		35.6			12/21	5/51	3rd-6th cycles clear with slight oscillations
	4	299	485	186		35.5			18/26	4/50	
	5	299	485	186		36.0			19/27	5/51	
	6	302	485	183		36.0			18/26	6/48	Max. chamber temp. 1370°F.
	Average	302	482	180		35.8					

Notes: H_2O_2 flow = .267 lbs/sec.
Pack loading = 20.4 PSIM (lbs. H_2O_2/inch² of catalyst frontal area/min).

* - Not recorded due to technical difficulties.

Tests conducted by Walter Kidde Co.

TABLE XXIX

98% H_2O_2 INITIAL SCREENING TESTS, CATALYST PACK NO. AP-9, THROAT DIAMETER 0.338 in.

Test Date 1966	Test Seq.	Chamber Pres. psia	H_2O_2 Inlet Pres. psia	Cat. Pack Δ psi	H_2O_2 Inlet Temp. °F	Thrust 1 Atm. Exhaust lbs.	ISP Sec.	Meas. C*	Start M Sec. 10%/90%	Decay M Sec. 90%/10%	Remarks
5-17	300 Cycles										
	Cycle No. 1	295	478	183	77	33.3			38/78	5/67	First two cycles good.
	3	292	482	190	77	32.7			23/32	8/70	Third cycle began severe oscillations.
	6	315	486	171	77	33.9			21/27	4/53	7th-8th cycles less oscillations.
	10	322	476	154	77	34.0			21/27	3/51	Severe oscillations remaining cycles.
	50	323	506	183	77	33.7			20/25	6/41	
	100	315	506	191	76	34.9			18/23	7/48	Max. chamber temp. 1735°F.
	150	315	513	198	76	34.3			16/23	7/42	
	200	325	517	192	76	33.7			17/23	7/32	
	250	317	512	195	76	33.5			16/25	6/44	
	300	310	515	205	76	33.8			14/23	3/40	
	Average	313	499	186	77	33.8					
6-17	30 Second Steady State										
	Second No.1	300	461	161	77	33.6					Oscillations began at 3 sec, increased to 20 sec.
	10	302	452	150	77	32.5					
	15	302	452	150	77	33.4					Oscillations severe last 10 sec.
	20	300	452	152	77	33.0					
	25	294	450	156	77	31.8					Max. chamber temp. 1735°F.
	30	298	445	147	77	31.4					
	Average	299	450	151	77	32.4	124.26	3315	42/85	3/120	
6-17	6 Cycles										
	1	296	470	174	77	33.0			39/106	7/74	First two cycles good.
	2	300	469	169	77	33.0			19/29	6/46	3rd-6th cycles severe oscillations.
	3	295	474	179	77	32.6			18/27	3/43	
	4	298	474	176	77	32.8			19/28	7/46	Max. chamber temp. 1420°F.
	5	296	474	178	77	32.6			18/26	4/49	
	6	296	472	176	77	32.6			19/26	4/48	
	Average	297	472	175	77	32.8					
6-17	6 Cycles										
	1	293	469	166	75	33.0			49/88	7/56	All cycles good.
	2	300	467	167	75	33.3			21/29	4/49	
	3	298	470	172	75	33.0			19/29	7/46	Max. chamber temp. 1455°F.
	4	300	472	172	75	33.0			20/27	6/51	
	5	300	470	170	75	33.4			20/28	9/58	
	6	300	474	174	75	33.2			19/27	8/51	
	Average	299	470	171	75	33.2					

Notes: H_2O_2 flow = .261 lbs/min.
Pack loading = 19.9 PSIM (lbs. H_2O_2/inch^2 of catalyst frontal area/min).

Tests conducted by Walter Kidde Co.

TABLE XXX

98% H_2O_2 INITIAL SCREENING TESTS CATALYST PACK NO. AF-10 THROAT DIAMETER .339 in.

Test Date 1966	Test Seq.	Chamber Pres. psia	H_2O_2 Inlet Pressure psia	Cat Pack Δ psi	H_2O_2 Inlet Temp. °F	Thrust 1 ATM. Exhaust lbs. F Experimental	ISP sec.	Measured C*	Start M. sec. 10%/90%	Decay M. Sec. 90%/10%	Remarks
	300 Cycles										
10-11	Cycle No. 1	222	413	191	70°	27.4			29/81	7/52	Slight mist
	3	254	427	173		30.2			29/51	7/53	on start up
	6	255	N/A	N/A		30.4			25/46	0/53	
	10	274	N/A	N/A		32.0			21/71	6/50	Oscillation
	50	290	449	159		33.4			18/40	3/31	present
	100	286	447	161		33.0			14/24	6/31	
	150	283	446	163		32.7			14/32	2/32	
	200	279	443	164		32.5			21/30	3/36	
	250	280	443	163		32.5			21/30	4/39	
	300	277	439	162		32.3			16/25	7/45	
	Average	270	440	170							
10-11	30 Second Steady State										
	Second No. 1*	270	444	174	70	31.6	127.02	3205	37/80		Motor started
	10	293	467	174		33.6					to oscillate
	15	292	461	169		33.5					after .5 sec.
	20	291	461	170		33.5					and stopped
	25	293	466	173		33.6					oscillating
	30	293	464	171		33.6				4/58	at 10 sec.
	Average	292	464	172		33.5					
10-11	6 Cycles										
	1	256	460	204	70	30.5			41/57	7/47	Oscillation in
	2	274	478	204		32.0			22/30	6/45	3rd to 6th
	3	278	479	200		32.4			21/32	4/50	cycles
	4	278	475	197		32.4			23/33	1/64	
	5	282	472	190		32.6			20/33	2/68	
	6	284	473	189		32.9			20/30	2/78	
	Average	275	473	198		32.2					
10-11	6 Cycles										
	1	255	460	205	70	30.3			39/77	6/63	Oscillation in
	2	274	470	196		32.0			34/51	5/50	3rd to 6th
	3	283	472	189		32.7			21/45	10/60	cycles
	4	280	463	183		32.5			21/45	7/78	
	5	280	469	139		32.5			24/45	2/75	
	6	283	471	183		32.7			20/33	5/77	
	Average	276	468	192		32.3					

Notes: H_2O_2 flow = .2637 lb./sec.
Pack loading = 20.4 PSIM (lbs. H_2O_2/inch^2 of catalyst frontal area/min.)

*Not in Average
NA - Not available due to severe oscillation

Tests conducted by Walter Kidde Co.

TABLE XXXI

98% H_2O_2 INITIAL SCREENING TESTS, CATALYST PACK NO. AF-11 THROAT DIAMETER .339 in.

Test Date 1966	Test Seq.	Chamber Pres. psia	H_2O_2 Inlet Pres. psia	Cat. Pack Δ psi	H_2O_2 Cham. Temp. °F	Thrust 1 ATM. Exhaust lbs. F	ISP sec.	Measured C*	Start M Sec. 10%/90%	Decay M Sec. 90%/10%	Remarks
	300 Cycles										
11-23	Cycle No. 1	30.3	60.2	29.9	150	N/A			72/165	20/39	First 10 ~ foggy
	3	111	167	56	360	N/A			32/53	13/88	
	6	237	320	83	440	28.5			28/54	10/68	Then motor cleared
	10	308	407	99	1520	35.0			22/33	13/64	and performed well
	50	333	445	112	1730	36.8			27/35	6/58	
	100	330	445	115	1745	36.6			23/32	8/51	
	150	328	448	120	1750	36.5			22/29	8/54	
	200	328	449	121	1750	36.5			19/29	11/52	Motor stable
	250	328	449	121	1760	36.5			19/21	6/51	
	300	328	449	121	1755	36.5			22/32	9/50	
	Average	266	364	98							
11-23	30 Second Steady State										Steady state had to be pulsed 2 times times, 150m sec. x 350m sec. in order to start, therefore, H_2O_2 flow slightly in error
	Second No. 1*	313	439	126	1655	35.3			26/62		
	10	326	436	110	1738	36.3					
	15	327	439	112	1750	36.4					
	20	328	439	111	1750	36.5					
	25	330	440	110	1750	36.6					
	30	331	439	108	1750	36.7				9/60	
	Average	328	439	111		36.5	123.0	3212			
11-23	6 Cycles										
	1	128	209	81	320	N/A			47/152	10/74	All pulses foggy
	2	182	276	94	400	N/A			24/56	10/80	
	3	221	315	94	460	26.8			21/43	12/70	
	4	269	373	107	765	32.1			21/50	12/60	Motor stable
	5	296	404	108	1270	33.8			19/42	15/48	
	6	314	433	119	1440	35.4			20/30	15/58	
	Average	235	335	100							
11-23	6 Cycles										
	1	60.8	120	59.2	210	N/A			75/184	4/74	All pulses foggy
	2	133	223	90	390	N/A			30/90	10/64	
	3	168	260	92	412	N/A			24/45	8/62	
	4	209	306	97	453	N/A			21/42	15/60	Motor stable
	5	258	360	102	700	30.5			19/43	9/59	
	6	273	395	122	1225	32.0			21/37	16/38	
	Average	184	277			N/A					

Notes: H_2O_2 flow = .2968 lbs./sec.
Pack loading = 22.7 PSIM (lbs. H_2O_2/inch^2 of catalyst frontal area/min.)

*Not included in Average

Tests conduced by Walter Kidde Co.

2. HIGH PRESSURE-HIGH PACK LOADING TEST DATA

The complete test data for catalyst packs AF-A1 through AF-A10 tested in the 3/4" diameter test chamber appear in the following tables, XXXII through LIII.

TABLE XXXII

HIGH PRESSURE-HIGH BED LOADING TEST NO. 1 OF CATALYST PACK AF-A2 WITH 97.6% H_2O_2 (10/14/66)

Chamber Characteristics	Pack Configuration	Packing Conditions
Exhaust orifice: 0.253" diam. Inlet orifice type C (13 holes 3/64" diam.) Internal diameter: 3/4"	8 Silver 40 mesh screens 7 Silver 20 mesh screens 73 Silver-30% palladium 20 mesh screens	Pack length: 1 1/2" Pack inlet located 2 1/16" upstream from retainer seat Pack compression: 4300 psi

Time (Sec)	5	10	15	20	25	30	35	40	45	50
Chamber Pressure (psia) Pc1	N/A	N/A	N/A	841	891	883	860	845	814	772
Pc2	N/A	N/A	N/A	902	890	877	856	834	834	796
Inlet Pressure (psia)	N/A	N/A	N/A	1681	1765	1792	1799	1813	1834	1841
ΔP Catalyst Bed (psi)	N/A	N/A	N/A	809	874	912	941	973	1010	957
H_2O_2 Inlet Temp. (°F)	64									
Cat. Bed Temp. T_2 (°F) 1/16" from inlet	1140	1105	1100	1109	1100	1100	1100	1100	1100	1105
Cat. Bed Temp. T_3 (°F) 1/2" from inlet	1580	1600	1605	1640	1660	1675	1680	1680	1680	1682
Cat. Bed Temp. T_4 (°F) 7/8" from inlet	1538	--	--	1738	--	--	1770	--	--	--
Cat. Bed Temp. T_5 (°F) 1 3/16" from inlet	510	--	458	--	--	1560	--	--	1582	--
Exhaust Temp. T_7 (°F) 2 1/4" from inlet	N/A Malfunction									
Propellant Flow (lb/sec)	N/A	N/A	N/A	0.476	0.476	0.465	0.450	0.450	0.450	0.450
C* Measured (ft/sec)	N/A	N/A	N/A	2965.3	3030.0	3063.4	3086.2	3021.6	2964.0	2820.2
C* Theoretical (ft/sec)	3325									
Per cent C* obtained				89.2	91.1	92.1	92.8	90.9	89.1	84.8

N/A - Not available due to severe oscillation.

Tests conducted by Walter Kidde Company.

TABLE XXXIII

HIGH PRESSURE-HIGH BED LOADING TEST NO. 1 OF CATALYST PACK AF-A3 WITH 97.5% H_2O_2 (10/17/66)

Chamber Characteristics

Exhaust orifice: 0.253" diam.
Inlet orifice type B (11 holes 3/64" diam)
Internal diameter: 3/4"

Pack Configuration

8 Silver 40 mesh screens
7 Silver 20 mesh screens
52 Silver-30% palladium 20 mesh screens
21 Nickel-5% manganese 14 mesh screens

Packing Conditions

Pack length: 1 3/8"
Pack inlet located 1 3/4" upstream from retainer seat
Pack compression: 4300 psi

Time (Sec)		5	10	15	20	25	30	35	40	45	50
Chamber Pressure (psia)	P_{c1}	N/A	N/A	N/A	1148	1204	1234	1249	1249	1245	1241
	P_{c2}	N/A	N/A	N/A	1153	1203	1241	1253	1245	1245	1237
Inlet Pressure (psia)		N/A	N/A	N/A	1674	1762	1831	1858	1858	1858	1844
ΔP Catalyst Bed (psi)		N/A	N/A	N/A	523	558	593	607	611	613	605
H_2O_2 Inlet Temp. (°F)		62									
Cat. Bed Temp. T_3 (°F) 5/16" from inlet		280	1340	1450	1220	1215	1100	1085	990	950	920
Cat. Bed Temp. T_4 (°F) 3/4" from inlet		1400	--	1600	--	--	--	1700	--	--	1725
Cat. Bed Temp. T_5 (°F) 1 3/32" from inlet		--	--	1540	--	--	1630	--	--	1750	--
Exhaust Temp. T_7 (°F) 1-15/16" from inlet		--	1020	--	--	1620	--	--	--	1760	--
Propellant Flow (lb/sec)		0.265	0.285	0.502	0.570	0.612	0.638	0.638	0.667	0.650	0.638
C* Measured (ft/sec)		N/A	N/A	N/A	3268.6	3184.5	3140.9	3174.0	3026.2	3100.5	3143.6
C* Theoretical (ft/sec)		3322									
Per cent C* obtained					98.4	95.9	94.5	95.5	91.1	93.3	94.6

N/A - Not available due to severe oscillation.

Tests conducted by Walter Kidde Company.

TABLE XXXIV

HIGH PRESSURE-HIGH BED LOADING TEST NO. 2 OF CATALYST PACK AP-A3 WITH 97.5% H_2O_2 (10/18/56)

Chamber Characteristics

Exhaust orifice: 0.253" diam.
Inlet orifice type B (11 holes 3/64" diam.)
Internal diameter: 3/4"

Pack Configuration

17 Silver 20 mesh screens
52 Silver-30% palladium 20 mesh screens
21 Nickel-5% manganese 14 mesh screens

Packing Conditions

Pack length: 1 3/8"
Pack inlet located 1 3/4" upstream from retainer seat
Pack compression: Pack AP-A3(1) recompressed to 2000 psi

Time (Sec)	5	10	15	20	25	30	35	40	45
Chamber Pressure (psia) Pc1	420	659	856	1008	1131	1208	1240	1251	1243
Pc2	419	654	843	1000	1115	1189	1240	1239	1240
Inlet Pressure (psia)	641	982	1201	1480	1663	1778	1845	1857	1857
ΔP Catalyst Bed (psi)	221	325	411	476	540	579	605	612	615
H_2O_2 Inlet Temp. (°F)	56°								
Cat. Bed Temp. T_3 (°F) 5/16" from inlet	1400	1260	910	660	620	595	570	558	570
Cat. Bed Temp. T_4 (°F) 3/4" from inlet	1550	--	--	--	1620	--	--	--	1045
Cat. Bed Temp. T_5 (°F) 1 3/32" from inlet	--	1580	--	1640	--	--	1497	--	--
Exhaust Temp. T_7 (°F) 1 15/16" from inlet	--	--	1785	--	--	1795	--	--	1320
Propellant Flow (lb/sec)	0.252	0.354	0.462	0.490	0.544	0.633	0.655	0.655	0.667
C* Measured (ft/sec)	2696	3004	2978	3317	3342	3066	3065	3077	3014
C* Theoretical (ft/sec)	3307								
Per cent C* obtained	81.5%	90.8%	90.1%	100%	101%	92.7%	92.7%	93%	91.1%

Tests conducted by Walter Kidde Company

TABLE XXXV

HIGH PRESSURE-HIGH BED LOADING TEST NO. 1 OF CATALYST PACK AP-A4 WITH 97.5% H_2O_2 (10/17/66)

Chamber Characteristics

Exhaust orifice: 0.253" diam.
Inlet orifice type B (11 holes 3/64" diam.)
Internal diameter: 3/4"

Pack Configuration

17 Silver 20 mesh screens
38 Silver-30% palladium 20 mesh screens
38 Nickel-5% manganese 14 mesh screens

Packing Conditions

Pack length: 1 3/8"
Pack inlet located 1 3/4" upstream from retainer seat
Pack compression: 4300 psi

Time (Sec)	5	10	15	20	25	30	35	40	
Chamber Pressure (psia) Pc1	N/A	733	977	1197	1285	1349	1376	1380	
Pc2	N/A	745	992	1169	1289	1351	1379	1388	
Inlet Pressure (psia)	N/A	1014	1343	1587	1752	1843	1880	1886	
ΔP Catalyst Bed (psi)	N/A	275	358	404	465	493	502	502	
H_2O_2 Inlet Temp. (°F)	61°								
Cat. Bed Temp. T_5 (°F) 5/16" from inlet	480	490	500	520	525	565	515	580	
Cat. Bed Temp. T_6 (°F) 3/4" from inlet	--	--	1520	--	--	--	1700	--	1680
Cat. Bed Temp. T_8 (°F) 1 1/16" from inlet	--	1638	--	--	1745	--	--	--	1745
Exhaust Temp. T_7 (°F) 1 15/16" from inlet	1778	--	--	1838	--	--	1845	--	
Propellant Flow (lb/sec)	N/A	0.350	0.490	0.560	0.645	0.678	0.698	0.703	
C* Measured (ft/sec)		3418	3254	3420	3230	3223	3196	3187	
C* Theoretical (ft/sec)	3320								
Per cent C* obtained		103%	98%	103%	97.3%	97.1%	96.8%	96%	

N/A - Not available due to oscillation.

Tests conducted by Walter Kidde Company

TABLE XXXVI

HIGH PRESSURE-HIGH BED LOADING TEST NO. 2 OF CATALYST PACK AP-A4 WITH 97.6% H_2O_2 (10/25/66)

Chamber Characteristics

Exhaust orifice: 0.253" diam.
Inlet orifice type B (11 holes 3/64" diam.)
Internal diameter: 3/4"

Pack Configuration

17 Silver 20 mesh screens
38 Silver-30% palladium 20 mesh screens
38 Nickel-5% manganese 14 mesh screens

Packing Conditions

Pack length: 1 3/8"
Pack inlet located 1 3/4" upstream from retainer seat
Pack compression: Not recompressed

Time (Sec)		10	20	30	40
Chamber Pressure (psia)	Pc1	698	1141	1320	1350
	Pc2	688	1133	1308	1349
Inlet Pressure (psia)		995	1582	1818	1872
ΔP Catalyst Bed (psi)		302	445	504	523
H_2O_2 Inlet Temp. (°F)		65°			
Propellant Flow (lb/sec)		0.374	0.596	0.689	0.719
C* Measured (ft/sec)		3000	3088	3087	3039
C* Theoretical (ft/sec)		3326			
Per cent C* obtained		90.2%	92.8%	92.8%	91.4%

Tests conducted by Walter Kidde Company

TABLE XXXVII

HIGH PRESSURE-HIGH BED LOADING TEST NO. 3 OF CATALYST PACK AF-A4 WITH 97.6% H_2O_2 (10/28/66)

Chamber Characteristics	Pack Configuration	Packing Conditions
Exhaust orifice: 0.138" diam. Inlet orifice type D (10 holes 3/64" diam.) Internal diameter: 3/4"	17 Silver 20 mesh screens 38 Silver-30% palladium 20 mesh screens 38 Nickel-5% manganese 14 mesh screens	Pack length: 1 3/8" Pack inlet located 1 3/4" upstream from retainer seat Pack compression: Not recompressed

Time (Sec)		15	25	35	40
Chamber Pressure (psia)	Pc1	763	1420	N/A	N/A
	Pc2	754	1393	1756	1813
Inlet Pressure (psia)		809	1442	1824	1895
ΔP Catalyst Bed (psi)		50	35	68	82
H_2O_2 Inlet Temp. (°F)		56.5	66.5	69.5	69.5
Propellant Flow (lb/sec)		0.115	0.215	0.257	0.257
C* Measured (ft/sec)		3179	3152	3291	3398
C* Theoretical (ft/sec)		3308	3313	3318	3318
Per cent C* obtained		96.1%	95.1%	99.2%	102%

N/A - Not available due to severe oscillation.

Tests conducted by Walter Kidde Company

TABLE XXXVIII

HIGH PRESSURE-HIGH BED LOADING TEST NO. 4 OF CATALYST PACK AP-A4 WITH 97.6% H_2O_2 (10/26/66)

Chamber Characteristics	Pack Configuration	Packing Conditions
Exhaust orifice: 0.138" diam.	17 Silver-20 mesh screens	Pack length: 1 3/8"
Inlet orifice type D (10 holes 3/64" diam.)	38 Silver-30% palladium 20 mesh screens	Pack inlet located 1 3/4" upstream from retainer seat
Internal diameter: 3/4"	38 Nickel-5% manganese 14 mesh screens	Pack compression: Not recompressed

Time (Sec)	16	26	36	41
Chamber Pressure (psia) Pc_1	1077	1419	1543	1546
Pc_2	1057	1401	1530	1530
Inlet Pressure (psia)	1096	1472	1603	1609
Δ P Catalyst Bed (psi)	29	62	67	71
H_2O_2 Inlet Temp. (°F)	69.3	69.3	68.5	66.5
Propellant Flow (lb/sec)	0.180	0.220	0.233	0.233
C* Measured (ft/sec)	2855	3087	3178	3180
C* Theoretical (ft/sec)	3317	3317	3315	3313
Per cent C* Obtained	86.1	93.1	95.9	96.0

Tests Conducted by Walter Kidde Co.

TABLE XXXIX

HIGH PRESSURE-HIGH BED LOADING TEST NO.5 OF CATALYST PACK AP-A4 WITH 97.5% H_2O_2 (10/31/66)

Chamber Characteristics

Exhaust orifice: 0.163" diam.
Inlet orifice type M (10 holes 1/16" diam.)
Internal diameter: 3/4"

Pack Configuration

17 Silver 20 mesh screens
38 Silver-30% palladium 20 mesh screens
38 Nickel-5% manganese 14 mesh screens

Packing Conditions

Pack length: 1 3/8"
Pack inlet located 1 3/4" upstream from retainer seat
Pack compression: Not recompressed

Time (Sec)	5	10	15	20	25	30	35	40	45	50	55
Chamber Pressure (psia) P_{c1}	643	917	N/A	N/A	N/A	N/A	N/A	1478	1478	1475	1471
P_{c2}	631	910	N/A	N/A	N/A	N/A	N/A	1469	1469	1465	1461
Inlet Pressure (psia)	713	1012	N/A	N/A	N/A	N/A	N/A	1615	1615	1605	1609
Δ P Catalyst Bed (psi)	76	98	N/A	N/A	N/A	N/A	N/A	141	141	139	144
H_2O_2 Inlet Temp. (°F)	74										
Cat. Bed Temp. T_3 (°F) 5/16" from inlet	1580	1540	1420	1420	1420	1430	1465	1590	1540	1090	970
Cat. Bed Temp. T_4 (°F) 3/4" from inlet	--	--	1498	--	--	1638	--	--	1745	--	--
Cat. Bed Temp. T_5 (°F) 1 1/16" from inlet	--	1795	--	--	1800	--	--	1860	--	--	--
Exhaust Temp. T_7 (°F) 1 15/16" from inlet	Malfunction										
Propellant Flow (lb/sec)	0.140	0.196	N/A	N/A	N/A	N/A	N/A	0.301	0.301	0.301	0.298
C* Measured (ft/sec)	3057	3133	N/A	N/A	N/A	N/A	N/A	3290	3290	3282	3306
C* Theoretical (ft/sec)	3319										
Per cent C* obtained	92.1	94.4						99.1	99.1	98.9	99.6

N/A - Not available due to severe oscillation.

Tests Conducted by Walter Kidde Co.

TABLE XL

HIGH PRESSURE-HIGH BED LOADING TEST NO. 8 OF CATALYST PACK AF-A4 WITH 97.5% H_2O_2 (11/3/66)

Chamber Characteristics	Pack Configuration	Packing Conditions
Exhaust orifice: 0.163" diam. Inlet orifice type F (10 holes 1/32" diam.) Internal diameter: 3/4"	2 Nickel-5% manganese 14 mesh screens 1 Nickel-5% manganese 20 mesh screens 17 Silver 20 mesh screens 38 Silver-30% palladium 20 mesh screens 38 Nickel-5% manganese 14 mesh screens	Pack length: 1-3/8" Pack inlet located 1-3/4" upstream from retainer seat Pack compression: Pack AF-A4 (1) recompressed to 4000 psi

Time (Sec)	5	10	15	20	25	30	35	40	45	47
Chamber Pressure (psia)	N/A									
Inlet Pressure (psia)	N/A									
ΔP Catalyst Bed (psi)	N/A									
H_2O_2 Inlet Temp. (°F)	60°									
Cat. Bed Temp. T_3 (°F) 5/16" from inlet	710	1220	1120	1160	1135	1118	1080	1060	1030	---
Cat. Bed Temp. T_4 (°F) 3/4" from inlet	1440	1620	770	1810	1830	1860	1880	1895	1905	1910
Cat. Bed Temp. T_5 (°F) 1-1/16" from inlet	620	----	----	----	----	----	742	----	----	1750
Exhaust Temp. T_7 (°F) 1-15/16" from inlet	750	-----	----	----	1620	----	----	1715	----	----
Propellant Flow (lb/sec)	----	.269	----	.325	----	.360	----	.393	----	.393
C* Measured (ft/sec)	N/A									

N/A - Not available due to severe oscillations

Tests Conducted by Walter Kidde Co.

TABLE XLI

HIGH PRESSURE-HIGH BED LOADING TEST NO. 11 OF CATALYST PACK AF-A4 WITH 97.5% H_2O_2 (11/10/66)

Chamber Characteristics	Pack Configuration	Packing Conditions
Exhaust orifice: 0.253" diam. Inlet orifice type B (11 holes 3/64" diam.) Internal diameter: 3/4"	2 Nickel-5% Mn 14 mesh screens 1 Nickel-5% Mn 20 mesh screens 17 Silver 20 mesh screens 38 Silver-30% palladium 20 mesh screens 38 Nickel-5% manganese 20 mesh screens	Pack length: 1 3/8" Pack inlet located 1 3/4" upstream from retainer seat Pack compression: Pack tightened by extra spacers added before test AF-A4(9)

Time (Sec)	2	7	12	17	22	27	32	37	42
Chamber Pressure (psia) Pc1	326	641	932	1022	1049	1022	989	949	952
Pc2	321	644	934	1024	1041	1024	992	955	943
Inlet Pressure (psia)	551	1087	1595	1773	1821	1833	1839	1845	1845
ΔP Catalyst Bed (psi)	228	445	662	750	781	810	848	893	962
H_2O_2 Inlet Temp. (°F)									~150
Cat. Bed Temp. T_3 (°F) 5/16" from inlet	935	--	--	--	718	--	--	660	--
Cat. Bed Temp. T_4 (°F) 3/4" from inlet	--	925	--	--	718	--	--	--	660
Cat. Bed Temp. T_5 (°F) 1 1/16" from inlet	1660	1700	1710	1720	1739	1742	1745	1745	1770
Exhaust Temp. T_7 (°F) 1 15/16" from inlet	920	1505	1770	1895	1940	1950	1965	1965	2000
Propellant Flow (lb/sec)	0.195	0.313	0.441	0.472	0.479	0.472	0.465	0.443	0.440
C* Measured (ft/sec)	2690	3326	3425	3509	3532	3509	3450	3481	3488
C* Theoretical (ft/sec)	3460								
Per cent C* obtained	77.7%	96.1%	99%	101%	102%	101%	99.7%	101%	101%

Tests conducted by Walter Kidde Company

TABLE XLII

HIGH PRESSURE-HIGH BED LOADING TEST NO. 2 OF CATALYST PACK AP-A5 WITH 97.6% H_2O_2 (10/26/66)

Chamber Characteristics	Pack Configuration	Packing Conditions
Exhaust orifice: 0.253" diam.	11 Silver 20 mesh screens	Pack length: 1 3/8"
Inlet orifice type B (11 holes 3/64" diam.)	30 Silver-30% palladium 20 mesh screens	Pack inlet located 1 3/4" upstream from retainer seat
Internal diameter: 3/4"	56 Nickel-5% manganese 14 mesh screens	Pack compression: Pack AP-A5(1) recompressed to 2000 psi

Time (Sec)	5	10	15	20	25	30	35	40	45
Chamber Pressure (psia) Pc1	N/A	964	1117	1200	1240	1240	1237	1224	1217
Pc2	N/A	966	1080	1215	1247	1251	1247	1239	1227
Inlet Pressure (psia)	N/A	1401	1675	1723	1784	1784	1784	1772	1754
AP Catalyst Bed (psi)	N/A	436	576	515	540	538	542	540	532
Tank Pressure (psia)	N/A								
H_2O_2 Inlet Temp. (°F)	58°								
Cat. Bed Temp. T_3 (°F) 5/16" from inlet	1398	1398	1390	1380	1380	1383	1398	1400	1360
Cat. Bed Temp. T_4 (°F) 3/4" from inlet	--	1620	--	--	1665	--	--	--	1718
Cat. Bed Temp. T_5 (°F) 1 1/16" from inlet	1635	--	--	1738	--	--	1750	--	--
Exhaust Temp. T_7 (°F) 1 15/16" from inlet	1745	--	--	1845	--	1850	--	--	--
Propellant Flow (lb/sec)*	N/A	0.666	0.745	0.799	0.813	0.813	0.813	0.813	0.799
C* Measured (ft/sec)	N/A	2346	2388	2447	2477	2481	2473	2453	2476
C* Theoretical (ft/sec)	3308								
Per cent C* obtained *		70.9%	72.2%	74%	74.9%	75%	74.8%	74.2%	74.8%

N/A - Not available due to severe oscillation.

* - Leakage noted at inlet fitting so values of flow and C* are in error.

Tests conducted by Walter Kidde Company

TABLE XLIII

HIGH PRESSURE-HIGH BED LOADING TEST NO. 3 OF CATALYST PACK AF-A8 WITH 98.1% H_2O_2 (11/22/66)

Chamber Characteristics

Exhaust orifice: 0.253" diam.
Inlet orifice type F (10 holes 1/32" diam.)
Interval diameter: 3/4"

Pack Configuration

51 Silver-30% palladium
20 mesh screens
38 Nickel-5% manganese
14 mesh screens

Packing Conditions

Pack length: 1 3/8"
Pack inlet located 2 5/8" upstream from retainer seat
Pack compression: Pack tightened by addition of extra spacers before test AF-A8(2)

Time (Sec)	5	10	15	20	25	30	35	40
Chamber Pressure (psia) Pcl	430	707	967	1211	1352	1432	N/A	N/A
Inlet Pressure (psia)	722	1078	1406	1619	1757	1847	N/A	N/A
ΔP Catalyst Bed (psi)	292	371	439	408	405	415	N/A	N/A
H_2O_2 Inlet Temp. (°F)	64							
Cat. Bed Temp. T_2 (°F)	1660	1610	1630	1680	1550	1015	760	490
Exhaust Temp. T_7 (°F)	2050	2130	2160	2185	2185	2185	2185	2185
Propellant Flow (lb/sec)	0.258	0.421	0.502	0.622	0.690	0.725	N/A	N/A
C* Measured (ft/sec)	2678	2718	3118	3152	3172	3197	N/A	N/A
C* Theoretical (ft/sec)	3325							
Per cent C obtained	80.5%	81.7%	93.8%	94.8%	95.4%	96.2%	N/A	N/A

N/A - Not available due to severe oscillation.

Tests conducted by Walter Kidde Company

TABLE XLIV

HIGH PRESSURE-HIGH FEED LOADING TEST NO. 1 OF CATALYST PACK AF-A9 WITH 98.4% H_2O_2 (11/28/66)

Chamber Characteristics

Exhaust orifice: 0.253" diam.
Inlet orifice type B (11 holes 3/64" diam.)
Internal diameter: 3/4"

Pack Configuration

17 Silver 20 mesh screens
39 Silver-30% palladium
20 mesh screens
38 Nickel-5% manganese
14 mesh screens

Packing Conditions

Pack length: 1 3/8"
Pack inlet located 1 3/4" upstream
from retainer seat
Pack compression: 4000 psi

Time (Sec)		10	20	30	40	45
Chamber Pressure (psia)	Pc1	915	1125	112[illegible]	1121	1112
	Pc2	921	1135	1135	1135	1131
Inlet Pressure (psia)		1553	1921	1931	1931	1931
ΔP Catalyst Bed (psi)		635	791	801	803	810
H_2O_2 Inlet Temp. (°F)		60	62	62	62	62
Propellant Flow (lb/sec)		0.490	0.570	0.570	0.570	0.570
C* Measured (ft/sec)		3033	3209	3209	3204	3186
C* Theoretical (ft/sec)		3320	3323	3323	3323	3323
Per cent C* obtained		91.4	96.6	96.6	96.4	95.9

Tests conducted by Walter Kidde Company

TABLE XLV

HIGH PRESSURE-HIGH BED LOADING TEST NO. 2 OF CATALYST PACK AF-A9 WITH 98.4% H_2O_2 (11/28/66)

Chamber Characteristics

Exhaust orifice: 0.253" diam.
Inlet orifice type B (11 hole 3/64" diam.)
Internal diameter: 3/4"

Pack Configuration

17 Silver 20 mesh screens
39 Silver-30% palladium 20 mesh screens
38 Nickel-5% manganese 14 mesh screens

Packing Conditions

Pack length: 1 3/8"
Pack inlet located 1 3/4" upstream from retainer seat
Pack compression: Not recompressed

Time (Sec)	5.8	10	12.4	20	21.6	30	40	45
Chamber Pressure (psia) Pc1	315	512	615	866	915	1038	1063	1063
Pc2	328	515	622	883	924	1056	1079	1082
Inlet Pressure (psia)	591	922	1110	1550	1618	1854	1901	1912
ΔP Catalyst Bed (psi)	270	409	492	676	599	807	841	840
H_2O_2 Inlet Temp. (°F)	59	59	60	61	61	62	61	61
Cat. Bed Temp. T_3 (°F) 5/16" from inlet	1630	1360	1220	445	445	445	445	435
Cat. Bed Temp. T_4 (°F) 11/16" from inlet	1750	1775	1780	1750	1745	1730	1730	1730
Exhaust Temp. T_7 (°F) 1 15/16" from inlet	1690	1725	1730	1735	1740	1740	1740	1745
Propellant Flow (lb/sec)	0.147	0.272	0.320	0.450	0.462	0.543	0.543	0.543
C* Measured (ft/sec)	3546	3059	3131	3148	3224	3121	3193	3199
C* Theoretical (ft/sec)	3319	3319	3320	3322	3322	3323	3322	3322
Per cent C* obtained	107	92.2	94.3	94.8	97.0	93.9	96.1	96.3

Tests conducted by Walter Kidde Company

TABLE XLVI

HIGH PRESSURE-HIGH BED LOADING TEST NO. 3 OF CATALYST PACK AF-A9 WITH 98.4% H_2O_2 (11/28/66)

Chamber Characteristics	Pack Configuration	Packing Conditions
Exhaust orifice: 0.283" diam. Inlet orifice type B (11 holes 3/64" diam.) Internal diameter: 3/4"	17 Silver 20 mesh screens 39 Silver-30% palladium 20 mesh screens 38 Nickel-5% manganese 14 mesh screens	Pack length: 1 3/8" Pack inlet located 1 3/4" upstream from retainer seat Pack compression: Not recompressed

Time (Sec)	7.6	10	15.7	20	30	35	40	45	50	54
Chamber Pressure (psia) Pc1	316	394	617	725	872	880	884	880	880	876
Pc2	336	410	628	734	882	897	901	897	893	890
Inlet Pressure (psia)	724	1013	1354	1595	1874	1900	1910	1910	1910	1905
ΔP Catalyst Bed (psi)	398	611	731	865	997	1011	1018	1021	1023	1022
H_2O_2 Inlet Temp. (°F)	59	60	61	61	61	61	61	61	61	61
Cat. Bed Temp T_3 (°F) 5/16" from inlet	1760	1500	455	430	415	410	415	408	408	410
Cat. Bed Temp. T_4 (°F) 11/16" from inlet	1740	1740	1745	1750	1730	1730	1730	1730	1730	1740
Exhaust Temp. T_7 (°F) 1 15/16" from inlet	1705	1705	1735	1740	1740	1740	1740	1740	1740	1740
Propellant Flow (lb/sec)	0.224	0.300	0.410	0.490	0.565	0.570	0.570	0.570	0.570	0.570
C* Measured (ft/sec)	2948	2714	3076	3017	3144	3159	3170	3159	3152	3138
C* Theoretical (ft/sec)	3319	3320	3322	3322	3322	3322	3322	3322	3322	3322
Per cent C* obtained	88.8	81.7	92.6	90.8	94.6	95.1	95.4	95.1	94.9	94.5

Tests conducted by Walter Kidde Company

TABLE XLVII

HIGH PRESSURE-HIGH BED LOADING TEST NO. 4 OF CATALYST PACK AP-A9 WITH 98.4% H_2O_2 (11/29/66)

Chamber Characteristics

Exhaust orifice: 0.299" diam.
Inlet orifice type B (11 holes 3/64" diam.)
Internal diameter: 3/4"

Pack Configuration

17 Silver 20 mesh screens
39 Silver-30% palladium 20 mesh screens
38 Nickel-5% manganese 14 mesh screens

Packing Conditions

Pack length: 1 3/8"
Pack inlet located 1 3/4" upstream from retainer seat
Pack compression: Not recompressed

Time (Sec)	10	10.4	20	21	30	40	48
Chamber Pressure (psia) Pc1	301	314	596	616	728	774	787
Pc2	313	317	601	623	743	784	795
Inlet Pressure (psia)	757	799	1462	1509	1783	1888	1914
ΔP Catalyst Bed (psi)	450	484	864	890	1048	1109	1123
H_2O_2 Inlet Temp. (°F)	55	56	58	58	58	58	58
Cat. Bed Temp. T_1 (°F) 5/16" from inlet	1630	1610	495	475	470	415	415
Cat. Bed Temp. T_4 (°F) 11/16" from inlet	1730	1730	1730	1730	1715	1715	1720
Exhaust Temp. T_7 (°F) 1 15/16" from inlet	1690	1690	1725	1725	1725	1735	1735
Propellant Flow (lb/sec)	0.259	0.272	0.450	0.462	0.543	0.570	0.583
C* Measured (ft/sec)	2680	2627	3010	3034	3065	3090	3068
C* Theoretical (ft/sec)	3315	3316	3317	3317	3317	3317	3317
Per cent C* obtained	80.8	79.2	90.7	91.5	92.4	93.2	92.5

Tests conducted by Walter Kidde Company

TABLE XLVIII

HIGH PRESSURE-HIGH BED LOADING TEST NO. 5 OF CATALYST PACK AP-A9 WITH 98.4% H_2O_2 (11/29/66)

Chamber Characteristics	Pack Configuration	Packing Conditions
Exhaust orifice: 0.253" diam. Inlet orifice type B (11 holes 3/64" diam.) Internal diameter: 3/4"	17 Silver 20 mesh screens 38 Silver-30% palladium 20 mesh screens 38 Nickel-5% manganese 14 mesh screens	Pack length: 3/8" Pack inlet located 3/4" upstream from retainer seat Pack compression: 4000 psi

Time (Sec)	2.5	5.3	7.3	10	20	30	40	46
Chamber Pressure (psia) Pc1	314	613	917	1228	1359	1359	1351	1347
Pc2	339	631	912	1243	1367	1367	1356	1353
Inlet Pressure (psia)	553	986	1247	1639	1843	1843	1848	1848
ΔP Catalyst Bed (psi)	227	366	333	404	480	480	495	498
H_2O_2 Inlet Temp. (°F)	53	54	55	56	56	56	56	56
Cat. Bed Temp. T_5 (°F) 3/8" from inlet	1708	1650	1568	1030	850	1100	1238	1280
Cat. Bed Temp. T_6 (°F) 3/4" from inlet	1718	1710	1640	1670	1660	1690	1690	1680
Exhaust Temp. T_7 (°F) 1 15/16" from inlet	1660	1690	1760	1715	1765	1730	1730	1730
Propellant Flow (lb/sec)	0.212	0.357	0.483	0.638	0.689	0.691	0.689	0.689
C* Measured (ft/sec)	2496.9	2820.4	3066.7	3136.1	3202.3	3193.1	3181.2	3171.8
C* Theoretical (ft/sec)	3312	3313	3315	3316	3316	3316	3316	3316
Per cent C* obtained	75.4	85.0	92.5	94.6	96.6	96.3	95.9	95.7

Tests conducted by Walter Kidde Company

TABLE II

HIGH PRESSURE - HIGH BED LOADING TEST NO. 6 OF CATALYST PACK AF-A9 WITH 98% H_2O_2 (11/29/66)

Chamber Characteristics

Exhaust orifice: 0.283" diam.
Inlet orifice type B (11 holes 3/64" diam.)
Internal diameter: 3/4"

Pack Configuration

17 Silver 20 mesh screens
38 Silver-30% palladium 20 mesh screens
38 Nickel-5% manganese 14 mesh screens

Packing Conditions

Pack length: 1-3/8"
Pack inlet located 1-3/4" upstream from retainer seat
Pack compression: Not recompressed

Time (Sec)	2	4.3	8.1	10	12.7	19.7	20	30	40	48
Chamber Pressure (psia) Pc1	212	314	614	790	917	1216	1225	1245	1241	1241
Pc2	210	320	621	789	925	1226	1233	1252	1244	1244
Inlet Pressure (psia)	344	501	946	1177	1364	1788	1793	1851	1840	1840
Δ P Catalyst Bed (psi)	133	184	329	388	443	567	564	603	598	598
H_2O_2 Inlet Temp. (°F)	53	53	54	55	55	56	56	56	56	56
Cat. Bed Temp. T_3 (°F) 3/8" from inlet	1670	1705	1620	1565	1515	1320	1320	1350	1390	1395
Cat. Bed Temp. T_4 (°F) 3/4" from inlet	1730	1730	1672	1672	1672	1672	1672	1672	1672	1672
Exhaust Temp. T_7 (°F) 1-15/16" from inlet	1690	1695	1710	1720	1720	1730	1730	1730	1730	1730
Propellant Flow (lb/sec)	~.15	.216	.415	.525	.598	.770	.770	.783	.783	.783
C* Measured (ft/sec)		2972	3016	3048	3119	3212	3233	3231	3215	3215
C* Theoretical (ft/sec)		3312	3313	3315	3315	3316	3316	3316	3316	3316
Per cent C* obtained		89.7	91.0	91.9	94.1	96.9	97.5	97.4	97.0	97.0

TABLE L

HIGH PRESSSURE - HIGH BED LOADING TEST NO. 7 OF CATALYST PACK AF-A9 WITH 98% H_2O_2 (11/29/66)

Chamber Characteristics

Exhaust orifice: 0.299" diam.
Inlet orifice type 2 (11 holes 3/64" diam.)
Internal diameter: 3/4"

Pack Configuration

17 Silver 20 mesh screens
38 Silver-30% palladium
20 mesh screens
38 Nickel-5% manganese
14 mesh screens

Packing Conditions

Pack length: 1-3/8"
Pack inlet located 1-3/4" upstream from retainer seat
Pack compression: Not recompressed

Time (sec)	1.5	3.3	9.1	10	20	30	40	46
Chamber Pressure (psia) Pc1	191	314	915	971	1132	1066	980	939
Pc2	183	319	919	978	1148	1073	985	941
Inlet Pressure (psia)	386	563	1471	1544	1821	1743	1623	1560
ΔP Catalyst Bed (psi)	191	247	554	570	684	674	641	620
H_2O_2 Inlet Temp. (°F)	53	54	55	56	56	56	56	56
Cat. Bed Temp. T_3 (°F) 3/8" from inlet	1650	1682	1542	1530	1360	1475	1500	1510
Cat. Bed Temp. T_4 (°F) 3/4" from inlet	1620	1667	1667	1670	1670	1672	1672	1672
Exhaust Temp. T_5 (°F) 1-15/16" from inlet	1670	1705	1725	1725	1735	1740	1735	1735
Propellant Flow (lb/sec)	~ .15	.216	.719	.719	.810	.768	.702	.680
C* Measured (ft/sec)		3318	2884	3066	3174	3150	3166	3125
C* Theoretical (ft/sec)		3313	3315	3316	3316	3316	3316	3316
Per cent C* obtained		100%	87.0%	92.5%	95.7	95.0	95.5	94.2

TABLE LI

HIGH PRESSURE-HIGH BED LOADING TEST NO. 8 OF CATALYST PACK AP-A9 WITH 98% H_2O_2 (11/30/66)

Chamber Characteristics

Exhaust orifice: 0.253" diam.
Inlet orifice type B (13 holes 3/64" diam.)
Internal diameter: 3/4"

Pack Configuration

17 Silver 20 mesh screens
38 Silver-30% palladium 20 mesh screens
5 Nickel-5% manganese 14 mesh screens

Packing Conditions

Pack length: 15/16"
Pack inlet located 1-13/16" upstream from retainer seat
Pack compression: Not recompressed

Time (Sec)	2.9	4.3	10	20	30	31
Chamber Pressure (psia) P_{c1}	916	1214	1505	1492	1492	1492
P_{c2}	918	1210	1506	1502	1499	1499
Inlet Pressure (psia)	1181	1532	1910	1916	1910	1910
ΔP Catalyst Bed (psi)	264	320	405	419	415	415
H_2O_2 Inlet Temp. (°F)	54	54	56	56	56	56
Cat. Bed Temp. T_3 (°F) 3/8" from inlet	1190	1050	1005	1070	1340	1350
Cat. Bed Temp. T_4 (°F) 3/4" from inlet	1672	1680	1680	1690	1690	1690
Exhaust Temp. T_7 (°F) 2" from inlet	1705	1720	1730	1735	1735	1735
Propellant Flow (lb/sec)	.518	.610	.741	.741	.741	.741
C* Measured (ft/sec)	2866	3216	3290	3270	3268	3268
C* Theoretical (ft/sec)	3313	3313	3316	3316	3316	3316
Per cent C* obtained	86.5	97.1	99.2	98.6	98.6	98.6

Tests conducted by Walter Kidde Company.

TABLE LII

HIGH PRESSURE-HIGH BED LOADING TEST NO. 1 OF CATALYST PACK AP-A10 WITH 98% H_2O_2 (11/30/66)

Chamber Characteristics

Exhaust orifice: 0.253" diam.
Inlet orifice type B (11 holes 3/64" diam.)
Internal diameter: 3/4"

Pack Configuration

47 Silver 30% palladium
20 mesh screens
7 Nickel-5% manganese
14 mesh screens

Packing Conditions

Pack length: 7/8"
Pack inlet located 1-3/4" upstream from retainer seat
Pack compression: Not recompressed, 1/16" void space not filled

Time (Sec)	5.9	10	20	30	40	50	59.5
Chamber Pressure (psia) P_{c_1}	913	1136	1173	1173	1181	1189	1197
P_{c_2}	933	1158	1188	1192	1203	1206	1214
Inlet Pressure (psia)	1138	1375	1390	1390	1390	1390	1375
ΔP Catalyst Bed (psi)	215	228	205	198	198	193	169
H_2O_2 Inlet Temp. (°F)	53	54	54	54	54	54	54
Cat. Bed Temp. T_3 (°F) 3/8" from inlet	1372	1102	720	630	610	475	430
Cat. Bed Temp. T_4 (°F) 3/4" from inlet	1700	1715	1730	1740	1740	1745	1750
Exhaust Temp. (°F) 1-15/16" from inlet	1720	1730	1720	1688	1670	1660	1650
Propellant Flow (lb/sec)	.435	.582	.590	.590	.598	.598	.598
C* Measured (ft/sec)	3435	3190	3240	3246	3227	3243	3265
C* Theoretical (ft/sec)	3312	3313	3313	3313	3313	3313	3313
Per cent C* obtained	104	96.3	97.8	98.0	97.4	97.9	98.6

Tests conducted by Walter Kidde Company

TABLE LIII

HIGH PRESSURE-HIGH BED LOADING TEST NO. 2 OF CATALYST PACK AP-A10 WITH 98% H_2O_2 (11/30/66)

Chamber Characteristics

Exhaust orifice: 0.253" diam.
Inlet orifice type B (11 holes 3/64" diam.)
Internal diamter: 3/4"

Pack Configuration

47 Silver-30% palladium
20 mesh screens
7 Nickel-5% manganese
14 mesh screens

Packing Conditions

Pack length: 7/8"
Pack inlet located 1-3/4" upstream from retainer seat
Pack compression: Not recompressed

Time (Sec)		2.5	3.9	10	20	30	40	50
Chamber Pressure (psia)	Pc_1	617	917	1132	1094	1057	1008	991
	Pc_2	616	934	1148	1106	1078	1015	1011
Inlet Pressure (psia)		824	1190	1440	1409	1424	1419	1424
AP Catalyst Bed (psi)		208	264	300	309	367	408	423
H_2O_2 Inlet Temp. (°F)		66	73	88	105	121	134	140
Cat. Bed Temp. T_5 (°F) 3/8" from inlet		1678	1550	1445	1380	1380	1678	1605
Cat. Bed Temp. T_6 (°F) 3/4" from inlet		1760	1760	1775	1760	1840	1860	1865
Exhaust Temp. T_7 (°F) 1-15/16" from inlet		1700	1730	1760	1790	1818	1830	1830
Propellent Flow (lb/sec)		.320	.421	.565	.550	.518	.515	.515
C* Measured (ft/sec)		3121	3561	3266	3238	3338	3181	3146
C* Theoretical (ft/sec)		3327	3335	3335	3375	3395	3410	3418
Per cent C* obtained		93.8	107	97.3	95.9	98.3	93.3	92.0

Tests conducted by Walter Kidde Company

SECTION VI

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13. ABSTRACT

(UNCLASSIFIED ABSTRACT)

Both laboratory and motor evaluation tests have been carried out on heterogeneous decomposition catalysts for 98% H_2O_2. Thirty-three metals and alloys and eighteen catalyst pellets were screened in the laboratory program. Surface activations and coatings on the metals and alloys were also tested. Catalyst packs containing various configurations of metal screens or catalyst pellets were then evaluated in thrust motors and gas generators. High pack loadings and chamber pressures and both heated and cooled H_2O_2 feed were used. Flow rates, chamber and inlet pressures and temperatures, and catalyst pack temperatures were measured. The performance was correlated in terms of catalyst pack configuration, pressure drop across the pack, chamber pressure, pack loading, feed temperature, and pack length. Results were also interpreted with respect to specific impulse, characteristic exhaust velocity, and start and decay transients. The results were used to illustrate the design of appropriate applications of 98% H_2O_2 catalyst packs.

14. KEY WORDS	LINK A		LINK B		LINK C	
	ROLE	WT	ROLE	WT	ROLE	WT
Hydrogen peroxide, decomposition Catalysts, hydrogen peroxide Rocket research Coatings						

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