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ABRADABLE GAS PATH SEALS

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Prepared by: *L. T. Shiembob*
L. T. Shiembob, Program Manager

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Pratt & Whitney Aircraft DIVISION OF UNITED AIRCRAFT CORPORATION

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Final Report

Development of Abradable Gas
Path Seals

by

L. T. Shiembob

PRATT & WHITNEY AIRCRAFT
DIVISION OF UNITED AIRCRAFT CORPORATION

Prepared for

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

NASA Lewis Research Center
Contract NAS3-18023

R. C. Bill, Project Manager

ABSTRACT

The comparative abrasability and erosion characteristics of

five gas path seal material systems were evaluated. The systems included:

- (1) Hastelloy-X honeycomb, which served as a baseline for comparison;
- (2) low density sintered NiCrAlY fibermetal; (3) honeycomb supported porous cermet; (4) honeycomb supported porous metal/diatomaceous earth composite;
- (5) spray coated NiCrAlY fibermetal. The performance of each material system was based on wear measurements, frictional torque measurements, microscopic studies, and rub debris characterization. The effects of interaction rate, rub velocity and seal material temperature on abrasability performance of each material system were studied. The most abrasable material was the sintered NiCrAlY fibermetal. The spray coated NiCrAlY fibermetal offered the best balance between abrasability and erosion resistance.

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FOREWORD

This report describes the work accomplished on NASA Contract NAS3-18023 and Modification 1 and 2 by the Pratt & Whitney Aircraft division of United Aircraft Corporation for the Lewis Research Center of the National Aeronautics and Space Administration. This work was initiated 20 December 1973 and completed 15 August 1974.

Dr. Robert C. Bill of the National Aeronautics and Space Administration was the Project Manager and Mr. Leonard W. Schopen, NASA Research Center was the Contracting Officer.

Mr. Lawrence T. Shienbob, was the Program Manager for Pratt & Whitney Aircraft from the inception of this contract.

Appreciation is extended for overall program assistance to P&WA personnel Gerald A. Majocha and Michael P. Harrington, Experimental Engineers, and Joseph A. Montineri, Engineering Technician.

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I. INTRODUCTION

A. Background

The increasing urgency for world wide fuel conservation has resulted in a significant effort to improve efficiency in today's gas turbine engines. A direct method to improve upon engine performance is through seal clearance control. As an illustration, reducing turbine operating clearances by 2.54×10^{-4} m (.010 inch) would result in a savings of approximately 1.89 x 106 liters (500,000 gallons) of fuel based on a 15 year span for a commercial gas turbine engine.

With this emphasis in increased performance requirements, gas turbine engine designs are utilizing higher turbine operating temperatures. Turbine gas path seals must therefore be provided which can operate in this higher temperature regime. This can be accomplished by 1) developing new seal materials or 2) supplying cooling air to current seal systems. Since overall engine performance will be decreased by the usage of more cooling air, it is desirable to develop new higher temperature seal systems.

While considering the basic requirement of higher temperature capability, the overall importance of maintaining or reducing turbine blade tip or interstage seal clearance must be considered. One of the difficulties in reducing seal clearance is accommodating the eccentricity caused by rotor shift or case ovalization. Circumferential heat flux variation on the seal shroud support, manufacturing tolerances and maneuver and/or landing loads will also result in an eccentric rub interaction as clearances are reduced. The gas path seal land must wear preferentially or abrade during rotor interaction to minimize the effect on operating clearance. The ultimate goal is to develop a seal land which will accommodate rotor displacement without wearing the rotor tip.

Dynamic abrasability rig tests, in which a simulated engine rotor tip is rubbed against a seal land specimen at engine operating conditions of temperature, speed, and interaction rate, provide data on the relative wear and rub generated heat flux into the rotor and seal land. By comparing this data for different seal land materials, a determination can be made as to which material will produce the least rotor wear during rub interaction in an engine. Durability of the seal material is evaluated in terms of erosion resistance. The greater the erosion susceptibility the more seal material will be removed per unit time and the larger the rotor/tip seal land clearance will become.

Abrasability and durability are the two most important characteristics of a seal system and form a sound basis for a preliminary comparative evaluation of material systems offering potential for higher temperature seal application. Various other characteristics, however, such as thermal conductivity of the material and the associated effect on thermal response, may be of equal importance with regard to a particular application. Results of this program, therefore, should not be used as the sole basis for determining the acceptability of any material for a particular application.

B. Program Objective

The primary objective of this program was to evaluate the comparative abrasability and erosion characteristics of five (5) seal systems with potential for turbine application. The long range goal is to develop superior abrasable seal materials for turbine tip seals operating at 1366K (2000°F), and for interstage labyrinth seals operating at 1144K (1600°F).

C. General Approach

On the basis of a preliminary screening study which considered factors such as probability of successful engine performance, cost and time constraints and adaptability of the system to engine hardware, five (5) materials were selected for evaluation. The five systems were evaluated on the basis of abrasability and erosion rig testing.

Phenomena such as knife edge wear, maximum interaction torque, material pickup, transfer of knife edge material and thermal effects as well as rub debris characterization were all noted for the rub tests. Material systems were ranked largely on the basis of volume ratio numbers (volume ratio is defined as the knife edge volume worn or picked up during rub interaction divided by volume of seal material abraded). These ratios were utilized for a comparative screening evaluation as well as a means for approximating wear rates for engine hardware interactions. For erosion experiments, weight losses and groove measurements were recorded and erosion rates calculated. Abradability and erosion mechanisms were further analyzed with the aid of microsectioning and SEM (Scanning Electron Microscope) studies.

II. TECHNICAL PROGRAM SUMMARY

A. Material Selection and Experimental Program Description

As a first step to screening and selection of the seal systems to be evaluated under this program, the state-of-the-art of relevant abrasable materials was reviewed. Second, the potential of applicable material systems for operation in the 1144K (1600°F) to 1366K (2000°F) range was assessed. The probability of obtaining specimens within program constraints of time and money, engine hardware fabrication and cost assessment for these seals were also considered. As a result, the following five seal systems were selected for experimental evaluation.

#1 - Honeycomb: A 1.57 x 10-3m (1/16 inch) cell size, 1.02 x 10-4m (.004 inch) thick wall, hexagonal cell honeycomb of Hastelloy X material was selected for a base line comparison with other systems to be evaluated. This honeycomb is a bill of material item in the low pressure turbine of some engines in operation today.

Cost of this seal system is considered to be low, less than \$.15/cm² (\$1/in²). Since honeycomb seals have been in production for some time, no fabrication difficulty will be encountered. A long-time maximum temperature capability of 1255K (1800°F) is estimated for the 1.02 x 10-4m (.004 inch) foil.

#2 - Sintered Fibermetal: Sintered fibermetal seals of Hastelloy X are used in both the compressor inner and outer air seals of engines in operation today. Development of a higher oxidation resistant metal known as NiCrAlY offers promise for use as a fiber, instead of Hastelloy X, to increase temperature capability of the fibermetal system. Based on oxidation tests results, an expected temperature capability of 1144K (1600°F) for the 19% dense configuration is anticipated. NiCrAlY fibermetal has been fabricated on experimental equipment and braze bonding is not expected to be a problem. Cost of the seal material is estimated to be less than \$.15/cm² (\$1/in²).

#3 - Porous Cermet, Honeycomb Supported: This material is produced by mechanically mixing pre-alloyed powders of NiCr, CoAlY, Mica and other minor constituents and slip casting the mixture into a 6.35 x 10-3m (.250 inch) square cell honeycomb reinforcing structure. After drying, the structure is fired to effect liquid phase sintering and diffusion reactions which bind the structure together. The resultant structure is conditioned by an oxidation heat treatment to stabilize the material. The structure has an open porosity of approximately 50% and a temperature capability of up to 1366K (2000°F). Cost is estimated at \$1.09/cm² (\$7/in²) which includes bonding to the seal support ring.

#4 - Porous Metal/Diatomaceous Earth, Honeycomb Supported: This material is comprised of a porous NiCoCrAlY metal matrix and diatomaceous earth constituent. The structure is created by mechanically mixing pure alloyed powders of Ni coated diatomaceous earth, NiCr and CoAlY and slip casting the mixture into a 6.35 x 10-3m (.250 inch) cell Hastelloy-X honeycomb. After drying, the structure is fired to effect liquid phase sintering and diffusion reactions which form a continuous metal matrix encapsulating particles of diatomaceous earth. The matrix is 50% porous. Maximum temperature capability is estimated at 1255K (1800°F). Cost of the seal material is estimated at less than \$1.09/cm² (\$7/in²) including bonding to the seal support material.

#5 - Spray Coated NiCrAlY Fibermetal: This material is comprised of a spray coating deposited on a sintered NiCrAlY fibermetal (system #2 description) base. Two different spray coatings were selected: 1) 67.0% Nichrome/16.5% Glass/16.5% CaF₂ and 2) 80% Nichrome/20% Glass without the calcium-fluoride. The purpose of the coating is to provide a dense high temperature protective coating for the fibermetal to increase its erosion resistance capability. The projected cost of this system will be somewhat more than the base fibermetal system (#2).

Fifty nine (59) abrasability and twenty (20) erosion tests were conducted. In addition, seal rub path microsections, rub debris characterizations and SEM studies were conducted to provide additional information. A listing of the abrasability test conditions is shown in Table 1. Two high response thermal instrumentation tests were conducted, one on the honeycomb and the other on the fibermetal system.

TABLE 1

Abrasability Rub Test Matrix

Temperature K	(°F)	Peripheral Speed		Penetration Speed	
		m/sec	(ft/sec)	m/sec x 10 ⁻⁵	(mils/sec)
288	(Amb)	183	(600)	2.54	(1.0)
922	(1200)	183	(600)	2.54	(1.0)
1366	(2000)	183	(600)	2.54	(1.0)
288	(Amb)	305	(1000)	2.54	(1.0)
922	(1200)	305	(1000)	2.54	(1.0)
1366	(2000)	305	(1000)	2.54	(1.0)
288	(Amb)	183	(600)	2.54	(.1)
288	(Amb)	183	(600)	25.4	(10.0)
288	(Amb)	305	(1000)	.254	(.1)
288	(Amb)	305	(1000)	25.4	(10.0)

High Response Thermal Instrumentation Tests

Temperature K (°F)	Peripheral Speed m/sec (ft/sec)	Penetration Speed m/sec x 10 ⁻⁵ (mils/sec)
288 (Amb)	305 (1000)	2.54 (1.0)

The test program was established to evaluate abrasability characteristics of each of the systems as a function of temperature, surface speed and interaction rate. The test parameters were chosen to simulate conditions typically experienced in engine applications. The slower surface speed conditions relate to interactions occurring during engine startup or shutdown cycles. All abrasability tests utilized only radial plunge testing in order to simplify the comparative analysis. Abrasability specimens of all five materials were designed to accept multiple interactions on each specimen to reduce time and cost of each rub test.

The knife edge test component used for rub testing was made of Waspalloy material and fabricated in a configuration simulating a low pressure turbine inner air seal rotor tip. A total of five disks were procured and refinished as required throughout the test program.

Rub debris collection was accomplished by using a high temperature silicone grease rather than water as had been originally planned. Windage caused by the high rotor speeds resulted in excessive water movement and a corresponding loss in rub debris collection efficiency. This grease provided the viscosity required and proved to be an effective means of rub debris particle collection.

The particulate erosion tests utilized aluminum oxide particles. Test conditions are presented in Table 2.

TABLE 2

Particulate Erosion Test Matrix

Test Point	Gas Temperature K (°F)	Test Time (Minutes)
1	1033 (1400)	20
2	1144 (1600)	20
3	1255 (1800)	20
4	1366 (2000)	20

Details of abrasability and erosion rig test hardware and procedures as well as a description of the high response thermal instrumentation tests are contained in Appendix A.

B. Program Results and Conclusions

All abrasability test data, observations during test, and post test inspection are summarized in Table 9, Appendix B. Abrasability, interaction torque and volume wear data has been plotted to facilitate a comparison of the five material systems and is presented in Section III. Rub debris and erosion data are also presented on comparative basis in Section III. Rub path analysis, visual documentation of the effects of temperature on erosion and significant abrasability trends as a function of test parameters are contained in Section IV. Of particular interest is the documented rub mechanism change from knife edge wear to material pickup on the knife edge as a function of rotor interaction rate for both the honeycomb supported porous metal/diatomaceous earth and coated fibermetal systems.

Several comments are required as a prelude to the presentation of test data and the results of the comparative evaluation. The data presented here represents the results of a valid, but preliminary, screening effort. Any determination of the "best" system for a particular engine application must be made after additional evaluation effort and details of the engine seal environment and dynamic characteristics are determined. The effect of physical properties of the material on thermal response and leakage associated with the structural configuration of the material must be considered together with cost, manufacturing, durability and repairability factors. For example, honeycomb, which performed well in these tests, has good heat transfer characteristics and probably would not be selected for an engine location where an abrasable with insulation characteristics would reduce the effect of thermal transients on clearance. Another consideration could be the fact that, at small clearances, the leakage around the knife edge through the honeycomb cells is appreciably greater than the leakage with a solid or porous (fibermetal) seal land. For these reasons, the results of this program should not be used as the sole basis for determining the suitability of any of these systems for a particular application.

Evaluation of abrasability and erosion test data resulted in the following ranking (Table 3).

TABLE 3
Experimental Results of Material Systems Evaluation

Material List	Abradability		Rub Induced		Erosion	
	Ranking		Temperature Ranking		Ranking	
Hastelloy-X Honeycomb	2		2		2	
NiCrAlY Fibermetal	1		1		5	
Honeycomb Supported Porous Metal/ Diatomaceous Earth	4		N/A		4	
Honeycomb Supported Porous Cermet	5		N/A		3	
Coated Fibermetal	3		N/A		1	

Abradability ranking was accomplished on the basis of volume wear ratios with number 1 ranking producing the least knife edge wear (lowest volume wear ratio). The two abrasability tests with high response thermal instrumentation revealed that at the same test conditions a fibermetal rub interaction produced less heat than the honeycomb system. Erosion ranking was based on a comparison of the volume loss rates for the five materials, the number 1 ranking was attributed to the material with lowest volume loss rate and, therefore, the highest erosion resistance. Testing of the base line Hastelloy-X honeycomb, which is currently used in gas turbine engines, confirmed its suitability as a candidate for seal application. It offered rather high particulate erosion resistance and very low knife edge wear. The honeycomb system, however, revealed rub induced knife edge temperatures of 1311K (1900°F), at least a factor of two times the temperatures recorded for the NiCrAlY uncoated fibermetal system. (The pyrometer base temperature was 811K (1000°F) and no temperatures over this base temperature were recorded for the fibermetal system.) Rub induced temperature is an indication of the heat flux into the rotor and has a bearing on the thermal stability of the seal system in an engine application.

Abradability testing indicated that NiCrAlY 19% dense fibermetal was the most rub tolerant of the five systems and has potential for low turbine seal application. The rub induced temperature data indicates that low thermal energy is produced during interaction. However, the particulate erosion resistance of this system is low and very temperature dependent compared to the particulate erosion behavior of the other materials. Further effort to investigate methods of improving the erosion resistance of this system is warranted.

The niobium/glass plasma sprayed coating deposited on the NiCrAlY fibermetal was the most erosion resistant material. However, surface cracks on the spray coating appeared in both erosion and abrasability specimens probably due to thermal stresses induced by the thermal mismatch between the coating and fibermetal base material. These surface cracks create surface weakening and possible material chipping into the engine airstream. Abradability tests of this system resulted in significantly higher wear and knife edge heating compared to the honeycomb and uncoated fibermetal systems.

The honeycomb supported porous metal/diatomaceous earth and honeycomb supported porous cement ranked as the least abrasable systems and on a comparative basis demonstrated average erosion resistance.

II. SEAL SYSTEM COMPARISON RESULTS

A. Abradability Testing

Fifty-nine abrasability tests were conducted at various temperatures, surface speeds, and interaction rates in order to evaluate the rub mechanism of each system. Rub interaction torque and volume ratios have been plotted as a function of these conditions. All test data, test conditions, rotor and seal wear, maximum torque and normal loads, are presented in Table 9 of Appendix B.

Figures I and II illustrate rub interaction torque as a function of temperature resulting from 183 and 305 m/sec (600 and 1000 ft/sec) tests respectively at a 2.54×10^{-5} m/sec (1.0 mil/sec) interaction rate. As shown by the curves, torque generated by interaction with the honeycomb material and 19% dense NiCrAlY fiber-metal was low and independent of temperature at both surface speed conditions. Torques recorded for honeycomb supported porous metal/diatomaceous earth, honeycomb supported porous cermet and coated (nichrome/glass) fibermetal were substantially higher than the honeycomb and uncoated fibermetal systems at the 183 m/sec (600 ft/sec) surface speed test condition (Figure I). In general, testing of the honeycomb supported porous metal/diatomaceous earth, honeycomb supported porous cermet and coated fibermetal systems at the faster surface speed 305 m/sec (1000 ft/sec) resulted in lower torque than the 183 m/sec (600 ft/sec) tests. Ambient temperature tests generally resulted in greater torque than tests at elevated temperatures.

Figures III and IV show rub interaction torque as a function of interaction rate for surface speeds of 183 and 305 m/sec (600 and 1000 ft/sec), respectively. Higher torques were recorded for increasing interaction rate for the honeycomb supported porous metal/diatomaceous earth and honeycomb supported porous cermet for both 183 and 305 m/sec (600 and 1000 ft/sec). However, the slower interaction rate $.254 \times 10^{-5}$ m/sec (.1 mil/sec) showed the higher torque for the coated fibermetal system, with the nichrome/glass coating producing the more severe torque (Figure III). The honeycomb system revealed a slightly higher torque reading for the slowest interaction rate at 183 m/sec (600 ft/sec) surface speed (Figure III). The uncoated NiCrAlY fibermetal system produced low torque at all test conditions.

Figure V indicates that slower surface speed will produce higher torque readings for tested materials if all other conditions are kept constant.

Volume ratio (volume of knife edge wear or pick-up divided by the volume of seal land material abraded) was plotted for the five material systems as a function of test temperature, interaction rate and surface speed (Figures VI-X). Knife edge volume was determined by the average of six pre and post test diametral measurements. The volume of seal material removed was calculated from a combination of 5 depth and chord measurements on the seal specimen.

Early testing indicated that the more rub tolerant systems did not produce sufficient knife edge wear to be accurately measured by micrometer measurement techniques. As a result, pre and post test surface traces were made with equipment such as Inde-Ron starting with Test No. 20. In addition to wear data, the traces identified the section of the knife edge which participated in the rub interaction. Volume ratios, using knife edge wear or pickup volumes calculated from these traces, are listed in Appendix B. Volume ratios calculated from micrometer measurements are also listed for comparison purposes.

Figures VI and VII show the volume ratio as a function of test temperature at an interaction rate of 2.54×10^{-5} m/sec (1.0 mil/sec) for 183 and 305 m/sec (600 and 1000 ft/sec) surface speeds, respectively. The data shows no significant wear or pickup resulted from the tests of the seal systems at these test conditions with the exception of the honeycomb supported porous cermet and coated fibermetal systems (Figure VII). The coated (nichrome/glass) fibermetal system showed a tendency for increasing volume ratios for increasing test temperature at 305 m/sec (1000 ft/sec) surface speed (Figure VII).

The effect of interaction rate on volume wear ratios is illustrated in Figure VIII and IX for 183 and 305 m/sec (600 and 1000 ft/sec) surface speed. Insignificant wear resulted from the Hastelloy-X honeycomb and sintered fibermetal tests at all test conditions depicted in these two figures. For the less rub tolerant materials, honeycomb supported porous metal/diatomaceous earth and honeycomb supported porous cermet, higher wear ratios were recorded at the faster, 25.4×10^{-5} m/sec (10.0 mil/sec) interaction rates. Both coated fibermetal materials exhibited noticeable wear at the slow, $.254 \times 10^{-5}$ m/sec (.1 mil/sec) interaction rate, less wear at the 2.54×10^{-5} m/sec (1.0 mil/sec) rate and pickup at the 25.4×10^{-5} m/sec (10.0 mil/sec) interaction rate. Significantly high wear resulted from tests at 305 m/sec (1000 ft/sec) surface speed for the honeycomb supported porous cermet system (Figure IX).

Figure X data indicates that both honeycomb supported porous metal/diatomaceous earth and honeycomb supported porous cermet result in relatively high wear at the fast interaction rate, ambient temperature conditions. This graph emphasizes that the rub mechanism for these materials varies considerably. The coated fibermetal system produces a pickup phenomenon for the 183 m/sec (600 ft/sec) and 25.4×10^{-5} m/sec (10.0 mil/sec) test conditions while for these same conditions honeycomb supported porous metal/diatomaceous earth and honeycomb supported porous cermet reveal high wear rates.

These observations pertaining to rub dynamics are based on single data points and specific test conditions. Additional testing or repeat testing should be conducted to substantiate trends in Figures I-X.

The volume wear ratio is not sufficient to compare highly abrasible seal systems, i.e. honeycomb and fibermetal. The performance of candidate seal systems must be compared by combined test observation and post test observations and appearances. For example, the honeycomb testing revealed scalloped-edge heat discoloration revealing a rub interaction temperature approximately 1366K (2000°F). These and other pertinent observations are included in Table 9 (Appendix B).

9

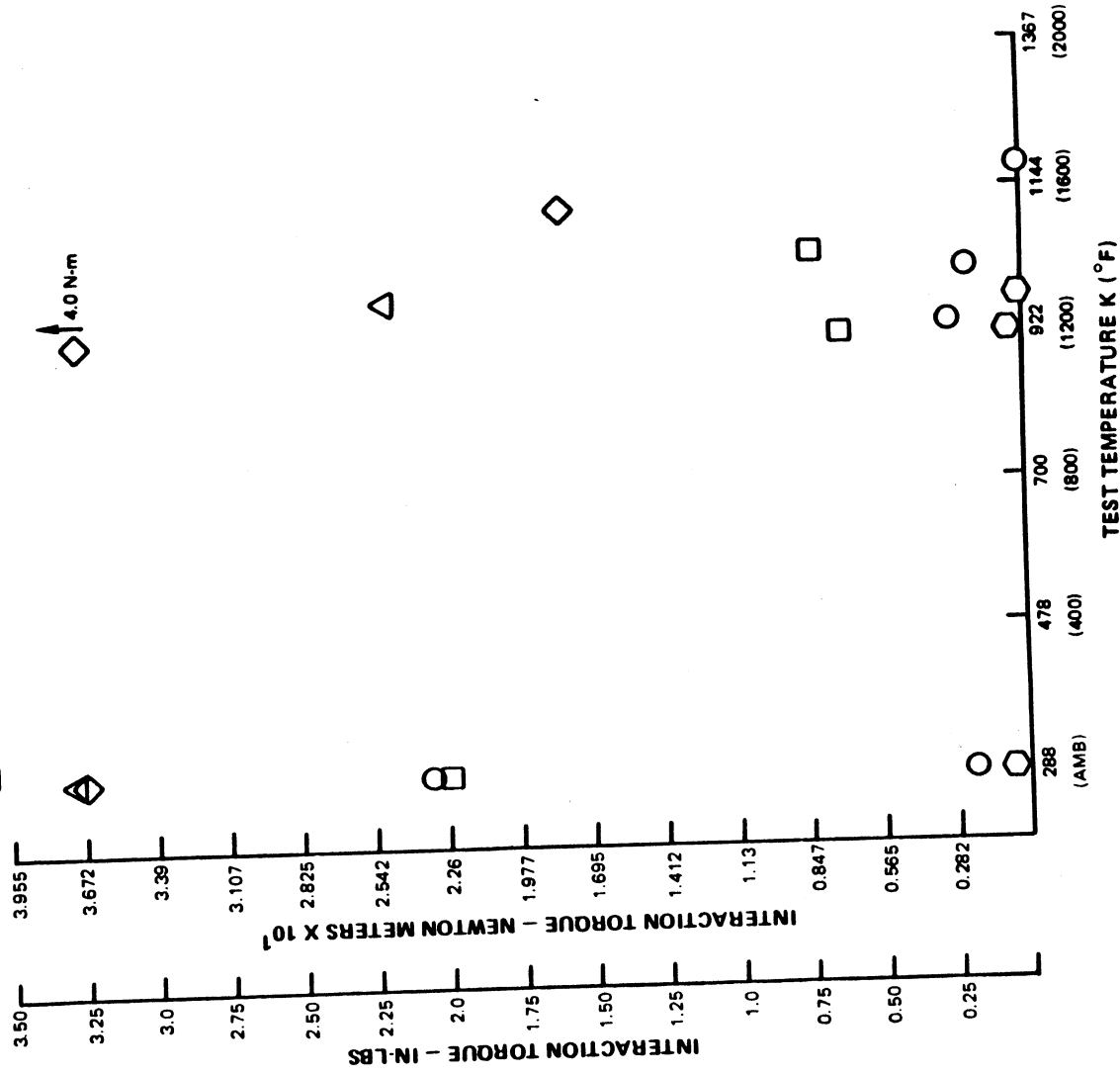
FIGURE 1
INTERACTION TORQUE VS TEST TEMPERATURE

SURFACE SPEED - 183 M/SEC (600 FT/SEC)

61 M/SEC (*200 FT SEC)

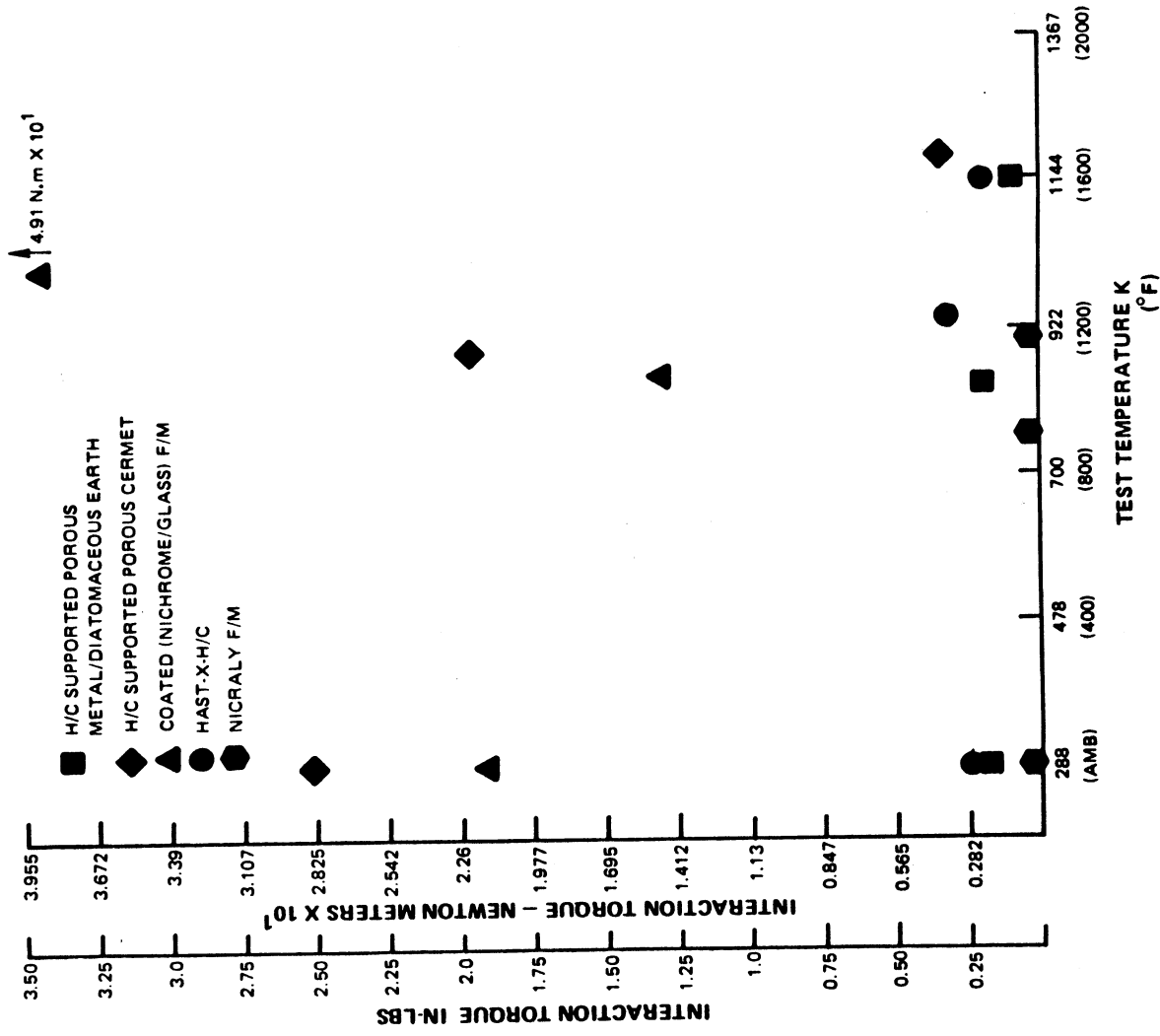
INTERACTION RATE 2.54 M/SEC X 10⁻⁵
(1.0 MIL/SEC)

- H/C SUPPORTED POROUS
- ◇ METAL/DIATOMACEOUS EARTH
- △ H/C SUPPORTED POROUS CERMET
- COATED (NICHROME/GLASS) F/M
- HAST-X/H/C
- ◇ NICKALY F/M



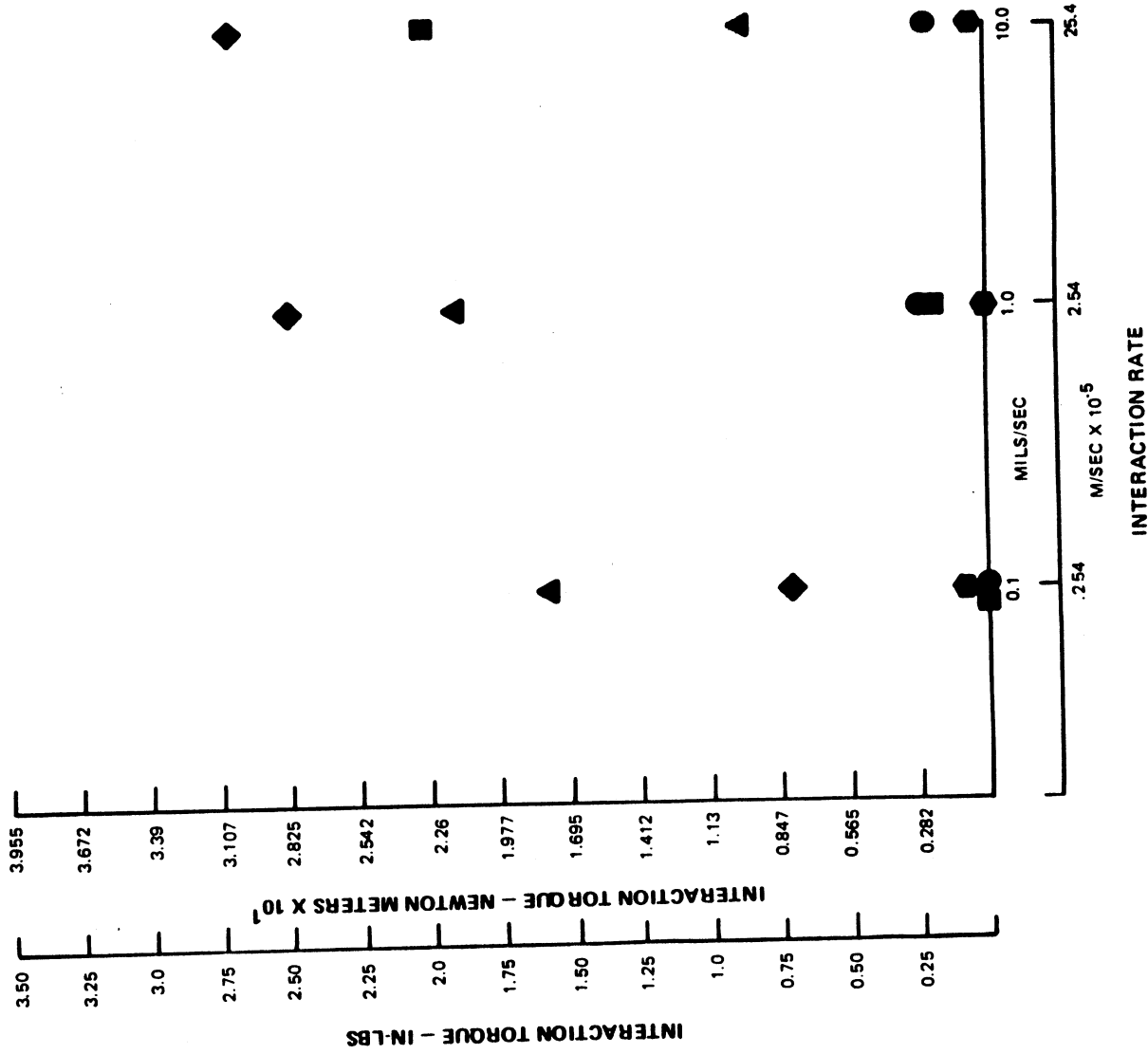
10

FIGURE II
INTERACTION TORQUE VS TEST TEMPERATURE
 SURFACE SPEED 305 M/SEC (1000 FT/SEC)
 INTERACTION RATE 2.54 M/SEC X 10⁻⁵ (1.0 MIL/SEC)



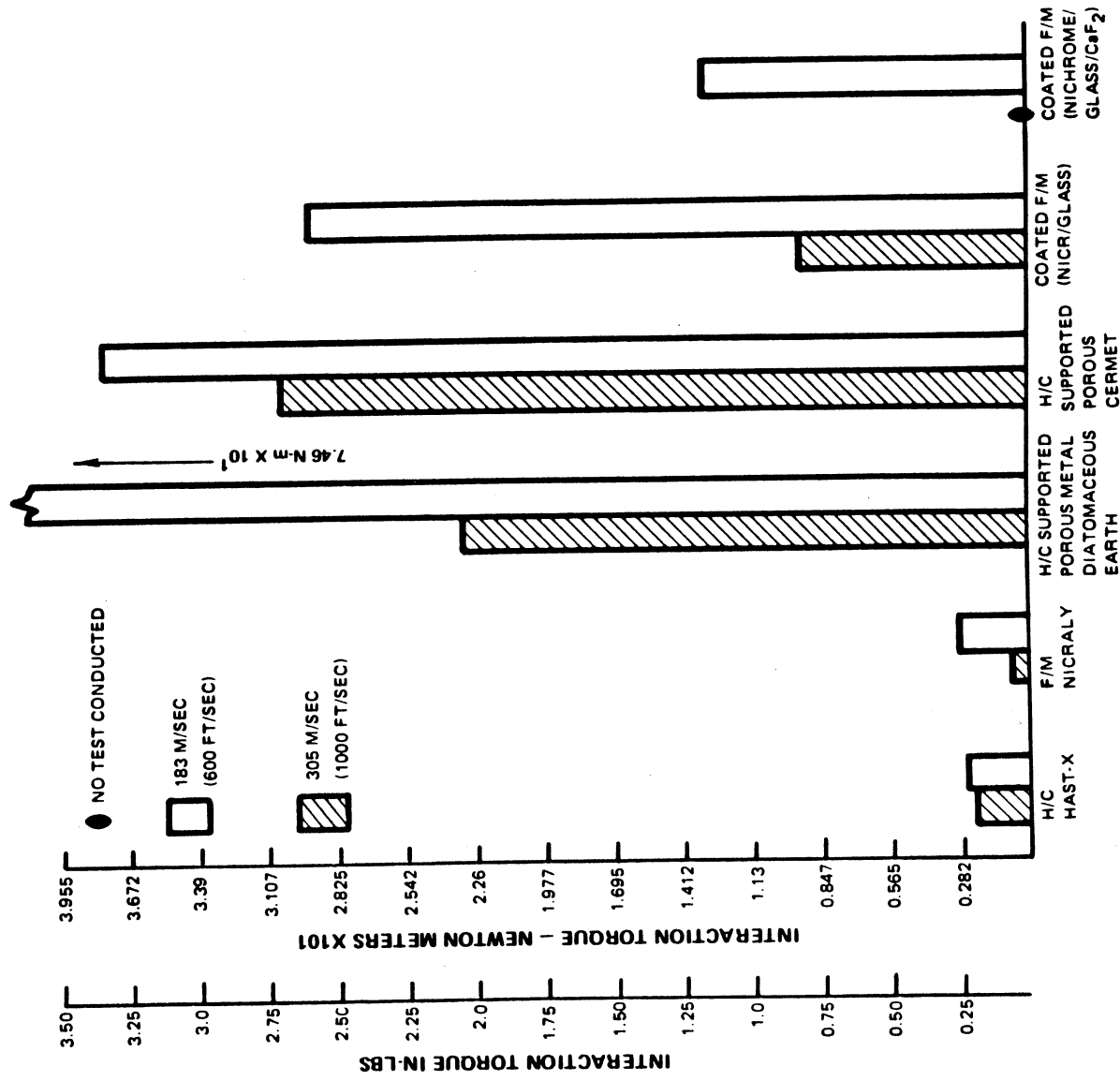
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FIGURE IV
INTERACTION TORQUE VS INTERACTION RATE
SURFACE SPEED - 305 M/SEC (1000 FT/SEC) - AMBIENT TEMPERATURE
 ■ H/C SUPPORTED POROUS METAL/DIATOMACEOUS EARTH
 ◆ H/C SUPPORTED POROUS CERMET
 ▲ COATED (NICHROME/GLASS) F/M
 ● HAST-X-H/C
 ● NICALY F/M



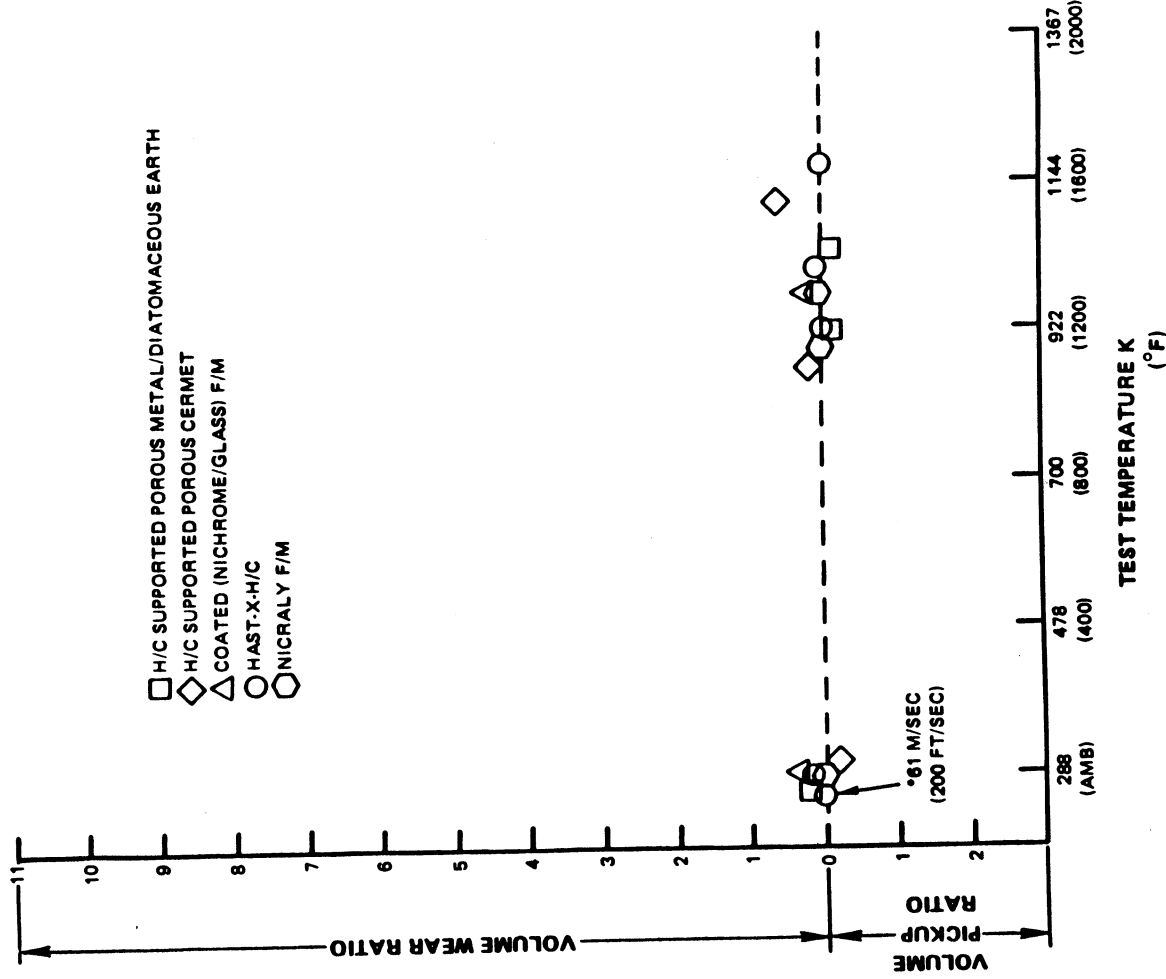
13

FIGURE V
INTERACTION TORQUE VS. SURFACE SPEED
INTERACTION RATE $25.4 \text{ M/SEC} \times 10^{-5}$ (10 MILS/SEC)
AMBIENT TEMPERATURE



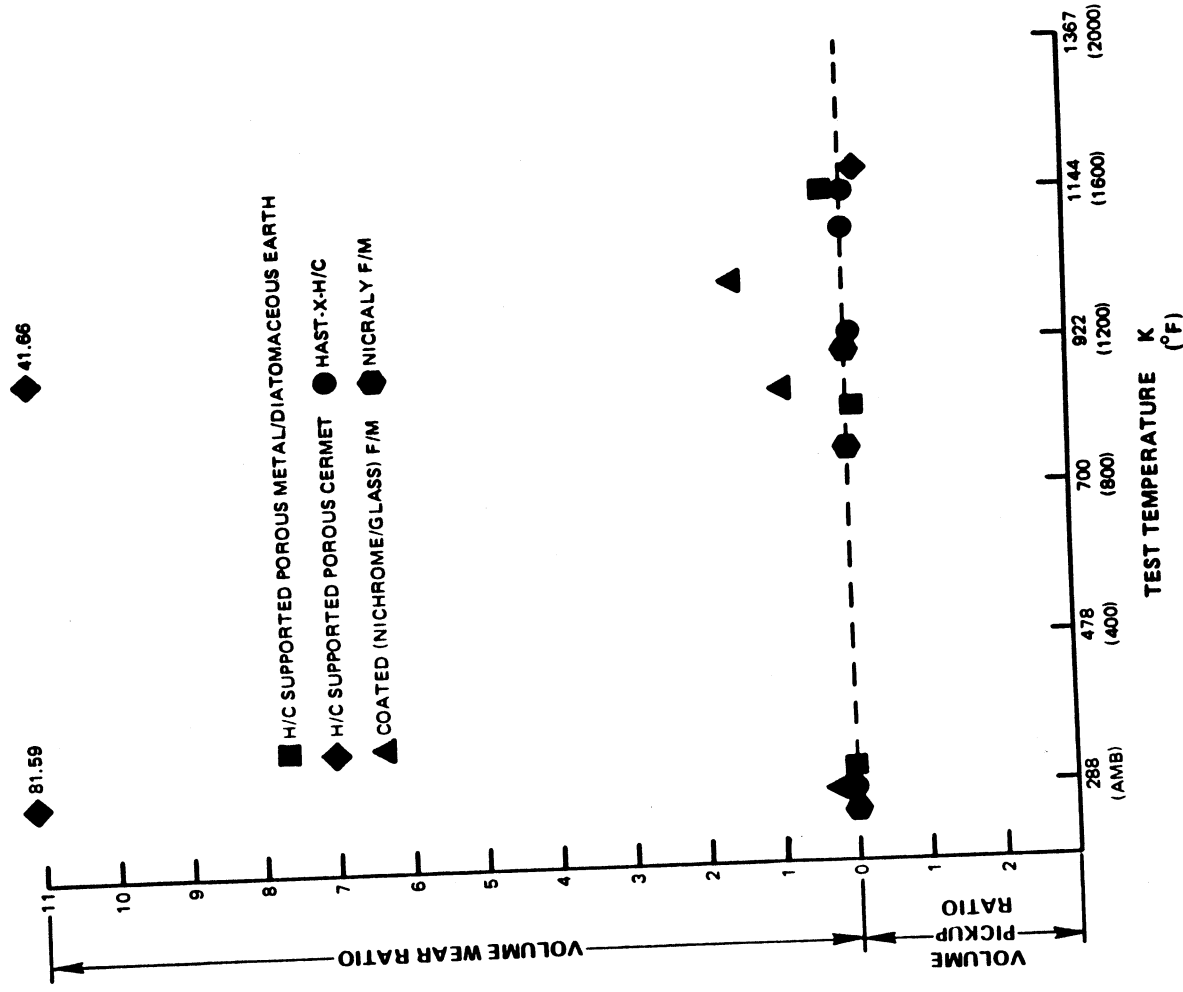
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FIGURE VI
VOLUME RATIO VS TEST TEMPERATURE
 SURFACE SPEED - 183 M/SEC (600 FT/SEC)
 INTERACTION RATE $2.54 \text{ M/SEC} \times 10^{-5}$ (1.0 MIL/SEC)



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FIGURE VII
VOLUME RATIO VS TEST TEMPERATURE
 SURFACE SPEED: 305 M/SEC (1000 FT/SEC)
 INTERACTION RATE $2.54 \text{ M/SEC} \times 10^{-5} \text{ (1.0 MIL/SEC)}$



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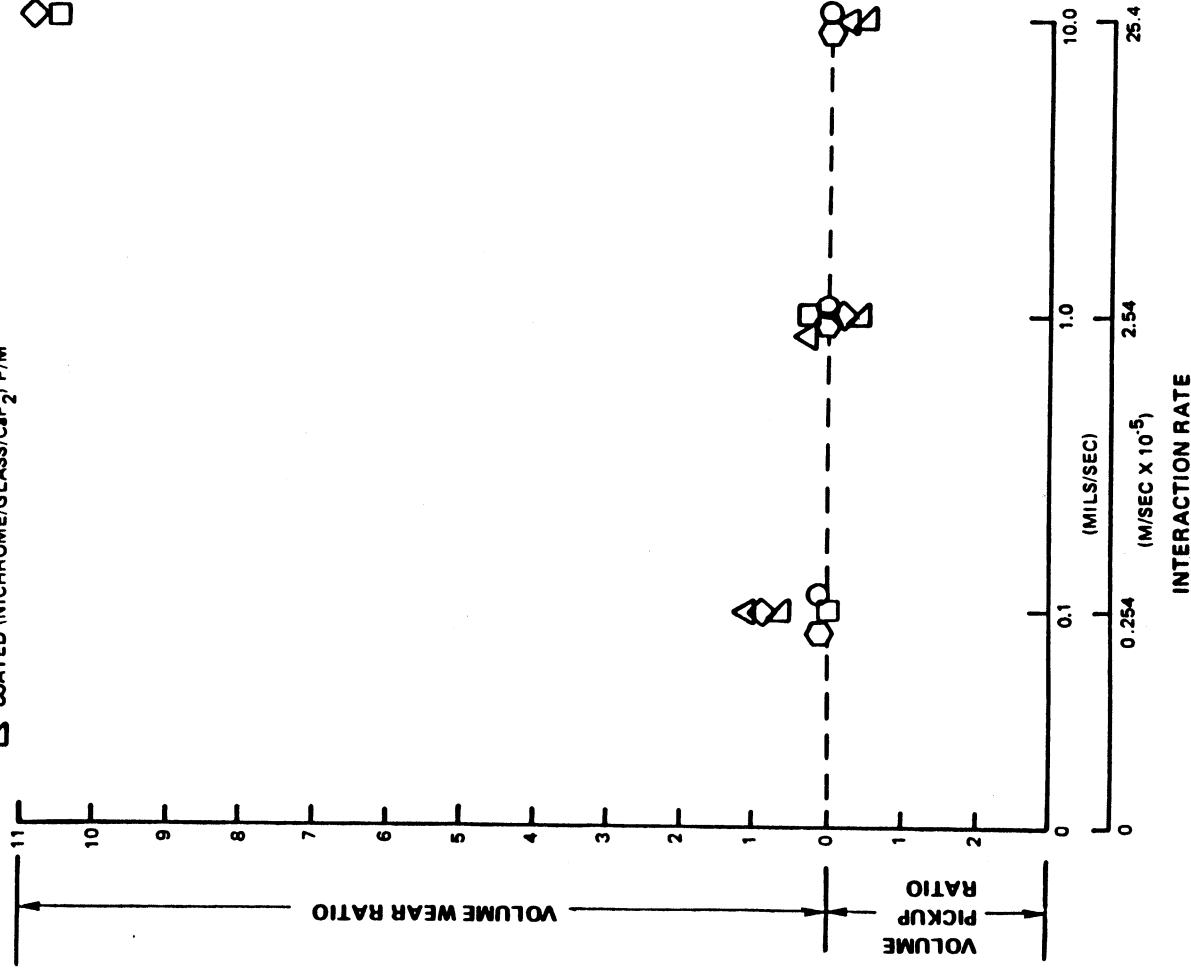
FIGURE VIII

VOLUME RATIO VS INTERACTION RATE

SURFACE SPEED - 183 M/SEC (600 FT/SEC)

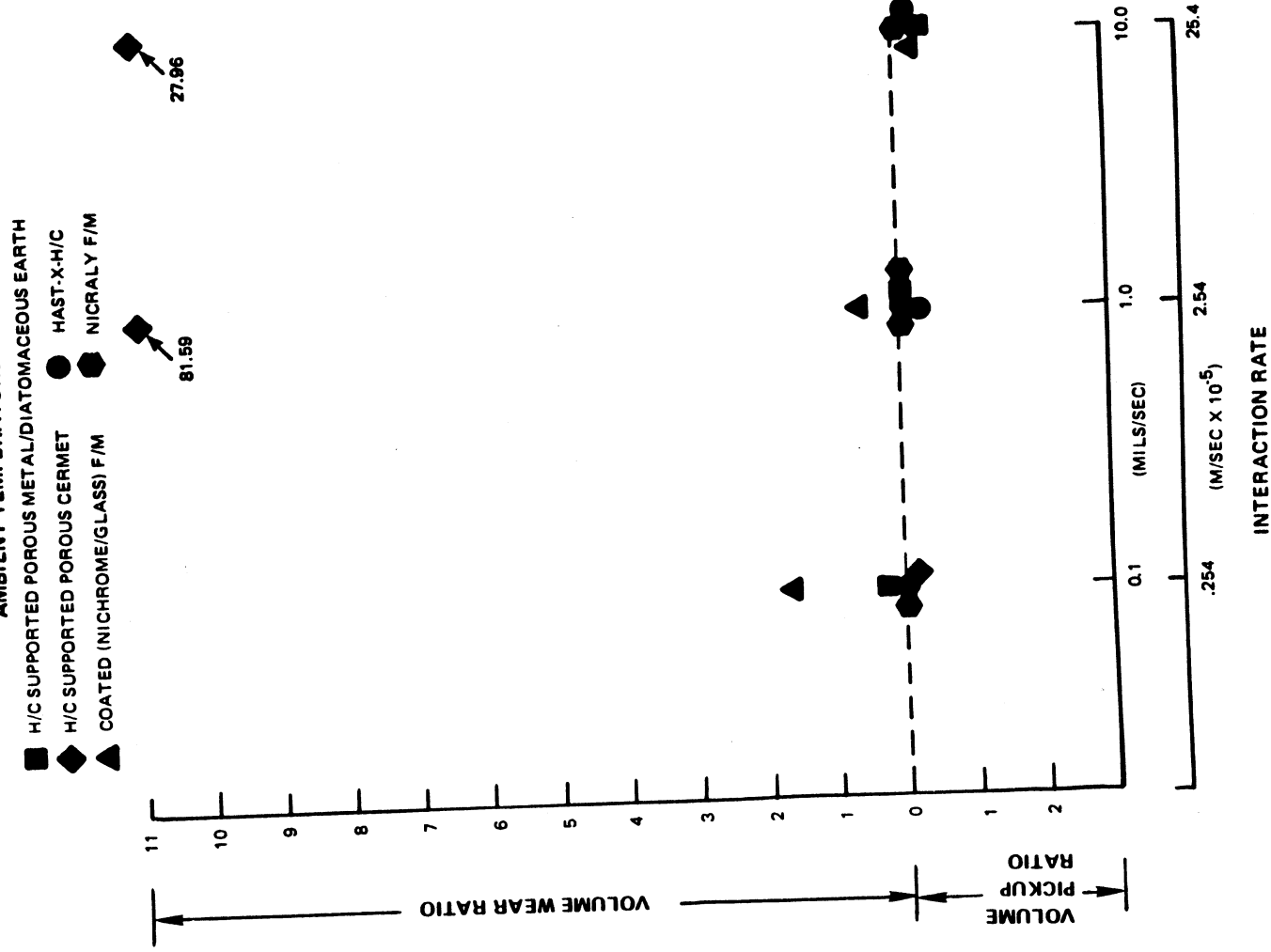
AMBIENT TEMPERATURE

- H/C SUPPORTED POROUS METAL/DIATOMACEOUS EARTH
- ◇ H/C SUPPORTED POROUS CERMET
- △ COATED (NICHROME/GLASS) F/M
- ▽ COATED (NICHROME/GLASS/CsF₂) F/M
- HAST-X-H/C
- ◊ NICALY F/M



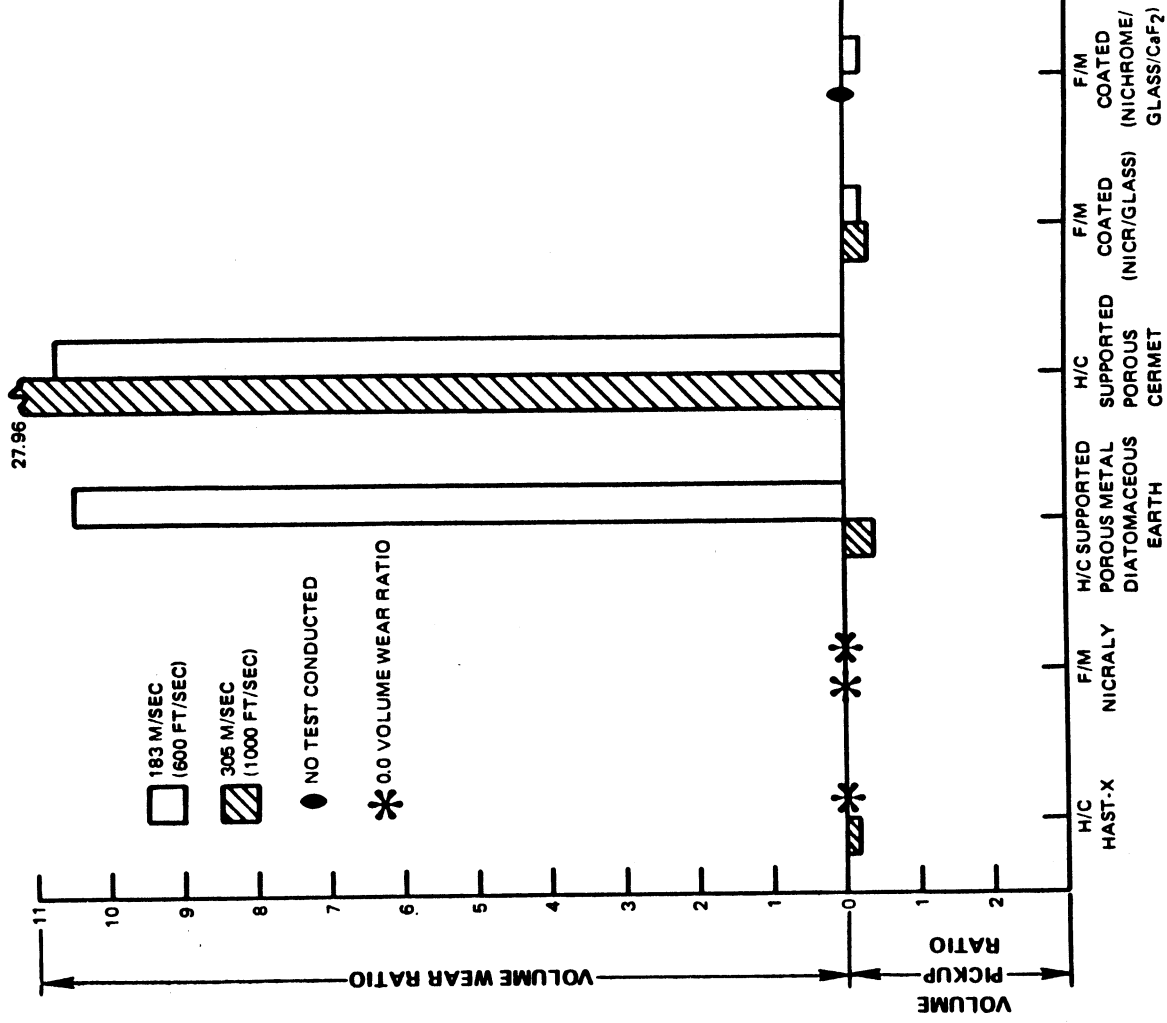
17

FIGURE IX
VOLUME RATIO VS INTERACTION RATE
SURFACE SPEED 305 M/SEC (1000 FT/SEC)
AMBIENT TEMPERATURE



18

FIGURE X
VOLUME RATIO VS SURFACE SPEED
 INTERACTION RATE $25.4 \text{ M/SEC} \times 10^{-5} \text{ (10.0 MILS/SEC)}$
 AMBIENT TEMPERATURE



B. Erosion Test Comparisons

Particulate erosion testing was conducted with size 80 grit, Al₂O₃ particles injected to the gas stream with a particulate mass flow rate of approximately 6 lbs/hr. Test time of 20 minutes was used for comparative evaluation purposes and weight measurements were taken at five minute intervals to provide information relative to the erosion/time characteristics of each seal system. Testing was conducted with a gas velocity of .35 Mach number and impingement angle of 7°. A JP5 burner was used to heat the air to required temperatures.

Since the tests were of relatively short duration the effect of long term oxidation on the structural integrity of each of the materials was not evaluated. Additional effort in this area should be pursued.

Six systems were tested for hot particulate erosion resistance in the 1033-1366 K (1400-2000°F) temperature range. For the test conditions employed, the metal/ceramic plasma sprayed coatings were shown to be the most erosion resistant structures tested. In order of decreasing erosion resistance the ranking of the remaining field is: Hastelloy-X honeycomb; honeycomb reinforced porous cermet; honeycomb reinforced porous metal/diatomaceous earth; NiCrAlY fibermetal.

The maximum depth, average width and average length erosion groove measurements are tabulated in Table 4. The weight losses for each specimen are recorded in Table 5. Weight loss data includes any gain resulting from oxidation during the test period. Volume equivalents of weight loss were determined by dividing the latter by the bulk density of the candidate materials listed in Table 6. The bulk densities (Table 6) were established through previous documentation for the honeycomb supported porous metal/diatomaceous earth, honeycomb supported porous cermet, NiCrAlY uncoated fibermetal and honeycomb systems. The bulk density for the coated fibermetal system was calculated with the distribution percentages of the spray material. Since the erosion of the coated fibermetal specimens did not advance beyond the coatings, the bulk density of the coating was used in the calculation of the volume loss.

The method of least squares was used to construct the best fit straight lines through the data points. The resultant slope of each line was converted to volume loss/unit time to obtain the steady-state erosion rates shown in Table 7. Figure XI is a graphic representation of the resultant erosion rates of the candidate materials as a function of test temperature.

Figure XI indicates that the particulate erosion resistance of the NiCrAlY fibermetal is very temperature dependent compared to the particulate erosion behavior of the other materials.

TABLE 4

Groove Measurements for Hot Particulate Erosion Specimens

Designation	Hastelloy-X	Honeycomb	NiCrAlY	Fibermetal	Honeycomb Supported Porous Metal/Diatomaceous Earth	Honeycomb Supported Porous Cermet	NiCr/Glass	NiCr/Glass/CaF ₂
K	1033	1144	1033	1033	1033	1033	1033	1033
Air Temperature	(1400)	(1600)	(1400)	(1600)	(1400)	(1400)	(1400)	(1400)
(°F)	(2000)	(1800)	(2000)	(1800)	(2000)	(2000)	(2000)	(2000)
Groove Max. Depth m (in.)	4.8 x 10 ⁻⁴	4.1 x 10 ⁻⁴	2.2 x 10 ⁻³	2.5 x 10 ⁻³	1.7 x 10 ⁻³	6.4 x 10 ⁻⁴	0.0	0.0
	(.019)	(.016)	(.088)	(.100)*	(.065)	(.025)	(0.0)	(0.0)
Groove Average Length m (in.)	3.46 x 10 ⁻²	3.61 x 10 ⁻²	3.45 x 10 ⁻²	3.44 x 10 ⁻²	3.63 x 10 ⁻²	3.33 x 10 ⁻²	0.0	0.0
	(1.362)	(1.422)	(1.360)	(1.357)	(1.430)	(1.312)	(0.0)	(0.0)
Groove Average Width m (in.)	1.72 x 10 ⁻²	1.87 x 10 ⁻²	1.55 x 10 ⁻²	1.56 x 10 ⁻²	1.91 x 10 ⁻²	1.23 x 10 ⁻²	0.0	0.0
	(.680)	(.737)	(.610)	(.621)	(.752)	(.485)	(0.0)	(0.0)
	2.12 x 10 ⁻²	2.13 x 10 ⁻²	1.93 x 10 ⁻²	1.93 x 10 ⁻²	1.93 x 10 ⁻²	1.79 x 10 ⁻²	0.0	0.0
	(.836)	(.839)	(.763)	(.763)	(.761)	(.704)	(0.0)	(0.0)
	1.41 x 10 ⁻²	1.41 x 10 ⁻²	1.41 x 10 ⁻²	1.41 x 10 ⁻²	1.41 x 10 ⁻²	1.32 x 10 ⁻²	0.0	0.0
	(.556)	(.556)	(.556)	(.556)	(.556)	(.521)	0.0	0.0
	1.17 x 10 ⁻²	1.17 x 10 ⁻²	1.17 x 10 ⁻²	1.17 x 10 ⁻²	1.17 x 10 ⁻²	1.36 x 10 ⁻²	0.0	0.0
	(.459)	(.459)	(.459)	(.459)	(.459)	(.536)	0.0	0.0

*Eroded to base metal.

TABLE 5
Cumulative Weight Loss (gms.) due to Hot Particulate Erosion

Designation	Test Temperature K	Test Temperature (°F)	Elapsed Time (Min.)				
			5	10	15	20	
			Weight Loss (gms.)				
Hastelloy-X Honeycomb	1033	(1400)	0.025	0.041	0.068	0.091	
	1144	(1600)	0.012	0.031	0.050	0.065	
	1255	(1800)	0.018	0.037	0.060	0.085	
	1366	(2000)	0.025	0.047	0.085	0.119	
NiCrAlY Fibermetal	1033	(1400)	1.026	1.495	1.602	1.765	
	1144	(1600)	0.910	1.392	1.748	1.958	
	1255	(1800)	1.328	1.864	2.328	2.751	
	1366	(2000)	1.890	2.636	Base Metal Exposed		
Honeycomb Supported Porous Metal/Diatomaceous Earth	1033	(1400)	0.980	1.274	1.660	1.884	
	1144	(1600)	0.820	1.258	1.505	1.740	
	1255	(1800)	0.841	1.216	1.479	1.690	
	1366	(2000)	0.415	0.647	0.936	1.156	
Honeycomb Supported Porous Cermet	1033	(1400)	0.176	0.260	0.311	0.368	
	1144	(1600)	0.105	0.237	0.319	0.392	
	1255	(1800)	0.140	0.361	0.450	0.540	
	1366	(2000)	0.360	0.495	0.596	0.674	
NiCr/Glass	1033	(1400)	0.037	0.071	0.097	0.137	
	1366	(2000)	*+0.015	0.005	0.025	0.055	
NiCr/Glass/CaF ₂	1033	(1400)	0.103	0.152	0.197	0.227	
	1366	(2000)	*+0.121	+0.131	+0.121	+0.101	

*Initial weight gains observed during the 1366 K (2000°F) are probably the result of oxidation of the coatings and fibermetal substructure.

TABLE 6
Bulk Densities of Seal Systems

<u>Designation</u>	<u>Bulk Density (g/cc)</u>
Hastelloy-X Honeycomb	1.23
NiCrAlY Fibermetal	1.37
Honeycomb Supported Porous Metal/Diatomaceous Earth	2.6
Honeycomb Supported Porous Cermet	3.1
NiCr/Glass	5.16
NiCr/Glass/CaF ₂	4.53

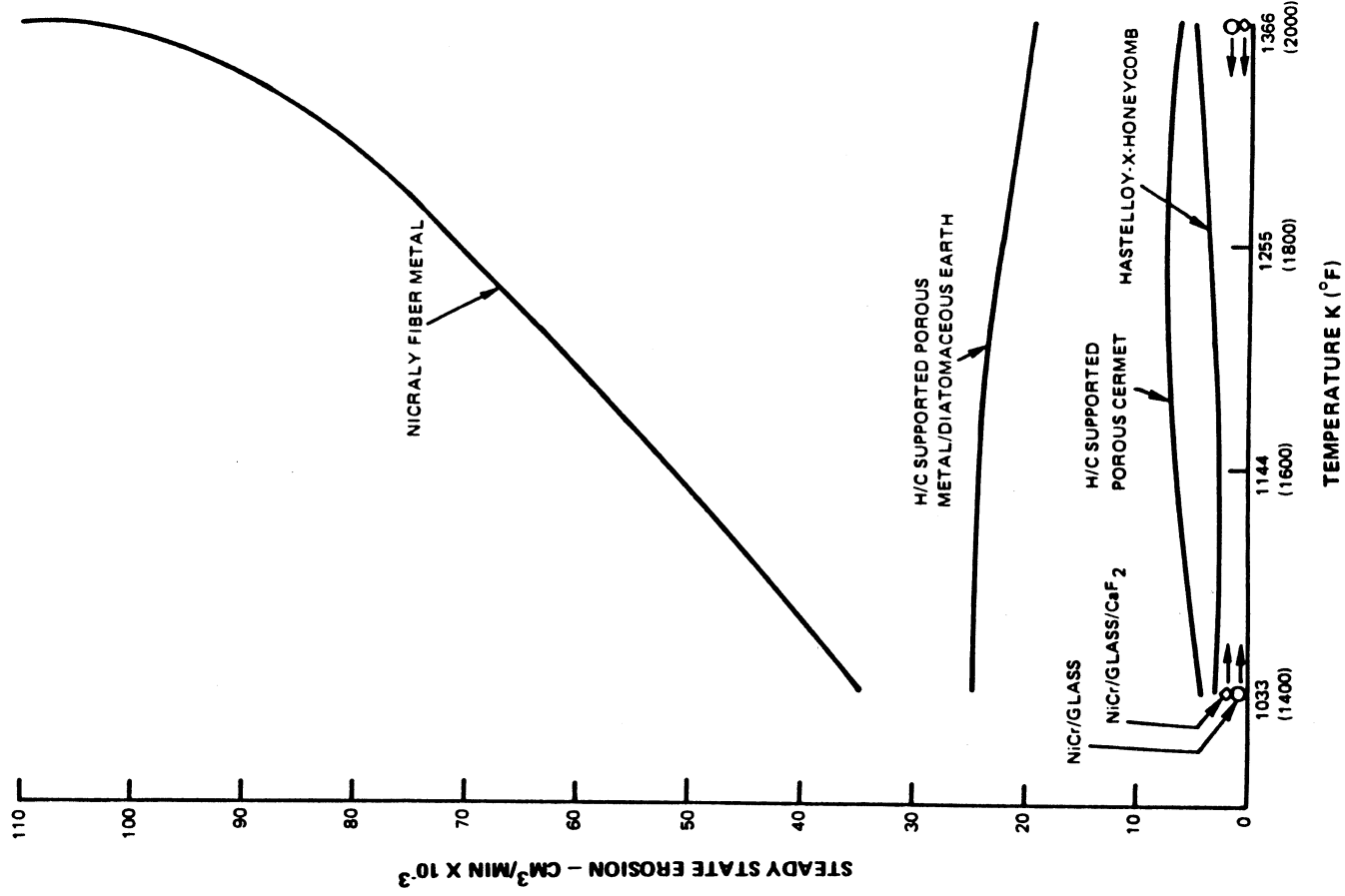
TABLE 7
Calculated Particulate Erosion Rates
for Candidate Materials - 10^3 cc/min.

Designation	(1400°F) 1033 K	(1600°F) 1144 K	(1800°F) 1255 K	(2000°F) 1366 K
Hastelloy-X Honeycomb	3.68	2.90	3.62	5.18
NiCrAlY Fibermetal	33.9	51.1	69.1	108.8
Honeycomb Supported Porous Metal/Diatomaceous Earth	23.86	23.11	21.59	19.32
Honeycomb Supported Porous Cermet	4.04	6.10	8.30	6.70
NiCr/Glass (1)	1.02			0.9
NiCr/Glass/CaF ₂ (1)	1.82			0.7

(1) Plasma sprayed coatings were not penetrated by the erosive media.
The fibermetal sublayers were not taken into account during calculations.

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FIGURE XI
VOLUME LOSS PARTICULATE EROSION RATES
AS A FUNCTION OF TEMPERATURE FOR
TURBINE GAS PATH SEAL CANDIDATE MATERIALS



C. Rub Debris and Rub Path Analysis

Analysis of rub debris particles included microscopic examination depicting particle shape, weight of debris collected and particle size distribution for the five abrasible gas path seal systems (Table 8). Rub debris particles were assessed and classified by microscopic point count techniques to determine particle size distribution. Debris was analyzed from test conditions of 183 m/sec (600 ft/sec) surface speed, 25.4 x 10-5 m/sec (10.0 mil/sec) interaction rate, and ambient temperature. The results indicate that the debris deposits of NiCrAlY fibermetal have the largest distribution of large particles (20% of 50-100 micron particles) compared to the other materials analyzed. The particles did not appear to be discrete fibermetal fibers but a combination of pulled-out material and fractured fibers. This phenomena may be related to the low rub temperature generation and excellent abrasability characteristics of the fibermetal system. The remaining material deposits consisted of approximately 90% distribution of particles in the < 50µ range.

Although not shown in Table 8 because the percentage was insignificant, the honeycomb test produced the largest size particles. Few particles in the vicinity of 400µ were observed in the honeycomb debris.

Figures XII and XIII show pictorially the particle debris appearance with the corresponding test numbers enumerated. In assessing the significance of rub debris data it is important to note that all tests involved only a radial penetration into the seal. During engine operation an axial traverse would be expected in addition to radial movement. The effect of this axial movement on rub debris particle size and distribution has yet to be evaluated.

To complete the rub analysis of the tests from which debris was analyzed, the seal specimens were sectioned to metallographically investigate the effect of the rub on the specimen microstructure. This analysis of the rub paths of the five seal systems revealed that the NiCrAlY fibermetal and honeycomb systems produced the cleanest, low distress rub paths. The coated fibermetal rub path showed noteworthy densification below the rub surface with thermal cracking at the surface and up the walls of the groove. Both the honeycomb supported porous metal/diatomaceous earth and honeycomb supported porous cermet showed rather heavy knife edge transfer on the rubbed surface. Thermal cracking of the transfer was evident on the honeycomb supported porous metal/diatomaceous earth. Details of each of the rub path analysis as well as scanning electron microscope results are presented under the "Individual System Results" in Section IV.

TABLE 8

Rub Debris Characterization

Results:

Macroscopic Examination:

Test #14 Hastelloy-X Honeycomb	Test #28 NICKRAIL Fibermetal	Test #33 Honeycomb Supported Porous Metal/Diatomaceous Earth	Test #35 Honeycomb Supported Porous Cermet	Test #38 Coated (Nichrome/Glass) Fibermetal
Deposit consisted predominantly of metallic particles (<25µ) with few larger metallic chips and shavings also present.	Deposit consisted predominantly of metallic shavings, curls, and irregular-shaped fragments and particles.	Deposit consisted predominantly of metallic spheres (<25µ) with few elongated grooved metallic shavings also present	Deposit consisted predominantly of jagged, irregularly-shaped metallic splinters, shavings, and particles.	Deposit consisted predominantly of metallic spheres and irregular metallic particle (<50µ) with few abrasive crystals also present.

Contaminant Recovered mg:

Particle Count Data:

Numerical Percent Distribution

Range, µ	5-15	15-25	25-50	50-100	100-150	150-200	* 200
Contaminant Recovered mg:	50.3	33.8	12.6	54.5	16.4	32.7	46.0
Particle Count Data:	3.6	17.7	1.8	0.9	0.9	2.4	1.2
Numerical Percent Distribution	5.2	119.4	13.0	6.5	0.7	0.8	0.7

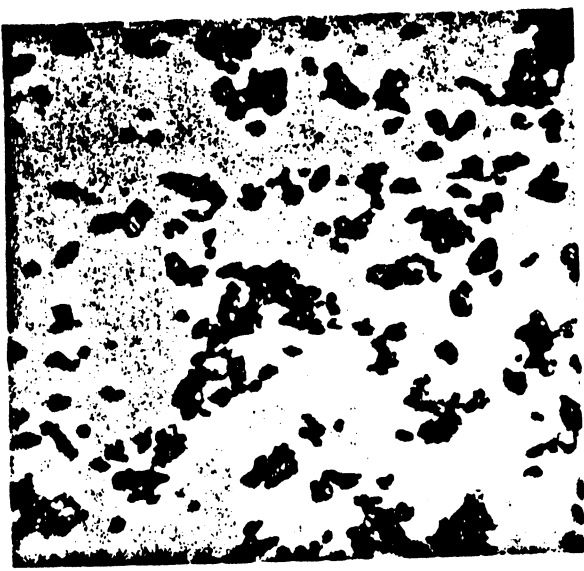
* Particles greater than 400 microns but insignificant percentages of total distribution

27

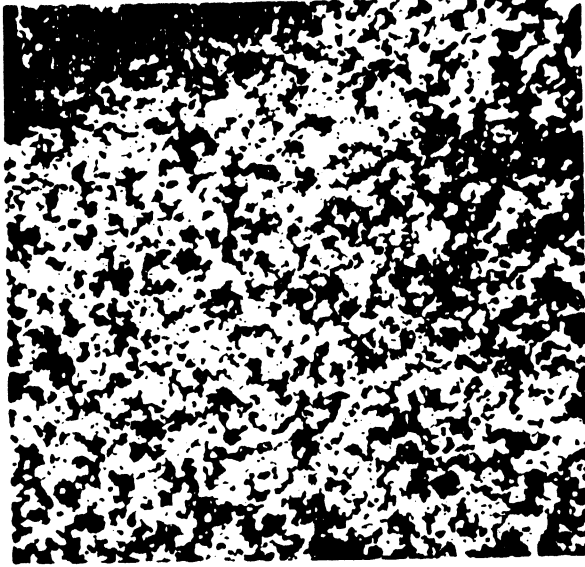
Figure XII
Wear Debris Analysis



Test # 14
Hast-X Honeycomb



Test # 28
NiCrAlY Fiber-Metal



Test # 33
Honeycomb supported porous
metal/diatomaceous earth

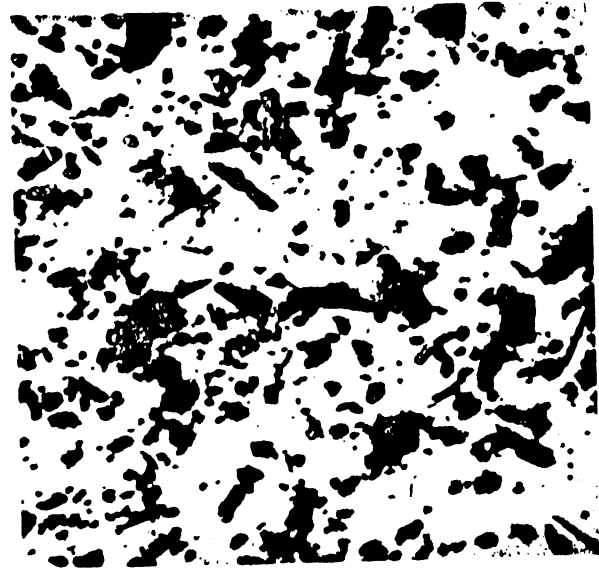
Mag: 40X

PAGE #27

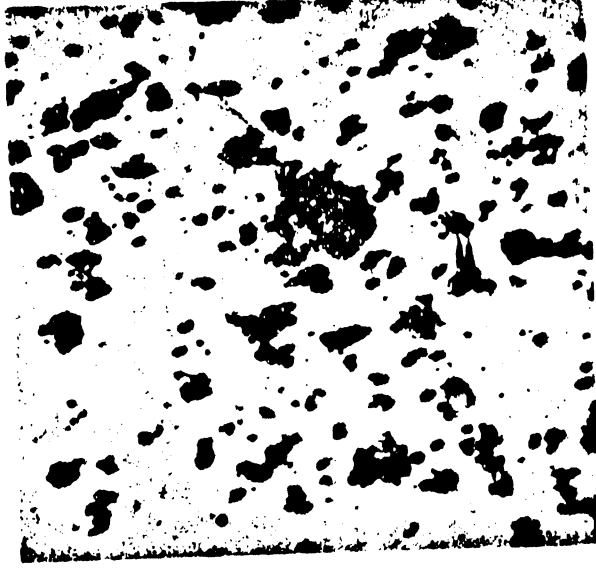
XPN-48613

28

Figure XIII
Wear Debris Analysis



TEST #35
Honeycomb supported
porous cermet



TEST #38
Coated (Nichrome/glass)
Fiber metal

Mag: 40X

PAGE #28

XPN-48614

IV. INDIVIDUAL SYSTEM RESULTS

Abradability tests revealed several interesting trends with respect to knife edge wear and/or pickup as a function of interaction rate for several of the seal systems. Details of these test trends, high response thermal instrumentation test data, rub path analysis and erosion test results for each system are discussed in this section. (Debris particle analyses were presented in Section III to facilitate a complete comparative evaluation of all five seal systems.)

A. Hastelloy-X Honeycomb

Low knife edge wear and torque were measured in all of the experiments performed on Hastelloy-X honeycomb. However, some scalloped edge heat discoloration resulted on the knife edge from temperatures, measured by an optical pyrometer, of approximately 1366K (2000°F). The localized heat discoloration marks are evidence that actual knife edge contact with the honeycomb specimen was discontinuous. Appearance of a typical post-test knife edge is presented in Figure XIV. The microsectioning of the seal specimen for Test #14 indicated light transfer of knife edge material in the rubbed area. The rubbed area was also characterized by plastic deformation of braze (AMS 4728) and honeycomb (AMS 5536) material (Figure XV).

Figure XVI presents information obtained from the high thermal response instrumentation, Test No. 57. The test set-up is described in Appendix A. Photograph XVI A shows temperature peaks for the No. 1 pyrometer (120° from bottom of rub specimen) and No. 2 pyrometer (90° from No. 1 pyrometer) at approximately 20 seconds into the 30 second test. The temperature peaks correspond to 1311K (1900°F) and 1122K (1560°F) for pyrometer No. 1 and 2 respectively. Photograph (B) shows an enlargement of a temperature peak of 1311K (1900°F) at approximately the same time of interaction. A reference point with the disk circumference was incorporated into the horizontal axis and provides a means of determining the location of temperature profile peak on the knife edge outer diameter circumference.

The appearance of the eroded surfaces of the erosion samples was characterized by deformation of the uppermost portions of the cell walls in the direction of particulate flow. The edges of the deformed metal appear ragged and indicated metal tearing. Cracks also appeared at the "feathered" locations (Figure XVII). With one exception, weight and volume loss due to particulate erosion showed a decrease in erosion resistance with increasing test temperature. This relationship is to be expected from mechanical properties and high temperature oxidation data as a function of temperature for Hastelloy-X material. At 1033, 1144, 1255, and 1366 K (1400°, 1600°, 1800° and 2000°F) the volume erosion rate was 3.68, 2.80, 3.62 and 5.18×10^{-3} cc/min respectively. At 1033K (1400°F), a greater volume loss occurred than was expected from tensile and fatigue properties of the AMS 5536 material (Table 5). This result is most probably due to the lower ductility of the alloy at 1033K (1400°F) since the ductility of AMS 5536 increase significantly between 1033K (1400°F) and 1144K (1600°F) temperature.

30

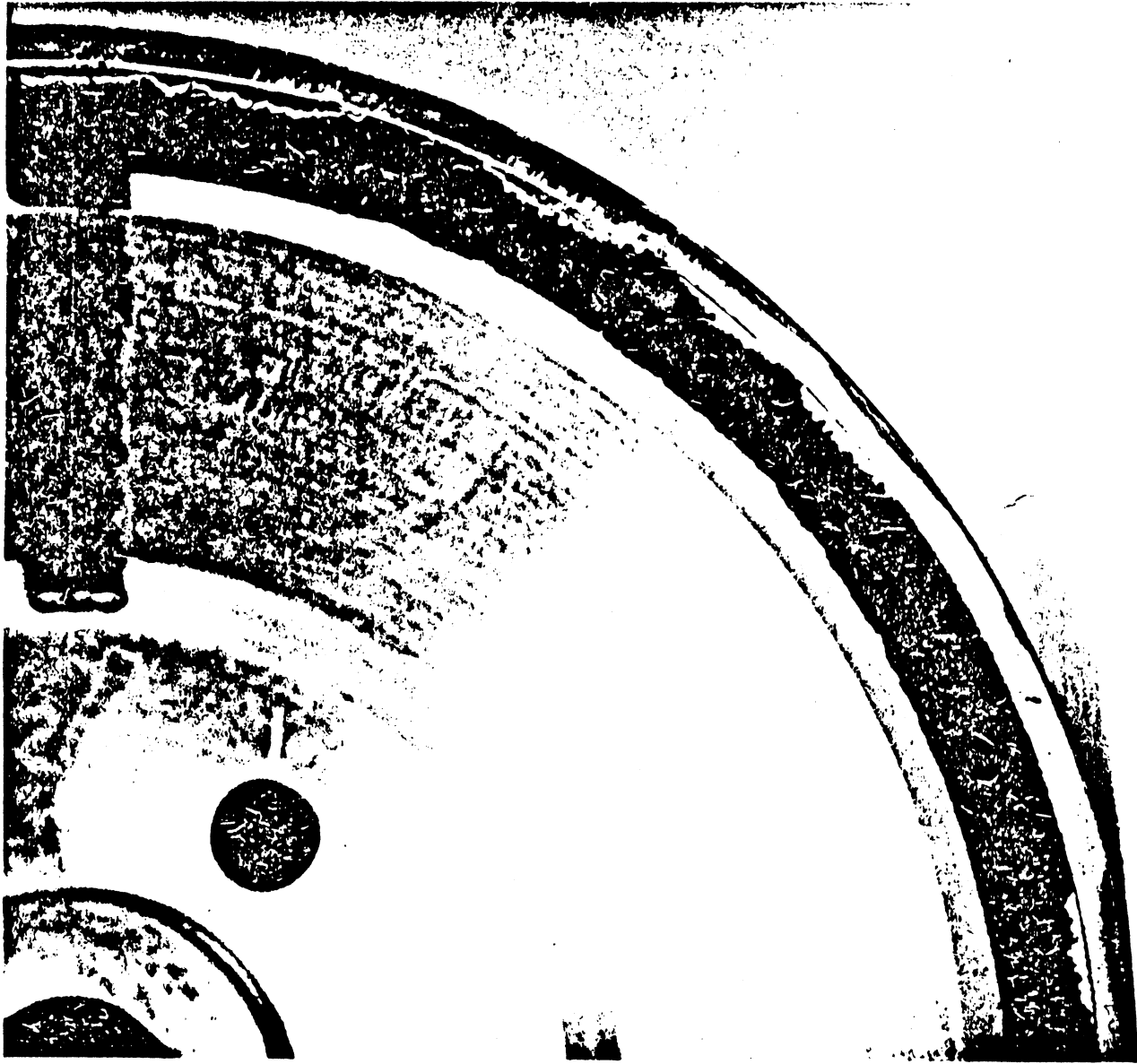


Figure XIV

Test No. 13 .020" WASPALOY disk SKN 59606 S/N 1. Test conditions:
ambient, 600 FPS, .030" rub at .0001"/sec interaction rate. Segment
was 1/16" (.004") hast-x, hex cell honeycomb SKN 56386.
4/19/74

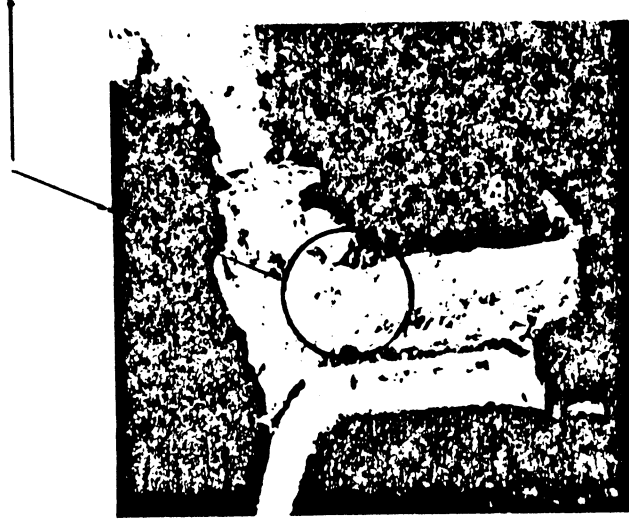
31



~200X



~200X



~50X

A

Figure XV

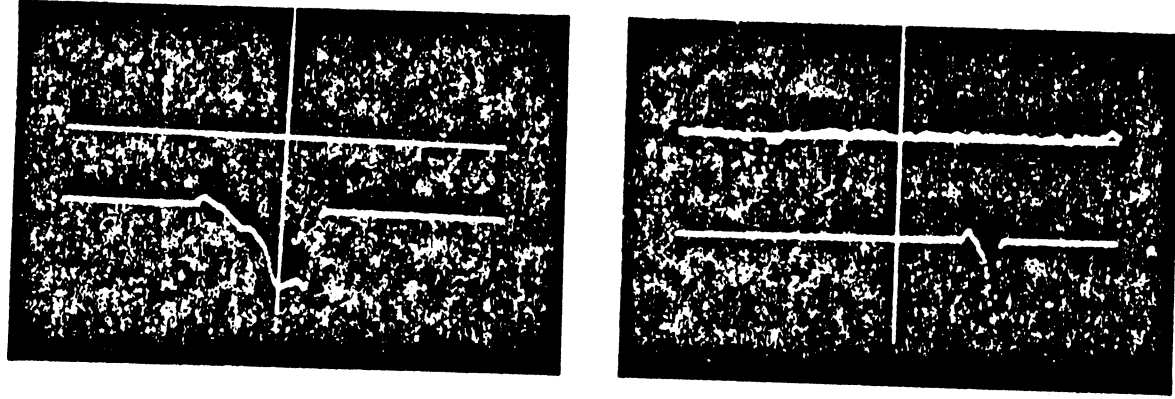
Knife edge abrasability test specimen - test # 14: 1/16 inch hexagonal cell AMS 5536 honeycomb. (A) and (B): rubbed node area; (C): unrubbed node area (wickered braze alloy exposed at surface). Note Machine-chip appearance of debris on rubbed surface.

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FIGURE XVI
HIGH THERMAL RESPONSE INSTRUMENTATION
(MEMORY SCOPE)
HASTELLOY - X HONEYCOMB TEST #57



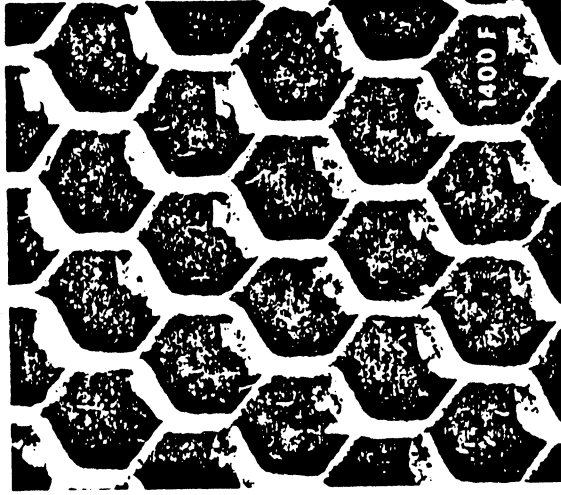
(A)

TOP LINE - NO. 1 PYROMETER
1311 K (1900° F)
BOTTOM LINE - NO. 2 PYROMETER
1104 K (1560° F)
(90° FROM PYROMETER 1)

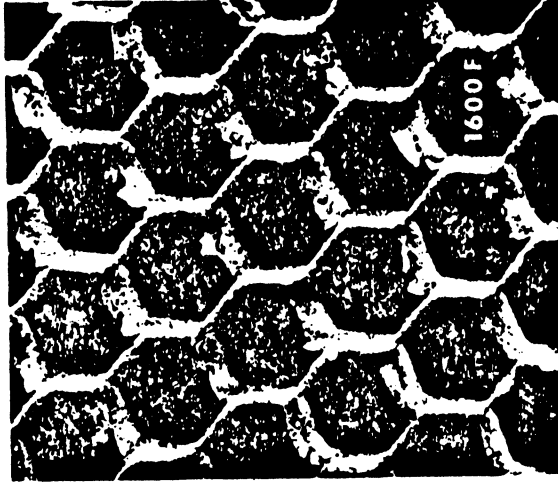
(B)

ENLARGEMENT OF PEAK OF
PYROMETER NO. 1 AT APPROXIMATELY
SAME TIME OF INTERACTION.
PEAK SHOWS PROFILE SPAN OF 20°
ARC ON KE OD CIRCUMFERENCE WITH
TEMPERATURE OF 1311 K (1900° F).

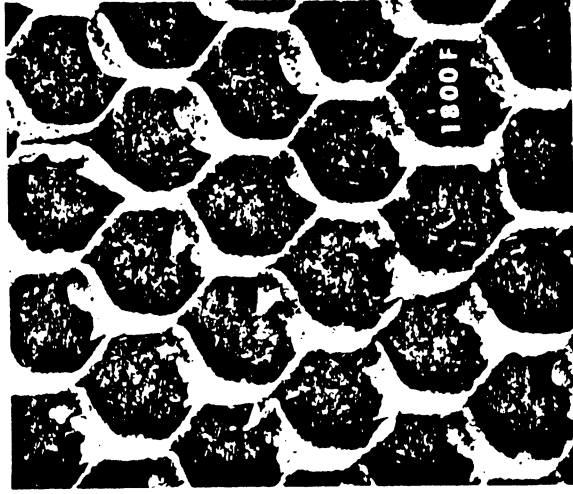
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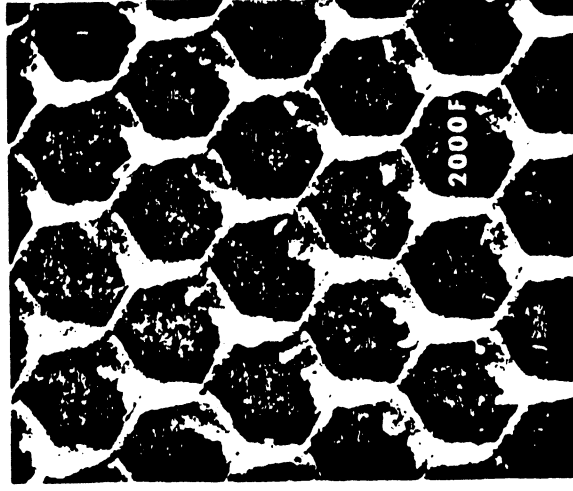
S/N 1 MA 488-5



S/N 2 MA 488-6



S/N 3 MA 488-7



S/N 4 MA 488-8



Figure XVII

Post-particulate erosion impingement surfaces of 1/16 inch hexagonal cell, 4 mil AMS 5536 honeycomb test specimens. Test temperatures are indicated. Arrow indicates particle flow direction.

Mag: 10X

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B. NiCrAlY Fibermetal

The NiCrAlY fibermetal system showed the best rub tolerance but the least erosion resistance of all the candidate seal materials. No knife edge wear and very low torque resulted from all test points. Test No. 28 (surface speed 183 m/sec (600 ft/sec) and 25.4×10^{-5} m/sec (10.0 mil/sec) interaction rate) produced the highest interaction torque and the only knife edge pickup occurrence for the fibermetal system (Figure XVIII). Even though this particular test produced the highest interaction torque for this system, the overall maximum reading was still much lower than all other systems with the exception of the honeycomb material. The test No. 28 specimen was sectioned and revealed flattening and very slight densification of fibers at the surface of the rub path (Figure XIX). Fracture of fibers and a limited amount of plastic flow were observed in the rub path. Elements characteristic of Waspaloy knife edge material were detected on the rubbed surface but no discrete particles or heavy smear deposits of the knife edge material were located. The groove was uniform with no signs of any heat generated during the interaction. There was an absence of the scalloped-edge heat discoloration noted in the honeycomb system. The high thermal response instrumentation test, No. 58, revealed no rub generated temperature peaks exceeding 811K (1000°F) (equipment low temperature base level) compared to the 1311K (1900°F) temperature peaks viewed for the honeycomb system.

Although maximum size of the debris particles of this system was less than that of the other four systems, it contained a relatively high percentage of intermediate size particles (54% in the 25-50 micron size range).

The surface of the erosion specimen showed selective fiber removal and complete loss of the characteristic fibrous structure in the areas receiving the greater concentration of erosive media. With additional microscopic examination, the surface material in this area appeared to be agglomerated fibers "welded" together due to particulate bombardment (Figure XX). The erosion characteristics of the NiCrAlY fibermetal are greatly influenced by the material's porous structure and to a lesser degree by the bulk physical properties of the NiCrAlY material. The erosion rates of 33.9, 51.1, 69.1 and 108.8 x 10⁻³ cc/min followed the trend expected.

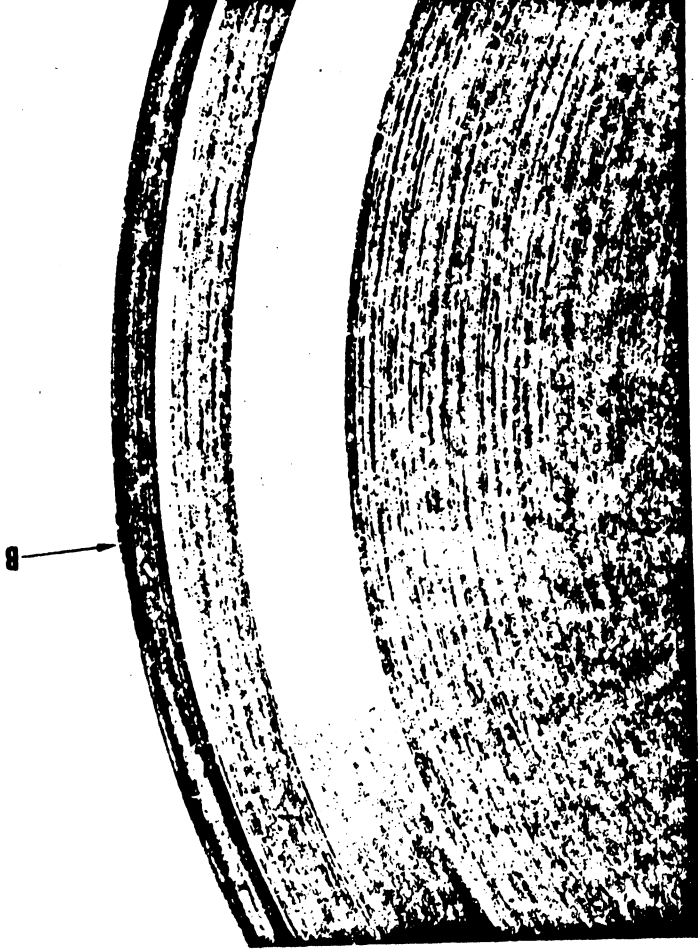
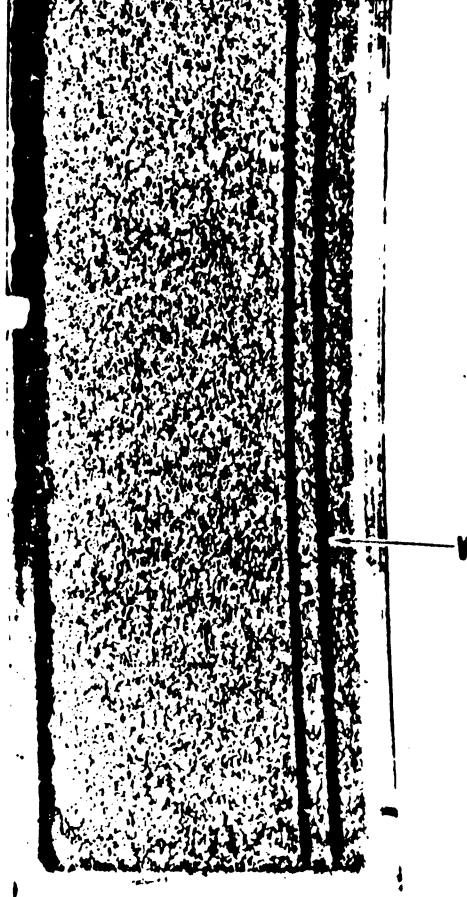


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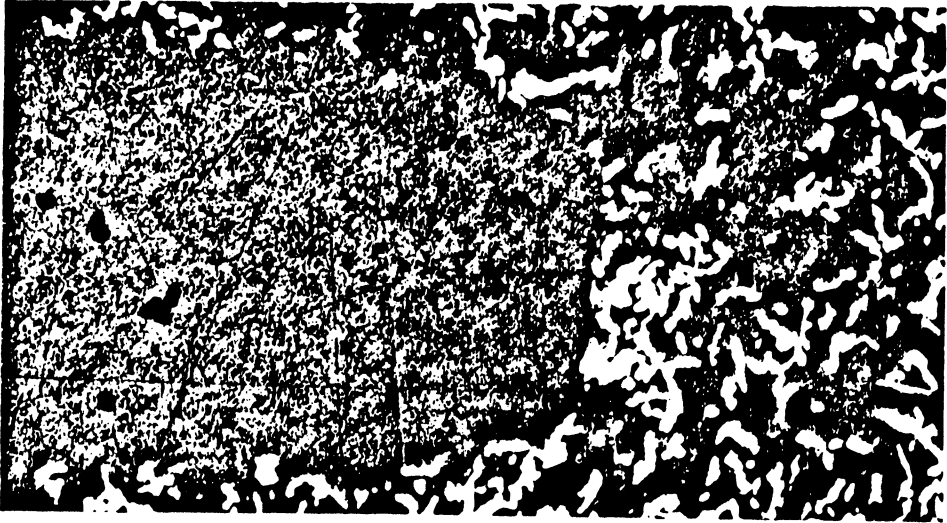
Test #28 - 65435-4-35, date 5/10/74, 19% micraloy F/M seal land (right rub) vs. .020 WAsPAlOY KE-S/N #3, interaction rate 10.0 MPS for 30 mils depth, surface speed 600 FPS, amb temp. 0 wear but 2 mil KE pickup one location. A.) Test #27 test conditions 1000 FPS, amb-temp 10.0 MPS interaction rate. B.) Pick-up material.

Figure XVIII



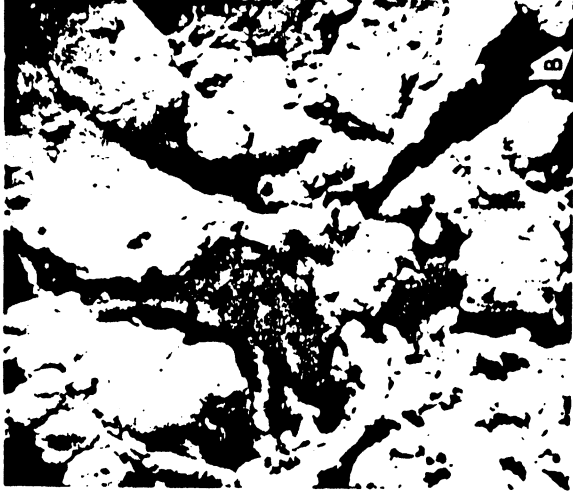
35

36

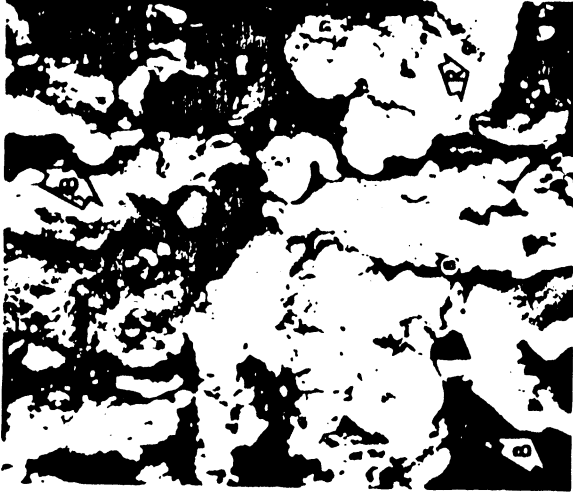


M74105

100X



SEM ~500X

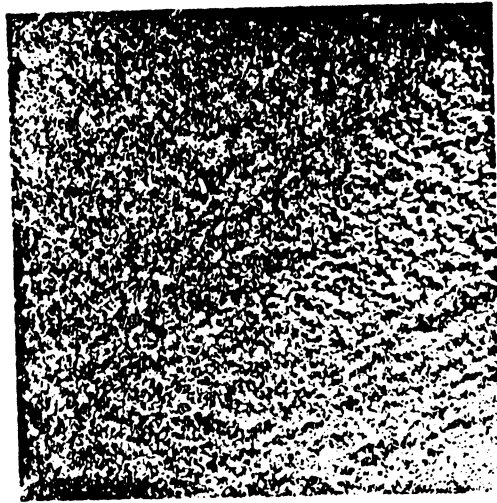


SEM ~500X

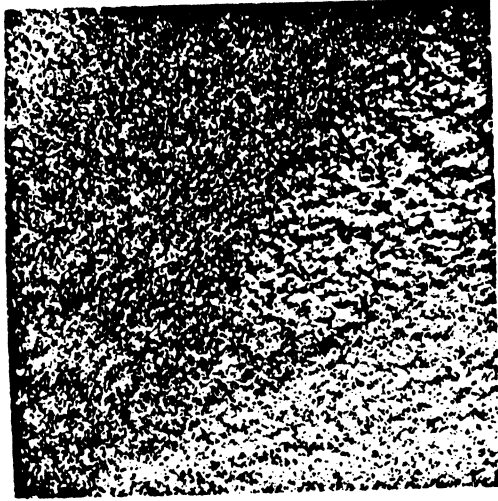


Figure XIX
Knife edge abrasability test specimen - test # 28: 19% dense NiCrAlY fiber metal. Microsection of rub groove showing densification at the bottom of the groove. SEM photographs of surface fibers in bottom of groove. Note broken bond sites (B) and striations caused by rub motion (R).
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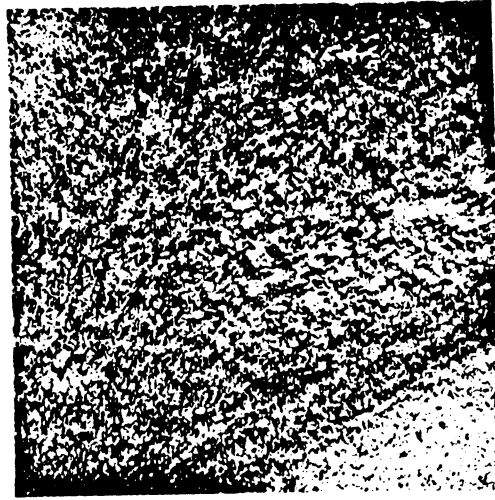
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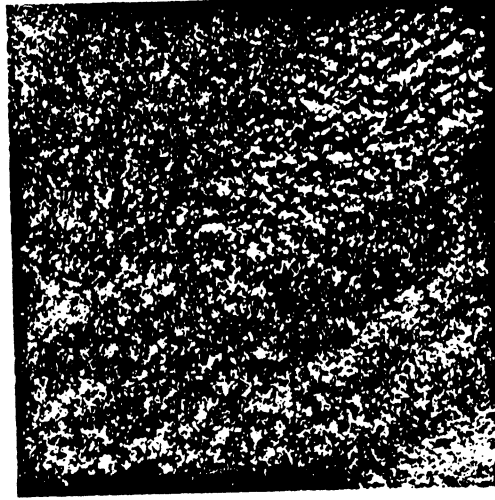
S/N 5



S/N 7



S/N 11



S/N 12

Figure XX

Post-particulate erosion impingement surfaces of 19% dense NiCrAlY fiber metal test specimens. Test temperatures are indicated. Arrow indicates particle flow direction.
Mag: 2X

K-9864

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C. Honeycomb Supported Porous Metal/Diatomaceous Earth

Honeycomb supported porous metal/diatomaceous earth seal material exhibited high wear at specific test conditions. The low surface speed 183 m/sec (600 ft/sec) and the fast interaction rate 25.4×10^{-5} m/sec (10.0 mil/sec) produced the most severe wear condition. Trends pertaining to both interaction rate and surface speed are illustrated in Figure XXI. The data indicates a trend toward greater wear with increasing interaction rate at 183 m/sec (600 ft/sec) surface speed. At a faster speed, 305 m/sec (1000 ft/sec), increasing the interaction rate to 25.4×10^{-5} m/sec (10.0 mil/sec) produced a knife edge pickup phenomena. Figure XXII is the post-test photograph of Test No. 33 (surface speed 183 m/sec (600 ft/sec) at 25.4×10^{-5} m/sec (10.0 mil/sec) interaction rate) which resulted in the high wear rate of 10.5 on the volume wear factor scale. The photograph shows knife edge material lining the grooved area and the knife edge "mushrooming" at the outer diameter. The high wear rate resulted from knife edge transfer to the seal segment and corresponding interaction between the knife edge and knife edge transferred material. This type of interaction, Ni vs. Ni, has proven to be a severe rub mode for abrasability testing. The microsection of Test No. 33 (Figure XXIII) revealed a plastically deformed dense lining built up on either side and on the bottom of the rub groove. The deposit was identified as knife edge material. Elements characteristic of Hastelloy-X honeycomb were also found in the dense layer, but the honeycomb walls were hidden by the smeared metal. Cracks appeared perpendicular to the rub arc across the rub floor as a result of thermal stresses occurring during specimen cooling (Figure XXIV).

Examination of the honeycomb supported porous metal/diatomaceous earth erosion specimens revealed flattened surface particles in the eroded area of the specimens. The matrix material within each of the individual cells of the honeycomb reinforcement showed a greater loss of material just aft of the protective honeycomb walls, Figure XXV. This material revealed a small but continuous decrease in steady state erosion rate with increasing test temperature. Volume erosion rates of 23.86, 23.11, 21.59, and 19.32×10^{-3} cc/min. resulted from testing at 1033, 1144, 1255 and 1366K (1400°, 1600°, 1800° and 2000°F) temperatures, respectively. The reasons for this unusual behavior are not known and cannot be explained at this time.

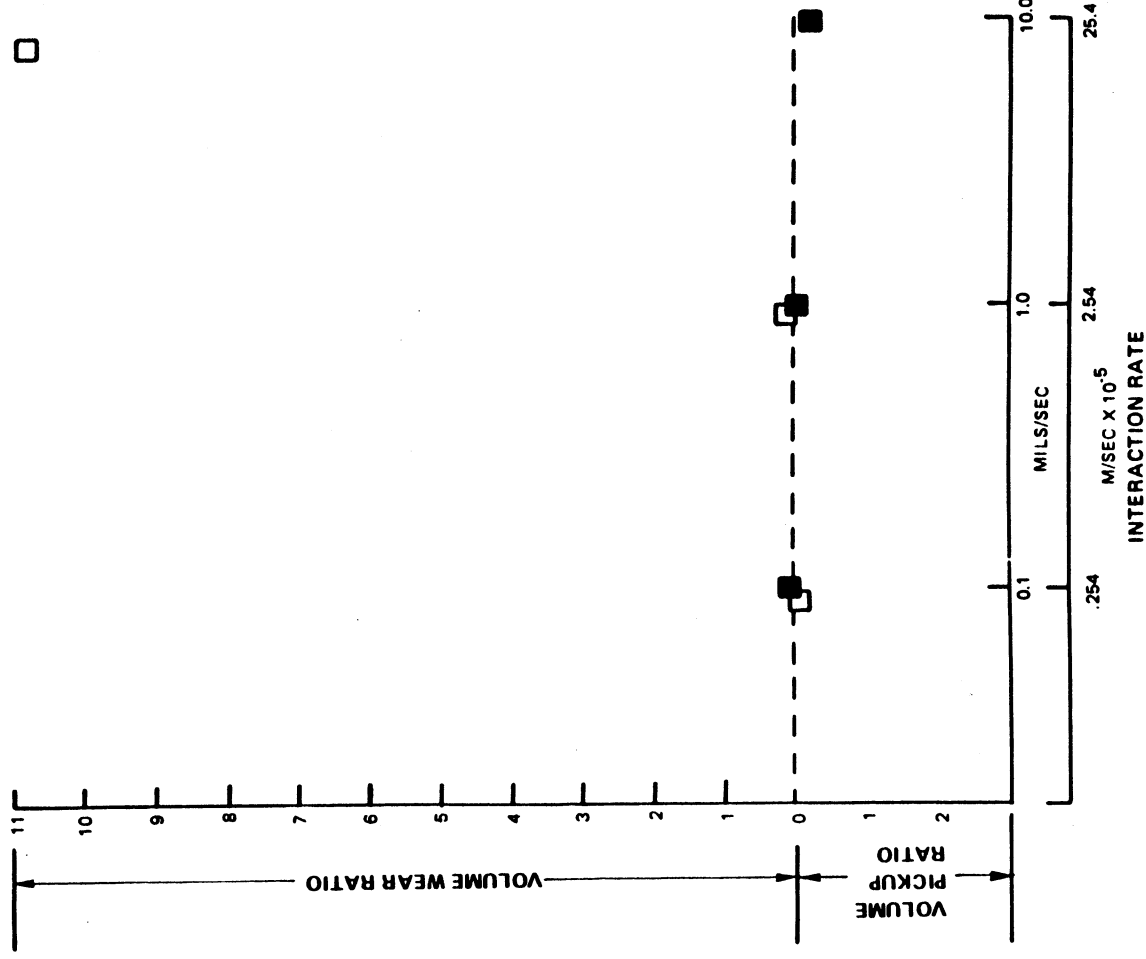
In total, this honeycomb supported material system resulted in significant particulate erosion even to the base metal at the point of introduction of flow of the erosive media.

39

FIGURE XXI
VOLUME RATIO VS INTERACTION RATE
H/C SUPPORTED POROUS METAL/DIATOMACEOUS EARTH MATERIAL
AMBIENT TEMPERATURE

□ 183 M/SEC
(600 FT/SEC)

■ 305 M/SEC
(1000 FT/SEC)

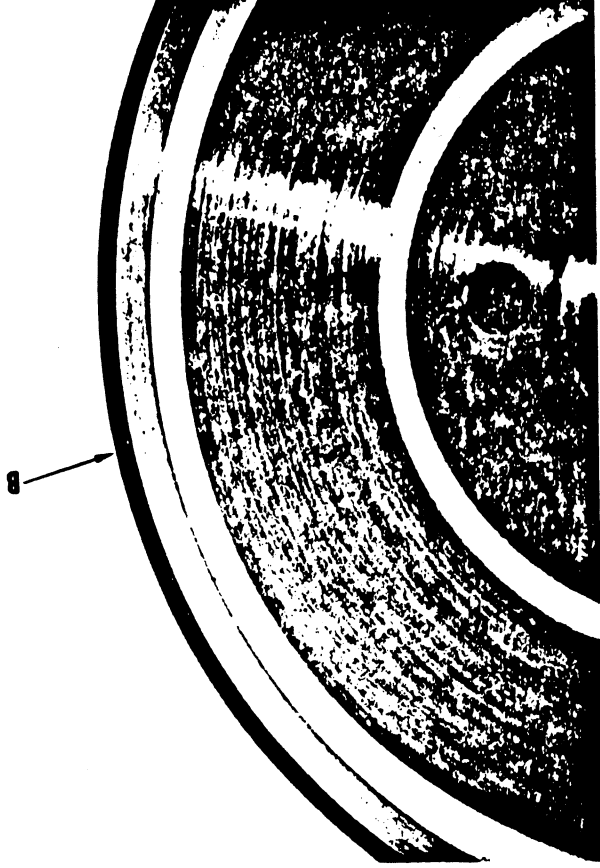
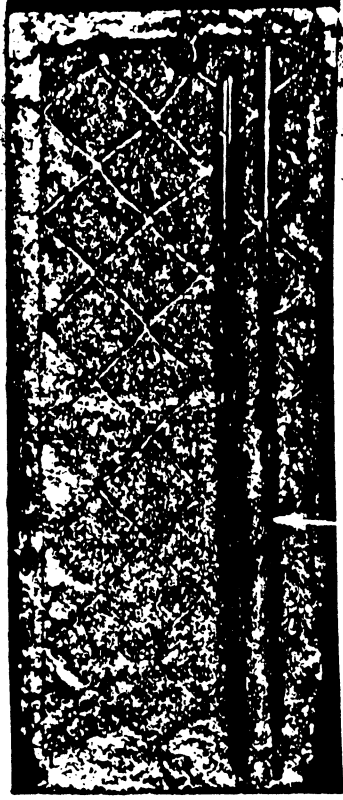


XFN-46669



Figure XXII
Test #33-65435-4-42, date 5/23/74, Honeycomb supported porous metal/
diatomaceous earth seal land (right rub) vs. .020 WASPALLOY KE-S/N 3,
interaction rate 10 MPS for 30 mil depth, surface speed 600 FPS, Temp-
Amb., .0133 radial KE wear, note-seal sample material lining grooved
area. A) Test #32 Test conditions 1000 FPS, Amb-Temp, 10.0 MPS
Interaction rate B.) Knife edge foldover.
6/5/74

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40



Figure XXIII

Knife edge abrasability test specimen - test #33: honeycomb supported porous metal/diatomaceous earth. Microsection of groove shows knife edge material in oxide and parent metal phases (arrows). Large knife edge mass (K) is actually above pre-test surface level (L).
Mag: 100X

K-9856

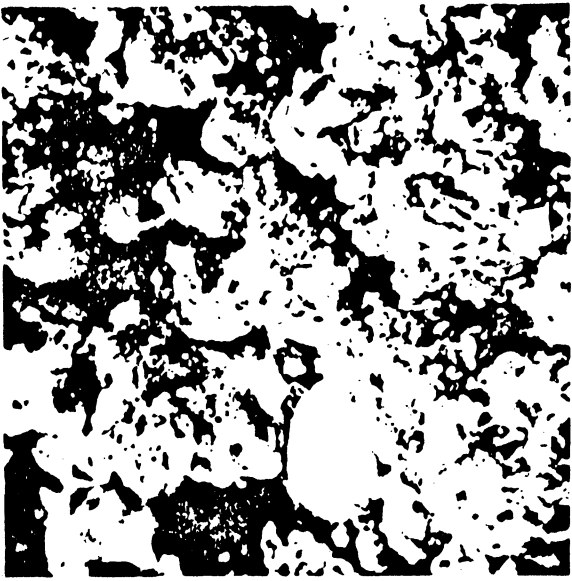
PAGE #41



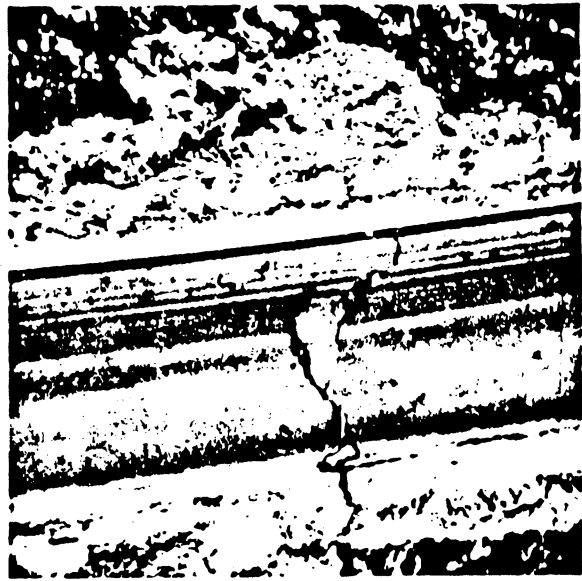
42



2X



SEM ~500X

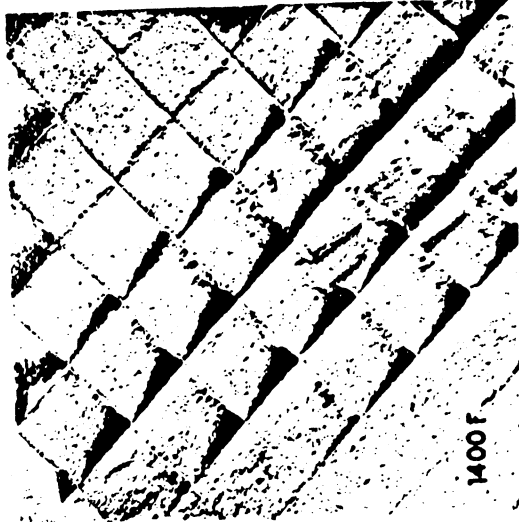


SEM ~50X

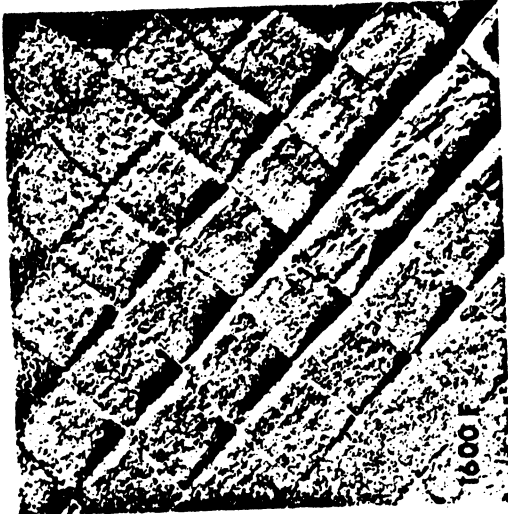


Figure XXIV
 Knife edge abrasability test specimen - test #33: honeycomb supported porous metal/diatomaceous earth. Arrow indicates point of maximum penetration and location of microanalyses. SEM photographs represent the unaffected surface structure and rub groove with surrounding structure. Axial crack is a result of thermal stresses occurring on cooling.

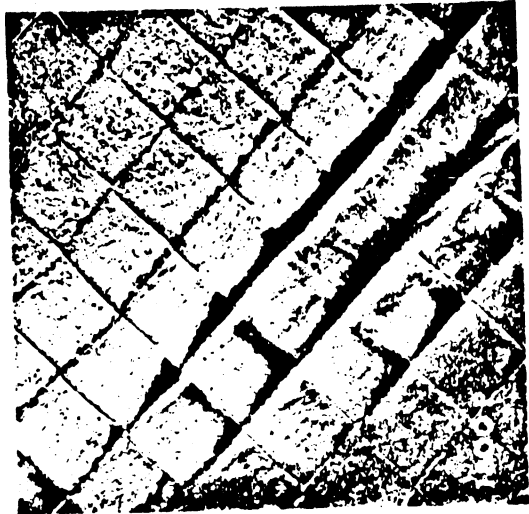
43



S/N E838-1



S/N E838-2



S/N E838-3



S/N E838-5



Figure XXV
 Post particulate erosion impingement surfaces of honeycomb support-
 ed porous metal/diatomaceous earth test specimens. Test temperatures
 are indicated. Arrow indicates particle flow direction.
 Mag: 2X
 K-9851
 PAGE #43

D. Honeycomb Supported Porous Cermet

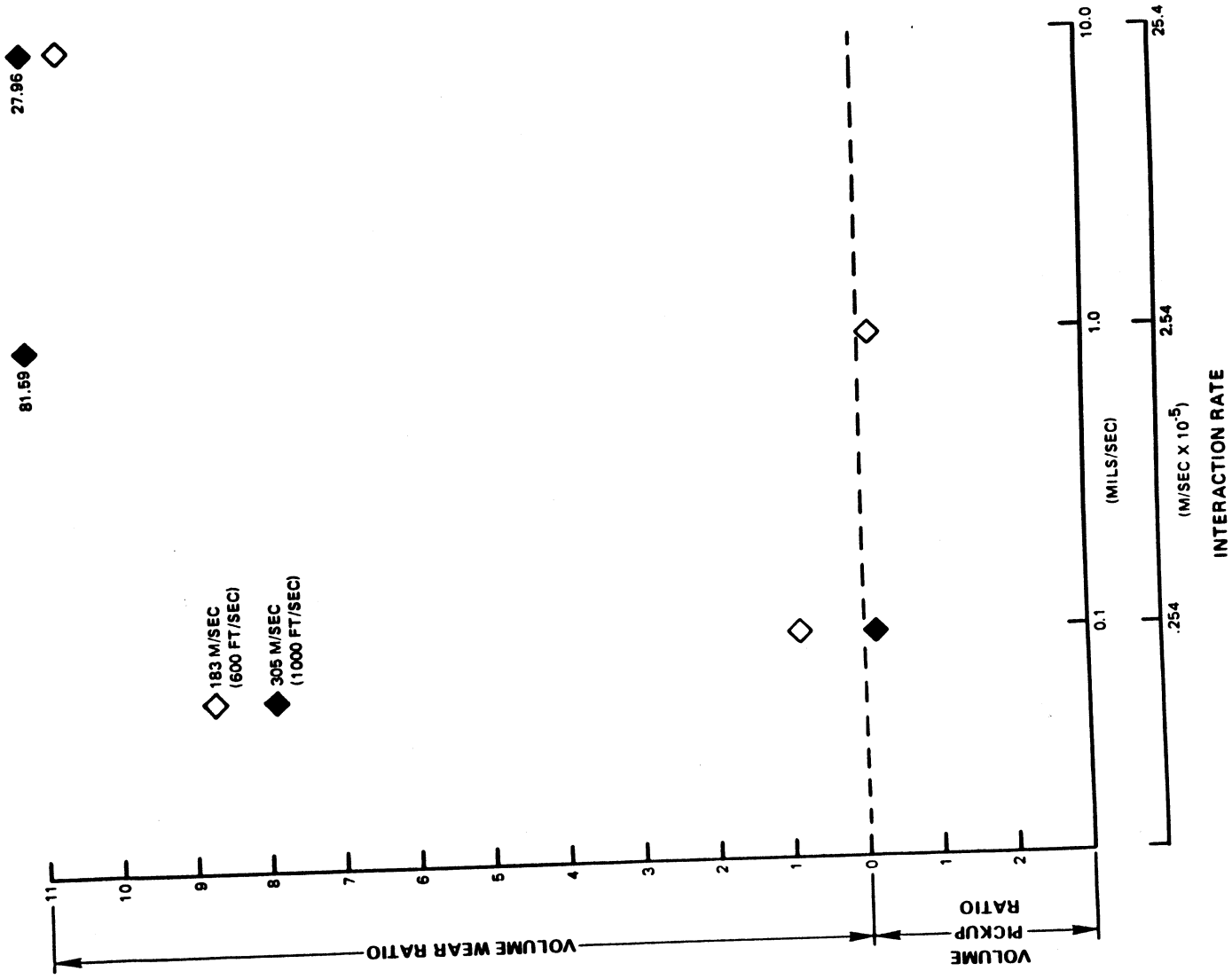
The honeycomb supported porous cermet material system showed the lowest rub tolerance of any of the material systems. High wear points were noted in many test conditions. Figure XXVI illustrates the high wear phenomena for this material and that only at the slowest interaction rate did it result in somewhat lower knife edge wear. Figure XXVII shows the knife edge and seal specimen after a fast interaction rate test. Of particular interest is the fact that knife edge material transferred to the seal segment, typical for high wear points of this system (surface speed 183 m/sec (600 ft/sec) and 25.4×10^{-5} m/sec (10.0 mil/sec) interaction rate). Again the high wear rate phenomena for this system, similar to that of the honeycomb supported porous metal/diatomaceous earth, was caused by the interaction of the knife edge with knife edge transferred material.

This particular specimen, Test No. 35, was microsectioned (Figure XXVIII) and analyzed. The rub characteristics were similar to those of honeycomb supported porous metal/diatomaceous earth: smeared, extruded metal identified as knife edge alloy lined the groove edges, walls and floor. The amount of metal transfer was greater than the metal/diatomaceous earth matrix on the groove floor. The smeared metal also obscured the honeycomb cell wall in the rub path. Axially oriented cracks were observed on the groove surface (Figure XXIX). The rub debris analysis revealed predominantly irregular shaped fine particles resulting from the porous cermet matrix. These shavings were particles recovered from the initial phase of interaction before the knife edge material transferred to the seal material.

The eroded surface of these specimens shown in Figure XXX, indicates a less severe but similar erosion pattern to those of metal/diatomaceous matrix material. Non-uniform erosion of the porous cermet matrix resulted in a "hilly" relief pattern characteristic at all test parameters utilized, and corresponds to the lesser eroded surfaces of honeycomb supported porous metal/diatomaceous earth in the peripheral areas of the main gas and particle stream. Erosion rates of 4.04, 6.10, 8.30, and 6.70×10^{-3} cc/min. resulted from testing at 1033, 1144, 1255 and 1366K (1400°, 1600°, 1800° and 2000°F) temperatures. Preliminary investigation of physical properties of the porous cermet material failed to support a reason for the decreased erosion rates at 1366K (2000°F).

45

FIGURE XXVI
VOLUME RATIO VS INTERACTION RATE
AMBIENT TEMPERATURE



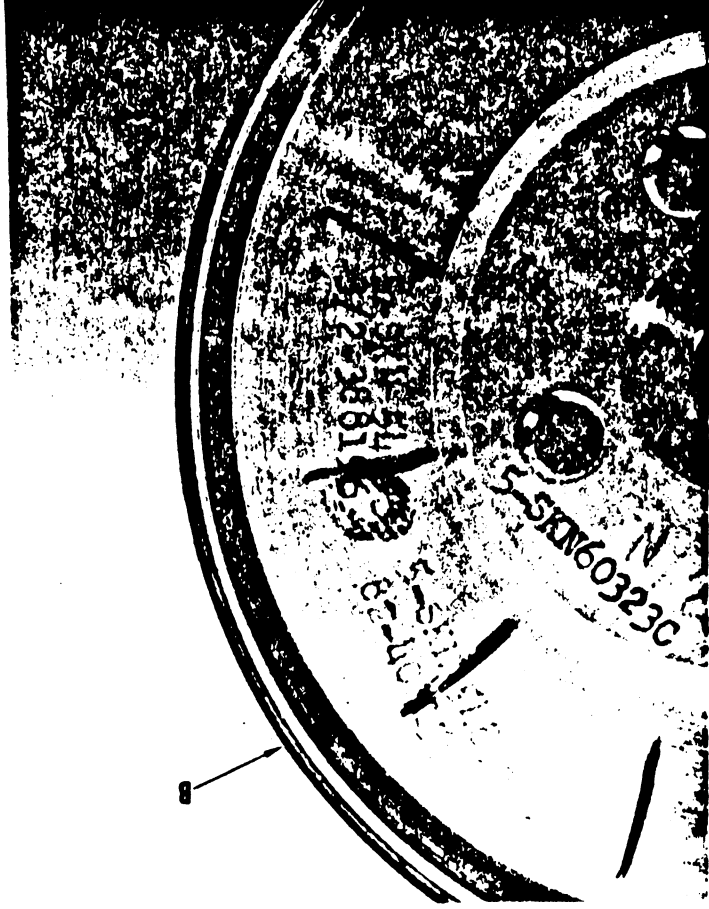
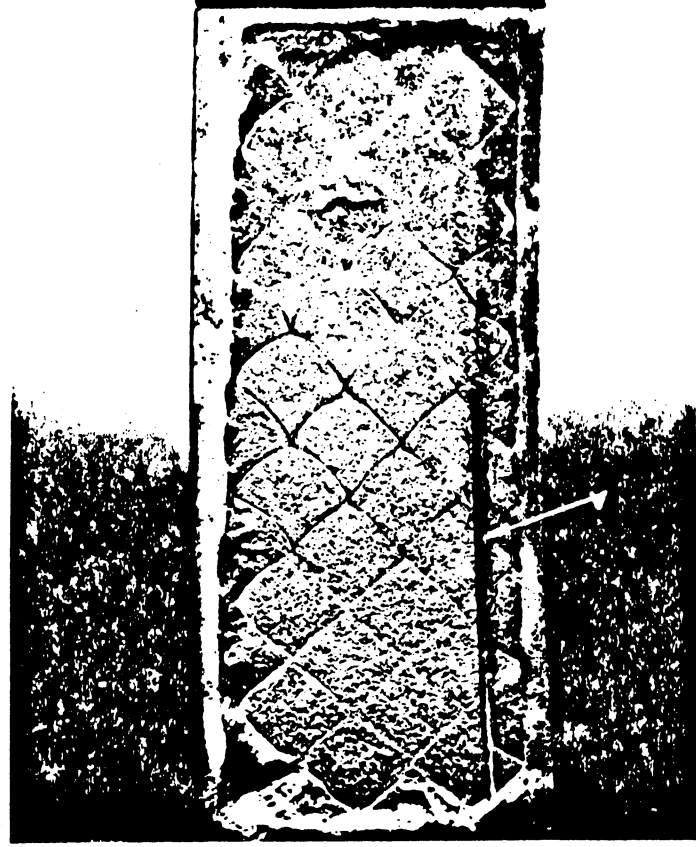
XPN-46724



5/31/74

Test #35 - 65435-4-45, date 5/30/74, honeycomb supported porous cermet seal land vs. .020 WASPALLOY KE - S/N 12, interaction rate 10.0 MPS for 30 mils depth, surface speed 600 FPS, temp amb. .0052 radial KE wear A.) Knife edge transfer material B.) Heavy heat discoloration

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46

47



Figure XXVIII
Knife edge abrasability test specimen - Test # 35: Honeycomb supported
porous cermet microsection of groove shows knife edge material build up
in oxide (o) and parent metal (M) phases.

K-9852

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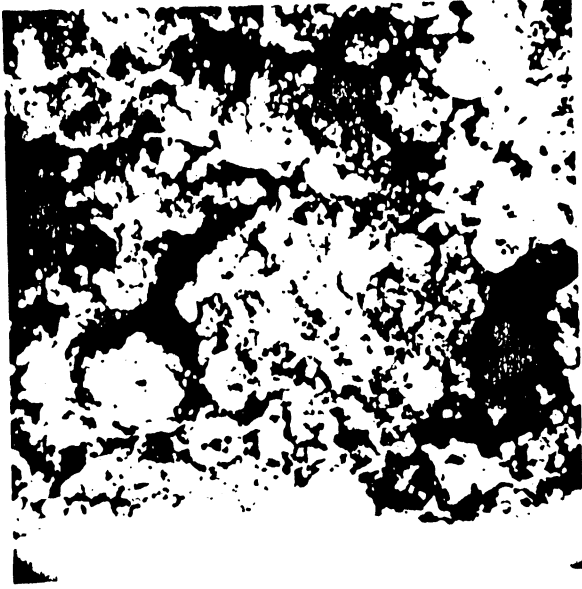
42



2x



SEM ~50x

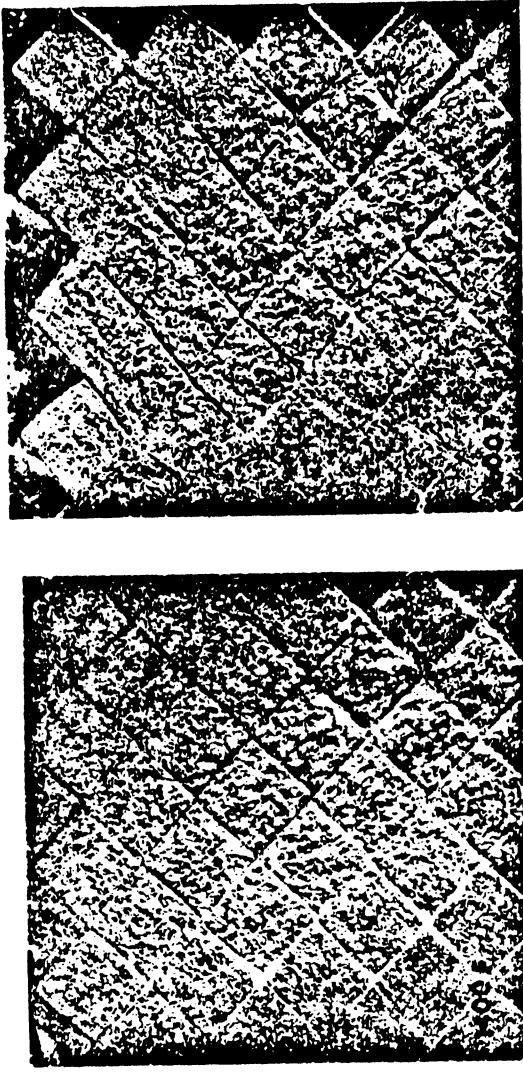


SEM ~500x

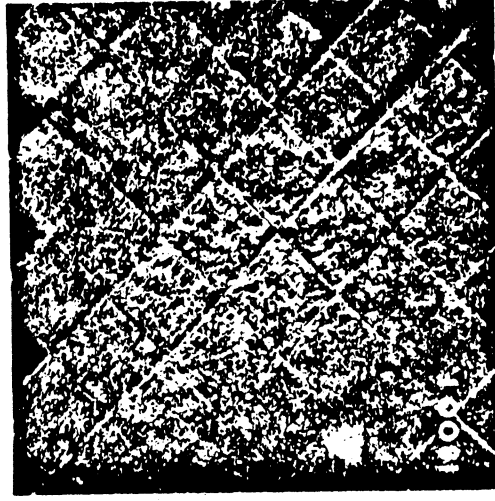


FIGURE XXIX
KNIFE EDGE ABRADABILITY TEST SPECIMEN - TEST #35:
HONEYCOMB SUPPORTED POROUS CERMET. ARROW INDICATES
POINT OF MAXIMUM PENETRATION AND LOCATION OF
MICROANALYSES. SEM PHOTOGRAPHS REPRESENT UNAFFECTED
SURFACE STRUCTURE AND RUB GROOVE WITH SURROUNDING
STRUCTURE. AXIAL CRACK IS A RESULT OF THERMAL STRESSES
OCCURRING ON COOLING. K-9854

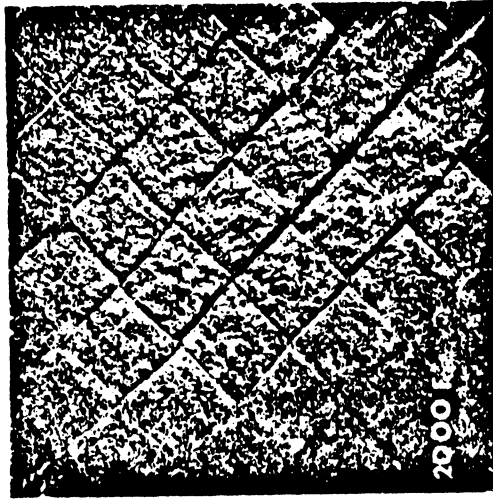
49



S/N E838-1



S/N E838-6



S/N E838-4

Figure XXX

Post-particulate erosion impingement surfaces of honeycomb supported porous cermet test specimens. Test temperatures are indicated. Arrow indicates particle flow direction.

Mag: 2X

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K-9850



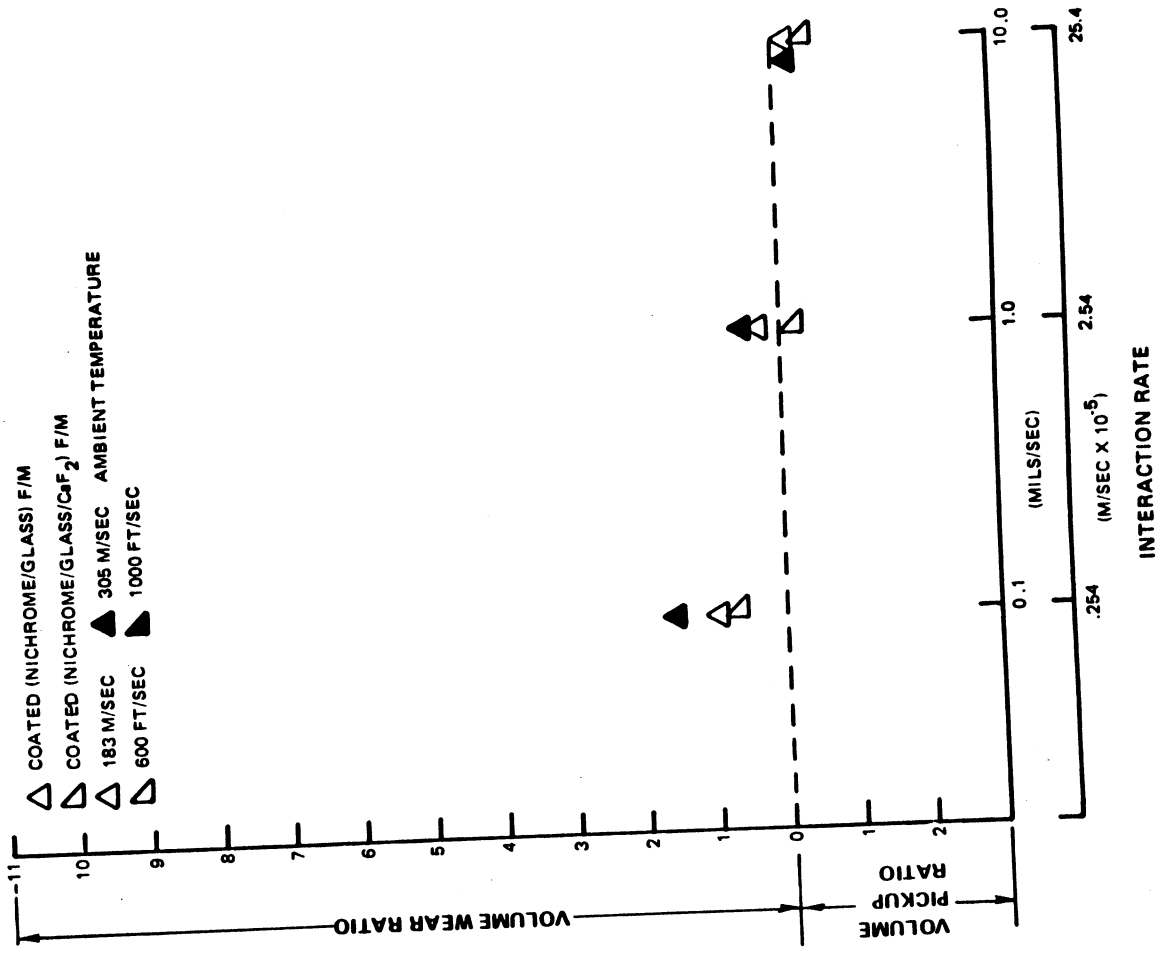
E. Coated (Nichrome/Glass) and (Nichrome/Glass/CaF₂) Fibermetal

The coated fibermetal system exhibited the most particulate erosion resistance of any system but fell well below the honeycomb and uncoated fibermetal in terms of abrasability. Torque readings revealed medium resistance to interaction compared to the honeycomb and uncoated fibermetal systems but much less than the honeycomb supported matrix materials. The coated (80% Nichrome/20% Glass and 67.0% Nichrome/16.5% Glass/16.5% CaF₂) systems revealed significant trends in rub tolerance compared to the other candidate materials. Figure XXXI illustrates the rub mechanism shift from wear to pickup for the 183 m/sec (600 ft/sec) surface speed as a function of interaction rate. Figure XXXII shows the knife edge and seal heat discoloration caused by the rub interaction of Test No. 38, the 25.4 x 10⁻⁵ m/sec (10.0 mil/sec) interaction rate point which is similar for all tests of the sprayed fibermetal system. The coated system exhibited bright glowing during interaction leading to extensive knife edge heat discoloration over the complete circumference. The presence of calcium-fluoride in the spray coating does not appear to result in a significant difference in abrasability. However, results did indicate a torque reduction for the coating containing CaF₂ (Figure III).

A microsection was made of that test specimen (Test No. 38). X-ray spectrometry identified the dense phase at the bottom and sides of the groove (Figure XXXIII) as the glass constituent of the coating. Axial cracks along the complete width of groove (Figure XXXIV) were located at random intervals along the rub path. These cracks appeared to be caused by thermal stresses occurring during cooling. Heat discoloration was noted adjacent to the rub path revealing the extensive heat generation caused by the interaction.

The cracks appearing on the erosion specimen surfaces of both coatings at 1033K (1400°F) and 1366K (2000°F) and the partial separation of the coating with CaF₂ from the fibermetal surface at 1366K (2000°F) were probably caused by thermal stresses induced by mismatch of the spray and fibermetal base structure (Figure XXXV). The apparent increase in erosion resistance at 1366K (2000°F) may be caused by the increased ductility of the total structure due to the increased ductility in the glass phase. The increased ductility probably results in compression or flowing of the material during testing, rather than fracture and resulting increase of material removal. This position is supported by the fact that the eroded surfaces are smoother than the surface of the unaffected areas. Nichrome/glass coating tests at 1033K (1400°F) and 1366K (2000°F) resulted in erosion rates of 1.02 and .9 x 10⁻³ cc/min. respectively. For the nichrome/glass/CaF₂ coating system, the corresponding rates were 1.82 and .7 x 10⁻³ cc/min.

FIGURE XXXI
VOLUME RATIO VS INTERACTION RATE

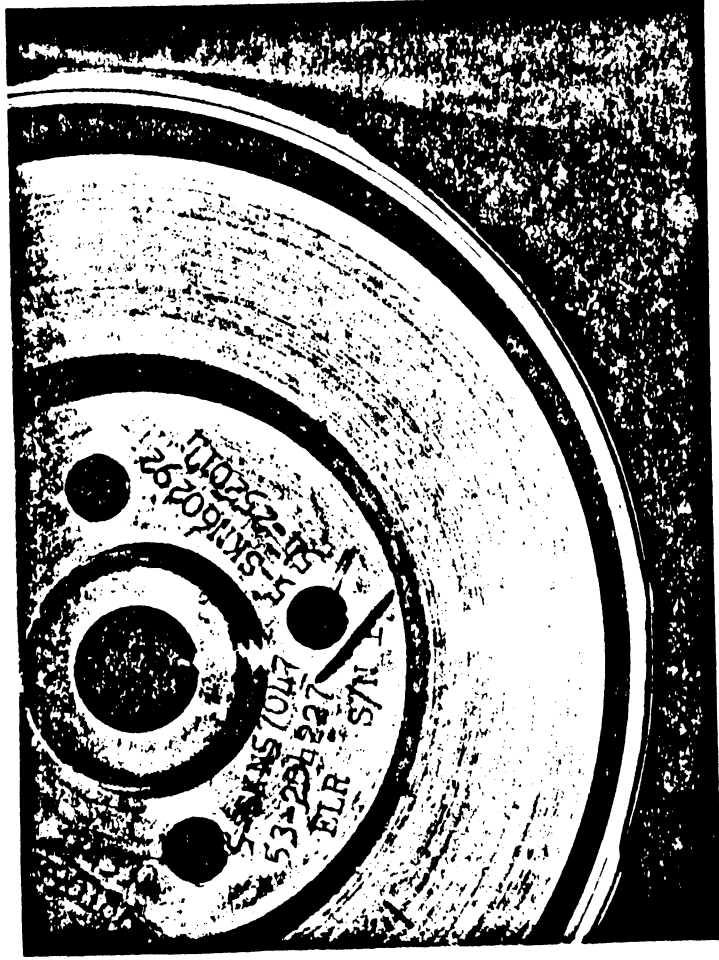
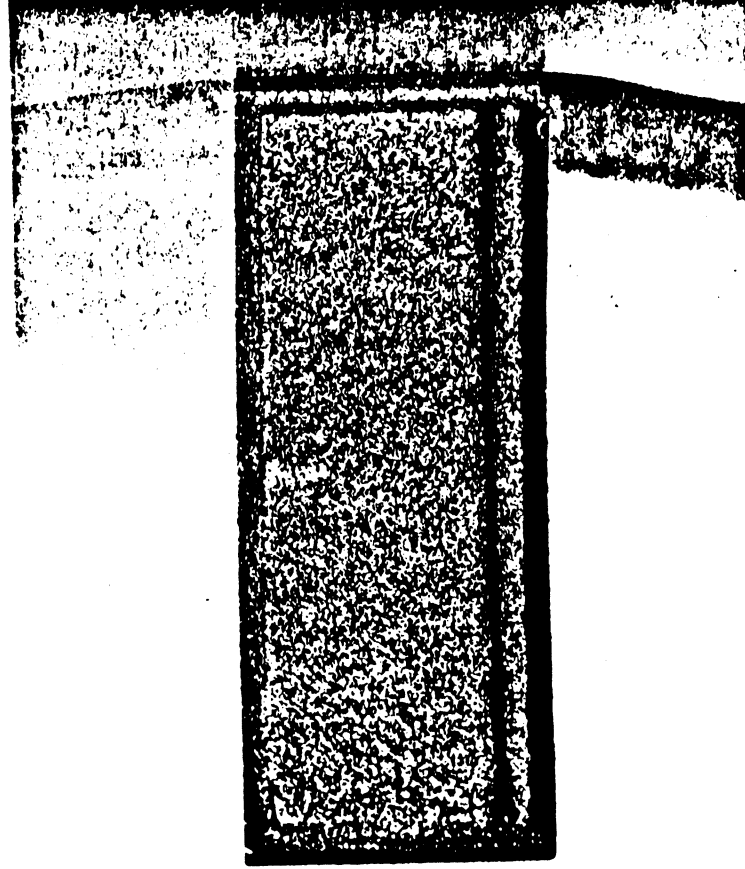


6189F-NDX



Figure XXXII
Test # 38-65435-4-48, date 6/4/74, coated 80% NiCR, 20% glass micrally
F/M vs. .020 WASPALLOY KE, S/N 1, interaction rate 10.0 MPS for 30
mils depth, surface speed 600 FPS, Temp-ambient, .0009 radial KE
pickup.

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53



H74100

Figure XXXIII

Knife edge abrasability test specimen - Test # 38: Plasma sprayed NiCr glass coating (applied to NiCrAlY fiber metal structure). Microsection shows glassy phase (arrows) at walls and bottom of rub groove. Note densification of fiber metal (F) beneath coating.

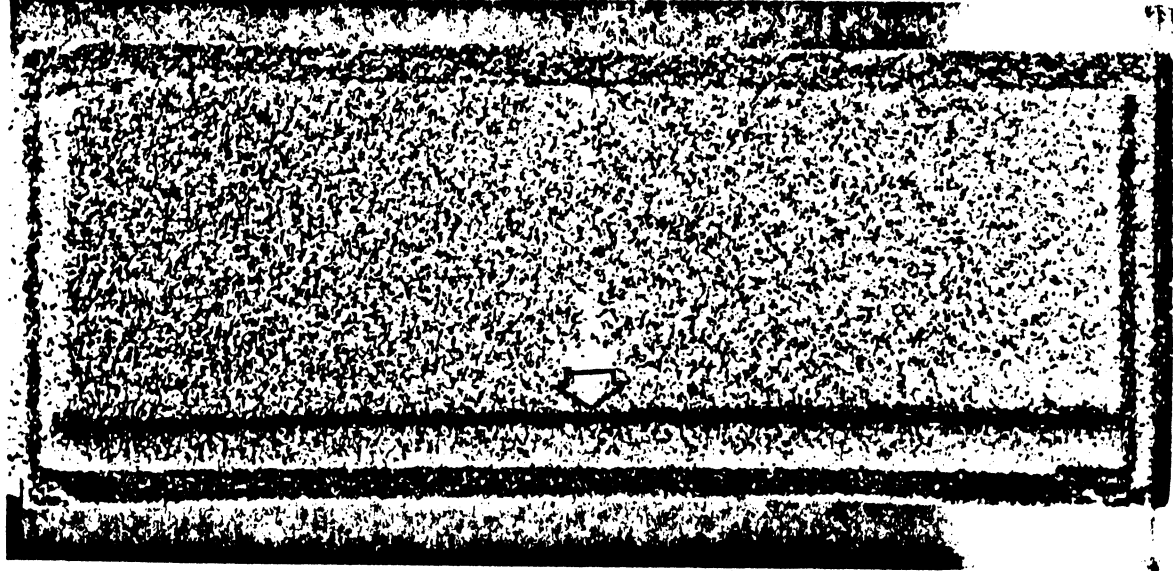
K-9862

Mag: 100X

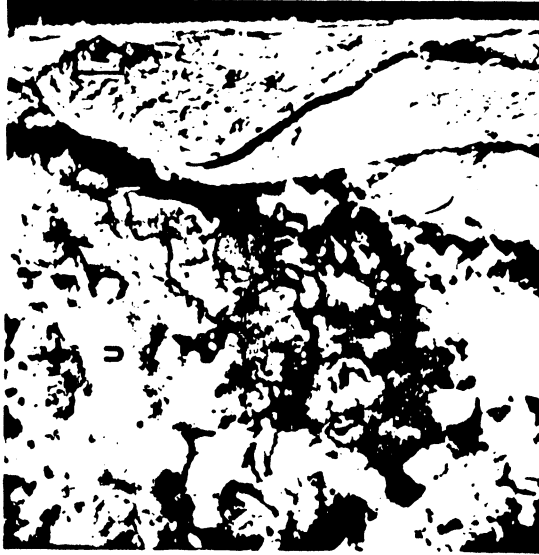
PAGE #53



54



2X



SEM ~ 500X



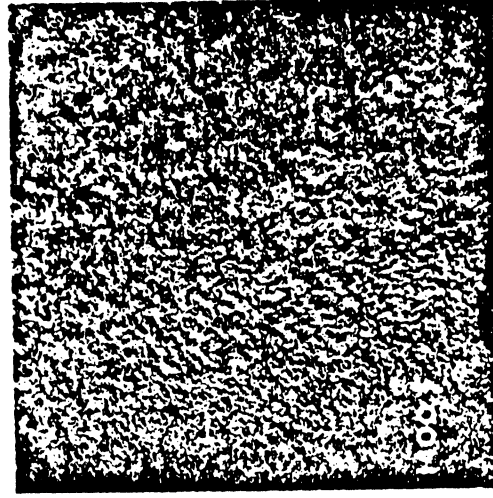
SEM ~ 225X

Figure XXXIV

Knife edge abrasability test specimen - test # 38: Plasma sprayed NiCr glass coating (applied to NiCrAlY fiber metal structure). Arrow indicates point of maximum penetration and location of microanalyses. Unaffected coating (U) and plastically deformed coating material at rub edge (R) is shown. Crack in rub path was caused by thermal stresses occurring during cooling.

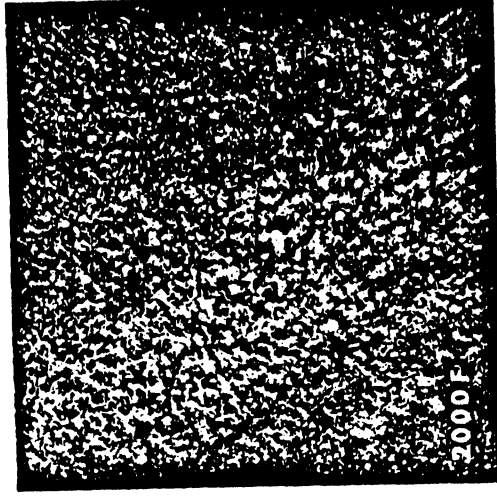


55



S/N 6

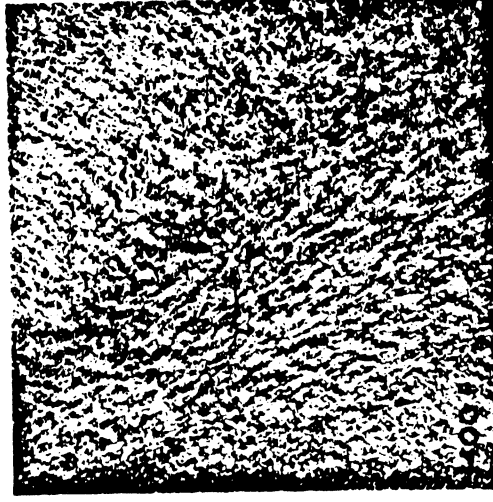
A



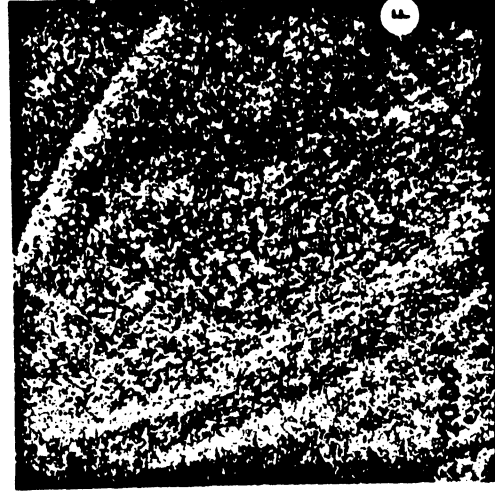
S/N 3



B



S/N 1



S/N 6

F



Figure XXXV

Post-particulate erosion impingement surfaces of plasma sprayed NiCr/Glass coating (A) and plasma sprayed NiCr-CaF₂ glass coating (B) which were applied to NiCrAlY fiber metal test specimen. Test temperatures are indicated. Fracture (F) of 2000F test specimen (B) occurred on handling after test. This portion had separated from sub-structure during test. Arrow indicates particle flow direction.

Mag: 2X

PAGE #55

K-9867

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APPENDICES

APPENDIX A

Test Equipment

Dynamic Abradability Rig

Figure A shows the general arrangement of the dynamic abradability rig used in this program. An air turbine is used to drive a .127 m (5.0 inch) diameter simulated seal knife edge rotor. The rotor shown in Figure B has an integral, parallel sided, square tipped knife edge which was 5.08×10^{-4} m (.020 inch) thick. This configuration closely resembles a low turbine shrouded blade knife edge design in engines today. Reoperations of the disks after tests were required to provide a flat knife edge tip. A 2.54×10^{-3} m (.100 inch) knife edge height was maintained.

The test specimens used with this rig have a diameter to match the .127 m (5.0 inch) rotor. These specimens are carried on a carriage which moves radially to provide a well-controlled penetration rate and distance.

Two gas fired heaters were used to obtain required specimen temperatures. One directed at the front of the specimen was turned off immediately before the rub interaction to prevent rotor knife edge heat distress. The second burner system was directed toward the back of the specimen and demonstrated effectiveness in maintaining temperature requirements after the front burner was extinguished. The rig is equipped for the measurement and recording of rotor speed, torque, specimen surface temperature and displacement. In addition to the physical results of a rub as determined by post-test inspection, the seal material was evaluated in terms of a volume wear ratio. This is simply the ratio of the volume of material worn from the rotor to the volume of material removed from the test specimen. A small value of volume factor is desirable; ideally it is zero.

Erosion Test Rig

The erosion equipment used in the program was designed to test abradable materials for turbine tip sealing under simulated engine conditions, both mechanical and chemical (Figure C). The rig consists of a combustor, a temperature equalizing (mixing) chamber, a specimen chamber and provisions for introducing erosive particles into the gas stream at a controlled rate. Particulate erosion testing described in this report was conducted with size 80 grit, Al_2O_3 particles injected into the gas stream with a particulate mass flow rate of approximately 6 lbs/hr. Testing was conducted with a gas velocity of .35 Mach number and impingement angle of 7° .

High Thermal Response Instrumentation

High thermal response instrumentation and high speed recording equipment were required for two tests, Nos. 57 and 58. This equipment provides temperature data from which values of the heat flux generated by rub interaction can be calculated. Ultimately, these heat flux values could be used to determine the thermal stability of a particular engine seal design.

The instrumentation and set-up is described below.

- . Two fast response pyrometers were aimed at the knife edge outer diameter to monitor temperatures during rub segment interaction. Pyrometer temperatures were recorded on a high speed magnetic tape recorder (Figure D).
- . A third pyrometer was aimed at the sides of the knife edge pedestal to measure variations in knife edge bulk temperature during the rotor/seal rub. Pyrometer output was recorded on the magnetic tape recorder.
- . An optical tachometer was used to monitor knife edge disk speed variations during the rub, and the tachometer output was recorded on the mag-tape.
- . A torque meter, mounted in line with the knife edge disk drive spindle, was used to measure the tangential force component during interaction. This data was also recorded on the mag-tape recorder.
- . A rub segment transducer, used to record the radial feed rate of the segment into the knife edge, was recorded on the mag-tape recorder.
- . A time-code-generator was plugged into one of the mag-tape recorder channels and supplied a reference time scale needed for the analysis and comparison of each of the six channels of mag-tape data for any given instant of a rub test.

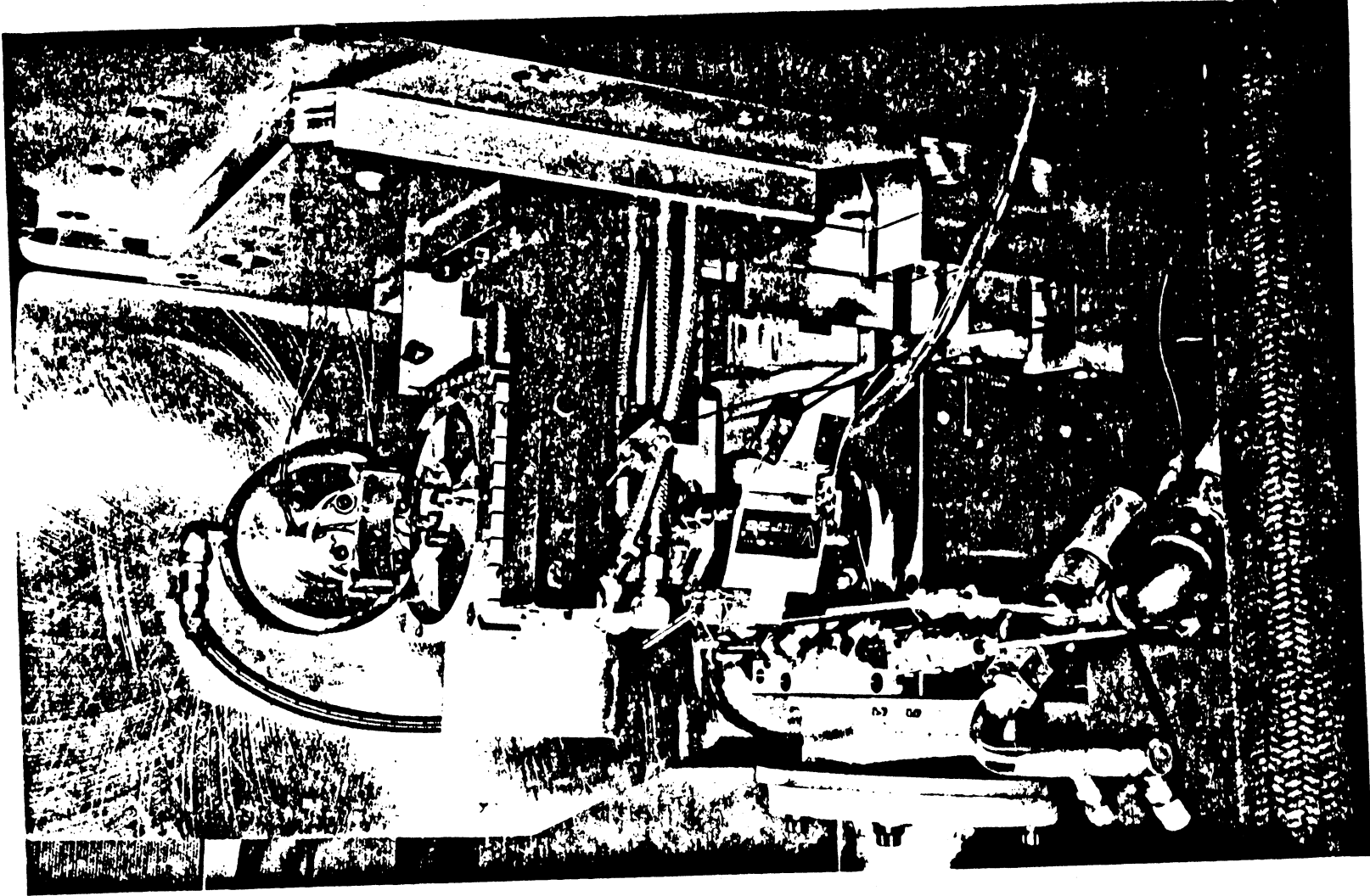
Polaroid photographs were taken from a memory oscilloscope which displayed a given time instant of data recorded on the magnetic tape. This data was illustrated in Figure XVI depicting both pyrometers recording a knife edge "hot spot".



Gas Path Seals Laboratory - 5" Dynamic Friction and Wear Rig.
CN-36505

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Figure A



125

XPN-41045-A

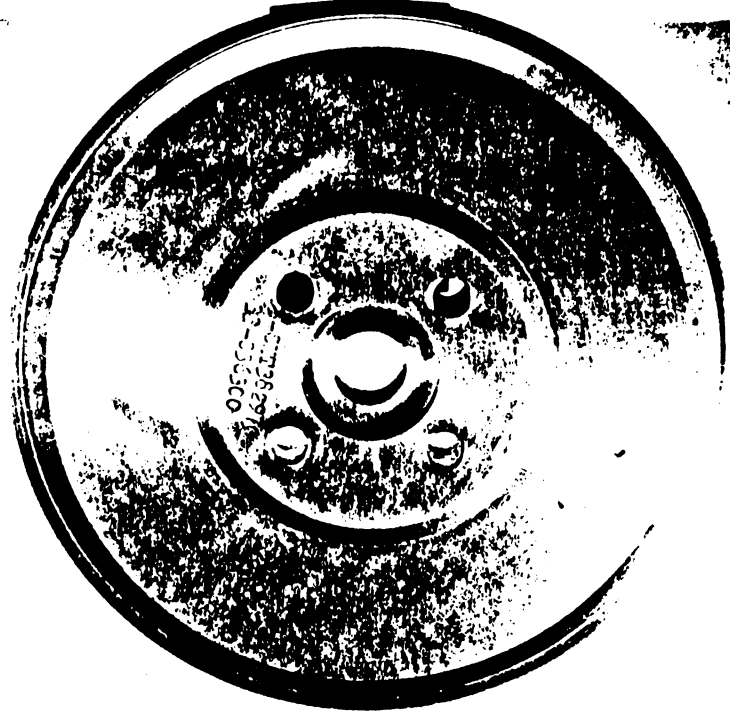


8/19/74

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5" diameter rotor for rub test.

FIGURE B



60

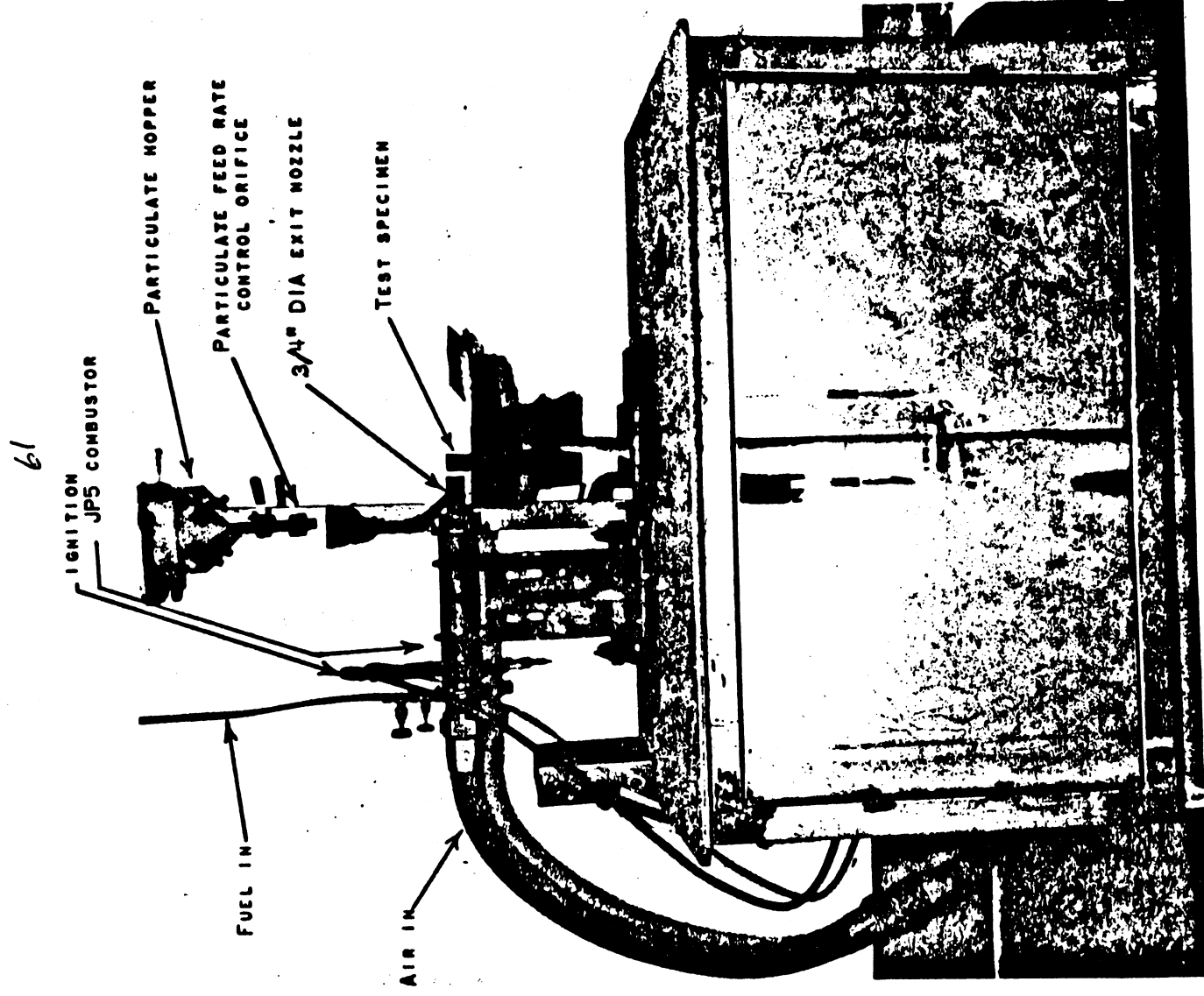


FIGURE C

Hot particulate erosion rig (shown without electric air heater).
 Z-46163
 K-6549

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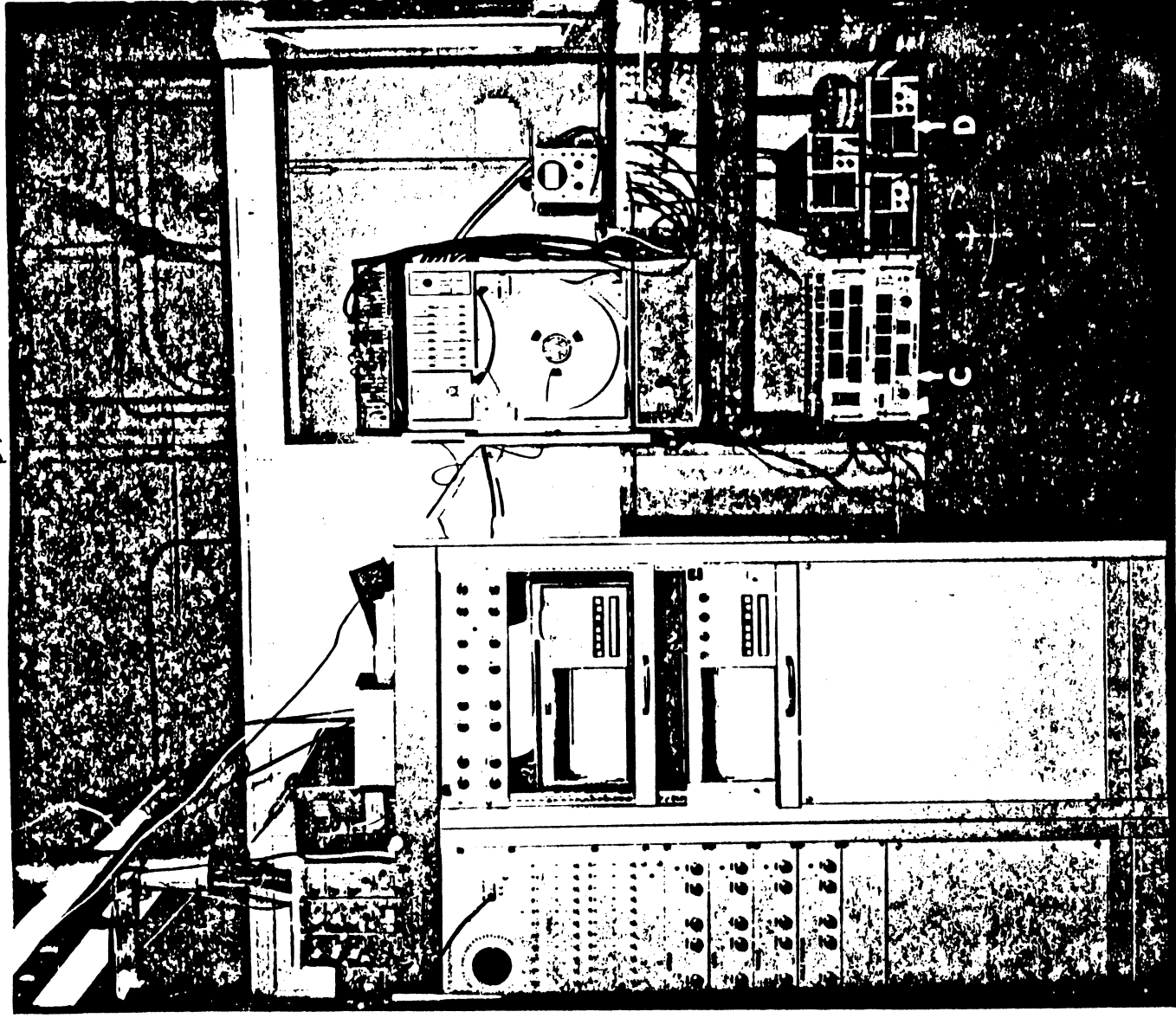


FIGURE D
MAGNETIC TAPE RECORDER AND ELECTRONIC DATA INSTRUMENTATION.
A. VISICORDER
B. MAGNETIC TAPE
C. TIME CODE GENERATOR
D. PYROMETER READOUT
CN-40358



APPENDIX B

Test Summary Chart

A. Discussion of Test Summary Chart Nomenclature

Table 9 presents a condensed description of all abrasability tests. The following is a list of definitions and abbreviations used in that table to assist in interpretation of that data.

"Seal Specimen Conditions" is classified in three specified areas: heat discoloration pertaining to the rub path, transfer or glazing at the rubbed area, and rub shape on the seal. Heat discoloration both on and adjacent to the interaction area was observed for some test conditions. Heat discoloration is defined as none, light, medium. Light discoloration pertains to discoloration in the groove area with noticeable heat marks adjacent to the grooves. Medium describes discoloration about 2.54×10^{-3} m (.100 inch) length on either side of the rub path in addition to discoloration within the rubbed area.

Transfer is knife edge material deposited on the rubbed area. Light transfer refers to small particles of knife edge material located in the seal rub interface while heavy transfer is extensively deposited knife edge material. Glazing is slight particle smearing at the surface of the groove.

Rub patterns were mainly continuous, which indicated the seal was grooved for the complete seal arc. End rubs consisted of both ends rubbing with no groove in the center of the seal specimen. This occurrence was due to warpage of the seal at high temperature test conditions. A top to center rub was caused either from warpage due to high temperature testing or misalignment of the test specimen (one test - No. 35).

"Knife Edge Condition" is classified according to heat discoloration, wear or pickup. Heat discoloration is categorized into three areas, intensity, depth along knife edge sides and number of locations. Light discoloration refers to burn areas just barely visible to the eye. Medium indicates a noticeable burn mark with approximately 2.54×10^{-4} m (.010 inch) in depth. Heavy discoloration indicates a dark-bluish discoloration with a 7.62×10^{-4} m to 1.02×10^{-3} m (.030 inch to .040 inch) depth. The honeycomb material revealed scalloped-edge heat discoloration which was classified by either severity or numerical count of burn marks. For those applicable test points, an indication of an approximate circumferential length of heat discoloration was made.

Knife edge pickup is defined as material transferred to the knife edge. Pickup can occur during any part of an interaction depending on the rub mechanism. In some cases, it was noted some pickup occurred after the knife edge was worn to some extent. Light pickup indicates that the pickup could only be seen clearly through microscopic examination. Heavy pickup refers to measurable and macroscopically visible accumulations around the complete circumference of the knife edge.

"Test remarks" note the intensity of visual heat production due to the rub interaction. Sparking refers to seal rub interface heat areas where a minimum of heat was produced. Glowing refers to illumination around the complete circumference of the knife edge. The intensity of the glowing or sparking is classified in the remarks section of Table 9. Documentation of the cracking due to thermal stresses is noted in the remarks column of test Nos. 49, 51, and 52.

"Setup Temperature" for all tests was the temperature obtained initially before interaction. However, to minimize damage and insure stability of the knife edge, the front torch was extinguished as the disk was about to interact. Temperature dropped to a steady state temperature which was attained through the back heat source. This final temperature was referred to as the "Actual Temperature".

Table 9A is a reproduction of Table 9 using Standard SI units.

Total Specimen Material	Test Conditions															Penetration Depth Mile Setup F Temp F/Sec Rate Mile/Sec	Inter- action	Remarks																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																							
	H/C	H/C	H/C	H/C	H/C	H/C	H/C	H/C	H/C	H/C	H/C	H/C	H/C	H/C	H/C				H/C	H/C	H/C	H/C	H/C	H/C	H/C	H/C	H/C	H/C	H/C	H/C	H/C	H/C	H/C	H/C	H/C	H/C	H/C	H/C	H/C	H/C	H/C	H/C	H/C	H/C	H/C	H/C	H/C	H/C	H/C	H/C	H/C	H/C	H/C	H/C	H/C	H/C	H/C	H/C	H/C	H/C	H/C	H/C	H/C	H/C	H/C	H/C	H/C	H/C	H/C	H/C	H/C	H/C	H/C	H/C	H/C	H/C	H/C	H/C	H/C	H/C	H/C	H/C	H/C	H/C	H/C	H/C	H/C	H/C	H/C	H/C	H/C	H/C	H/C	H/C	H/C	H/C	H/C	H/C	H/C	H/C	H/C	H/C	H/C	H/C	H/C	H/C	H/C	H/C	H/C	H/C	H/C	H/C	H/C	H/C	H/C	H/C	H/C	H/C	H/C	H/C	H/C	H/C	H/C	H/C	H/C	H/C	H/C	H/C	H/C	H/C	H/C	H/C	H/C	H/C	H/C	H/C	H/C	H/C	H/C	H/C	H/C	H/C	H/C	H/C	H/C	H/C	H/C	H/C	H/C	H/C	H/C	H/C	H/C	H/C	H/C	H/C	H/C	H/C	H/C	H/C	H/C	H/C	H/C	H/C	H/C	H/C	H/C	H/C	H/C	H/C	H/C	H/C	H/C	H/C	H/C	H/C	H/C	H/C	H/C	H/C	H/C	H/C	H/C	H/C	H/C	H/C	H/C	H/C	H/C	H/C	H/C	H/C	H/C	H/C	H/C	H/C	H/C	H/C	H/C	H/C	H/C	H/C	H/C	H/C	H/C	H/C	H/C	H/C	H/C	H/C	H/C	H/C	H/C	H/C	H/C	H/C	H/C	H/C	H/C	H/C	H/C	H/C	H/C	H/C	H/C	H/C	H/C	H/C	H/C	H/C	H/C	H/C	H/C	H/C	H/C	H/C	H/C	H/C	H/C	H/C	H/C	H/C	H/C	H/C	H/C	H/C	H/C	H/C	H/C	H/C	H/C	H/C	H/C	H/C	H/C	H/C	H/C	H/C	H/C	H/C	H/C	H/C	H/C	H/C	H/C	H/C	H/C	H/C	H/C	H/C	H/C	H/C	H/C	H/C	H/C	H/C	H/C	H/C	H/C	H/C	H/C	H/C	H/C	H/C	H/C	H/C	H/C	H/C	H/C	H/C	H/C	H/C	H/C	H/C	H/C	H/C	H/C	H/C	H/C	H/C	H/C	H/C	H/C	H/C	H/C	H/C	H/C	H/C	H/C	H/C	H/C	H/C	H/C	H/C	H/C	H/C	H/C	H/C	H/C	H/C	H/C	H/C	H/C	H/C	H/C	H/C	H/C	H/C	H/C	H/C	H/C	H/C	H/C	H/C	H/C	H/C	H/C	H/C	H/C	H/C	H/C	H/C	H/C	H/C	H/C	H/C	H/C	H/C	H/C	H/C	H/C	H/C	H/C	H/C	H/C	H/C	H/C	H/C	H/C	H/C	H/C	H/C	H/C	H/C	H/C	H/C	H/C	H/C	H/C	H/C	H/C	H/C	H/C	H/C	H/C	H/C	H/C	H/C	H/C	H/C	H/C	H/C	H/C	H/C	H/C	H/C	H/C	H/C	H/C	H/C	H/C	H/C	H/C	H/C	H/C	H/C	H/C	H/C	H/C	H/C	H/C	H/C	H/C	H/C	H/C	H/C	H/C	H/C	H/C	H/C	H/C	H/C	H/C	H/C	H/C	H/C	H/C	H/C	H/C	H/C	H/C	H/C	H/C	H/C	H/C	H/C	H/C	H/C	H/C	H/C	H/C	H/C	H/C	H/C	H/C	H/C	H/C	H/C	H/C	H/C	H/C	H/C	H/C	H/C	H/C	H/C	H/C	H/C	H/C	H/C	H/C	H/C	H/C	H/C	H/C	H/C	H/C	H/C	H/C	H/C	H/C	H/C	H/C	H/C	H/C	H/C	H/C	H/C	H/C	H/C	H/C	H/C	H/C	H/C	H/C	H/C	H/C	H/C	H/C	H/C	H/C	H/C	H/C	H/C	H/C	H/C	H/C	H/C	H/C	H/C	H/C	H/C	H/C	H/C	H/C	H/C	H/C	H/C	H/C	H/C	H/C	H/C	H/C	H/C	H/C</

TABLE NO. 9

RUB TEST SUMMARY

-66-

Test No.	Specimen Material	Inter-action Rate	Test Conditions				Seal Specimen				Knife Edge				Post Test Information						
			Penetration Depth Setup	Heat Dissipation	Mile coloration	Transfer/Clazing	Rub Pattern	Heat Discoloration	KE Rad Wear	Pickup	Total Penetration	Δ Load	Max Torque	RPM	Volume Removed	VR (mic.)	VR (Ind-Rom)	Remarks			
19	H/C Supp Porous Metal	1.0	1000	1200	30	None	None	Con's	One loc	+ .0001	Medium	1040	30	2.1	.19	590	1.386	+ .045	N/A	Intermittent glowing	
20	H/C Supp Porous Metal	1.0	600	1200	30	None	Light Clazing	Con's	Medium 180°	+ .0002	Light to Medium	1200	32	3.2	.62	2830	1.558	+ .045	+ .008	Heavy glowing	
21	H/C Supp Porous Cerm	1.0	1000	2000	30	None	Light Clazing	End rubs only	Light	+ .0001	Medium	1650	20	0.7	.32	910	.340	+ .092	+ .120	Light glowing	
22	H/C Supp Porous Cerm	1.0	1000	1200	30	Medium	Heavy Clazing	Con's	Heavy 360°	.0195	Light	1150	24	4.5	1.92	5400	.145	41.66	43.06	Very bright glowing	
23	H/C Supp Porous Cerm	1.0	600	1200	30	None	Light Clazing	Con's	Medium 315°	.0004	Very Light	1100	22	9.2	4.00	10850	.637	.197	.175	Heavy sparking	
24	NiCrAlY F/M	1.0	1000	2000	30	None	None	End rubs only	Very Light	0	None	1180	49	1.0	.02	300	.506	0	.055	No glowing	
25	H/C Supp Porous Metal	1.0	1000	1000	30	None	Light Clazing	Con's	Very Light	0	None	28	28	3.7	.20	430	1.271	0	0.0	Intermittent glowing	
26	H/C Supp Porous Metal	1.0	600	600	30	None	Light Transfer	Con's	Medium 270°	.0007	Light	28	28	7.1	2.07	8300	1.223	.178	.125	Intermittent glowing	
27	NiCrAlY F/M	10.0	1000	1000	30	None	None	Con's	Very Light	0	None	32	32	0	.07	80	1.530	0	.006	No glowing	
28	NiCrAlY F/M	10.0	600	600	30	None	None	Con's	Very Light	0	Light One loc	35	35	6.9	.26	320	1.662	0	.015	Light glowing	
29	NiCrAlY F/M	0.1	1000	1000	30	Light	None	Con's	Very Light	0	None	31	31	3.7	.10	330	1.361	0	.012	No glowing	
30	NiCrAlY F/M	0.1	600	600	30	Very Light	None	Con's	Very Light	.0001	None	29	29	4.3	.02	760	1.158	.027	.013	No glowing	
31	NiCrAlY F/M	1.0	600	2000	30	None	None	End rubs only	None	0	None	1300	17	0.9	0	0	.331	0	.003	No glowing	
32	H/C Supp Porous Metal	10.0	1000	1000	30	None	Light Clazing	Con's	Medium 270°	+ .0011	Light	32	32	6.7	2.05	1800	1.418	+ .243	+ .311	Medium glowing	
33	H/C Supp Porous Metal	10.0	600	600	30	Medium	Medium Transfer	Con's	Heavy 360°	.0137	None	27	27	16.5	6.60	13400	.408	10.53	10.51	Heavy glowing	
34	H/C Supp Porous Metal	0.1	1000	1000	30	None	Light Clazing	Con's	Very Light	.0001	None	28	28	3.1	.02	440	1.098	.026	.037	No glowing	
35	H/C Supp Porous Cerm	10.0	600	600	30	None	Medium Top to Center	Con's	Heavy 360°	.0052	Medium	13	13	17.1	3.35	4400	.143	10.06	10.38	Heavy glowing	
36	H/C Supp Porous Metal	0.1	600	600	30	None	None	Con's	Very Light	0	None	29	29	2.9	.14	550	1.065	0	0.0	Light glowing	
37	NiCr/Clase Coated F/M	1.0	600	600	30	Medium	Light Clazing	Con's	Heavy 360°	.0008	Light	26	26	8.1	3.30	14800	.927	.256	.243	Medium glowing	

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TABLE NO. 9

RUB TEST SUMMARY

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Test No.	Specimen Material	Inter-Action					Penetration					Seal Specimen					Knife Edge					Post Test Information				
		Rate	Surface	Temp	Depth	Mils/Speed	Sec/Ft/Sec	Mils	Heat Discoloration	Transfer/ Glazing	Light	Con's	Heat Discoloration	Wear Inches	KE Rad	Pickup	Total	Pencil Load	Max Torque	RPM Drop	Volume Removed	VR (Mic.)	VR (Ind-Non)	Remarks		
38	NiCr/Glass Coated F/M	10.0	Amb	600	30	Light	Light	Light	Glazing	Con's	Heavy 200°	+ .0009	Medium	Amb	39	4.3	2.60	350	1.67	+ .156	+ .114	Heavy glowing				
39	H/C Supp. Porous Ceram	1.0	Amb	600	30	None	None	Light	Glazing	Con's	Heavy 180°	+ .0002	Light	Amb	28	5.5	3.26	10750	1.09	+ .054	+ .083	Light glowing				
40	NiCr/Glass Coated F/M	1.0	Amb	1000	30	Light	Light	Light	Glazing	Con's	Medium 360°	.0020	None	Amb	28	3.2	1.90	6350	1.13	.540	N/A	Heavy glowing				
41	H/C Supp. Porous Ceram	0.1	Amb	600	30	None	None	Light	Glazing	Con's	Heavy 360°	.0027	Light	Amb	26	2.5	7.00	5600	.818	.915	.664	Medium glowing				
42	H/C Supp. Porous Ceram	1.0	600	2000	30	None	None	Light	Glazing	Con's	Medium 90°	.0002	Light	1550	6	2.8	1.61	1050	.111	.550	.542	Light glowing				
43	NiCr/Glass Coated F/M	0.1	Amb	600	30	Light	Light	Light	Glazing	Con's	Heavy 360°	.0028	Light	Amb	26	10.8	3.38	9500	.894	.954	.797	Intermittent glowing				
44	H/C Supp. Porous Ceram	1.0	Amb	1000	30	None	None	Heavy	Transfer	Con's	Heavy 360°	.0207	Light	Amb	26	9.0	2.52	4800	.068	81.59	80.71	Heavy glowing				
45	H/C Supp. Porous Ceram	10.0	Amb	1000	30	None	None	Heavy	Transfer	Con's	Heavy 360°	.0232	Light	Amb	33	18.0	2.70	2650	.253	27.96	27.71	Heavy glowing				
46	H/C Supp. Porous Ceram	0.1	Amb	1000	30	None	None	Light	Glazing	Con's	Light 360°	+ .0003	Light	Amb	27	3.7	.72	1250	.872	+ .130	+ .066	Light glowing				
47	NiCr/Glass Coated F/M	1.0	600	2000	30	Medium Oxidation	Light	Light	Glazing	Con's	Medium 360°	.0009	Light	1300	12	4.0	2.20	6900	.215	1.10	1.27	Light glowing				
48	NiCr/Glass Coated F/M	1.0	1000	1200	30	None	None	Light	Glazing	Con's	Heavy 330°	.0021	None	1075	22	2.5	1.30	4300	.780	.783	.798	Intermittent glowing				
49	NiChrome/Glass/CaF2 Coated F/M	1.0	Amb	600	30	None	None	Light	Glazing	Con's	Heavy 300°	+ .0002	Light	Amb	22	4.2	2.20	9050	.833	+ .068	+ .041	Heavy glowing				
50	NiChrome/Glass/CaF2 Coated F/M	10.0	Amb	600	30	Light	Light	Light	Glazing	Con's	Heavy 3-Loc	+ .0006	Medium	Amb	26	7.2	1.15	1100	1.12	+ .167	+ .202	Rub area cracking				
51	NiChrome/Glass/CaF2 Coated F/M	0.1	Amb	600	30	None	None	Light	Glazing	Con's	Heavy 360°	.0018	None	Amb	26	6.4	1.90	6800	.712	.730	.953	No glowing				
52	NiChrome/Glass/CaF2 Coated F/M	10.0	Amb	600	30	None	None	None	None	Con's	None	.0000	Light	Amb	32	2.9	.09	110	1.487	0.0	.038	Light glowing				
53	NiCrAlY F/M	10.0	Amb	600	30	None	None	None	None	Con's	None	.0002	Light	Amb	28	3.8	.20	120	.914	+ .060	+ .052	Heavy glowing				
54	Hast-X H/C	10.0	Amb	1000	30	None	None	None	None	Con's	Light	+ .0002	Light	Amb	28	3.2	.83	1950	1.201	+ .198	+ .178	Heavy glowing				
55	NiCr/Glass Coated F/M	10.0	Amb	1000	30	Medium	Light	Glazing	Light	Con's	Heavy 4-Loc	+ .0008	Medium	Amb	28	3.2	.83	1950	1.201	+ .198	+ .178	Heavy glowing				

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(1)	Stalled rig.
(2)	Continuous rub extending for most of 60' seal segments
(3)	One location approximately 10-20' arc and 30 mil depth burn discoloration
(4)	One or two isolated K. E. O. D. locations where pickup was microscopically evident
(5)	"Light" and heavier accumulations that are measurable
(6)	Inde-Ron traces initiated to measure K. E. wear
(7)	+ denotes knife edge pickup occurrence
(8)	High thermal response tests

RUB TEST SUMMARY

TABLE NO. 9A											
Test No.	Specimen Material	Test Conditions					Seal Specimen				
		Blot Rate	Surface Temp	Setup	Temp	Depth	Heat Transfer/ Glazing	Pattern	Heat Dis- Wear	Knife Edge	Total
		M/Sec	M/Sec	K	M/Sec	M x 10 ⁻⁴	coloration	coloration	K. E. Rad	M x 10 ⁻⁵	M x 10 ⁻⁴
1	Heat-X H/C	2.54	305	Amb.	7.62		None	Continuous	One loc (3)	0	Amb. 7.36
2	Heat-X H/C	2.54	305	1144	7.62		None	Con's (2)	One loc	0	1144 7.11
3	Heat-X H/C	2.54	305	922	7.62		None	Con's	None	0	939 7.11
4	Heat-X H/C	2.54	305	1366	7.62		None	End heavy con's	One loc	0	1094 6.05
5	Heat-X H/C	2.54	61	Amb	6.60 (1)		None	Con's	Scal light	0	Amb 6.60
6	Heat-X H/C	2.54	183	922	7.62		None	End heavy con's	Very light	0	939 7.36
7	Heat-X H/C	2.54	183	1366	7.62		None	End rubs only	Light	0	1177 6.09
8	Heat-X H/C	2.54	183	1144	7.62		None	Con's	Very light	.254	1022 7.11
9	NiCrAlY F/M	2.54	305	Amb	7.62		Light	Con's	Very light	0	Amb 6.60
10	NiCrAlY F/M	2.54	183	Amb	7.62		None	Con's	None	0	Amb 6.60
11	NiCrAlY F/M	2.54	305	922	7.62		Very light	End rubs only	Very light	0	761 7.87
12	NiCrAlY F/M	2.54	183	922	7.62		None	End rubs only	Light	0	922 8.63
13	Heat-X H/C	.254	183	Amb	7.62		Very light	Con's	22 loc. scal	.762	Amb 6.85
14	Heat-X H/C	25.4	183	Amb	7.62		None	Con's	One loc	0	Amb 7.11
15	Heat-X H/C	.254	305	Amb	7.62		Light	Con's	4 loc light	0	Amb 7.11
16	Heat-X H/C	2.54	183	Amb	7.62		Light	Con's	One loc	0	Amb 7.36
17	H/C Supp. Porous Metal Dial. Earth	2.54	305	1366	8.89		None	Con's	Medium 360°	1.01	1144 11.1
18	H/C Supp. Porous Metal Dial. Earth	2.54	183	1366	8.89		None	Con's	Light to medium	0	922 8.12
19	H/C Supp. Porous Metal Dial. Earth	2.54	305	922	7.62		None	Con's	One loc	+ .254	839 7.62
20	H/C Supp. Porous Metal Dial. Earth	2.54	183	922	7.62		None	Con's	Medium 180°	+ .508	922 8.12
21	H/C Supp. Porous Cerm	2.54	305	1366	7.62		None	End rubs only	Light	+ .254	955 5.08
22	H/C Supp. Porous Cerm	2.54	305	922	7.62		Medium	Heavy	Heavy 360°	49.5	900 6.09
23	H/C Supp. Porous Cerm	2.54	183	922	7.62		None	Con's	Very light	1.01	872 5.58
24	NiCrAlY F/M	2.54	305	1366	7.62		None	End rubs only	Very light	0	916 12.4
25	H/C Supp. Porous Metal Dial. Earth	2.54	305	Amb	7.62		None	Con's	Very light	0	Amb 7.11

Post Test Information

Specimen	Volume	Removed	VWR	(Ind-Ron)
	M ³ x 10 ⁻⁸			

Remarks

Actual Penetration	Temp	Load	Max	Drop	RPM	Volume	Removed	VWR	(Ind-Ron)
Temp	Temp	Temp	Temp	Temp	Temp	Temp	Temp	Temp	Temp
Temp	Temp	Temp	Temp	Temp	Temp	Temp	Temp	Temp	Temp
Temp	Temp	Temp	Temp	Temp	Temp	Temp	Temp	Temp	Temp

TABLE NO. 9A

RUB TEST SUMMARY

Test Conditions										Seal Specimen										Knife Edge										Post Test Information																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																					
Test No.	Specimen Material	Inter Penetration Rate	Surface Temp	Speed Setup	M/Sec	M/Sec	Heat Die-coloration	Transfer/ Die-coloration	Rub Pattern	Heat Die-wear	K. E. Rad	Heat Die-coloration	Pickup	Actual Temp	Pene-tration	Load	Max Torque	RPM Drop	Volume Removed	VWR	VWR	Remarks	Test No.	Specimen Material	Inter Penetration Rate	Surface Temp	Speed Setup	M/Sec	M/Sec	Heat Die-coloration	Transfer/ Die-coloration	Rub Pattern	Heat Die-wear	K. E. Rad	Heat Die-coloration	Pickup	Actual Temp	Pene-tration	Load	Max Torque	RPM Drop	Volume Removed	VWR	VWR	Remarks																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																						
26	H/C Supp. Porous Metal	2.54	183	Amb	7.62		None	Light	Transfer	Con'e	Medium 270°	1.78	Light	Amb	7.11	31.6	.234	8300	2.00	.178	.125	Intermittent glowing																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																													

TABLE NO. 9A

RUB TEST SUMMARY

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Test Conditions																										Seal Specimen										Knife Edge										Post Test Information									
Test No.		Specimen Material		Inter- action Rate		Surface Temp		M/Sec		x 10 ⁻⁵		Heat Dia-		coloration		Heat Dia-		coloration		K. E. Rad		Wear		M x 10 ⁻⁵		Pickup		Actual Temp		Penetration		Load		Max Torque		N.m		RPM Drop		Volume Removed		WVR		(Ind-Rom)		Remarks									
48		NiCr/Glass	2.54	305	922	7.62	None	Light	Clazing	Con's	Heavy 360°	5.33	None	None	858	5.58	11.1	.147	4300	1.28	.783	.798	Intermittent glowing	48		Heat Dia-	coloration	Heat Dia-	coloration	K. E. Rad	Wear	M x 10 ⁻⁵	Pickup	Actual Temp	Penetration	Load	Max Torque	N.m	RPM Drop	Volume Removed	WVR	(Ind-Rom)	Remarks												
49		NiCr/Glass	2.54	305	1366	7.62	Light	Light	Clazing	Con's	Heavy 360°	10.9	None	None	1022	5.84	17.8	.452	6000	1.38	1.58	1.63	Rub area cracking	49		Heat Dia-	coloration	Heat Dia-	coloration	K. E. Rad	Wear	M x 10 ⁻⁵	Pickup	Actual Temp	Penetration	Load	Max Torque	N.m	RPM Drop	Volume Removed	WVR	(Ind-Rom)	Remarks												
50		Nichrome/Coated F/M	2.54	183	Amb	7.62	None	Light	Clazing	Con's	Heavy 300°	4.508	Light	Light	Amb	5.58	18.7	.475	9050	1.37	4.068	4.041	Heavy glowing	50		Heat Dia-	coloration	Heat Dia-	coloration	K. E. Rad	Wear	M x 10 ⁻⁵	Pickup	Actual Temp	Penetration	Load	Max Torque	N.m	RPM Drop	Volume Removed	WVR	(Ind-Rom)	Remarks												
51		Nichrome/Coated F/M	25.4	183	Amb	7.62	Light	Light	Clazing	Con's	Heavy 3-Loc	1.52	Medium	Medium	Amb	6.60	32.0	.130	1100	1.84	4.167	4.202	Rub area cracking	51		Heat Dia-	coloration	Heat Dia-	coloration	K. E. Rad	Wear	M x 10 ⁻⁵	Pickup	Actual Temp	Penetration	Load	Max Torque	N.m	RPM Drop	Volume Removed	WVR	(Ind-Rom)	Remarks												
52		Nichrome/Coated F/M	.254	183	Amb	7.62	None	Light	Clazing	Con's	Heavy 360°	4.56	None	None	Amb	6.60	28.5	.215	6800	1.17	.730	.953	Rub area cracking	52		Heat Dia-	coloration	Heat Dia-	coloration	K. E. Rad	Wear	M x 10 ⁻⁵	Pickup	Actual Temp	Penetration	Load	Max Torque	N.m	RPM Drop	Volume Removed	WVR	(Ind-Rom)	Remarks												
53		NiCrAlF F/M	25.4	183	Amb	7.62	None	None	None	Con's	None	0	Light	Light	Amb	8.12	12.09	.010	110	2.44	0.0	.038	No glowing	53		Heat Dia-	coloration	Heat Dia-	coloration	K. E. Rad	Wear	M x 10 ⁻⁵	Pickup	Actual Temp	Penetration	Load	Max Torque	N.m	RPM Drop	Volume Removed	WVR	(Ind-Rom)	Remarks												
54		Heat-X H/C	25.4	305	Amb	7.62	None	None	None	Con's	Light	.508	Light	Light	Amb	7.11	16.91	.023	120	1.50	4.060	4.052	Light glowing	54		Heat Dia-	coloration	Heat Dia-	coloration	K. E. Rad	Wear	M x 10 ⁻⁵	Pickup	Actual Temp	Penetration	Load	Max Torque	N.m	RPM Drop	Volume Removed	WVR	(Ind-Rom)	Remarks												
55		NiCr/Glass	25.4	305	Amb	7.62	Medium	Light	Clazing	Con's	Heavy 4-Loc	2.03	Medium	4-Loc	Amb	7.11	14.24	.094	1950	1.97	4.198	4.178	Heavy glowing	55		Heat Dia-	coloration	Heat Dia-	coloration	K. E. Rad	Wear	M x 10 ⁻⁵	Pickup	Actual Temp	Penetration	Load	Max Torque	N.m	RPM Drop	Volume Removed	WVR	(Ind-Rom)	Remarks												
56		NiCr/Glass	.254	305	Amb	7.62	Medium	Light	Clazing	Con's	Medium 360°	13.7	None	None	Amb	7.87	15.13	.179	3500	1.43	1.633	1.758	Heavy glowing	56		Heat Dia-	coloration	Heat Dia-	coloration	K. E. Rad	Wear	M x 10 ⁻⁵	Pickup	Actual Temp	Penetration	Load	Max Torque	N.m	RPM Drop	Volume Removed	WVR	(Ind-Rom)	Remarks												
57		Heat-X H/C	2.54	305	Amb	7.62	None	None	None	Con's	Light	.254	Light	Two-Loc	Amb	7.36	8.46	.016	500	1.57	4.027	4.032	Light glowing	57		Heat Dia-	coloration	Heat Dia-	coloration	K. E. Rad	Wear	M x 10 ⁻⁵	Pickup	Actual Temp	Penetration	Load	Max Torque	N.m	RPM Drop	Volume Removed	WVR	(Ind-Rom)	Remarks												
58		NiCrAlF F/M	2.54	305	Amb	7.62	None	None	None	Con's	None	0	None	None	Amb	7.62	3.11	.002	180	1.53	0.0	.005	None	58		Heat Dia-	coloration	Heat Dia-	coloration	K. E. Rad	Wear	M x 10 ⁻⁵	Pickup	Actual Temp	Penetration	Load	Max Torque	N.m	RPM Drop	Volume Removed	WVR	(Ind-Rom)	Remarks												
59		H/C Supp. Porous Cerm	2.54	305	922	7.62	Medium	Medium	Transfer	Con's	Heavy 360°	46.9	Medium	Medium	Amb	7.62	73.43	.192	5980	.546	15.07	15.23	Heavy glowing	59		Heat Dia-	coloration	Heat Dia-	coloration	K. E. Rad	Wear	M x 10 ⁻⁵	Pickup	Actual Temp	Penetration	Load	Max Torque	N.m	RPM Drop	Volume Removed	WVR	(Ind-Rom)	Remarks												

Key

- (1) Stalled rig
 (2) Continuous rub extending for most of 60" seal segments
 (3) One location approximately 10-20° arc and 30 mil depth burn discoloration
 (4) One or two isolated K. E. O.D. locations where pickup was microscopically evident
 (5) Light and heavier accumulations that are measurable
 (6) Ind-Ron trace instituted to measure K. E. wear
 (7) + denotes knife edge pickup occurrence
 (8) High thermal response tests

17.

