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THREE-STAGE POTASSIUM VAPOR TURBINE TEST

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16. Abstract

A three-stage potassium vapor turbine was tested for 5000 hours in a stainless steel test facility at 18,250 RPM, 1.54 lb/sec nominal vapor flow rate, 1500° F inlet temperature, inlet total/exit static pressure ratio of 10, vapor qualities of 99% (inlet) to 87% (exit), and approximately 235 kw of power. The vapor quality into the third stage inlet was no greater than 93% for 4300 hours. The primary objectives of studying the effects of vapor wetness on impingement damage of different rotor-blade materials, including molybdenum alloys, were met. Rotor blade wear due to impingement was minimal and did not preclude testing beyond 5000 hours. Assessment of molybdenum blade wear by impingement was difficult due to washing corrosion caused by oxygen in the potassium working fluid.

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FOREWORD

The research described in this report was conducted by the General Electric Company under NASA contract NAS 3-10606. Mr. George M. Kaplan of the Lewis Research Center Space Power Systems Division was the NASA Project Manager. The report was originally issued as General Electric report GESP-547.

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SUMMARY

Wet vapor potassium turbines incorporated in nuclear space power systems are expected to operate unattended for 5 years. Turbine erosion was considered to be a barrier problem with this life objective. A turbine was tested in order to determine if, with exit vapor quality as low as 87 percent, blade erosion limits turbine life.

Blade damage experienced by impingement erosion during 5000 test hours under conditions typical of KTA low pressure turbine stages was negligible, confirming a 3 to 5 year life potential.

The test conditions were far from ideal. Weld failures were not uncommon, and resulted in facility shutdown, leakage of potassium from the facility, and leakage of air, particularly oxygen, into the system. Potassium dizirconate deposits from a gettering zirconium hot trap accumulated on turbine rotor and stator blading. The test turbine itself did not cause a single test interruption, and, especially, the turbine rotor was still in good mechanical condition at the end of the test.

I. INTRODUCTION

This report covers the results of a 5000 hour endurance test of a three-stage potassium test turbine under operating conditions specified in Table I. The test represents a continuation of erosion tests carried out with a two-stage turbine and an earlier three-stage test turbine. The two-stage test turbine exposed a number of turbine blades of wrought Udimet 700 and wrought molybdenum TZM and TZC to 5000 hours of endurance testing at the operating conditions of Table I. The blades survived this test in excellent form. No cavitation or erosion pits were observed, and only minor corrosive attack and signs of incipient erosion were visible under the microscope.(1)

By adding a third stage to a turbine otherwise the same, Figure 1,(2-4) the calculated moisture level entering the last turbine stage was increased from 3.3 to 8.9 percent, a value more representative of utility practice. At the same time, the tip diameter and tip speed of the final stage were increased (Table I). The basic test objective was to find out whether blade erosion at this more severe combination of moisture level, blade speed, blade material and temperature could be tolerated in space turbines with a three- to five-year life objective. The 5000 hour endurance test period was assumed to be representative of the difficulties to be encountered in operating three to five years.

A 1400-hour test, carried out in 1968, ended with inconclusive results. The turbine was shut down as a result of excessive and inexplicable output torque reduction. Upon opening the turbine, it was discovered that the four Mo-TZM third-stage blades had lost substantial portions of their tip shrouds. In addition, many of the blade retainer clips of all stages had strain age hardened and fractured at the non-annealed aft assembly bend. Mechanical damage due to the retainer clip fragments was noted generally on rotor and stator blades. The damage to the leading edges of the third-stage rotor blades was such as to preclude separation of mechanical and erosive effects, Figure 2. The tip shroud fragments could have contributed to this leading edge damage.

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(1) Numbers in parentheses refer to documents listed in the References section.

TABLE I

NOMINAL OPERATING CONDITIONS FOR POTASSIUM VAPOR TURBINES

Turbine - General	Two-Stage	Three-Stage
Test Period, hours	5000	5000
Inlet Vapor Temperature, °F (°C)	1500 (816)	1500 (816)
Inlet Total Pressure, psia (KN/m^2)	24.66 (166.7)	24.66 (166.7)
Outlet Static Pressure, psia (KN/m^2)	7.1 (48)	2.5 (17)
Rotational Speed, rpm	18,250	18,250
Inlet Vapor Quality, %	99	99
Vapor Flow Rate, lb/sec (Kg/sec)	1.5 (0.68)	1.54 (0.70)(1)
Turbine - Final Rotor Stage	**2**	**3**
Inlet Temperature, °F (°C)	1390 (754)	1276 (691)
Inlet Total Pressure, psia (KN/m^2)	14.4 (97.4)	7.7 (52)
Outlet Temperature, °F (°C)	1240 (691)	1140 (616)
Outlet Static Pressure, psia (KN/m^2)	7.1 (48)	2.5 (17)
Inlet Moisture, %	3.3	8.9
Outlet Moisture, %	8.0	14.5
Rotor Inlet Absolute Gas Velocity, ft/sec (m/sec)	1048 (319)	1222 Pitchline (372)
Rotor Inlet Relative Gas Velocity, ft/sec (m/sec)	446 (136)	601 Pitchline (183)
Rotor Inlet Wheel Speed, ft/sec (m/sec)	691 (211)	743 Pitchline (226)
Rotor Inlet Absolute Gas Velocity at Tip, ft/sec (m/sec)	926 (282)	1094 Estimated (333)
Rotor Inlet Relative Gas Velocity at Tip, ft/sec (m/sec)	298 (91)	481 Estimated (147)
Rotor Inlet Wheel Speed at Tip, ft/sec (m/sec)	770 (235)	838 Estimated (255)

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(1) Vapor flow rate varied during testing from 1.4 lb/sec (0.64 kg/sec) to 1.8 lb/sec (0.82 kg/sec) as shown on Figure 14a.

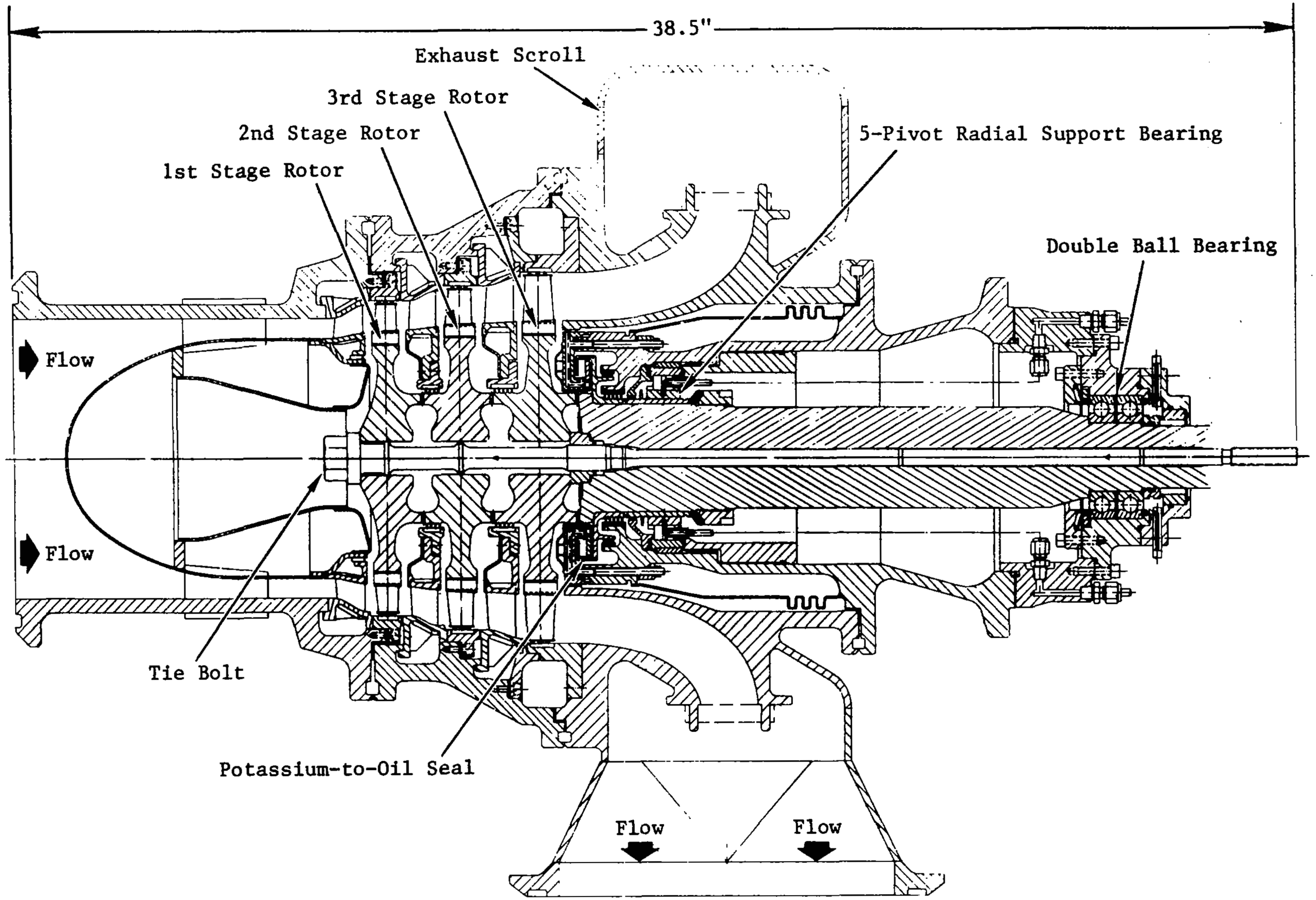


Figure 1. Three Stage Potassium Vapor Test Turbine.

Another three stage turbine buildup was made utilizing new rotor components where required. To insure some data being available in case the turbine was damaged after accumulation of many test hours, periodic shutdowns for blade inspection and erosion measurements were planned. A blade inspection port, Figure 3, was added to the turbine casing to permit direct, as well as borescope, inspection of the third-stage blading. A removable stator vane and tip seal insert, Figure 5, permitted the use of a large diameter borescope to visually observe the third-stage blade leading edges and to obtain close-up pictures of selected blades with a 35 mm SLR camera mounted on the borescope, Figure 4. A steel rod of known diameter (0.047 in.) served as a reference scale.

The photographic parameters were:

35 mm Nikon-F SLR camera with 35 mm focal length used at f1.2.
Kodak Plus-X Panchromatic black-and-white film (ASA 125).
Camera speed of one second for leading edge photos.
Camera speed of four seconds for trailing edge photos.
Lighting by American Cystoscope Makers, Inc., Model B34-A borescope (0.400 inch diameter) at full rheostat setting. The borescope objective end was shortened about 0.3 inch and a camera holder was fabricated for the eyepiece.

In addition, a dial indicator method of measuring the leading edge contours of the rotor blades was established. The front face of each blade dovetail tang is the reference for the blade contour. Repeatable measurements of the blade contour were obtained, Figure 6.

To eliminate the previous source of mechanical damage, new spring type bucket retainers, Figure 7, were developed and incorporated in the turbine. The tip shrouds of the third-stage rotor blades were removed to eliminate another potential for damage, Figure 8. This permitted direct visual blade tip inspection.

The aging stainless-steel turbine test facility,(5) which already had 7000 operating hours above 1400°F at this time, was inspected and overhauled.

The successful 5000 hour endurance test began on August 26, 1969, and was terminated on July 5, 1970. The 5000 hour test was completed with a single turbine build-up in contrast to the inspection and reassembly

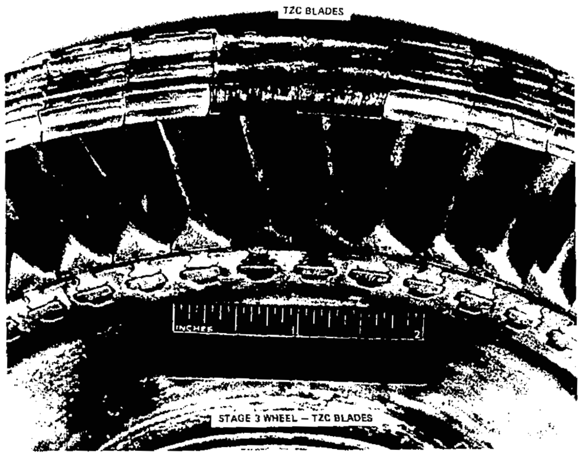


Figure 2. Third Stage Turbine Wheel Showing Combined Mechanical and Erosion Damage After 1400 Test Hours in 1968. (P68-9-8J)

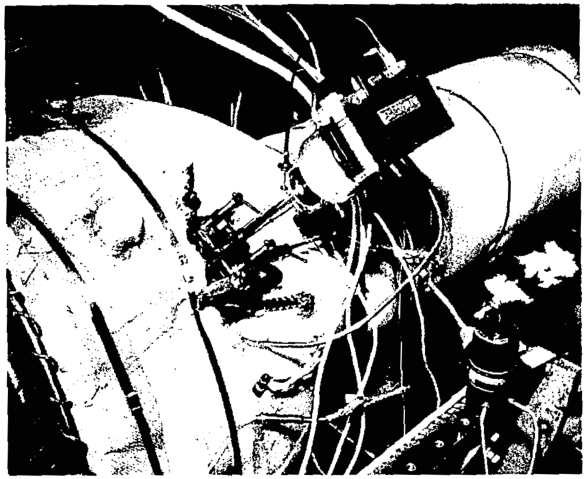


Figure 4. Blade Inspection Port Equipped With Borescope and Camera. (P69-8-1D)

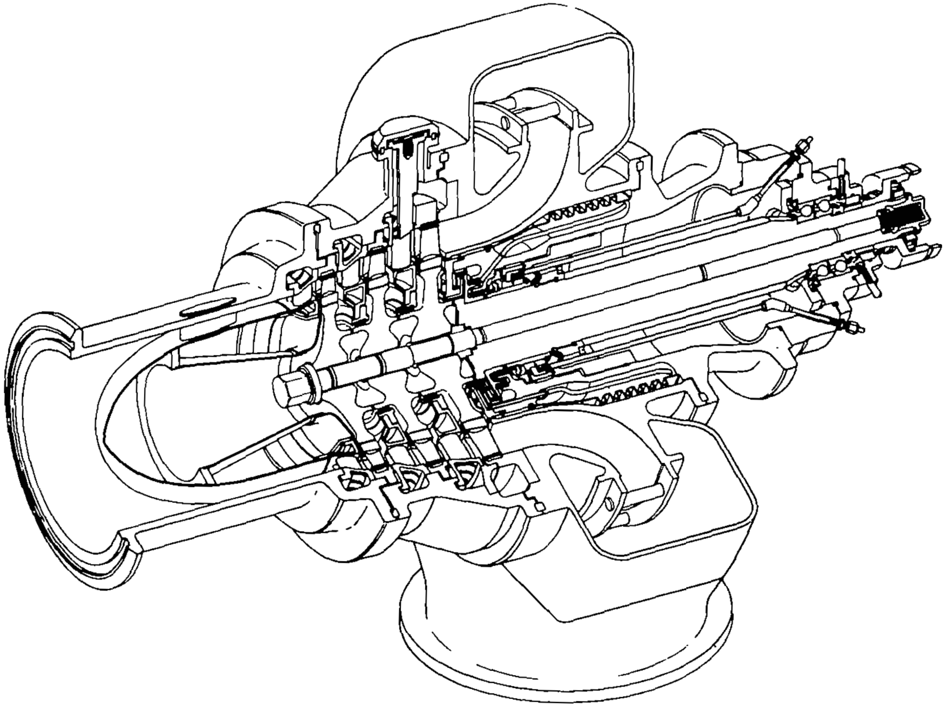


Figure 3. Three-Stage Potassium Test Turbine With Blade Inspection Port. (AS-857)

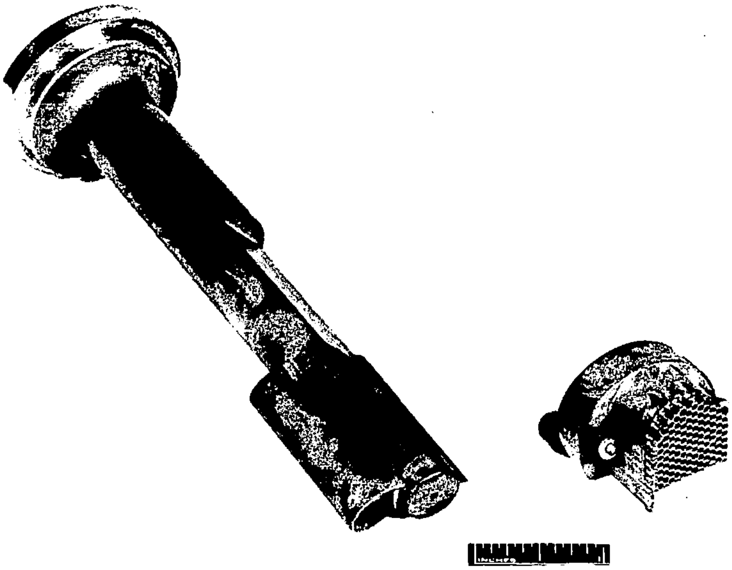


Figure 5. Stage 3 Removable Nozzle Vane and Tip Seal Insert After 405 Hr of Testing. (P69-9-25A)

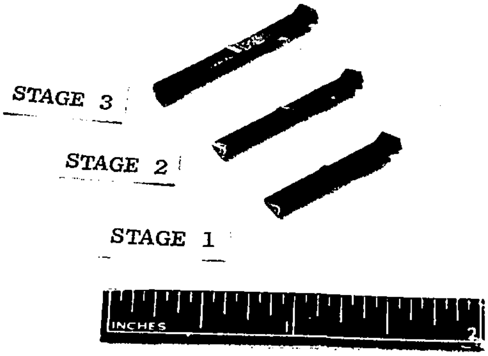


Figure 7. Three-Stage Turbine Blade Retainers - Material, Rene' 41. (P69-5-38Q)

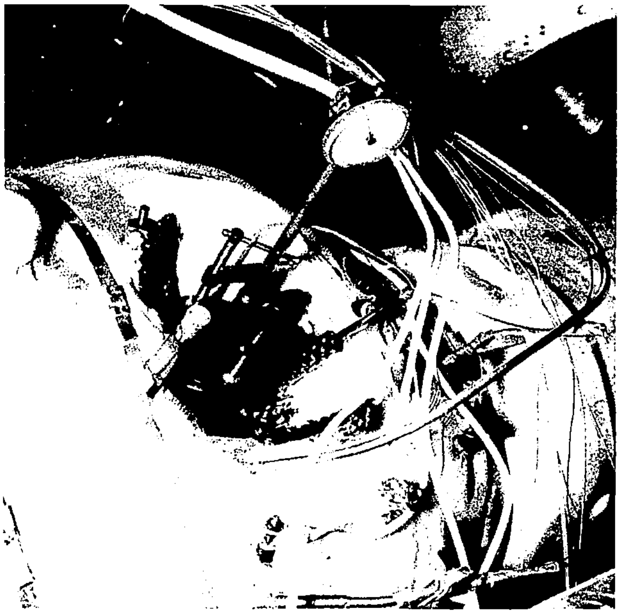


Figure 6. Dial Indicator Used to Measure Blade Leading Edges. (P69-8-1E)

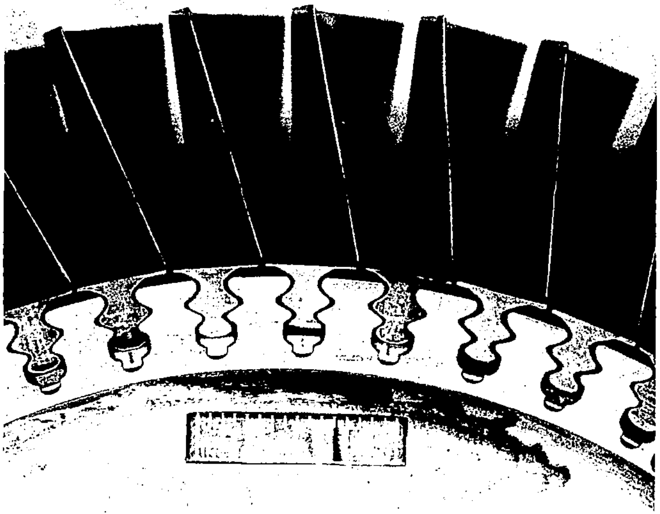


Figure 8. Third-Stage Rotor Blades With Tip Shrouds Removed and New Blade Retainers. (P69-5-38AG)

of the two-stage turbine after 2000 hours of testing. Originally shutdowns were planned every 500 hours to inspect the third-stage rotor blades. However, a facility breakdown at 405 hours replaced the first planned shutdown and provided sufficient time for blade inspection. The next two shutdowns at 1000 hours and 1856 hours were scheduled, as was the final shutdown at 5000 hours. All other inspections utilized facility breakdown and repair periods. Figure 9 details the shutdown and startup dates, causes of shutdowns, and total testing hours.

On ten occasions the turbine facility or turbine instrumentation piping developed potassium leaks which necessitated unscheduled shutdowns. The early detection of each discrepancy and accelerated controlled shutdown procedures resulted in minimal possible damage. None of the shutdowns resulted from basic turbine failure or operator error. The locations of the various leaks and number of occurrences were: boiler and inlet piping - 8, turbine instrumentation piping - 3, and condenser inlet - 1. Repair time intervals were minimized by around-the-clock utilization of the three man test crews and supporting personnel.

At the completion of the test, the turbine had successfully reached its design testing goal and the boiler and facility had accumulated a total of 11,610 hours of operation above 1400°F. The effective utilization of the 7600 hours of elapsed time from start to finish of testing was 66 percent.

II. OPERATIONAL EXPERIENCE

Turbine-Ball Bearings

During the performance testing of the turbine which preceded the start of endurance testing, dynamic instability of the turbine rotor and bearing system was experienced. Normally, the rotor orbit was circular and approximately one mil peak-to-peak as measured by eddy-current displacement transducers. During the instabilities the Lissajous figure on an oscilloscope gave a grossly distorted displacement indication of approximately four mils peak-to-peak. Accelerometers attached to the bearing housing indicated an increase from three to eight g's when the instabilities occurred.

The instabilities apprently were caused by the greater unbalance of this assembly than previous ones. The unbalance was caused to some

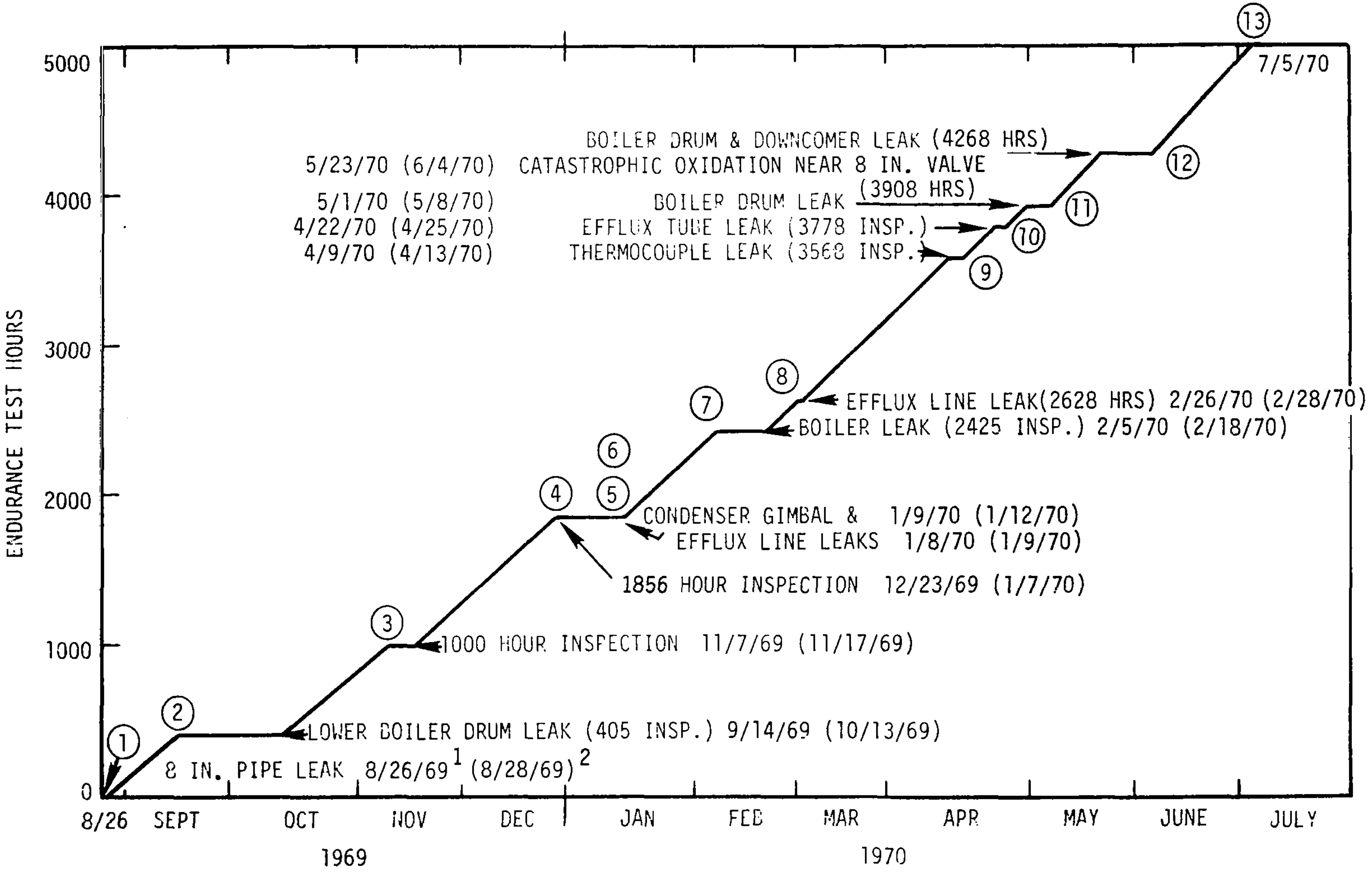


Figure 9. Three Stage Potassium Turbine Accumulated Endurance Test Hours Versus Time
1 = Shutdown Date, 2 = Startup Date.

extent by the new retainer design, which permitted axial shifting of buckets more than desired. The centrifugal forces due to unbalance unloaded the two 27° angular contact ball bearings at the rear of the turbine. Axial preload was provided to maintain continuous contact of the balls and races.

The unacceptable rotor instability at the start of testing occurred at the intended operating condition of 18,250 rpm and turbine outlet pressure of 3.9 psia. Rotor stability was regained by reducing the turbine outlet pressure to 2.5 psia, which produced greater rotor thrust in the aft direction (downstream, or to the right in Figure 1). The horizontal and vertical displacement sensors indicated 1 ± 0.5 mils and the accelerations were about 2 ± 1.5 g's.

Various turbine shutdowns were used to change bearing preload and to improve the bearing alignment by increasing the clearance between the floating ball bearing and its housing. After several trials an arrangement evolved which applied a preload of 660 pounds acting in a forward direction to support the vector of gas loads acting on the turbine rotor. This vector always is in the forward direction and assumes various magnitudes during startup and turbine operation. This dynamic instability resulted in the possibility of very short bearing lives by pitting balls and races. Ball bearings were replaced at each shutdown to 2425 test hours, with damage seen at one time after 856 hours of use.

Preloading in the forward direction was applied to the ball bearing by a redesigned coil spring arrangement at the 2425 hour shutdown. Although this change eliminated the rotor instabilities which had occurred at 3.9 psia outlet pressure the remainder of the endurance test continued to use the 2.5 psia turbine outlet pressure.

The bearing instability experienced is typical for ball bearing which offer no damping capability. The use of sleeve or pivoted-pad bearings with inherent damping capability is anticipated for a full-scale potassium turboalternator (KTA).

Turbine - Buffer Seal Breakdown

After 3775 hours of operation a breakdown of the Argon buffer seal separating oil and potassium was experienced. Instead of terminating turbine operation for repair of the buffer seal, the test personnel, after some trial and error, established a new mode of buffer seal operation by injecting two times the normal amount of argon used. Post-test inspection showed that a 20° segment of the outer seal ring of the buffer seal rotor was lost. This failure was probably the result of high thermal stresses. It was remarkable that the test could be continued for another 1225 hours despite this severe buffer seal damage. It should be noted that this buffer seal is typical only of a test turbine operating on oil lubricated bearings. A KTA operating on potassium bearings does not require a buffer seal.

Turbine - Efflux Tubes

Most of the efflux pressure sensing tubes were cut off and plugged by welding prior to the 5000 hour test. In the course of testing, several leaks were encountered at the junction of the tubes with the inlet duct and the turbine casing. These leaks occurred in the weld and were probably caused by refluxing of potassium within the two inch long tube stubs. Further leaks were eliminated by removing these stubs flush with the casing and welding.

Turbine - Inlet Duct Bulletnose

After approximately 750 test hours, the flow rate began to increase and eventually leveled off at a value greater than its initial value. Flow bypassing the nozzle diaphragms was suspected but the location could not be determined. At shutdown a 1.5 inch x 3 inch oval hole was found at the bottom side of the inlet duct bullet nose which permitted one third of the flow to bypass the stage 1 nozzle diaphragm. This hole appeared to be the result of corrosion from the inside of the bullet nose where a stagnant pool of potassium condensate rich in oxides had formed in an undrained area.

Facility - Post-Test Inspection

After the completion of testing, visual and dye penetrant inspections of boiler tube welds did not reveal any external surface cracks. The inside of the boiler vapor drum was inspected using a 10-foot long borescope. No internal cracks in critical welds were observed in the minor portion of the vapor drum which could be seen. The most significant observation was that the interior of the vapor drum was surprisingly clean and free of debris. The internal vapor drum baffles, feedlines, and screen separators were generally in good condition except that the south splash baffle broke loose, dislodged the adjacent boiler feedline and pulled it out of the downcomer. Thus the returning condensate could no longer discharge directly into the downcomer. The vapor drum was bowed downward about 3 to 4 inches on each end and forced against the fire-box thermal insulation, breaking out relatively large sections of the insulation. No "catastrophic oxidation" of the boiler metal was found.

The boiler hot trap was removed and examined. The 0.025 inch thick zirconium plates were quite brittle and badly oxidized. The inlet to the trap was partially plugged. The outlet dirt trap contained potassium dizirconate. The hot trap is assumed to be the principal source of the potassium dizirconate which entered the turbine and deposited on the rotor and stator blades.

No damage to the condenser was found by visual examination. Borescope inspection of the condenser hot trap showed the brittle, oxidized zirconium ducts to be buckled and cracked. The condenser hot trap is not considered to have contributed significantly to the formation of potassium dizirconate in the flow components.

III. SUMMARY OF BORESCOPE OBSERVATIONS DURING TESTING

Borescope visual observations and photographs of the Stage 3 record buckets were made at every opportunity during testing shutdowns. Table II synopsizes the development of the major events.

The deposits were always removed from the removable nozzle vane prior to its reinstallation into the turbine.

The designations of "washing corrosion" and "impact erosion" are the observers' best estimates of the mechanisms involved. The comments concerning the progressive washing erosion are based primarily on the visual impressions of the observer.

IV. POST-TEST MECHANICAL INSPECTION

General Observations

Turbine disassembly and inspection after 5000 hours of testing confirmed the impressions obtained in borescope inspections during test

TABLE II

SUMMARY OF BORESCOPE INSPECTIONS

Test Time	Stage 3 Mo and Rene' 77 Blades Washing Corrosion Comments	Stage 3 Mo and Rene' 77 Blades Impact Erosion Comments	Deposit Comments	Other Comments
405 Hr.	Serious corrosion grooves along lower leading edges and top of dovetail platform of Mo blades, roughly parallel to the direction of vapor flow. Leading edges were thinned and sharp. 33-50% of Rene' 77 blades showed minor flat at leading edge tips.	No evidence.	Deposits on all components appeared to be potassium oxides or hydroxides, probably formed when the viewport was opened.	Dial indicator measurements through viewport showed some leading edge loss from all types of blades.
1000 Hr.	Corrosion apparently continued in previous patterns at a reduced rate. Light corrosion pitting of convex surfaces appeared, but observations were somewhat obscured by the presence of a potassium film.	First indications appeared as pits on the convex tip leading edge corners of a few Rene' 77 buckets.	One mil thick Fe/Ni deposits were flaking off the blades, and Fe/Ni and potassium dizirconate deposits were present on the removable nozzle vane.	Increased leading edge material loss measurements.
1856 Hr.	Corrosion apparently continued in previous patterns. Rounded leading edges and convex tips on Mo blades.	Pits observed in a triangular pattern at the tip leading edges of many Rene' 77 blades were generally <10 mil (0.25 mm) diameter hemispheres.	Lighter potassium dizirconate deposits on the removable nozzle vanes than previously.	Increased leading edge material loss measurements.
2425 Hr.	Corrosion apparently continued in previous patterns. Mo blade inboard leading edges very rough. Radial corrosion grooves appeared to be starting on all types of buckets.	First evidence of impact erosion pits on Mo blades. >10 mil (0.25 mm) diameter hemispherical pitting observed on all Rene' 77 blades. The triangular wear pattern increased.	Potassium film deposits obliterated some details.	Increased leading edge material loss measurements.
3568 Hr.	Corrosion apparently continued in previous patterns.	One Rene' 77 blade lost small volume of tip leading edge corner by pitting through parent material.	All buckets had a gray-brown appearance. No potassium deposits were evident.	All moly buckets have ragged but sharp leading edges.
3778 Hr.	Corrosion apparently continued in previous patterns.	More Rene' 77 blades lost tip leading edge materials. The bordering surface had a spongy pitted appearance.	Buckets coated with silvery potassium film and gray powder, globules and whiskers.	Axial position measurements showed ±10 mil (0.25 mm) variations in location over the full blade complement.
5000 Hr.	Corrosion continued. Mo buckets had very sharp leading edges and were axially grooved severely in the lower halves of airfoil leading edges and tops of platforms. Airfoil roots and trailing edges were grooved radially. Concave surfaces and aft half of convex surfaces were virtually like new. Rene' 77 blades had radial grooves on both sides of the trailing edges and concave side of the leading edges. Convex tips were slightly rounded, with minor grooving.	Rene' 77 blades had convex tip leading edge pitting and tip corner erosion. Mo blade pits were microscopic in size. The damage to either type of blade was mechanically insignificant. The maximum triangular wear pattern was about 150 mil (3.66 mm) axial x 75 mil (1.83 mm) radial. For example, see tip of bucket on right side of Figure 11.	All rotating and static components were covered with Fe/Ni film about one mil thick. All had potassium dizirconate deposits which were thin on rotating components but closed some stator vane exit passages.	See Figures 10-13.

shutdowns: the impact erosion damage was limited to the third stage rotor blading and was completely insignificant. The blade tips were eroded but required magnification to be readily observed, Figure 10. This damage had no measurable effect on turbine performance. More significant were the effects of washing corrosion upon the molybdenum blades of stages 2 and 3. These blades exhibited grooves near the leading and trailing edge roots where impact damage would not be anticipated, Figure 11. The grooves are attributed to the presence of oxygen in the potassium condensate.

Washing corrosion was concentrated on the blades, with some minor evidence of its presence on tip seal honeycombs and the forward faces of the wheels, where the potassium vapor flowed through the interstage labyrinth seals. Oxygen ingestion through the efflux tube leaks washed grooves through the tip seal honeycombs and into their supporting structure at a few discrete locations adjacent to the leaks.

The turbine rotor as a whole was still a perfectly integral assembly, with no bucket retainers missing or broken off. The blade tips showed no indication of tip rubs and the tip clearances had hardly changed. The buckets were evenly covered with a thin (1 mil) metallic deposit. In addition, the blades had white potassium dizirconate deposits concentrated at flowpath stagnation points. The potassium dizirconate deposits on the stator were much more severe, increasing in depth from forward to aft until the third stage stator had deposits locally up to 0.25 inch high. Additional metallic deposits aligned with the bulletnose hole were found on the first stage wheel.

Minor damage by impaction of metallic bodies, which most probably were slugs of bulletnose material, could be seen on nozzle vanes and tip seal honeycombs, and stage 1 rotor buckets.

Minor galling was present on curvic coupling teeth. The curvic teeth had bonded where the teeth were both of Mo-TZM. This can be an advantage in a long-life system by causing curvic joints to become almost welded together. Bonding did not occur where the teeth were of dissimilar materials (Mo-TZM to U-700 wheels, U-700 wheel to A286 shaft).

Rubbing damage was non-existent at the tip seals and was minimal at the interstage labyrinth seals. It was more evident at the labyrinth seals forward of the pad bearing and the outer labyrinth seal of the

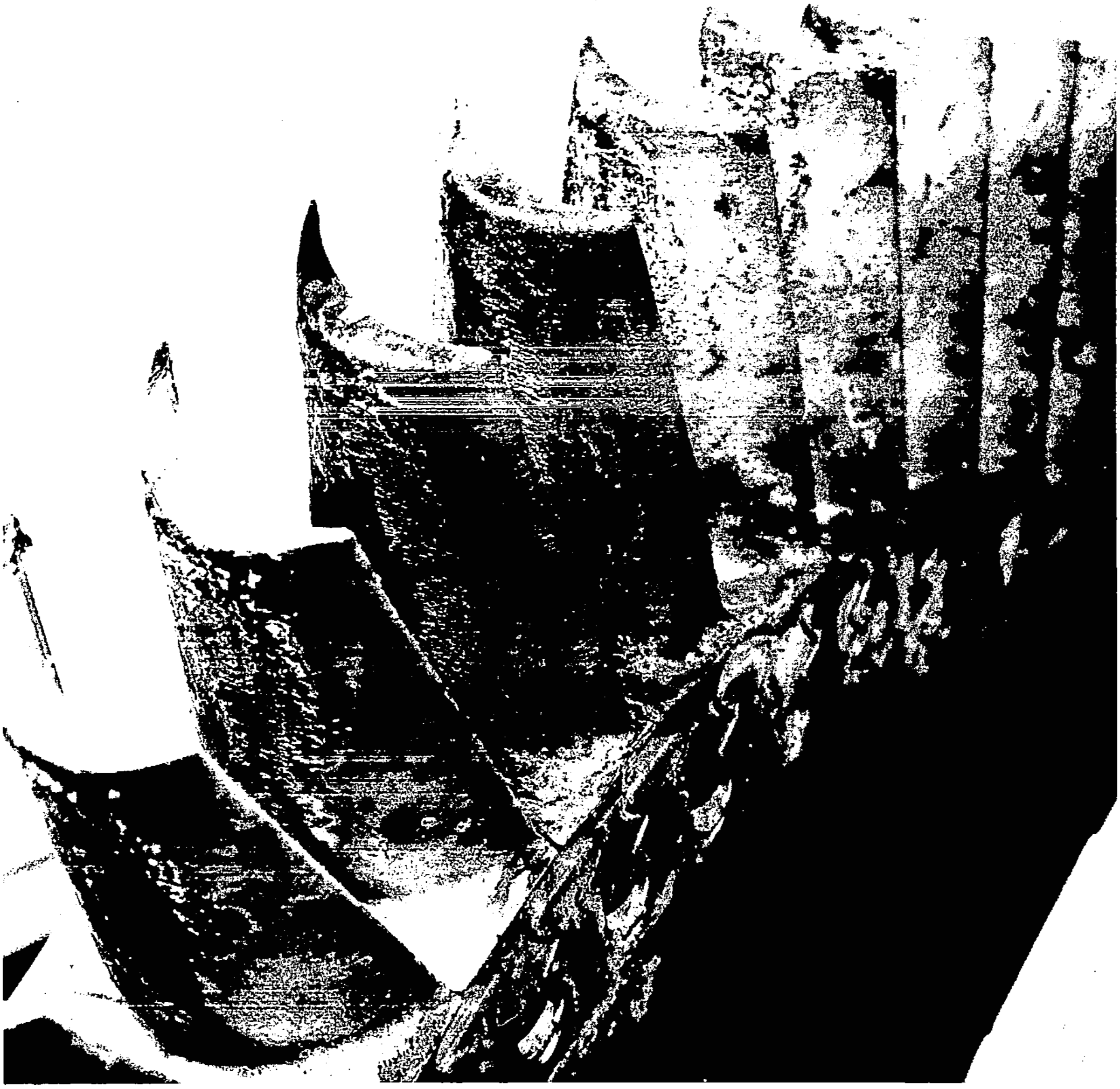


Figure 10. Forward Convex Surfaces of Stage 3 Rotor Buckets and Wheel After 5000 Hour Test. Mo Alloy Buckets Third and Fourth From Left. (P70-6-19T)

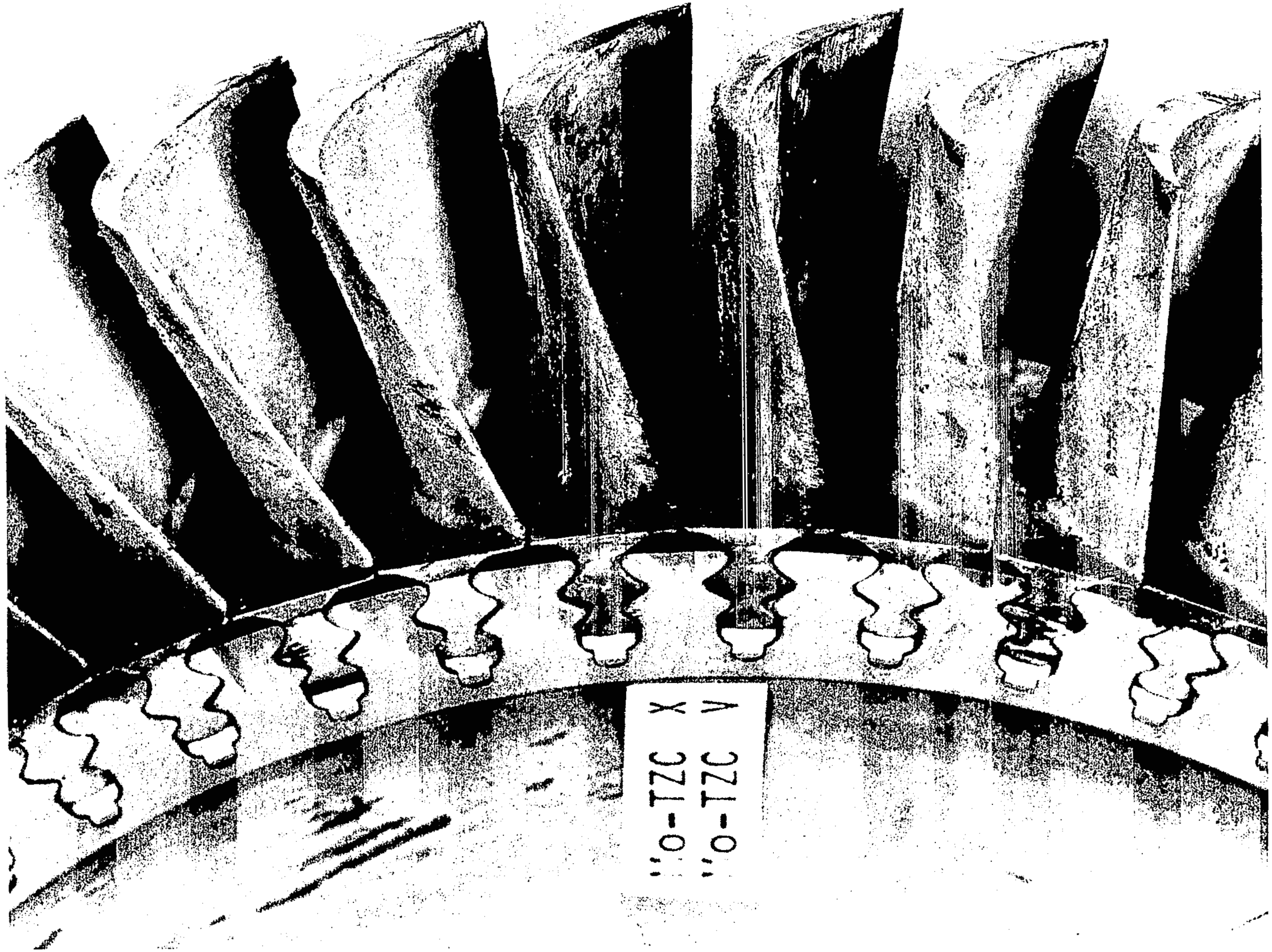


Figure 11. Forward Surface of Stage 3 Rotor Bucket and Wheel After 5000 Hour Test. Mo-TZC Buckets X and V in Center. (P70-6-19AE)

hydrodynamic seal, both caused by thermal distortion effects. Thermal cracks in the outer seal ring of the hydrodynamic seal also contributed to the damage.

The pad bearing assembly was in very good condition, with the minor amount of extrusion of the silver plating on the pads leaving them in condition to operate perhaps to 50,000 hours.

The ball bearings, after operating for 2575 hours, retained their original appearance. The casing assembly, scroll, tiebolt, and shaft were virtually as assembled except for stains and very light deposits.

V. SUMMARY OF MEASUREMENTS

The average weight changes of the rotor buckets and retainers are summarized in Table III. Almost all of the buckets and retainers were weighed after washing with water to remove metallic potassium and potassium salts. Next, a smaller number of buckets and retainers were vapor honed with -320 grit Al_2O_3 to remove potassium dizirconate deposits, and reweighed.

The Rene' 77 buckets primarily exhibited airfoil wear, pitting, and surface roughening with some roughening of the dovetail platform. The molybdenum buckets exhibited obvious thinning of the platforms in addition to the airfoil damage. All buckets had a metallic coating determined to be almost a 50-50 iron-nickel mixture. For weight estimates, a coating thickness of one mil and a density of 8.42 g/cc were assumed.

The Rene' 77 buckets and retainers exhibited a net weight increase after washing due to the presence of potassium dizirconate and/or iron-nickel deposits. After vapor honing, some buckets and retainers still had weights greater than their original values. All molybdenum buckets exhibited weight loss after washing and additional weight loss after vapor honing.

After subtraction of the assumed film weight, the weight change of the second stage Rene' 77 buckets became negative. On this basis, the average Rene' 77 bucket exhibited about one-fourth the average weight loss of the molybdenum buckets, and one-third the loss as a percentage of the original average component weight. Similarly, the third stage Rene' 77 buckets exhibited one-half the weight loss and one-half the percentage

TABLE III

AVERAGE BUCKET AND RETAINER WEIGHT CHANGE DURING 5000 HOURS OF TESTING IN POTASSIUM VAPOR

Stage No.	Material	Sample Size W(1)	Sample Size VH(1)	Avg. Weight Change After Washing %	Avg. Weight Change After Washing g(2)	Avg. Weight Change After Vapor Honing %	Avg. Weight Change After Vapor Honing g(2)	Avg. Weight Change/Component After W g	Avg. Weight Change/Component VH-W g	Avg. Weight Change/Component After VH g	Film Weight g(3)	Avg. Wt. Change/Bucket After VH - Film Weight %	Avg. Wt. Change/Bucket After VH - Film Weight g	Avg. Original Weight g	Airfoil Wt./Bucket Wt. %
Buckets															
1	Rene' 77	62	31	+0.641	+7.27	-0.030	-0.34	+0.117	-0.122	-0.005	0.500	-2.8	-0.51	18.289	49.6
2	Rene' 77	52	26	+0.722	+9.36	+0.107	+1.38	+0.179	-0.152	+0.027	0.605	-2.3	-0.58	24.927	56.3
	Mo-TZM	4	2	-3.097	-4.22	-4.827	-6.63	-1.055	-0.604	-1.659	↓	-6.6	-2.26	34.065	↓
	Mo-TZC	4	2	-2.982	-4.04	-3.276	-4.42	-1.011	-0.094	-1.105	↓	-5.0	-1.71	33.901	↓
3	Rene' 77	43	22	+0.412	+5.05	-0.151	-1.86	+0.115	-0.157	-0.042	0.665	-2.5	-0.71	27.874	64.1
	Mo-TZM	3	2	-2.321	-3.36	-2.610	-3.77	-0.840	-0.104	-0.944	↓	-4.4	-1.61	36.174	↓
	Mo-TZC	3	1	-2.258	-3.27	-2.534	-3.70	-0.817	-0.108	-0.925	↓	-4.4	-1.59	36.164	↓
Retainers															
1	Rene' 41	62	9	+1.101	+0.36	-0.378	-0.12	+0.006	-0.008	-0.002				0.529	
2	Rene' 41	60	10	+0.641	+0.24	+0.027	+0.01	+0.004	-0.004	+0				0.635	
3	Rene' 41	52	9	+0.126	+0.05	-0.318	-0.12	+0.001	-0.003	-0.002				0.745	

(1) W = Washed, VH = Vapor Honed.

(2) Weight changes estimated for the full complement of buckets of each material:
Stage 1 - 62 Rene' 77
Stage 2 - 52 Rene' 77, 4 Mo-TZM, 4 Mo-TZC
Stage 3 - 44 Rene' 77, 4 Mo-TZM, 4 Mo-TZC

(3) Based on a metallic film at 8.42 g/cc (50%Fe + 50%Ni) one mil thick over original bucket area.

loss. The calculations obviously depend upon the assumed film weight. Further, there is no way to compare Rene' 77 and molybdenum weight changes in the airfoils alone.

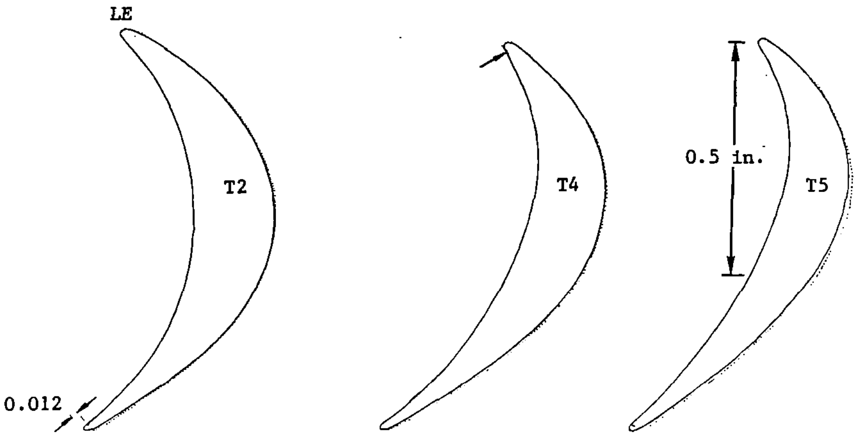
A different indication of airfoil material loss is the Pantascribe results for three Stage 3 buckets. Pantascribing is an inspection procedure wherein the airfoil is traced by a sharp stylus, with the contour permanently recorded on a coated glass plate. Pretest and post-test contours were recorded at the same locations on the same buckets. Separate plates made before and after testing were superimposed to a judged "best match" condition at 20X magnification, Figure 12. The Pantascribe stations are identified in Figure 13. The potassium dizirconate deposits were present during the post-test measurements, but most of the deposits were removed by the sharp stylus during measurement. The concave surfaces matched best, possibly because they were relatively free of the potassium dizirconate deposits.

Rene' 77 bucket 45, Figure 12a, showed no loss of leading edge material except for a 5 mil deep x 10 mil wide corrosion groove on the T4 concave surface (see arrow). The 0-12 mil deposits not penetrated by the stylus were primarily potassium dizirconate. The trailing edge lost 12 mils at section T4, which is the approximate location where the concave and convex surface radial corrosion grooves intersect.

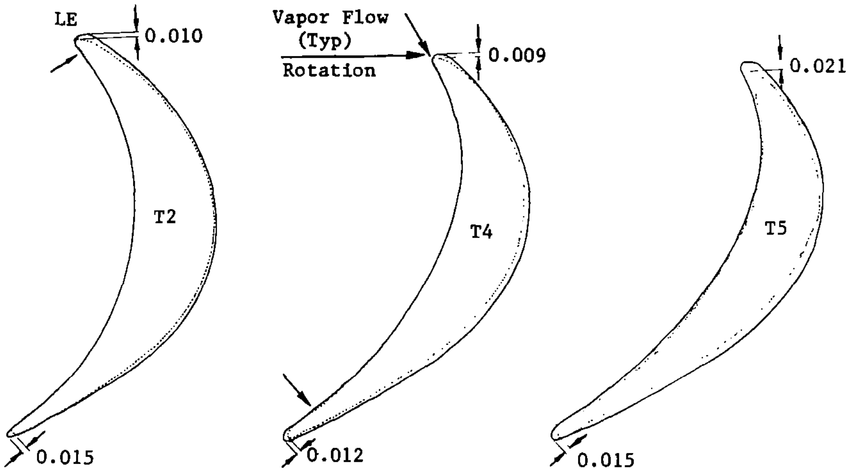
Mo-TZM bucket AA, Figure 12b, showed substantial leading edge and trailing edge material losses. The T2 and T4 concave surfaces were unchanged except for 0-5 mil deep radial grooves near the leading edge and trailing edge. The T5 concave surface lost material generally, up to 10 mils depth. All convex surfaces lost material generally, up to 20 mils depth, an indication of washing corrosion.

Mo-TZC bucket W, Figure 12c, showed wear patterns similar to those of Mo-TZM bucket AA. Both Mo-TZC and Mo-TZM are similarly susceptible to corrosion by potassium which contains oxygen. The difference in material loss at comparable positions is a function of the ability of the stylus to penetrate the deposits on the buckets and of the observer to accurately match the pretest and post-test airfoil contours.

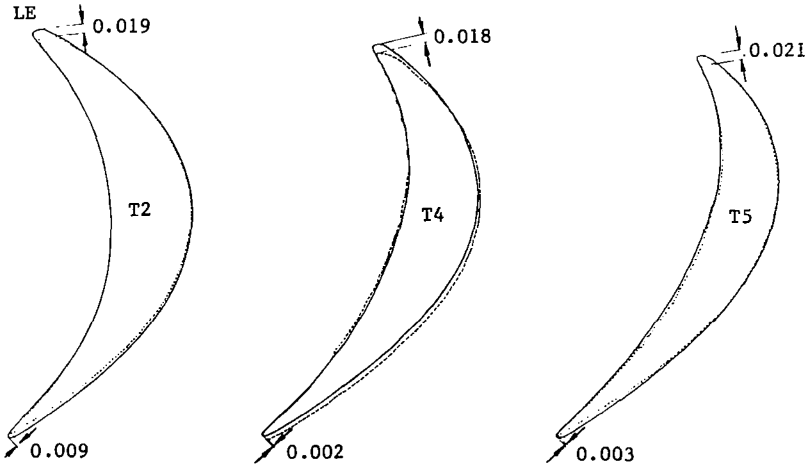
A third method of estimating material loss is shown in Figure 13, where the root-to-tip leading edge profiles after testing are measured



a - Rene' 77 Bucket 45



b - Mo-TZM Bucket AA



c - Mo-TZC Bucket W

Figure 12. Pantascribe Measurements of Three Stage 3 Rotor Buckets Before and After 5000 Hour Test With Potassium Dizirconate Deposits Present.

(All Dimensions in Inches)

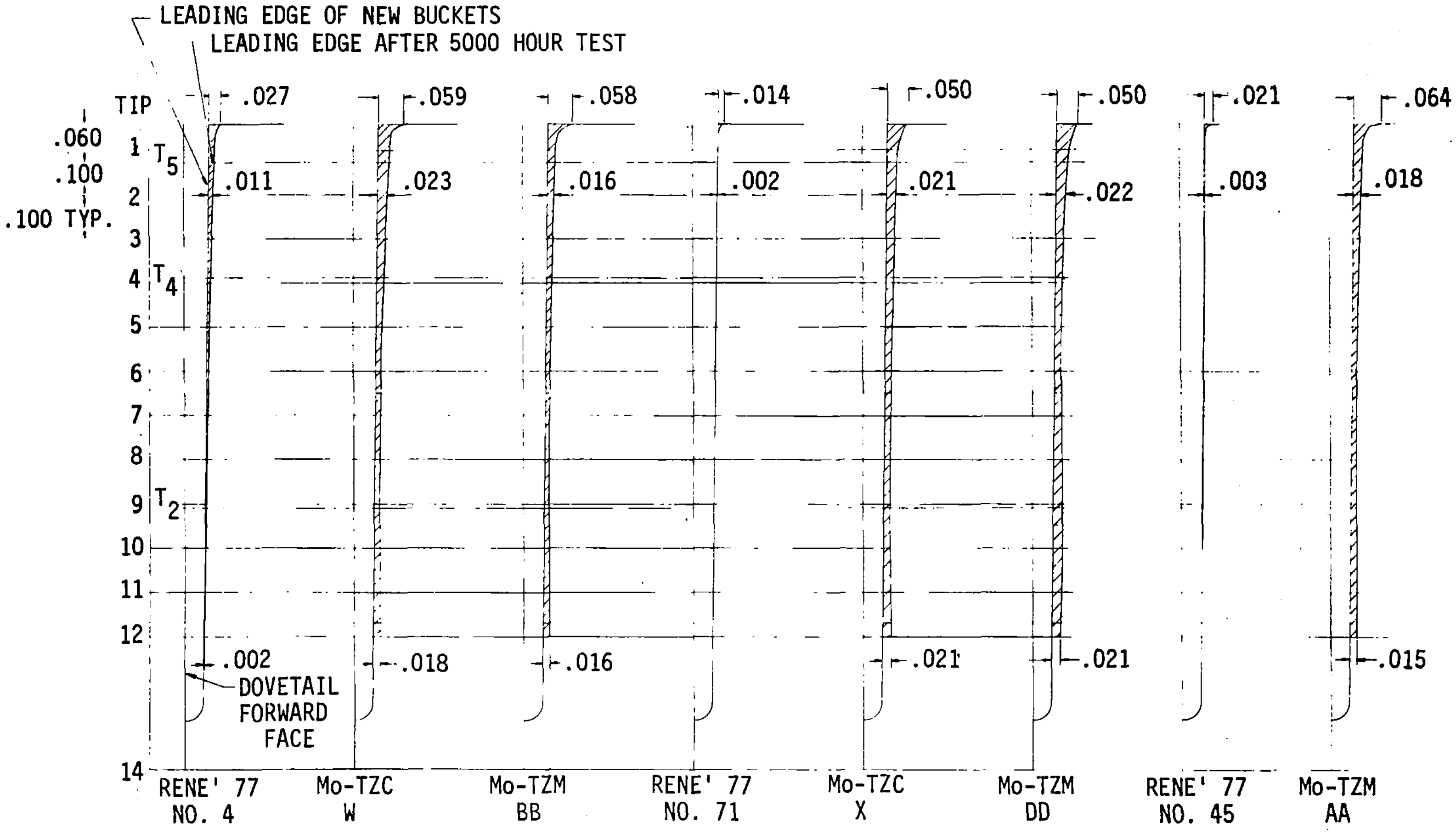


Figure 13. Surface Plate Measurements of Stage 3 Bucket Leading Edges.
(All dimensions in inches)

at 0.1 inch increments. The dovetail forward faces were used as a reference since shallow pretest identification marks and machining grooves could be seen when not covered by the metallic film. The differences between pretest and post-test configurations correlate well with the Pantascribe measurements of Figure 12.

The leading edges of the three Rene' 77 Stage 3 buckets of Figure 13 exhibited only minor material loss (0-2 mils) near the airfoil roots. The loss increased toward the tips to a maximum of 27 mils. The Mo-TZM buckets, on the other hand, had substantial root material removal (15-21 mils) which increased toward the tips. The tip loss (50-64 mils) was about twice the maximum Rene' 77 tip loss. The Mo-TZC buckets had material losses very similar to those of Mo-TZM.

Leading edge measurements were made during each shutdown through the viewing port. The measurements established the relative leading edge profiles and identified the greater loss of material from the molybdenum buckets. However, post-test measurements showed that the viewport measurements indicated material losses substantially greater than the actual losses. This error could arise from inaccurate determination of the reference dovetail forward face. An improved method is required if the viewport is to be used for periodic measurements as originally intended.

Clearance Measurements

The critical diametral clearances between the turbine static and rotating components, plus the tiebolt length, before and after the 5000 hour test are listed in Table IV.

The tip seal changes are caused by conical thermal distortion of the static tip seals. Measurements at two or more axial stations show that these are larger on their unsupported ends. The measurements do not include the effects of the light scoring. The appearance of the scoring marks suggests random contact by irregularly shaped metallic bodies. The bulletnose fragments were the most likely source of such bodies.

The cold wheel assembly diameters increased only 1-2 mils. The changes in interstage seal diameters were similar, based on diametral measurements which ignored the light scoring grooves caused by contact with the rotating labyrinth seal teeth.

TABLE IV

THREE STAGE POTASSIUM TURBINE CRITICAL DIAMETRAL CLEARANCES

Components	Characteristic Dimension In.	(CM)	Pre-Test Clearance Mils	(MM)	Post-Test Clearance Mils	(MM)	Change Mils	(MM)
Tip Seals								
Stage 1	9.114	(23.15)	40	(1.02)	11-19	(0.28-0.48)	-21/-29	(-0.53/-0.74)
Stage 2	9.954	(25.28)	40	(1.02)	37	(0.94)	-3	(-0.08)
Stage 3	10.503	(26.68)	40	(1.02)	13-35	(0.33-0.89)	-5/-27	(-0.13/-0.69)
Interstage Seals								
Stage 1-2	4.081	(10.37)	20	(0.51)	18.5	(0.47)	-1.5	(-0.04)
Stage 2-3	4.081	(10.37)	20	(0.51)	12	(0.30)	-8	(-0.21)
Stage 3-Ni Seal	3.871	(9.83)	20	(0.51)	3	(0.08)	-17	(-0.43)
Shaft-Ni Seal	3.871	(9.83)	20	(0.51)	20	(0.51)	0	
Tiebolt								
Length (70F)	28.4359	(72.23)			28.434 In.	(72.22 CM)	-1.9	(-0.05)

The tiebolt length change of 1.5 mils decrease is probably a measurement error, since the tiebolt length would be expected to increase slightly due to creep in 5,000 hours. The original tiebolt load of 10,000 lb. decreased to 7,400 lb. as a result of the creep.

VI. AEROTHERMODYNAMIC PERFORMANCE

The three stage potassium vapor turbine was run for 5,000 hours at 18,250 rpm, with 1500°F inlet vapor temperature and a turbine total-to-static pressure ratio of 9.86. The third stage rotor, with a tip speed of 837 ft/sec and a temperature of 1176°F, operated in an environment of wet potassium vapor with a quality of 0.91 for the initial part of the test and no more than 0.93 up until the shutdown at 4268 hours.

Shown in Figure 14 are the important performance parameters plotted as a function of time. It can be seen that the flow rate and net torque decreased significantly after the first shutdown. Subsequently the flow rate increased to a value greater than the initial value while the torque increased only slightly. It appears likely that the initial decrease in flow and torque was caused by potassium dizirconate or iron-nickel deposits on the turbine blades, and the subsequent increase in flow rate was due to the hole in the bulletnose which eventually permitted about one-third of the flow to bypass the first stage nozzle. This rationale is supported by the temperature plot which shows an increase in the first stage nozzle exit temperature, T_4, in the 700- to 1500-hour time period when the flow rate was increasing. Thus the hole in the bulletnose seems to have occurred after 700 hours. The decreases in torque at 1856 and 4268 hours are attributed to potassium dizirconate deposits found on the turbine blades. The decrease in flow after 4200 hours is attributed to heavy potassium dizirconate deposits on the third stage nozzle vanes. This conjecture is supported by the significant increase in the temperature after the second stage rotor, T_7, which could result, for instance, from the partial blockage of the third stage nozzle.

The values of the vapor quality at the inlet to the third stage, which is a measure of the maximum condensate which can damage the third stage rotor, was estimated in the following way: the results from the 5000 hour endurance test taken on the first two days were in good

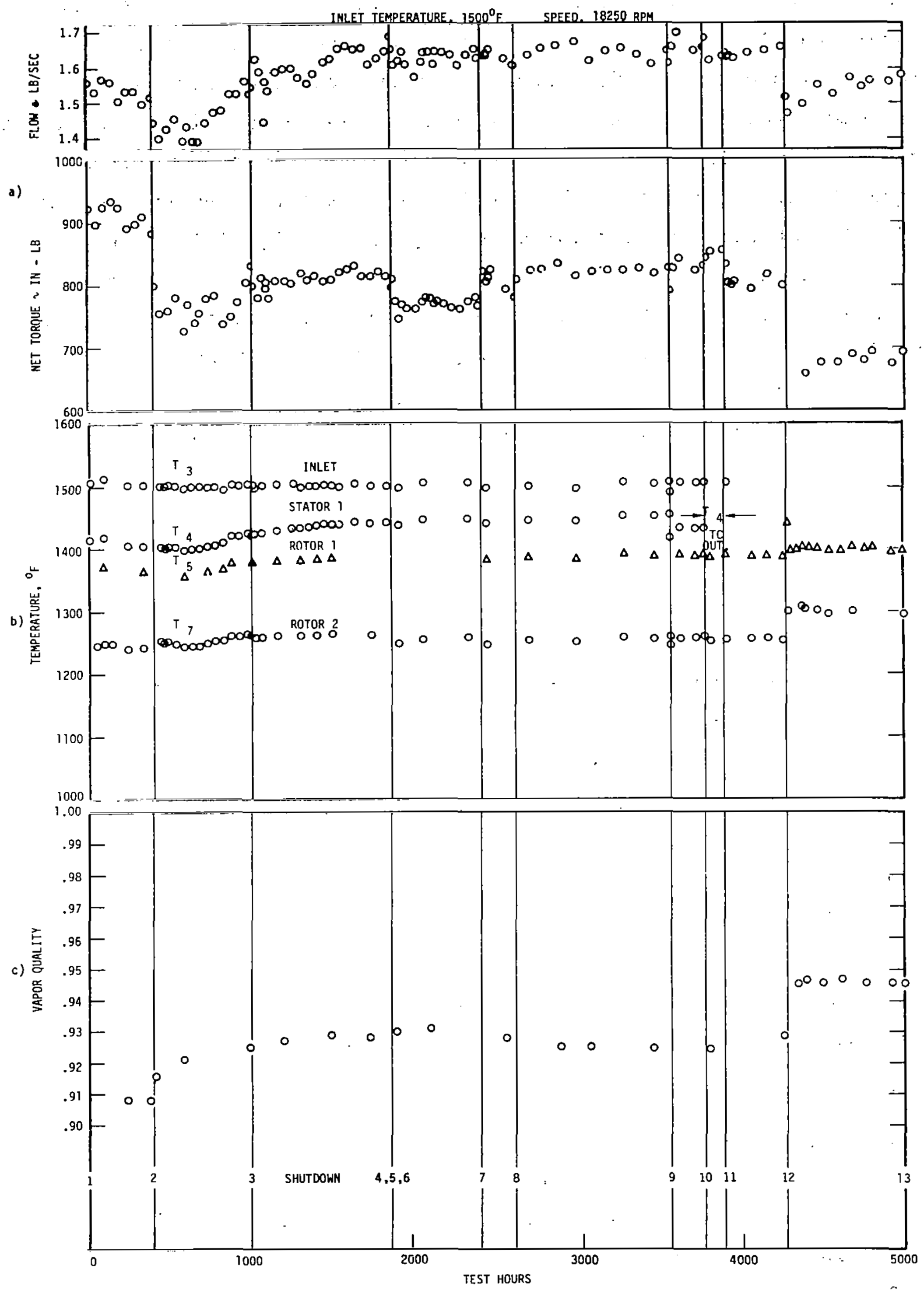


Figure 14. Flow Rate, Net Torque, Temperature, and Stage 3 Inlet Vapor Quality Performance During 5000 Hour Test.

agreement with the 1968 performance test results(4) which determined a benchmark turbine efficiency. For subsequent test points the turbine efficiency was estimated from measured values of flow rate, speed, and net torque. The turbine efficiency, exit pressure, and inlet conditions locate the condition line of the turbine on the potassium Mollier diagram. The quality at the inlet to the third stage was estimated from the measured value of the second rotor exit temperature, T_7, (Figure 14) and its location on the turbine condition line on a Mollier diagram. The third stage inlet quality varied from 0.91 at the beginning of the test to 0.93 after the bulletnose was fully opened, continuing at 0.93 until 4268 hours. After the next shutdown the quality rose to about 0.95 when the performance decreased due to heavy deposits on the third stage nozzle vanes.

Shown in Figure 15 is a comparison of performance test results obtained from the 1968 performance test, before the 5,000 hour endurance test, and after the endurance test. The flow rate is about the same for all three tests, but the torque after 5,000 hours is about 25% lower than the original values. This is about the same decrease shown on Figure 14 for the 5,000 hour endurance test.

Air tests of the defective bulletnose showed that about one-third of the flow bypassed the first stage nozzle. Additional air tests showed that the flow coefficients of the three nozzle diaphragms were reduced 1, 5, and 13% respectively due to deposits on the nozzle vanes. By incorporating these changes into the off-design calculation program and increasing the blade loss coefficients by a factor of five(6) to simulate the roughness of the deposits, the performance decrease of the turbine was simulated within 2% at a pressure ratio of ten.

In summary:

1. The bulletnose failure was probably initiated after 700 hours and was probably completed at about 1700 hours.
2. For most of the test (4268 hours) the third stage inlet quality was no more than 0.93.
3. The decrease in flow and torque after the next-to-last shutdown was caused by heavy deposits, primarily in the third stage nozzle.

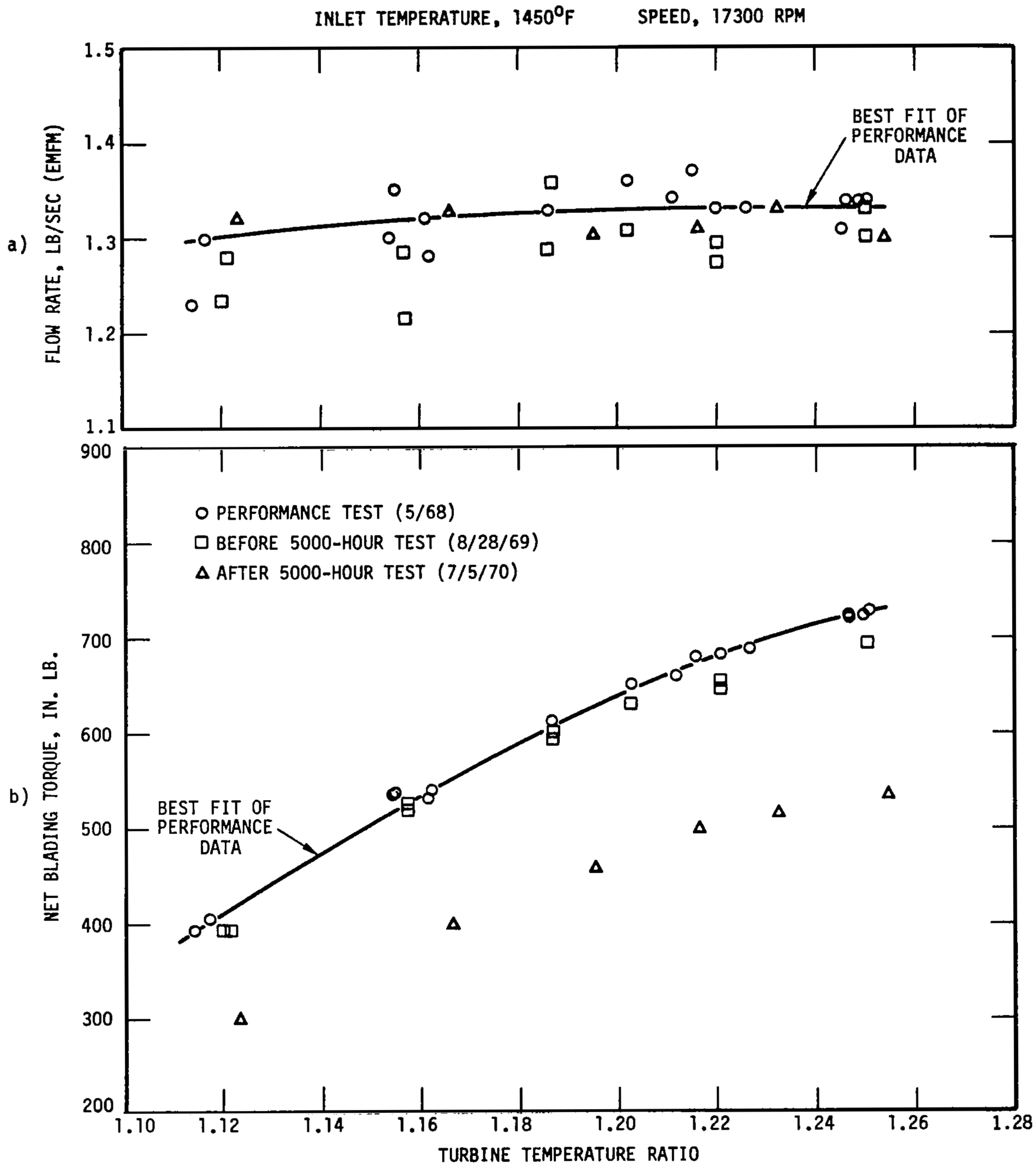


Figure 15. Net Blading Torque and Flow Rate Performance in 1968 and Before and After 5000 Hour Test.

4. Calculations utilizing measured nozzle flow area changes and estimated blade loss coefficients to account for roughness caused by blade deposits correlate with the observed performance degradation.

VII. POTASSIUM LOOP CHEMISTRY

Potassium reacts with oxygen to form potassium oxide which has a high solubility in potassium. Potassium which contains oxygen is known to corrode refractory metal alloys; e.g., molybdenum alloys. Consequently, oxygen getters are introduced into the potassium loop at three places and the oxygen concentration in the potassium is monitored during startup, operation and shutdown.

The oxygen getters are zirconium sheets located in the condenser, zirconium sheets in a boiler by-pass hot trap, and titanium sheets located in the facility dump tank. The titanium serves as a getter while heating the potassium prior to filling the boiler. During operation the condenser zirconium is exposed to the full potassium flow. The boiler zirconium sees only a small by-pass flow due to material circulation from the boiler upper drum to the boiler lower drum.

Potassium samples can be removed, for oxygen analysis, from the loop at the condenser bowl and from the EM pump by-pass. An electrochemical oxygen meter is located in a similar EM pump by-pass. The condenser bowl catches liquid potassium from the two-phase exhaust flow prior to condensation. Consequently, the oxygen concentration is expected to be greater for these samples than for the diluted (from condensation) single phase liquid potassium from the condenser (the EM pump by-passes).

The oxygen in the potassium samples was determined using the amalgamation method. This method has limited accuracy because of a blank associated with sampling and analysis which amounts to five to ten micrograms, and a standard deviation which is about 2.5 micrograms. The amalgamation oxygen values were always in error on the high side and normally ran between five and ten ppm. Such values were considered to indicate essentially 0 ppm oxygen concentration.

The oxygen meter electrode consisted of a thoria-yttria electrolyte through which electricity may pass by oxide ion migration. It was quite susceptable to mechanical and thermal shock, two conditions which were sometimes difficult to avoid. The calibration data was obtained at relatively high oxygen concentrations. In actual operation in the turbine facility, this data must be extrapolated over three orders of magnitude. The oxygen meter was originally installed as a safety device to rapidly indicate leaks in the subatmospheric sections of the loop. It was never intended as an accurate method for determining oxygen concentrations; however, it was a good method for following trends.

Figure 16a shows the oxygen meter data for the first 2425 hours of endurance testing. During the initial operation the indicated oxygen concentration dropped rapidly. After the boiler hot trap leak the rate of decrease was much less. During this same period the condenser bowl and bypass samples also showed higher than normal values (5 to 10 ppm) with the bypass values being lower, as expected. The oxygen meter values were, of course, still lower because of the blank in the amalgamation data. The data indicated that the loop was contaminated to a considerable extent. A torque decrease was noted at the 405-hour startup and potassium dizirconate ($K_2O \cdot 2ZrO_2$) was noted on the stator vanes at the 1000-hour inspection. The ensuing data indicated that subsequent problems did not result in serious contamination, as indicated by the very rapid drop in oxide concentration during startups and the continually decreasing values during normal operation. Analysis of condenser bowl samples, during the period when no oxygen meter was operating, indicated the usual values between five and ten ppm. At about 2200 hours a new electrode was installed during operation and the noted spike was due to cleanup of the oxygen meter loop.

Figure 16b shows that the boiler leak which occurred after 2425 hours of operation did not result in serious contamination nor did subsequent mishaps until the leak in the top boiler drum at about 3900 hours. Another electrode was installed at this point. It had been used previously in a NaK system and had to be cleaned up by an alcohol washing before installation in the turbine facility. It is not possible to say whether the apparent slow cleanup of the loop after this mishap was due to contamination or to conditioning of the elctrode. However, the condenser bowl

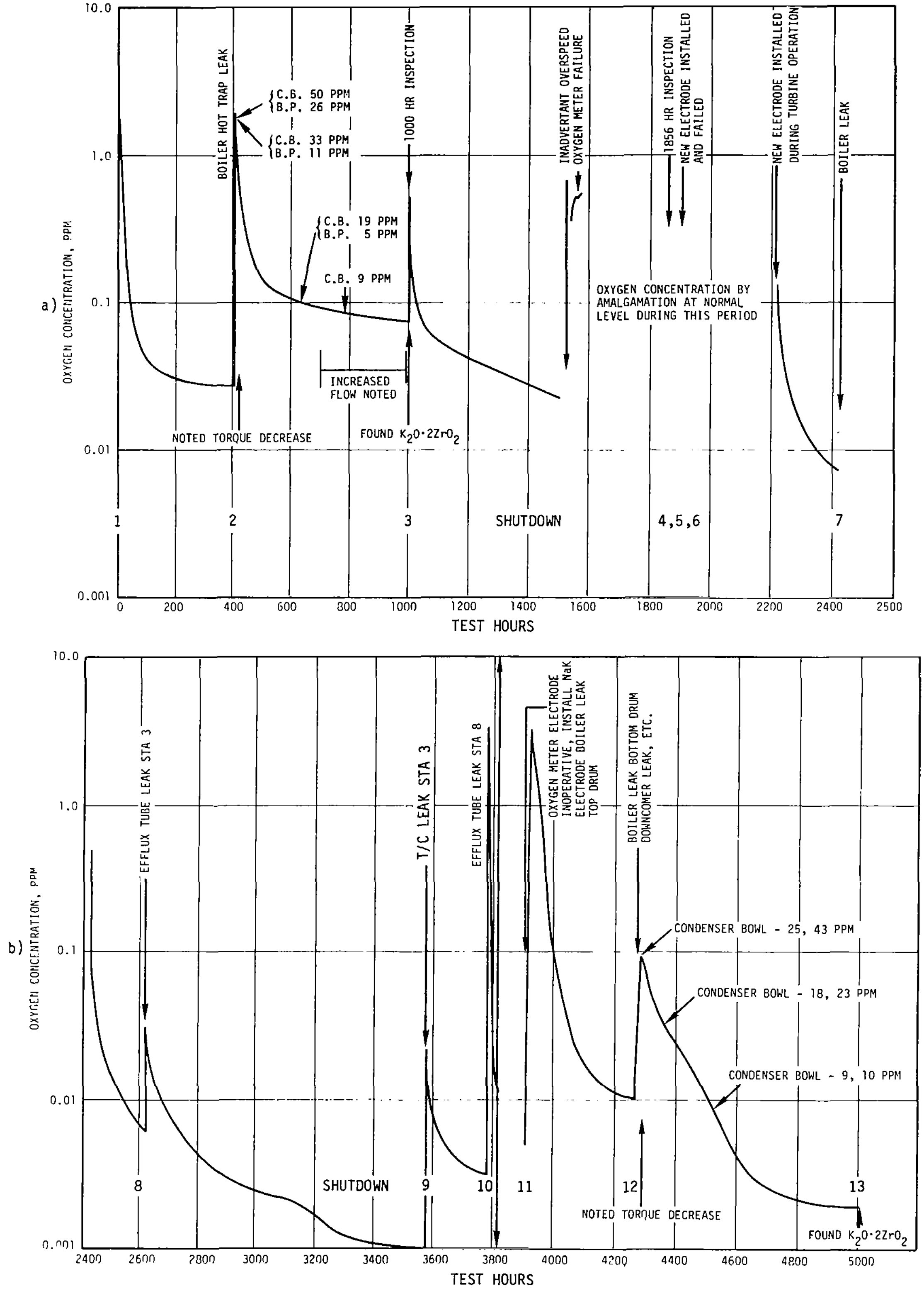


Figure 16. Three Stage Turbine Oxygen Meter Data During 5000 Hour Test.

sample indicated seven ppm oxygen at the startup and supports the contention that contamination was not excessive. In contrast, the boiler leak at 4268 hours definitely resulted in contamination, as indicated by the relatively slow decrease in oxygen meter concentration and by the high values obtained from the condenser bowl samples. A decrease in torque was again seen and at the final inspection potassium dizirconate was again found to be deposited on the stator vanes. After the 5000-hour test, visual inspection of the condenser zirconium hot trap showed it to be cracking, but essentially intact. X-ray diffraction indicated that the black powder found on the surfaces consisted of Zr_4Fe and a trace of potassium dizirconate. In contrast, inspection at the boiler bypass zirconium hot trap showed that it was disintegrating and contained a considerable quantity of potassium dizirconate. Therefore, it was the principal source of the turbine deposits.

The important point to be noted from this continual monitoring of loop cleanliness is that serious contamination occurred only twice due to air ingestion during a leak. Both incidents caused a step decrease in torque and heavy deposits of potassium dizirconate. A refractory metal system, operating of necessity in a vacuum, would not be contaminated by similar leaks.

Metallic impurity concentrations were generally below the detection limits of 2-30 ppm. Zirconium was always below 10 ppm, which is the detection limit.

VIII. METALLURGICAL RESULTS

The post-test material evaluation is focused on a limited number of flow path components and turbine specimens from the standpoint of liquid metal corrosion and liquid metal erosion. Superimposed on these effects are the effects of the stainless steel facility, where the mass transfer of elements such as iron, nickel, and chromium through potassium is deposited on the flow path components which could cause accelerated corrosion of the molybdenum alloy buckets by the formation of complex compounds.(7,8,9) Most of the damage observed could have occurred over a relatively short period of time, during a leak when air had the opportunity to enter the turbine.(10) It has been reported that the mass transfer of molybdenum in potassium increases with increasing oxygen content.(11)

Overall, the turbine buckets looked good after 5000 hours of operation. A small amount of impact erosion was observed at the tip of the leading edges of both molybdenum alloys and cast Rene' 77* nickel-base superalloy buckets. Most of the metal removal observed, especially on molybdenum alloy buckets, was associated with oxygen-accelerated washing corrosion.

Rotor Buckets

To characterize the third stage buckets and the thin films found on them, metallographic and chemical analysis techniques were employed. Figure 17c shows the leading edge of a Stage 3 Mo-TZM bucket. The heaviest washing corrosion occurred at the root of the blade. On top of the dovetail platform, where undercutting can be noted, the upper portion of the airfoil has been worn to a knife edge. A small amount of

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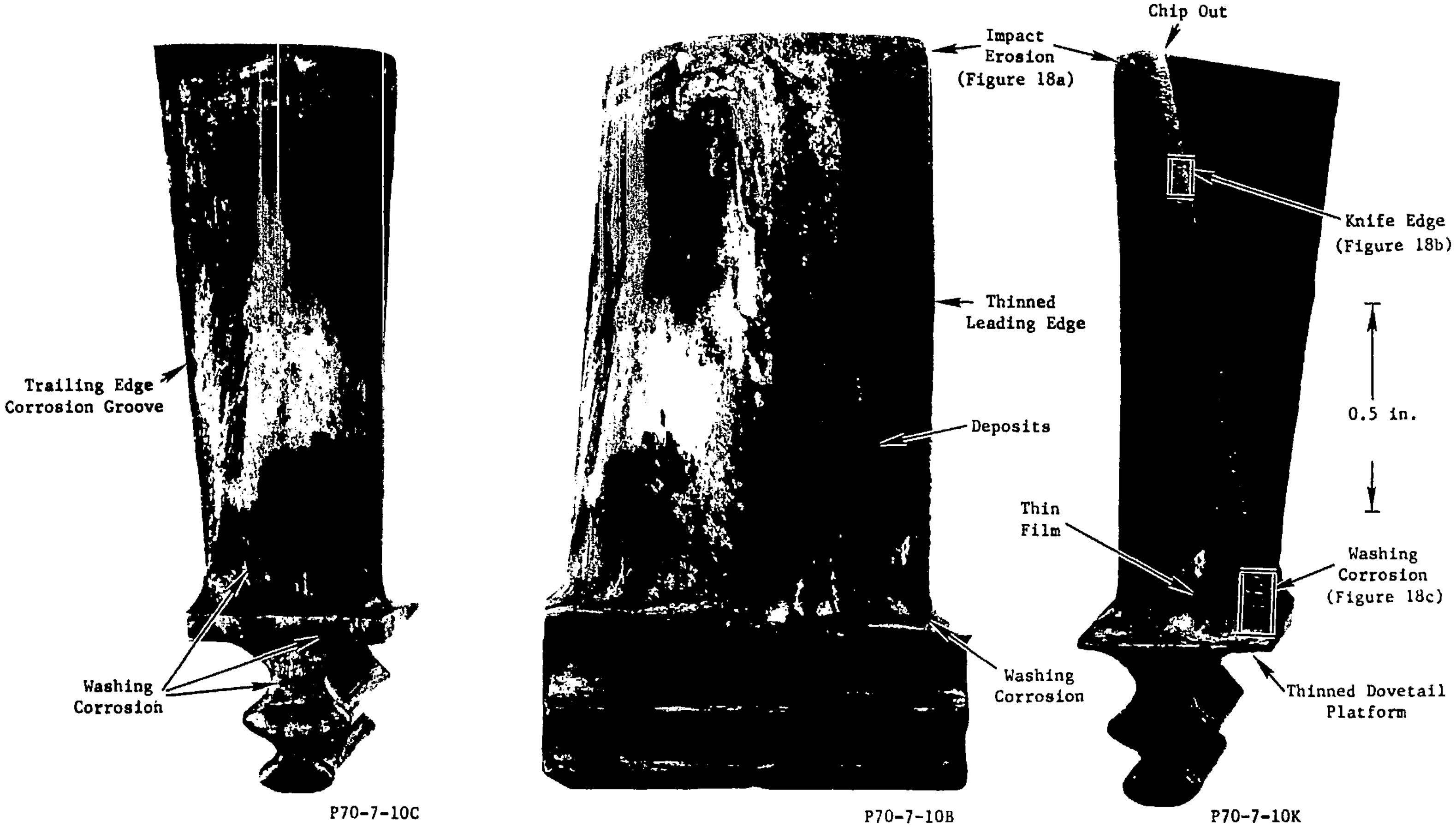
*Composition: Mo-TZM - Mo + 0.08Zr + 0.5Ti + 0.02C
Mo-TZC - Mo + 0.15Zr + 1.25Ti + 0.12C
Rene' 77 - Ni + 15Co + 14Cr + 4Al + 3Ti + 0.07C



a) Trailing Edge b) Convex Surface c) Leading Edge

Figure 17. Mo-TZM CC Third Stage Rotor Bucket Following 5000 Hours Exposure to Potassium - Inlet Vapor Temperature 1250°F, Vapor Quality 90-93%, Tip Speed 845 ft/sec.

impact erosion damage is evident at the tip of the blade despite the washing corrosion which also occurred at the tip.

Figure 17b shows a deep corrosion groove that starts on the pressure surface and extends radially upward on the suction surface. These observations are typical for both Mo-TZM and Mo-TZC buckets.

Figure 18a is a scanning electron micrograph of the impact erosion at the tip of a Mo-TZM bucket. Great similarity is seen between this surface and impingement erosion surfaces reported in the literature;(12) however, no cracks were noted at the base of the pits. The evidence of corrosion products, seen as white particles in Figure 18a,* indicated the surface has been altered by washing corrosion.

Figures 18b and 18c show the scanning electron micrographs of the damaged surfaces at the upper portion and root, respectively, of the leading edge of the Mo-TZM bucket. At the root of the airfoil where washing corrosion has occurred the surfaces on the incline of the ridges are very smooth even at 200X, a surface typical of a bulk corrosion effect. However, in the area of the thinned leading edge the surfaces are rougher and pitted and have great similarity to reported impingement erosion surfaces. It appears that both corrosion and erosion occurred at the leading edge of the blade.

Figure 19 shows the microstructure of a third-stage Mo-TZC bucket. Washing corrosion has occurred on both the concave and convex surfaces at the base of the airfoil leading edge. Some of the material removal occurred on the concave surface of the thinned leading edge. Also, signs of corrosion are seen at the trailing edge convex surface where a groove runs almost the entire length of the convex surface of the airfoil. The groove is 0.030 inch wide and has a maximum depth of 0.005 inch.

Figure 20 shows a Stage 3 Rene' 77 bucket. Except for signs of impact erosion at the tip of the bucket and the presence of the thin films and deposits, the Rene' 77 buckets show very few signs of detrioration.

Apparently the differences in appearance between the molybdenum alloy and nickel alloy buckets can be attributed to oxygen effects.

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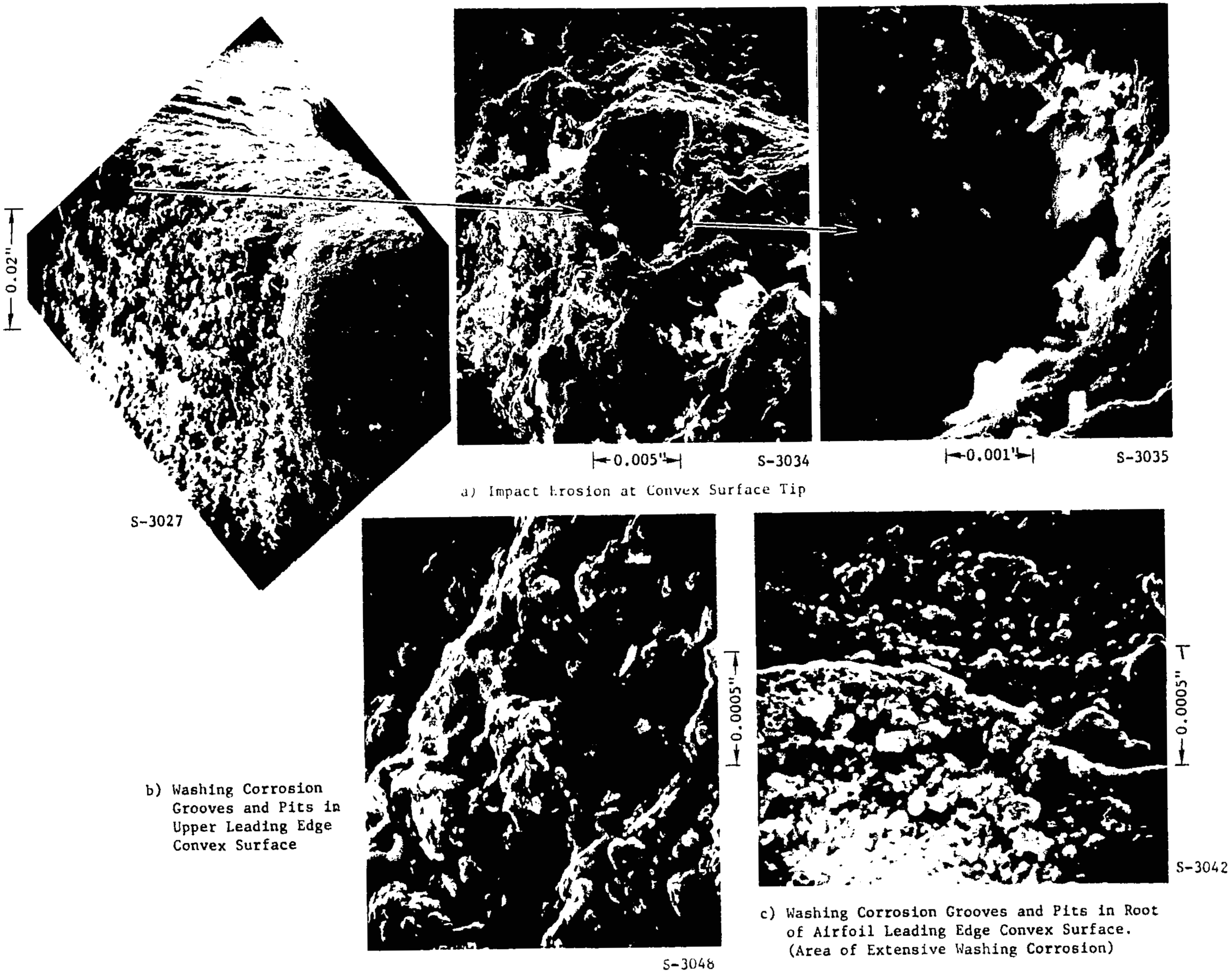
*White particles identified to be ceramic in origin by back scatter scanning electron microscopic techniques.



a) Impact Erosion at Convex Surface Tip

b) Washing Corrosion Grooves and Pits in Upper Leading Edge Convex Surface

c) Washing Corrosion Grooves and Pits in Root of Airfoil Leading Edge Convex Surface. (Area of Extensive Washing Corrosion)

Figure 18. Magnified Views of Damage on Stage 3 Mo-TZM Bucket No. CC.

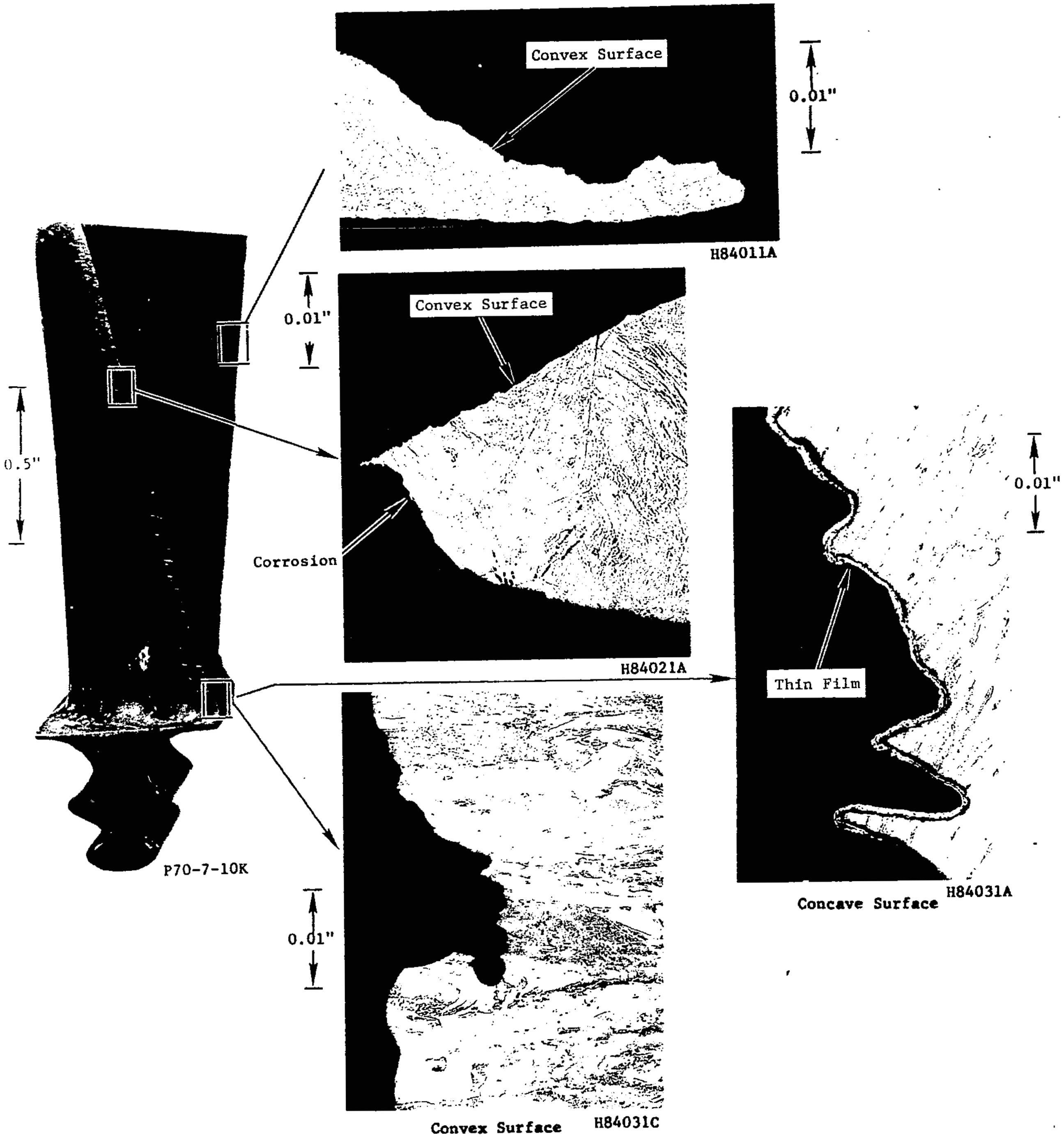


Figure 19. Microstructure of Mo-TZC #U Third Stage Rotor Bucket.

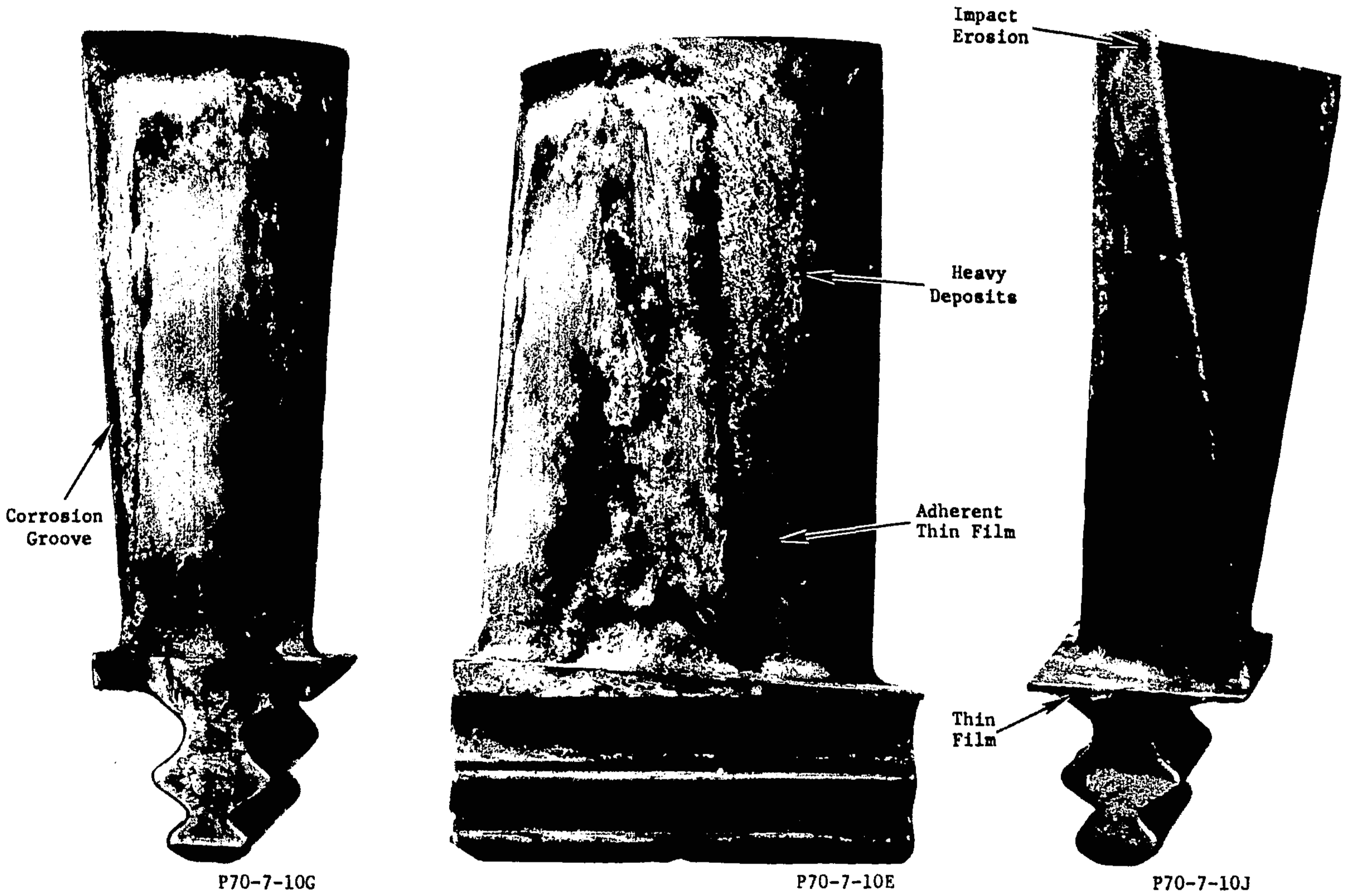


Figure 20. Rene' 77 No. 19 Third Stage Rotor Bucket Following 5000 Hours Exposure to Potassium-Vapor Temperature 1250°F, Vapor Quality 90-93%, Tip Speed 845 ft/sec.

Washing corrosion of the roots and leading edges of the molybdenum blades was observed through the borescope at the shutdown for the leak at 405 hours of testing. Also, as mentioned earlier, the mass transfer of molybdenum increases with increasing oxygen in potassium; however, the oxygen concentration has little effect on the dissolution of nickel,(13) the principal constituent of Rene' 77.

Erosion Inserts and Refractory Metal Ring Specimens

Ten erosion inserts consisting of Mo-TZM, Mo-TZC, Rene' 77, and U-700 materials were located aft of the Stage 3 rotor and subjected to liquid droplet impact at 838 ft/sec at 1200°F. Figure 21 shows the location of the erosion inserts relative to the Stage 3 blades. Droplets departing tangentially from the trailing edge forward to the mid-chord impact onto the erosion inserts. As can be seen in Figure 21, all the erosion inserts showed classical impact erosion as characterized by pits. Scanning electron micrographs show that cracks are present at the bottom of the pits. The impact surfaces of the molybdenum alloy specimens also contained signs of corrosion. Figure 22, which shows the cross section of a Mo-TZC and Rene' 77 specimen, indicates that the crack front on the Mo-TZM is contained very close to the bottom of the pit. The maximum depth and diameter of the pits are indicated.

Table V contains the summary of erosion insert volume loss which indicates that the molybdenum alloys lost about 0.1 cubic centimeter, sixteen times that of Rene' 77 and eight times that of the U-700. However, the material loss of the molybdenum inserts by washing corrosion is part of the total volume loss.

The summary of the weight change and interstitial element pickup of the refractory metal ring probes is also contained in Table V. The upstream position was forward of the test turbine, exposed to the inlet vapor temperature of 1500°F. The downstream position was aft of the turbine, exposed to the outlet vapor temperature of 1160°F. The specimens were in a perforated stainless steel tube. The Cb-1Zr specimens, the best indicators of the oxygen content of the potassium which the flow components see, indicate 1911 ppm oxygen pickup upstream and 544 ppm oxygen pickup downstream. However, the surface of the downstream Cb-1Zr specimen had holes up to 26 mils deep, presumably due to spalling

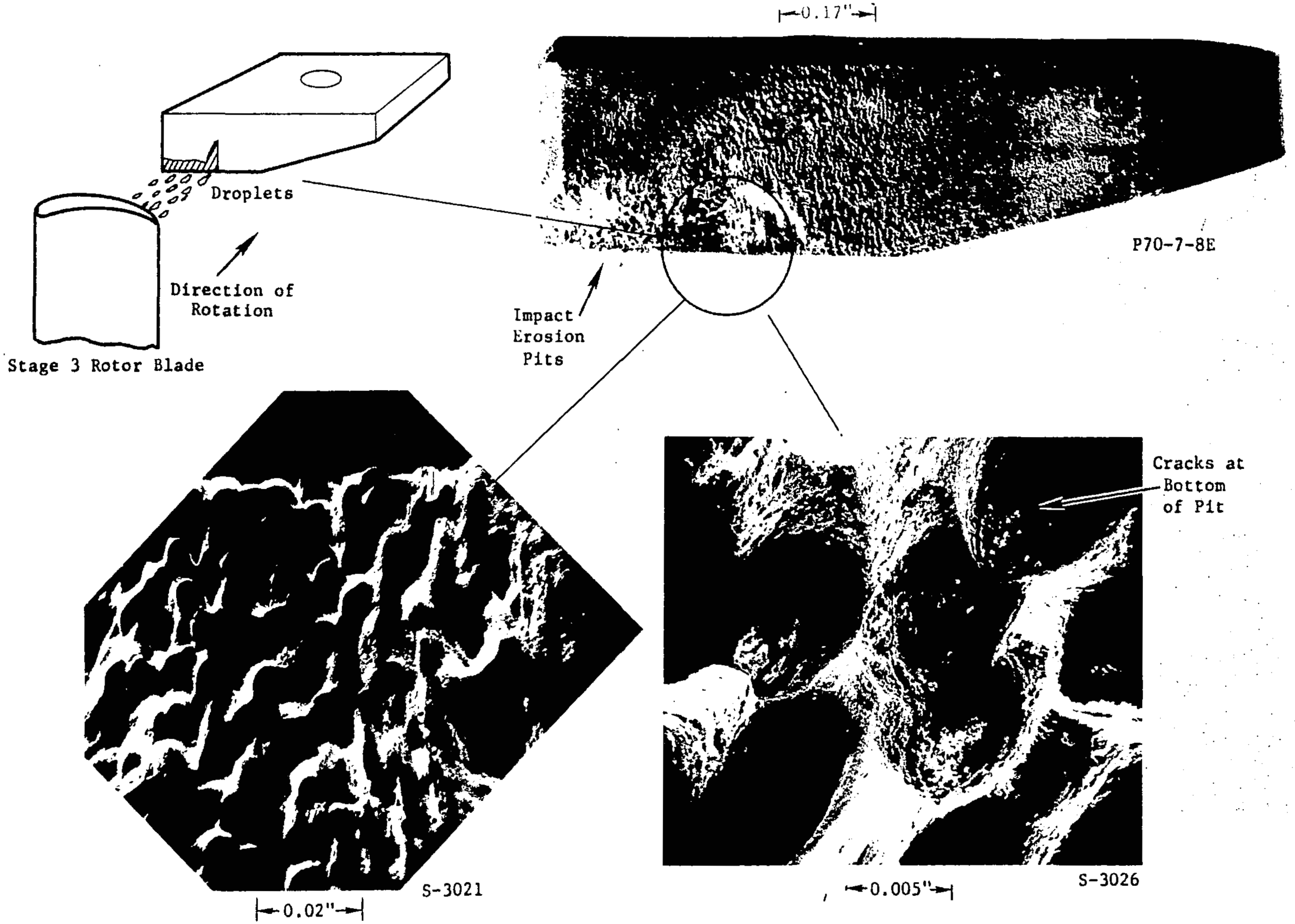
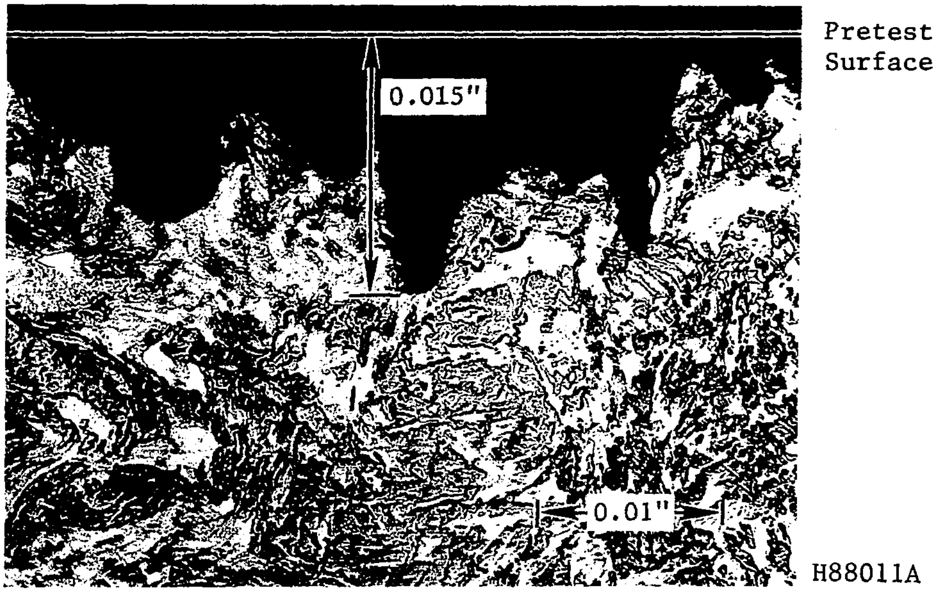
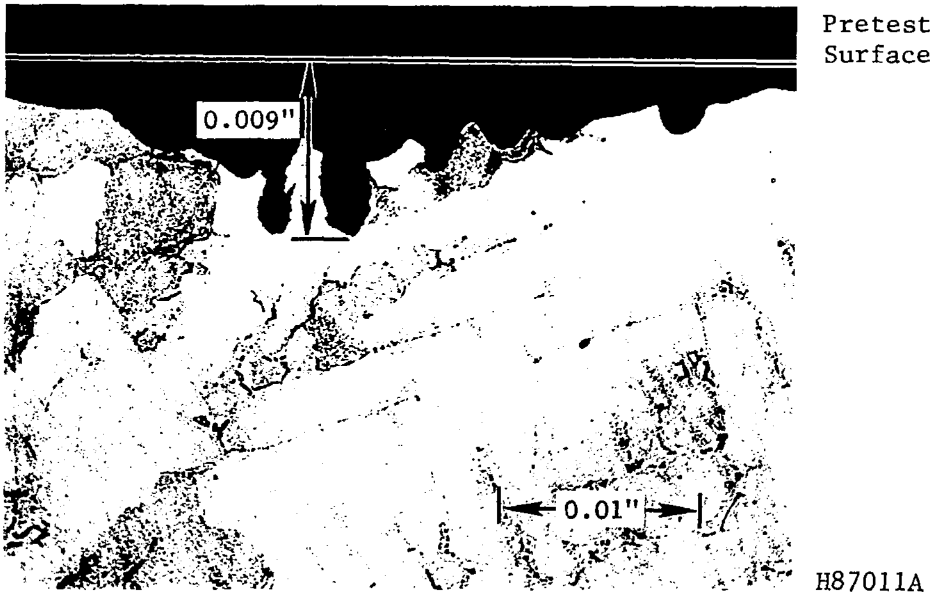


Figure 21. Impact Surface of Mo-TZM No. 1 Erosion Insert and Magnifications of Damage After 5000 Hours of Test.



a) Mo-TZC - Maximum Pit Diameter = 0.0090 In.



b) Rene' 77 - Maximum Pit Diameter = 0.0025 In.

Figure 22. Magnified Cross-Sections of Mo-TZM and Rene' 77 Erosion Inserts.

TABLE V

MATERIAL LOSS AND CHANGE OF SURFACE INTERSTITIAL ELEMENT CONTENT FOR EROSION INSERTS AND REFRACTORY METAL RING SPECIMENS

Erosion Insert Specimen	Pre-Test Weight, g	Post-Test Weight, g	Weight Change, g	Volume Loss, cc	Density, g/cc
Mo-TZM S/N 1	34.1256	33.0363	-1.0893	0.1065	10.22
Mo-TZC S/N 2	35.8980	34.9172	-0.9778	0.0956	10.22
Rene' 77 S/N 1	29.3050	29.2501	-0.0549	0.00694	7.91
Rene' 77 S/N 2	29.0121	28.9680	-0.0441	0.00557	7.91
U700 S/N 2	28.2771	28.1568	-0.1203	0.01203	7.91
U700 S/N 3	29.3178	29.2069	-0.1109	0.01402	7.91
Upstream Ring Specimen(1)					
Cb-1Zr#7	8.5265	8.2091	-0.3174		
TZC#19	9.8925	9.8753	-0.0172		
TZM#17	9.3881	-	-		
TZM#23	9.9290	9.8985	-0.0305		
TZM#18	9.3297	9.2783	-0.0514		
Downstream Ring Specimen(1)					
Cb-1Zr#9	8.5301	8.3231	-0.2070		
TZC#21	10.0023	9.9790	-0.0233		
TZM#14	9.3050	9.2848	-0.0202		
TZC#24	9.7691	9.7404	-0.0287		
TZM#12	-	9.3984	-		

Specimen	O, ppm			N, ppm			H, ppm			C, ppm		
	Pre Test	Post Test	Change	Pre Test	Post Test	Change	Pre Test	Post Test	Change	Pre Test	Post Test	Change
Upstream Ring Specimen(1)												
Cb-1Zr	120	2031	1911	45	995	950	2.6	25	22.4	40	565	525
TZC	10	96	86	3	18	15	<1	4	3	1500	1200	-300
TZM	7	163	156	1.5	5	3.5	<1	1.5	1	258	214	-24
Downstream Ring Specimen(1)												
Cb-1Zr	120	664	544	45	329	284	2.6	14	11.4	40	354	314
TZC	10	132	122	3	8	5	<1	3.5	2.5	1500	1400	-100
TZM	7	109	102	1.5	2	0.5	<1	3	2	238	202	-36

(1) Data for final 4600 hours of testing.

of oxidized Cb-1Zr. It is possible that oxygen does not really diffuse into the Cb-1Zr at the lower temperature; instead, it could form an oxide skin which eventually spalls off.

The weight loss measurements indicate that more material was lost from the upstream Cb-1Zr specimens, despite the holes in the downstream specimen. Unfortunately, the samples were destroyed for chemical analyses before they could be reweighed to verify the anamolous apparently greater weight loss of the upstream specimens.

Deposits and Films

The thick deposits found on all the flow path components were identified by X-ray diffraction as potassium dizirconate. Spectrographic analysis reported the major elements as K and Zr, with a minor addition of Mo, Ni, Fe, Co, and Cr, and a trace of Ag, Al, Ca, Cu, Mg, Mn, Si, Ti, V, and W.

The film which was found on all the rotor buckets had a thickness of approximately one mil and was magnetic. The analyses showed:

Analysis Method	Mo Buckets	Rene' 77 Buckets
X-ray Fluorescent	Fe, Mo, Ni, Cr, Zr	Fe, Ni, Mo, Cr, Zr, Co, Mn
Spectrographic (weight percent)	1-10Fe, 1-10Mo, >10Ni, 0.1-1.0Cr, 0.5-5Zr, 5.25Mn, 0.1-1Si, 0.5-5Al, 0.05-0.5Ti 0.1-1Ca	5-25Fe, 1-10Mo, >10Ni, 0.1-1Cr, 0.5-5Zr, 1-10Mn, 0.5-5Si, 0.1-1Ca, 0.5-5Al, 0.05-0.5Ti

Apparently the thick deposits originated from the zirconium hot traps of the test facility. The thin films primarily result from mass transfer of elements from the stainless steel boiler facility.

Materials Summary

The results of the material evaluation indicated that most of the material removed from the molybdenum alloy rotor buckets was associated with oxygen-accelerated washing corrosion. A small amount of impact erosion was observed at the convex tip of both molybdenum- and nickel-base rotor buckets. However, the scanning electron micrographs indicated that, on the molybdenum alloy buckets, washing corrosion was superimposed on the tip. Also, washing corrosion of the molybdenum buckets has masked some minimal impact erosion that had occurred on other areas of the leading edge. From the erosion results only, it is estimated that the turbine buckets and vanes would successfully last for 50,000 hours, which would satisfy the requirements of a program such as the Potassium Turboalternator (KTA) using Mo-TZM or Mo-TZC blades and refractory metal containment of the system.

IX. CONCLUSIONS

In 5000 hours of testing with oxygen levels higher than desirable only a negligible amount of impingement erosion damage has been experienced with rotating buckets exposed to vapor of an average 7% wetness, when entering Stage 3 at 1200°F and 838 fps tip speed.

Borescope observations established the higher resistance to impingement erosion of molybdenum versus Rene' 77. Considerable corrosion was experienced, especially on molybdenum buckets. Based on 5000 and 10,000 hours of corrosion loop operation it is concluded that in a clean refractory metal loop the corrosion problem would be eliminated.

The hole in the bulletnose and the potassium dizirconate deposits on turbine blading created abnormal flow conditions in the turbine. It was possible, however, to represent these flow conditions and their effects on temperatures, moisture levels, and performance by computerized analysis.

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