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Burner Rig Study of Variables Involved in Hole Plugging of Air-cooled Turbine Engine Vanes

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February 1983

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BURNER RIG STUDY OF VARIABLES INVOLVED IN HOLE PLUGGING OF AIR-COOLED TURBINE ENGINE VANES

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E-1547

SUMMARY

The effects of combustion gas composition, flame temperatures, and cooling air mass flow on the plugging of film cooling holes by a Ca-Fe-P-containing deposit were investigated. The testing was performed on film-cooled vanes exposed to the combustion gases of an atmospheric Mach 0.3 burner rig. The extent of plugging was determined by measurement of the open hole area at the conclusion of the tests as well as continuous monitoring of some of the tests using stop-action photography. In general, as the P content increased, plugging rates also increased. The plugging was reduced by increasing flame temperature and cooling air mass flow rates. At times up to approximately 2 hours little plugging was observed. This apparent incubation period was followed by rapid plugging, reaching in several hours a maximum closure whose value depended on the conditions of the test.

INTRODUCTION

As turbine inlet temperatures are driven higher in response to needs for better performance and greater efficiency, two approaches to retaining vane and blade durability are employed: better coatings and/or improved airfoil cooling. The most common type of the latter approach is film cooling. This type of cooling has been successfully applied in many aircraft and marine gas turbines. However, this approach carries risks along with its benefits. Large metal temperature increases and ultimate destruction of air-cooled turbine engine vanes could result if the air cooling holes become plugged to any appreciable extent. Such plugging has been observed in engine stand tests by the Navy (ref. 1). The plugging is the result of excessive deposition caused by impurities from the fuel and/or combustion air. Similar deposition and hole plugging have been produced in an atmospheric pressure laboratory burner as reported previously (refs. 1 and 2).

While much work has been done in an attempt to evaluate condensation deposition kinetics of relatively simple systems on smooth surfaces (ref. 3) and the prediction of the composition of complex deposits (refs. 4 and 5), little work has been done on the prediction of either kinetics or composition of complex deposits on film-cooled surfaces or in the cooling holes themselves.

The purpose of the work reported here was to investigate experimentally some variables involved in hole plugging. Simulation was accomplished using burner rigs burning doped, clean fuel as in reference 2. The degree of plugging of leading edge cooling holes was determined for preheated cooling air temperatures in the range from 297 to 886 K (75° to 1100° F). The effect of combustion product gas temperature, in the range 1573 to 1873 K, on degree of plugging was also investigated, as was the influence of 1/2 and 1 ppm of phosphorus additions to the Ca-Fe mixture used to produce the deposit on the vane. These compositions were chosen as a result of analysis of the deposit found on the vanes from the Navy test engine (ref. 1). A time lapse movie was made of the plugging process and from enlargements of 35 mm frames, the extent of hole plugging versus time was determined for one set of conditions.

EXPERIMENTAL

A photograph of the test arrangement is presented in figure 1. An air-cooled vane for an LM2500 engine was clamped in a holder and preheated cooling air was directed into the leading edge cooling chamber. This air exited through the leading edge holes. No cooling air was admitted to the trailing edge cooling chamber. An atmospheric pressure burner flame (described in ref. 6) was aimed at the leading edge at right angles to the centerline of cooling holes. The burner was turned on and its flame temperature set before it was directed at the vane. Cooling air (mass flow ranged from 6.0 to 21.0 kg/sec), at a given pre-set temperature, was passed through the cooling holes so that the surface at the area of flame impingement reached a desired temperature as measured by optical pyrometry. Flow pressure was maintained constant throughout each run. Deposit components (Fe, Ca, and P) contained in a water solution were aspirated into the combustion chamber to dope the flame. After 8 hours, the burner and cooling air were shut off and the vane was removed and weighed. The diameter of the centerline of cooling holes was measured by an optical microscopic method.

The average percent of the 16 centerline cooling holes remaining unplugged was calculated by summing the reduced diameter of these holes and dividing by the sum of the diameters of the 16 holes prior to testing. A minimum percent of cooling holes remaining open was calculated by including only those holes contained in the flame impingement area. The average percent open holes is for the entire length of the vane, both in the flame and outside of it.

A time lapse movie of a 17-hour run was made, selected frames were enlarged, and the diameters of the center line holes were determined. From this, it was possible to follow the extent of the hole plugging with time. The run conditions for the movie were the same as for run N-1 (see table I).

A photograph of an unused vane is presented in figure 2. The small twist drills (22.5 mils diameter) inserted in the leading edge cooling holes give a visual idea of the angle of cooling air flow.

RESULTS AND DISCUSSION

Table I presents the test conditions and results of all runs. Several cooling air temperatures were used. It is to be noted that as the cooling air temperature was increased, a greater mass flow and linear velocity of air was required to maintain the desired leading edge metal temperature. Also, as cooling air flow and temperature increased, the average and minimum cooling hole opening at the end of the 8-hour run increased. Macrophotos of the leading edge after 8 hours for runs N-1 and N-6 are presented in figure 3. The area of direct flame impingement shows the greatest plugging of the cooling holes. The deposit on the N-6 run vane did not spall on cooling, while that on the N-1 run vane spalled to reveal that slag fills many of the holes to a considerable depth.

Figure 4 presents a profile of the leading edge cooling hole plugging for runs N-6 and N-10. The N-10 run, with a higher cooling air temperature and thus higher velocity of cooling air, shows a higher degree of open holes than the N-6 which used lower cooling air temperatures. This is especially true in the area of direct flame impingement.

A multiple linear regression analysis was performed using the average percent cooling holes open as the dependent variable. Cooling air temperature (T_c), phosphorous content of the flame (W), and flame temperature (T_f) were used as independent variables. This anaylsis yielded a correlation coefficient of about 0.9 and a standard error of estimate of 7.0. The equation is:

$$Q = 0.3\ T_c + 0.05\ T_f - 8.6\ W - 48.24$$

where Q is the percent open cooling holes for 8 hours of the run. Figure 5 is a plot of this fit for 1 ppm P. As the temperature of the cooling air rises, a greater percent of open holes results for a given flame temperature. As the cooling air temperature increases, more mass flow must be used to cool the vane leading edge and because the diameters of the holes are constant, the velocity of air flow through the holes must increase. This suggests that the higher velocity air flow produces a higher percent of open holes. The higher flame temperature, for a given cooling air temperature, results in a greater percent of open holes. Here again more cooling air flow with higher velocity is needed with a hotter flame.

An increase in phosphorous from 1/2 to 1 ppm produces a decrease in open holes or increased plugging (a negative coefficient for the phosphorous term in the regression fit). If one does a similar multiple regression fit, using the minimum percent of plugging as the independent variable, cooling air temperature and flame temperature are positive and of about the same value as above, but the phosphorous coefficient becomes -30 as against -8.6 above. Thus, the area of flame impingement and the phosphorous content become more significant and tend to further decrease the percent open holes for a given cooling air temperature and flame temperature. This suggests that phosphorous may be producing a more "sticky" deposit and increased hole plugging results as the phosphorous content rises (in the 1/2 to 1 ppm range).

Figure 6 presents the plugging of holes versus total weight gain of the vanes after 8 hours. Assuming a linear relation between weight gain and hole plugging, a multiple linear regression line is superimposed on the experimental points. The linear correlation coefficient is 0.55 and standard error of estimate is 15. Even though much of the gain is due to adherence of deposit to areas other than the leading edge, and much scatter exists, this does indicate that the greater the weight gain the fewer holes are open. This probably indicates that the conditions which favor adherence of the slag also favor hole plugging.

A piece of the deposit buildup in the flame impingement area on the leading edge during run N-13 was removed and a SEM photo at 0° tilt and 100X was taken of the outer and inner surfaces. The outer surface is the top of the deposit and the inner surface is that in contact with the metal or the fracture area. Figure 7(a) is the outer surface and figure 7(b) is the inner surface. Although the vane surface is covered with a deposit, the cooling air coming through the hole has kept a small flow path opening through the deposit. EDS anaylses of the inner and outer surfaces are presented in figures 7(c) and (d), respectively. One can clearly see that the deposit is composed of Fe, Ca, and P, the doping components aspirated into the combustion chamber.

A time lapse movie of the hole plugging for conditions of run N-1 was made for a total run time of 17 hours. By projecting the film at normal speed it was observed that the sticking started at the side holes and progressed toward the center line holes. To examine the plugging in more detail, selected frames were enlarged 5X and the diameter of the five top-most holes were measured and averages taken. Only five holes were measured because of the restricted field of view. This same measurement was done for both the center line and side holes on the leading edge. Figure 8 is a plot of these results. For a period of about 2-1/2 hours there is no measurable plugging of either the center line or side holes. However, by 3 hours a measurable amount of hole plugging has occurred and the plugging is very rapid up to about 8 hours. The center line holes do not plug further for times up to 17 hours. However, the side holes are completely plugged by 17 hours. The air flow through the center line holes has probably kept them open to some extent and they may never completely plug under these conditions. The fact that there is an initial time period, here 2 to 2-1/2 hours, when no plugging occurs, may be due to very low initial sticking probability of the deposit around the holes. If this could be extended indefinitely, no hole plugging would occur. It is easier for deposits to stick to side holes rather than center line holes, possibly because of curvature or direct trapping or entry of the deposit material into these holes.

CONCLUSIONS

1. When air-cooled vanes were exposed to high velocity atmospheric pressure burner rig flames containing a few ppm of Ca, Fe, and P, the leading edge cooling holes were soon partially or completely plugged.
2. The use of higher temperature cooling air decreased this plugging, probably because more air must be used to cool the leading edge vanes and this suggests that increased cooling air flow velocity keeps down plugging.
3. Increase of the flame temperature tended to produce less plugging of the holes, but an increase of phosphorous content in the combustion gas tended to increase hole plugging.
4. The holes in the vane do not plug linearly with time. Instead there is an initial period of time in which no measurable plugging occurs, apparently due to very low sticking of deposit material. When plugging starts, it proceeds very rapidly until a maximum plugging occurs for the conditions used. Holes off the center line of the vane are plugged more completely, probably due to the curvature of the leading edge of the vanes which causes deposit trapping in the corners of the holes.

REFERENCES

1. Deadmore, D. L.; and Lowell, C. E.: Plugging of Cooling Holes in Film-Cooled Turbine Vanes. NASA TM X-73661, 1977.
2. Deadmore, D. L.; and Lowell, C. E.: Airfoil Cooling Hole Plugging by Combustion Gas Impurities of the Type Found in Coal Derived Fuels. DOE/NASA/2593-79/1, NASA TM-79076, 1979.
3. Stearns, C. A.; Kohl, F. J.; and Rosner, D. E.: Combustion System Processes Leading to Corrosive Deposits. DOE/NASA/2593-27, NASA TM-81752, 1981.
4. Santoro, G. J.; Calfo, F. D.; and Kohl, F. J.: Material Response from Mach 0.3 Burner Rig Combustion of a Coal-Oil Mixture. DOE/NASA/2593-23, NASA TM-81686, 1981.
5. Santoro, G. J.; et al.: Deposition and Material Response from Mach 0.3 Burner Rig Combustion of SRC-II Fuels. DOE/NASA/2593-20, NASA TM-81634, 1980.
6. Lowell, C. E.; and Deadmore, D. L.: Effect of a Chromium-Containing Fuel Additive on Hot Corrosion. Corros. Sci., vol. 18, no. 8, 1978, pp. 747-763.

TABLE I. - COOLING HOLE PLUGGING RESULTS

Set	Run	Dopant concentration, ppm[a]			Flame temperature		Initial leading edge temperature		Cooling air		Weight gain, mg	Percent cooling holes open (8 hr)		Cooling air temperature	
		Fe	Ca	P	K	°F	K	°F	Mass, kg/sec	Velocity, m/sec[b]		Min.	Avg.	K	°F
A	N-1	2.0	0.5	1.0	1873	2912	1088	1500	8.4	117	512	7.5	40.7	279	75
	2								7.9	109	604	0	35.6	422	300
	3								9.3	128	492	0	34.6	589	600
	4								12.0	166	592	53.8	65.5	811	1000
	5								21.0	290	507	58.2	69.8	866	1100
B	6	2.0	0.5	1.0	1573	2371	1088	1500	6.3	87	355	0	23.6	279	75
	7								6.0	83	532	0	28.8	589	600
	8								7.6	105	548	0	34.7	700	800
	9								8.4	117	460	9.0	40.9	811	1000
	10								10.4	139	460	14.9	38.1	866	1100
C	11	2.0	0.5	1.0	1873	2912	1192	1650	7.3	109	499	0	38.8	589	600
	12								8.7	130	479	28.4	51.3	811	1000
	13								8.7	130	377	64.7	41.8	866	1100
D	16	2.0	0.5	.5	1873	2912	1088	1500	8.7	120	359	13.5	46.6	422	300
	14								7.9	109	289	35.9	50.7	589	600
	15								9.3	128	205	49.3	59.5	811	1000

[a]Parts per million by weight of combustion gases.
[b]At start.

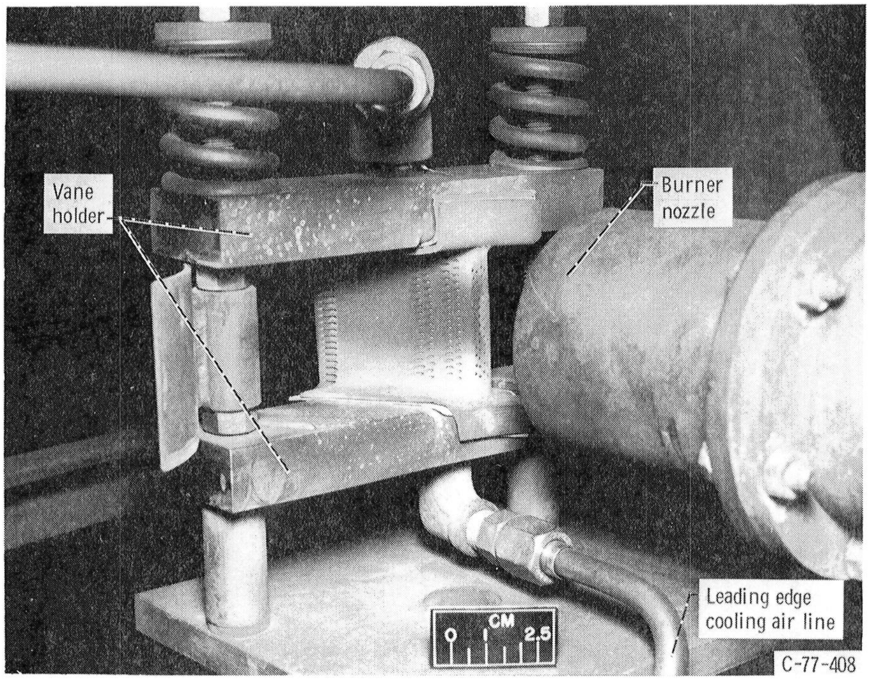


Figure 1. - Photograph of test arrangement.

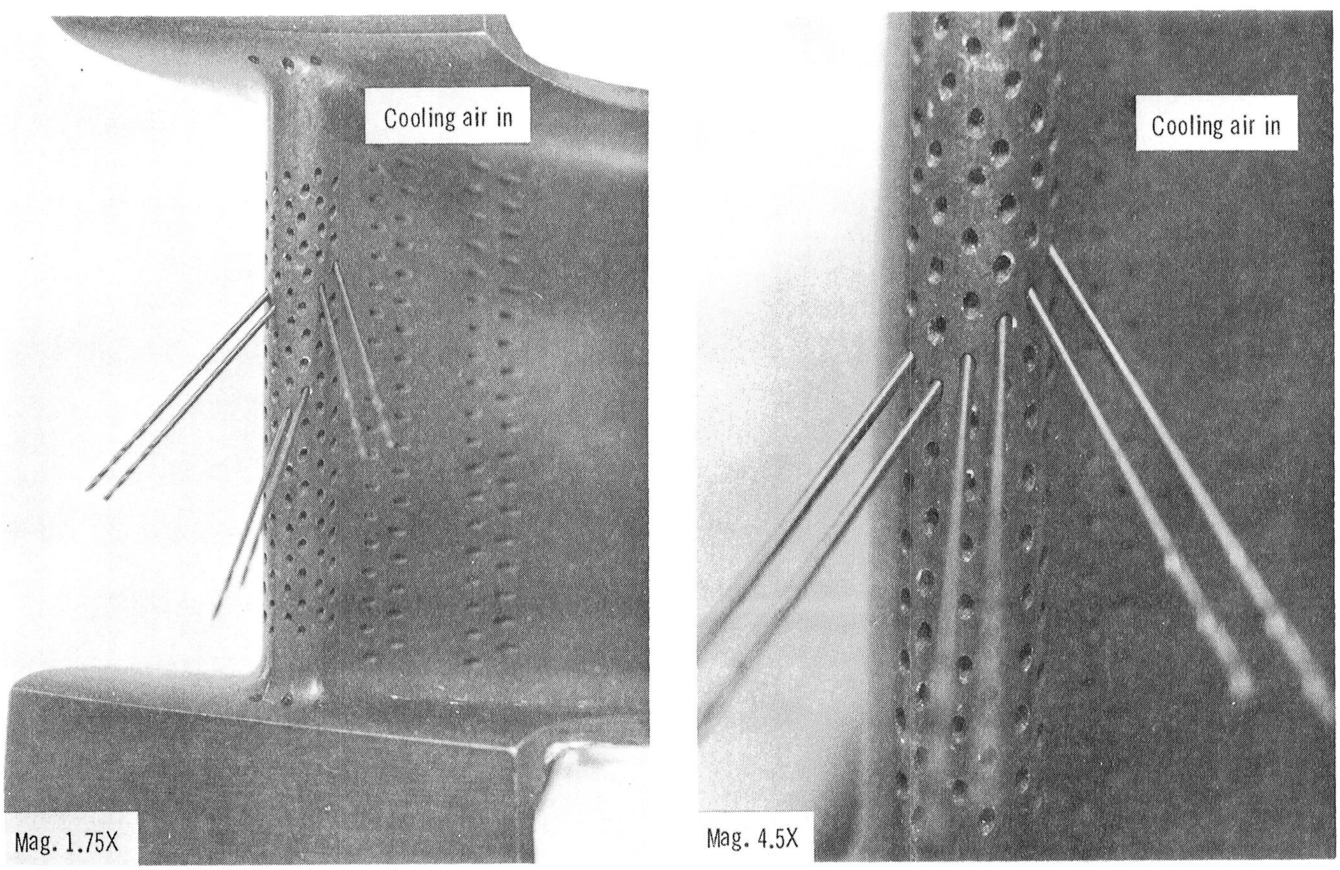
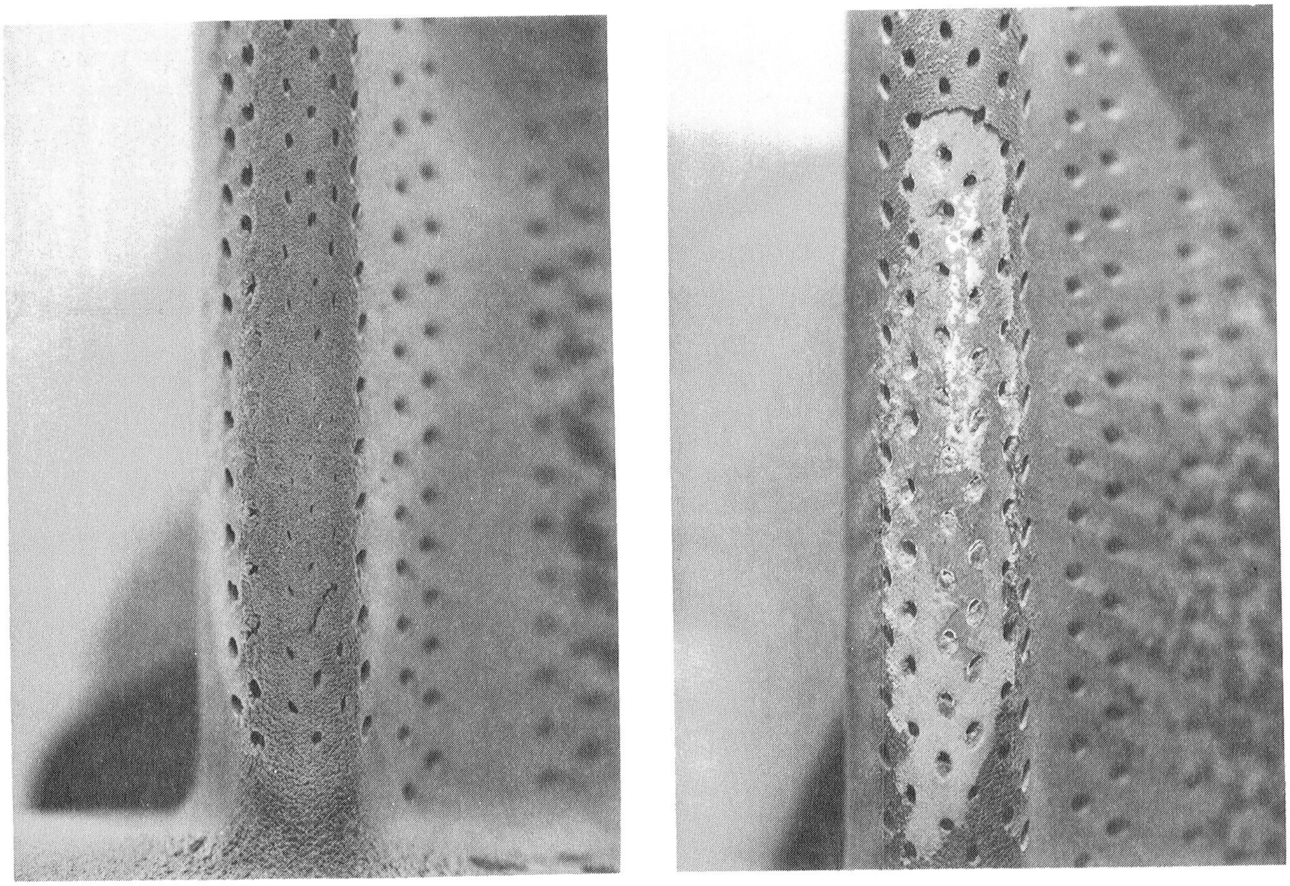


Figure 2. - Enlarged macro - photographs of unused vane leading edge. Twist drills are number 74, 0.057 cm dia. (22.5 mils).



(a) Mag. 3X. Run N-6.

(b) Mag. 4X. Run N-1.

Figure 3. - Macro - photograph of the leading edge of vanes after test.

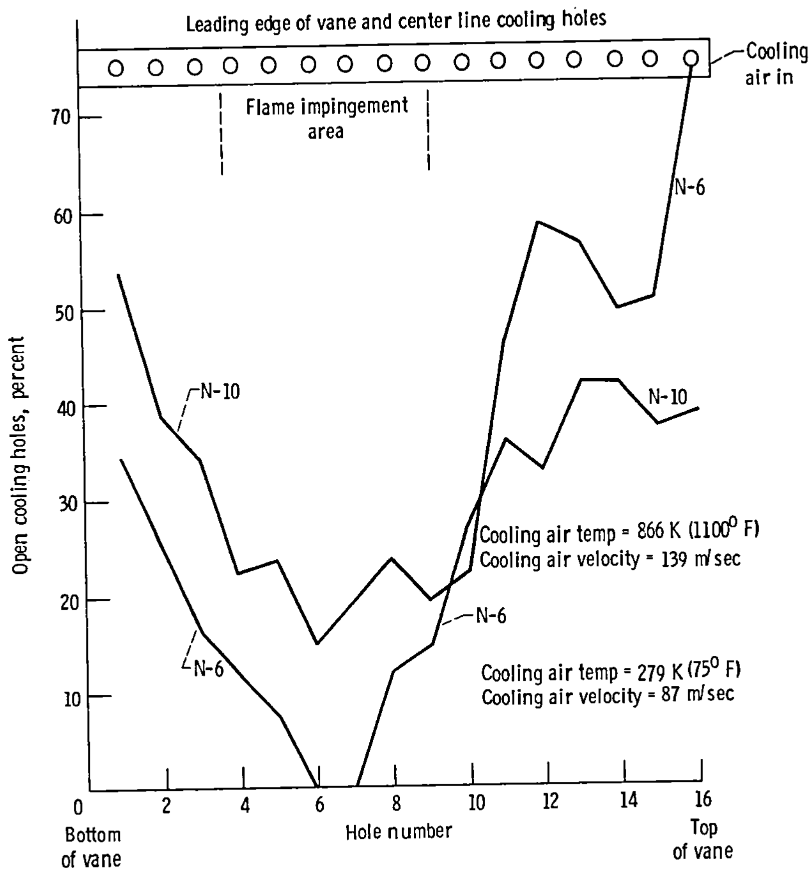


Figure 4. - Plugging profile of leading edge cooling holes. Flame temperature = 1573 K (2372° F); initial leading edge temperature = 1088 K (1500° F) (2 Fe, 0.5 Ca, 1.0 P).

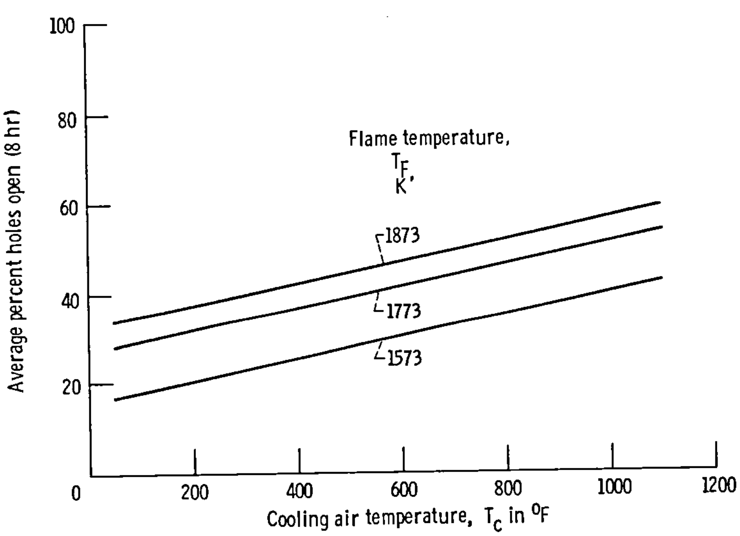


Figure 5. - Plot of multiple regression fit - (1 ppm P).

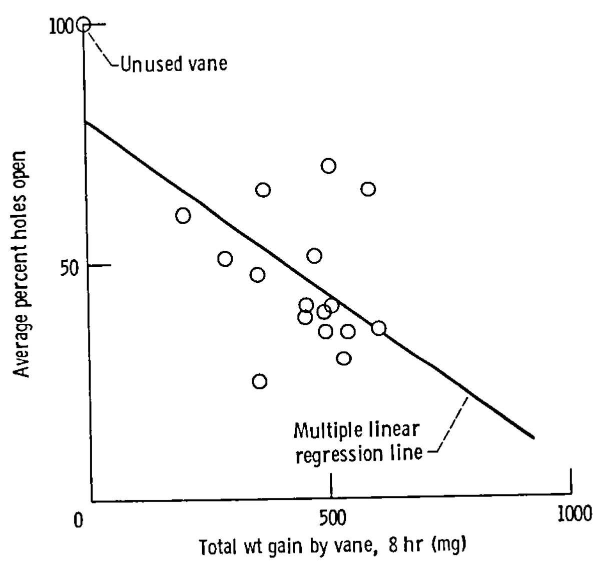
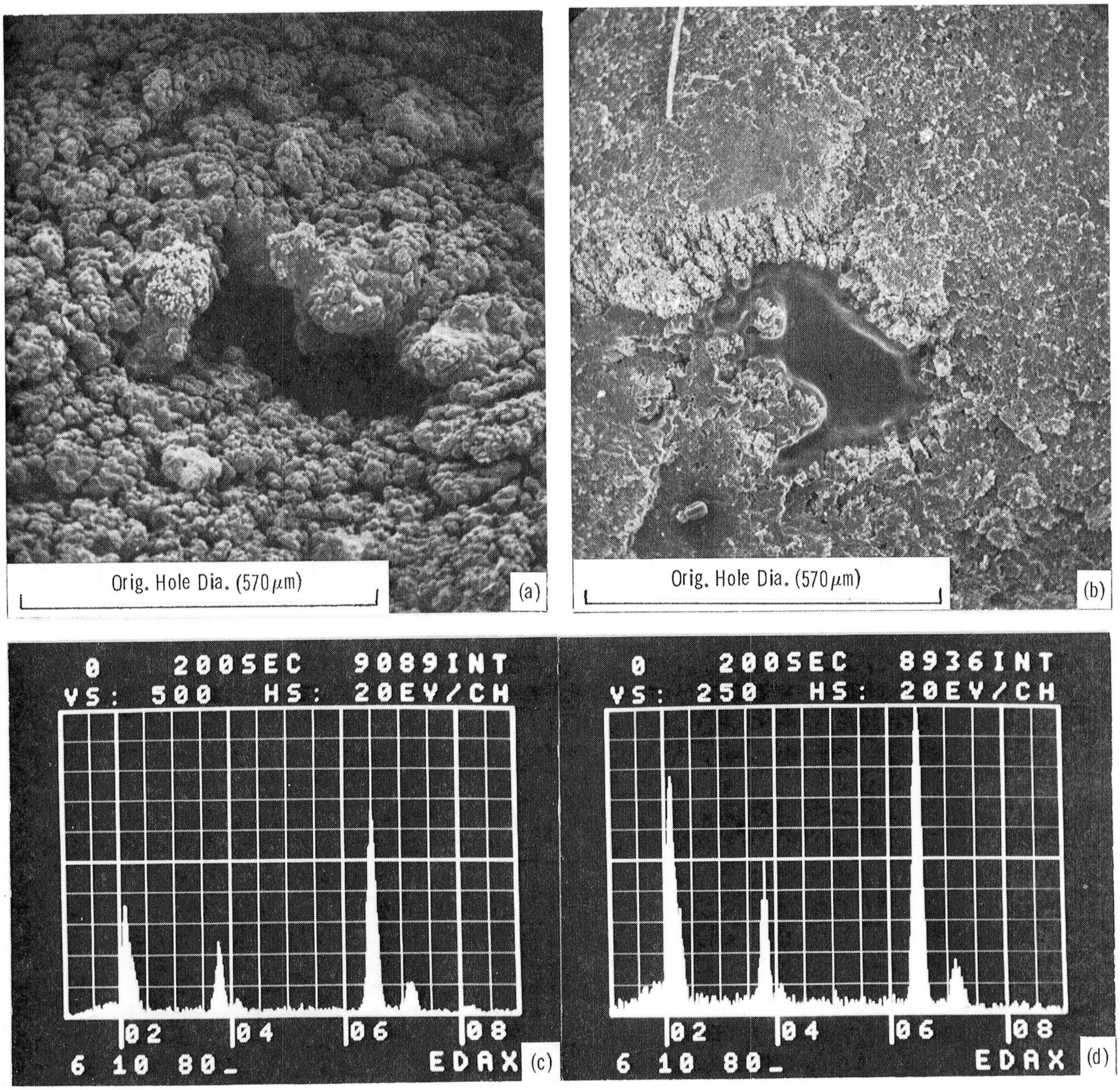


Figure 6. - Percentage cooling holes open vs total weight gain of vane after 8 hr.



(a) Outer surface (0° tilt).

(b) Inner surface (0° tilt).

(c) EDS of outer surface.

(d) EDS of inner surface.

Figure 7. - SEM photographs and EDS of N-13 slag from leading edge of vane (inner surface is that nearest metal - outer surface is at the air-slag interface).

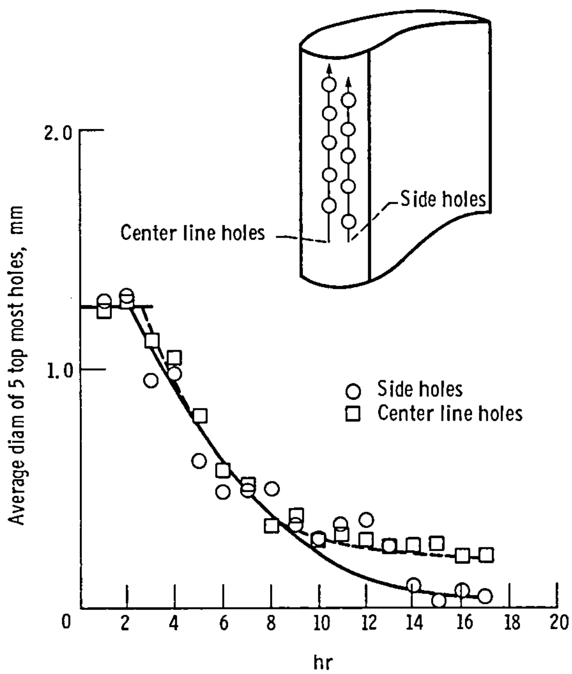


Figure 8. - Hole plugging vs time for air-cooled vane (taken from time lapse movie frames).

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15. Supplementary Notes

16. Abstract

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