N71-14817

CR-72743

MICROFOG LUBRICANT APPLICATION SYSTEM FOR ADVANCED TURBINE ENGINE COMPONENTS - PHASE II

by

J. Shim and S. J. Leonardi

MOBIL RESEARCH AND DEVELOPMENT CORPORATION

prepared for

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

NASA Lewis Research Center

CONTRACT NO. NAS 3-13207

William R. Loomis, Project Manager

Requests for copies of this report should be referred to:

National Aeronautics and Space Administration
Scientific and Technical Information Facility
P. O. Box 33
College Park, Md. 20740

MICROFOG LUBRICANT APPLICATION SYSTEM FOR ADVANCED TURBINE ENGINE COMPONENTS - PHASE II

TASKS I AND II - WETTABILITIES OF MICROFOG STREAMS OF VARIOUS LUBRICANTS AND OPTIMIZATION OF MICROFOG LUBRICATION

by

J. Shim and S. J. Leonardi

MOBIL RESEARCH AND DEVELOPMENT CORPORATION
RESEARCH DEPARTMENT, PAULSBORO LABORATORY
PAULSBORO, NEW JERSEY

Prepared for

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

May 15, 1970

CONTRACT NAS 3-13207

NASA Lewis Research Center
Cleveland, Ohio
William R. Loomis, Project Manager
Fluid System Components Division

MICROFOG LUBRICANT APPLICATION SYSTEM FOR ADVANCED TURBINE ENGINE COMPONENTS - PHASE II

by

J. Shim and S. J. Leonardi

ABSTRACT

Using the techniques and equipment developed under contract NAS 3-9400, wettabilities of microfog streams of five high temperature lubricants on a static metal surface were determined under an inert atmosphere of nitrogen at temperatures ranging from 600 to 800°F. The wetting data are discussed in relation to the rate of oil-mist output, impaction velocity, temperature and surface characteristics of the wetted plate, and properties of the lubricants.

Table of Contents

Page

I. Introduction.. 1

II. Summary and Conclusions.................................. 2

III. Detailed Report... 3

A. Materials... 3

B. Experimental Apparatus and Procedure...................... 3

C. Results and Discussion.................................... 3

1. Rate of Oil-Mist Output................................... 3

2. Particle Velocity Distribution............................ 10

3. Particle Size Distribution................................ 12

4. Wetting Rate Determinations............................... 16

i) Effect of (Oil/Gas) Mass Flow Ratio........ 16

ii) Effect of Impaction Velocity............... 24

iii) Effect of Plate Temperature................ 25

iv) Comparison of the Wetting Rates of Different Test Lubricants........................... 30

v) Wetting Patterns of Test Lubricants........ 33

vi) Effect of Lubricant Temperature............ 36

vii) Effect of Additives........................ 42

viii) Effect of Plate Surface.................... 43

IV. Notations.. 53

V. References.. 54

VI. Appendices... 55

A. Statement of Work, Contract NAS 3-13207.............. 56

B. Wettability Determination of Test Lubricants......... 64

Table of Contents (Continued)

Page

C. Effect of Gas and Lubricant Temperature.............. 75

D. Effect of Test Plate Surface......................... 80

Tables

1. Physical Properties of Test Lubricants.................. 4

2. Effects of Physical Properties on Rate of Oil-Mist Output 8

3. Mean Particle Velocity for Different Spray Nozzles...... 11

4. Particle Size Distribution of Test Lubricants........... 13

5. Summary of Mean Particle Sizes.......................... 15

6. Summary of Wetting Rate Data for Different Test Lubricants.. 32

7. Effect of Lubricant Temperature on Wetting Rate......... 41

8. Effects of Various Additives on Wetting Rate............ 44

Figures

1. Viscosity-Temperature Relation for Test Lubricants...... 5

2. Vapor Pressure-Temperature Data for Test Lubricants (by Isoteniscope)... 6

3. Effect of Viscosity on Rate of Oil-Mist Output.......... 9

4. Cumulative Particle Size Distribution Curves for Test Lubricants.. 14

5. Wettability of XRM 109 F at Different Gas Flow Rates.... 17

6. Effect of (Oil/Gas) Mass Flow Ratio on Wetting Rate for FN 2961.. 18

7. Effect of (Oil/Gas) Mass Flow Ratio on Wetting Rate for Krytox 143 AC.. 19

8. Effect of (Oil/Gas) Mass Flow Ratio on Wetting Rate for Krytox 143 AC.. 20

9. Effect of (Oil/Gas) Mass Flow Ratio on Wetting Rate for XRM 109 F... 21

Table of Contents (Continued)

Page

Figures (Cont'd)

10. Effect of (Oil/Gas) Mass Flow Ratio on Wetting Rate for XRM 109 F.......... 22

11. Effect of (Oil/Gas) Mass Flow Ratio on Wetting Rate for XRM 209 A.......... 23

12. Effect of Plate Temperature on Wetting Rate for FN 2961.......... 26

13. Effect of Plate Temperature on Wetting Rate for Krytox 143 AC.......... 27

14. Effect of Plate Temperature on Wetting Rate for XRM 109 F.......... 28

15. Effect of Plate Temperature on Wetting Rate for XRM 209 A.......... 29

16. Effect of (Oil/Gas) Mass Flow Ratio on Wetting Rate for Test Lubricants at 600°F.......... 31

17. Uniform Wetting Patterns Formed by a Microfog Jet of XRM 109 F Impinging on a Metal Surface at 72°F...... 34

18. Streaky Wetting Patterns Formed by a Microfog Jet of MCS 293 Impinging on a Metal Surface at 72°F........ 35

19. Effect of (Oil/Gas) Mass Flow Ratio on Wetting Rate for FN 2961.......... 37

20. Effect of (Oil/Gas) Mass Flow Ratio on Wetting Rate for XRM 109 F.......... 38

21. Effect of (Oil/Gas) Mass Flow Ratio on Wetting Rate for FN 2961.......... 39

22. Effect of (Oil/Gas) Mass Flow Ratio on Wetting Rate for XRM 109 F.......... 40

23. Effect of Plate Surface on Wettability of XRM 109 F at 600°F.......... 46

24. Effect of Plate Surface on Wettability of XRM 109 F at 700°F.......... 47

25. Effect of Plate Surface on Wettability of FN 2961 at 700°F.......... 48

26. Effect of Plate Surface on Wetting Rate at 700°F.... 49

I. INTRODUCTION

Earlier work (1, 2) under contract NAS 3-9400 established new techniques and equipment for investigating the wetting characteristics of lubricants as microfogs under a range of conditions simulating the environment of advanced turbine engine bearings. Wettabilities of five potential high temperature lubricants on a heated metal surface were related to the conditions of microfog generation, drop-size and concentration distribution, impaction velocity, properties of the lubricants and other system variables.

In order to define the essential requirements and to guide the development of an advanced microfog lubricant application system, the present program seeks additional information by investigating the effects of the physical and chemical properties of lubricants on microfog lubrication, and additional operating variables, including lubricant temperature, additives, and nature of the wetted surface. The Statement of Work for this contract is attached hereto as Appendix A.

This is the first report submitted under contract NAS 3-13207, entitled "Microfog Lubricant Application System for Advanced Turbine Engine Components-Phase II", and covers Task I and II of this contract.

II. SUMMARY AND CONCLUSIONS

The wetting characteristics of microfog streams of five high temperature lubricants, FN 2961, Krytox 143 AC, MCS 293, XRM 109 F, and XRM 209 A, on a flat surface of WB 49 material were determined under an inert atmosphere of nitrogen at temperatures ranging from 600 to 800°F.

Wetting rates obtained with nozzles of two different orifice sizes vary considerably for a given operating condition: for a given (oil/gas) mass flow ratio and particle size distribution, a nozzle providing increased impaction velocity greatly increases wetting rate, whereas for a given nozzle, the wetting rates increase with increasing (oil/gas) mass flow ratios established by varying gas flow rate to the microfog generator.

As plate temperature increases, wetting rate increases for the less volatile lubricants such as Krytox 143 AC and XRM 109 F, but the rate decreases sharply for the more volatile lubricants such as FN 2961, MCS 293, and XRM 209 A. Microfog particles of MCS 293 sprayed on a hot surface, even at high (oil/gas) mass flow ratios, fail to form a uniform film spreading over the surface regardless of its temperature, which ranged from 72 to 800°F. Formation of the uniform and streaky wetting patterns of lubricants on the surface is briefly discussed and a possible relation to their performance in full-scale bearing test is suggested.

The wettabilities of these test lubricants, compared in terms of the specific and minimum wetting rates and on the basis of the minimum oil flow concept, were found to fall in the following order:

XRM 109 F > Krytox 143 AC > XRM 209 A > FN 2961 > MCS 293

As lubricant temperature at the microfog generator increases, wetting rates increase, but not as rapidly as would be expected from the viscosity of the lubricant.

Additives representing several types in the three blended lubricants - Krytox 143 AC plus 5% (by wt.) duPont additive No. 9530-49, MCS 2931, and XRM 210 A, have little effect on mist generation, particle size, and wetting rate. On the other hand, Kendall super-refined paraffinic heavy resin ($\sim$20,000 SUS at 100°F) in XRM 109 F markedly increases both the rate of oil-mist output and wetting rate, although it has little effect on particle size distribution.

Surface properties of the test plate have a pronounced effect on the wetting rates of XRM 109 F and FN 2961 at 700°F. Wetting rates were reduced by the presence of black oxide coating on the plate, and by increasing surface roughness. On the other hand, deposits produced by lubricant decomposition have little influence on wetting rate.

III. DETAILED REPORT

A. Materials

The five high temperature lubricants tested are:

1. FN 2961, Humble Oil and Refining Co.
2. Krytox 143 AC, E. I. duPont de Nemours and Co.
3. MCS 293, Monsanto Chemical Co.
4. XRM 109 F, Mobil Research and Development Corp.
5. XRM 209 A, Mobil Research and Development Corp.

The four blended lubricants are:

1. Krytox 143 AC blended with 5% (by weight) duPont additive No. 9530-49
2. MCS 2931
3. XRM 109 F plus 10% (by weight) Kendall super refined paraffinic heavy resin (∿20,000 SUS at 100°F)
4. XRM 210 A

These lubricants are identified broadly by chemical type in Table 1, which also lists other pertinent physical properties for each lubricant. Viscosity-temperature relations for the base lubricants are shown in Figure 1, and vapor pressure-temperature data determined by isoteniscope in Figure 2.

The test plate and nitrogen gas employed in this program are identical to those described in the previous work (2).

B. Experimental Apparatus and Procedure

The microfog lubricant generator, test rig, and instrumentation were designed and fabricated for use under NASA Contract NAS 3-9400. This equipment and its operating procedure have already been described in great detail elsewhere (1, 2).

C. Results and Discussion

1. Rate of Oil-Mist Output

In the previous study (2), with the aid of the experimental data, an empirical relation was formulated to predict the rate of oil mist output from the generator at any given condition and was given by

$$W = 0.8\left(\frac{Qg^{1.7}}{\gamma^{0.4}}\right)^{*}$$

* Symbols are explained in Section IV Notations of this report.

Table 1

Physical Properties of Test Oils

Property	MCS-293	MCS-2931	Krytox 143 AC	Krytox 143 AC + 5% DP9530-49	FN 2961	XRM 209 A	XRM 210 A	XRM 109 F	XRM 109 F + 10% K-resin
Chemical Type	Modified Polyphenyl Ether (C-ether)	MCS-293 Containg Wetting Agent	Perfluro-alkylpoly-ether	Krytox 143 AC Containing duPont Additive No. 9530-49(1)	Super-refined Naphthenic Mineral Oil	Penta-erythritol ester	Formulated Penta-erythritol ester(2)	Synthetic Paraffinic Hydrocarbon	XRM 109 F Containing Kendall Paraffinic Heavy Resin (20,000 SUS @ 100°F)
Flash Point, °F	475	465	---	---	485	485	470	520	535
Fire Point, °F	525	530	---	---	510	550	550	595	610
Pour Point, °F	-30	-30	<-35	<-35	-30	<-35	<-35	<-35	<-35
Autogenous Ignition Point, °F	910	910	---	---	690	740	740	760	750
Kinematic Viscosity, cs									
@ 400°F	1.14	1.15	3.99	4.00	1.65	1.34	1.32	5.98	6.50
@ 210°F	4.07	4.09	26.6	26.8	8.31	5.09	5.08	39.8	46.3
@ 100°F	24.2	24.1	269	277	78.0	26.8	27.8	443	555
@ 0°F	10,708	10,691	31,876	33,704	9,677	689	837	38,524	57,008
Density @ 20°C, g/cm³	1.196	1.195	1.905	1.905	0.882	0.955	0.962	0.847	0.851
Surface Tension @ 25°C, dynes/cm	45.3	44.9	18.5	17.4	30.9	31.5	31.9	30.8	31.5
Specific Heat, BUT/lb/°F									
@ 300°F	0.42	0.41	0.27	0.29	0.60	0.53	0.49	0.65	0.64
@ 400°F	0.45	0.44	0.30	0.29	0.65	0.55	0.52	0.67	0.68
@ 500°F	0.49	0.48	0.31	0.31	0.72	---	0.66	0.73	0.73
Thermal Conductivity,(3) BTU/hr-ft² (°F/ft)									
@ 300°F			0.051		0.070	0.079		0.075	
@ 500°F			0.051		0.066	---		0.070	

(1) High temperature corrosion inhibitor.

(2) Formulated against oxidation, corrosion and wear.

(3) The values of thermal conductivity were furnished by the suppliers of test oils.

Figure 1

VISCOSITY-TEMPERATURE RELATION
FOR TEST LUBRICANTS

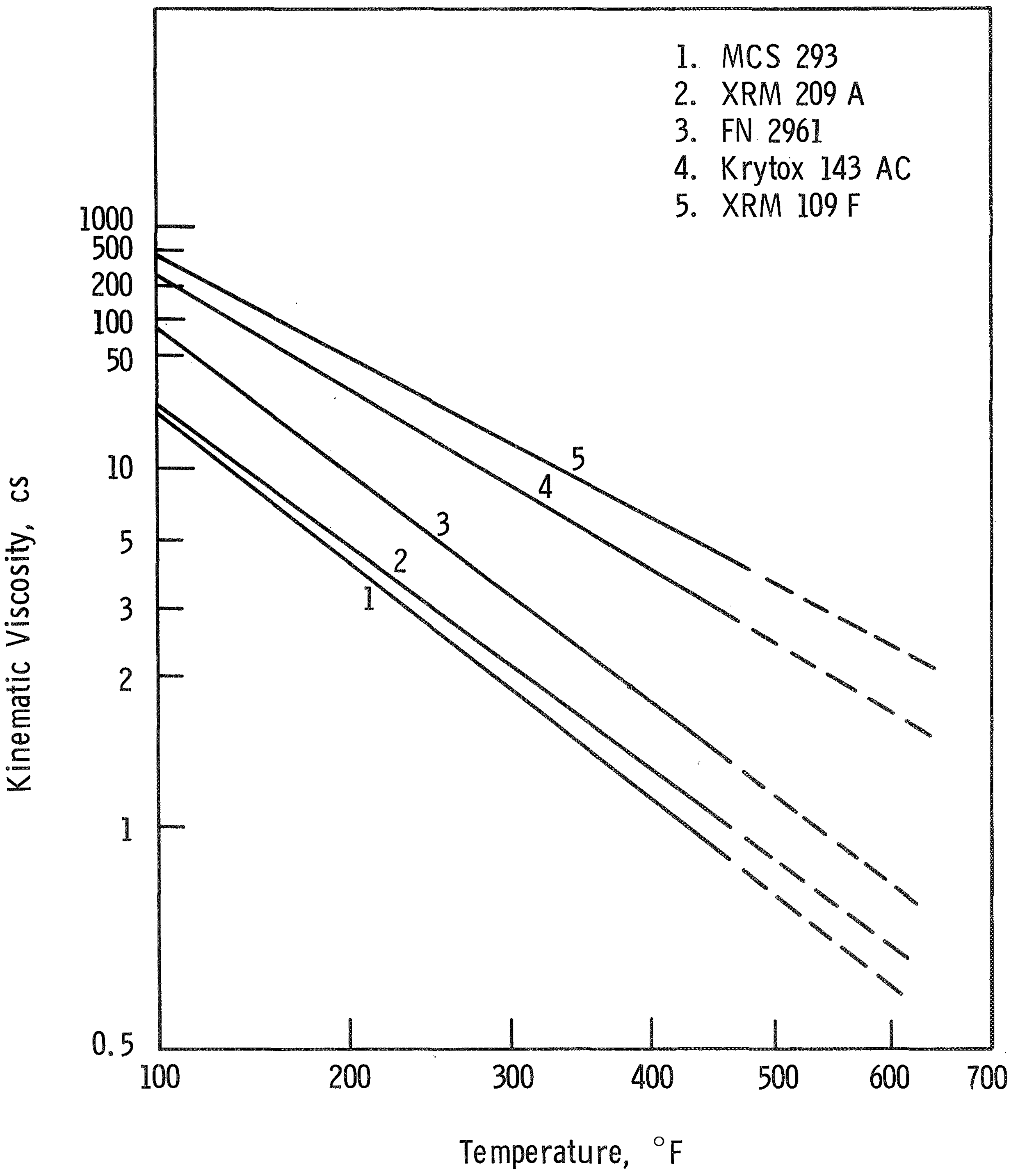
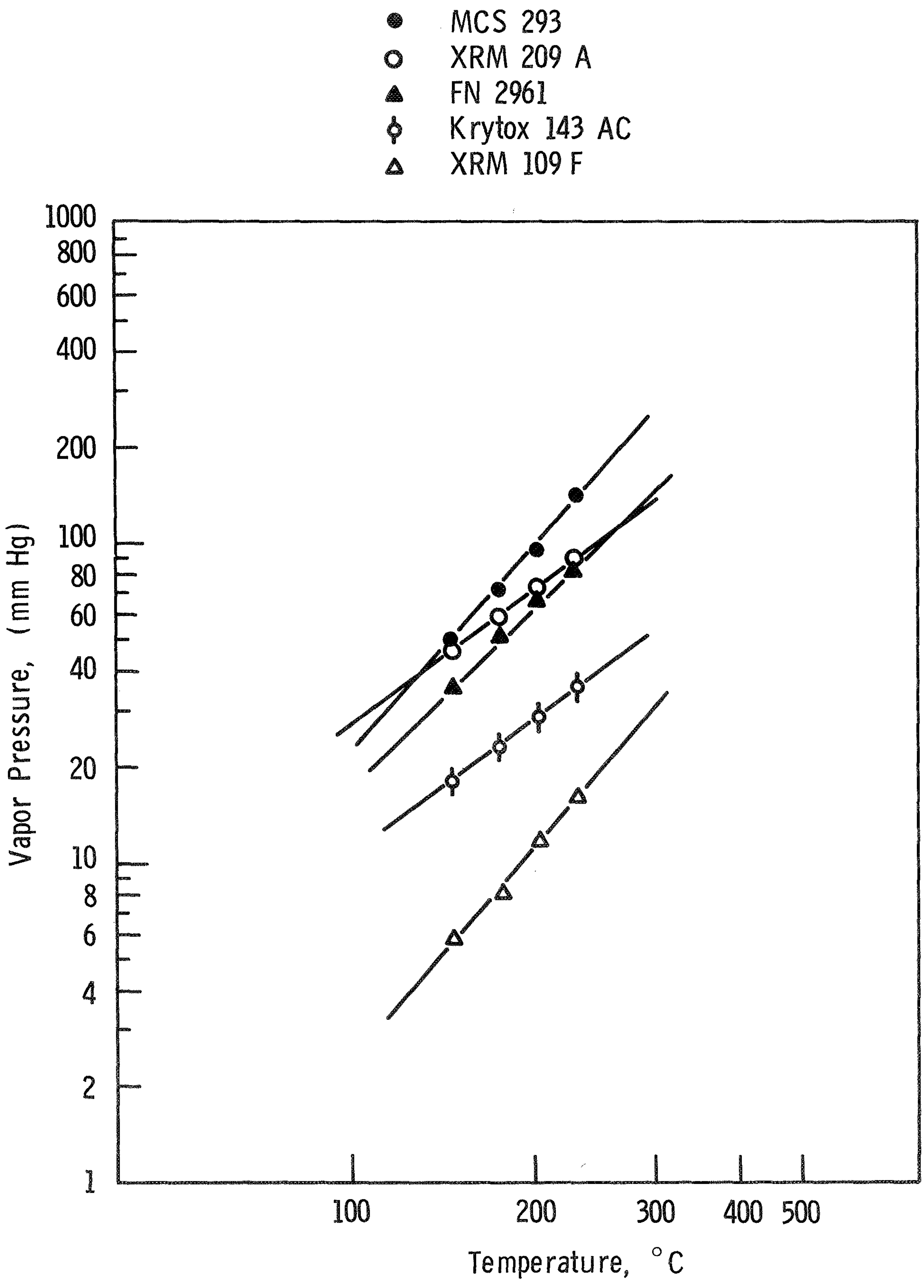


Figure 2

VAPOR PRESSURE - TEMPERATURE DATA
FOR TEST OILS (BY ISOTENISCOPE)



provided that the surface tension and density of oil have little influence on rate of oil-mist output. While Equation (1) was in very good agreement with the experimental data, it is only a first approximation. To further generalize this development, the effects of surface tension, density and possibly additives on the rate of oil-mist output should be included.

To examine the effects of these factors, the rates of oil-mist output for the five base lubricants and the four blended lubricants were determined in the present generator at 2, 3, and 4 cfm. In addition to these lubricants at 200°F, the output rates for FN 2961 and XRM 109 F at 100 and 300°F were also determined. The experimental data, including the data from the previous study (Items 10 through 14), are summarized in Table 2. The new experimental data (Items 1 through 9) are also presented in Figure 3 in which Equation (1) is shown by solid lines.

Review of Table 2 and Figure 3 indicates that increasing the surface tension and density of the test lubricant decreases oil-mist output. With the limited data available, however, it is difficult to single out the separate effects of each property to determine which of these properties exerts the greater influence on the rate of oil-mist output. A comparison between Items (2) and (6) reveals that Krytox 143 AC has oil-mist output below that which would be expected based on its viscosity. The same is true for MCS 293 in comparison with XRM 209 A. The most serious disadvantage of Krytox 143 AC with regard to mist generation seems to be its high density which may limit the loading of oil-mist particles suspended in a given gas flow. This effect seems to overbalance the increase in the rate of oil-mist output normally expected with decreasing surface tension. For MCS 293, the increase in both surface tension and density results in a considerable decrease in the oil-mist output. The data of Figure 3 clearly indicate that the rate of oil-mist is influenced not only by viscosity of the lubricant, but by its surface tension and density as well. Equation (1) therefore requires modification to

$$W = K\left(Q_g\right)^a \left(\mu\right)^b \left(\sigma\right)^c \left(\rho\right)^d \qquad (2)$$

where a, b, c, and d are constants to be experimentally determined.

As part of the investigation of additive effects on microfog lubrication, the rates of oil-mist output of the four blended lubricants were determined and compared (Table 2) with those of their base lubricants. The comparison shows that the additives in these oils, except for 10% Kendall super-refined paraffinic resin blended in XRM 109 F, have little influence on the oil-mist output rates. This is not unexpected, since the original purpose of these additives was not the improvement of mist generation characteristics. The effects of the various additives provide an analogy with experience in industrial mist lubricants, where additives commonly employed are considered to have little effect

Table 2

EFFECT OF PHYSICAL PROPERTIES ON RATE OF OIL-MIST OUTPUT

Item	Test Oil	Density[(a)] (g/cm^3)	Surface Tension[(b)] (dynes/cm)	Kinematic Viscosity[(c)] (cs)	Rate of Oil-Mist Output,[(d)] cc/min 2cfm	3cfm	4cfm
1	FN 2961	0.882	30.9	9.5	0.8	2.1	4.2
2	Krytox 143AC	1.905	18.5	34	-	1.1	1.8
3	Krytox 143AC+5%	1.905	17.5	35	-	1.1	1.9
4	MCS 293	1.196	45.3	4.5	0.7	1.8	3.0
5	MCS 2931	1.195	44.9	4.5	0.8	1.9	3.0
6	XRM 109F	0.847	30.8	47	0.6	1.2	2.0
7	XRM 109F+10% Kendall resin	0.851	31.5	55	-	1.5	2.4
8	XRM 209A	0.955	31.5	5.5	0.9	2.4	4.0
9	XRM 210A	0.962	31.9	5.5	1.0	2.4	4.2
10	Hercolube F	1.008	30.1	9.7	1.1	2.3	3.3
11	Sunthetic 18HB	0.845	29.7	145	0.3	0.8	1.2
12	Turbo Oil 4040	0.927	30.1	3.4	1.5	3.2	5.6
13	Ucon 50HB-5100	1.056	36.9	220	0.3	0.6	1.0
14	XRM 177F	0.848	31.0	47	0.5	1.1	1.8

(a): at 20°c

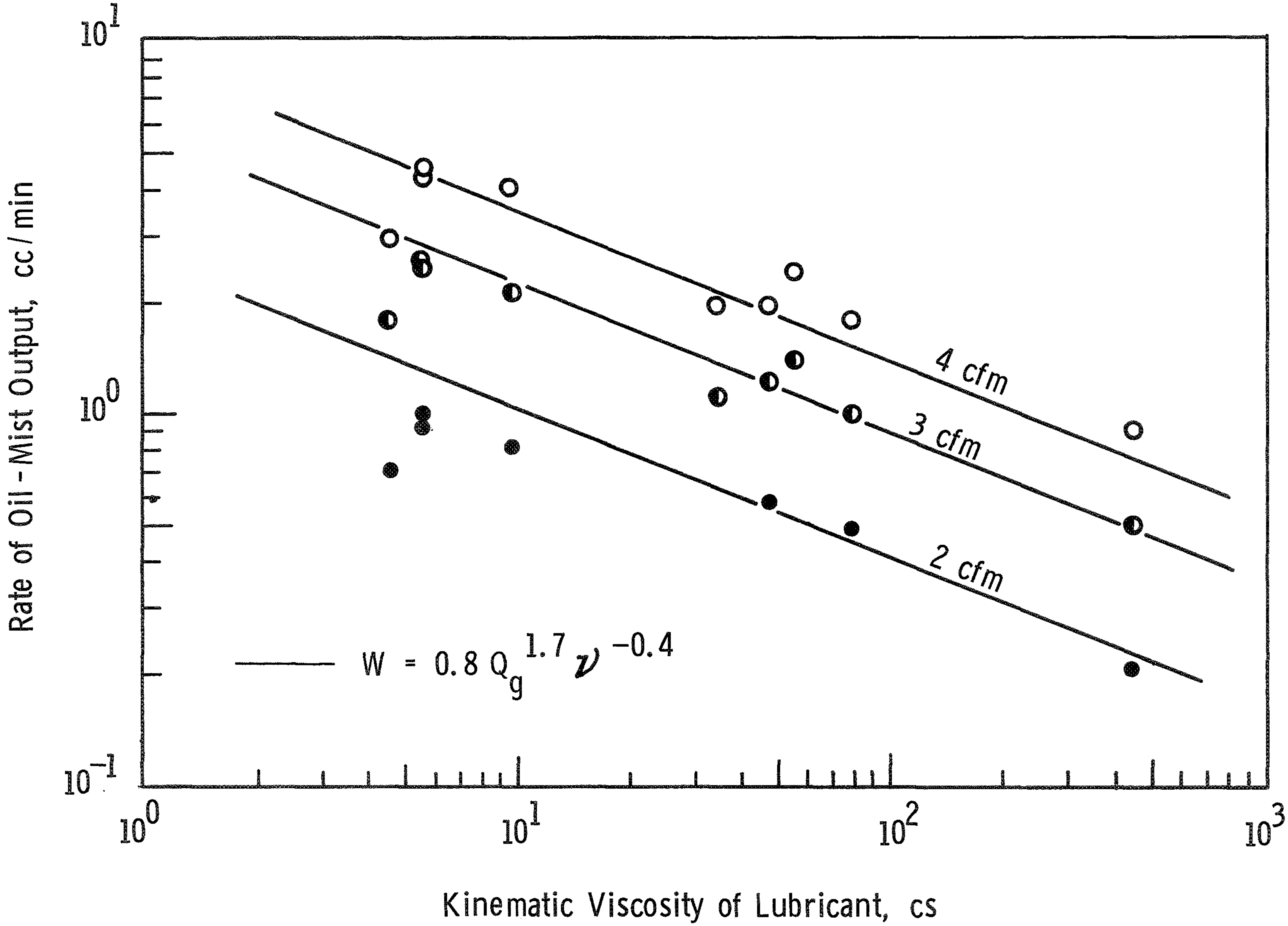
(b): at 25°c

(c): at 200°F

(d): at 200°F & 45 psig

Figure 3

EFFECT OF VISCOSITY ON RATE OF OIL-MIST OUTPUT



on mist generation except for certain polymers which are believed to cause higher, and in some cases lower, mist output than normally expected based on viscosity[3]. Reduction of oil mist lost as stray fog, which has been attributed to the presence of polymeric materials, may be another example of polymer effects on mist generation. The behavior of the Kendall paraffinic resin in raising the oil-mist output rate may be similar to that of a polymer. While the nature of polymer effects in enhancing or hindering mist generator operation is not clear, a possible explanation is a change in lubricant flow rates through the orifice of the atomizing nozzle. According to a relation for pneumatic atomization, all operating variables being equal, the atomization is, in general, inversely related to the relative velocity between the gas and liquid through the atomizing nozzle. Thus, the rate of oil-mist output changes depending upon the response of lubricant flow characteristics to the presence of different types of polymeric additives.

For example, by hindering the flow of oil through the atomizer orifice, some viscosity improvers may reduce oil-mist output and hence stray fog, while drag reducing additives, an example of which may be the Kendall super-refined paraffinic resin, can enhance generator operation by increasing the rate of oil-mist output without increasing gas flow rate. If the stray fog is a problem, the use of lubricant containing the former type polymers can be considered. With this approach, however, some caution must be exercised to assure that the rates of oil-mist output are adequate for the application. It is well known that when used in substantial amounts, viscosity improver type additives can change the rheological properties of a lubricant even to the extent of changing a Newtonian fluid into a non-Newtonian one. Drag reducing type polymers can also change the fluid flows of the lubricant by reducing either friction or turbulence.

2. Particle Velocity Distribution

Determinations of the microfog particle velocities, using the techniques developed and described in the previous report, were made with two different nozzles - Nos. 1 and 3 (refer to Figures 24 and 25 in Reference 2), at gas flow rates of 2, 3, and 4 cfm. The test chamber conditions were at 45 psi and 72°F. These tests, in most cases, employed Krytox 143 AC and XRM 109 F at a microfog generator temperature of 200°F.

Experimental results representing the local velocities at 2, 4, and 6 inches, as expected, were in good agreement with those from our earlier work (2), but the particle velocities of Krytox 143 AC at 4 and 6 inches lag slightly behind the velocities of XRM 109 F, which has a considerably lower density. Thus, for a given gas flow, increase in the density difference between the gas and particles causes the relative velocity to increase, i.e., the

Table 3

Axial Distribution of Mean Microfog Stream Velocity

Gas Flow Rate	Pressure, psi		Calculated Gas Stream Velocity, ft/sec				Experimental Microfog Stream Velocity, ft/sec		
(cfm at 45 psi & 200°F)	Nozzle	Chamber	Spray Nozzle	2"	4"	6"	2"	3"	4"
Nozzle No. 1 (0.171" orifice diameter)									
2	48.5	46	290	99	50	33	125	65	40
3	53	46.5	411	141	71	47	170	80	45
4	61	46.5	593	204	102	68	190	130	85
Nozzle No. 3 (0.281" orifice diameter)									
2	47	46	168	95	47	32	---	---	---
3	48	46.5	213	119	60	40	105	70	40
4	49.5	46.5	268	150	75	50	135	80	55

particles are less completely entrained by the given-scale gas motions. However, near the spray nozzle no lag is noted because here large-scale turbulent eddies can still entrain the particles together with portions of gas surrounding them, and transfer gas and particles as a single unit.

3. Particle Size Distribution

Determinations of the microfog particle sizes and distributions for the test lubricants were made at a generator temperature of 200°F with two different nozzles at gas flow rates of 2, 3, and 4 cfm. Data for FN 2961 and XRM 109 F were also obtained at generator temperatures of 100 and 300°F.

Listed in Table 4 are the particle size distribution data for the different test lubricants, and their mean particle diameters in two forms, determined with No. 1 nozzle at a gas flow rate of 3 cfm. This particular operating condition was chosen to illustrate the effects of different lubricants on particle size distribution because all other data show a basically similar trend. The corresponding cumulative (integral) particle size distribution curves are also shown in Figure 4, where particle diameter is plotted against percent (by number) of the particles smaller than the indicated diameter in a log-probability scale. Results, in general, indicate that as described in Table 4, XRM 109 F produces the largest particle size under the given operating condition, and that the number frequency curves of these lubricants represent a uni-modal distribution.

The mean particle diameters calculated by different methods are summarized in Table 5. This summary indicates again that, for a given condition, XRM 109 F produces the largest particle size. Table 5, considered together with Table 1, also indicates that the surface tension and density of the lubricant are important factors affecting the action of an atomizing nozzle in regulating particle size. The summary further suggests that presence of additives in the lubricants and variation of lubricant viscosity have little effect on particle size and distribution.

It is of interest to note at this point that particle size distribution curves on a number basis, in all cases tested in this study, have a uni-modal distribution, i.e., one peak, contradicting those data reported in our previous work in which a bi-modal distribution was generally exhibited. While the reason for this difference in the number frequency distribution curves is uncertain, it may be related to modifications of the particle counter aimed at increasing its stability and capacity. To achieve these improvements, a newly marketed photomultiplier tube having higher stability (Du Mont KM 2433) was adopted and the corresponding electrical circuits of the amplifying systems and the pulse height analyzer were modified. The resulting reduction of background noise

Table 4

PARTICLE SIZE DISTRIBUTION DATA OF TEST OILS

Test Conditions	Channel	Particle Size (μm)	FN 2961	Krytox 143AC	MCS293	XRM109F	XRM209A
Oil Temp: 200°F							
Nozzle No. 1							
3 cfm	1	0.6	722	207	744	709	654
10 sec. sampling time	2	0.9	688	76	1041	1100	629
	3	1.2	351	16	713	778	333
	4	1.7	12	2	53	87	8
	5	2.4	2	1	3	2	3
	6	3.4	0	0	0	1	1
	7	4.8	0	0	0	0	0
Arithmetic Mean Diameter, μm			0.82	0.70	0.89	0.91	0.83
Mean Volume Diameter, μm			0.89	0.72	0.97	0.99	0.90

Figure 4

CUMULATIVE PARTICLE SIZE
DISTRIBUTION CURVES FOR TEST OILS

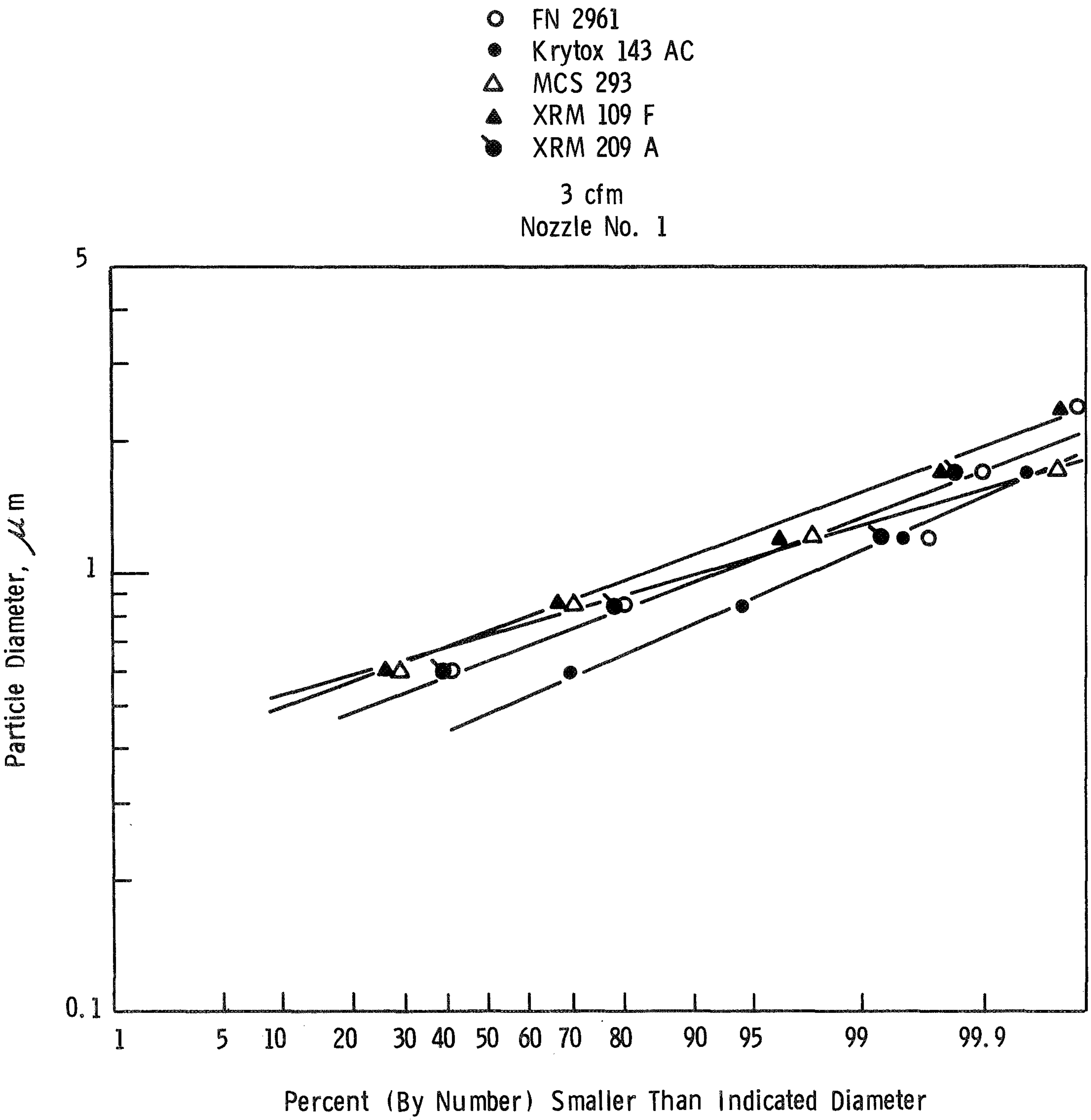


Table 5

SUMMARY OF MEAN PARTICLE SIZES

Item	Test Oils	Oil Temp. (°F)	Nozzle No.	Arithmetic Mean Diameter (μm)			Mean Volume Diameter (μm)		
				2cfm	3cfm	4cfm	2cfm	3cfm	4cfm
1	FN2961	100	1	0.70	0.86	0.95	0.73	0.93	1.16
			3	0.70	0.84	0.92	0.75	0.91	1.01
		200	1	0.71	0.82	0.87	0.75	0.89	0.94
			3	0.72	0.81	0.84	0.78	0.88	0.91
		300	1	0.73	0.84	0.87	0.77	0.90	0.94
			3	0.72	0.83	0.86	0.76	0.89	0.92
2	Krytox 143AC	200	1	----	0.70	0.73	----	0.72	0.93
			3	----	0.68	0.70	----	0.71	0.83
3	Krytox 143AC+ 5% duPont 9530-49	200	1	----	0.68	0.74	----	0.71	0.92
			3	----	0.67	0.68	----	0.70	0.79
4	MCS293	200	1	0.70	0.89	0.92	0.74	0.97	1.00
			3	0.70	0.83	0.88	0.74	0.90	0.94
5	MCS2931	200	1	----	0.88	0.95	----	0.96	1.08
			3	----	0.83	0.86	----	0.89	0.93
6	XRM109F	100	1	0.69	0.89	0.93	0.72	0.96	1.00
			3	0.71	0.84	0.87	0.76	0.91	0.94
		200	1	0.70	0.91	1.02	0.75	0.99	1.11
			3	0.71	0.89	0.93	0.75	0.96	1.01
		300	1	0.75	0.93	0.99	0.84	1.01	1.08
			3	0.78	0.93	0.95	0.84	1.02	1.04
7	XRM109F+ 10% Kendall resin	200	1	0.72	0.87	0.93	0.76	0.95	1.02
			3	0.70	0.82	0.87	0.73	0.89	0.94
8	XRM209A	200	1	0.71	0.83	0.87	0.75	0.90	0.96
			3	0.73	0.82	0.82	0.78	0.89	0.89
9	XRM210A	200	1	0.73	0.85	0.88	0.78	0.93	0.95
			3	0.75	0.85	0.88	0.81	0.94	0.95

level and faster traverse time should yield more reliable and accurate particle size distribution data.

4. Wetting Rate Determinations

Determinations of the wetting rates of the five base lubricants (FN 2961, Krytox 143 AC, MCS 293, XRM 109 F, and XRM 209 A) were made with the two different spray nozzles under various test conditions as specified in Task I.

Test results, reporting wetting times at different radial distances, are listed in Appendix B, with other pertinent data. The wetting rates, estimated graphically by taking the slopes of the straight line relations between fraction of area covered and wetting time, are also included in the appendix. Typical experimental results, illustrated by the wetting data for XRM 109 F with No. 1 spray nozzle at plate temperature of 700°F, are shown in Figure 5. In general, the test data for other lubricants have similar relations except for MCS 293, which has a unique wetting pattern that will be discussed in a later section of this report.

Discussion of the test results summarized in Appendix B will employ the specific and minimum wetting rate concepts as defined in our previous work (2). Instead of dealing with individual experimental runs, discussion will be confined to significant factors which may play an important role in microfog lubrication, citing typical examples to illustrate general trends. Any test results deviating from the general trend will be specified and discussed separately.

i) Effect of Oil/Gas) Mass Flow Ratio

In order to facilitate discussion of the effect of (oil/gas) mass flow ratio, the wetting rates of four test lubricants at 600, 700, and 800°F with the two nozzles, taken from Appendix B, are shown in Figures 6 through 11. FN 2961 and XRM 209 A with No. 3 nozzle, and MCS 293, were excluded from these plots because they failed to yield complete sets of data points.

With increasing (oil/gas) mass flow ratios, the wetting rates for the test lubricants, as expected, increase linearly in most cases at varying slopes, implying that the wettabilities of these lubricants under these test conditions are vastly different. The increased (oil/gas) mass flow ratios were established by increasing gas flow rates to the microfog generator, a procedure which also increases the impaction velocity for a given nozzle. Hence, the increases in wetting rates shown in Figures 6 through 11 are due not entirely to the increase in (oil/gas) mass flow ratio, but to a combination of increases in impaction velocity and mass flow ratio. The wetting

Figure 5

WETTABILITY OF XRM 109 F
AT DIFFERENT GAS FLOW RATES

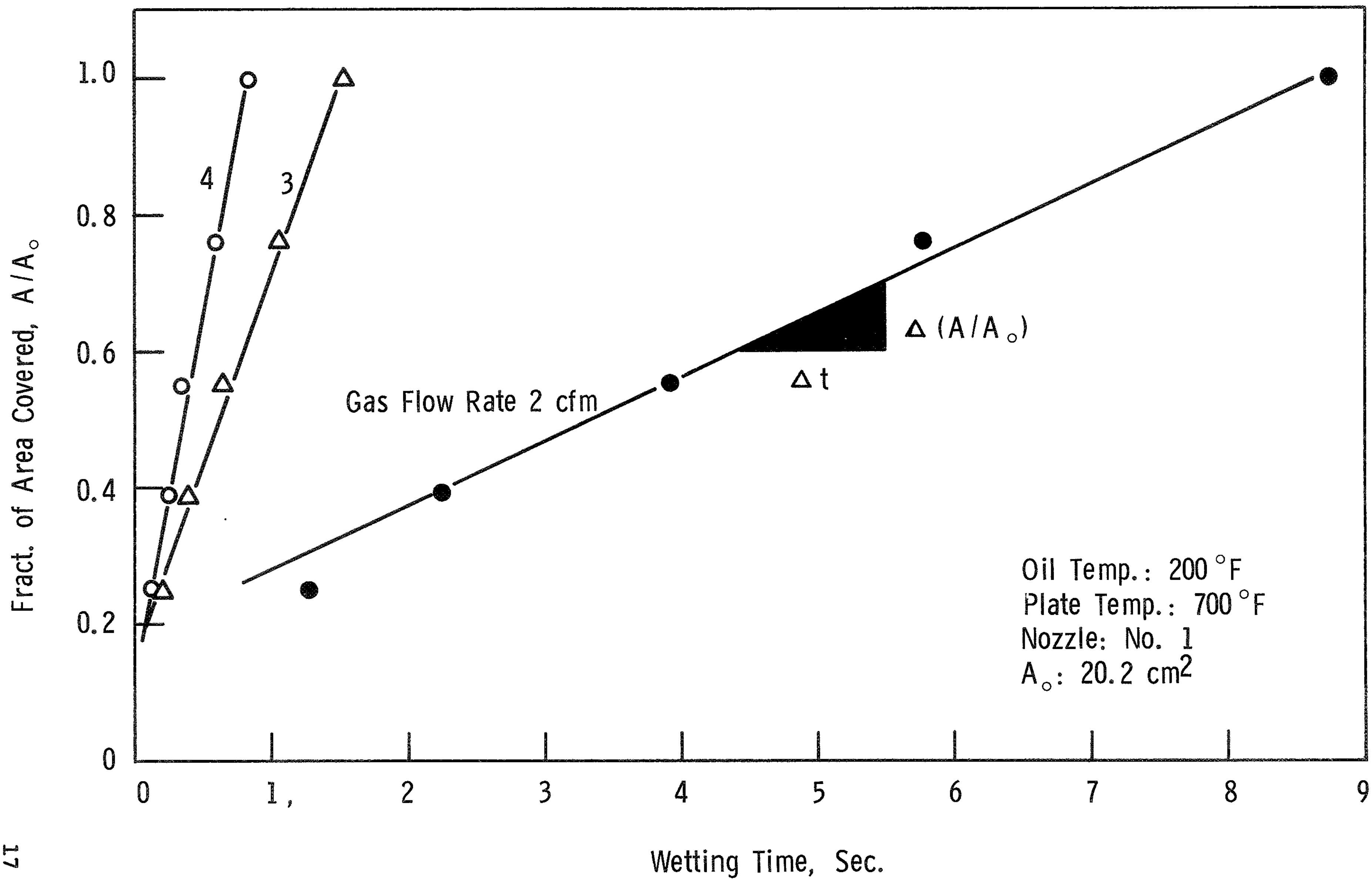


Figure 6

EFFECT OF (OIL/GAS) MASS FLOW RATIO
ON WETTING RATE FOR FN 2961

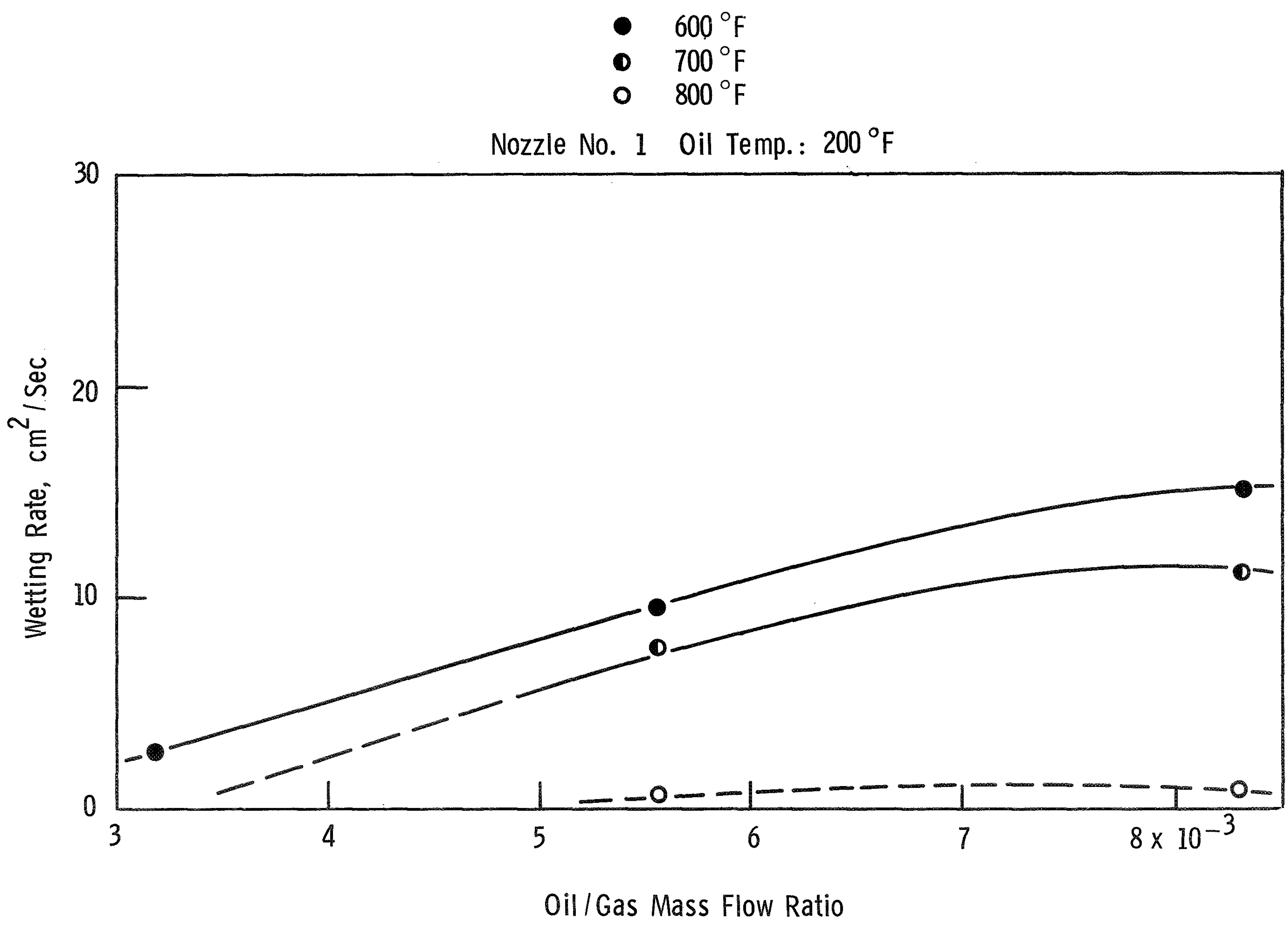


Figure 7

EFFECT OF (OIL/GAS) MASS FLOW RATIO ON WETTING RATE FOR KRYTOX 143 AC

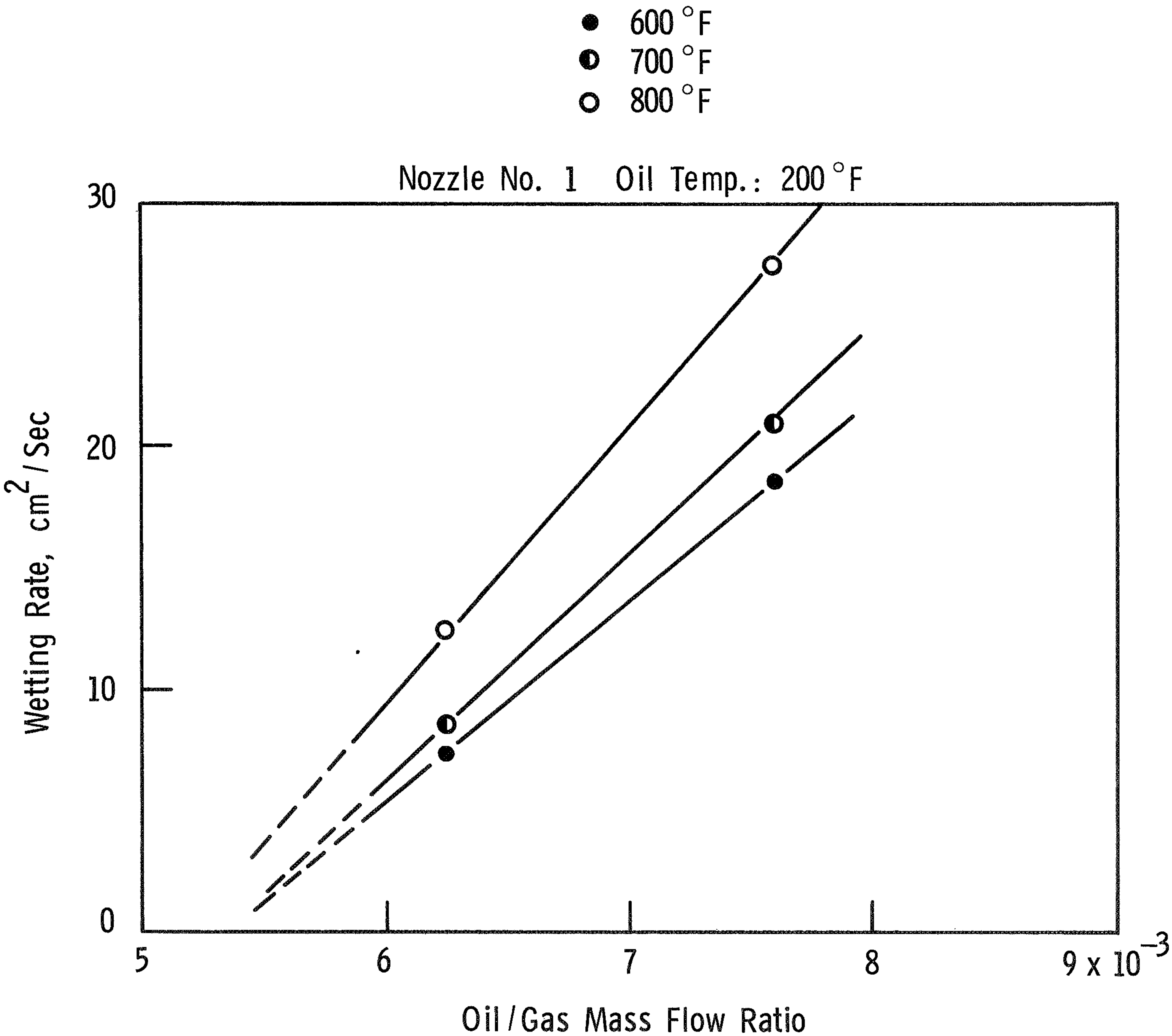


Figure 8

EFFECT OF (OIL/GAS) MASS FLOW RATIO
WETTING RATE FOR KRYTOX 143 AC

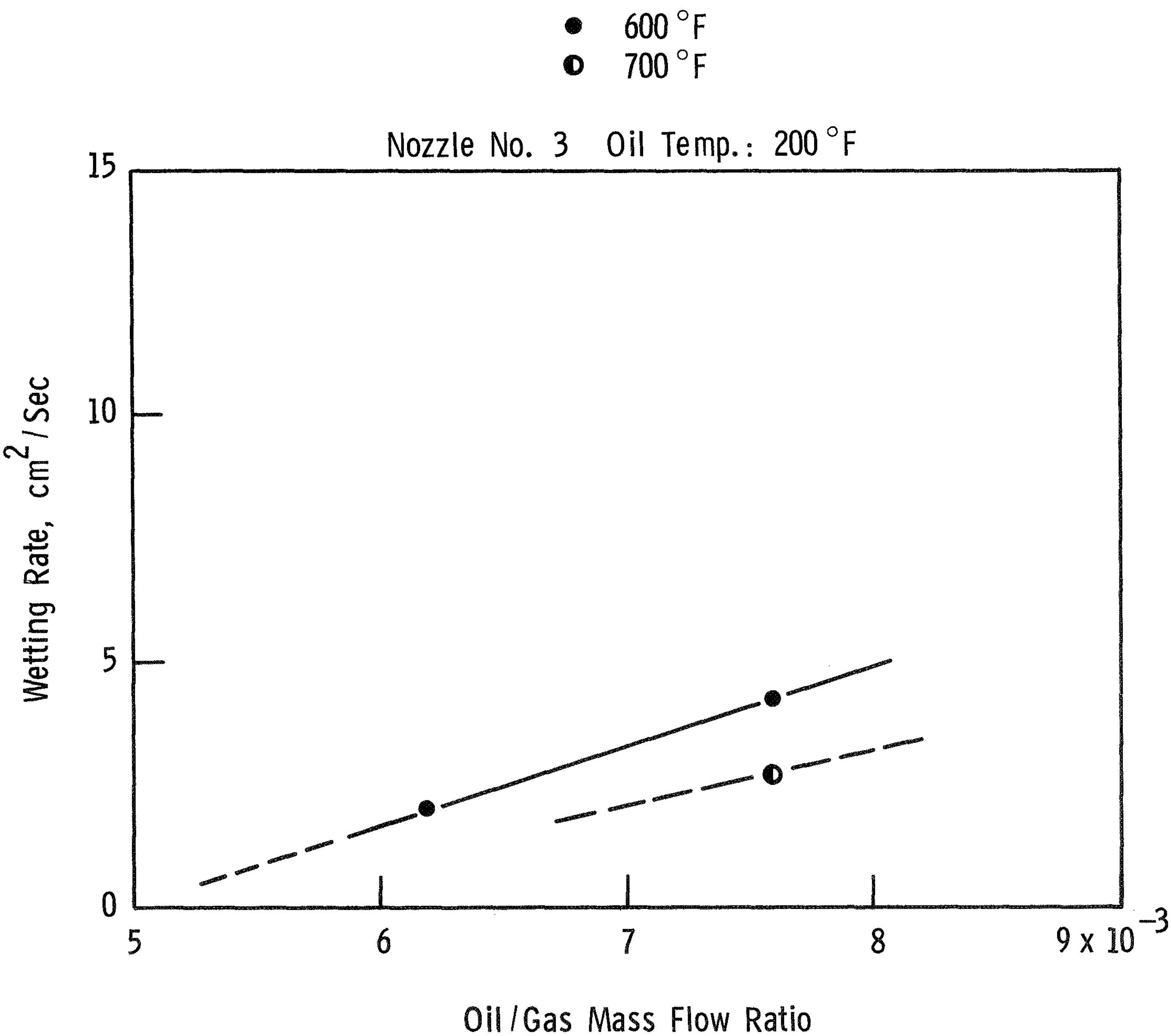


Figure 9

EFFECT OF (OIL/GAS) MASS FLOW RATIO ON WETTING RATE FOR XRM 109 F

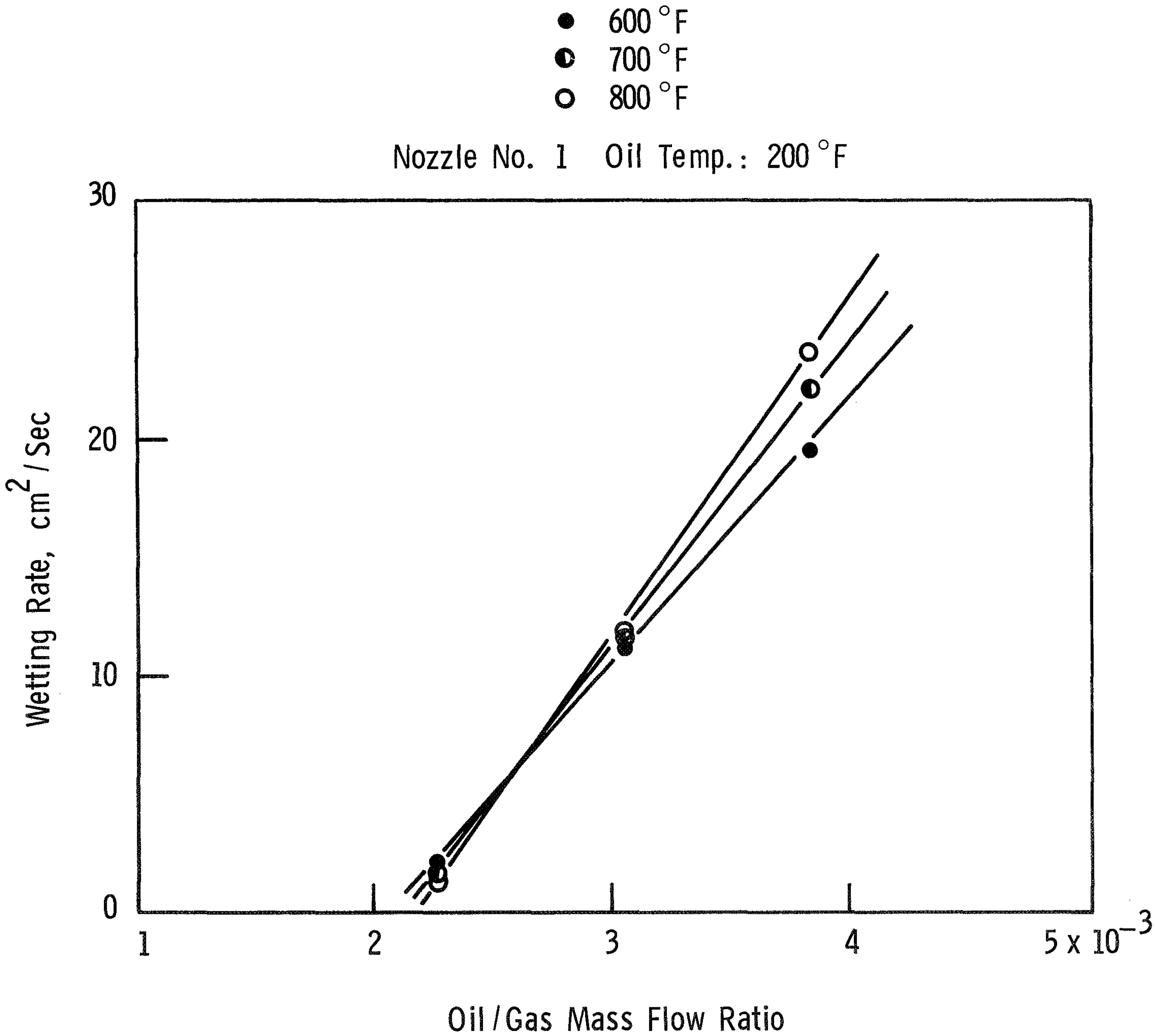


Figure 10

EFFECT OF (OIL/GAS) MASS FLOW RATIO ON WETTING RATE FOR XRM 109 F

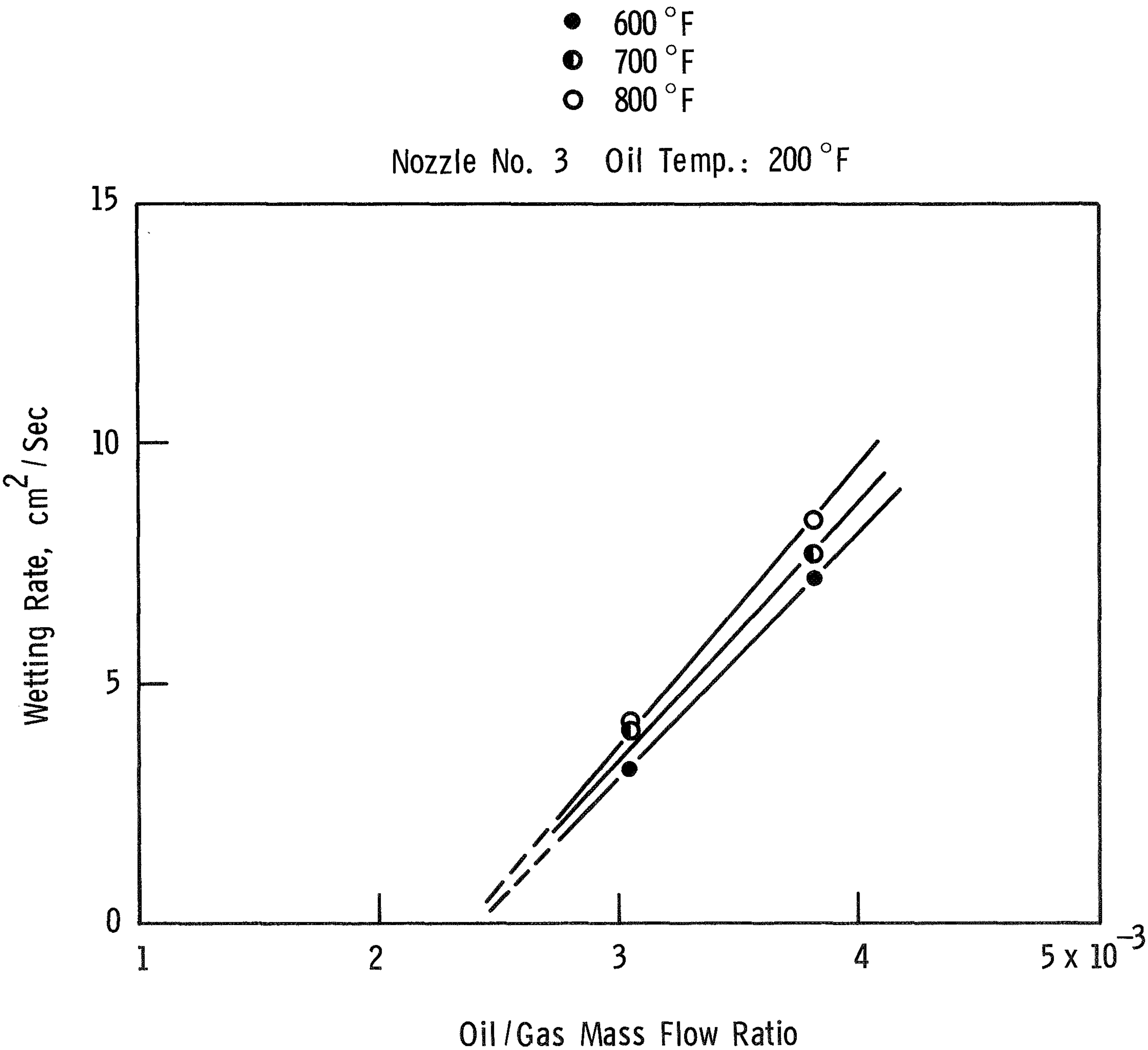
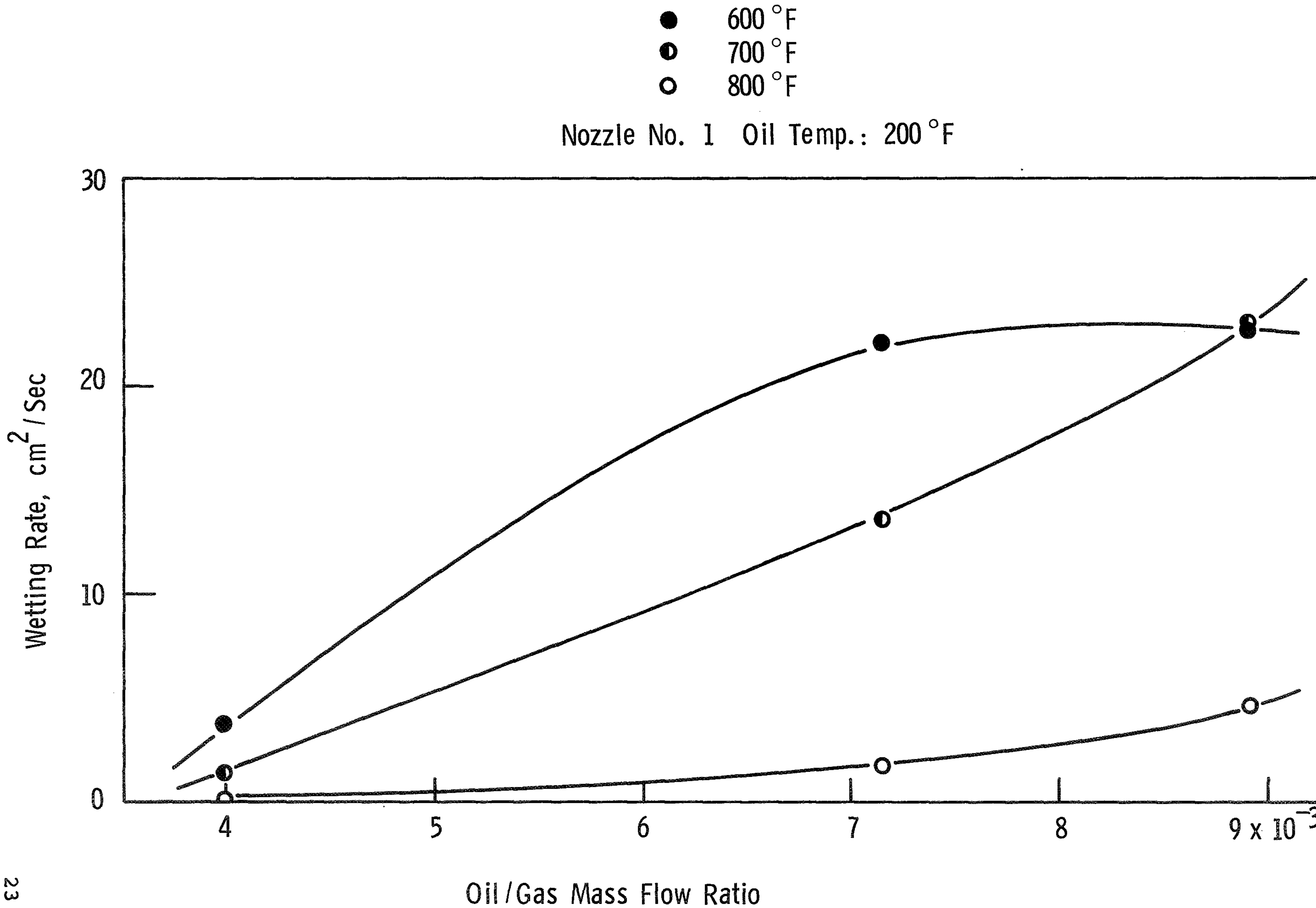


Figure 11

EFFECT OF (OIL/GAS) MASS FLOW RATIO
ON WETTING RATE FOR XRM 209 A



rate data also indicate that the slopes of the linear relations for Krytox 143 AC and XRM 109 F generally are higher than those for FN 2961 and XRM 209 A, suggesting that the former lubricants wet the test plate more effectively than the latter. This is more apparent when the slopes are compared at plate temperature of 800°F.

Unfortunately, the present microfog generator does not allow the effects of (oil/gas) mass flow ratio to be isolated from effects of impaction velocity since there is no means of independently controlling the rate of oil-mist output with a fixed gas flow rate to the generator. However, the effects of mass flow ratios on wetting rate can be discussed qualitatively. When a microfog stream having a given particle size distribution is sprayed on a collector, depending upon impaction efficiency, which is related to impaction velocity, only the particles in certain size ranges carry sufficient momentum to penetrate through the layers of impaction pressure created by the gas stream along the collector, and impinge and spread on the surface of the collector. Now, with the same particle size distribution and impaction velocity, any increase in the (oil/gas) mass flow ratio established by suspending more microfog particles in the given gas flow will raise a number of particles in the size ranges which can impact on the collector, thereby increasing the quantity of lubricant available for spreading on the collector. Such an increase in the volume of lubricant on the collector, or test plate, obviously would increase spreading and wetting rates. This qualitative discussion suggests that (oil/gas) mass flow ratio, in addition to impaction velocity, is a key variable in controlling wetting rate.

ii) Effect of Impaction Velocity

Discussion in the preceding section has indicated important effects of impaction velocity on wetting rate. In order to demonstrate these effects, the wetting data for XRM 109 F obtained with Nos. 1 and 3 nozzle at 600°F are compared in conjunction with the impaction velocity data for these nozzles at gas flow rates of 2, 3, and 4 cfm. Test results are summarized below:

Gas Flow Rate (cfm)	Rate of Oil-Mist Output (cc/min)	Impaction Velocity, ft/sec		Wetting Rate, cm^2/sec	
		Nozzle No. 1	Nozzle No. 3	Nozzle No.1	Nozzle No.3
2	0.6	148	79	2.2	---
3	1.2	236	119	11.6	3.2
4	2.0	352	163	19.6	7.2

Thus, for a given (oil/gas) mass flow ratio, any increase in the wetting rates between No. 1 nozzle and No. 3 is due almost entirely to increasing impaction velocity by means of a nozzle since the particle size distribution data (refer to Table 5) show little difference in the mean particle sizes for these nozzles. For example, at a gas flow rate of 3 cfm, corresponding to the (oil/gas) mass flow ratio of 3.06×10^{-3}, the wetting rates with Nos. 1 and 3 nozzles are 11.6 and 3.2 cm^2/sec, respectively, while the impaction velocities vary from 236 ft/sec for No. 1 nozzle to 119 ft/sec for No. 3 nozzle, and the arithmetic mean particle diameter for both nozzles remains fairly unchanged at 0.9 μm.

In a similar manner, the effect of impaction velocity in terms of specific wetting rate can be illustrated by using the wetting rate data for Krytox 143 AC and XRM 109 F at 600°F. The wetting rate data are summarized as follows:

Spray Nozzle	Specific Wetting Rate, cm^2/sec/(oil/gas) mass flow ratio	
	Krytox 143 AC	XRM 109 F
No. 1 (0.171" dia.)	8.2×10^3	11.5×10^3
No. 3 (0.281" dia.)	1.6×10^3	4.8×10^3

In this comparison, the specific wetting rates with Nos. 1 and 3 nozzles for a unit (oil/gas) mass flow ratio increase from 1.6×10^3 to 8.2×10^3 cm^2/sec for Krytox 143 AC and from 4.8×10^3 to 11.5×10^3 cm^2/sec for XRM 109 F, while the mean particle diameter with these nozzles changes little. Consequently, the increases in specific wetting rate can be attributed to the increase in impaction velocity.

The comparisons of the wetting rate data lead to the conclusion that impaction velocity greatly affects wetting rate and is one of the most important operating variables in a microfog lubricant application system.

iii) Effect of Plate Temperature

In order to aid discussion of the effect of plate temperature, the wetting rates of four test lubricants (FN 2961, Krytox 143 AC, XRM 109 F, and XRM 209 A) have been plotted as a function of plate temperature, as shown in Figures 12 through 15. Test results clearly reveal that as plate temperature rises from 600 to 800°F, the wetting rates of FN 2961 and XRM 209 A decrease sharply, while the rates of Krytox 143 AC and XRM 109 F slightly increase at sufficiently high (oil/gas) mass flow ratios or remain essentially unchanged at lower (oil/gas) mass flow ratios. Examination of the results also suggests that in discussing the effect of plate

Figure 12

EFFECT OF PLATE TEMPERATURE ON WETTING RATE FOR FN 2961

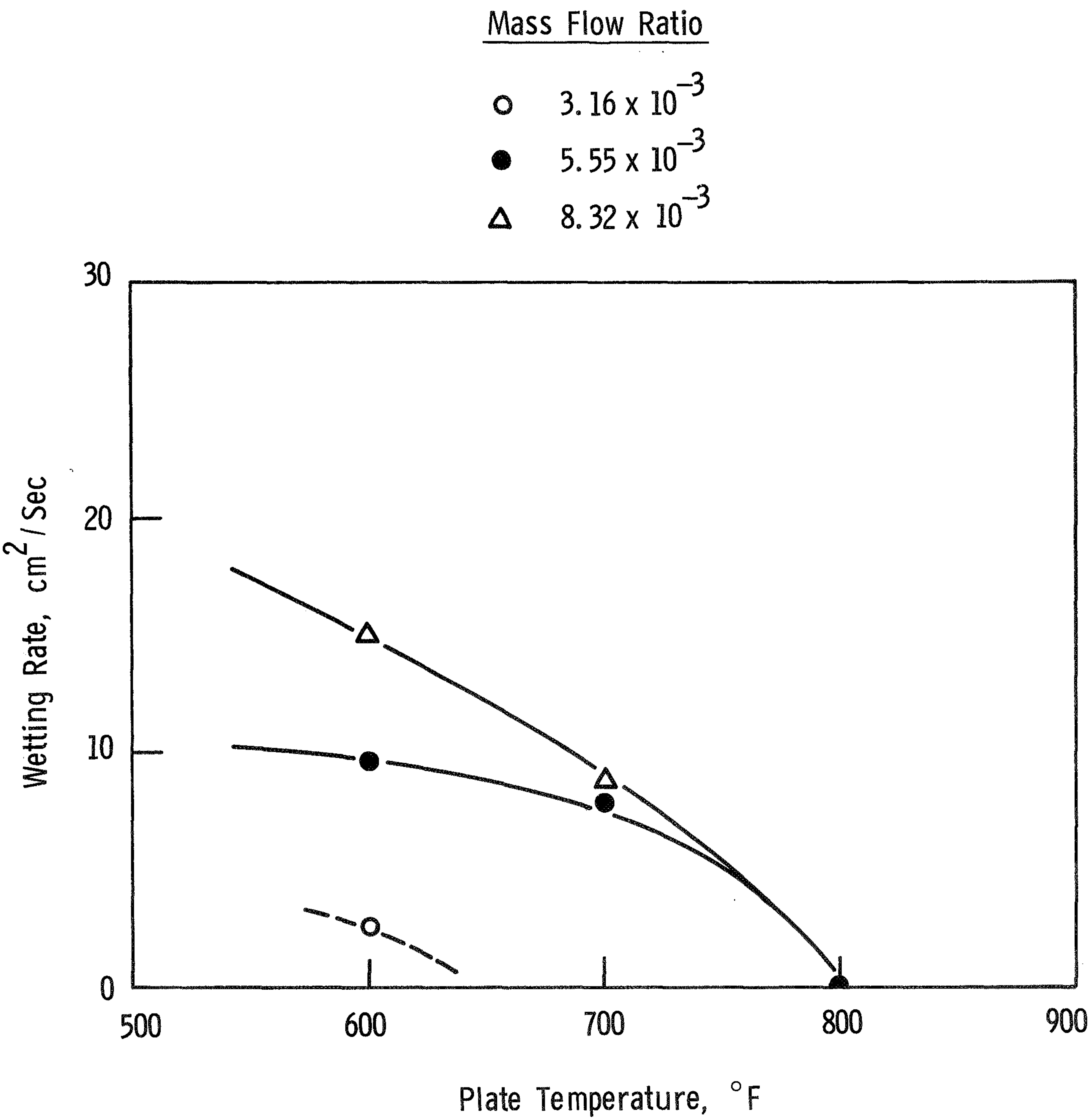


Figure 13

EFFECT OF PLATE TEMPERATURE ON WETTING RATE FOR KRYTOX 143 AC

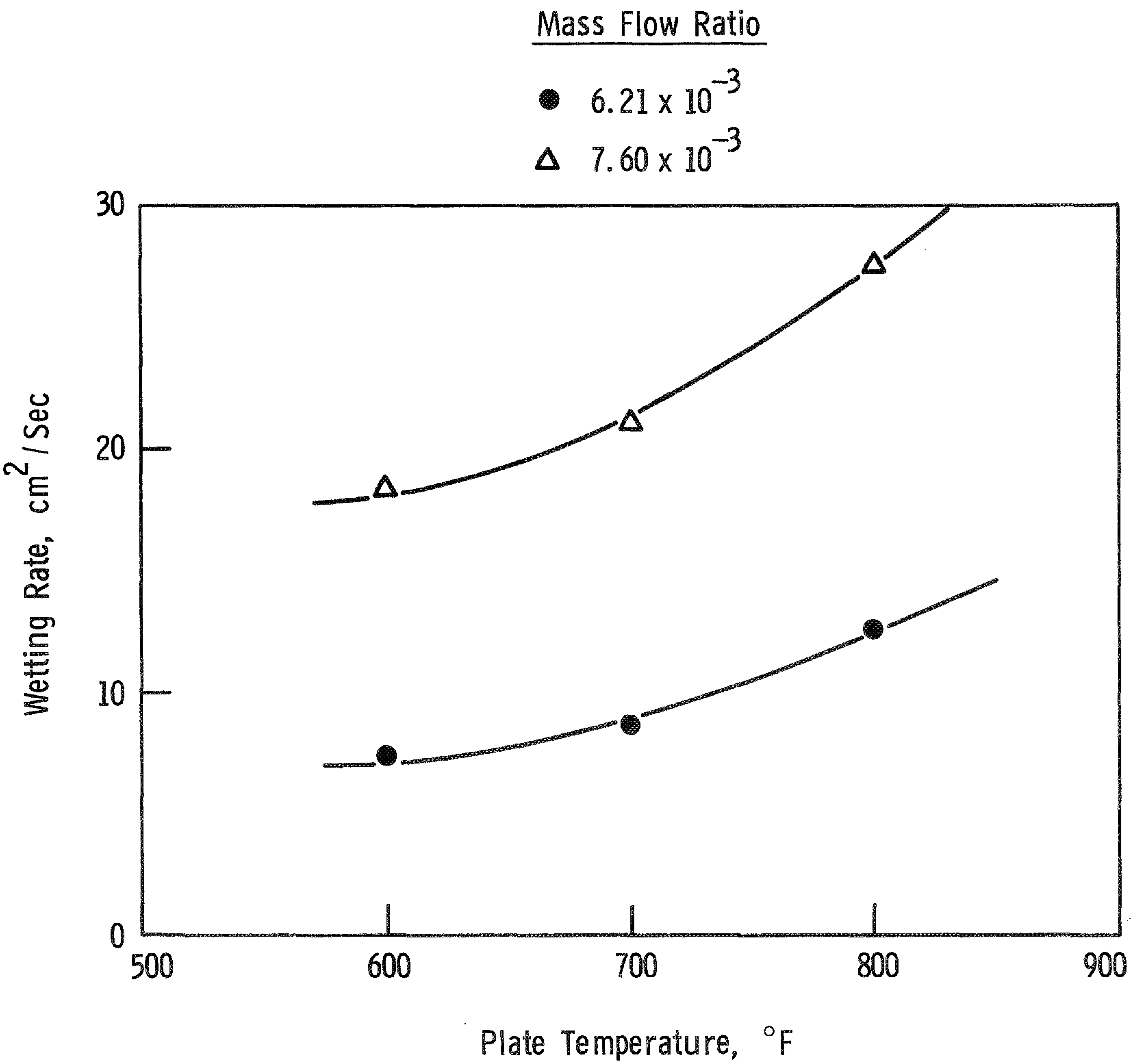


Figure 14

EFFECT OF PLATE TEMPERATURE ON WETTING RATE FOR XRM 109 F

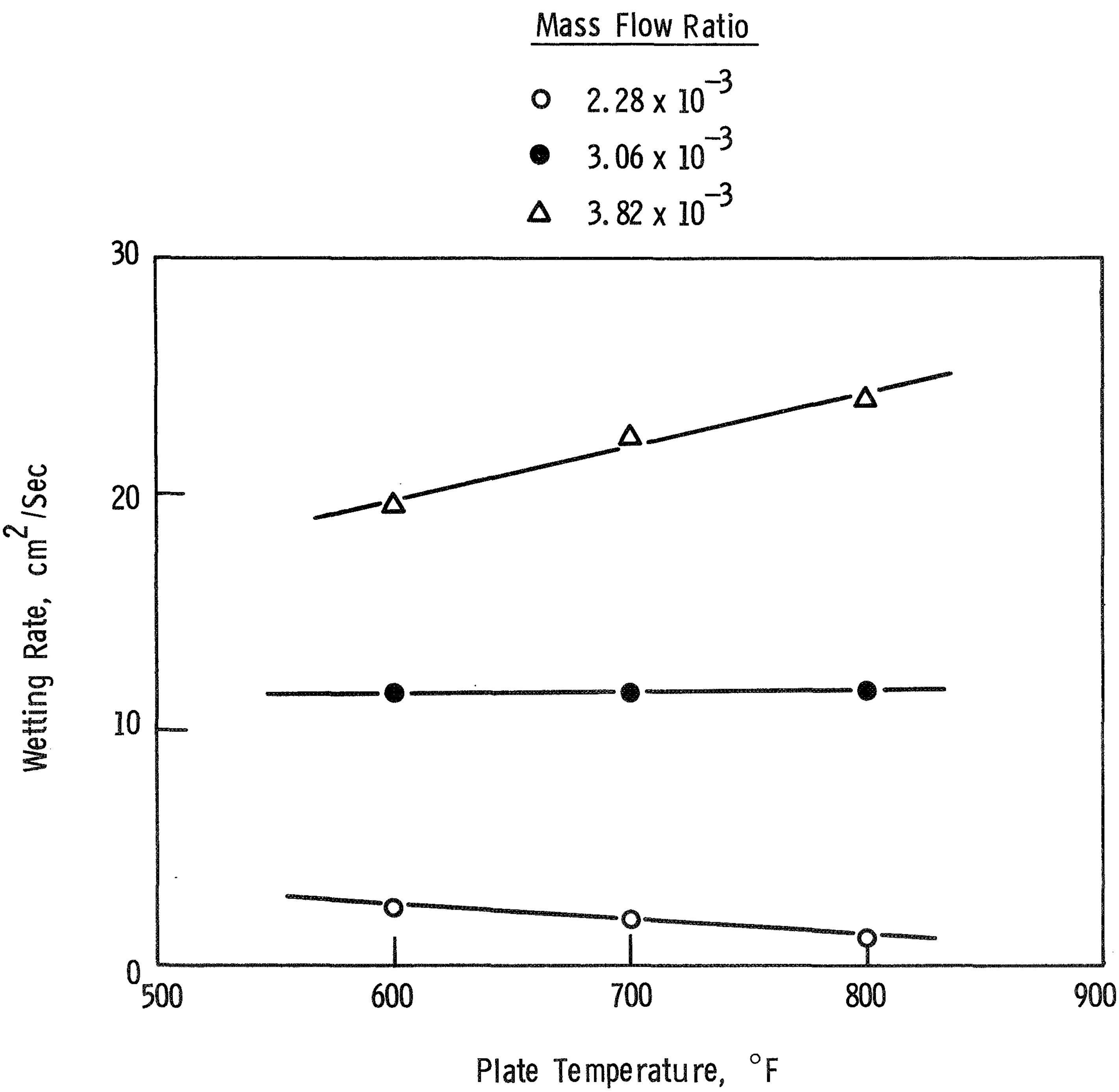
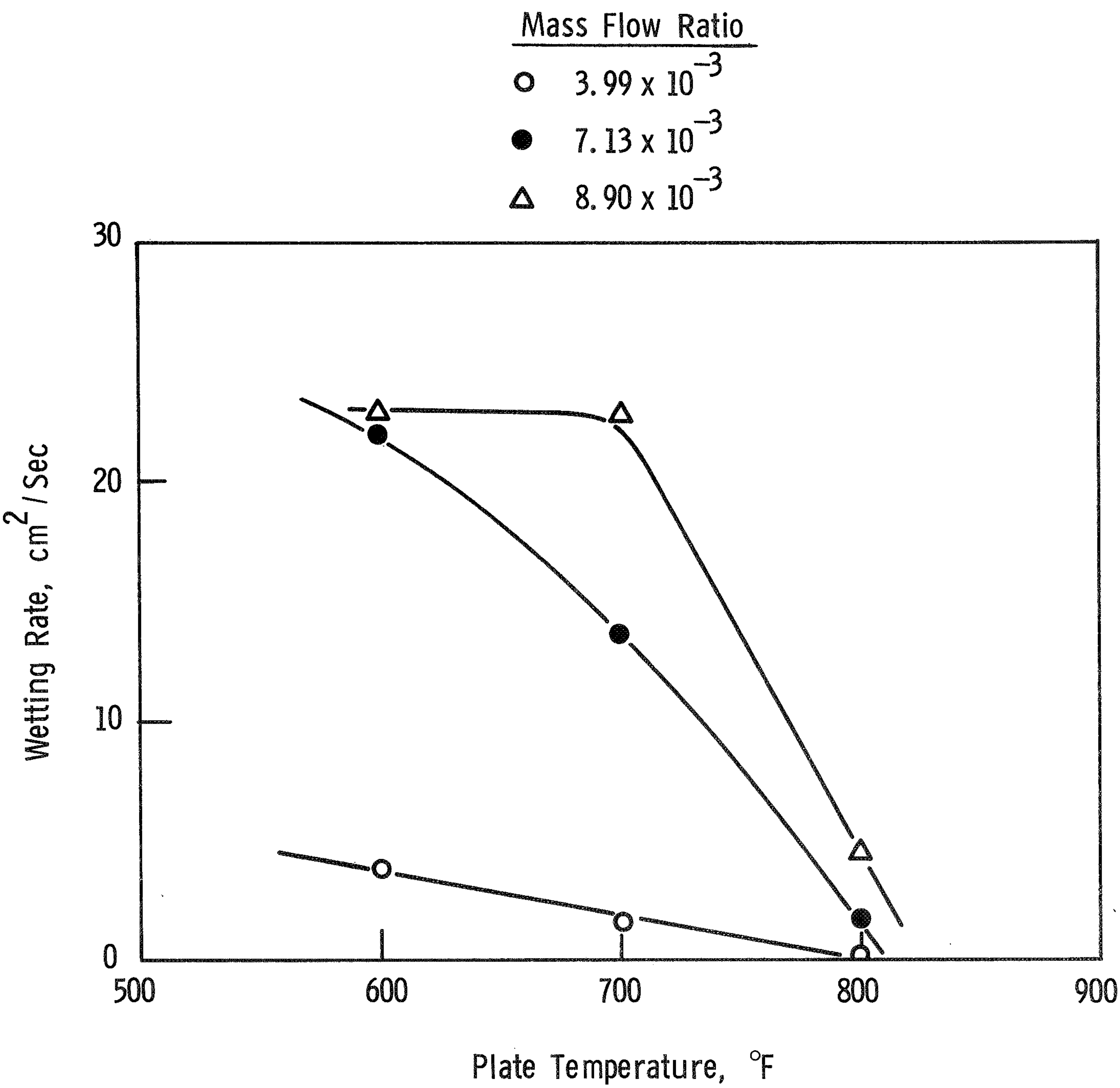


Figure 15

EFFECT OF PLATE TEMPERATURE ON WETTING RATE FOR XRM 209 A



temperature, the importance of the heat-and mass-transfer processes at the interface between the surface of the test plate and spreading lubricant film cannot be ignored.

For a given (oil/gas) mass flow ratio and a fixed impaction velocity which practically controls the amount of microfog particles that can impinge on a test plate, the quantity of lubricant available for spreading on the plate may depend solely upon evaporation loss at a steady temperature which the spreading lubricant film approaches after absorbing heat from the plate. Therefore, variations in the wetting rates of the test lubricants with test plate temperature may be explained on the basis of the thermal properties (and stabilities) and vapor pressure of the lubricants. To discuss the wetting rates in relation to evaporation which we consider more meaningful for the purpose than vapor pressure data, we obtained evaporation loss data for the four test lubricants by using modified ASTM method D972 (wt. % loss at 400°F for 6-1/2 hours). Results are shown below:

	Evaporation Loss (modified D972), Wt. % Loss		
FN 2961	Krytox 143 AC	XRM 109 F	XRM 209 A
13.7	1.1	2.7	5.7

The evaporation loss data are in agreement with the vapor pressure data (refer to Figure 2), indicating that FN 2961 and XRM 209 A are more volatile than Krytox 143 AC and XRM 109 F. Thus, comparison of the volatility properties of each lubricant with the effects of test plate temperature on wetting rate clearly suggests that high temperature wetting rates will rise or fall with rising plate temperature.

iv) Comparison of the Wetting Rates of Different Test Lubricants

Since the determinations of wetting rate with No. 3 nozzle in some cases did not yield useful data, the wetting rates obtained with No. 1 nozzle at 600°F were chosen for discussion comparing the wettabilities of the five test lubricants having widely different properties. The wetting rates versus the (oil/gas) mass flow ratios for these lubricants are plotted in Figure 16 in an effort to establish a correlation similar to those discussed in the previous sections. Since no meaningful experimental data could be obtained from the photographic movie films because of difference in the wetting patterns (refer to the following section), the wetting rate data of MCS 293 were not presented in Figure 16 for comparison. A more complete list of the specific and minimum wetting rates, which are determined by taking slope and intercept at zero wetting rate, respectively, is presented in Table 6. Summary of the wetting rate data shows that on tha basis of the specific and minimum wetting rates, the wettabilities of these lubricants at 600°F are in the following order: XRM 109 F > Krytox 143 AC > XRM 209 A > FN 2961 > MCS 293. For a unit (oil/gas) mass flow ratio, XRM 109 F has the best overall wetting characteristics and requires a minimum (oil/gas) mass flow ratio of only 2.1×10^{-3} to wet the test plate at 600°F, while MCS 293 is the least effective in wetting the test

Figure 16

EFFECT OF (OIL/GAS) MASS FLOW RATIO ON
WETTING RATE FOR TEST OILS AT 600°F

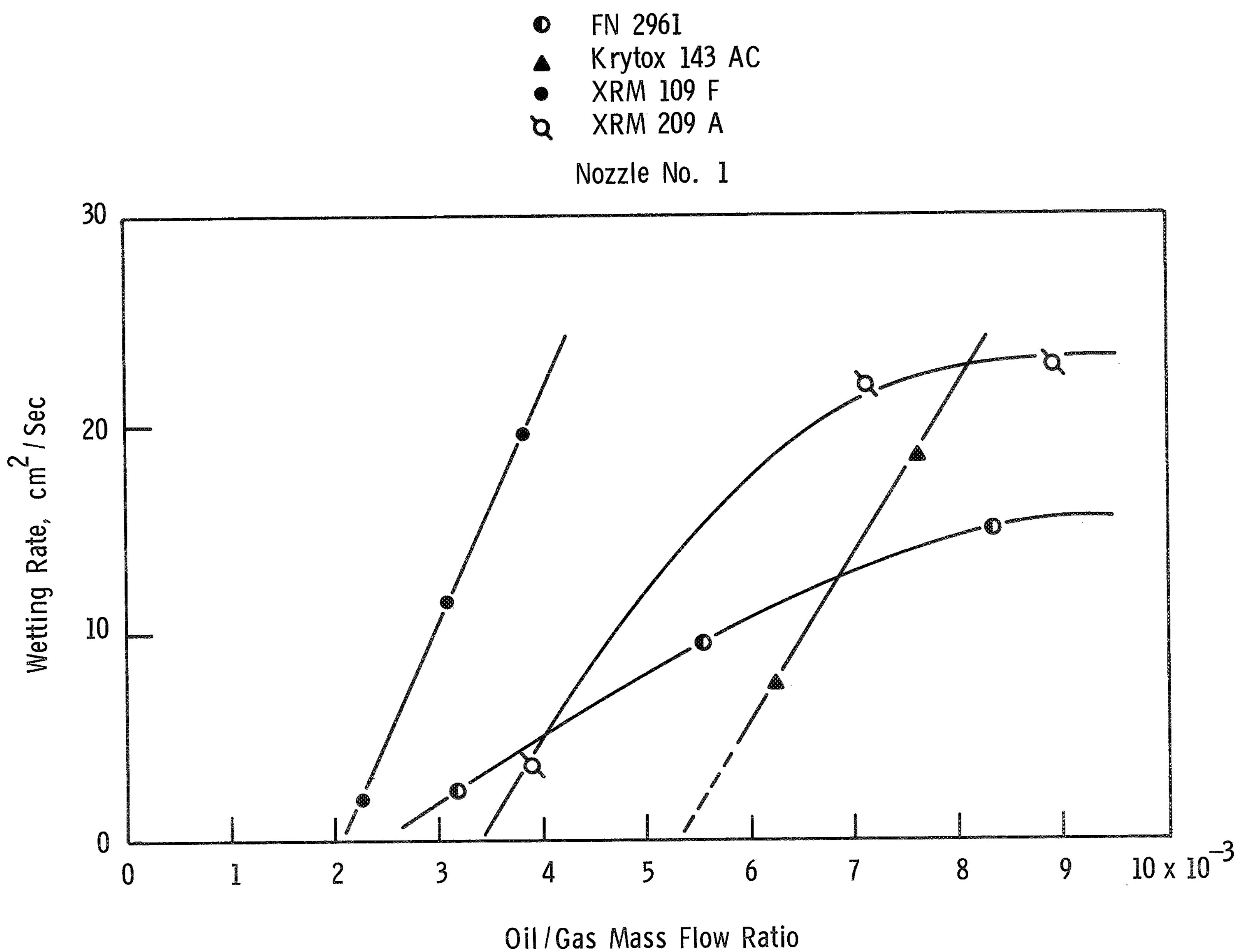


Table 6

SUMMARY OF WETTING RATE DATA FOR TEST OILS

Item	Test Oil*	Plate Temp. (°F)	Specific Wetting Rate [Cm^2/sec/(oil/gas) mass flow ratio] x10^{-3}	Minimum Wetting Rate [(oil/gas)Mass flow ratio] x10^3
1	FN 2961	600	2.6	2.4
2	Krytox 143AC	600	8.2	5.3
3	MCS 293	600	$\ll 1$	---
4	XRM 109F	600	11.5	2.1
5	XRM 209A	600	4.7	3.3
6	FN 2961	700	2.1	2.6
7	Krytox 143AC	700	9.4	5.3
8	XRM 109F	700	12.8	2.1
9	XRM 209A	700	4.4	3.8
10	Krytox 143AC	800	11.5	5.2
11	XRM 109F	800	13.1	2.2

*Oil Temp: 200°F

plate. The excellent wettability of XRM 109 F, as reported in our earlier work (2), is a reflection of its physical properties which, at high temperature, provide excellent fluidity and thermal stability with low oil loss by evaporation or streaking.

Conclusions concerning the wetting characteristics of these test lubricants at other temperatures can be based on similar comparisons of the appropriate wetting rate data.

v) Wetting Patterns of Test Lubricants

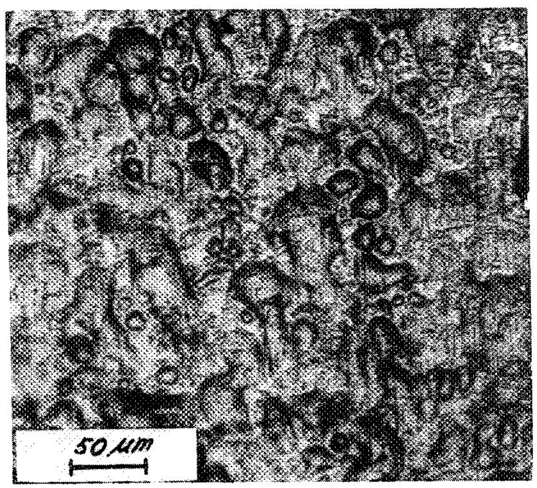
In the previous study (2), the typical sequential spreading patterns of oil films, based on photographic test results, were illustrated schematically. In one type of flow, a continuous oil film gradually spread out to the edge, while in another type, discontinuous oil streaks (streaky flow) rapidly extended out to the edge of the test plate. It has also been reported from other NASA investigations (4,5) that XRM 177 F performed well in full-scale bearing rig tests at 700°F under high speed and load with an inert atmosphere, while MCS 293 exhibited much less capability under similar extreme conditions, though it is thermally and oxidatively stable.

To better understand the wetting patterns of thin oil films flowing over a solid surface, and how they might relate to the bearing test experience, investigation of the basic wetting mechanisms of oil-mist particles impinging on the solid surface was undertaken. The wetting patterns of XRM 177 F and MCS 293 at different stages of oil film spreading on the test plate at 72°F were recorded by a still camera. For these experiments, No. 1 nozzle was used and gas flow rate was at 3 cfm. Photographic results reveal that when a test plate is sprayed with a microfog lubricant stream, it is spattered with adhering drops at an early stage of spray. As spray continues, the drops grow in size by further impaction and coagulation with neighboring drops. During this process, the drops eventually grow to a critical size above which the drops spread on the surface. The spreading of these lubricant drops to form a uniform lubricant film is a key step in the wetting process. Therefore, in any microfog lubricant application, when the microfog particles once impact on the surface of a body, adhesion of the particles to the surface, and coagulation and spreadability of the particles on the surface to form a uniform film, will basically control the amount of lubricant available for lubrication.

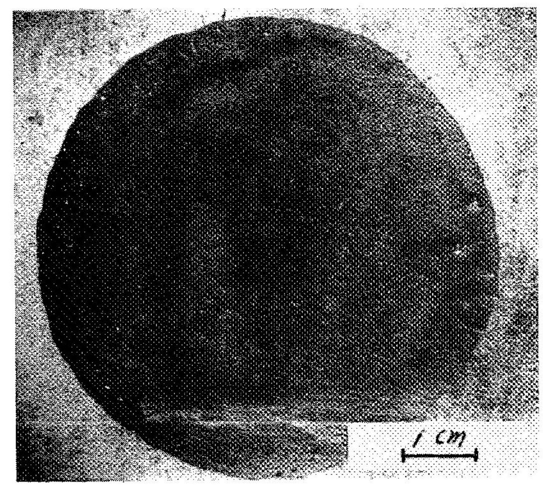
The present study revealed marked differences in the wetting patterns of XRM 177 F and MCS 293, characterized, respectively, by uniform and streaky film flow. Photographs representing the wetting patterns of the two lubricants, formed by microfog jets impinging on a test plate, are shown in Figures 17 and 18. The photographs were taken at two different stages: photomicrographs

Figure 17

UNIFORM WETTING PATTERNS FORMED BY MICROFOG JET OF XRM 109 F IMPINGING ON A METAL SURFACE AT 72°F



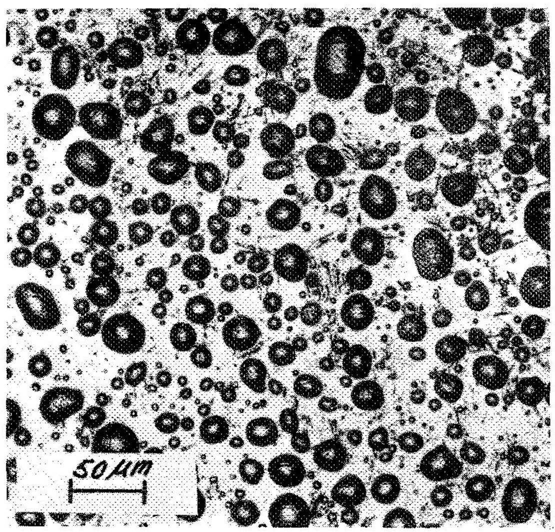
Photomicrograph of the oil droplets adhered on surface at an early stage of microfog spray (200 X)
(Spraying time: 1.5 sec.)



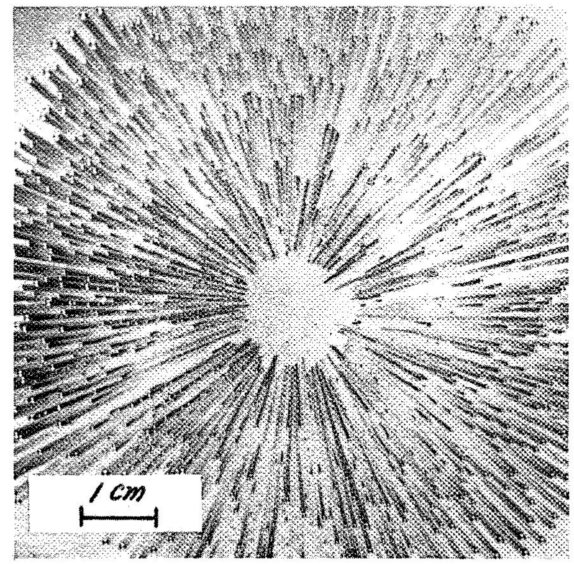
Wetting pattern of a uniform oil film
(Spraying time: 6.0 sec.)

Figure 18

STREAKY WETTING PATTERNS FORMED BY MICROFOG JET OF MCS 293 IMPINGING ON A METAL SURFACE AT 72°F



Photomicrograph of the oil droplets adhered on surface at an early stage of microfog spray (200 X)
(Spraying time: 1.5 sec.)



Wetting pattern of a streaky oil film
(Spraying time: 6.0 sec.)

(200X) were taken after the test plates were sprayed for 1.5 seconds, while the wetting patterns, or patterns of oil flow, were taken after spraying 6 seconds. Figure 17 shows the wetting pattern obtained with XRM 177 F, which illustrates formation of a uniform oil film conforming to the spreading mechanism described above. On the other hand, Figure 18 reveals that drops of MCS 293 adhering to the test plate, instead of spreading as described, remain in the spheroidal or ellipsoidal shapes suggesting that the drops do not readily spread on the plate. As spraying continues, the drops grow in size by impaction and coagulation with neighboring drops. The growing drops, however, fail to form a spreading oil film, but instead develop streaky oil flow, as shown by the photograph on the right in Figure 18. When this experiment was repeated at a plate temperature of 700°F, oil streaking was more extensive and the moving oil drops appeared to be much smaller. These contrasting wetting characteristics may quite possibly account for the markedly different performances of the two lubricants in the high temperature bearing rig studies cited earlier.

As a matter of interest, spreading of a sessile drop of MCS 293 on the test plate was visually observed at 72°F. Observation again indicates no measurable spreading of the drop within a 24-hour test period, another indication that MCS 293 does not effectively wet the CVM WB-49 test plate material. It would be interesting to determine how this lubricant spreads on other solid surfaces.

vi) Effect of Lubricant Temperature

It has been seen that the wetting characteristics of a microfog lubricant are influenced by such oil temperature dependent factors as the lubricant properties, rate of oil-mist output, and (oil/gas) mass flow ratio. To evaluate the overall effects of lubricant temperature on wetting, the gas and lubricant temperature at the microfog generator were varied ranging from 100 to 300°F. Determinations of the wetting rates for FN 2961 and XRM 109 F were made with No. 1 nozzle at plate temperatures of 600, 700, and 800°F. Wetting data, summarized in Appendix C, are shown in Figures 19 through 22, where wetting rate has been plotted against (oil/gas) mass flow ratio for different temperatures. The wetting rate data and the specific and minimum wetting rates determined from the plots are summarized in Table 7. Also included are the wetting data for the test lubricants at 200°F.

It is apparent from Figures 19 to 22, and Table 7, that for a given gas flow rate and a fixed plate temperature, as generator temperature increases, the wetting rate and minimum wetting rate increase, while specific wetting rate decreases. For example, for the case of XRM 109 F at 600°F and gas flow rate of 3 cfm, the wetting rate increases from 5.1 to 12.5 cm^2/sec, when the

Figure 19

EFFECT OF (OIL/GAS) MASS FLOW RATIO ON WETTING RATE FOR FN 2961

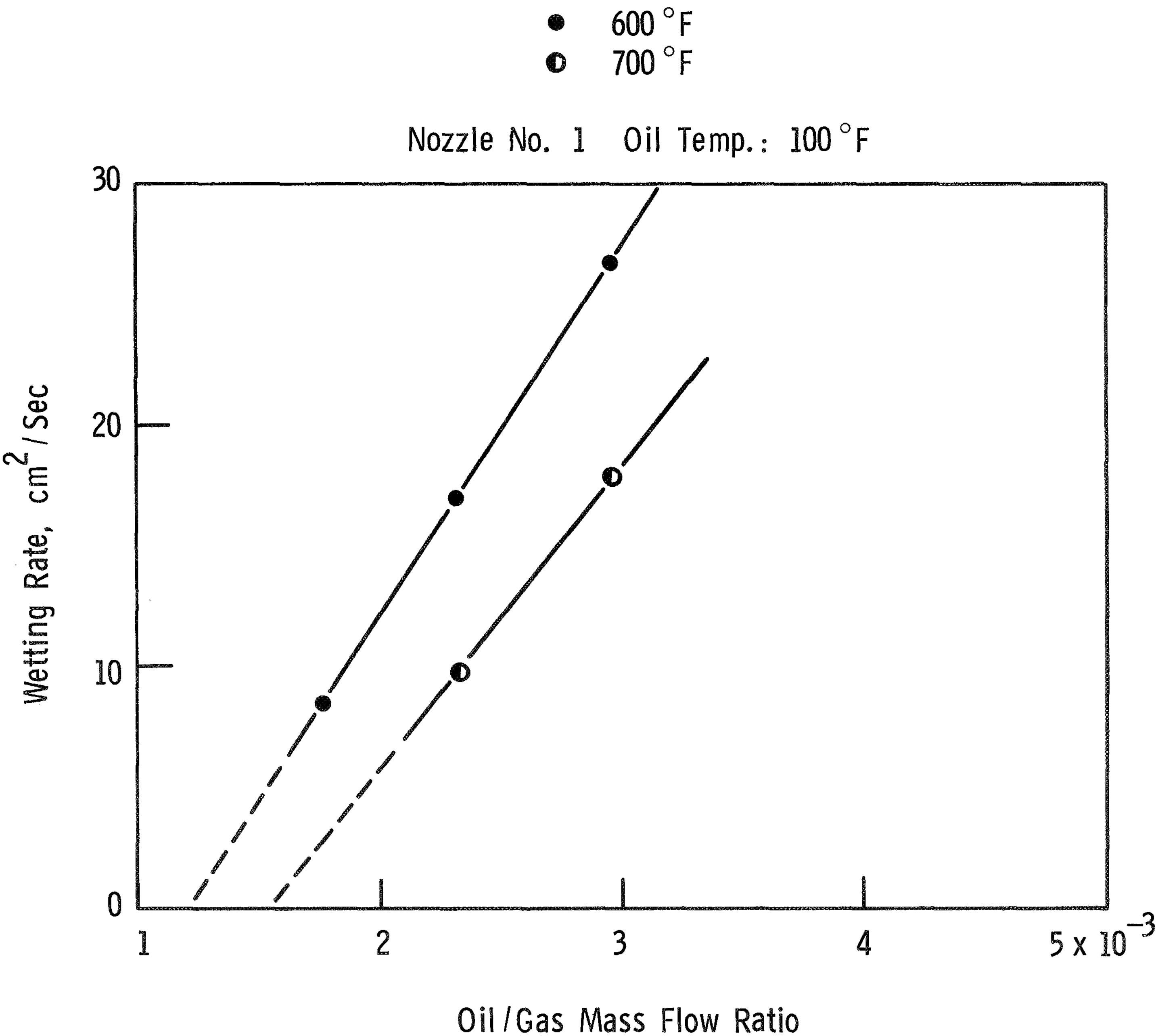


Figure 20

EFFECT OF (OIL/GAS) MASS FLOW RATIO ON WETTING RATE FOR XRM 109 F

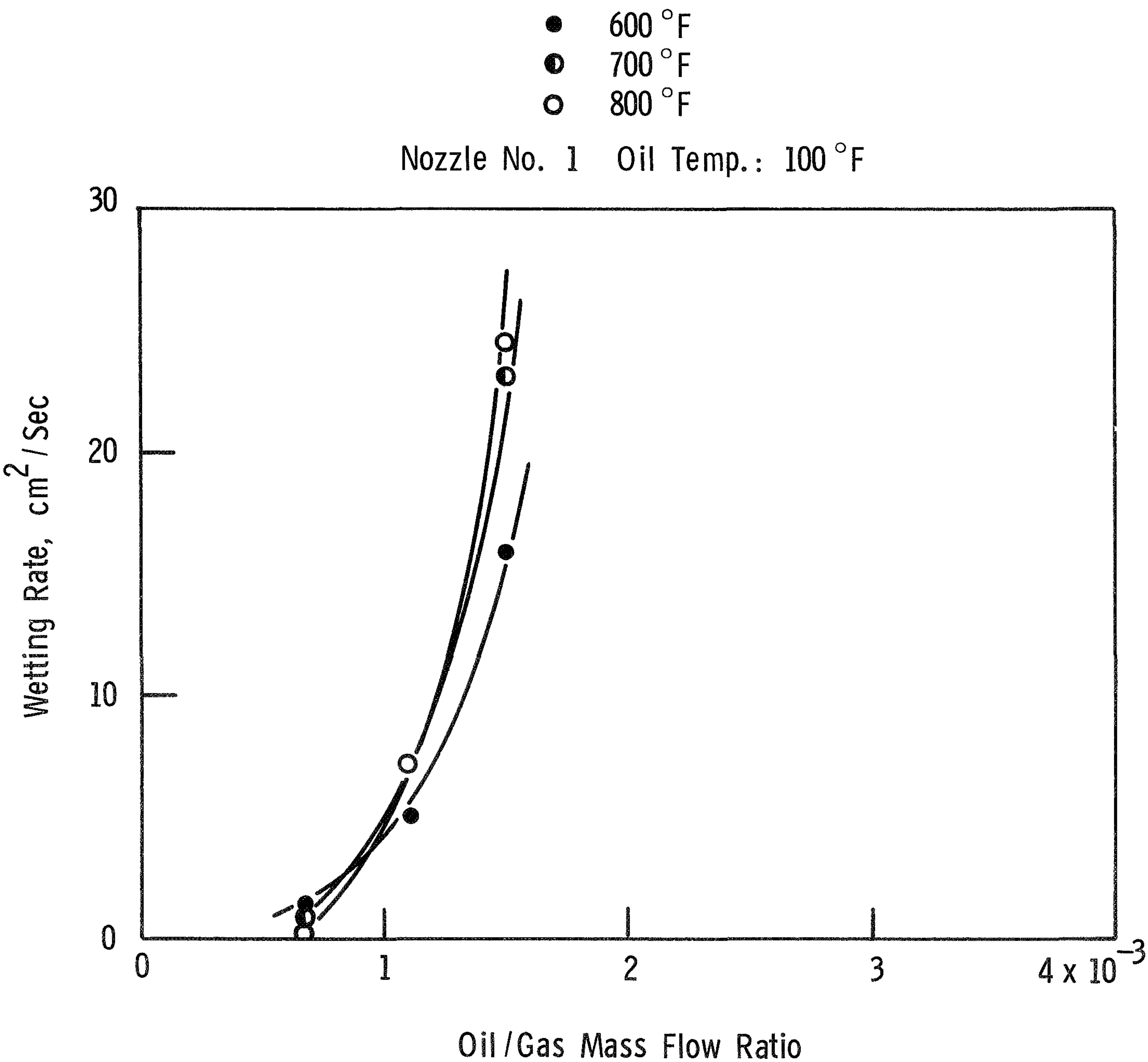


Figure 21

EFFECT OF (OIL/GAS) MASS FLOW RATIO ON WETTING RATE FOR FN 2961

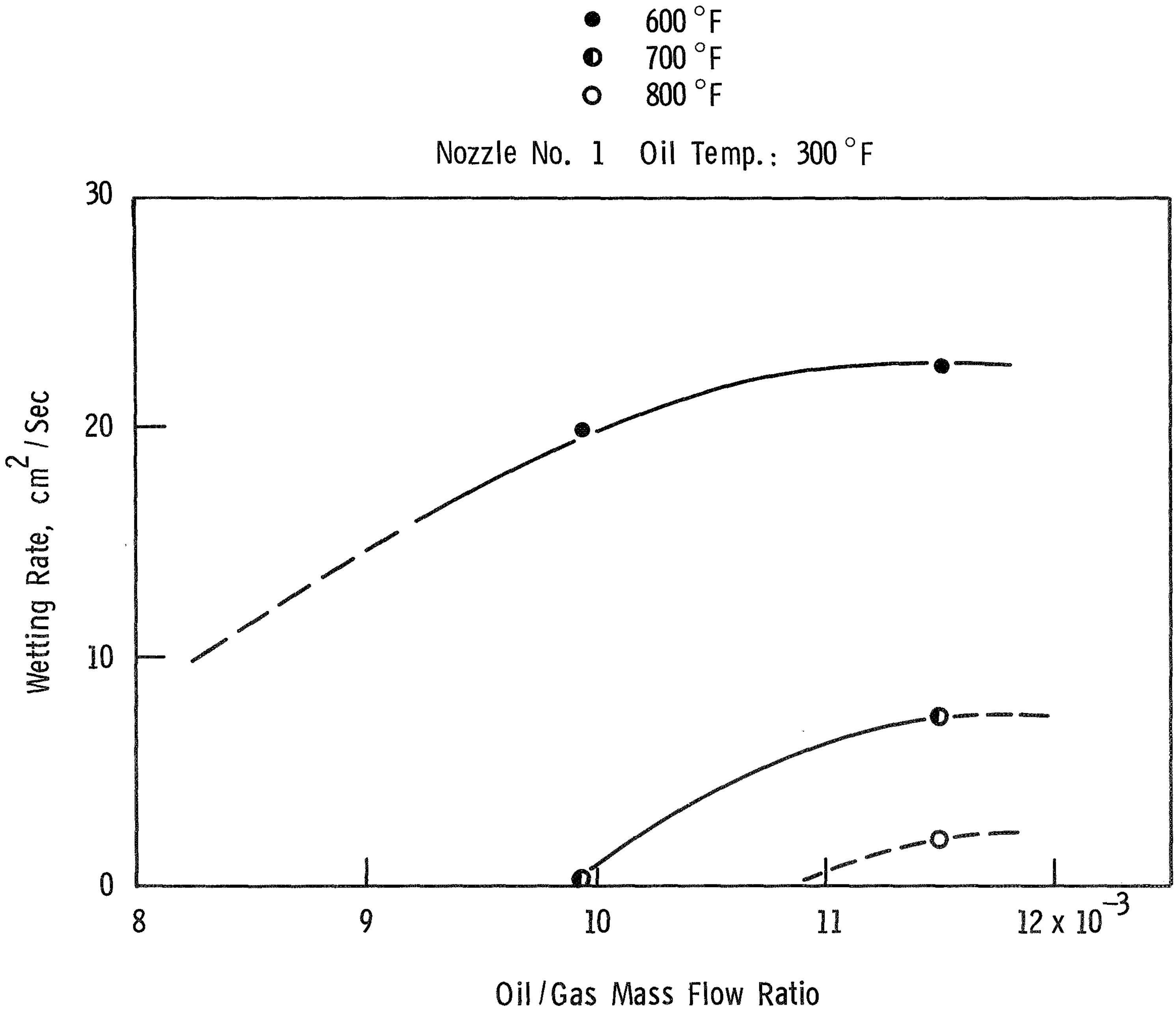


Figure 22

EFFECT OF (OIL/GAS) MASS FLOW RATIO ON WETTING RATE FOR XRM 109 F

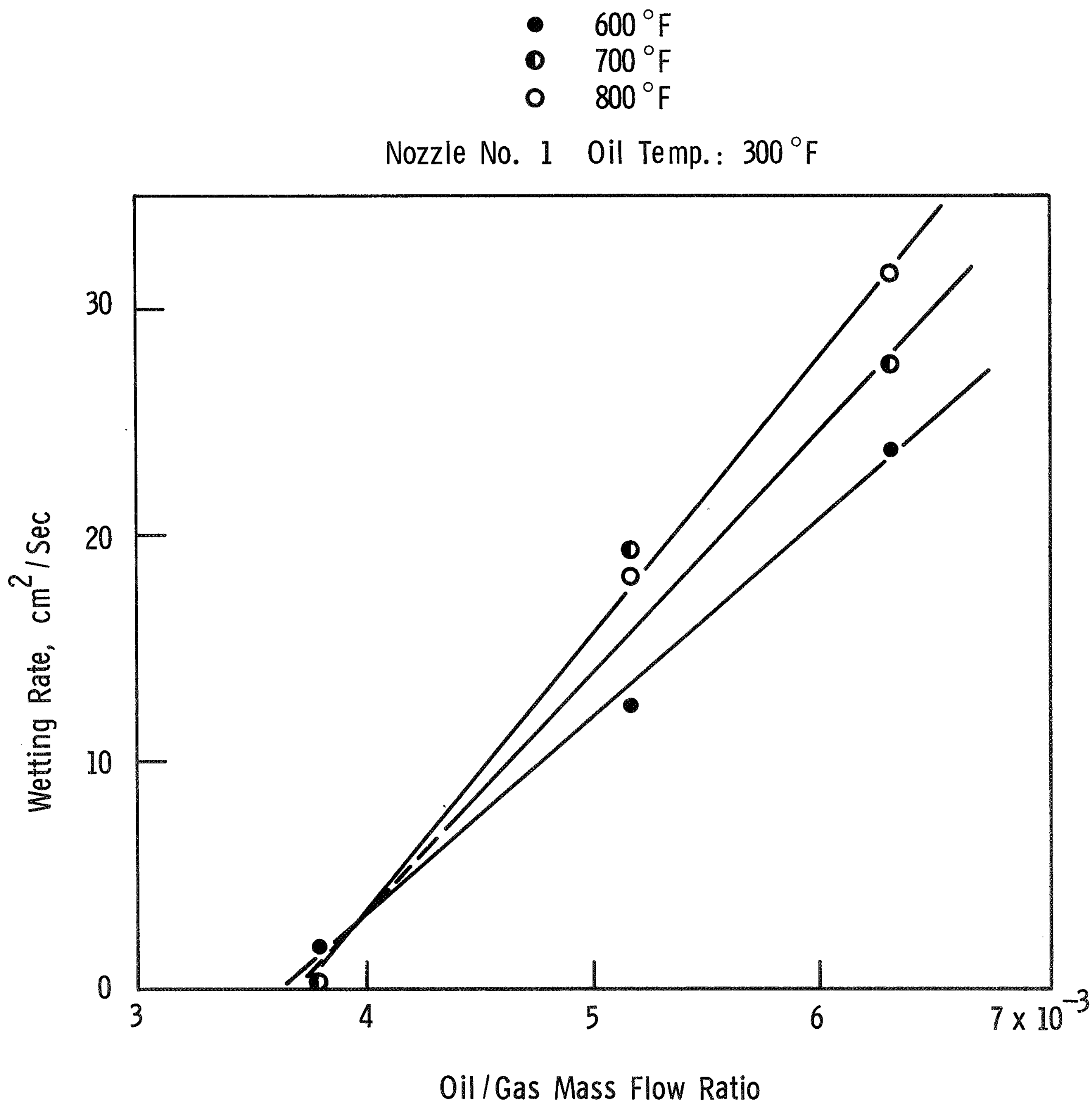


Table 7

Effect of Oil Temperature on Wettability

Test Oil	Plate Temp.	Oil Temp.	Wetting Rate, cm^2/sec			Specific Wetting Rate	Minimum Wetting Rate
	(°F)	(°F)	2 cfm	3 cfm	4 cfm	$\left[\frac{cm^2/sec/(oil/gas)\ mass}{flow\ ratio}\right] \times 10^{-3}$	$\left[(oil/gas)\ mass\ flow\ ratio\right] \times 10^{3}$
FN 2961	600	100	8.5	17.0	26.8	15.3	1.2
		200	2.6	9.6	15.0	2.6	2.4
		300	---	20.0	22.7	2.3	---
	700	100	---	9.9	17.8	12.5	1.6
		200	---	7.9	8.4	2.1	2.6
XRM 109 F	600	100	1.4	5.1	15.9	16.2	0.6
		200	2.2	11.6	19.6	11.5	2.1
		300	1.9	12.5	23.8	8.7	3.6
	700	100	1.2	7.3	23.2	26.2	0.7
		200	1.9	11.7	22.3	12.8	2.1
		300	---	19.1	27.5	10.7	3.7
	800	100	< 1	7.2	24.4	28.6	0.7
		200	1.3	11.7	23.8	13.1	2.2
		300	---	18.3	31.5	12.5	3.8

generator temperature is raised from 100 to 300°F. A similar trend can be found for 4 cfm and the other oil tested, FN 2961. At the same time the specific wetting rate, which is an arbitrary comparative term based on (oil/gas) mass flow ratio, is reduced from 16.2×10^3 to 8.7×10^3 $cm^2/sec/(oil/gas)$ mass ratio, while the minimum wetting rate increases from 0.6×10^{-3} to 3.6×10^{-3}. All these results may seem contradictory; they simply reflect, and illustrate, the difference between wetting rate and specific wetting rate. As mentioned previously, when lubricant temperature is raised, the rate of oil-mist output for a given gas flow rate is increased; hence the wetting rate, in which wetting is referred simply to time, is also increased. The increase in wetting rate is, however, lower than expected for the increase in (oil/gas) mass flow ratio; hence the specific wetting rate, which refers wetting rate to mass flow ratio, is decreased. The increase in minimum wetting rate with rising lubricant temperature is probably caused by more lubricant loss through streaking and evaporation.

Test results for FN 2961, although more erratic, indicate a similar general trend in the effects of lubricant temperature on wetting rate. Extensive streaking of the oil films at a lubricant temperature of 300°F caused analysis of the FN 2961 wetting data more difficult and less certain. This type of wetting behavior is characteristic of lighter lubricants, and is reflected in low specific and high minimum wetting rates.

From the comparison of these wetting results, it may be concluded that for a given lubricant, optimum operation of a microfog lubrication system requires that generator temperature be held as low as possible, provided that a sufficient amount of oil-mist may be generated by simply varying gas flow rate. Moreover, low gas and lubricant temperatures would offer the additional advantages of more effective heat transfer from heated solid surfaces, and less thermal stress of the lubricant.

vii) Effect of Additive

The wetting rates of four blended lubricants were determined at 700°F with No. 1 nozzle and a gas flow rate of 3 cfm, in order to investigate additive effects on microfog lubrication. The blended lubricants consisted of Krytox 143 AC containing 5% (by wt.) duPont additive No. 9530-49, MCS 2931, XRM 109 F plus 10% (by wt.) Kendall super-refined paraffinic resin (20,000 SUS), and XRM 210 A. The various additives have several different functions which are summarized in Table 1. None were intended primarily to improve performance of the lubricants for microfog lubrication, and this portion of the program seeks only to determine generally whether the various types of additives which may be encountered in advanced lubricants might affect microfog lubrication.

Wetting data of the four blended lubricants and their base lubricants are summarized in Table 8, which also includes data for XRM 177 F at 3 and 4 cfm taken from our earlier study (2). Comparison of test results for Items 1, 2, 3, 4, 11, and 12 indicates that presence of the additives used in Krytox 143 AC, MCS 293, and XRM 209 A has little effect on wetting rate. The presence of a wetting agent which distinguishes MCS 2931 from MCS 293, does not alter the wetting pattern of MCS 293, which remains streaky as shown in Figure 18.

Of particular interest are the additives in XRM 109 F. Examination of the wetting data in Items 5 through 10 of Table 8 shows that the additives--an antiwear agent, and a Kendall paraffinic resin--markedly increase the wetting rates of XRM 109 F at 700°F. It has also been reported that the additives improve lubricating performance in a full scale bearing high temperature test (6). The exact cause of the improved performance imparted by these additives in XRM 109 F has not been established. In the case of XRM 177 F, a proprietary antiwear agent is known to improve high temperature lubrication, particularly boundary lubrication. Improvement of boundary lubrication generally involves surface activity, which may also be the cause of improved wetting. Improved wetting may, in turn, enhance high temperature lubrication through its influence on film characteristics as discussed earlier under wetting patterns.

The nature of the effects of the Kendall paraffinic resin in XRM 109 F on wetting and on high temperature lubrication is even less apparent. The sharp increase in oil-mist output when the resin is present, which was discussed earlier, may account for much, if not all, of the increase in wetting rate. This could not, however, account for the enhanced high temperature lubrication in the bearing test program cited, which employed conventional rather than mist lubrication. A careful review of the physical properties of the resin reveals no obvious connection between these properties and the effect of the resin on wetting rate. It may be, therefore, worthwhile to vary the concentrations of minor constituents of the resin, such as sulfur and nitrogen, to determine whether these may account for the effects of the resin on wetting rate, either as wetting additive or misting agent. It would also be of interest to try out lighter fractions of Kendall super-refined paraffinic resins.

viii) <u>Effect of Plate Surface</u>

Our earlier studies indicated that any surface oxides and oil degradation products that might be formed on the test plate in the short duration of exposure to air, had little influence on the wetting rates of XRM 177 F at 600°F. To further investigate the effects of surface conditions on wettability, a series of test runs was made with four different surface conditions as follows:

Table 8

EFFECT OF VARIOUS ADDITIVES ON WETTING RATE

Item	Run No.	Test Oil	Plate Temp. (°F)	Gas Flow Rate cfm @ 45 psig & 200°F	Rate of Oil-Mist Output (cc/min)	Wetting Time, sec. 1"	1 1/4"	1 1/2"	1 3/4"	2"	Wetting Rate (Cm^2/sec)
1	K 1-8	Krytox 143AC	700	3	1.1	0.31	0.47	0.88	1.44	2.00	8.6
2	K 3-1	Krytox 143AC+ 5% duPont 9530 -49	700	3	1.1	0.20	0.47	0.88	1.40	1.92	8.6
3	MCS 1-4	MCS 293	700	3	1.8	0.16	---	0.50	streaky	flow	---
4	MCS 2-1	MCS 2931	700	3	1.8	0.14	0.17	0.22	streaks		---
5	XRM 6-2	XRM 109F	700	3	1.2	0.20	0.39	0.63	1.05	1.51	11.7
6	M 34-3	XRM 177F	700	3	1.1	0.28	0.56	0.66	---	1.35	16.6
7	XK 1-1	XRM 109F+10% Kendall Resin	700	3	1.5	0.09	0.17	0.32	0.60	0.89	19.1
8	XRM 6-1	XRM 109F	700	4	2.0	0.14	0.25	0.33	0.59	0.83	22.3
9	M 32-3	XRM 177F	700	4	1.7	---	0.30	0.42	0.53	0.75	27.0
10	XK 1-2	XRM 109F+10% Kendall Resin	700	4	2.4	---	0.09	0.19	0.31	0.47	36.0
11	XRM 17-4	XRM 209A	700	3	2.4	0.22	0.37	0.66	1.00	1.25	13.5
12	MCS 2-5	XRM 210A	700	3	2.4	0.22	0.37	0.59	0.76	1.12	16.6

Test Conditions - Oil Temp: 200°F

Nozzle: No. 1 (0.171" dia.)

- 2 μ in. (RMS) surface roughness
- 40 μ in. (RMS) surface roughness
- Black oxide deposit for coating
- Coating of oil decomposition products

Test plate surfaces were finished circumferentially ground to the indicated roughnesses, which were determined by using a Brush surface indicator, and the measurements were averaged over an entire test plate by applying the following expression:

$$\langle \bar{\varepsilon} \rangle = \frac{1}{\pi R_o^2} \int_o^{R_o} 2\pi R \quad \bar{\varepsilon}(R)\, dR \qquad (3)$$

where $\bar{\varepsilon}(R) = \sqrt{\dfrac{\sum_{i=1}^{N} \varepsilon^2(R)}{N}}$

Black oxide coating was applied to the test specimens by a proprietary alkaline oxidizing mixture (usually a mixture of sodium hydroxide and sodium nitrate, nitrites, and chromates, with certain trace chemicals) to provide a coating of magnetic Fe_2O_3 in conformance with Military Specification MIL-C-13924, Class I.

Products of oil decomposition were deposited on a test plate, cleaned as specified in the contract, by preheating the plate and test lubricant to 350°F, spreading the lubricant uniformly over the plate, and then baking it in an oven at 650°F for 30 minutes. The process was repeated until a uniform deposit formed on the plate.

Using these plates prepared as described above, the wetting rates of XRM 109 F at 600 and 700°F, and of FN 2961 at 700°F were determined with No. 1 nozzle at a gas flow rate of 3 cfm. Wetting data, summarized in Appendix D, are presented in Figures 23, 24, and 25. A summary of the wetting rate data on different surfaces is also shown in Figure 26. Test results from these Figures indicate that the nature of plate surfaces has a profound influence on wettability. In particular, Figure 26 clearly demonstrates that the wetting rates of FN 2961 and XRM 109 F are decreased by increasing surface roughness and by the presence of black oxide coating on the test plate, while the rates are unaffected by deposits of lubricant decomposition products on the plate.

Figure 23

EFFECT OF PLATE SURFACES ON WETTABILITY OF XRM 109 F AT 600°F

□ 2 μin Roughness
-○- 6 μin Roughness
△ 40 μin Roughness
● Black Oxide Coating
○ Deposit of Decomposition Products

Mass Flow Ratio: 3.06×10^{-3}
Impaction Velocity: 236 ft/sec

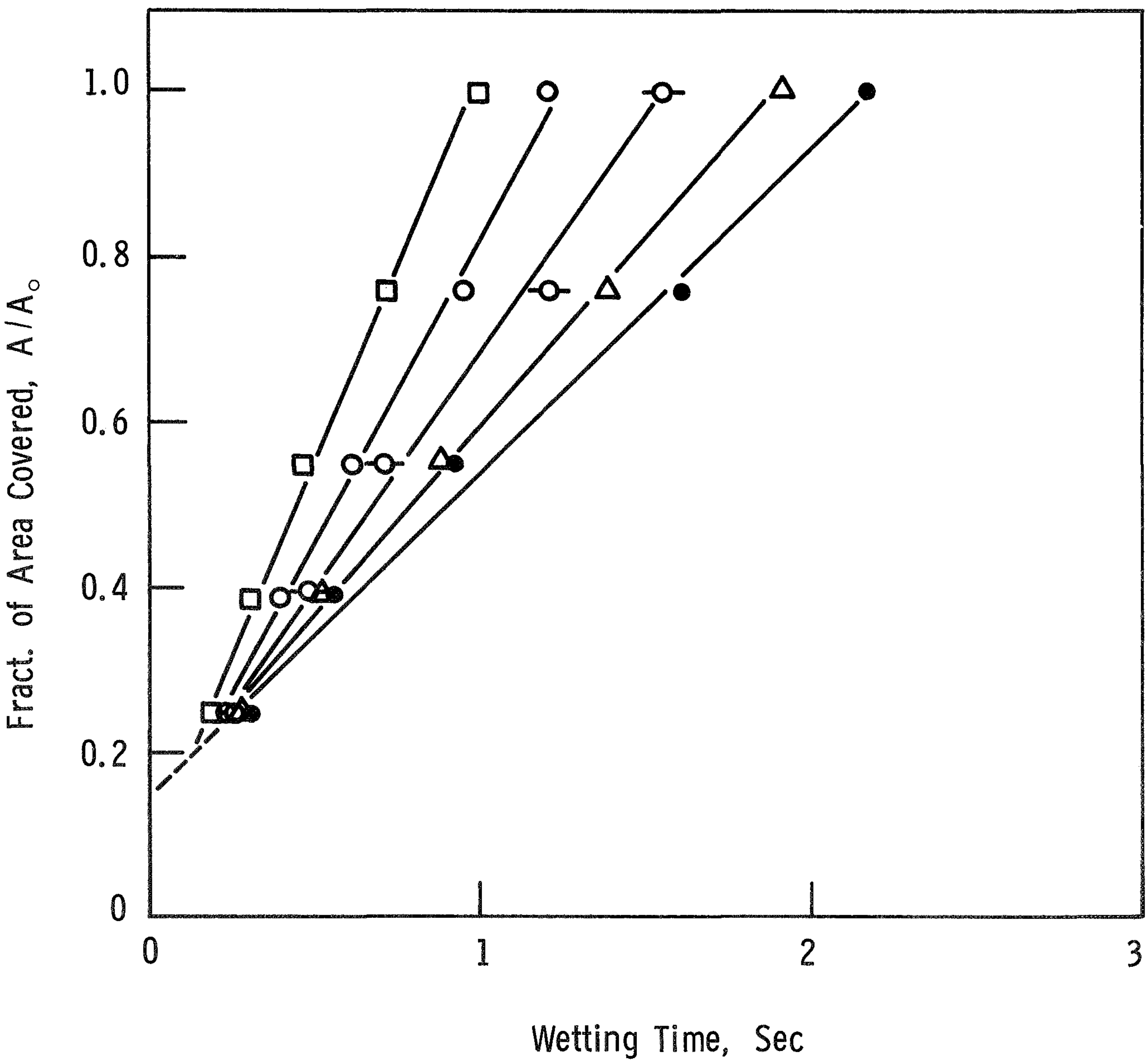


Figure 24

EFFECT OF PLATE SURFACES ON WETTABILITY OF XRM 109 F AT 700°F

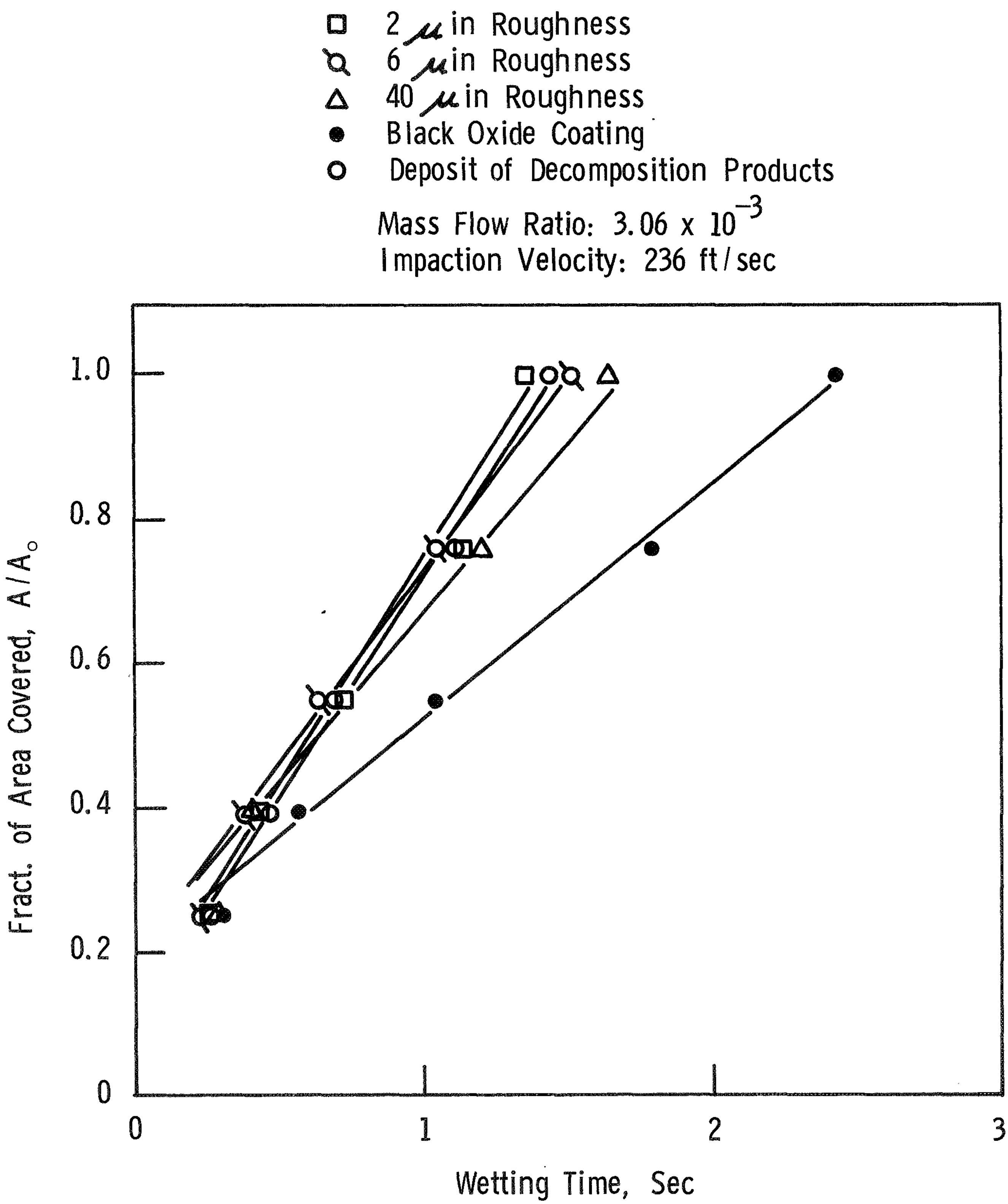


Figure 25

EFFECT OF PLATE SURFACES ON WETTABILITY OF FN 2961 AT 700°F

- □ 2 μin Roughness
- -○- 6 μin Roughness
- △ 40 μin Roughness
- ● Black Oxide Coating
- ○ Deposit of Decomposition Products

Mass Flow Ratio: 5.55×10^{-3}
Impaction Velocity: 236 ft/sec

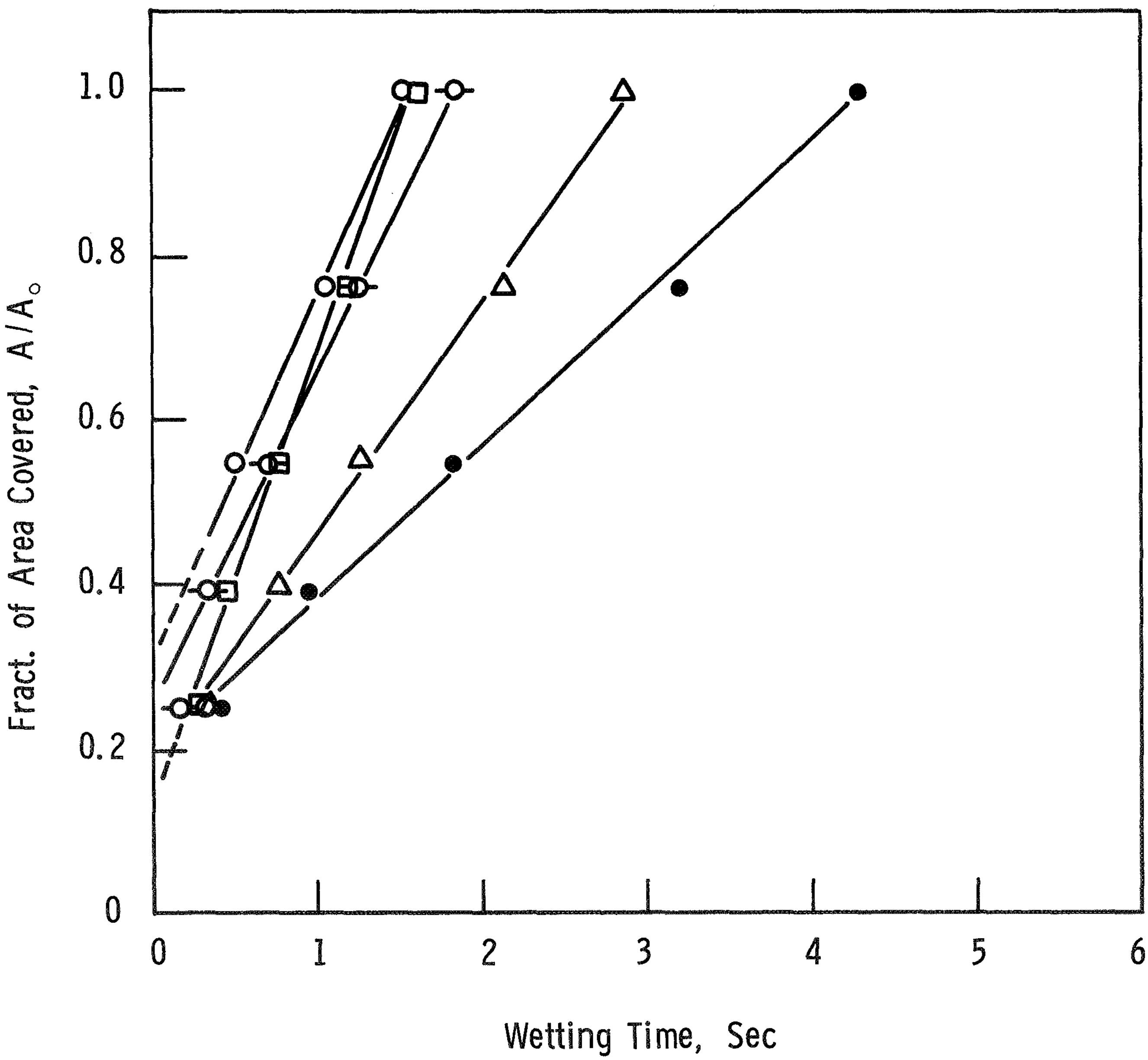
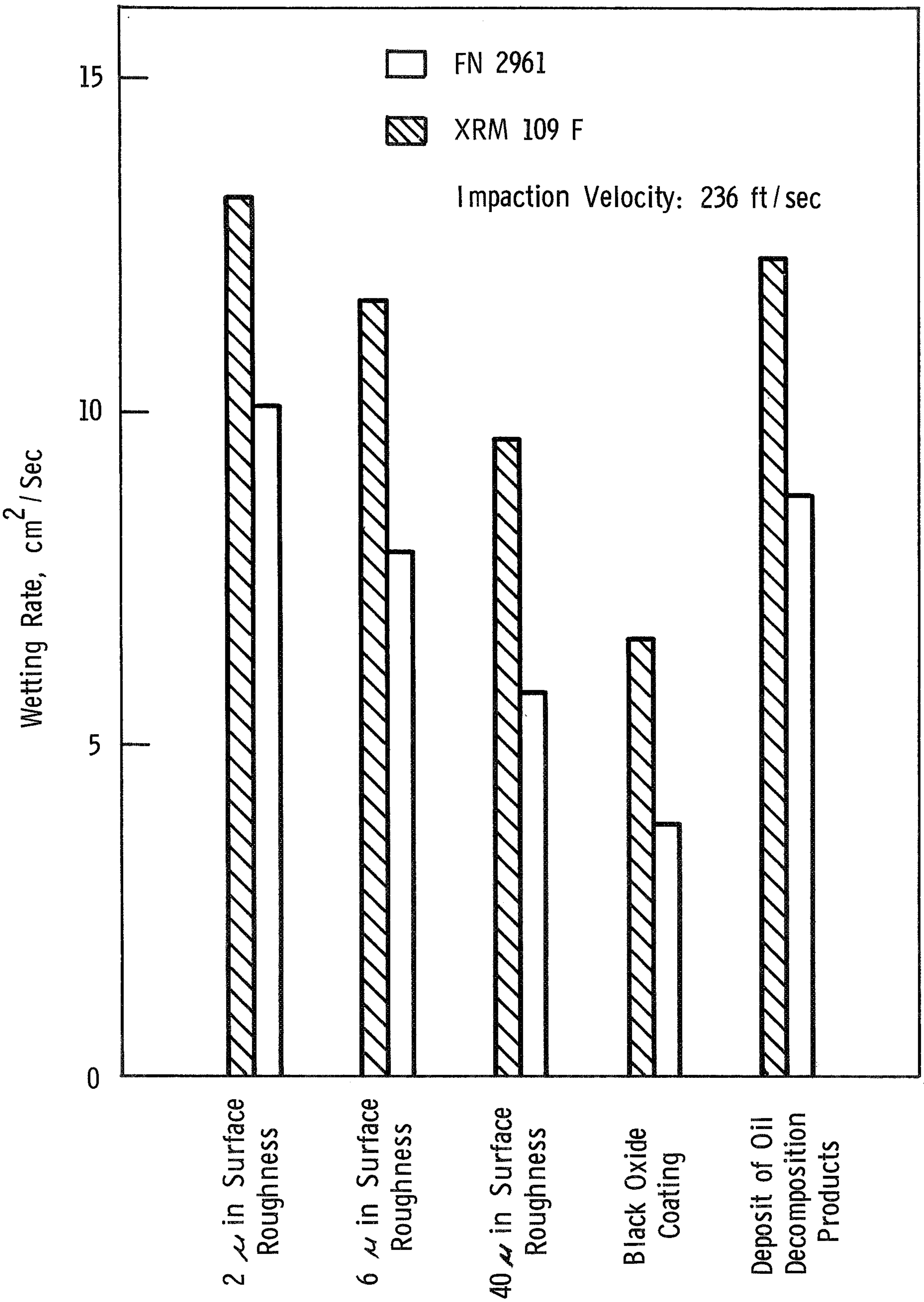


Figure 26

EFFECT OF PLATE SURFACES ON WETTING RATE AT 700°F



Before discussing the wetting data, it is of interest to clarify the conceptual difference between spreading (or wetting) and flow, although we have not in discussion thus far distinguished between the two transport processes at the interface between liquid and solid. Spreading occurs at the interface only whereas flow assumes the liquid layer adjacent to the solid to be stagnant. The mechanics and physical variables which control the processes are also different--the driving force is supplied externally for viscous flow while the spreading force is intrinsic. Hence, the surface properties are dominant in spreading but become unimportant in flow.

Keeping this difference in mind, it is of interest to determine whether our study deals, in fact, with spreading or merely with flow, and if spreading is involved, to what extent the surface properties, such as surface roughness and modifications of plate surface, influence the wetting rates of two chemically different lubricants, FN 2961 (naphthenic oil) and XRM 109 F (paraffinic oil). As mentioned above, the test results indicate that the micro scratches left by circumferential grinding - i.e., scratches perpendicular to the oil film spreading - reduce spreading rates. This reduction of spreading rates with increasing surface roughness, which is contrary to Poiseuill's law for the flow of Newtonian liquid through cylindrical tubes, suggests that the present study involves spreading phenomena rather than flow. For the Poiseuill's flow the dimensionless pressure drop is independent of the surface roughness, but dependent upon Reynolds number, and is given by

$$\frac{\Delta P}{\frac{\rho U^2}{2}} = 64 \frac{L}{D} \left(\frac{\nu}{DU} \right) = \frac{64}{N_{Re}} \left(\frac{L}{D} \right) \qquad (4)$$

The apparent dominance of spreading over flow phenomena in this study is unexpected considering that for a thin liquid film flow induced by a high speed gas stream, surface roughness should have little effect on wettability since the surface forces of the liquid film at the liquid-solid interface would become negligible in comparison with the hydrodynamic forces at the gas-liquid interface. Nevertheless, the experimental results indicate that the spreading forces at the plate surface are still a dominant factor for this study.

In considering the wetting properties of solid surfaces, as is shown above, wetting rates for a given lubricant would be expected to be greatly affected by the surface energy of the solid with which the lubricant is in contact. It is also well known (7) that lubricants, because of their comparatively low specific surface free energies, spread freely on solids of high surface energy, since there would result a large decrease in the surface free energy of the system. On solids of low surface free energies comparable to those of lubricants, however, the lubricants should exhibit non-spreading characteristics.

The investigation of surface composition effects on wettability utilized two different surface coatings--one comprised of black oxide and the other of oxidative lubricant degradation products. These are presumed to have, respectively, a high and a low specific surface free energy. The wetting rate data for XRM 109 F and FN 2961, shown in Figure 26, reveal that the black oxide coating greatly reduces the wetting rates of the test lubricants, while deposits from lubricant decomposition have little effect. In addition, careful review of the movie films reveals that thin lubricant films advancing on a black oxide surface seem to have somewhat high contact angles.

Since metal oxides generally increase the specific surface free energies of solids, one would expect a lubricant to spread more freely on an oxide surface than on the free metal. To examine this theory, the spreading time of XRM 109 F was determined at 75°F by photographically following the enlargement of the interfacial contact area after carefully introducing a sessile drop (equivolume) onto either a test plate with a black oxide surface or one with the surface free of oxide. The interfacial contact areas measured at three different stages are:

Time (hr)	Diameter of Wetted Area, mm	
	Non-oxide	Black oxide
0	5.5	6.0
4	9.0	13.0
22	11.0	20.0

The data obtained from this crude experiment seem to confirm the theoretical analysis discussed above, which predicted faster spreading of XRM 109 F on the oxide surface than on the free metal. Nevertheless, contrary to both theory and the results of this simple experiment, comparison of the wetting rates of XRM 109 F on the black oxide surface and the free metal (both at 6 μ in surface roughness) clearly indicates that the black oxide surface increases the friction coefficient of spreading at 600 and 700°F, which in turn increases spreading time. A similar conclusion can be drawn when the wetting rates of FN 2961 at 700°F are compared. These contradictory results are presently unexplained. Possibly, at high plate temperature, surface-chemical changes of the black oxide may alter the surface properties in such a way as to impede free spread of the lubricant. This qualitative reasoning has not been verified experimentally.

In discussing the effects of plate surface, one must consider another common case in which the surface is covered with the chemical reaction products of the lubricant. When the temperature becomes high, lubricants often undergo chemical changes, such as thermal decomposition, oxidation, or hydrolysis, to form undesirable products. The reaction products in the lubricants may be highly adsorbable and may cause the formation of new low-energy surface films on which the lubricants may not readily spread. It is, therefore, of interest to determine whether the new low-energy surfaces formed by lubricant degradation products have any effect on wetting rate. Figures 23 through 26 show that the new surfaces prepared as previously described have no influence on the wetting rates of FN 2961 and XRM 109 F at 700°F. Thus, deposits from lubricant oxidative degradation neither enhance nor hinder the wettabilities of the two lubricants. In practice, such as bearing operations, there is some evidence that such deposits of lubricant decomposition products actually prevent metal fatigue.

Another interesting point to note from these wetting data is that chemical differences between naphthenic lubricant FN 2961 and paraffinic XRM 109 F have little apparent effect on wettability regardless of the surface conditions of test plates.

Finally, review of these wetting data indicates a need for a better understanding of the hydrodynamics of the spreading of thin oil films on solids, which would be consistent with the Navier-Stokes equation of motion. Moreover, techniques must be developed to provide first-hand information on the metallurgical changes and chemical nature of surfaces, particularly on the interface thermodynamic properties at elevated temperatures. Until then, many questions remain unanswered.

IV. NOTATIONS

A : surface area of test plate

A_o : total surface area of test plate

a : constant in Equation (2)

b : constant in Equation

c : constant in Equation

d : constant in Equation

D : diameter of pipe

K : geometric constant for microfog generator

L : length of transfer path

N : total number of test measurement

N_{Re} : Reynolds number = (UL/ν)

P : pressure

Q_g : volumetric gas flow rate

R : radius

R_o : radius of total area

U : velocity

W : rate of oil-mist output

Greek Letters

Δ : denoting a small increment

ε : area-mean surface roughness of test plate

μ : dynamic viscosity

ν : kinematic viscosity

π : 3.14

ρ : density

σ : surface tension

V. REFERENCES

1. Shim, J. and S. J. Leonardi; "Microfog Lubricant Application System for Advanced Turbine Engine Components", Task I Report, NASA CR-72291 Sept. (1967).

2. Shim, J. and S. J. Leonardi; "Microfog Lubricant Application System for Advanced Turbine Engine Components", Final Report NASA CR-72489 Sept. (1968).

3. Henrikson, K. G.; Lubrication Engineering, Feb. (1969), pp. 69-74.

4. Bamberger, E. N., E. V. Zaretsky, and W. J. Anderson; J. of Lubrication Technology, Trans ASME, Series F, Jan. (1970), pp. 23-32.

5. Loomis, W. R., D. P. Townsend, and R. L. Johnson; "Lubricants for Inerted Lubrication Systems in Engines for Advanced Aircraft", SAE paper 680317 presented at Air Transport Meeting, New York, April (1968).

6. Rhoads, W. L.; "Supersonic Transport Lubrication Systems Investigation" NASA CR-73496, Dec. (1968).

7. Fox, H. W. and W. A. Zisman, J. Colloid Sci., 5, 514 (1950).

VI. APPENDICES

APPENDIX A

STATEMENT OF WORK

APPENDIX A

Statement of Work
Contract NAS3-13207

I. SCOPE OF WORK

The Contractor shall furnish the necessary personnel, facilities, services, and materials (except the Government Furnished Property as specified in Article XIV) and otherwise do all things necessary for, or incident to, the work described below:

A. Task I - Mist Generator Tests

The Contractor shall investigate the wettability of five test lubricants under a range of ambient conditions and in a manner as prescribed in this task.

1. Test Lubricants

The following five lubricants shall be used in this investigation:

a. Dupont Krytox 143 AC perfluorinated fluid (non-formulated).

b. Monsanto MCS-293 modified polyphenyl ether.

c. Mobil XRM-109F synthetic paraffinic hydrocarbon.

d. Mobil XRM-209A, pentaerythritol ester.

e. Humble FN-2961 super refined (deep-dewaxed) naphthenic mineral oil (base for Humble FN-3158).

Substitution of items in this list shall be made if recommended by the Contractor and approved by the NASA Project Managers.

2. Test Rig and Instrumentation

The Contractor shall provide the microfog lubricant applicator test rig, test specimens, and instrumentation that were designed, fabricated, and used under NASA Contract NAS3-9400. This equipment is described in Task I of Appendix I, Statement of Work, and subsequent amendments of that contract.

3. Test Procedure and Conditions

The Contractor shall perform a series of wettability tests using each of the five test lubricants listed in Task I, paragraph A.1 under each set of standard test conditions. These standard test conditions are as listed below and shall be used throughout this contract unless otherwise specified.

a. Standard Test Conditions

(1) Oil and gas temperatures in generator: 200 (± 10) °F.

(2) Test specimen temperature: 600, 700, and 800 (± 10) °F.

(3) Nitrogen flow rate: 2, 3, and 4 cfm (at 45 psig and 200°F).

(4) Spray nozzle: converging type, orifice diameter of 0.171 in. and 0.281 in.

(5) Spray distance between nozzle and test plate: 1 inch.

(6) Test chamber pressure: 45 (± 5) psig.

(7) Test specimen: 2 (± 1/2) in. x 2 (± 1/2) in. x 1/4 (± 1/16) in. made of hardened CVM WB-49 material and finished circumferentially ground to 4 to 8 μ in. RMS.

b. Wettability shall be determined using the photographic technique developed in Contract NAS3-9400.

c. Prior to the start of each run, the test chamber and specimen shall be brought to the required temperature. A stream of pure nitrogen, at the same rate as the nitrogen stream to be introduced from the microfog generator, shall then be sprayed through the nozzle. The run shall be started by switching to the nitrogen stream carrying fog from the microfog generator when the specimen temperature has recovered to the control temperature, and the nozzle temperature has reached equilibrium.

d. All lubricants shall be degassed for a 72 hour period immediately before running by means of a mechanical vacuum pump capable of maintaining a pressure of 10^{-3} mm Hg, while vibrating the fluid. The test chamber shall be pumped down with a mechanical pump prior to a run and then purged with nitrogen during the run.

e. Test Runs

(1) Metal test specimens shall be cleaned before each test in the following manner:

(a) Rinsed with acetone.

(b) Scrubbed with moist levigated alumina and a soft polishing cloth.

(c) Thoroughly rinsed with tap water.

(d) Rinsed briefly with distilled water.

(e) Rinsed with ethyl alcohol.

(2) A run shall consist of operating the generator with a test lubricant under a set of conditions while impinging the mist on the specimen. After reaching equilibrium conditions of pressure, temperature, and flow, the wettability shall be recorded by measuring the time required to cover the entire metal specimen with a complete film of oil. Similarly, the particle size and velocity shall be determined under the identical conditions. A minimum of 90 runs shall be made to include all test conditions in Task I.

B. Task II - Optimization of Microfog Lubrication

The Contractor shall investigate the effects of various factors on wetting rate in microfog lubrication. These shall include the effect of gas and oil temperature on wettability, modification oil properties by additives, and the effect of test plate surface condition. Two reference test fluids common to both the Task I and Task II shall be selected, one of which will be Mobil XRM-109F synthetic paraffinic hydrocarbon. Selection of the second fluid by the Contractor shall be subject to approval by the NASA Project Manager. One spray nozzle, selected by the Contractor and approved by the NASA Project Manager, shall be used in this task. The test procedure and equipment of Task I shall be used.

1. Effect of Gas and Generator Temperature

   The Contractor shall perform two series of wettability tests under the standard test conditions as listed in Task I, paragraph C, with the exception that the gas and generator temperature shall be 100 and 300 ($\pm$ 10)°F. A minimum of 36 runs shall be made to include all these conditions.

2. Effect of Additives

   The Contractor shall perform a series of wettability tests under the standard test conditions as listed in Task I, paragraph 3, with the following exceptions:

   a. Test plate temperature shall be held at 700 ($\pm$ 10)°F only.

   b. Nitrogen flow rate shall be held at 3 cfm only.

   c. Four blended fluids shall be tested. The blended fluids shall consist of: (1) Mobil XRM-109F plus 10 weight percent of Kendall paraffinic resin (20,000 SUS), (2) Mobil XRM-210A, formulated pentaerythritol ester, (3) Monsanto MCS-2931 and (4) DuPont additive No. 9530-49. Substitution of any of these fluids shall be made if recommended by the Contractor and approved by the NASA Project Manager. A minimum of 4 runs shall be made to include all these conditions.

3. Effect of Test Plate Surface

   The Contractor shall perform a series of wettability tests using two fluids (XRM-109F and another fluid common to Task I and Task II selected by the Contractor and approved by the NASA Project Manager) with varying surface roughnesses of test plate under the standard test conditions as described in Task I, paragraph 3 except that the test plate temperature shall be held at 700 ($\pm$ 10) °F and the nitrogen flow rate held at 3 cfm during all the runs. The surface roughnesses of test plate shall include two finish types (i.e., honed and lapped) and two coating types (i.e., black oxide and fluid decomposition product). A minimum of 8 runs shall be made to include all these conditions.

C. Task III - Wettability of Lubricants on a Rotating Disk

The Contractor shall investigate the stability of a thin oil film on a heated rotating metal disk and its effect on wettability.

1. Test Chamber

The Contractor shall design and fabricate a test chamber with a rotating, flat disk or test specimen. Test chamber design shall be approved by the NASA Project Manager prior to its fabrication. The disk shall be 4 inches in diameter, made of CVM WB-49 tool steel circumferentially ground to 4 ~ 8 μ inches RMS, and shall be capable of variable rotative speeds up to 5,000 rpm and higher as limited by the power requirement for a driving motor. The disk shall be mounted in a vertical position in the test chamber with a flat side facing the spray nozzle, positioned at a right angle to the disk surface and at one inch from that surface. The chamber shall be a thermostatically and pressure controlled oven for simulation of pressures up to 80 psia and temperatures up to 1000°F. The chamber shall have an observation port through which visual and photographic observations of the test specimen can be made. A heater mounted closely behind the rotating disk shall be capable of maintaining the required temperature during operation. The disk shall also be equipped with a thermal flux transducer by which the rate of heat transfer through the disk can be measured during operation. A dropwise oil feed system shall be provided as well as the microfog spray system.

2. Film Formation and Wettability Tests on a Rotating Disk

The Contractor shall perform two series of wettability tests under the standard conditions as described in Task I, Section 3, using the test chamber and test disk described in Section A of this Task. One spray nozzle, selected by the Contractor and approved by the NASA Project Manager, shall be used in this Task. In one series the dropwise oil feed system shall be used and in the other the microfog spray system. The oil feed shall be located at a one inch horizontal distance from the disk surface and directed normal to that surface. The oil feed shall be directed at a radial distance of one-half inch to one inch from the center of the disk as recommended by the Contractor and approved by the NASA Project Manager. Two reference test fluids, the same as tested in Task II, shall be used in both series of tests. These tests shall be conducted while the test disk is under static condition and at two different speeds up to 5,000 rpm or higher as recommended by the Contractor and approved by the NASA Project Manager. A minimum of 108 runs shall be made to include all these conditions.

D. Task IV - Surface Cooling Studies

Using the microfog lubricant applicator test rig specified in Task III, the Contractor shall measure the cooling effect of oil-fog sprays on the heated rotating disk for four different oils or formulations. The disk shall be maintained at the required temperature while spraying each of four test fluids on the disk. After reaching steady state conditions of temperature, pressure, and flow, the rate of heat transfer through the disk shall be measured by using a thermal flux transducer in conjunction with a recording potentiometer. Test conditions shall be used as defined in Task III, Section 2, except that the dropwise feed system shall not be used, with two blended fluids. The blended fluids shall consist of: (1) Mobil XRM-109 F synthetic paraffinic hydrocarbon plus 10 weight percent of Mobil XRM-126A fluid. A minimum of 108 runs shall be made to include all these conditions.

E. Task V - Evaluation of a Novel Reclassifying Nozzle and a Mist Generator

Using the test equipment and test conditions as specified in Task III for the microfog feed system, the Contractor shall perform a series of wettability tests with one reference base fluid and one rotative speed to be selected by the Contractor and approved by the NASA Project Manager, with the novel reclassifiers and flight weight-mist generator as described in the following sections.

1. Tests shall be made with two new reclassifier nozzles in conjunction with the microfog generator supplied in Task I. The Government will provide one of these nozzles, and the Contractor shall design and fabricate the second nozzle which shall be capable of delivering a secondary gas stream to the test specimen, in addition to a primary microfog stream from the generator. Nozzle design shall be approved by the NASA Project Manager prior to its fabrication. A minimum of 18 runs shall be made to include all these conditions.

2. Two series of wettability tests shall be made with a new flight weight mist generator to be supplied by NASA. In one series, one conventional nozzle from Task I shall be used selected by the Contractor and approved by the NASA Project Manager, and in the other series the new reclassifier nozzles specified in Section A of this task shall be used. A minimum of 18 runs shall be made to include all these conditions.

F. Special Calibration and Data Requirements

1. Specific Data to be Reported

As a part of the data to be reported under Article VII - REPORTS OF WORK, of this contract, the Contractor shall specifically include the following data:

a. Average drop particles size (microns) and size range for each condition of nozzle operation.

b. Wettability of fluid on metal test specimen as a function of particle size, gas velocity, metal temperature and other parameters as can be determined from the data such as vapor pressure, viscosity, density and surface tension.

2. Calibration and Additional Data Requirements

a. Apparatus and instruments used shall be calibrated prior to the start and at scheduled intervals during the program.

b. An equipment log shall be maintained for each apparatus and instrument. Dated entries shall be made for all calibration results, all uses of the equipment, all inspection data, and all maintenance operations on the equipment.

APPENDIX B

WETTABILITY DETERMINATION OF TEST LUBRICANTS

WETTING RATE STUDY

Item No.	Run No.	Plate Temp. (°F)	Gas Flow Rate cfm @ 45 psig & 200°F	Rate of Oil-Mist Output (cc/min)	Wetting Time, sec.					Wetting Rate (Cm^2/sec)
					1"	1 1/4"	1 1/2"	1 3/4"	2"	
1	FN 1-1	600	2	0.8	0.47	1.25	2.41	3.98	5.82	2.6
2	FN 1-2	600	3	2.1	0.16	0.31	0.63	1.22	1.60	9.6
3	FN 1-3	600	4	4.2	0.11	0.19	0.34	0.70	1.03	15.0
4	FN 2-1	700	2	0.8	0.48	1.81	7.06	19.6	No further spreading	
5	FN 2-2	700	3	2.1	0.16	0.28	0.68	1.25	1.81	7.9
6	FN 2-3	700	4	4.2	0.14	0.28	0.59	1.16	1.78	8.4
7	FN 2-4	800	2	0.8	1.31	No further spreading				---
8	FN 2-5	800	3	2.1	0.12	0.97	2.97	5.43	8.13 (streaky flow)	<1
9	FN 2-6	800	4	4.2	0.11	0.31	1.75	6.07	10.48 (heavy streaks)	<1

* Test Conditions - Test Oil: FN 2961

Oil Temp: 200°F

Nozzle: No. 1 (0.171" dia.)

WETTING RATE STUDY

Item	Run No.	Plate Temp. (°F)	Gas Flow Rate (cfm @ 45 psig & 200°F)	Rate of Oil-Mist Output (cc/min)	Wetting Time Sec 1"	$1\frac{1}{4}$"	$1\frac{1}{2}$"	1 3/4"	2"	Wetting Rate (cm^2/sec)
1	FN 1-4	600	2	0.8	No visible wetting					---
2	FN 1-5	600	3	2.1	1.58		streaky oil flow			---
3	FN 1-6	600	4	4.2	1.33		2.41	3.20	4.28	4.3
4	FN 1-7	700	3	2.1	1.50	5.94	10.6	s t r e a k s		---
5	FN 1-8	700	4	4.2	5.63	11.56	12.80	s t r e a k s		---
6	FN 2-7	800	3	2.1	No visible wetting					---
7	FN 2-8	800	4	4.2	Extremely thin oil streaks					---

* Test Conditions - Test Oil: FN 2961
Oil Temp: 200°F
Nozzle : No. 3 (0.281" dia.)

WETTING RATE STUDY

Item	Run No.	Plate Temp. (°F)	Gas Flow Rate (cfm @ 45 psig & 200°F)	Rate of Oil-Mist Output (cc/min)	Wetting Time Sec. 1"	1¼"	1½"	1 3/4"	2"	Wetting Rate (cm^2/sec)
1	K 1-4	600	2	---	15.3	No further wetting				---
2	K 1-5	600	3	1.1	0.31	0.47	0.94	1.53	2.12	7.4
3	K 1-6	600	4	1.8	0.125	0.25	0.38	0.69	0.84	18.5
4	K 1-7	700	2	---	12.96	No further wetting				---
5	K 1-8	700	3	1.1	0.31	0.47	0.88	1.44	2.00	8.6
6	K 1-9	700	4	1.8	0.14	0.23	0.38	0.59	0.81	21.0
7	K 2-4	800	2	---	9.38	No further wetting				---
8	K 2-5	800	3	1.1	0.23	0.33	0.66	1.10	1.38	12.5
9	K 2-6	800	4	1.8	0.09	0.16	0.27	0.47	0.63	27.5

* Test Conditions - Test Oil: Krytox 143AC
Oil Temp: 200°F
Nozzle : No. 1 (0.171" dia.)

WETTING RATE STUDY

Item	Run No.	Plate Temp. (°F)	Gas Flow Rate (cfm @ 45 psig & 200°F)	Rate of Oil-Mist Output (cc/min)	Wetting Time Sec. 1"	$1\frac{1}{4}$"	$1\frac{1}{2}$"	1 3/4"	2"	Wetting Rate (cm^2/sec)
1	K 1-1	600	2	---	No visible wetting			19+ seconds		---
2	K 1-2	600	3	1.1		0.75	2.78	4.78	7.18	2.0
3	K 1-3	600	4	1.8			1.10	1.88	3.25	4.2
4	K 1-10	700	3	1.1	No visible oil films			9.75	13.7	---
5	K 2-1	700	4	1.8			1.69	3.34	5.16	2.6
6	K 2-2	800	3	1.1	15.2		No further wetting			---
7	K 2-3	800	4	1.8				2.60	5.82	---

* Test Conditions - Test Oil: Krytox 143AC
Oil Temp: 200°F
Nozzle : No. 3 (0.281" dia.)

WETTING RATE STUDY

Item	Run No.	Plate Temp. (°F)	Gas Flow Rate (cfm @ 45 psig & 200°F)	Rate of Oil-Mist Output (cc/min)	Wetting Time Sec. 1"	$1\frac{1}{4}$"	$1\frac{1}{2}$"	1 3/4"	2"	Wetting Rate (cm^2/sec)
1	K 3-7	600	2	0.7	No visible flow					
2	K 3-6	600	3	1.8	0.08		0.16	0.50	streaks	
3	K 3-5	600	4	3.0	0.09	0.13	0.16	0.20	streaks	
4	MCS 1-4	700	3	1.8	0.16		0.50	streaky flow		
5	MCS 1-3	700	4	3.0	0.08	0.13	0.27	heavy streaks		
6	MCS 1-6	800	3	1.8		0.25	0.50	streaks		
7	MCS 1-5	800	4	3.0	0.11	0.13	0.16	0.23	streaks	

* Test Conditions - Test Oil: MCS-293
Oil Temp: 200°F
Nozzle : No. 1 (0.171" dia.)

WETTING RATE STUDY

Item	Run No.	Plate Temp. (°F)	Gas Flow Rate (cfm @ 45 psig & 200°F)	Rate of Oil-Mist Output (cc/min)	Wetting Time Sec. 1"	1¼"	1½"	1 3/4"	2"	Wetting Rate (cm²/sec)
1	K 3-9	600	3	1.8	No visible oil flow					
2	K 3-8	600	4	3.0	Occasional streaking					
3	MCS 1-2	700	3	1.8	No visible oil flow					
4	MCS 1-1	700	4	3.0	No visible oil flow					
5	MCS 1-8	800	3	1.8	No visible oil flow					
6	MCS 1-7	800	4	3.0	No visible oil flow					

* Test Conditions - Test Oil: MCS-293
Oil Temp: 200°F
Nozzle: No. 3 (0.281" dia.)

WETTING RATE STUDY

Item	Run No.	Plate Temp. (°F)	Gas Flow Rate (cfm @ 45 psig & 200°F)	Rate of Oil-Mist Output (cc/min)	Wetting Time Sec. 1"	1¼"	1½"	1 3/4"	2"	Wetting Rate (cm^2/sec)
1	XRM 1-3	600	2	0.6	1.50	2.97	4.11	5.99	8.60	2.2
2	XRM 1-2	600	3	1.2	0.30	0.49	0.69	1.25	1.61	11.6
3	XRM 1-1	600	4	2.0	0.19	0.33	0.50	0.68	0.91	19.6
4	XRM 6-3	700	3	0.6	1.28	2.24	3.92	5.78	8.75	1.9
5	XRM 6-2	700	3	1.2	0.20	0.39	0.63	1.05	1.51	11.7
6	XRM 6-1	700	4	2.0	0.14	0.25	0.33	0.59	0.83	22.3
7	XRM 6-4	800	2	0.6	2.73	4.92	8.25	11.31	----	1.3
8	XRM 8-1	800	3	1.2	0.25	0.44	0.67	1.02	1.41	11.7
9	XRM 7-2	800	4	2.0	0.10	0.19	0.30	0.48	0.74	23.8

* Test Conditions - Test Oil: XRM-109F
Oil Temp: 200°F
Nozzle : No. 1 (0.171: dia.)

WETTING RATE STUDY

Item	Run No.	Plate Temp. (°F)	Gas Flow Rate (cfm @ 45 psig & 200°F)	Rate of Oil-Mist Output (cc/min)	Wetting Time Sec. 1"	1¼"	1½"	1 3/4"	2"	Wetting Rate (cm^2/sec)
1	XRM 2-1	600	2	0.6	22.6	No further spreading				---
2	XRM 16-1	600	3	1.2	0.78	1.22	1.56	2.97	4.70	3.2
3	XRM 15-5	600	4	2.0	0.25	0.38	0.56	1.28	1.87	7.2
4	XRM 5-1	700	2	0.6	23.4	No further spreading				---
5	XRM 15-1	700	3	1.2	0.63	0.91	1.56	2.66	3.90	4.0
6	XRM 15-2	700	4	2.0	0.25	0.31	0.56	1.03	1.72	8.4
7		800	2	0.6	No run made					---
8	XRM 15-3	800	3	1.2	---	0.91	1.66	2.62	3.84	4.1
9	XRM 15-4	800	4	2.0	0.25	0.59	0.91	1.42	2.25	7.8

* Test Conditions - Test Oil: XRM-109F
Oil Temp: 200°F
Nozzle : No. 3 (0.281" dia.)

WETTING RATE STUDY

Item	Run No.	Plate Temp. (°F)	Gas Flow Rate (cfm @ 45 psig & 200°F)	Rate of Oil-Mist Output (cc/min)	Wetting Time, sec 1"	1-1/4"	1-1/2"	1-3/4"	2"		Wetting Rate (cm^2/sec)
1	XRM 16-4	600	2	0.9	0.72	1.44	2.62	3.69	4.53		3.8
2	XRM 16-3	600	3	2.4	0.19	0.31	0.47	0.64	0.81		22.0
3	XRM 16-2	600	4	4.0	0.03	0.12	0.31	0.59	0.78		22.7
4	XRM 17-5	700	2	0.9	0.62	1.47	3.66	6.44	9.78		1.5
5	XRM 17-4	700	3	2.4	0.22	0.37	0.66	1.00	1.25		13.5
6	XRM 17-3	700	4	4.0	0.14	0.22	0.41	0.59	0.75		22.8
7	XRM 18-3	800	2	0.9	0.96	2.32	5.85	8.72	16.60	heavy	<1
8	XRM 18-4	800	3	2.4	0.25	0.81	2.32	6.06	8.68	streaks	1.6
9	XRM 18-5	800	4	4.0	0.19	0.59	1.69	2.45	3.32		4.4

* Test Conditions - Test Oil: XRM 209 A
Oil Temp: 200 F
Nozzle : No. 1 (0.171" dia.)

WETTING RATE STUDY

Item	Run No.	Plate Temp. (°F)	Gas Flow Rate (cfm @ 45 psig& 200°F)	Rate of Oil-Mist Output (cc/min)	Wetting Time, sec 1"	1-1/4"	1-1/2"	1-3/4"	2"	Wetting Rate (cm^2/sec)
1	XRM 17-1	600	2	0.9	--	14.84	34.60	No further spreading		--
2	XRM 16-6	600	3	2.4	--	2.44	4.06	5.90	9.06	1.7
3	XRM 16-5	600	4	4.0	1.85	2.22	2.72	4.22	5.24	3.1
4	XRM 17-6	700	3	2.4	3.35	No visible oil film				--
5	XRM 17-2	700	4	4.0	1.12	2.28	2.96	3.91	4.81	4.0
6	XRM 18-1	800	3	2.4	5.32	No further oil spreading				--
7	XRM 18-2	800	4	4.0	0.78	1.50	2.75	3.83	Streaky flow	3.2

* Test Conditions - Test Oil: XRM 209 A
Oil Temp: 200 F
Nozzle : No. 3 (0.281" dia.)

APPENDIX C

EFEECT OF GAS AND LUBRICANT TEMPERATURE

WETTING RATE STUDY

Item	Run No.	Plate Temp. (F)	Gas Flow Rate (cfm @ 45 psig& 100 F)	Rate of Oil-Mist Output (cc/min)	Wetting Time, sec 1"	1-1/4"	1-1/2"	1-3/4"	2"	Wetting Rate (cm^2/sec)
1	XK 1-5	600	2	0.5		0.66	0.92	1.43	1.94	8.5
2	XK 1-6	600	3	1.0	0.27	0.37	0.55	0.81	1.09	17.0
3	XK 1-7	600	4	1.8	0.16	0.25	0.36	0.55	0.74	26.8
4	XK 2-5	700	2	0.5	No visible oil film					--
5	XK 2-4	700	3	1.0	0.20	0.33	0.64	1.04	Streaks	9.9
6	XK 2-3	700	4	1.8	0.10	0.19	0.43	0.67	1.00	17.8
7	XK 2-6	800	3	1.0	0.75	4.22	12.40	Streaks		--
8	XK 2-7	800	4	1.8	0.17	0.34	1.47	Streaks		--

* Test Conditions - Test Oil: FN 2961
Oil Temp: 100 F
Nozzle : No. 1 (0.171" dia.)

WETTING RATE STUDY

Item	Run No.	Plate Temp. (°F)	Gas Flow Rate (cfm @ 45 psig & 300°F)	Rate of Oil-Mist Output (cc/min)	Wetting Time Sec. 1"	$1\frac{1}{4}$"	$1\frac{1}{2}$"	1 3/4"	2"	Wetting Rate (cm^2/sec)
1	XK 5-6	600	2	1.5	0.84	1.81	4.16	streaks		---
2	XK 5-5	600	3	3.2	0.14	0.23	0.34	0.63	0.85	20.0
3	XK 5-4	600	4	5.3	0.13	0.19	0.31	0.59	0.75	22.7
4	XK 4-1	700	2	1.5	0.81	3.09	7.54	11.60	14.84	< 1
5	XK 4-2	700	3	3.2	0.31	1.69	5.54	11.30	15.62	< 1
6	XK 4-3	700	4	5.3	0.16	0.28	0.53	1.12	1.87	7.3
7	XK 3-5	800	3	3.2	0.19	0.37	streaky	flooding		---
8	XK 3-6	800	4	5.3	0.19	0.41	1.87	4.64	6.31	2.0

* Test Conditions - Test Oil: FN 2961
Oil Temp: 300°F
Nozzle : No. 1 (0.171" dia.)

WETTING RATE STUDY

Item	Run No.	Plate Temp. (°F)	Gas Flow Rate (cfm @ 45 psig & 100°F)	Rate of Oil-Mist Output (cc/min)	Wetting Time, sec					Wetting Rate (cm^2/sec)
					1"	1-1/4"	1-1/2"	1-3/4"	2"	
1	XRM 9-3	600	2	0.2	2.42	4.20	7.10	10.21	12.60	1.4
2	XRM 9-2	600	3	0.5	0.25	0.41	1.11	2.02	2.62	5.1
3	XRM 9-1	600	4	0.9	0.17	0.28	0.47	0.81	1.00	15.9
4	XRM 11-3	700	2	0.2	2.56	4.94	7.45	11.86	Streaks	1.2
5	XRM 11-2	700	3	0.5	0.28	0.45	0.83	1.48	2.15	7.3
6	XRM 11-1	700	4	0.9	0.14	0.19	0.30	0.50	0.76	23.2
7	XRM 11-6	800	2	0.2	3.36	6.60	No further spreading			1
8	XRM 11-5	800	3	0.5	0.42	0.70	1.23	1.78	2.42	7.2
9	XRM 11-4	800	4	0.9	0.14	0.22	0.34	0.50	0.70	24.4

* Test Conditions - Test Oil: XRM 109 F
Oil Temp: 100 F
Nozzle : No. 1 (0.171" dia.)

WETTING RATE STUDY

Item	Run No.	Plate Temp. (°F)	Gas Flow Rate (cfm @ 45 psig & 300°F)	Rate of Oil-Mist Output (cc/min)	Wetting Time Sec. 1"	$1\frac{1}{4}$"	$1\frac{1}{2}$"	1 3/4"	2"	Wetting Rate (cm^2/sec)
1	XRM 12-1	600	2	0.9	0.81	1.88	3.56	6.15	8.28	1.9
2	XRM 12-2	600	3	1.9	0.16	0.28	0.50	0.88	1.34	12.5
3	XRM 12-3	600	4	3.0	0.14	0.19	0.31	0.50	0.67	23.8
4	XRM 12-4	700	2	0.9	0.58	1.22	2.33	streaks		---
5	XRM 12-5	700	3	1.9	0.14	0.23	0.36	0.56	0.84	19.1
6	XRM 12-6	700	4	3.0	0.14	0.17	0.31	0.48	0.58	27.5
7	XRM 13-1	800	2	0.9	No wetting					---
8	XRM 13-2	800	3	1.9	---	0.23	0.44	0.64	0.94	18.3
9	XRM 13-3	800	4	3.0	0.09	0.17	0.31	0.42	0.53	31.5

* Test Conditions - Test Oil: XRM 109 F
Oil Temp: 300°F
Nozzle : No. 1 (0.171" dia.)

APPENDIX D

EFFECT OF TEST PLATE SURFACE

EFFECT OF PLATE SURFACES ON WETTABILITY

Item	Run No.	Plate Temp. (°F)	Gas Flow Rate (cfm @ 45 psi & 200°F)	Rate of Oil-Mist Output (cc/min)	Surface Condition of Test Plate	Wetting Time Sec. 1"	$1\frac{1}{4}$"	$1\frac{1}{2}$"	1 3/4"	2"	Wetting Rate (cm^2/sec)
1	FN 3-1	700	3	2.1	2 μ in. Roughness	0.25	0.37	0.71	1.19	1.67	10.1
2	FN 2-2	700	3	2.1	6 μ in. Roughness	0.16	0.28	0.68	1.25	1.81	7.9
3	FN 3-2	700	3	2.1	40 μ in. Roughness	0.30	0.50	1.19	2.19	2.84	5.8
4	FN 3-3	700	3	2.1	Black oxide coating (6 μ in.)	0.37	0.78	1.69	3.19	5.26	3.8
5	FN 3-4	700	3	2.1	Deposit of oil decomposition products (8 μ in.)	0.22	0.30	0.50	1.06	1.59	8.7

Test Conditions - Test Oil: FN 2961
Oil Temp: 200°F
Nozzle : No. 1 (0.171" dia.)

EFFECT OF PLATE SURFACE ON WETTABILITY

Item	Run No.	Plate Temp. (°F)	Gas Flow Rate (cfm @ 45 psi & 200°F)	Rate of Oil-Mist Output (cc/min)	Surface Condition of Test Plate	Wetting Time Sec. 1"	$1\frac{1}{4}$"	$1\frac{1}{2}$"	1 3/4"	2"	Wetting Rate (cm^2/sec)
1	XRM 14-9	600	3	1.2	2 μ in. Roughness	0.19	0.31	0.47	0.72	1.00	18.9
2	XRM 1-2	600	3	1.2	6 μ in. Roughness	0.30	0.49	0.69	1.25	1.61	11.6
3	XRM 14-1	600	3	1.2	40 μ in. Roughness	0.27	0.52	0.88	1.39	1.91	9.2
4	XRM 14-2	600	3	1.2	Black oxide coating (6 μ in.)	0.30	0.50	0.88	1.58	2.28	8.0
5	XRM 14-3	600	3	1.2	Deposit of oil decomposition products (8 μ in.)	0.25	0.39	0.66	0.95	1.20	11.5
6	XRM 14-8	700	3	1.2	2 μ in. Roughness	0.25	0.44	0.72	1.14	1.36	13.2
7	XRM 6-2	700	3	1.2	6 μ in. Roughness	0.25	0.39	0.63	1.05	1.51	11.7
8	XRM 14-5	700	3	1.2	40 μ in. Roughness	0.25	0.36	0.69	1.19	1.64	9.6
9	XRM 14-4	700	3	1.2	Black oxide coating (6 μ in.)	0.31	0.56	1.03	1.78	2.42	6.6
10	XRM 14-6	700	3	1.2	Deposit of oil decomposition products (8 μ in.)	0.27	0.45	0.69	1.12	1.44	12.3

Test Conditions - Test Oil: XRM 109 F
Oil Temp: 200°F
Nozzle : No. 1 (0.171" dia.)

DISTRIBUTION LIST FOR TASK REPORT

CONTRACT NAS 3-13207

DISTRIBUTION LIST FOR TASK REPORT, CONTRACT NAS3-13207

		Number of Copies
1.	NASA-Lewis Research Center 21000 Brookpark Road Cleveland, Ohio 44135	
	Attention: John E. Dilley, MS 500-309	1
	P. E. Foster, MS 3-19	1
	Dr. B. Lubarsky, MS 3-3	1
	A. Ginsburg, MS 5-3	1
	E.E. Bisson, MS 5-3	1
	C.H. Voit, MS 5-3	1
	R.L. Johnson, MS 23-2	2
	W.R. Loomis, MS 23-2	5
	M.A. Swikert, MS 23-2	1
	W.J. Anderson, MS 23-2	1
	E.V. Zaretsky, MS 6-1	1
	D.P. Townsend, MS 6-1	1
	Fred Macks, MS 3-15	1
	Library, MS 60-3	2
	Report Control Office, MS 5-5	1
2.	NASA Headquarters 600 Independence Avenue, SW Washington, D.C. 20546	
	Attention: N.F. Rekos (RAP)	1
	G.C. Deutsch (RRM)	1
3.	NASA-Langley Research Center Langley Station Hampton, Virginia 23365	
	Attention: Mark R. Nichols	1
4.	NASA-Scientific and Technical Information Facility P.O. Box 33 College Park, Maryland 20740	
	Attention: NASA Representative	6
5.	Air Force Aero Propulsion Laboratory Wright-Patterson AFB, Ohio 45433	
	Attention: APFL, J. L. Morris	1
	APFL, G. A. Beane IV	1
6.	Air Force Materials Laboratory Wright-Patterson AFB, Ohio 45433	
	Attention: MANL, R. Adamczak	1
	MANL, R.L. Benzing	1

		Number of Copies
7.	Air Force Systems Engineering Group Wright-Patterson AFB, Ohio 45433 Attention: SEJDF, S. Prete	1
8.	Department of the Army U.S. Army Aviation Materials Labs. Fort Eustis, Virginia 23604 Attention: J. W. White, Propulsion Division	1
9.	Department of the Navy Washington, D.C. Attention: Bureau of Naval Weapons A. B. Nehman, RAAE-3	1
	C. C. Singleterry, RAPP-44	1
	Bureau of Ships Harry King, 634A	1
10.	U.S. Army Ordnance Rock Island Arsenal Laboratory Rock Island, Illinois 61201 Attention: R. LeMar	1
11.	U.S. Naval Air Material Center Aeronautical Engine Laboratory Philadelphia, Pennsylvania 15212 Attention: Engine Lubrication Branch A. L. Lockwood	1
12.	U.S. Naval Research Laboratory Washington, D.C. 20390 Attention: Dr. William Zisman	1
13.	FAA Headquarters 800 Independence Avenue, SW Washington, D.C. 20553 Attention: General J. C. Maxwell	1
	F. B. Howard	1
14.	Aerojet-General Corporation 20545 Center Ridge Road Cleveland, Ohio 44116 Attention: D. B. Rake	1
15.	AiResearch Manufacturing Company Department 93-3 9851 Sepulveda Boulevard Los Angeles, California 90009 Attention: Hans J. Poulsen	1

	Number of Copies
16. Alcor Incorporated 2905 Bandera Road San Antonio, Texas Attention: Mr. L. Hundere	1
17. Avco Corporation Lycoming Division 550 Main Street Stratford, Connecticut Attention: Mr. Saboe	1
18. Battelle Memorial Institute Columbus Laboratories 505 King Avenue Columbus, Ohio 43201 Attention: Mr. C. M. Allen	1
19. Boeing Aircraft Company Aerospace Division Materials and Processing Section Seattle, Washington 98124 Attention: J. W. Van Wyk	1
20. Borg-Warner Corporation Roy C. Ingersoll Research Center Wolf and Algonquin Roads Des Plaines, Illinois	1
21. C. A. Norgren Company Englewood, Colorado Attention: D. G. Faust	1
22. California Research Corporation Richmond, California 94800 Attention: Neil Furby	1
23. Chevron Research Company 576 Standard Avenue Richmond, California 94804 Attention: Douglas Godfrey	1
24. Continental Oil Company Research and Development Department Ponca City, Oklahoma 74601 Attention: R. W. Young	1
25. Curtiss-Wright Corporation Wright Aeronautical Division 333 West First Street Dayton, Ohio 45400 Attention: S. Lombardo	1

		Number of Copies
26.	Dow Chemical Company Abbott Road Buildings Midland, Michigan Attention: Dr. R. Gunderson	1
27.	Dow Corning Corporation Midland, Michigan 48690 Attention: R. W. Awe and H. M. Schiefer	1
28.	E. I. duPont de Nemours and Company Petroleum Chemicals Division Wilmington, Deleware 19898 Attention: Neal Lawson	1
29.	EPPI Precision Products Company 227 Burlington Avenue Clarendon Hills, Illinois 60514 Attention: C. Dean	1
30.	Eaton, Yale and Town, Incorporated Farval Division 3249 East 80th Street Cleveland, Ohio 44104 Attention: E. J. Gesdorf	1
31.	Eaton, Yale and Towne, Incorporated Research Center 26201 Northwestern Highway Southfield, Michigan 48075 Attention: H. M. Reigner W. Mannhardt	1 1
32.	Esso Research and Engineering Company P.O. Box 51 Linden, New Jersey 07036 Attention: Jim Moise A. Beerbower	1 1
33.	Fairchild Engine and Airplane Corporation Stratos Division Bay Shore, New York	1
34.	Fairchild Hiller Corporation Republic Aviation Division Space Systems and Research Farmingdale, Long Island, New York 11735 Attention: R. Schroder	1
35.	Franklin Institute Research Labs 20th and the Parkway Philadelphia, Pennsylvania 19103 Attention: W. Shugart	1

		Number of Copies
36.	General Electric Company Gas Turbine Division Evendale, Ohio 45215 Attention: B. Venable E. N. Bamberger	 1 1
37.	General Electric Company General Engineering Laboratory Schenectady, New York 12305	1
38.	General Electric Company Silicone Products Department Waterford, New York 12188 Attention: J. C. Frewlin	1
39.	General Motors Corporation Allison Division Plant 8 Indianapolis, Indiana 46206	1
40.	General Motors Corporation New Departure Division Bristol, Connecticut Attention: W. O'Rourke	1
41.	Gulf Research and Development Company P.O. Drawer 2038 Pittsburgh, Pennsylvania 15230 Attention: Dr. H. A. Ambrose	1
42.	Hercules Powder Company, Inc. 900 Market Street Wilmington, Delaware 19800 Attention: R. G. Albern	1
43.	Heyden Newport Chemical Corporation Heyden Chemical Division 290 River Drive Garfield, New Jersey Attention: D. X. Klein	1
44.	Hughes Aircraft Company International Airport Station P.O. Box 90515 Los Angeles, California 90209	1
45.	IIT Research Institute 10 West 35 Street Chicago, Illinois 60616 Attention: Warren Jamison	1

		Number of Copies
46.	Industrial Tectonics, Inc. Research and Development Division 18301 Santa Fe Avenue Compton, California 90024 Attention: Heinz Hanau	1
47.	Kendall Refining Company Bradford, Pennsylvania 16701 Attention: F.I.I. Lawrence	1
	L.D. Dromgold	1
48.	Lockheed Aircraft Corporation Lockheed Missile and Space Company Material Science Laboratory 3251 Hanover Street Palo Alto, California Attention: Francis J. Clauss	1
49.	Marlin-Rockwell Corporation Jamestown, New York 14701 Attention: Arthur S. Irwin	1
50.	McDonnell-Douglas Aircraft Company 3000 Ocean Park Boulevard Santa Monica, California 90406 Attention: Robert McCord	1
51.	Mechanical Technology Incorporated 968 Albany-Shaker Road Latham, New York 12110 Attention: Dr. B. Sternlicht	1
52.	Midwest Research Institute 425 Volker Boulevard Kansas City, Missouri 64110 Attention: V. Hopkins and A.D. St.John	1
53.	Monsanto Company 800 North Lindbergh Boulevard St. Louis, Missouri 63166 Attention: Dr. W.R. Richard	1
	Dr. E. J. Stejskal	1
	Dr. R. Hatton	1
54.	North American Rockwell Corporation Los Angeles Division, International Airport Los Angeles, California 90209 Attention: Frank J. Williams	1
55.	Olin Mathieson Chemical Corporation Organics Division 275 Winchester Avenue New Haven, Connecticut 06504 Attention: Dr. C. W. McMullen	1

		Number of Copies
56.	Pennsylvania Refining Company Butler, Pennsylvania 16001	1
57.	Pennsylvania State University Dept. of Chemical Engineering University Park, Pennsylvania 16802 Attention: Prof. E.E. Klaus	1
58.	Ransburg Electro-Coating Corp. P.O. Box 88220 Indianapolis, Indiana 46208 Attention: Dr. E. Miller	1
59.	Rohm and Haas Company Washington Square Philadelphia, Pennsylvania 19105 Attention: V. Ware and P. M. Carstensen	1
60.	Shell Development Company Emeryville, California Attention: Dr. C. L. Mahoney	1
61.	Shell Oil Company Wood River Research Laboratory Advanced Products Group Wood River, Illinois Attention J. J. Heithaus	1
62.	Sinclair Refining Company 600 Fifth Avenue New York, New York 10020 Attention: C. W. McAllister	1
63.	Sinclair Research, Inc. 400 East Sibley Boulevard Harvey, Illinois 60426 Attention: M. R. Fairlie	1
64.	SKF Industries, Incorporated Engineering and Research Center 1100 First Avenue King of Prussia, Pennsylvania 19406 Attention: L. B. Sibley H. E. Mahncke	1 1
65.	Southwest Research Institute P.O. Drawer 28510 San Antonio, Texas 78228 Attention: P. M. Ku	1

		Number of Copies
66.	Stauffer Chemical Company 299 Park Avenue New York, New York 10017 Attention: T. M. Downer, Jr.	1
67.	Stewart-Warner Corporation 1826 Diversey Parkway Chicago, Illinois 60614	1
68.	Sun Oil Company Automotive Laboratory Marcus Hook, Pennsylvania 19061 Attention: J. Q. Griffith	1
69.	Sun Oil Company Research and Development Marcus Hook, Pennsylvania 19061 Attention: G. H. Hommer	1
70.	Texaco, Incorporated P.O. Box 509 Beacon, New York 12508 Attention: Dr. G. B. Arnold	1
71.	Timken Roller Bearing Company Physical Laboratories Canton, Ohio 44706 Attention: W. C. West	1
72.	Union Carbide Corporation Union Carbide Chemicals Company Tarrytown, New York 10591	1
73.	United Aircraft Corporation Pratt & Whitney Aircraft East Hartford, Connecticut 06108 Attention: R. P. Shevchenko P. Brown	1
74.	United Aircraft Corporation Pratt & Whitney Aircraft Engineering Department West Palm Beach, Florida 33402 Attention: R. E. Chowe	1
75.	Westinghouse Electric Corporation Research Laboratories Beulah Road, Churchill Borough Pittsburgh, Pennsylvania 15235 Attention: J. Boyd S. M. DeCorso	1 1

	Number of Copies
76. Bray Oil Company 1925 North Marianne Avenue Los Angeles, California 90032 Attention: Martin Fainman	1