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**THE EFFECTS OF NUCLEAR RADIATION ON SOLID
FILM LUBRICANTS**

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FOREWORD

This report was prepared by the Organic Materials Branch, Materials Laboratory, Directorate of Laboratories, Wright Air Development Center, with William L. R. Rice acting as project engineer. The work reported herein was initiated under Project Number 3044, "Aviation Lubricants," Task Number 73312, "Lubricant Mechanical Evaluation."

This report covers work conducted during the period October 1955 to August 1958.

All irradiations were performed under the supervision of Lt. Robert H. Johnson and Lt. William R. Daniels, Materials Physics Branch, Materials Laboratory, Directorate of Laboratories, Wright Air Development Center.

Particular credit is due to Lt. Roy C. Williamson, Organic Materials Branch, Materials Laboratory, Directorate of Laboratories, Wright Air Development Center. Lt. Williamson conducted the studies on solid film resistance to corrosion, thermal effects, and solvent action. His assistance in developing and conducting the new test methods was invaluable and is gratefully acknowledged.

The purpose of this report is to evaluate the performance of a number of products for a specific application. Many of the materials tested were not developed or intended by the manufacturer for the conditions to which they have been subjected. Any failure or poor performance of a material is therefore not necessarily indicative of the utility of the material under less stringent conditions or for other applications.

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ABSTRACT

The effect of nuclear radiation on twelve commercial solid film lubricants was determined. The lubricants were typically phenolic or epoxy resin bonded, incorporating graphite or molybdenum disulfide. Gamma exposures covered the range 8.71×10^9 through 2.61×10^{11} ergs per gram carbon. Neutron exposures were over the range 1×10^{15} to 3×10^{16} nvt fast.

Data were obtained on the wear life, corrosion resistance, fluid resistance, and thermal stability. It was observed that radiation, in certain instances, improved wear life rather than decreasing it. Also, those solid films that possessed good corrosion and fluid resistance and good thermal stability prior to irradiation generally were not seriously changed in these properties. Films of poor initial properties were greatly degraded by the radiation.

It was concluded that certain of the films should be useable up to the maximum dosages used, but that careful selection would be necessary.

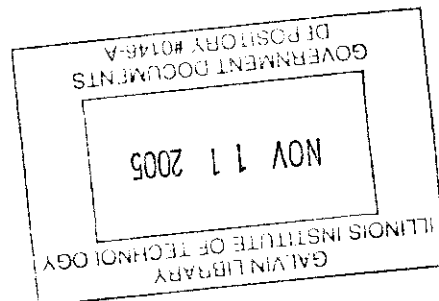
PUBLICATION REVIEW

This report has been reviewed and is approved.

FOR THE COMMANDER:



R. T. SCHWARTZ
Chief, Organic Materials Branch
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Introduction

Nuclear radiation resistant lubricants are of major importance to the development of nuclear powered weapon systems. The divided shield concept for manned aircraft, for example, has resulted in greatly increased radiation levels in the zone between the reactor shield and the crew shield. This radiation intensity is unique to flight vehicles, since it is only in systems operating off the surface of the earth or out of the oceans that weight is so critical, with the resultant reduction in shield weights to minimum values.

A great deal of research has been conducted and is currently in progress with the intent of developing radiation resistant lubricating oils, greases, hydraulic fluids, and related materials. This research has resulted in the development of outstanding materials, chief among them being the unsubstituted polyphenyl ethers. However, it appears at present that there is little possibility of developing organic fluids capable of extended operation for temperatures much above the range of 800°F to 900°F, unless one is willing to use materials of exceptionally high melting point and resultant limited low temperature useability.

Among the more interesting possibilities for lubrication at extended temperatures are the solid film lubricants. These lubricants consist in general of a finely divided solid material, such as graphite or molybdenum disulfide, affixed to the bearing surface by a suitable bonding agent. Details of past work on solid film lubricants in non-nuclear environments are presented in many excellent references (1, 2, 3, 5, 6, and 11).

The advantages of solid film lubricants are manyfold. They are independent of temperature, up to the decomposition point, since there need be no consideration of melting point or limiting viscosities. They require no maintenance, since they are expected to remain functional during the normal operational lifetime of the bearing surface. And, quite important for applications in the presence of nuclear radiation, the binder and the dispersed material would be expected to show resistance to radiation effects to higher dosage levels than organic fluids.

The development efforts discussed herein represent the first phase in the Air Force program to assess the potentialities of solid film lubricants for use in nuclear powered systems.

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Evaluation Criteria

In the past efforts on the development of solid film lubricants, many and varied criteria were established, depending on the expected end item use. Air Force requirements for solid film lubricants are reflected in the provisions of Specification MIL-L-25504. This specification establishes the minimum performance and testing requirements for a bonded, solid film lubricant applied to the surface of parts used in aircraft and missiles to reduce wear and prevent galling and seizure. The test provisions of this specification are given in Appendix I. The solvent resistance, corrosion resistance, and thermal stability studies reported in Tables I, II, and III were performed in accordance with these specification methods.

The most interesting consideration in the use of a solid film lubricant is its wear life. Many devices have been used to measure the frictional characteristics of solid film coated surfaces. One such machine, the Falex Wear Tester, had its inception in studies of lubricating oils. This machine has been extensively used in evaluation of solid film lubricants. Details of operation are given in references (6) and (10). Tables IV and V give data obtained through use of this machine. Table VI gives wear-life data using a Midwest Research Institute friction tester, details of which are outlined in reference (8). Wear life data for Table VII are based on the Hartmann-Modified MacMillan machine.

The requirements for solid film performance are outlined in Air Force Specification MIL-L-25504 (USAF). Unless special environmental tests are conducted, most laboratory evaluation at the Wright Air Development Center is now conducted in accordance with said requirements.

Irradiation of Samples

Details of the irradiation history of the Falex sets and coated panels are given in Appendix I. Dosimetry values for gamma exposures in the MTR gamma canal are reported in roentgens. The roentgen values have been converted to the basis of ergs per gram carbon, as recommended by reference (4). It was assumed that one roentgen is equivalent to 87.1 ergs per gram carbon.

The gamma irradiation facility at the MTR is under some twenty feet of water for shielding purposes. Occasionally, an irradiation canister leaks due to a defective lead seal. Samples of coated panels for several coatings were contaminated due to such water leakage. There are many places in Tables I, II, and III where data could not be obtained due to panels ruined in this manner.

Lubricant Composition

The materials used in this preliminary study were from commercial sources. They were typically phenolic or epoxy resin bonded, incorporating graphite or molybdenum disulfide. The exact compositions were not made available. The manufacturers and their materials are listed in Appendix IV, page 30.

Other concepts have arisen in lubrication by solid surfaces that do not depend on bonding materials to the surface. One idea is that of incorporating a lubricating material (graphite or molybdenum disulfide) in a sintered metal matrix and using this composition as a self-lubricating medium. Another type of material is one of a relatively high carbon content metal alloy of self-lubricating characteristics. While not directly related to the purposes of this report, data on such materials might be of certain related interest. Therefore, Appendix II presents data on a sintered metal product and Appendix III discusses a brief study made of a series of self-lubricating metal alloys.

Performance of Irradiated Solid Film Lubricants

The reaction of the irradiated films under a number of external environments and their ability to lubricate under load were considered as indices of the performance of the films. The film reaction to immersion in potential solvents, to the corrosive effects of salt spray, and to wide variation in temperature are shown in detail in the tables of data. The picture, based on this series of evaluations, is as follows:

The fluid resistance tests performed on the irradiated solid film coated panels, while of a somewhat qualitative nature, were nevertheless conclusive. It was observed, in general, that if a coated panel showed good resistance to solvent action prior to irradiation, it could be expected to show the same relative resistance subsequent to irradiation. Also, panels of exceedingly poor solvent resistance could not be expected to improve with exposure to radiation.

In only one instance was an irradiated panel corroded to a greater extent than the uncoated anodized panel. Other than that, the radiation appeared to have little detrimental effect on those panels that had good initial resistance to the salt spray. Salt spray corrosion would not appear to be increased, therefore, as a result of irradiation.

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The same conclusions could be reached for the coated panels subjected to -65°F or 600°F as were reached for the fluid resistance data. If a composition had good initial properties, radiation did not change them seriously. If a composition did not show resistance to thermal extremes prior to irradiation, then little improvement, if any, could be expected as a result of exposure.

The major function of these films is to reduce or prevent wear of rubbing surfaces. The geometry of the specimens used in the Falex tester offers a simple and qualitative approach to comparison of pre-irradiation and post-irradiation effects.

Interpretation of the Falex wear life of the irradiated compositions was complicated by an error on the part of the operators. The runs were to have been at 250 pounds applied load, but many were conducted at 355 pounds, which explains the lack of control in many instances.

Figure 1 shows the results of testing of film A. The neutron and gamma irradiation data are shown on the same figure for convenience only. The data points are not to be considered as being at equivalent dosages on an absorbed energy basis. Falex life was apparently better for the samples tested at 250 pounds after neutron exposure and showed a slight decrease for the 355 pound jaw load. The same general trend was observed for the gamma irradiated pins, but the scatter is so great that further testing would be necessary to verify this point.

In Figure 2, it is seen that film C showed apparent improvement as a result of reactor irradiation, while the gamma exposures were detrimental. Film B showed greater wear life after neutron exposure and apparently some improvement with gamma irradiation. However, the low wear life for the irradiation at 8.71×10^{10} ergs/gm C casts some doubt on the effects of the gamma radiation.

Film D unfortunately had no control data run, but appears to improve with gamma exposure. Wear life after neutron irradiation is questionable.

Film G, as shown in Figure 3, displayed improvement with gamma irradiation. There is no control point for the wear life at 355 pounds, but it would appear that reactor irradiation also improves the wear life for this lubricant.

Film H had considerable scatter in wear life data points, as shown in Figure 3. It is apparent, however, that exposure to radiation was undoubtedly harmful to the wear life characteristics of this film.

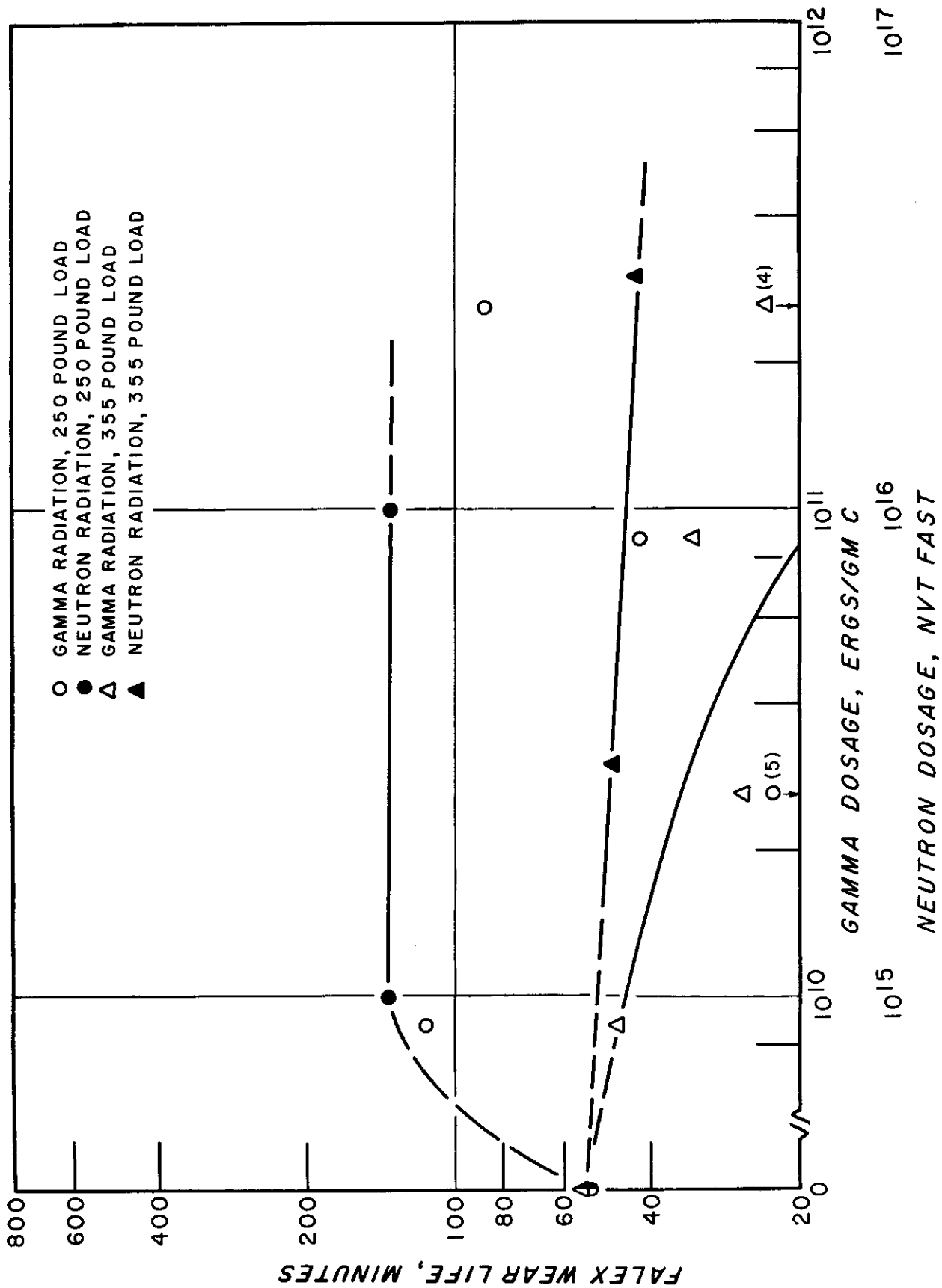


FIGURE 1. FALEX WEAR LIFE OF SOLID FILM A

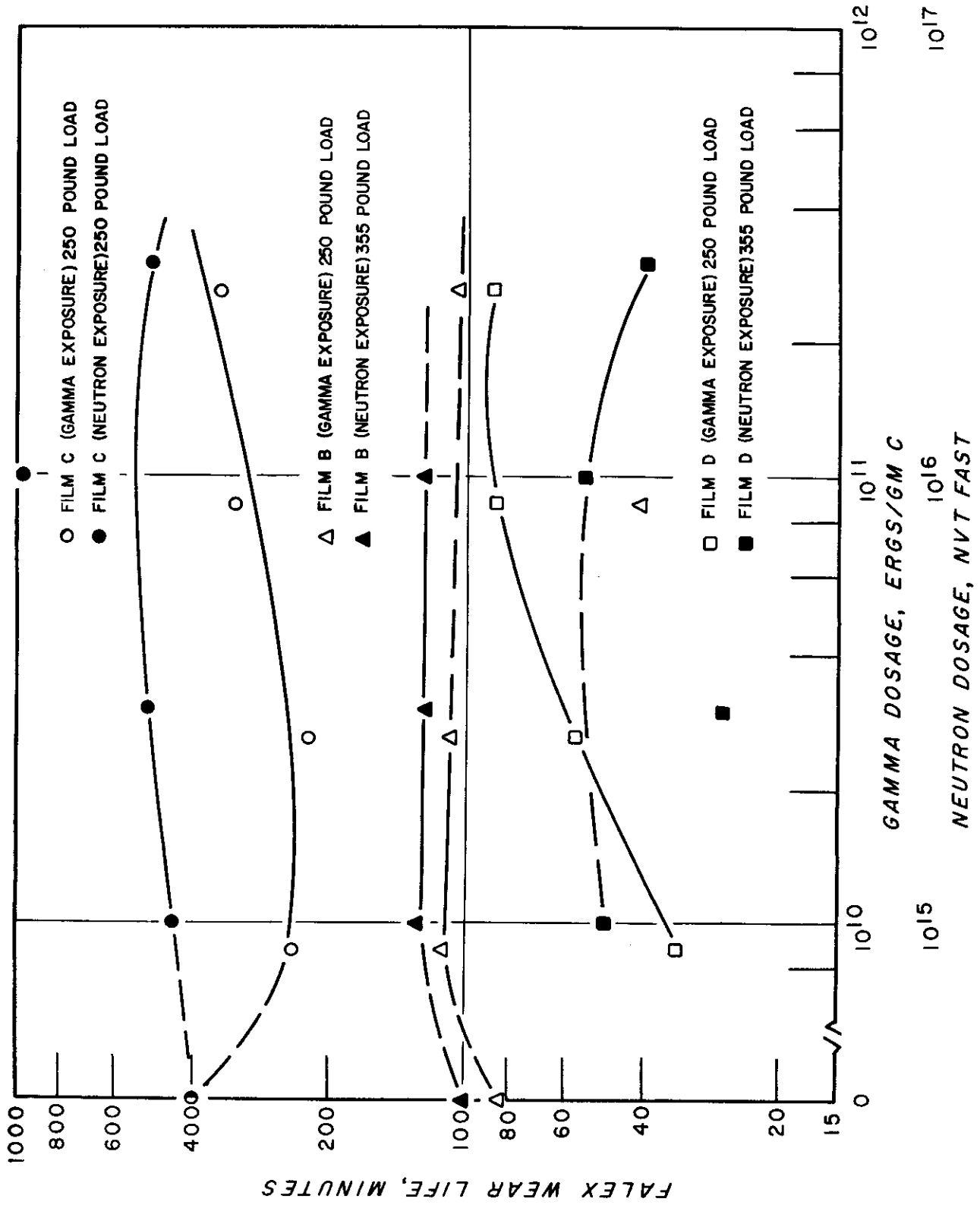


FIGURE 2. FALEX WEAR LIFE OF SOLID FILMS B, C, AND D

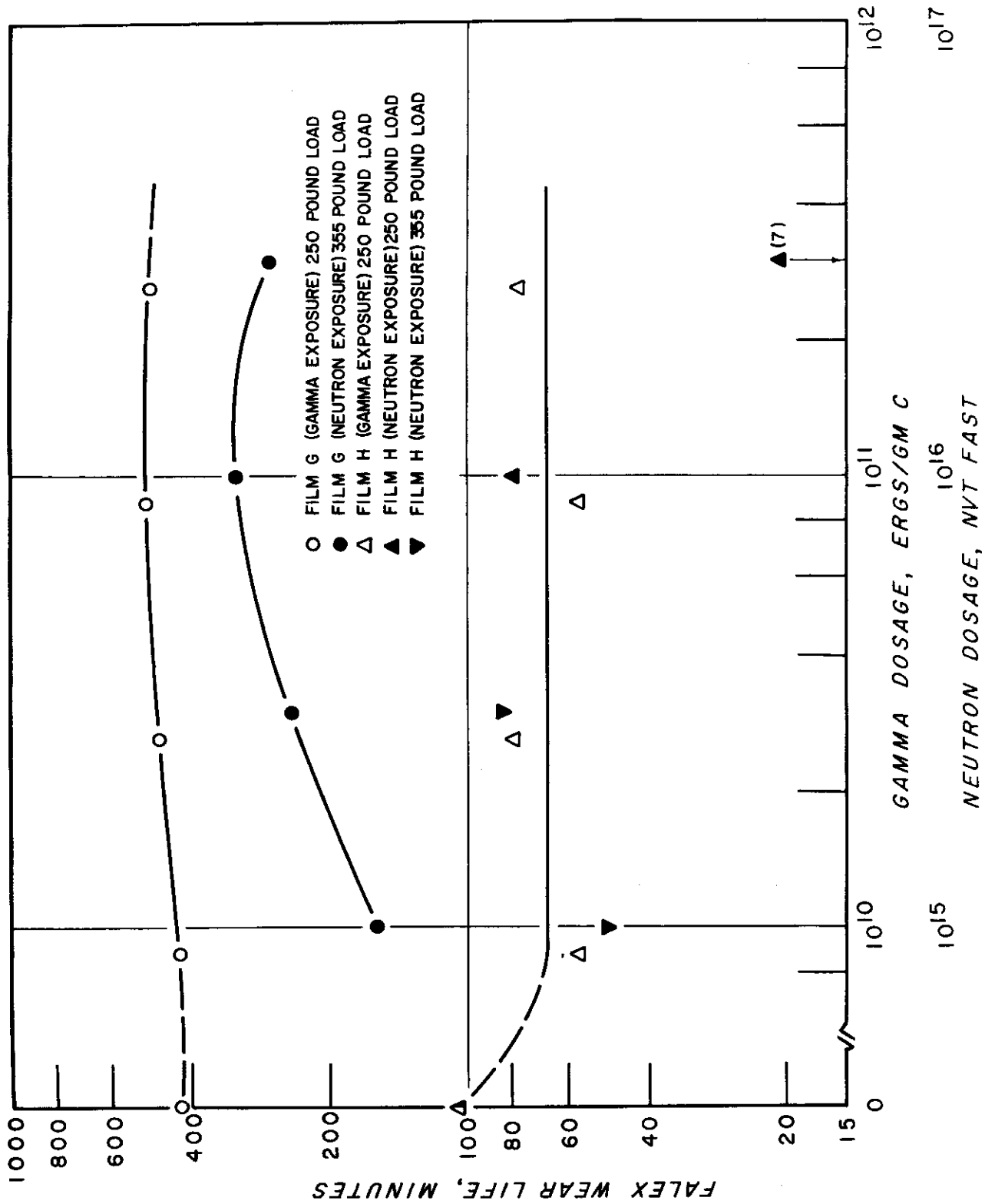


FIGURE 3. FALEX WEAR LIFE OF SOLID FILMS G AND H

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It is interesting to note that film E, which was exposed only to gamma radiation (Table V), had very poor wear life both for the control and for the dosages up to 2.61×10^{10} ergs/gm C. At this level, the film displayed a very remarkable improvement in wear life, comparatively speaking.

Film F was poor in wear life both for the control and for all dosages of gamma radiation, as shown in Table V.

Based on the data obtained, two facts became apparent. First, it is entirely possible that exposure to nuclear radiation could improve the lubricating characteristics of solid film lubricants, at least as indicated by the Falex Tester at ambient temperature. Secondly, compositions of superior wear life under non-nuclear environments would probably be preferable for use in a radiation field, since one would have no reason to believe that relatively poorer films would have superior radiation resistance.

Figure 4 shows data for solid film wear life at 400°F and 550°F following exposure to gamma radiation (8). As could be expected, the wear life at the higher temperature is considerably reduced. The general trend is to an improvement in wear life or at least relatively little change. The only exception is film D, which showed a remarkable drop in 400°F stability but little change in wear life at 550°F. The reason for this difference is not apparent. It was postulated by the experimenter, reference (8), that this difference might be due to different stress concentration relief at the higher temperature. If so, this is a strong function of the film composition, since film I showed a marked improvement with irradiation in the 400°F evaluation.

Further data will be published by the Midwest Research Institute on similar tests conducted on neutron irradiated samples.

Conclusions and Future Plans

Based on the preliminary data thus far, it becomes evident that there is great promise for using solid film lubricants at extended temperatures and in the presence of nuclear radiation.

Studies to date have been mainly devoted to evaluation of the properties of commercial products of unknown composition. Research in the future will include basic studies of binder mechanisms, investigations of optimum lubricant-binder ratios and compositions, and study of the effects of radiation dose, dose rate, and temperature. Particular emphasis will be placed on evaluation in a radiation field.

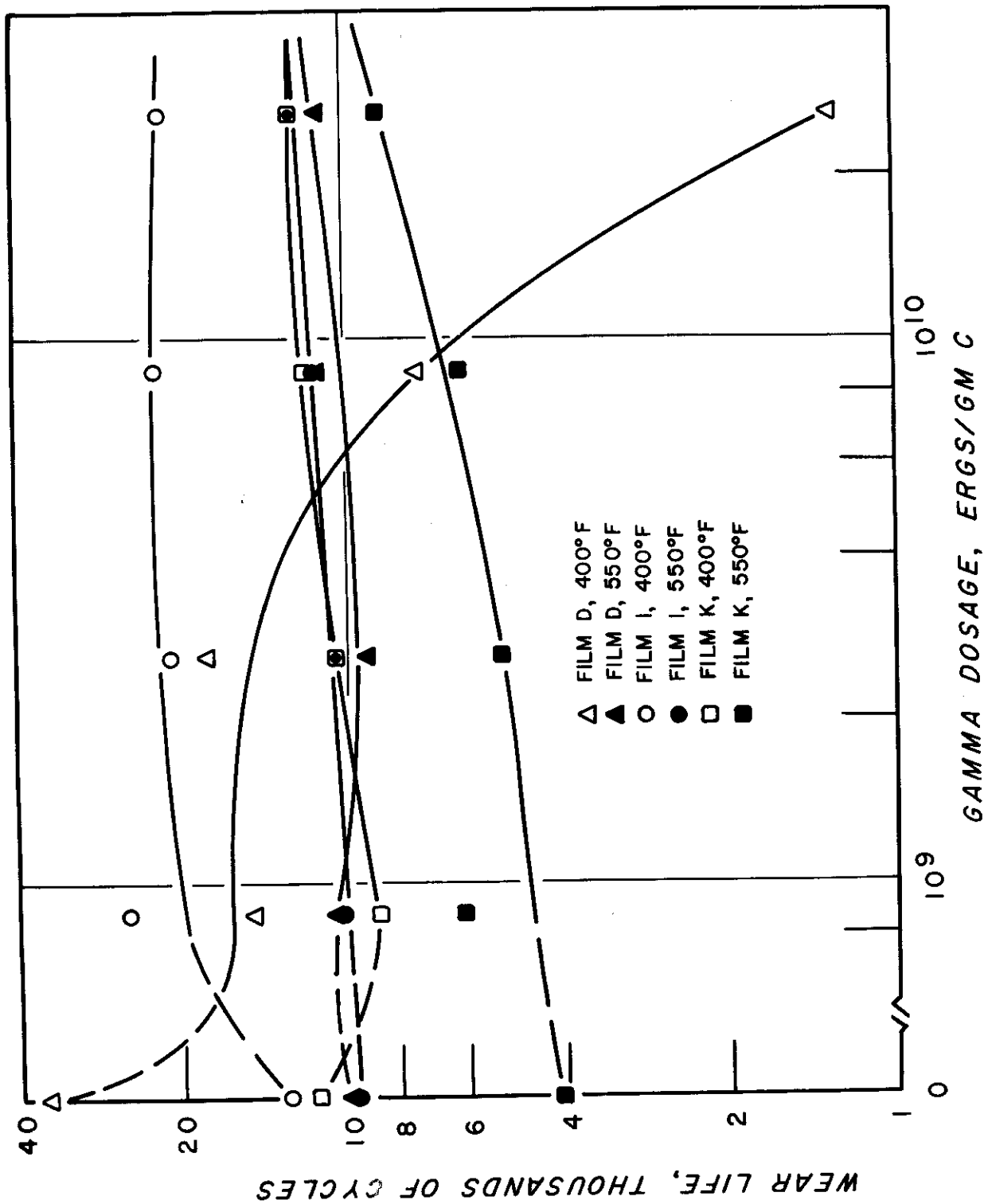


FIGURE 4. SOLID FILM WEAR LIFE AT 400°F. AND 550°F.

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Work on stability of glass fiber reinforced plastic laminates to nuclear radiation has indicated a very interesting trend. Certain phenolic resins have actually shown improvement when irradiated at 500°F in the presence of gamma radiation as compared to the control held at the same temperature for the same time. They have also shown the highest stability to gamma radiation of the various resin types. Thus, the phenolics will receive major attention as binder materials for low temperature films.

Unlike other lubricant compositions, the solid film lubricants have a different reaction to reactor radiation. Since the binder and lubricant are in the solid form rather than liquid, solid state radiation effects become of importance. It is therefore planned to devote considerable effort to the study of reactor irradiation on the graphite used in solid film lubricants in order to determine the effect on the lubricity characteristics. Also to be studied will be the effect of reactor irradiation at temperature, to find the rate of defect annealment, if any, and its influence on lubricity characteristics.

Future contract research will emphasize studies of glassy ceramic binders with lubricating additives such as molybdenum disulfide, graphite, cadmium chloride, and lead oxide. Cermet materials will also be examined. The most attractive of the formulations studied will then be evaluated for resistance to nuclear radiation. Based on knowledge obtained to date, it is felt that substantial increases will be made in the stability of solid film lubricants to nuclear radiation.

Particular note should be made of Appendix IV, page 30, which is the list of vendors supplying the coatings to the panels and Falex sets summarized in Tables I through V.

TABLE I. FLUID RESISTANCE OF IRRADIATED SOLID FILM LUBRICANT COATED ALUMINUM PANELS (ADHESION TEST)

Gamma Dosage*		0		2.61 x 10 ¹⁰	8.71 x 10 ¹⁰	2.61 x 10 ¹¹
Coating	Solvent					
A	MIL-H-3136	No discoloration, trace of powder, tendency to flake	No discoloration, trace of powder	No discoloration, trace of powder	No discoloration, powder	No panels
	MIL-H-5606	No discoloration, trace of powder, tendency to flake	No discoloration, powder, 90% flaking not to metal	No discoloration, powder, 90% flaking not to metal	No discoloration, powder	No discoloration, powder
	MIL-L-7808	No discoloration, trace of powder, tendency to flake	No discoloration, trace of powder	No discoloration, trace of powder	No discoloration, powder	No discoloration, powder
	MIL-H-8446	No discoloration, trace of powder, tendency to flake	No discoloration, trace of powder	No discoloration, trace of powder	No discoloration, trace of powder	No discoloration, trace of powder
	DC-550	No discoloration, trace of powder, tendency to flake	No discoloration, trace of powder	No discoloration, trace of powder	No discoloration, trace of powder	No discoloration, trace of powder
B	MIL-H-3136	No discoloration, 50% flaking not to metal	No discoloration, no powder, tendency to flake	No discoloration, no powder, tendency to flake	Nothing	No discoloration, 50% flaking not to metal
	MIL-H-5606	No discoloration, 30% flaking not to metal	No discoloration, flaking not to metal	No discoloration, flaking not to metal	No discoloration, no powder, flaking not to metal	No discoloration, 60% flaking not to metal
	MIL-L-7808	No discoloration, no flaking	No discoloration, no powder, tendency to flake	No discoloration, no powder, tendency to flake	Nothing	No discoloration, 60% flaking not to metal
	MIL-H-8446	No discoloration, flaking not to metal	No discoloration, flaking not to metal	No discoloration, flaking not to metal	Nothing	No discoloration, 5% flaking not to metal
	DC-550	No discoloration, trace of powder	No discoloration, trace of powder	No discoloration, trace of powder	Nothing	No discoloration, 50% flaking not to metal
C	MIL-H-3136	Nothing	Nothing	Nothing	Nothing	No panels
	MIL-H-5606	Nothing	Nothing	Nothing	Nothing	No panels
	MIL-L-7808	Nothing	Nothing	Nothing	Nothing	No panels
	MIL-H-8446	Nothing	Nothing	Nothing	Nothing	No panels
	DC-550	Nothing	Nothing	Nothing	Nothing	No panels
D	MIL-H-3136	No discoloration, powder	No discoloration, powder	No discoloration, powder	No discoloration, powder	No panels
	MIL-H-5606	No discoloration, powder	No discoloration, powder	No discoloration, powder	No discoloration, powder	No panels
	MIL-L-7808	No discoloration, powder	No discoloration, powder	No discoloration, powder	No discoloration, powder	No panels
	MIL-H-8446	No discoloration, powder	No discoloration, powder	No discoloration, powder	No discoloration, powder	No panels
	DC-550	No discoloration, powder	No discoloration, powder	No discoloration, powder	No discoloration, powder	No panels

TABLE I. FLUID RESISTANCE OF IRRADIATED SOLID FILM COATED ALUMINUM PANELS (ADHESION TEST) (Continued)

Gamma Dosaget		0	2.61 x 10 ¹⁰	6.71 x 10 ¹⁰	2.61 x 10 ¹¹
Coating	Solvent				
E	MIL-H-3136	No discoloration, trace of powder	No discoloration, trace of powder	Nothing	Nothing
	MIL-H-5606	No discoloration, trace of powder	No discoloration, trace of powder	Nothing	Nothing
	MIL-L-7808	No discoloration, trace of powder	No discoloration, trace of powder	Nothing	No discoloration, 1% flaking to metal
	MIL-H-8446	No discoloration, trace of powder	No discoloration, trace of powder	Nothing	Nothing
	DC-550	No discoloration, trace of powder	No discoloration, trace of powder	Nothing	Nothing
F	MIL-H-3136	No discoloration, trace of powder	No discoloration, trace of powder	No discoloration, trace of powder	No discoloration, trace of powder
	MIL-H-5606	No discoloration, trace of powder	No discoloration, trace of powder	No discoloration, trace of powder	No discoloration, trace of powder
	MIL-L-7808	No discoloration, trace of powder	No discoloration, trace of powder	No discoloration, trace of powder	No discoloration, trace of powder
	MIL-H-8446	No discoloration, trace of powder	No discoloration, trace of powder	No discoloration, trace of powder	No discoloration, trace of powder
	DC-550	No discoloration, trace of powder	No discoloration, trace of powder	No discoloration, trace of powder	No discoloration, trace of powder
G	MIL-H-3136	No discoloration, trace of powder	No discoloration, 2% flaking to metal	No discoloration, 2% flaking to metal	No panels
	MIL-H-5606	No discoloration, trace of powder	No discoloration, 2% flaking to metal	No discoloration, 2% flaking to metal	No discoloration, 30% flaking to metal
	MIL-L-7808	No discoloration, trace of powder	No discoloration, 2% flaking to metal	No discoloration, 2% flaking to metal	No discoloration, 2% flaking to metal
	MIL-H-8446	No discoloration, trace of powder	Trace of powder	Trace of powder	Trace of powder
	DC-550	No discoloration, trace of powder	No discoloration, 2% flaking to metal	Trace of powder	Trace of powder
H	MIL-H-3136	No discoloration, 100% flaking to metal	No discoloration, 2% flaking to metal	Nothing	No panel
	MIL-H-5606	Nothing	No panel	No discoloration, 2% flaking to metal	No panel
	MIL-L-7808	Nothing	Nothing	Nothing	No discoloration, 2% flaking to metal
	MIL-H-8446	No discoloration, 5% flaking to metal	Nothing	No discoloration, 10% flaking to metal	No discoloration, 2% flaking to metal
	DC-550	No discoloration, 50% flaking to metal	No discoloration, 2% flaking to metal	No discoloration, 2% flaking to metal	No panel

* Gamma dosages are in ergs per gram carbon.

Control

TABLE II. SALT SPRAY CORROSION OF IRRADIATED SOLID FILM COATED ALUMINUM PANELS (ADHESION TEST)

Gamma Dosage*	Control		2.61 x 10 ¹⁰		8.71 x 10 ¹⁰		2.61 x 10 ¹¹	
	Corrosion	Adhesion	Corrosion	Adhesion	Corrosion	Adhesion	Corrosion	Adhesion
A	High	Not run	High	Not run	High	Not run	High	Not run
B	None	Tendency to flake (2%)	None	Tendency to flake with some powder (2%)	None	Flaking (not to metal) (10-15%)	None	Traces of powder, flaking (not to metal)
C	None (1)	No powder	None (1)	Flaking to metal along edges (1%)	None (1)	Flaking to metal along edges (1%)	No panels	No panels
D	High (1)	Not run	No panels		High (1)	Not run	No panels	
E	None (1)	Powder	None (1)	Traces of powder	None (1)	No powder, water marked	None (1)	No powder
F	None (1)	Powder	None (1)	Powder	(3)	Powder and flaking to metal	None (1)	Powder, water marked
G	None (1)	Traces of powder	None (2)	Slight powder, flaking to metal (10%)	Slight (1)	Powder and flaking to metal (20%)	No panels	No panels
H	High (1)	Not run	High	Not run	High	Not run	High	Not run

* Gamma dosages are expressed in ergs per gram carbon.
 (1) Anodized uncoated panel corroded.
 (2) Anodized uncoated panel uncorroded.
 (3) Corrosion high and worse than anodized panel.

TABLE III. THERMAL STABILITY OF IRRADIATED SOLID FILM COATED STEEL PANELS (ADHESION TEST)

Gamma Dosage*	Control		2.61 x 10 ¹⁰		8.71 x 10 ¹⁰		2.61 x 10 ¹¹	
	-65°F	600°F	-65°F	600°F	-65°F	600°F	-65°F	600°F
Coating								
A	Slight powder, flaking not to metal (1%)	Flaking not to metal (50%)	Slight powder	Flaking not to metal (50%)	Slight powder, flaking not to metal (1%)	Flaking not to metal (50%)	No panels	No panels
B	Flaking not to metal (30%)	Flaking not to metal (95%)	Slight powder, flaking not to metal (1%)	Flaking not to metal (95%)	No panels	No panels	Flaking not to metal (1%)	Flaking not to metal (95%)
C	Nothing	No flaking	Nothing	No flaking	Nothing	No flaking	No panels	No panels
D	Powder	Powder (95%)	No panels	No panels	Powder	Powder (95%)	No panels	No panels
E	Nothing	Nothing	Nothing	Nothing	Nothing	Nothing	Nothing	Nothing
F	Powder	Traces of powder	Powder	Traces of powder	Nothing	Nothing	Nothing	Nothing
G	Nothing	Powder (95%)	No panels	No panels	Nothing	Powder (95%)	No panels	No panels
H	Nothing	Traces of powder	No panels	Traces of powder	No panels	Traces of powder	No panels	Traces of powder

* Gamma dosages are expressed in ergs per gram carbon.

TABLE IV. FALEX WEAR LIFE FOR NEUTRON IRRADIATED SOLID FILM COATED PINS AND V-BLOCKS

Neutron Dosage (nvt fast)	Control		1 x 10 ¹⁵		3 x 10 ¹⁵		1 x 10 ¹⁶		3 x 10 ¹⁶	
	Wear Life (Min.)	Total Wt. Loss (mg)	Wear Life (Min.)	Total Wt. Loss (mg)	Wear Life (Min.)	Total Wt. Loss (mg)	Wear Life (Min.)	Total Wt. Loss (mg)	Wear Life (Min.)	Total Wt. Loss (mg)
Coating A	55*	2.7	120	4.4	58*	3.2	89	4.6	52*	3.7
	81	4.1	154	6.0	38*	5.0	179	2.8	33*	4.6
	24 (53)	---	(137)	---	(48)	---	(134)	---	(43)	---
B	101*	17.4	136*	9.8	118*	11.8	99*	10.5	194	16.9
	84	11.7	119*	6.8	127*	10.2	149*	9.3	153	16.0
C	371	6.2	394	28.7	655	19.9	1045	16.0	656	26.7
	285	8.9	495	39.0	370	14.3	894	23.1	346	15.5
	538 (399)	7.7	(445)	---	(513)	---	(970)	---	(501)	---
D	Pins lost		41*	24.5	17*	---	41*	7.8	20*	---
			57*	68.3	36*	---	68*	11.8	59*	10.2
G	409	19.9	165*	17.0	216*	7.4	304*	7.7	245*	7.1
	443 (126)	17.7	152*	8.0	271*	7.4	339*	6.0	300*	7.0
H	111	10.8	69*	3.6	51*	2.7	86	2.6	9	---
	100 (106)	10.7	28*	---	116*	3.7	72	3.7	5 (7)	---

* 355 lb. load (all other data for 250 lb. load).

Notes: Values in parenthesis () represent average wear life.

TABLE V. PALEX WEAR LIFE FOR GAMMA IRRADIATED SOLID FILM COATED PINS AND V-BLOCKS

Gamma Dosage (ergs/gm C)	Control		8.71 x 10 ⁹		2.61 x 10 ¹⁰		8.71 x 10 ¹⁰		2.61 x 10 ¹¹	
	Wear Life (Min.)	Total Wt. Loss (mg)	Wear Life (Min.)	Total Wt. Loss (mg)	Wear Life (Min.)	Total Wt. Loss (mg)	Wear Life (Min.)	Total Wt. Loss (mg)	Wear Life (Min.)	Total Wt. Loss (mg)
A	55* 81 24 (53)	2.7 4.1 ---	47* 97 130 (114)	5.0 6.6 5.0	26* 5	---	33* 42	4.8 6.5	4* 71 102 (87)	---
B	101* 84	17.4 11.7	124* 113	10.4 10.9	90* 123 93 (108)	4.9 14.0 12.1	43 39 (41)	10.8 17.6	17 113 185 (105)	---
C	371 285 538 (399)	6.2 8.9 7.7	190 153 383 (242)	5.9 2.9 8.2	189 255 (222)	8.2 7.2	172 179 (326)	5.3 9.7	513 189 (351)	9.6 7.4
D	Pins lost		58 9 (34)	3.4 ---	106 7 (57)	2.9 ---	74 116 69 (86)	2.6 3.1 3.0	65 111 (88)	3.8 3.2
E	25 43 (34)	9.8	16 9 (13)	---	20 11 14 (15)	---	52 11 7 (23)	6.9 ---	101 136 (120)	10.5 8.6
F	3 4	---	3 3	---	2 1	---	2 2	---	3 3	---
G	409 443 (426)	19.9 17.7	504 349 (427)	27.6 18.1	423 528 (476)	37.4 32.7	319 693 (506)	17.9 33.6	475 521 (498)	19.8 18.3
H	111 100 (106)	10.8 10.7	39 84 (57)	11.2 9.4	63 92 (79)	17.0 5.0	32 89 (57)	24.7 8.4	88 74 (77)	8.1 7.4

* 355 lb. load (all other data for 250 lb. load).
Note: Values in parenthesis () represent average wear life.

TABLE VI. WEAR-LIFE TEST RESULTS FOR LUBRICANTS EXPOSED TO GAMMA IRRADIATION

Gamma Dosage (ergs/gm C)	Control	8.71 x 10 ⁸	2.61 x 10 ⁹	8.71 x 10 ⁹	2.61 x 10 ¹⁰
Coating					
	Control	8.71 x 10 ⁸	2.61 x 10 ⁹	8.71 x 10 ⁹	2.61 x 10 ¹⁰
Coating	Control	8.71 x 10 ⁸	2.61 x 10 ⁹	8.71 x 10 ⁹	2.61 x 10 ¹⁰
D	35.7* 9.9	14.8 10.4	18.0 9.1	7.3 11.2	1.3 11.0
I	12.8 9.7	25.1 10.1	20.8 10.3	22.0 11.4	21.6 12.3
J	0.71 Not run	----	0.22	0.60	0.38
K	11.4 4.1	8.8 6.1	10.3 5.2	11.7 6.1	12.2 8.6

* Wear life, thousands of cycles.

Test conditions:

- Load - 400 pounds
- Speed - 130 ft/min (375 cycles/min)
- Thickness - Approximately 0.0004 in.
- Motion - Unidirectional
- Substrate hardness - 40-45 Rc
- Machine - Hohman Friction Machine, Model A-3
- Timken cups (Part No. T-54148)
- Irradiated in MTR gamma canal.

Data from reference (8).

TABLE VII. EVALUATION OF SOLID FILM LUBRICANTS IN THE PRESENCE OF GAMMA RADIATION

Coating	Relative Humidity (%)		Ambient Temperature (°F)		Steady State Temperature (°F)	Wear Scar Area (sq. in.)	Radiation to Failure (ergs/gm C)	Wear Life (Hours)
	Start	End	Start	End				
C	69	60	72	76	158	0.0267	None	85.5
	59	60	76	75	146	0.0230	None	20.7
	66	66	75	76	160	0.0273	None	14.7
	69	68	75	71	155	0.0204	None	60.6
			67	67	144	0.0209	8.85 x 10 ⁸	34.7
G	66	61	77	73	139	0.0164	None	151.9
	54	55	75	75	138	0.0229	None	87.7
	65	78	74	76	150	0.0167	None	77.2
			67	67	124	0.0158	1.58 x 10 ⁹	60.6(1)
K	70	74	76	74	157	0.0231	None	17.8
	61	61	75	79	140	0.0192	None	33.9
	69	67	75	76	150	0.0233	None	7.5
	63	53	75	79	156	0.0188	None	48.2(1)
			67	67	147	0.0200	5.87 x 10 ⁸	20.2(1)
L	51	74	76	76	145	0.0172	None	129.7
	74	58	74	78	140	0.0202	None	114.7
	62	66	76	75	144	0.0263	None	79.8

(1) Tests interrupted for approximately 5 hours due to power failure. Load was removed before re-starting and replaced gradually.

Test conditions:

Load - 630 pounds

Speed - 72 ± 2 rpm

Machine - Hartmann-Modified MacMillan

Timken cups (Part No. T-54148)

Irradiated in Inland Testing Laboratory's 52,000 Curie Co-60 source (all test results in this table were obtained under Contract AF 33(616)-3865.

Tested according to CRC method dated 2 February 1958, Appendix B.

APPENDIX I
IRRADIATION HISTORY OF TEST SPECIMENS

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Gamma Irradiations

The metal test panels and Falex sets exposed to gamma radiation and tested as shown in Tables I through V were irradiated in the gamma canal of the Materials Testing Reactor, Arco, Idaho. For details of exposure techniques and dosimetry, a summary is given in reference (9). Such information will not be presented herein.

For each gamma dosage, five coated steel and eight coated aluminum panels were irradiated for each solid film lubricant studied. Also, two anodized, uncoated aluminum comparison panels were irradiated to each given dosage. The panels were irradiated in packs, each pack consisting of two or three steel panels in the center with two aluminum panels on each side. These packs were mounted vertically in the standard irradiation canisters at the midplane and exposed in the gamma canal.

All gamma dosages are given in terms of the unperturbed fuel element array, that is, before the canisters with contents were inserted. Therefore, no corrections have been made for attenuation in the canister wall or in the outer panels shielding the interior panels. This should be carefully noted, since the gamma exposures are to be considered as nominal rather than absolute and serve to give comparative effects of increasing gamma irradiation only.

For each gamma dosage, three sets of Falex pins and V-blocks were irradiated for each solid film lubricant studied. Each set, consisting of one Falex pin and two V-blocks, was irradiated with the notch of each V-block facing outward from the vertically positioned pack. As in the case of the test panels, no attenuation corrections were made either for the canister or its contents. The wear data given in Tables IV and V should be considered therefore as based on comparative exposures and not on well defined exposures to the coatings.

Neutron Irradiations

Only Falex sets were exposed to neutron irradiation. For each solid film lubricant studied, three Falex sets were irradiated to each of the given dosages. Exposures were in the X-10 reactor at Oak Ridge, Tennessee. Information pertinent to the irradiations is as follows:

Relative thermal neutron flux: $6.50 \pm 0.05 \times 10^{11}$ n/cm²/sec

Epithermal (cadmium ratio): 10.8

Contrails

Fast neutron dosages:

neutrons above 2.9 mev	2.0×10^9 n/cm ² /sec
neutrons above 6.3 mev	$1.40 \pm 0.06 \times 10^9$ n/cm ² /sec
neutrons above 8.1 mev	$0.93 \pm 0.01 \times 10^9$ n/cm ² /sec

The above data were obtained by the use of Co-Al, S, Al, and Mg monitors.

APPENDIX II

EFFECT OF GAMMA RADIATION ON A SINTERED METAL LUBRICATING MATERIAL

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TABLE VIII. EFFECT OF GAMMA RADIATION ON THE FALEX WEAR OF A SINTERED METAL LUBRICATING MATERIAL

Gamma Dosage (ergs/gm C)	Run 1	Run 2	Run 3	Average
None	22.1 ⁽¹⁾	29.2	53.9 ⁽²⁾	25.7
2.61×10^9	(3)	(4)	(5)	----
8.71×10^9	32.7	30.1	28.9	30.6
2.61×10^{10}	18.4	32.6	24.7	25.2
8.71×10^{10}	26.3	22.5	26.7	25.2

(1) Weight loss in mg (after run).

(2) At 200 pound load.

(3) Pin sheared after 9 minutes, gummy substance deposited during run.

(4) Pin sheared after 14 minutes, gummy substance deposited during run.

(5) Pin sheared after 18 minutes, gummy substance deposited during run.

Test conditions:

Load - 100 pounds for 30 minutes

Speed - 290 rpm

Machine - Falex Lubricant Testing Machine

Samples irradiated in the WADC 1500 Curie Cobalt-60 pipe

Pins were cleaned with fine sand paper, washed with naphtha, and oven dried for 30 minutes at 120°F prior to testing. The pins were then run on standard steel V-blocks.

APPENDIX III

FALEX MACHINE EVALUATION OF DEVA METALS

Falex Machine Evaluation of Deva Metals

The purpose of this evaluation was to investigate four Deva Metal types to determine if any show superiority to commercial dry film lubricants. A chemical analysis was conducted concurrently to allow nuclear activation calculations should any of the metals prove attractive enough to merit reactor irradiation for purposes of studying their nuclear radiation resistance.

Deva Metal, a "self-lubricating" bearing material, has potential interest in areas where environmental conditions preclude the use of conventional lubricants. Examples would be areas of extreme high or low temperature. It would also be of interest for use in the presence of nuclear radiation where organic lubricants are readily degraded and lose their lubricating characteristics.

Four Deva Metal types were machined to standard Falex Pin size and evaluated on the Falex Test Machine using conventional steel V-blocks. The results of the testing are shown in Table IX. Chemical analyses of the metals are given in Table X.

The Deva Metal specimens were first run at a 500 pound jaw load on the Falex machine. At this load, the pins machined to such an extent that results could not be obtained. It was evident that test conditions were too severe so the pins were then tested at 50 and 100 pound jaw loads. Under these lighter loads, the metals gave similar results, either machining to such an extent that jaw load could not be maintained or breaking at the shear pin.

Uncoated steel Falex Pins were run under the same loads against bare V-blocks. Machining again took place at an even greater rate than for the Deva Metal pins. By comparison, certain commercial solid film lubricants, when coated on similar steel pins, give the following results: When run at a 500 pound jaw load for the standard one-half hour, weight losses were obtained varying from 0.6 mg up to 250 mg, depending on the coating used. Average values for the better coatings are about 10 to 12 mg weight loss for the pin following this test.

On the basis of the tests conducted, it can be concluded that when compared with commercial solid film lubricants, the four Deva Metal types evaluated perform quite poorly when tested on the Falex machine. However, when compared to bare steel on steel, they show a superiority, limited though it might be. It should be noted that the conclusions reached herein are valid only with respect to the conditions described. Under lighter loads, it is quite possible that Deva Metals would show superior qualities to other methods of lubrication, especially at elevated temperatures where organic solids would tend to decompose.

Contrails

As a result of the testing described above, it was decided to discontinue further evaluation of the Deva Metal specimens and to abandon plans to subject them to nuclear radiation. With the test apparatus used, the Faalex Test Machine, the test conditions were so severe that it would not be possible to determine what effect, if any, nuclear radiation would have on the metal properties. Any decrease in the already poor qualities measured would not show up as a significant change in the metal capabilities.

It is felt that in applications where use of solid film lubricants is required, Deva Metals of the type described herein be used only if solid film lubricants can be shown to be inferior.

TABLE IX. FALEX MACHINE EVALUATION OF DEVA METALS

Pin Composition	Run #	Time to Failure (minutes)	
		50 lb. load	100 lb. load
Steel (1)	1	2	1
1F-15-S4	1	2 (Broke)	1 (Broke)
	2	3 (Broke)	2 (Broke)
1F-10-S5	1	12	0.2668 gm wt loss ⁽²⁾
	2	16	0.2601 gm wt loss ⁽³⁾
2N-15-S4	1	17	24
	2	18	20
2N-8-S2	1	17	12
	2	16	14
	3	--	9

- (1) SAE 3140 or 3145 steel
- (2) Original weight was 6.9458 gm
- (3) Original weight was 6.9640 gm

Note: All tests were run at 295 rpm (or 19.3 ft./min.) and room temperature (about 75°F). Steel V-blocks were used for all tests, the composition being SAE 1141 or 1144 steel. Failure time is the time at which the pins machined to such an extent that the jaw load could not be maintained. No pins were weighed, since the tests did not run full half hour (except for the 1F-10-S5).

TABLE X. CHEMICAL ANALYSIS OF DEVA METALS

Metal Type	1F-15-S4	1F-10-S5	2N-15-S4	2N-8-S2
% Carbon (total)	13.75	9.31	13.59	6.90
% Iron	79.38	83.85	-----	-----
% Nickel	-----	-----	79.32	87.13
% Copper	3.47	3.54	3.93	3.94
% Aluminum	1-3.4(1)	1-3.3(2)	1-3.2(3)	1-2.0(4)

(1) The aluminum, which is approximately 10 times as great as any other element, plus silicon, magnesium, calcium, manganese, tin, and chromium constitute the remainder.

(2) The aluminum, which is approximately 10 times as great as any other element, plus silicon, magnesium, calcium, manganese, tin, chromium, and titanium constitute the remainder.

(3) The aluminum, which is approximately 10 times as great as any other element, plus silicon, magnesium, calcium, manganese and tin constitute the remainder.

(4) The aluminum, which is approximately 10 times as great as any other element, plus silicon, magnesium, lead, calcium, manganese, and tin constitute the remainder.

APPENDIX IV
LIST OF VENDORS

Contrails

The following list gives the addresses of the vendors supplying the coatings to the panels and Falx sets summarized in Tables I through V:

<u>Company</u>	<u>Product</u>
Acheson Colloids Company Attn: Mr. F. M. Hunter Sales Engineering Lab. Port Huron, Michigan	'Dag' Dispersion #213 'Dag' Dispersion #223
Electrofilm, Incorporated Attn: Mr. Ralph E. Crump Chief Engineer Post Office Box 106 7116 Laurel Canyon Boulevard North Hollywood, California	Solid Film Lubricant #4396 Solid Film Lubricant #4856
Everlube Corporation of America Attn: Mr. A. R. Booker Exec. Vice President 6940 Farndale Avenue North Hollywood, California	Everlube #620 Everlube #810
McGee Chemical Company, Inc. Attn: Mr. Zell G. McGee President 8000 West Chester Pike Upper Darby, Pennsylvania	McLube MoS ₂ -830 McLube MoS ₂ -835
Deva-Metal Corporation Attn: Mr. Charles G. Welchman President Post Office Box 146 Ridgewood, New Jersey	Deva-Metals

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