

MTL TR 88-36

AD

# EVALUATION OF SOLID LUBRICANTS: TEMPERATURE PROGRAMMED DESORPTION OF MoS<sub>2</sub> ON MOLYBDENUM AND OF ION-IMPLANTED MoS<sub>2</sub> ON MOLYBDENUM

AD-A203 741

RICHARD P. BURNS and DANIEL E. PIERCE  
UNIVERSITY OF ILLINOIS AT CHICAGO

HELEN M. DAUPLAISE, KENNETH A. GABRIEL,  
and LAWRENCE J. MIZERKA  
MATERIALS SCIENCE BRANCH

November 1988

Approved for public release; distribution unlimited.

DTIC  
ELECTE  
30 JAN 1989  
S D  
E



US ARMY  
LABORATORY COMMAND  
MATERIALS TECHNOLOGY LABORATORY

U.S. ARMY MATERIALS TECHNOLOGY LABORATORY  
Watertown, Massachusetts 02172-0001

89 1 27 051

The findings in this report are not to be construed as an official Department of the Army position, unless so designated by other authorized documents.

Mention of any trade names or manufacturers in this report shall not be construed as advertising nor as an official indorsement or approval of such products or companies by the United States Government.

**DISPOSITION INSTRUCTIONS**

Destroy this report when it is no longer needed.  
Do not return it to the originator.

UNCLASSIFIED

SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

REPORT DOCUMENTATION PAGE		READ INSTRUCTIONS BEFORE COMPLETING FORM
1 REPORT NUMBER MTL TR 88-36	2 GOVT ACCESSION NO.	3 RECIPIENT'S CATALOG NUMBER
4 TITLE (and Subtitle) EVALUATION OF SOLID LUBRICANTS: TEMPERATURE PROGRAMMED DESORPTION OF MoS <sub>2</sub> ON MOLYBDENUM AND OF ION-IMPLANTED MoS <sub>2</sub> ON MOLYBDENUM		5 TYPE OF REPORT & PERIOD COVERED Final Report
		6 PERFORMING ORG REPORT NUMBER
7 AUTHOR(s) Richard P. Burns,* Daniel E. Pierce,* Helen M. Dauplaise, Kenneth A. Gabriel, and Lawrence J. Mizerka		8 CONTRACT OR GRANT NUMBER(s)  DAALO4-86-K-0003
9 PERFORMING ORGANIZATION NAME AND ADDRESS U.S. Army Materials Technology Laboratory Watertown, Massachusetts 02172-0001 SLCMT-EMS		10 PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS D/A Project: 1L161101A91A AMCMS Code: 611101.91A0011 Agency Accession: DA308489
11 CONTROLLING OFFICE NAME AND ADDRESS U.S. Army Laboratory Command 2800 Powder Mill Road Adelphi, Maryland 20783-1145		12 REPORT DATE November 1988
		13 NUMBER OF PAGES 24
14 MONITORING AGENCY NAME & ADDRESS (if different from Controlling Office)		15 SECURITY CLASS (of this report)  Unclassified
		15a DECLASSIFICATION/DOWNGRADING SCHEDULE
16 DISTRIBUTION STATEMENT (of this Report)  Approved for public release; distribution unlimited.		
17 DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)		
18 SUPPLEMENTARY NOTES  *Department of Chemistry, University of Illinois at Chicago.		
19 KEY WORDS (Continue on reverse side if necessary and identify by block number)  Solid lubricants, Surface analysis X-ray photoelectron Molybdenum disulfide Thermal degradation spectroscopy. JFS Mass spectrometry Thermal stability		
20 ABSTRACT (Continue on reverse side if necessary and identify by block number)  (SEE REVERSE SIDE)		

Block No. 20

## ABSTRACT

Thermal programmed desorption (TPD) is utilized in order to assess the lubricating properties of metal dichalcogenide films applied to a number of metal substrates. TPD spectra documenting desorption and decomposition products were analyzed for MoS<sub>2</sub> burnished on molybdenum metal with and without subsequent 86 kV nitrogen ion implantation. Desorption order, rate, energy, and the pre-exponential of evolved lubricant and nitrogen species from the molybdenum substrates were determined. The surface chemistry of heated lubricant-substrate system was investigated by means of X-ray photoelectron spectroscopy (XPS). The results presented clearly indicate that the mass spectroscopic TPD techniques developed for this investigation coupled with careful surface analysis yield critical in situ assessment of the capability and the operational limits of this and other solid lubrication systems.

# CONTENTS

	Page
INTRODUCTION . . . . .	1
EXPERIMENTAL. . . . .	2
<b>RESULTS</b>	
Electron Micrographs . . . . .	4
MoS <sub>2</sub> Coated Non-Implanted (C). . . . .	4
XPS Spectra. . . . .	6
MoS <sub>2</sub> Coated, Ion-Implanted Metal (CI). . . . .	6
DISCUSSION. . . . .	8
CONCLUSIONS . . . . .	9
ACKNOWLEDGMENTS . . . . .	10
REFERENCES. . . . .	21

Accession For	
NTIS GRA&I	<input checked="" type="checkbox"/>
DTIC TAB	<input type="checkbox"/>
Unannounced	<input type="checkbox"/>
Justification	
By _____	
Distribution/ _____	
Availability Codes	
Dist	Avail and/or Special
<b>A-1</b>	



## INTRODUCTION

The need for advanced materials for use in either high temperature and/or high vacuum and space environments have recently promoted significant research and development efforts<sup>1-7</sup> in the area of solid lubrication technology. Although several metals, metal oxides, metal halides, metal sulfides, metal selenides, and other compounds and mixtures of compounds have been shown to exhibit good solid lubrication properties, metal dichalcogenides in general and molybdenum disulfide<sup>8-10</sup> in particular have emerged as the most promising candidates for solid lubrication in a number of important vacuum and space applications.

The structure of  $\text{MoS}_2$ ,<sup>11</sup> shown in Figure 1, is characterized by a layer configuration which consists of a hexagonal layer of Mo atoms sandwiched between two planes of hexagonal sulfur atoms. The atoms are arranged so that the sulfur planes are staggered with respect to the plane of metal atoms allowing each Mo atom to be placed at the center of a trigonal prism formed by the surrounding six sulfur atoms. A consequence of this structure is that relatively weak forces between the sulfur-sulfur planes account for the excellent lubricating properties similar to those of graphite and other similar layered structures.

The deleterious effects of environmental conditions on the performance of these materials are two critical engineering parameters which have been examined by several tribologists<sup>12-14</sup> in order to optimize these compound's lubricity for specified application conditions. In this work we utilize the method of thermal programmed desorption (and/or decomposition) (TPD) to determine the desorption and/or decomposition kinetics of burnished and nitrogen ion- beam mixed  $\text{MoS}_2$  films on molybdenum.

Thermal programmed desorption<sup>15-17</sup> is a technique in which the temperature of an adsorbed film or coating on a surface of interest is raised from an ambient or low temperature in a programmed manner, usually linearly with time, and the resulting desorbed, evaporated, or decomposed species are monitored and recorded by a suitable detector, usually a mass spectrometer. This process yields a spectrum of the rate of

evolution of various species from the surface as a function of surface temperature. Analysis of sets of TPD spectra yield kinetic information on the bonding of the film or coating to the surface, as well as provide insight into the processes occurring at the surface and leading to the evolution of the evaporated species.

The present work was undertaken in order to assess the usefulness of the TPD technique in the analysis of the high temperature degradation mechanisms of lubricating metal dichalcogenide films applied to various systems. A better understanding of such degradation mechanisms can lead to the development of improved preparation techniques, improved application techniques, and also the development of surface modification techniques capable of blocking particular degradation pathways.

In this report of phase one activity, results on the modification of a MoS<sub>2</sub> film by ion implantation are also presented. Ion implantation can introduce high energy, metastable states into the metal-film systems and in principle the presence of these metastable states can modify the properties of the lubricating film-metal system.

This phase of our effort focuses on the effect of temperature not only as a degradative process, but also as a diagnostic tool for investigating solid lubricant systems. In particular, TPD spectra are presented for: molybdenum metal; ion-implanted molybdenum metal; ion-implanted MoS<sub>2</sub> coated molybdenum metal; and MoS<sub>2</sub> coated molybdenum metal which was not ion implanted, but the MoS<sub>2</sub> was applied by various burnishing techniques.

## EXPERIMENTAL

The TPD evaluation system shown in simplified form in Figure 2 has been developed in order to study the gaseous species evaporating at elevated temperatures from solid lubricant coated surfaces. It consists of a pumping chamber which includes a 400 l/s ion pump and a titanium sublimation pump and an experimental chamber separated from the pump by a gate valve. After baking overnight at 370 K, the base pressure was in the low 10<sup>-9</sup> Torr range. The sample holder conveniently held three samples but could be used to hold several more. Each sample was positioned so that when heated the gaseous

species evaporating from the surface could enter the mass spectrometer ionizer by a line of sight path. The mass spectrometer is a Finnigan Model 1015 quadrupole mass spectrometer modified for molecular beam studies. Mass and transmission calibration was performed by introducing perfluorotributylamine which has a known fragmentation pattern.

Finely ground crystals of  $\text{MoS}_2$  were applied to clean etched 0.002-inch-thick molybdenum metal foils. The lubricants were burnished onto a defined area of one side of the foil with a paper lab wipe, a nylon wiper, or a clean tantalum foil. About 100 micrograms  $\text{cm}^{-2}$   $\text{MoS}_2$  adhered to the paper-rubbed metal surface as determined with a Cahn RH electrobalance. This amount of  $\text{MoS}_2$  constitutes a coating containing 375 layers or 2300 Å thick. Chemical analysis indicates that the  $\text{MoS}_2$  powder used in this investigation contains between 1.6 and 1.9% carbon (depending on the sample) and less than 0.3% oxygen for all samples. The amount of carbon impurity is equivalent to one carbon for every 3.8 to 4.6 formula units of  $\text{MoS}_2$ .

The coated foils were attached to specially designed holders. These holders enabled resistive heating of the metal foil to temperatures higher than 2000 K. A calibrated 3% Re/W-25% Re/W thermocouple pair was spot welded to the back of the sample for temperature measurement. The thermocouple signal was compared to a reference voltage and the difference was used to control the output of the heater power supply. The reference voltage was programmable and was adjusted to give a ramp rate of 7.5 degrees  $\text{sec}^{-1}$ .

A Teknivent Model 1050 mass spectrometer data system controlled the quadrupole, recorded ion currents and temperature, and initiated the heating of the sample. Experiments were first undertaken to survey the entire mass spectrum as the sample temperature was ramped. Next, the experiment was repeated and only those masses indicated by the survey were recorded, greatly increasing the signal to noise ratio. The lowest mass monitored was carbon at 12 amu. The high mass limit of the quadrupole was about 750 amu and this allowed the gaseous molybdenum oxide species  $(\text{MoO}_3)_x$ , ( $x = 1, 2, 3, 4$ ) to be monitored.

X-ray photoelectron spectra (XPS) were taken for coated foil samples in both the survey and high resolution mode. The MTL Leybold-Hereaus LHS-12 Surface Analysis System was used to obtain these spectra. It includes a hemispherical electron energy analyzer, Mg and Al X-ray anodes, and a heated probe capable of heating samples to 950 K.

Some of the coated foils were ion-beam modified with nitrogen ions. The implantation was performed with the MTL Zymet system. An 86 keV ion beam consisting of nitrogen ions ( $N^+$  and 10%  $N_2^+$ ) was used. A 4 ma beam current was maintained for 92 minutes giving a total dose of  $2 \times 10^{17}$  ions  $cm^{-2}$ . Foil samples were attached to an aluminum plate, and during the implantation the temperature which was measured with a thermocouple reached  $177 \text{ }^\circ\text{C} \pm 17 \text{ }^\circ\text{C}$ .

A JEOL JSM-35C scanning electron microscope was used to study the physical appearance of the metal surface and the  $MoS_2$  coated metal surface before and after ion implantation.

## RESULTS

### Electron Micrographs

A comparison of Figures 3 and 4 illustrates the smoothing and compacting effect of burnishing the  $MoS_2$  crystals. From Figures 5 and 6, the surface modification caused by the ion implantation of molybdenum can be seen. A comparison of Figures 4 and 7 demonstrates the dramatic effect of the ion implantation process on the  $MoS_2$  coating. Figures 8 and 9 show this dramatic effect at higher magnification, and clearly indicate surface reconstruction.

### $MoS_2$ Coated Non-Implanted(C)

The decomposition of the coating starts as low as approximately 565 K (292  $^\circ\text{C}$ ). This low temperature decomposition results in  $SO_2$  vaporization. At higher temperatures both  $S_2$  and  $CS_2$  vaporize.

1. Low Temperature Mass 64 Peak (see Figure 10) - Though both  $S_2$  and  $SO_2$  molecules have masses of 64, the isotope ratio between mass 64 and mass 66 indicates  $SO_2$  instead of  $S_2$ . The maximum rate of vaporization occurs near 700 K. The peak shape suggests second order kinetics with an activation energy for vaporization of 19 kcal mol<sup>-1</sup> and a pre-exponential factor of  $1 \times 10^{10}$ .

2. High Temperature Mass 64 Peak (see Figure 10) - Based on the isotope ratio and fragmentation pattern, this peak was found to represent vaporization of  $S_2$  molecules. This mass 64 peak represents a major fraction of the total volatile sulfur species formed during coating decomposition. The peak begins at about 1140 K and reaches a maximum rate of vaporization at 1465 K. The peak shape indicates first order kinetics, with an activation energy of 81 kcal mol<sup>-1</sup> and a pre-exponential factor of  $5 \times 10^{11}$ .

3. High Temperature Mass 76 Peak (see Figure 10) - The peak at mass 76 represents vaporization of  $CS_2$  molecules. This peak is comparable in size to the mass 64 peak, but is more complex. Both the mass 64 and mass 76 peaks have their maximum rate of vaporization at 1465 K. In the area immediately surrounding this temperature, the mass 76 peak has nearly the same shape as the 64 peak. Features indicating smaller peaks begin to appear at about 150 degrees on either side of the main mass 76 peak. Analysis of the main peak indicates first order kinetics with an activation energy of 80 kcal mol<sup>-1</sup> and a pre-exponential factor of  $2 \times 10^{11}$ .

4. The Effect of Burnishing on the Mass 76 Peak (See Figure 11) - Clean Ta metal which is not a source of carbon shows one main peak with a low temperature shoulder in the bottom panel of Figure 11. This low temperature peak is seen in the spectra for both the nylon and paper-rubbed samples. Paper rubbing induces a substantial high temperature  $CS_2$  state as shown in the top panel of Figure 11. The nylon-rubbed sample shows peak broadening due to the presence of these two additional states as indicated in the middle panel of Figure 11.

5. Evidence for Interaction of  $H_2O$  with the  $MoS_2$  Coating (see Figure 12) - The top panel of Figure 12 shows the simultaneous production of  $H_2O$  and  $SO_2$ . It is well known that water oxidizes  $MoS_2$  and causes degradation of lubrication properties<sup>14</sup>.

6. Other Sulfur Species (See Figure 12) - Elemental sulfur vaporizes to various polymers ( $S_8$ ,  $S_6$ , . . .). The  $MoS_2$  coating vaporizes primarily as  $S_2$ , however some  $S_4$  is observed as illustrated in the bottom panel of Figure 12.

### XPS Spectra

Recent enhancements to the MTL Leybold-Heraeus LHS-12 Surface Analysis System have enabled the acquisition of XPS spectra before and after heating the  $MoS_2/Mo$  sample to 450 °C. Figure 13 shows an XPS survey spectrum which was taken before any surface treatment, including heating, took place. Figure 14 shows the molybdenum 3d peaks before heating. The peak at 228.9 eV is interpreted as one of a pair of Mo 3d (IV) peaks. The peak at 232.1 is interpreted as the sum of Mo 3d(VI) and the Mo 3d(IV) lines. The peak at 235 eV is interpreted as one member of a pair of Mo 3d(VI) peaks. Based on these assumptions, a synthesized Mo 3d spectrum based on  $MoS_2$ ,  $MoO_2$ , and  $MoO_3$  is shown in Figure 14 along with the experimental points. The agreement is satisfactory.

Figure 15 shows a survey spectrum of the  $MoS_2$  surface after heating to 450 °C. It should be noted that this temperature is high enough to desorb the water and  $SO_2$ . Figure 16 shows the Mo 3d peaks after heating. Note that the peak at 235 eV is now missing and the Mo 3d peak pair ratio more nearly corresponds to that for  $MoS_2$ . Figure 16 also shows a synthesized Mo 3d spectrum based on  $MoS_2$  and  $MoO_2$  along with the experimental points obtained after heating. The agreement is satisfactory.

### $MoS_2$ Coated, Ion-Implanted Metal (CI)

The decomposition of the coated ion-implanted sample (CI) is distinctly different from that of the coated, non-implanted (C) sample. There is a marked reduction in the  $SO_2$  peak, and the  $S_2$  and  $CS_2$  peaks are shifted to lower temperatures. The nitrogen implantation of molybdenum metal and  $MoS_2$  coated molybdenum metal resulted in nitrogen vaporization as monitored at mass 14.

1. Low Temperature SO<sub>2</sub> Peak (see Figure 17) - This peak with a maximum in the 700 K region is due to SO<sub>2</sub> vaporization. The relative magnitude of the ion-implanted SO<sub>2</sub> peak is greatly reduced compared to the non ion-implanted sample. Figure 17 shows a comparison between the SO<sub>2</sub> and H<sub>2</sub>O peaks.

2. High Temperature S<sub>2</sub> and CS<sub>2</sub> Peaks (see Figure 18) - The top panel in Figure 18 shows that the major mass 64 peak due to S<sub>2</sub> vaporization occurs at 1378 K. This is 87 degrees lower than the major peak of the coated non-implanted sample. On the low temperature side of the 1378 K peak, a smaller unresolved peak has been produced.

The mass 76 spectrum shown in the lower panel of Figure 18, due to CS<sub>2</sub> vaporization, is characterized by a combination of at least three peaks. The only resolved peak is the largest one which is found at 1378 K, precisely the same temperature as the major S<sub>2</sub> peak. As in the case of the 64 peak, on the low temperature side, there exists a smaller unresolved peak. On the high side of the CS<sub>2</sub> peak, slow tailing suggests another small unresolved peak.

3. Nitrogen Mass 14 Peak (see Figure 19) - The nitrogen vaporization from molybdenum metal and from MoS<sub>2</sub> coated molybdenum metal is shown in the top panel of Figure 19. In both cases the spectra show that the nitrogen is released from discrete states. For the metal alone, a large peak at 1248 K and a small peak at 1413 K are observed. For the coated sample the main peak occurs at 1428 K. It may be noted that the presence of the coating has caused a 180 degree increase in the nitrogen release temperature.

The lower panel of Figure 19 shows that a large fraction of the sulfur is released before the nitrogen release reaches its maximum. One may also note the simultaneous release of nitrogen and sulfur for the minor states occurring at approximately 1050 K.

## DISCUSSION

1. The Low Temperature  $\text{SO}_2$  Peak (see Figures 10, 12, and 17) - The low temperature  $\text{SO}_2$  peak shown in Figures 10, 12, and 17 arises from a desorption process which obeys second order kinetics and appears to be related to the presence of water. Since the Mo 3d XPS spectrum indicates that some of the Mo(IV) was oxidized to Mo(VI) on the surface, one possible mechanism for the production of  $\text{SO}_2$  may involve the reaction between the  $\text{MoS}_2$  and oxygen containing species. The area of the low temperature  $\text{SO}_2$  TPD peak is 20 % of the area of the high temperature  $\text{S}_2$  peak as shown in Figure 10. This comparison indicates that  $\text{SO}_2$  production can be an important pathway leading to lubricant failure. In contrast, Figure 17 shows that ion implantation has reduced the low temperature  $\text{SO}_2$  peak by more than a factor of 10. Therefore, the importance of this pathway to lubricant failure may also be reduced by ion implantation of the lubricant.

2. The High Temperature Sulfur Peak - Figure 10 summarizes the TPD results for the  $\text{MoS}_2$  film on molybdenum metal (with no ion implantation). The dominant feature shown in Figure 10 is the first order  $\text{S}_2$  peak. This  $\text{S}_2$  peak arises from the thermal decomposition of the  $\text{MoS}_2$  film. The decomposition process starts at 1140 K and reaches a maximum rate at 1465 K. Clearly, the onset of decomposition sets an upper temperature limit for long term lubrication applications.

Figure 7 shows that the onset of  $\text{CS}_2$  vaporization starts at 1128 K and reaches a maximum at 1465 K. The main part of this  $\text{CS}_2$  peak is similar in shape to the first order  $\text{S}_2$  peak. This similarity suggests that both  $\text{S}_2$  and  $\text{CS}_2$  share a common rate determining process in their formation. The  $\text{CS}_2$  peak is roughly equal in area to that of the  $\text{S}_2$  peak. This suggests that a large carbon impurity is present in the film-metal system. The XPS spectra and elemental analysis confirm the presence of carbon as an impurity in the  $\text{MoS}_2$ .

Figure 18 summarizes the TPD results for the ion implanted molybdenum metal- $\text{MoS}_2$  film system. The main  $\text{S}_2$  and  $\text{CS}_2$  peaks are shifted to lower temperatures by

87 degrees. Figure 18 also shows that ion implantation dramatically reduces the thermal stability of the MoS<sub>2</sub> coating, because the film vaporization rate is increased for temperatures between 1150 and 1350 K.

The lower panel of Figure 19 shows that ion implantation has induced a minor peak at 1048 K. Figure 19 also indicates that there is a corresponding minor nitrogen peak at the same temperature.

3. The Nitrogen Peaks - The TPD spectrum for ion-implanted bare metal is shown in Figure 19. This spectrum is characterized by one major peak at 1248 K and one minor peak at 1413 K. These peaks may arise from nitrogen trapped in metal defect sites such as interstitials or vacancies. The interpretation of these peaks as originating from a nitride phase(s) is being considered.

Figure 19 shows that the main nitrogen peak for the ion-implanted MoS<sub>2</sub> coated system is shifted to a higher temperature by 180 degrees. There remains a small peak at 1258 K which may result from the same state of nitrogen observed at 1248 K for nitrogen implanted bare metal.

It is worth noting that the presence of the MoS<sub>2</sub> coating changes the main nitrogen peak to a higher temperature state. This shift to a higher energy state could result in improved system performance. At this time, the mechanism for the preferential filling of the high energy state is unclear, but this should be investigated in the future.

## CONCLUSIONS

The results presented in this phase one report clearly indicate that the mass spectrometric TPD techniques developed for this investigation can produce a wealth of new information about the thermal and chemical stability of thin solid lubricant films. In particular, TPD is sensitive to the film burnishing technique, as well as to the effect of ion-implantation. These results strongly suggest the TPD may contribute to our understanding of the thermal and chemical stability of thin films applied by other techniques such as sputtering and ion plating.

In the future, we hope to continue our joint program and to use our combined TPD and XPS techniques to better understand various properties of coating systems of importance to selected Army missions.

### ACKNOWLEDGMENTS

We wish to thank the staff of UIC for their contribution to this effort. In particular, we acknowledge the efforts of Don Rippon, Paul Michaud, and John Costa. In addition, we acknowledge the expert photographic laboratory services donated by Mr. Desmond Pierce.

We also wish to thank the staff of MTL for their help with this program. In particular, we appreciate the efforts of Dr. Ed Johnson and Mr. Forrest Burns in ion implanting the samples for this investigation. Our appreciation is also extended to Dr. James Marzik for helpful discussion and comments, as well as to Ms. Marion Gould for her skilled assistance in preparing this report for publication.

Finally, we wish to thank Dr. James McCauley for his encouragement, insight, and support.

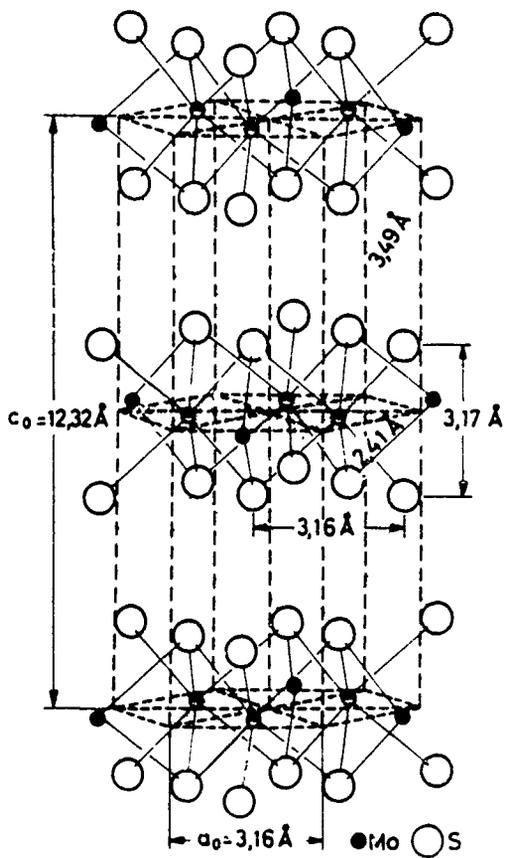


Figure 1. Crystal structure of molybdenum disulfide.

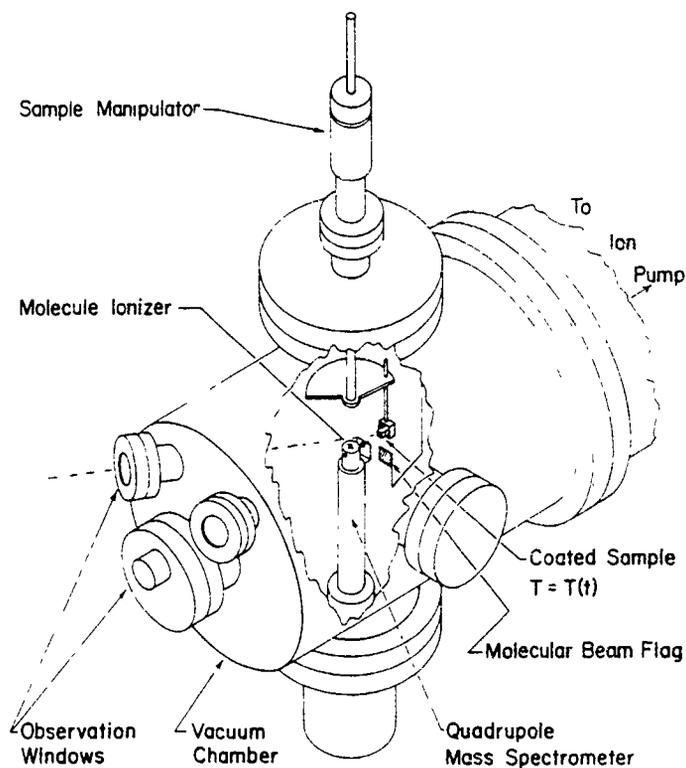


Figure 2. System for the evaluation of the thermal and chemical stability of solid lubricants.

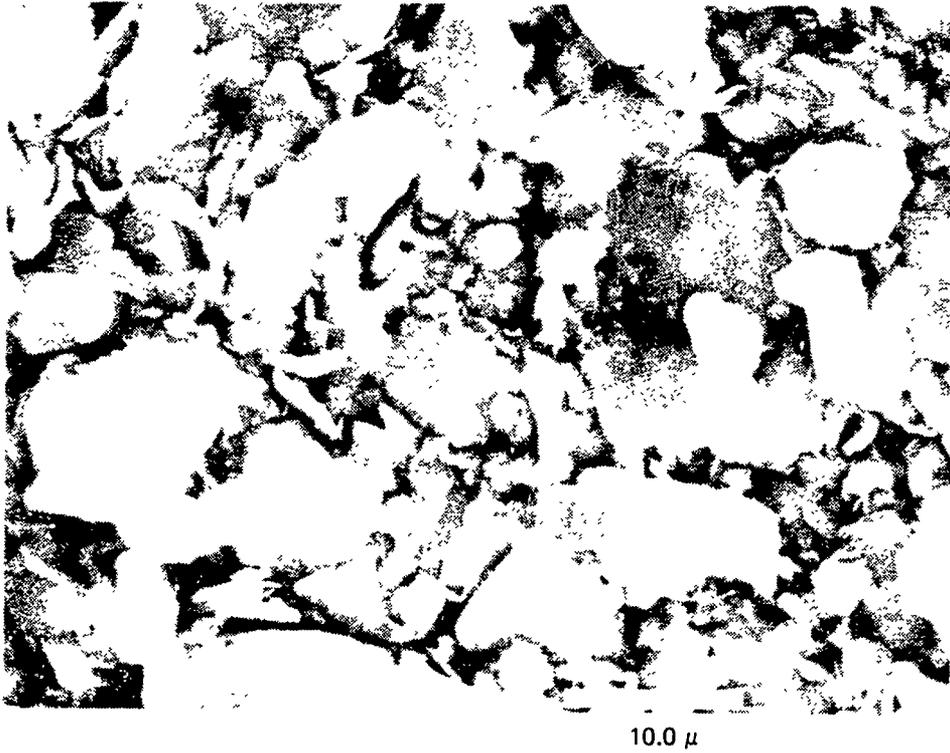


Figure 3. MoS<sub>2</sub> powder (25 kV, Mag. 2000X).



Figure 4. MoS<sub>2</sub> coated molybdenum metal (MoS<sub>2</sub>/Mo) (CM) (Mag. 2000X).



10.0  $\mu$

Figure 5. Molybdenum metal (M) (25 kV, Mag. 2000X).



10.0  $\mu$

Figure 6. Ion-implanted molybdenum metal (IM) (25 kV, Mag. 2000X).

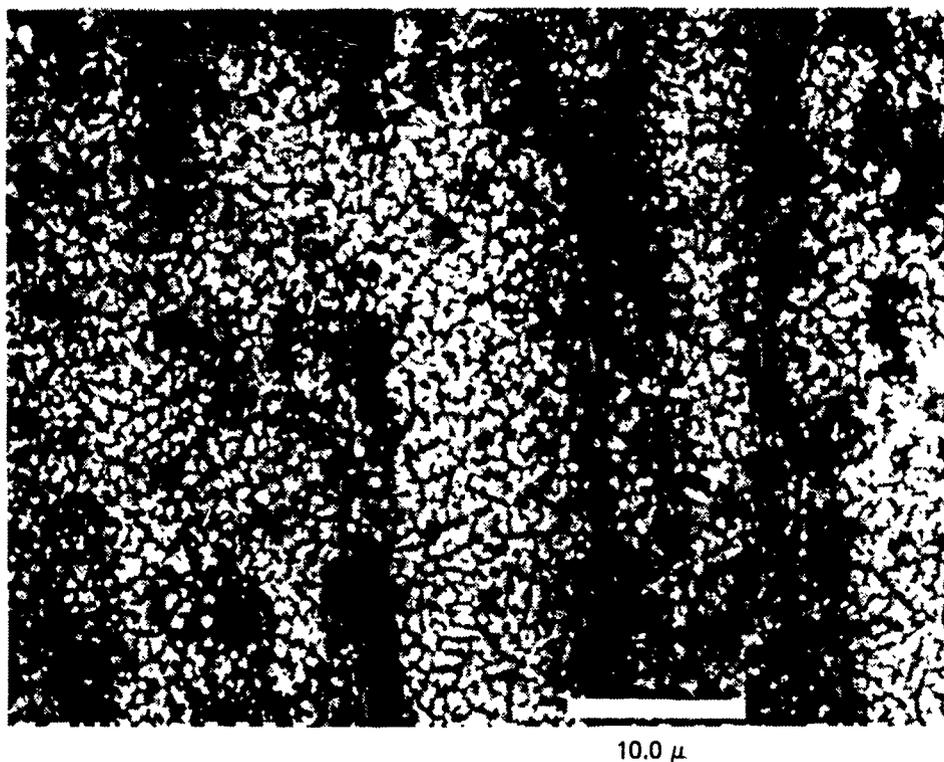


Figure 7. Ion-implanted MoS<sub>2</sub>/Mo (ICM) (25 kV, Mag. 2000X).



Figure 8. MoS<sub>2</sub>/Mo (CM) (Mag. 6000X).



Figure 9. Ion-implanted MoS<sub>2</sub>/Mo (ICM) (25 kV, Mag. 10,000X).

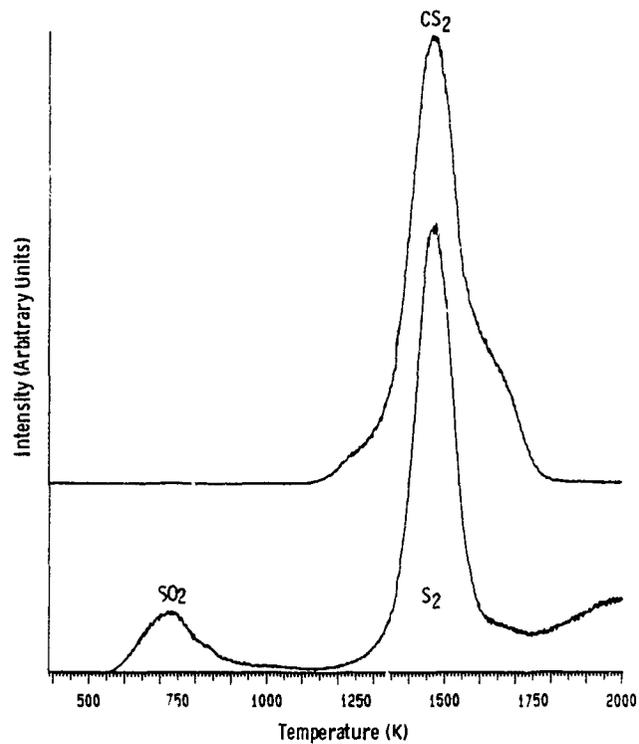


Figure 10. Intensity (desorption rate) of SO<sub>2</sub>, S<sub>2</sub>, and CS<sub>2</sub> as a function of temperature for MoS<sub>2</sub>(burnished)/Mo (CM).

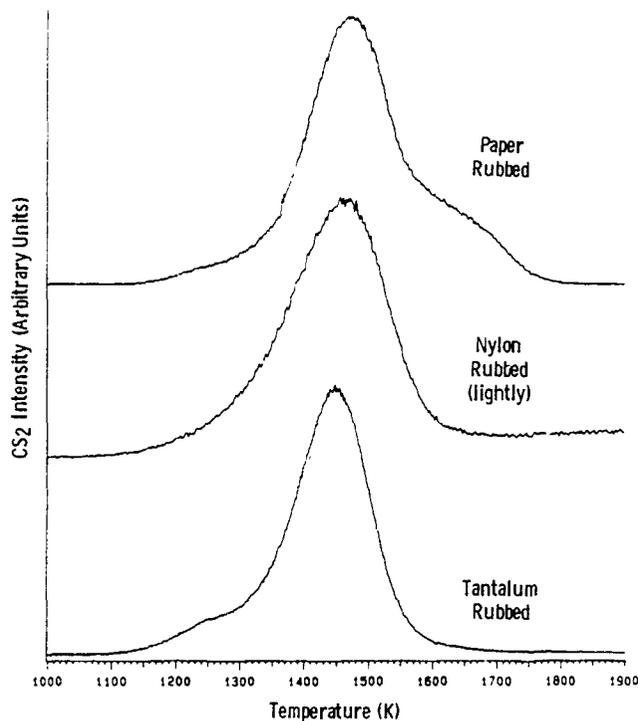


Figure 11. Intensity (desorption rate) of CS<sub>2</sub> as a function of temperature for MoS<sub>2</sub>(burnished)/Mo (CM) for different burnishing techniques.

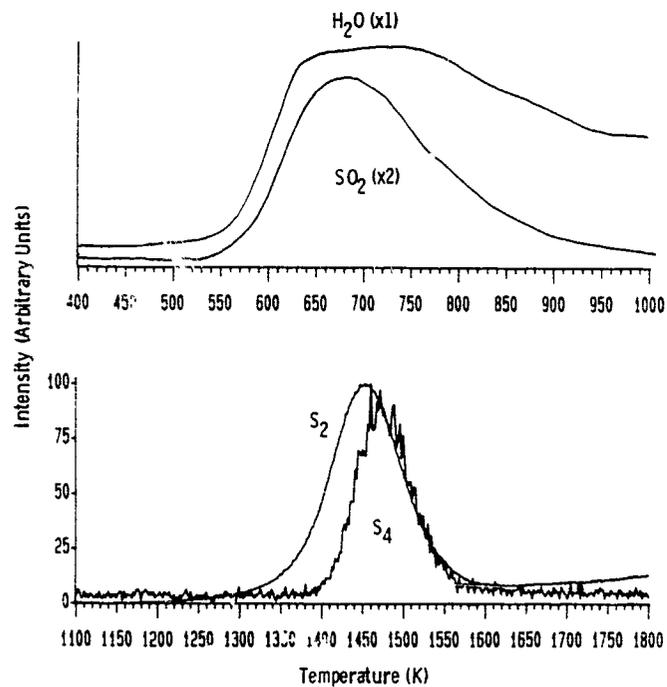


Figure 12. Top - intensity (desorption rate) of H<sub>2</sub>O and SO<sub>2</sub> as a function of temperature for MoS<sub>2</sub>(burnished)/Mo (CM); bottom - intensity (desorption rate) of S<sub>2</sub> and S<sub>4</sub> as a function of temperature for MoS<sub>2</sub>(burnished)/Mo (CM).

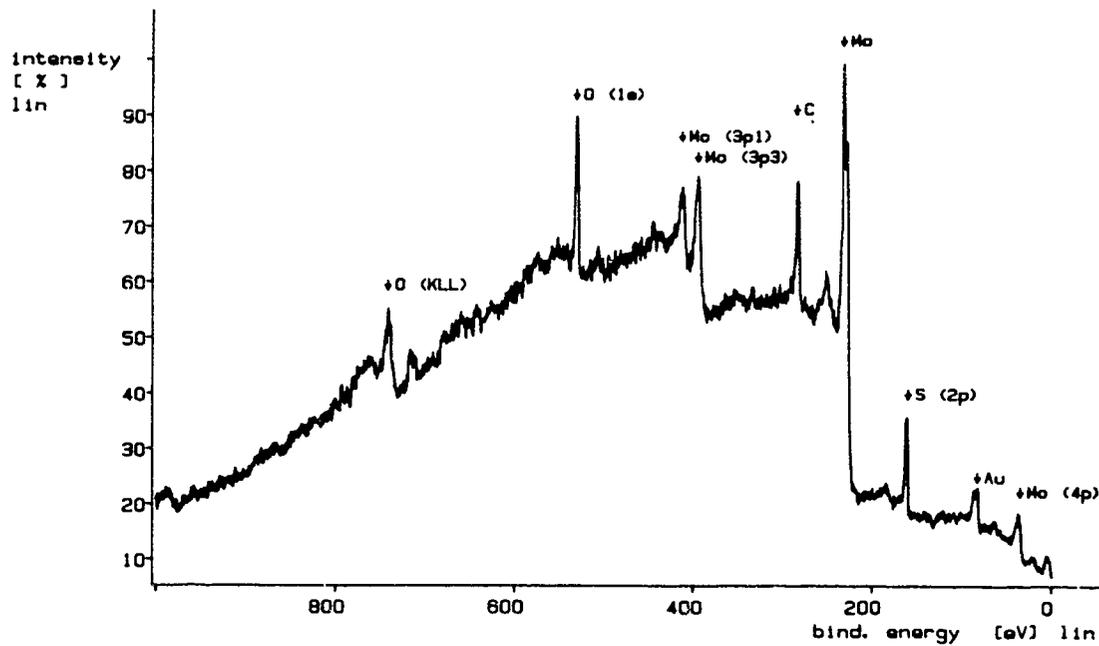


Figure 13. XPS survey spectrum for MoS<sub>2</sub>/Mo (CM) before heating.

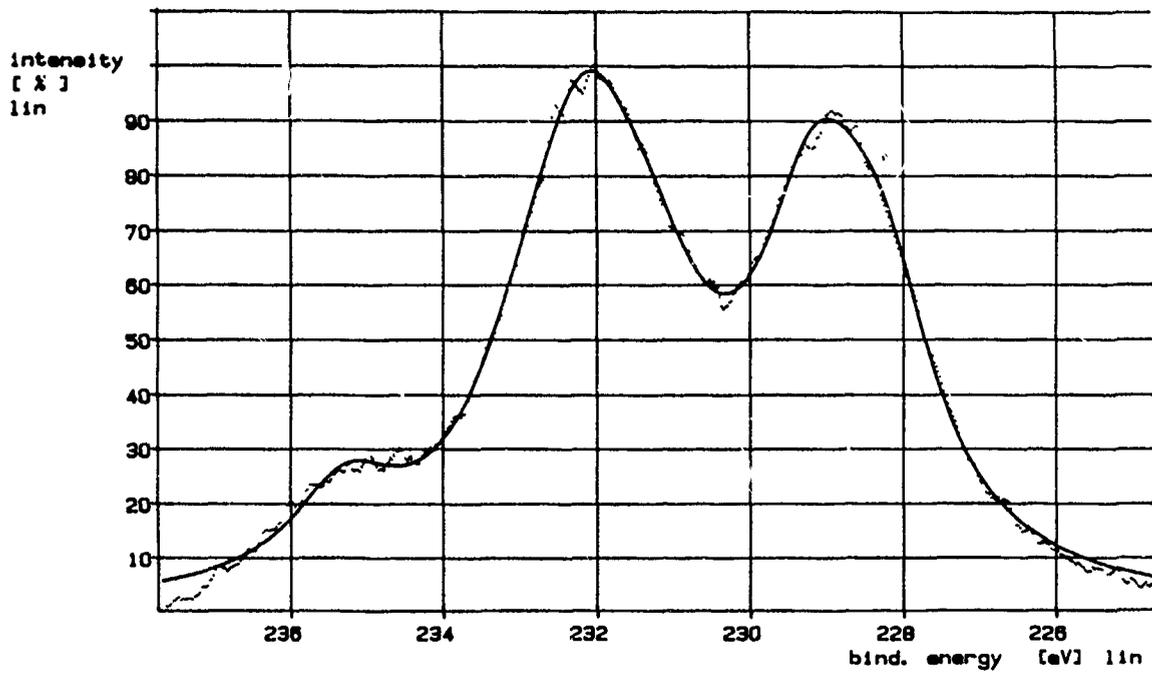


Figure 14. Synthesized Mo 3d spectrum (solid line) and the experimental Mo 3d spectrum (points) before heating.

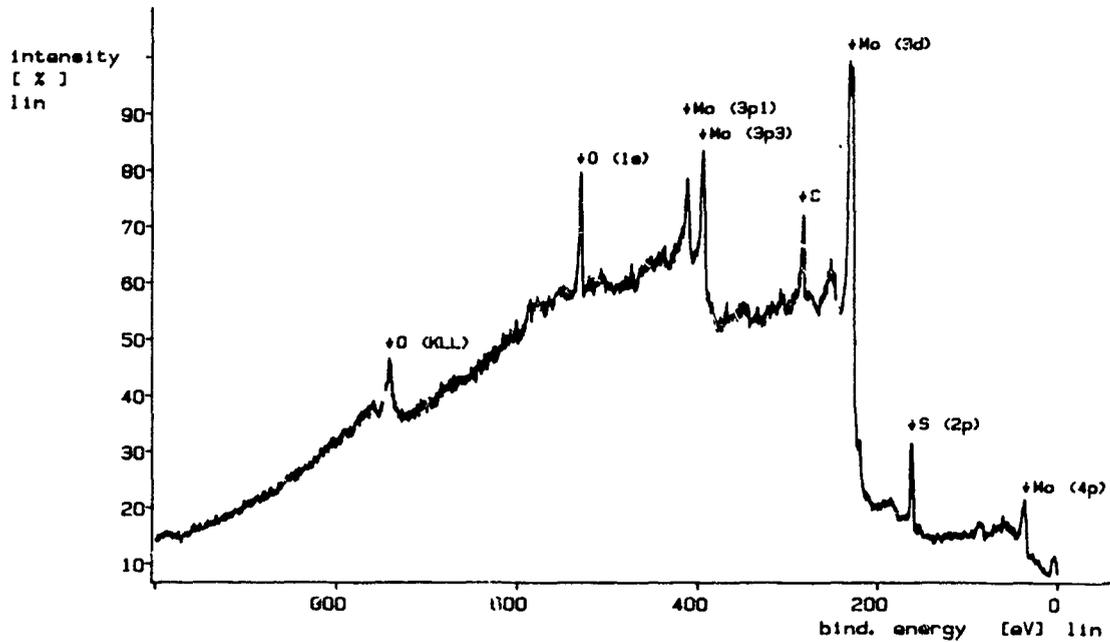


Figure 15. XPS survey spectrum for MoS<sub>2</sub>/Mo (CM) after heating to 450°C.

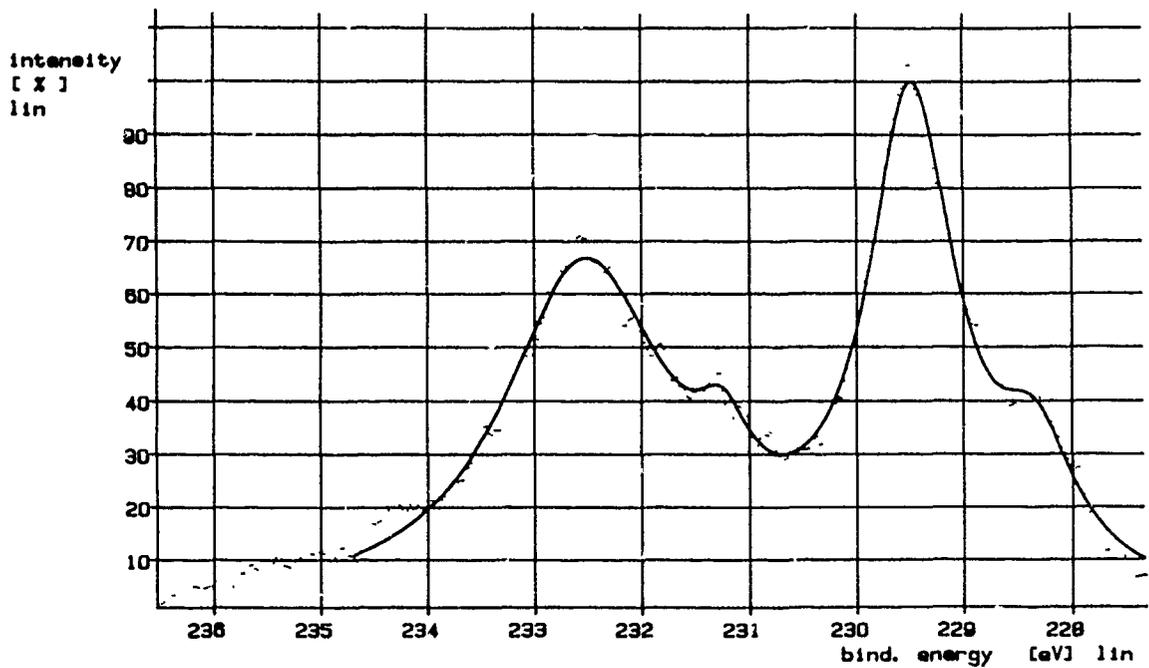


Figure 16. Synthesized Mo 3d Spectrum (solid line) and the experimental Mo 3d spectrum (points) after heating to 450°C.

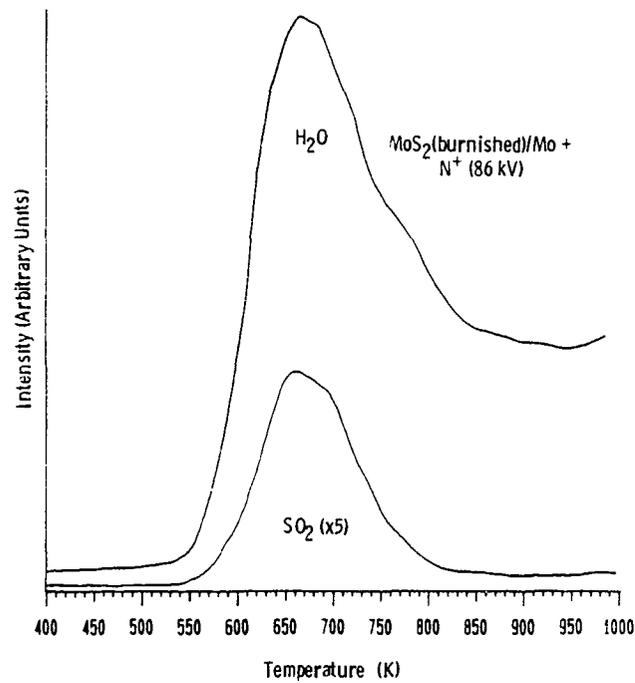


Figure 17. Intensity (desorption rate) of H<sub>2</sub>O and SO<sub>2</sub> as a function of temperature for ion-implanted MoS<sub>2</sub>/Mo (ICM).

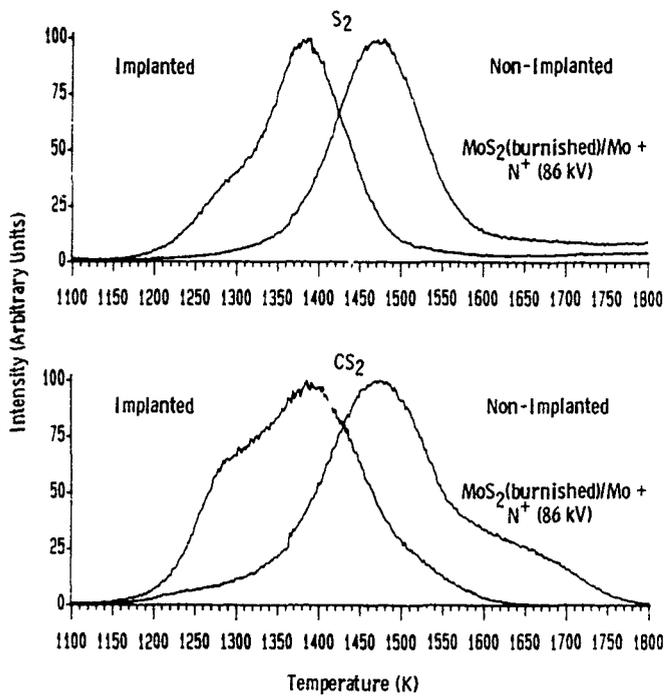


Figure 18. Top - changes in the  $S_2$  release due to ion implantation for the  $MoS_2/Mo$  system; bottom - changes in the  $CS_2$  release due to ion implantation for the  $MoS_2/Mo$  system.

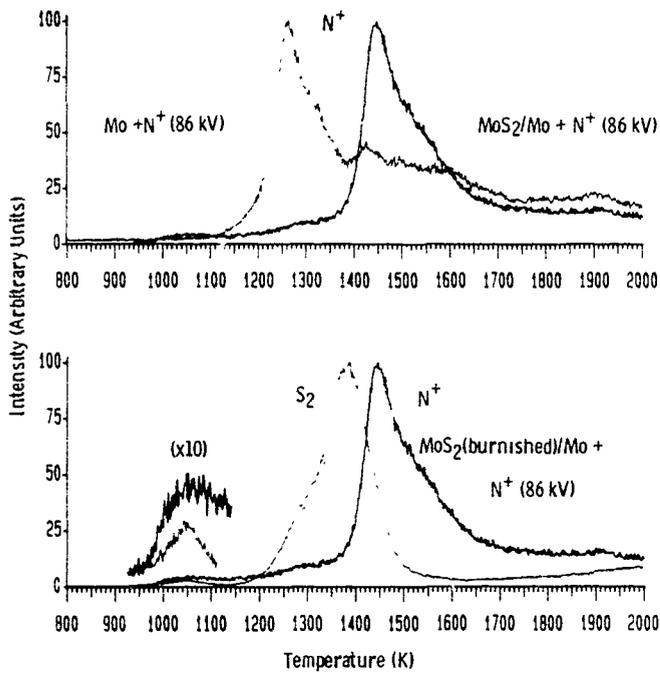


Figure 19. Top - comparison of the nitrogen release from  $N^+$  implanted metal (IM) and from  $MoS_2/Mo$  (ICM); bottom - comparison of the  $S_2$  release with the nitrogen release for  $N^+$  implanted  $MoS_2/Mo$  (ICM).

## REFERENCES

1. BUCKLEY, D. H. Friction and Wear of Ceramics. Amer. Cer. Soc. Bull., v. 51, 1972, p. 884.
2. LINCE, J. R., and FLEISCHAUER, P. D. Summary Abstract: Noble Gas Ion Bombardment of the Basal Plane Surface of MoS<sub>2</sub>. J. vac. Sci. Tech. A, v. 5, 1986, p. 1312.
3. KANAKIA, M. D., PETERSON, M. B. Literature Review of Solid Lubrication Mechanisms. Defense Technical Information Center, AD A185010, Alexandria, VA, 1986.
4. KOBBS, K., DIMIGEN, H., HUBSCH, H., TOLLE, H. J., LEUTENECKER, R., and RYSSEL, H. Improved Tribological Properties of Sputtered MoS<sub>x</sub> Films by Ion Beam Mixing. Appl. Phys. Lett., v. 49, 1986, p. 496.
5. McCONNELL, B. D., SNYDER, C. E., and STRANG, J. R. Analytical evaluation of Graphite Fluoride and Its Lubrication Performance Under Heavy Loads. Lubr. Eng., v. 33, 1977, p. 184.
6. SLINEY, H. E. Solid Lubricant Materials for High Temperatures - A Review. Tribol. Int., v. 15, 1982, p. 303.
7. SPALVINS, T. J. A Review of Recent Advances in Solid Film Lubrication. J. Vac. Sci. Tech. A, v. 5, 1987, p. 212.
8. LINCE, J. R., CARRE, D. J., and FLEISCHAUER, P. D. Effects of Argon Ion Bombardment on the Basal Plane Surface of MoS<sub>2</sub>. Langmuir, v. 2, 1986, p. 805.
9. STUPP, B. C. Synergistic Effects of Metals Co-Sputtered with MoS<sub>2</sub>. Thin Solid Films, v. 84, 1982, p. 257.
10. SUZUKI, K., SOMA, M., ONISHI, T., and TAMARU, K. Reactivity of Molybdenum Disulfide Surfaces Studied by XPS. J. Electr. Spect. Relat. Phen., v. 24, 1981, p. 283.
11. WYCKOFF, R. W. G. Crystal Structures, v. I, Chapter IV, Interscience Publishers, NY, 1957.
12. FLEISCHAUER, P. D. Effects of Crystallite Orientation on Environmental Stability and Lubrication Properties of Sputtered MoS<sub>2</sub> Thin Films. ASLE Trans., v. 27, 1983, p. 82.
13. STEWART, T. B., and FLEISCHAUER, P. D. Chemistry of Sputtered Molybdenum Disulfide Films. Inorg. Chem., v. 21, 1982, p. 2426.
14. ROBERTS, E. W. The Tribology of Sputtered Molybdenum Disulphide Films. Proc. I. Mech. Eng., v. 1, 1987, p. 503.
15. CHAN, C. M., ARIS, R., and WEINBERG, W. H. An Analysis of Thermal Desorption Mass Spectra. I. Appl. Sur. Sci., v. 1, 1978, p. 360.
16. HABENSCHADEN, E., and KUPPERS, J. Evaluation of Flash Desorption Spectra. Sur. Sci., v. 138, 1984, p. L147.
17. FALCONER, J. L., and SCHWARTZ, J. A. Temperature-Programmed Desorption and Reaction: Applications to Supported Catalysts. Catal. Rev.-Sci. Eng., v. 25, 1983, p. 141.

## DISTRIBUTION LIST

No. of Copies	To	No. of Copies	To
1	Office of the Under Secretary of Defense for Research and Engineering, The Pentagon, Washington, DC 20301	1	Commander, U.S. Army Missile Command, Redstone Scientific Information Center, Redstone Arsenal, AL 35898-5241
1	ATTN: Mr. J. Persh	1	ATTN: AMSMI-RD-CS-R/ILL Open Lit
1	Dr. L. Young	1	AMSMI-R, Dr. W. C. McCorkle
1	Mr. K. R. Foster		
	Commander, U.S. Army Laboratory Command, 2800 Powder Mill Road, Adelphi, MD 20783-1145		Commander, U.S. Army Aviation Systems Command, P.O. Box 209 St Louis, MO 63120
2	ATTN: AMSLC-IM-TL	1	ATTN: AMSAV-NS, Mr. M. L. Baucchio
1	AMSLC-TD	1	Technical Library
1	AMSLC-TD-A		
1	AMSLC-PA		Commander, U.S. Army Natick Research, Development, and Engineering Center, Natick, MA 01760
1	AMSLC-TP	1	ATTN: Technical Library
	Commander, Defense Technical Information Center, Cameron Station, Building 5, 5010 Duke Street, Alexandria, VA 22304-6145	1	Dr. J. A. Sousa
2	ATTN: DTIC-FDAC	1	Dr. R. J. Byrne
	National Technical Information Service, 5285 Port Royal Road, Springfield, VA 22161	1	Dr. R. Lewis
1	National Technical Information Service, 5285 Port Royal Road, Springfield, VA 22161		
	Director, Defense Advanced Research Projects Agency, 1400 Wilson Boulevard, Arlington, VA 22209		Commander, U.S. Army Satellite Communications Agency, Fort Monmouth, NJ 07703
1	ATTN: Dr. P. Parrish	1	ATTN: Technical Document Center
1	Dr. B. Wilcox		
1	Dr. K. Harumann-Rhyne		Commander, U.S. Army Science and Technology Center Far East Office, APO San Francisco, CA 96328
	Battelle Columbus Laboratories, Metals and Ceramics Information Center, 505 King Avenue, Columbus, OH 43201	1	ATTN: Terry L. McAfee
1	ATTN: Mr. W. Duckworth		
1	Dr. D. Niesz		Commander, U.S. Army Communications and Electronics Command, Fort Monmouth, NJ 07703
	Department of the Army, Office of the Assistant Secretary of the Army (RDA), Washington, DC 20310	1	ATTN: AMSEL-TDD, Mr. T. A. Pfeiffer, Technical Dir
1	ATTN: Dr. J. G. Prather, Dep for Sci & Tech		Director, Electronic Technology and Devices Lab, Fort Monmouth, NJ 07703
1	Dr. J. R. Sculley, SARD	1	ATTN: DELET-D, Dr. C. G. Thornton
	Deputy Chief of Staff, Research, Development, and Acquisition, Headquarters, Department of the Army, Washington, DC 20310		
1	ATTN: DAMA-ZE, Mr. C. M. Church		Commander, U.S. Army Tank-Automotive Command, Warren, MI 48090
	Commander, U.S. Army Research and Development Office, Chief Research and Development, Washington, DC 20315	1	ATTN: Dr. W. Bryzik
1	ATTN: Physical and Engineering Sciences Division	1	D. Rose
	Commander, Army Research Office, P.O. Box 12211, Research Triangle Park, NC 27709-2211	1	AMSTA-RKA
1	ATTN: Information Processing Office	1	AMSTA-UL, Technical Library
1	Dr. J. Hurt	1	AMSTA-R
1	Dr. A. Crowson	1	AMSTA-NS, Dr. H. H. Dobbs
1	Dr. R. Reeber		
1	Dr. R. Shaw		Commander, U.S. Army Armament, Munitions and Chemical Command, Dover, NJ 07801
	Commander, U.S. Army Materiel Command, 5001 Eisenhower Avenue, Alexandria, VA 22333	1	ATTN: Mr. J. Lannon
1	ATTN: AMCQA-EQ, Mr. H. L. Light	1	Mr. H. E. Peibly, Jr., PLASTEC, Director
1	AMCQA, Mr. S. J. Lorber	1	Technical Library
	Commander, U.S. Army Electronics Research and Development Command, Fort Monmouth, NJ 07703	1	Dr. T. Davidson
1	ATTN: AMDET-ES, Dr. A. Tauber	1	Dr. B. Ebihara
	Director, Electronics Warfare Laboratory, Fort Monmouth, NJ 07703	1	AMSMC-LC(D), Dr. J. T. Frasier
1	ATTN: AMDEW-D, Mr. M. Adler		
	Commander, U.S. Army Materiel Systems Analysis Activity, Aberdeen Proving Ground, MD 21005		Commander, U.S. Army Armament, Munitions and Chemical Command, Rock Island, IL 61299
1	ATTN: AMXSY-MP, H. Cohen	1	ATTN: Technical Library
	Commander, U.S. Army Night Vision Electro-Optics Laboratory, Fort Belvoir, VA 22060		
1	ATTN: DELNV-S, Mr. P. Travesky		Commander, Aberdeen Proving Ground, MD 21005
1	DELNV-L-D, Dr. P. Buser	1	ATTN: AMDAR-CLB-PS, Mr. J. Vervier
1	DELNV-D, Dr. L. Cameron		U.S. Army Corps of Engineers, Construction Engineering Research Lab, P.O. Box 4005, Champaign, IL 61820
	Commander, Harry Diamond Laboratories, 2800 Powder Mill Road, Adelphi, MD 20783	1	ATTN: Dr. Robert Quattrone
1	ATTN: Technical Information Office		
1	SLCHD-RAE		Commander, U.S. Army Belvoir RD&E Center, Fort Belvoir, VA 22060-5606
	Director, U.S. Army Research & Technology Labs., Ames Research Center, Moffett Field, CA 94035	1	ATTN: STRBE-FS, Mr. W. McGovern, Fiel & Wtr Sup Div
1	ATTN: DAVDL-D, Dr. R. Larison	1	AMDME-V, Mr. E. York
1	DAVDL-AL-D, Dr. J. C. Statler, MS215-1, Aeromechanics Laboratory	1	AMDME-HS, Dr. K. H. Steinbach
		1	AMDME-ZT, Mr. T. W. Lovelace, Tech Dir
		1	Mr. M. Lepera
			Director, U.S. Army Ballistic Research Laboratory, Aberdeen Proving Ground, MD 21005
		1	ATTN: SLCBR-BLT, Dr. A. M. Dietrich
		1	SLCBB-BLF, Dr. A. Miller
			Commander, Rock Island Arsenal, Rock Island, IL 61299
		1	ATTN: SARRI-EN
			Director, U.S. Army Industrial Base Engineering Activity, Rock Island, IL 61299
		1	ATTN: AMXIB-MT, Mr. G. B. Ney
			Chemical Research and Development Center, Aberdeen Proving Ground, MD 21010
		1	ATTN: AMSMC-CLD(A), Dr. B. Richardson

No. of Copies	To	No. of Copies	To
1	Commander, U.S. Army Test and Evaluation Command, Aberdeen Proving Ground, MD 21005	1	National Aeronautics and Space Administration, Langley Research Center, Hampton, VA 23665
1	ATTN: AMSTE-ME	1	ATTN: Mr. J. Buckley, MS 387
1	AMSTE-TD, Mr. H. J. Peters	1	Dr. J. Heyman, MS 231
		1	Mr. R. L. Long, MS 266
1	Commander, U.S. Army Foreign Science and Technology Center, 220 7th Street, N.E., Charlottesville, VA 22901	1	Commander, White Sands Missile Range, Electronic Warfare Laboratory, OMEW, ERADCOM, White Sands, NM 88002
1	ATTN: Military Tech	1	ATTN: Mr. Thomas Reader, AMSEL-WLM-ME
1	Mr. J. Crider		
1	Ms. P. Durrer		
1	Mr. P. Greenbawn		
1	Chief, Benet Weapons Laboratory, Watervliet, NY 12189	1	Department of Energy, Division of Transportation, 20 Massachusetts Avenue, N.W., Washington, DC 20545
1	ATTN: AMDAR-LCB-TL	1	ATTN: Dr. R. J. Gottschall, EK-131, GTN
1	Dr. G. D'Andrea		
1	AMDAR-LCB, Dr. F. Sautter		
1	Director, Eustis Directorate, U.S. Army Mobility Research and Development Laboratory, Fort Eustis, VA 23604	1	Department of Transportation, 400 Seventh Street, S.W., Washington, DC 20590
1	ATTN: SAVDL-E-MOS (AMCCOM)	1	ATTN: Mr. M. Lauriente
1	Commander, U.S. Army Engineer Waterways Experiment Station, Vicksburg, MS 39180	1	Mechanical Properties Data Center, Belfour Stulen Inc., 13917 W. Bay Shore Drive, Traverse City, MI 49684
1	ATTN: Research Center Library		
1	Project Manager, Munitions Production Base, Modernization and Expansion, Dover, NJ 07801	1	National Bureau of Standards, Washington, DC 20234
1	ATTN: AMCPM-PBM-P	1	ATTN: E. S. Etz, Bldg. 222, Rm A-121
		1	D. L. Hunston, Bldg. 224, Rm A-209
		1	Dr. D. H. Reneker, Dep. Dir., Ctr for Mat'l's Sci.
		1	Dr. Lyle Schwartz
		1	Dr. Stephen Hsu
		1	Dr. Allan Draggoo
1	Technical Director, Human Engineering Laboratories, Aberdeen Proving Ground, MD 21005-5001	1	U.S. Bureau of Mines, Mineral Resources Technology, 2401 E. Street, N.W., Washington, DC 20241
1	ATTN: SLCHE-D, Dr. J. D. Weisz	1	ATTN: Mr. M. A. Schwartz
1	Chief of Naval Research Arlington, VA 22217	1	National Bureau of Standards, Gaithersburgh, MD 20760
1	ATTN: Code 471	1	ATTN: Dr. S. Wiederhorn
1	Dr. A. Diness	1	Dr. N. Tighe
1	Dr. R. Pohanka		
1	Naval Research Laboratory, Washington, DC 20375	1	National Research Council, National Materials Advisory Board, 2101 Constitution Avenue, Washington, DC 20418
1	ATTN: Code 5830	1	ATTN: Dr. K. Zwilsky
		1	D. Groves
		1	J. Lane
1	Headquarters, Naval Air Systems Command, Washington, DC 20360	1	National Science Foundation, Materials Division, 1800 G Street, N.W., Washington, DC 20006
1	ATTN: Code 5203	1	ATTN: Dr. L. Toth
		1	Dr. J. Hurt
1	Headquarters, Naval Sea Systems Command, 1941 Jefferson Davis Highway, Arlington, VA 22376	1	AiResearch Manufacturing Company, AiResearch Casting Company, 2525 West 190th Street, Torrance, CA 90505
1	ATTN: Code 035	1	ATTN: Mr. K. Styhr
1	Headquarters, Naval Electronics Systems Command, Washington, DC 20360		
1	ATTN: Code 504		
1	Commander, Naval Ordnance Station, Louisville, KY 40214	1	AVCO Corporation, Applied Technology Division, Lowell Industrial Park, Lowell, MA 01887
1	ATTN: Code 85	1	ATTN: Dr. T. Vasilos
1	Commander, Naval Material Industrial Resources Office, Building 537-2, Philadelphia Naval Base, Philadelphia, PA 19112	1	Case Western Reserve University, Department of Metallurgy, Cleveland, OH 60605
1	ATTN: Technical Director	1	ATTN: Prof. A. H. Heuer
1	Commander, Naval Weapons Center, China Lake CA 93555	1	Defence Research Establishment Pacific, FMO, Victoria, B.C., VOS 1B0, Canada
1	ATTN: Mr. F. Markarian	1	ATTN: R. D. Barer
1	Commander, U.S. Air Force Wright Aeronautical Labs, Wright- Patterson Air Force Base, OH 45433	1	Ford Motor Company, Turbine Research Department, 20000 Rotunda Drive, Dearborn, MI 48121
1	ATTN: Dr. N. Tallan	1	ATTN: Mr. A. F. McLean
1	Dr. H. Graham	1	Mr. J. A. Mangels
1	Dr. R. Ruh		
1	Aero Propulsion Labs, Mr. R. Marsh		
1	Dr. H. M. Burte	1	Ford Motor Company, P.O. Box 2053, Dearborn, MI 48121
1	AFWAL/MLLP, Mr. D. Forney	1	ATTN: Dr. D. Compton, Vice President Research
1	AFML/MLLM, Mr. H. L. Geigel		
1	AFSC/MLLM, Dr. A. Katz		
1	Commander, Air Force Armament Center, Eglin Air Force Base, FL 32542	1	General Electric Company, Research and Development Center, Box 8, Schenectady, NY 12345
1	ATTN: Technical Library	1	ATTN: Dr. R. J. Charles
		1	Dr. C. D. Greskovich
		1	Dr. S. Prochazka
1	National Aeronautics and Space Administration, Lewis Research Center, 21000 Brookpark Road, Cleveland, OH 44135	1	Georgia Institute of Technology, EES, Atlanta, GA 30332
1	ATTN: J. Accurio, USAMRDL	1	ATTN: Mr. J. D. Walton
1	Dr. H. B. Probst, MS 49-1		
1	Dr. S. Dutta	1	GTE Sylvania, Waltham Research Center, 40 Sylvania Road, Waltham, MA 02154
		1	ATTN: Dr. W. H. Rhodes
1	National Aeronautics and Space Administration, Washington, DC 20546	1	Martin Marietta Laboratories, 1450 South Rolling Road, Baltimore, MD 21227
1	ATTN: AFSS-AD, (Office of Scientific and Technical Info. -	1	ATTN: Dr. J. Venables

No. of Copies	To	No. of Copies	To
1	Massachusetts Institute of Technology, Department of Metallurgy and Materials Science, Cambridge, MA 02139	1	Sandia Laboratories, Albuquerque, NM 87185
1	ATTN: Prof. R. L. Coble	1	ATTN: Dr. F. Gerstle, Div 5814
1	Prof. H. K. Bowen		The John Hopkins University, Department of Civil Engineering/
1	Prof. W. D. Kingery	1	Materials Science and Engineering, Baltimore, MD 28218
1	Prof. J. Vander Sande	1	ATTN: Dr. R. E. Green, Jr.
1	Materials Research Laboratories, P.O. Box 50, Ascot Vale, VIC 3032, Australia	1	Director, Office of Science and Technology Policy, Old Executive Office Building, Washington, DC 20223
1	ATTN: Dr. C. W. Weaver		Subcommittee on Science, 2319 Rayburn House Office Building, Washington, DC 20515
1	Midwest Research Institute, 425 Volker Boulevard, Kansas City, MO 64110	1	ATTN: Mr. P. C. Maxwell
1	ATTN: Mr. G. W. Gross, Head, Physics Station		Aerospace Corporation, Materials Science Laboratory, 2350 East El Segundo Boulevard, El Segundo, CA 90245
1	Pennsylvania State University, Materials Research Laboratory, Materials Science Department, University Park, PA 16802	1	ATTN: Dr. L. R. McCreight
1	ATTN: Prof. R. Roy		IBM Corporation, Thomas B. Watson Research Center, Yorktown Heights, NY 10598
1	Prof. R. E. Newnham	1	ATTN: Dr. G. Onoda
1	Prof. R. E. Tressler		Corning Glass Works, Research and Development Division, Corning, NY 14830
1	Dr. C. Pantano	1	ATTN: Dr. W. R. Prindle
1	Mr. C. O. Ruud		3M Company, New Products Department, 219-01-01, 3M Center, St. Paul, MN 55144
1	State University of New York at Albany, Department of Physics, Albany, NY 12222	1	ATTN: R. E. Richards
1	ATTN: Prof. W. A. Lanford		Technology Strategies, Inc., 10722 Shingle Oak Ct., Burke, VA 22015
1	State University of New York at Stony Brook, Department of Materials Science, Long Island, NY 11790	1	ATTN: Dr. E. C. Van Reuth
1	ATTN: Prof. F. F. Y. Wang		Rutgers University, Center for Ceramics, Rm A274, P.O. Box 909, Piscataway, NJ 08854
1	Stanford Research International, 333 Ravenswood Avenue, Menlo Park, CA 94025d	1	ATTN: Prof. J. B. Wachtman, Jr., Director
1	ATTN: Dr. P. Jorgensen		Syracuse University, 304 Administration Building, Syracuse, NY 13210
1	Dr. D. Rowcliffe	1	ATTN: Dr. V. Weiss
1	United Technologies Research Center, East Hartford, CT 06108		Lehigh University, Materials Research Center #32, Bethlehem, PA 18015
1	ATTN: Dr. J. Brennan	1	ATTN: Dr. D. M. Smyth
1	Dr. K. Prewo		Alfred University, New York State College of Ceramics, Alfred, NY 14802
1	University of California, Lawrence Livermore Laboratory, P.O. Box 808, Livermore, CA 94550	1	ATTN: Dr. R. L. Snyder
1	ATTN: Mr. R. Landingham		Alfred University, Center for Advanced Ceramic Technology, Alfred, NY 14806
1	Dr. C. F. Cline	1	ATTN: R. M. Spriggs
1	Dr. J. Birch Holt		University of California, Center for Advanced Materials, 058, Hildebrand Hall, Berkeley, CA 94720
1	University of Florida, Department of Materials Science and Engineering, Gainesville, FL 32611	1	ATTN: Prof. G. Somorjai
1	ATTN: Dr. L. Hensch		Boeing Aerospace Company, 11029 Southeast 291, Auburn, MA 98002
1	University of Washington, Ceramic Engineering Division, FB-10, Seattle, WA 98195	1	ATTN: W. E. Strobel
1	ATTN: Prof. R. Bradt		University of California, Materials Science and Mineral Engineering, Heart Mining Building, Rm 284, Berkeley, CA 94720
1	Westinghouse Electric Corporation, Research Laboratories, Pittsburgh, PA 15235	1	ATTN: Prof. G. Thomas
1	ATTN: Dr. R. J. Bratton		Director, U.S. Army Materials Technology Laboratory, Watertown, MA 02172-0001
1	Battelle Pacific Northwest Lab, NDT Section, Richland, WA 99353	2	ATTN: SLCMT-TML
1	ATTN: Mr. A. Birks, Associate Manager	5	Authors
1	Rensselaer Polytechnic Institute, Department of Materials Engineering, Troy, NY 12181		
1	ATTN: R. J. Diefendorf		
1	Oak Ridge National Laboratory, P.O. Box X Oak Ridge, TN 37830		
1	ATTN: P. F. Becher		
1	V. J. Fenner		
1	R. Johnson		

AD UNCLASSIFIED UNLIMITED DISTRIBUTION  
Key Words  
Solid lubricants  
Molybdenum disulfide  
Mass spectrometry

AD UNCLASSIFIED UNLIMITED DISTRIBUTION  
Key Words  
Solid lubricants  
Molybdenum disulfide  
Mass spectrometry

U.S. Army Materials Technology Laboratory, Watertown, Massachusetts 02172-0001  
EVALUATION OF SOLID LUBRICANTS: TEMPERATURE PROGRAMMED DESORPTION OF MoS<sub>2</sub> ON MOLYBDENUM AND OF ION-IMPLANTED MoS<sub>2</sub> ON MOLYBDENUM  
Richard P. Burns, Daniel E. Pierce, Helen M. Dauplaise, Kenneth A. Gabriel, and Lawrence J. Mizerka  
Technical Report MTL TR 88-36, November 1988, 24 pp -  
111us., D/A Project 1L161101A91A

U.S. Army Materials Technology Laboratory, Watertown, Massachusetts 02172-0001  
EVALUATION OF SOLID LUBRICANTS: TEMPERATURE PROGRAMMED DESORPTION OF MoS<sub>2</sub> ON MOLYBDENUM AND OF ION-IMPLANTED MoS<sub>2</sub> ON MOLYBDENUM  
Richard P. Burns, Daniel E. Pierce, Helen M. Dauplaise, Kenneth A. Gabriel, and Lawrence J. Mizerka  
Technical Report MTL TR 88-36, November 1988, 24 pp -  
111us., D/A Project 1L161101A91A

AD UNCLASSIFIED UNLIMITED DISTRIBUTION  
Key Words  
Solid lubricants  
Molybdenum disulfide  
Mass spectrometry

AD UNCLASSIFIED UNLIMITED DISTRIBUTION  
Key Words  
Solid lubricants  
Molybdenum disulfide  
Mass spectrometry

U.S. Army Materials Technology Laboratory, Watertown, Massachusetts 02172-0001  
EVALUATION OF SOLID LUBRICANTS: TEMPERATURE PROGRAMMED DESORPTION OF MoS<sub>2</sub> ON MOLYBDENUM AND OF ION-IMPLANTED MoS<sub>2</sub> ON MOLYBDENUM  
Richard P. Burns, Daniel E. Pierce, Helen M. Dauplaise, Kenneth A. Gabriel, and Lawrence J. Mizerka  
Technical Report MTL TR 88-36, November 1988, 24 pp -  
111us., D/A Project 1L161101A91A

U.S. Army Materials Technology Laboratory, Watertown, Massachusetts 02172-0001  
EVALUATION OF SOLID LUBRICANTS: TEMPERATURE PROGRAMMED DESORPTION OF MoS<sub>2</sub> ON MOLYBDENUM AND OF ION-IMPLANTED MoS<sub>2</sub> ON MOLYBDENUM  
Richard P. Burns, Daniel E. Pierce, Helen M. Dauplaise, Kenneth A. Gabriel, and Lawrence J. Mizerka  
Technical Report MTL TR 88-36, November 1988, 24 pp -  
111us., D/A Project 1L161101A91A

Thermal programmed desorption (TPD) is utilized in order to assess the lubricating properties of metal dichalcogenide films applied to a number of metal substrates. TPD spectra documenting desorption and decomposition products were analyzed for MoS<sub>2</sub> burnished on molybdenum metal with and without subsequent 86 kv nitrogen ion implantation. Desorption order, rate, energy, and the pre-exponential of evolved lubricant and nitrogen species from the molybdenum substrates were determined. The surface chemistry of heated lubricant-substrate system was investigated by means of X-ray photoelectron spectroscopy (XPS). The results presented clearly indicate that the mass spectroscopic TPD techniques developed for this investigation coupled with careful surface analysis yield critical in situ assessment of the capability and the operational limits of this and other solid lubrication systems.

Thermal programmed desorption (TPD) is utilized in order to assess the lubricating properties of metal dichalcogenide films applied to a number of metal substrates. TPD spectra documenting desorption and decomposition products were analyzed for MoS<sub>2</sub> burnished on molybdenum metal with and without subsequent 86 kv nitrogen ion implantation. Desorption order, rate, energy, and the pre-exponential of evolved lubricant and nitrogen species from the molybdenum substrates were determined. The surface chemistry of heated lubricant-substrate system was investigated by means of X-ray photoelectron spectroscopy (XPS). The results presented clearly indicate that the mass spectroscopic TPD techniques developed for this investigation coupled with careful surface analysis yield critical in situ assessment of the capability and the operational limits of this and other solid lubrication systems.