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FOREWORD

This report was compiled by the Materials Integrity Branch, Systems Support Division Materials Laboratory, Wright Aeronautical Laboratories, Wright-Patterson Air Force Base, Ohio. It was initiated under Project 2418, Task 241807 with Mr. Fred H. Meyer Jr. as the project engineer.

The 1980 Tri-Service Corrosion Conference is a follow-up to similar conferences held in 1967, ~~1969,~~ 1972, 1974, 1976, and 1978.

The purpose of the conference is to make Department of Defense personnel and contractors aware of important corrosion problems in military equipment; to provide a forum for exchange of corrosion control information and to present the status of significant corrosion research and control projects being carried out by the military services.

Proceedings of the earlier conferences were issued as:

1967 - AFML-TR-67-329 (AD 826-198)

1969 - No Proceedings

1972 - MCIC-73-19

1974 - AFML-TR-75-42, Vol I (ADA 021053)
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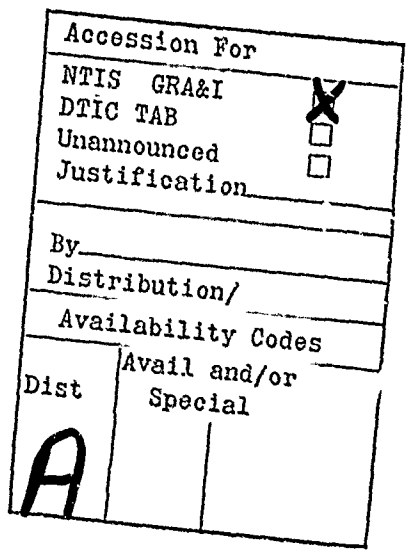

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Opening Remarks
by
FRED H MEYER Jr.; General Chairman

Welcome to the seventh biannual Tri-Service Corrosion Conference. This Conference was established in 1967 with subsequent Conferences in 1969, 1972, 1974, 1976, and 1978. Sponsorship alternates among the Air Force, Navy and Army.

This year's Conference is sponsored by the Materials Integrity Branch, Systems Support Division of the Air Force Wright Aeronautical Laboratories, Materials Laboratory, Wright-Patterson Air Force Base, Ohio.

The purpose of this Conference is to present current research and development relating to current problems in corrosion control and prevention of deterioration of military and aerospace systems due to corrosion. Corrosion of equipment continues to be a major problem for the Armed Forces especially in this era of limited material and energy resources.

This area has received considerable attention by the highest military and governmental levels as evidenced by the National Bureau of Standards study "Economics Effects of Metallic Corrosion in the United States and the establishment of the Joint DARCOM/NMC/AFLC/AFSC Commander Agreement on Support of the Corrosion Prevention and Control Program."

Another prime purpose of this Conference is to present information on in-service systems problems and associated field experiences. Much of the current corrosion research and development is directed toward helping to solve these field originating problems.

A free exchange of the best methods currently available for combating the serious corrosion problem will lead to the incorporation of better materials and methods in the acquisition of new systems. Discussions by leading experts in the field and the airing of current problems will not only provide valuable guidances to the Air Force, Navy, and Army programs but will assist in stimulating high level technical people from key industrial and academic organizations to assist in solving critical DOD corrosion problems.

The earlier Tri-Service Corrosion Conferences concluded that greater implementation of existing technology is especially needed within the Services. There has been considerable difficulty in the past in implementing transitioning in the state-of-the-arts in solving design and field problems.

This has been one of the major goals of the Tri-Service Corrosion Conferences in the past and will continue to be a primary goal. This Conference is dedicated to the rapid efficient transfer in advanced state of the art technology in corrosion science and engineering into the direct use in the production of more effective systems for national defense.

We hope, by the sponsorship of this Conference, to make a significant contribution to keeping our defense system more reliable, more durable, and economical by providing an open forum for the discussion of corrosion problems which at the present time continue to plague all of the services.

We would like to recognize at this time the member of the Executive Planning Committee without whose considerable personal efforts this Conference would have not been possible.

Fred H. Meyer Jr.

FRED H MEYER Jr.
General Chairman
1980 Tri-Service Corrosion
Conference

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PUBLICATIONS/PATENTS:
"Corrosion Problems Associated with Uranium Refining"
Corrosion, 15, No. 4, 168 (1959)
36 reports dealing with corrosion problems in uranium refining (published by AEC)
1967, 1974, Tri-Service Corrosion Conference Proceedings
Corrosion Performance of New Aircraft Fastener Coatings on Operational Aircraft Paper No 115, Corrosion/73
Recent Air Force Electronics Systems Corrosion Problems
Corrosion/74

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An Address By

General Bryce Poe II

Commander, Air Force Logistics Command

to

The Tri-Service Corrosion Conference

at

The U.S. Air Force Academy, Colorado

November 5, 1980

I can't think of an activity more important yet more humbling than keynoting this Tri-Service Corrosion Symposium.

Any keynoter senses the urge to be profound, persuasive and precise and I am finding that difficult to do on this subject. As I checked my notes, reviewed programs and generally gathered my thoughts, I realized I would produce more questions than answers.

However, I did uncover one dubious consolation: I couldn't find anyone who had ever been completely profound, persuasive and precise on this subject. And I will not pretend to solve in 15-20 minutes a problem that has plagued humankind for hundreds of years.

Saint Matthew warned us not to store our treasures where 'moths and rust corrupt.' He wrote that about two thousand years ago, and I am sure the problem had been around for centuries. Corrosion control may not be the world's oldest profession, but it's close. Whenever metal has been exposed to the elements, there have been problems.

It may be, however, that we are beginning to turn some corners--at least in terms of recognition and support.

A 1975 study by the National Bureau of Standards found that corrosion cost the United States economy approximately $70 billion annually. (That figure is probably closer to $100 billion today.) It was further estimated that $10-20 billion could have been prevented using current technology. The study also concluded that annual losses in the federal government approached $8 billion with about 20 percent avoidable. The Air Force alone spends a billion dollars a year fighting the problems. A billion dollars may not seem like much in this era of high costs and large budgets. But I assure you it is. With that same billion, for example, I could fund one-third of our FY-81 shortfall in aircraft replenishment spares.

There are a number of systemic forces driving the corrosion problem. They are true of the Air Force but also apply to the other services and generally to our Allies as well. First, we continue to operate major weapon systems and support equipment far beyond the originally intended life. The average age of our active duty aircraft today is over 12 years .. . .15 for the Reserves. Not only are they old, but they were developed with performance as the primary consideration. Little thought was given to deterioration over time because a 20-30 year service life was not anticipated. Today, those systems are still flying and we have to resort to significant--sometimes extraordinary--corrosion programs to keep them useful.

Second, the defense budget is not keeping pace with the rising cost of systems and components. That means we rely on fewer but what we hope are qualitatively superior systems. Therefore, downtime, for any reason, has become serious indeed.

Thirdly, operation and support costs continue to increase, leaving less and less money for developing new systems or for improving existing ones. That means less money for correcting corrosion and a greater premium on initial prevention.

Finally, the scope and span of control show no signs of diminishing. We in Log Command, as the corrosion control focal point for the Air Force, support over 9,000 aircraft in the U.S. inventory. We do that for over 100 bases in this country and 27 other American installations overseas. Also, we support about 8,000 aircraft belonging to friendly foreign governments. In each of those situations, we are dealing with different environmental conditions. In the case of the hundred or so stateside bases, we have a reasonably firm grip on our problems. But the foreign bases are a different matter. The environmental constraints our aircraft face are neither well known or completely understood.

For all of these reasons, and more, the Joint Logistics Commanders have taken a sharp look at corrosion problems. We have formed a panel to emphasize management of the corrosion prevention and control program, to share lessons learned and generally to exploit existing technology to deal with the problem.

Essentially, we have a two-pronged approach in the Air Force--making sure corrosion concerns are accommodated in our developmental programs and treating and preventing corrosion with our exisiting systems. That sounds simple enough, but I assure you it isn't.

Our developmental efforts resolve around Mil Standard 1568, first published in 1975 and updated continuously since then. It has done and is doing a number of things for use. First, we have codified lessons learned over the past 25 years so that mistakes will not be repeated.

Second, we have established Corrosion Prevention Advisory Boards for every major weapons system under development--including the F-15, A-10, F-16, KC-10, M-X and Cruise Missiles. We have also established boards for several older systems, including the C-5, C-141 and C-130. The board consists of representatives from the Air Force Materials Laboratory, the SPO, the ultimate using command, the gaining Air Logistics Center and the Air Force corrosion office in AFLC. The board advises on materials selected, work procedures and other pertinent factors to make sure we don't design-in "known" corrosion problems.

The board has the power to reject certain types of materials that have proven to be deficient. Using commands and the design community have historically assigned a low priority to corrosion control. Many times a corrosion-sensitive material is chosen because of its fracture toughness or lower acquisition cost.

A good case in point is 7075-T6 aluminum and magnesium. Those materials are now disqualified from use in forgings and milled products. But we had to learn the hard way--including the complete redesign and remanufacture of gear assemblies, for several of our aircraft. The KC-135 alone cost us over $73 million for main landing gear remanufacture.

In a totally "performance" oriented development program, 7075-T6 aluminum alloy may be justifiable. It's tremendously strong, fatigue resistant, and some ten percent lighter than 7075-T73 aluminum. But the advantages quickly fade after that. T6 is considerably more corrosion-prone than T73. For example, we are having to replace the outer wing box beam in all C-130 Bs and Es because of T6 aluminum. In the

switch, we will surrender that 10 percent weight advantage, expend a great amount of resources and manhours and log considerable downtime. T6 simply was a poor life cycle choice.

AISI 4340 steel in C-141 main landing gears is another example. We paid $5 million for that learning process.

The board also specifies certain tests for corrosion that every material must pass. It additionally requires the contractor to define a corrosion prevention plan--not only in development and production but throughout the life cycle of a system.

We are serious about this early involvement in the developmental process. We have found that a dollar spent to properly seal, coat, isolate dissimilar metals and generally apply sound corrosion control principles during the early stages of a system will save us ten dollars in life cycle costs. In this case, a dollar of prevention should prevent a ten-dollar cure. We cannot afford to ignore savings of that magnitude. . . and we won't.

Our newer systems--the F-15, F-16, A-10--all were designed with very stringent corrosion factors. Consequently, we haven't had--and I do not believe we will have--significant corrosion problems.

However, "curing" our older systems has had some bumps and grinds. We in AFLC should know. We feel the impact most directly. Sooner or later, they all come to us for correction.

Part of the problem is the slow pace of technological advance--particularly with regard to non-destructive inspection. Even with our advances in eddy current, ultrasonic, x-ray and acoustical techniques, we still haven't turned the corner. For example, we do not not have an NDI technique to rapidly survey a large surface area, such as a C-5 wing. Ultrasonics are fine for fastner sections, but the law of diminishing returns rapidly takes over after that.

Many of our NDI techniques cannot distinguish corrosion from other normal or abnormal conditions. Eddy current is useful for detecting corrosion on C-141 windshield frames. . . at least to a point. But the overall windshield structure consists not only of the frame, but other layers of material--two skin layers and possibly other reinforcing members. Eddy current quickly gets confused when faced with this stack of materials. It cannot distinguish between corrosion or non-uniform spacing. If corrosion is present, it must be treated. If it's non-uniformity, maintenance generally is not required.

We are involved in some promising NDI work. Corrosion probes have been adapted for inaccessible areas of some C-141s.

The probe is made from the same material we are attempting to check; therefore, it should corrode at the same rate.

The probe is located in the wing to pylon mount area. Each time a C-141 comes to our depot at Warner Robins for Programmed Depot Maintenance, we take the pylon down to check for corrosion. Four things can happen when we do that--three of them

are bad. If there is corrosion, we correct it. That's the "good" one. If there is corrosion, we correct it. That's the "good" one. If there is no corrosion, we waste 1,167 manhours, extend the PDM cycle and increase the overall downtime of that aircraft. In addition, if the seal was good originally, we break it. When we reseal it, we risk an imperfect patch.

If the corrosion probe experiment works--and we are in the second year of a four-year program--we can inspect aircraft quickly, at low cost and without disassembly. So far, it appears to be working well.

Overall, we will be spending $200,000 beginning mid-FY81 to evaluate current NDI techniques and determine which can be improved and developed into a general corrosion detection system. Hopefully, that will be followed in mid-FY83 with a one million dollar development program.

We do have some "corrective" success stories to report. The best example is the repair of C-130 upper wings. In the early days, corrosion treatment of the C-130 upper wings required 300 grind-outs per panel. In 1969 alone, we spent $6 million repairing C-130s assigned to Pacific Air Force.

Finally, we changed our procedures. We began coating the upper wing with inhibited polysulfide sealant followed by a polyurethane topcoat--all to an unprecedented 8-13 mill thickness. The change-and the associated lowered costs--have been dramatic. The upper wing surfaces now require less than three grind-outs per panel. Our C-141s, C-5s, B-52s, and KC-135s now receive a new polysulfide primer rather than sealant although still topcoated with polyurethane. With that improved process, we get the same protection with 3-4 mills as we received with 8-13 mills thickness.

Another area of intense concern involves support or non-flying equipment. We have the technology. Our people at San Antonio are doing some excellent work in this area. But our procurement contracts must demand this level of protection.

At Sacramento, we have a tremendous workload with Communications-Electronics vans, shelters and components. The same funding squeeze has predictably affected the C-E community. Much of the equipment, some with designs dating back to the 1940s, has not been replaced. About 90 percent of the C-E shelter repair work at Sacramento is devoted to corrosion control. Over 180 people work full time in the van shop. Overall, we expend at least 260,000 manhours per year in this role at a cost of almost eight million dollars. We simply have to do a better job in designing our non-flying assets. As the people in the maintenance shops say, "corrosion control is eating our lunch, wrapper and all."

In a "joint logistics" sense, inter-service cooperation and sharing of technology must blossom. We need a scientific data base not only to build our technology but to justify funding for research and construction programs. Washing aircraft is a good example. Essentially, we wash aircraft the same way we did in World War II. We are employing some promising new techniques at MacDill, but we are having difficulty developing the necessary data base. The unit there has changed aircraft three times during the testing period--from F-4Es to F-4Ds and now to F-16s. It's frustrating in terms of "scientific method."

On the other hand, the Navy, the Royal Air Force and the Royal Australian Air Force are using the same techniques, swear by them, but have no significant data base to back up their claims. We cannot afford that!

What can be done through inter-service cooperation is being demonstrated in work with neutron radiography. Theoretically, neutron radiography holds tremendous promise for non-destructive inspection. It is the only NDI method that will detect corrosion per se. . . that is, it reveals "active" corrosion. The other methods detect the absence of sound metal.

The Navy did much of the early research, but the problem has always been the safety constraints associated with radio-activity. The Army has now found a way to generate neutrons without a radioactive source. Early next year at Sacramento, we will be using that Army developed equipment to inspect F-106s, F and FB-111s and A-10s. It could be the breakthrough we need for rapid NDI of large surfaces.

We need more of that type of cooperation. Corrosion does not favor one service branch over the other. It does not recognize ethnic or racial groups and national boundaries. Corrosion eats at all metal surfaces, in all services, in all countries.

Through the Joint Logistics Commanders and through our strong association with allies and friends, we have focused a great deal of multi-service and multi-national attention on this problem. But a considerable amount of work remains to be done.

Corrosion is both tenacious and insidious. We urgently need to solve the many problems in this area. My instincts tell me those solutions will come much quicker if we pool our resources in a united effort. That's why I have come today. And that's why I place so much importance on this conference and what can come from it.

In an era when our weapons and support system are so expensive, when production lead times are so extended and when our potential adversary holds considerable numerical advantages in a broad range of systems, the pervasive impact of corrosion must be stopped . . . and stopped quickly.

In the final analysis, I am sure we all agree with Shakespeare's Othello: "Keep up your bright swords, for the dew will rust them."

Thank you.

Born in Kansas in 1924, General Bryce Poe II completed Army Air Forces pilot training and graduated from the United States Military Academy at West Point in 1946. A member of one of the first jet-equipped units in the Air Force, General Poe flew in more than 80 air shows demonstrating the new aircraft. A veteran of over 300 combat missions and 5,000 flying hours, General Poe flew RF-80s in the Korean conflict and RF-4Cs in Vietnam. About half of his military service has been overseas with assignments in both Europe and Asia. General Poe has served in the Tactical Air Command, Strategic Air Command, Air Research and Development Command, the Far East Air Forces, U. S. Air Forces in Europe, NATO, and the Office of the Secretary of the Air Force. In addition to duties flying reconnaissance and fighter aircraft, he has been a missile man, an aide,an executive officer, a planner, and a liaison officer to the Congress. Before becoming Commander of the Air Force Logistics Command in 1978 he was Commander of the Air Force Acquisition Logistics Division (1976-1977), Vice Commander in Chief, USAFE (1974-1976) and Commander Ogden Air Logistics Center (1973-1974). He is a graduate of the Armed Forces Staff College and the National War College and holds advanced degrees from the University of Omaha (history) and the George Washington University (International Affairs).

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GENERAL BRYCE POE II

General Bryce Poe II is Commander of the Air Force Logistics Command (AFLC), with headquarters at Wright-Patterson Air Force Base, Ohio. The command mission is to provide worldwide technical logistics support to all Air Force active and reserve force activities, Military Assistance Program countries, and designated U.S. Government agencies.

General Poe was born in Wichita, Kans., on Oct. 10, 1924. He attended the Colorado School of Mines and Kansas University, and was graduated from the U.S. Military Academy, West Point, N.Y., in 1946. He completed Army Air Forces pilot training prior to graduation from the Academy. He received a master of arts degree in history from the University of Omaha in 1964 and a master of science degree in international affairs from the George Washington University in 1965, and graduated from the Armed Forces Staff College in 1960 and the National War College in 1965.

From November 1946 to September 1948, General Poe was a member of one of the first jet-equipped units in the U.S. Air Force and flew in more than 80 airshows demonstrating the new type aircraft. He next was transferred to the Far East and assigned to the 82d Tactical Reconnaissance Squadron, equipped with RF-80 jet aircraft, in Japan.

At the beginning of the Korean War, he was transferred to Korea and flew the first U.S. Air Force jet reconnaissance sortie and 90 combat missions. He returned to the United States, and in January 1951 was assigned to a Strategic Air Command fighter escort squadron at Bergstrom Air Force Base, Tex., and later was officer in charge of a reconnaissance replacement training unit at Shaw Air Force Base, S.C.

In 1952 General Poe was assigned to Allied Forces Northern Europe, Oslo, Norway, as a fighter operations officer. In this capacity he flew Vampires, Meteors, F-84, and F-86 aircraft with the Royal Norwegian and Royal Danish Air Forces. He returned to the United States in July 1956 and was assigned as aide and then executive officer in the office of General B. A. Schriever, Commander, Western Development Division, Inglewood, Calif.

OVER

(Current as of October 1978)

(Local reproduction authorized)

In August 1959 he entered the Armed Forces Staff College, and in January 1960 he went to Offutt Air Force Base, Nebr., as operations officer of an Atlas D squadron. In 1962 he was transferred to Headquarters Strategic Air Command as missile plans officer, and later was Chief, Missile Plans Section, Operations and Training Division. In 1964 General Poe was selected to enter the National War College. Following his graduation in July 1965, he served as Chief, Plans Group, Office of Legislative Liaison, Office of the Secretary of the Air Force. In July 1967 he was transferred to Bergstrom Air Force Base, Tex., where he became Vice Commander, 75th Tactical Reconnaissance Wing.

In July 1968 General Poe went to Southeast Asia as Vice Commander, 460th Tactical Reconnaissance Wing, Tan Son Nhut Airfield, Republic of Vietnam. During his Vietnam tour of duty, General Poe flew 213 combat missions, 200 of which were in RF-4C aircraft.

From July 1969 to July 1970, General Poe was Commander of the 26th Tactical Reconnaissance Wing, Ramstein Air Base, Germany. He assumed duties as Deputy Chief of Staff, Logistics, United States Air Forces in Europe (USAFE), with headquarters at Wiesbaden, Germany, in July 1970.

General Poe became Commander of the Ogden Air Materiel Area (now Ogden Air Logistics Center) at Hill Air Force Base, Utah, in February 1973. In June 1974, he became Vice Commander in Chief of USAFE with headquarters at Ramstein Air Base, Germany.

He was assigned to Wright-Patterson Air Force Base, Ohio, in July 1976 as Commander of the Air Force Acquisition Logistics Division, an AFLC organization. On January 30, 1978, General Poe assumed his current duties as Commander of the Air Force Logistics Command.

He is a command pilot, and holds a Master Missileman Badge. His military decorations and awards include the Distinguished Service Medal with 1 oak leaf cluster, Legion of Merit, Distinguished Flying Cross with 3 oak leaf clusters, Bronze Star Medal, Air Medal with 19 oak leaf clusters, Air Force Commendation Medal with 3 oak leaf clusters, Presidential Unit Citation Emblem with 2 oak leaf clusters, Air Force Outstanding Unit Award Ribbon with 1 oak leaf cluster, and the Republic of Vietnam Cross of Gallantry with palm.

General Poe is married to the former Kari Rollum of Oslo, Norway. They have three children: Susan, Karen, and Bryce, III.

He was promoted to the grade of general on February 2, 1978.

PERSONAL FACT SHEET - General Bryce Poe II

A. Personal Data

1. Born - Oct. 10, 1924, Wichita, Kans.
Father - Bryce Poe; mother - Aileen Keith.

2. Married - Mar. 24, 1955; wife - Kari Rollum.
Children - Susan, Karen, & Bryce, III.

B. Education

1. Attended, Colorado School of Mines, 1941-42; Kansas University, 1942-43.

2. Graduate, U.S. Military Academy, West Point, N.Y., B.S., 1946; Army Air Forces Flying School, 1946; Armed Forces Staff College, 1960; University of Omaha, Nebr., M.A., 1964; The George Washington University, M.S., 1965; National War College, 1965.

C. Service

1. July 1943 - Nov 1946 Cadet, USMA, West Point, N.Y.; & plt. tng., Williams Fld., Ariz.

2. Nov 1946 - Sept 1948 Plt., 363d Recon. Gp., Brooks Fld., Tex., & Langley Fld., Va.

3. Sept 1948 - June 1950 Plt., 82d Tac. Recon. Sq., FEAF, Yokota AB, Japan.

4. June 1950 - Jan 1951 RF-80 plt., 8th Tac. Recon. Sq., Korea.

5. Jan 1951 - Apr 1951 Plt., 561st Ftr. Escort Sq., Bergstrom AFB, Tex.

6. Apr 1951 - Aug 1952 RTU Comdr., 18th Photo. Recon. Sq., Shaw AFB, S.C.

7. Aug 1952 - July 1956 Ftr. ops. off., AFNORTH, Oslo, Norway.

8. July 1956 - Sept 1956 Ops. stf. off. (guided msls.), ICBM Ops. Gp., HQ ARDC, Inglewood, Calif.

9. Sept 1956 - Aug 1959 Aide & exec. off. to Comdr., HQ ARDC.

10. Aug 1959 - Jan 1960 Stu., AFSC, Norfolk, Va.

11. Jan 1960 - Oct 1961 Guided msl. ops. off., later msl. lch. off., 566th Strat. Msl. Sq., Offut AFB, Nebr.

12. Oct 1961 - Jan 1963 Msl. ops. stf. off., later msl. plans off., HQ SAC, Offutt AFB.

13. Jan 1963 - Aug 1964 Ch., Msl. Plans Sec., HQ SAC.

14. Aug 1964 - Aug 1965 Stu., NWC, Ft. McNair, Washington, D.C.

15. Aug 1965 - July 1967 Dep. Ch. & later Ch., Plans Gp., Ofc. of Legislative Ln., OSAF, Washington, D.C.

16. July 1967 - May 1968 Vice Comdr., 75th Tac. Recon. Wg., Bergstrom AFB, Tex.

17. May 1968 - July 1969 Vice Comdr., 460th Tac. Recon. Wg., Tan Son Nhut Afld., RVN.

18. July 1969 - July 1970 Comdr., 26th Tac. Recon. Wg., Ramstein AB, Germany.

19. July 1970 - Jan 1973 DCS/Log., HQ USAFE, Wiesbaden, Germany.

20. Feb 1973 - June 1974 Comdr., OOAMA, Hill AFB, Utah.

21. July 1974 - June 1976 Vice CINC, USAFE, Ramstein AB, Germany.

22. July 1976 - Jan 1978 Comdr., AFALD, Wright-Patterson AFB, Ohio.

23. Jan 1978 - Present Comdr., AFLC, Wright-Patterson AFB, Ohio.

D. Decorations and Service Awards

Distinguished Service Medal
w/1 oak leaf cluster
Legion of Merit
Distinguished Flying Cross
w/3 oak leaf clusters
Bronze Star Medal
Air Medal w/19 oak leaf clusters
Air Force Commendation Medal
w/3 oak leaf clusters
Presidential Unit Citation Emblem
w/2 oak leaf clusters
Air Force Outstanding Unit Award
Ribbon w/1 oak leaf cluster
Combat Readiness Medal
World War II Victory Medal
Army of Occupation Medal (Japan)
National Defense Service Medal
Korean Service Medal
Vietnam Service Medal
Air Force Longevity Service Award
Ribbon w/6 oak leaf clusters
Small Arms Expert Markmanship
Ribbon
Republic of Korea Presidential Unit
Citation Ribbon
United Nations Service Medal
Republic of Vietnam Campaign Medal
Republic of Vietnam Cross of Gallantry
w/palm
Master Missileman Badge

E. Effective Dates of Promotion

Grade	Temporary	Permanent
2d Lt	June 4, 1946	June 4, 1946
1st Lt	Feb 4, 1948	June 4, 1949
Capt	Sept 10, 1951	June 4, 1953
Maj	Apr 17, 1957	June 4, 1960
Lt Col	July 15, 1962	June 4, 1967
Col	Sept 1, 1965	Aug 1, 1969
Brig Gen	Aug 1, 1970	Feb 26, 1971
Maj Gen	Sept 1, 1972	Apr 2, 1973
Lt Gen	July 1, 1974	
Gen	Feb 2, 1978	

(Date of rank Feb. 2, 1978)

THE AIR FORCE CORROSION PROGRAM - 1980

Major Larry C. McCourry
Warner Robins Air Logistics Center
Robins Air Force Base, GA

(Slide 1) Good morning. I'm Major Larry McCourry, chief of the Material Corrosion Section at Warner Robins ALC. As chief of our section, which contains a variety of corrosion, nondestructive inspection, and metallurgical engineering functions, I also wear the hat of the Air Force and Air Force Logistics Command Corrosion Program Manager. I was formerly an aircraft maintenance officer with the Military Airlift Command, and I've been in my present position for a little over one year. This is the first opportunity I've had to participate in a multi-service corrosion conference, and I'm pleased to be able to present an overview of the Air Force Corrosion Program to you today.

(Slide 2) I've chosen the areas shown here for brief discussion in my overview today. I think coverage of these topics will enable you to see where we are in our Air Force Program, some of the major tools which we're using to manage the program, and a few projections on what we'd like to do in the future.

(Slide 3) First, I'll discuss the major point in my presentation today - that is, the transfer of the responsibility for management of the Air Force Corrosion Program. As some of you know, we at Warner Robins Air Logistics Center have been the primary agent responsible for corrosion prevention and control for the Air Force for about 14 years in our role as manager of the Logistics Command Corrosion Program. In October 1979, we were delegated the responsibility for management of the total Air Force Corrosion Program which was formerly assigned to HQ USAF. This transfer gave us the authority and resources needed to better accomplish many of the goals that we've had for several years throughout our corrosion community. It also enables us to embark on some new approaches to improve the overall Air Force corrosion prevention and control effort. Since we didn't receive any personnel with the initial transfer, our first major task was to analyze the program, develop a management plan, identify the tasks to be accomplished, and identify the personnel and other resources required. Through this effort, we were able to obtain 7 personnel authorizations for program management. All of the positions aren't filled yet, so if any of you are interested in a good job, please see me during the coffee break. After tackling the manpower program, we next had the task of rewriting our Air Force Corrosion Bible, AFR 400-44. We're in the midst of that effort now and hope to complete it by the end of the year. Our main thrust in the revision is to make program management more active and to require a greater degree of participation from major operating commands.

(Slide 4) On the next slide are some examples of areas in which we plan to direct our efforts in managing the Air Force Corrosion Program. (Slide 4)

(Slide 5) We have several tools which we're using to help us in our program management. The major ones are shown here. While some are relatively new, the majority are necessary expansions of activities which we've been using for some time in our Logistics Command program.

(Slide 5A) We will expand the scope of our participation in Corrosion Prevention Advisory Boards and insure that these boards are established early in the system design phase. The Corrosion Prevention Advisory Boards were created to give the system program manager (SPO) technical information on corrosion prevention and control. This information is developed by a pool of Air Force and contractor specialists and is meant to influence the designer in corrosion protection through proper selection of materials and coatings. The board applies lessons learned from corrosion problems on previous weapon systems, thereby making new weapon systems as corrosion-proof as possible.

(Slide 5B) We will continue to publish our widely accepted quarterly Corrosion Summary which we now publish in over 1200 copies and distribute worldwide. We continuously receive requests for increased distribution of this valuable cross-feed tool. In the future, we plan to include more information from systems command and the operating commands so this publication will reflect a true total Air Force effort. The Summary contains information on the topics shown here and is of interest to all personnel in the DOD and allied nations corrosion community.

(Slide 5C) We will also continue to determine the effectiveness of major command corrosion programs through periodic surveys. These surveys offer a convenient method of evaluating command corrosion programs, providing on-the-spot assistance, and identifying areas where appropriate agencies need to take actions to better support field units. The end result is improvement of our total corrosion prevention and control effort.

(Slide 5D) Talk from slide.

(Slide 5E) Talk from slide. Our experience over the years has shown that the survey costs are easily amortized through savings resulting from actions taken as a result of our visits.

(Slide 5F) 1. The next tool which we believe is very important in our corrosion program management is the base corrosion severity classification system called PACER LIME. The objective of project PACER LIME was to develop an environmental corrosion severity classification system which compared the relative corrosion severity of Air Force bases worldwide.

2. After several years of data gathering by our AFLC Corrosion Office, a study was conducted by Michigan State University to analyze the data. The analysis developed by Michigan State considered weather, atmospheric pollutants, and geographical factors to compute a severity index for three aspects of corrosion maintenance: aircraft washing, painting, and corrosion repair. We expect to receive the final PACER LIME report soon and begin using the data in management of our corrosion activities. For those interested, Prof Bob Summitt, of Michigan State University, will present a paper on PACER LIME during Session 3A of the conference.

(Slide 5G) 1. Moving into some of the more recently initiated activities, I'll now discuss our corrosion prevention and control facilities plan. This plan is a HQ USAF/LE directed attempt to develop a coordinated long-range construction program for Air Force corrosion-related facilities that is both affordable and justifiable. The plan was established in June 1979 to enable us to provide more meaningful information to DOD and the Congress on our requests for CPC facilities in the military construction program.

2. HQ AFLC was tasked to implement the plan, with the assistance of our program management office and the major command corrosion program managers.

(Slide 5H) The plan included the major tasks shown here: A very comprehensive survey was conducted to determine the type of facilities available at all Air Force bases. The minimum essential equipment requirements for the operation of corrosion facilities were also determined. From the results of these two tasks, we were able to list the CPC facilities construction requirements. The alternative concepts task called for a study of the economic and mission impact of various alternatives on complete strip and repaint facilities. The study contractor investigated concepts ranging from all painting being done by major commands to all painting being done by ALCs or contractors. This is where we are now - in the midst of this contracted task. When this effort is completed, HQ AFLC will present the developed program to HQ USAF, Office of the Secretary of Defense, and congressional committees as required. As a matter of note, Lt Col Cooke of LOEA is briefing this subject to the USAF Deputy Commanders for Logistics at their conference in Washington today.

(Slide 5I) The most recently established tool which will enable us to obtain greatest benefit from our program management efforts is the Joint Logistics Commander's Panel on Corrosion. As shown on this slide, the Joing Logistics Commanders have been interested in corrosion for several years. This interest culminated in the establishment of a special panel last November. Our Commander, General Poe, together with the commanders of AF Systems Command, Navy Material Command, and Army Development and Readiness Command signed the joint agreement and charter. Basically, the panel represents a concerted effort to increase the general level of awareness of corrosion among designers and developers in all services, and to provide better equipment and techniques to working-level maintenance personnel.

(Slide 5J) The goals, as taken from the charter, are shown here:

a. Review and evaluate total management approach for each service to include R & D, material acquisition, maintenance, and support.

b. Review technology efforts to identify overlaps, voids, and opportunities for sharing.

c. Review selected acquisition and support programs to insure feedback of corrosion lessons learned.

d. Review data reporting systems for effectiveness in providing corrosion maintenance costs. [Try to find new and better systems to increase the amount of accurate and usable field data available.]

e. Coordinate development of a credible method of predicting the impact of development dollar expenditures for corrosion prevention on system life cycle costs. (so managers can have more reliable comparisons of program costs versus support costs)

f. Review existing corrosion publications. [Compare, revise, rescind, combine, and joint use where possible. (Give special attention to electronic systems corrosion prevention here)]

g. Review service training; and develop joint programs [for engineers, technicians, and maintenance personnel] where possible.

(Slide 5K) These four subpanels have been formed to accomplish the goals of the panel. Our Air Force Corrosion Managers are involved in the activities of the JLC panel and subpanels as are many of you. We look forward to working with other services in this area and believe that this mutual effort will enable us to save valuable time and dollars and have a more effective corrosion effort DOD-wide.

(Slide 6) Finally, let's briefly take a look at some of the things we plan to do in the future in our Air Force Corrosion Program. These first two areas have been relegated low priority in the past. With increased emphasis throughout the Air Force on conservation of resources through corrosion prevention and control, we now are able to focus more attention on these important mission support areas.

(Slide 7) We have recently completed a contract effort to develop a new data automation requirement in support of the first goal shown on this slide. We're awaiting implementation of this new system now and expect considerable improvement in identification of Air Force corrosion man-hours in the near future. With these results, we'll be better able to accomplish the second goal shown here. Lac of sufficient capability in this area in the past has slowed progress in our program considerably.

(Slide 8) 1. As General Poe mentioned, there is considerable room for expansion of our corrosion detection and evaluation capabilities through greater use of nondestructive inspection techniques. We've recently initiated research and development efforts along this line through our Materials Laboratory.

2. Although there is nothing magic or astounding about these future goals, we feel that they are very solid management approaches which will significantly reduce the economic impact of corrosion on Air Force systems and equipment.

(Slide 9) In summary, I've given you some idea of where we are in our Air Force Corrosion Program management, the major tools with which we apply our management efforts, and a little insight on some approaches we have planned for the future.

(Slide 10) Thank you.

AIR FORCE CORROSION PROGRAM

MAJOR LARRY McCOURRY

OVERVIEW

- PROGRAM MANAGEMENT
- MAJOR MANAGEMENT TOOLS
- FUTURE EMPHASIS

PROGRAM MANAGEMENT RESPONSIBILITY TRANSFER

- MANPOWER ADDITIVE
- REVISION OF AFR 400-44
- EXAMPLES OF EFFORT

EXAMPLES OF EFFORT

- PROVIDE PROGRAM DIRECTION TO COMMANDS/LABS
- INTEGRATE R & D AND CORROSION EFFORTS OF COMMANDS
- EVALUATE CORROSION FACILITIES REQUIREMENTS
- APPLY LIFE CYCLE COSTING TO NEW AND EXISTING SYS
- COORDINATE WITH AIRLINES AND INDUSTRY
- COORDINATE WITH OTHER SERVICES AND ALLIED NATIONS

MAJOR MANAGEMENT TOOLS

- CORROSION PREVENTION ADVISORY BOARDS
- AFLC CORROSION SUMMARY
- COMMAND CORROSION SURVEYS
- BASE CORROSION SEVERITY CLASSIFICATION (PACER LIME)
- CORROSION PREVENTION & CONTROL FACILITIES PLAN
- JOINT LOGISTICS COMMANDERS PANEL

CORROSION PREVENTION ADVISORY BOARDS

- COMPOSITION
  - SYSTEMS COMMAND
  - LOGISTICS COMMAND
  - OPERATING COMMAND
  - CONTRACTOR
- CORROSION PROTECTION
  - DESIGN
  - MATERIALS
  - COATINGS
- LESSONS LEARNED

AFLC CORROSION SUMMARY

- EVALUATION OF MATERIALS, TECHNIQUES, EQUIPMENT
- STATUS OF TECHNICAL MANUAL CHANGES
- TRAINING COURSES
- PROJECT STATUS
- MISCELLANEOUS CORROSION INFORMATION

COMMAND CORROSION SURVEYS

- 3 YR SURVEYS OF 10 COMMANDS
- SAMPLING OF BASES, ACFT, EQUIPMENT
- ACTION ITEM FOLLOWUP
- COORDINATED MULTI-COMMAND EFFORT

SURVEY TEAM COMPOSITION

- LOGISTICS COMMAND
  - CORROSION MANAGEMENT OFFICE (LEADER)
  - SUPPORTING PRIME AIR LOGISTICS CENTERS
- SYSTEMS COMMAND
  - MATERIALS LABORATORY
- HOST OR USING COMMAND CORROSION MANAGER
- OTHERS
  - ELECTRONIC SECURITY COMMAND
  - COMMUNICATIONS COMMAND
  - ACQUISITION LOGISTICS DIVISION
  - AERONAUTICAL SYSTEMS DIVISION
  - TRAINING COMMAND

BENEFITS OF SURVEYS

- TANGIBLE
  - COST AVOIDANCES
  - REDUCED CORROSION PROBLEMS
  - IMPROVED PRODUCTS
- INTANGIBLE
  - IMPROVED MORALE
  - BETTER COMMUNICATIONS WITH FIELD UNITS
  - IMPROVED SUPPORT FOR FIELD PROBLEMS

PROJECT PACER LIME
INPUT
OUTPUT
WEATHER DATA
POLLUTION DATA
GEOGRAPHICAL DATA
PACER LIME
AIRCRAFT WASH CYCLE
AIRCRAFT PAINT CYCLE
AIRCRAFT CORROSION REPAIR FREQUENCY

USAF CORROSION PREVENTION & CONTROL (CPC) FACILITIES PLAN

- INITIATED BY HQ USAF, JUNE 1979
- IMPLEMENTED BY HQ AFLC
- INVOLVES WR-ALC/MMETC AND MAJOR COMMANDS

MAJOR TASKS

- CONDUCT BASE FACILITIES SURVEY
- DETERMINE FACILITY EQUIPMENT REQUIREMENTS
- CONSTRUCT FACILITY FUNDING PROFILE
- EVALUATE ALTERNATIVE CONCEPTS
- PRESENT DEVELOPED PROGRAM

BACKGROUND

- 1970 - JLC PANEL REPORT, PROTECTIVE COATINGS
- 1975 - JSATG, SYSTEM PROGRAM REVIEW
- 1978 - CORROSION CONTROL SELECTED FOR REVIEW
- 1979 - REVIEW OF CORROSION PROGRAMS
- NOV 79 - CORROSION PANEL ESTABLISHED

JLC PANEL GOALS

- REVIEW/EVALUATE EACH SERVICE'S MANAGEMENT APPROACH
- REVIEW TECHNOLOGY TO IDENTIFY OVERLAPS/ OPPORTUNITIES FOR SHARING
- FIND AND COORDINATE LESSONS LEARNED
- REVIEW AND REFINE DATA/COSTS REPORTING SYSTEMS
- DEVELOP USABLE LIFE CYCLE COSTING METHODS
- REVIEW/CONSOLIDATE/JOINT USE PUBLICATIONS
- REVIEW/CONSOLIDATE TRAINING FOR ENGINEERS/ MAINT PERSONNEL

SUBPANELS

- TECHNOLOGY
- TRAINING
- DATA COLLECTION AND LESSONS LEARNED
- PUBLICATIONS

FUTURE EMPHASIS

- PROVIDE GUIDANCE AND DIRECTION NECESSARY TO ESTABLISH AND MAINTAIN AN EFFECTIVE CORROSION PREVENTION AND CONTROL PROGRAM FOR AIR FORCE COMMUNICATIONS, ELECTRONIC AND METEOROLOGICAL EQUIPMENT.
- PROVIDE GUIDANCE AND DIRECTION NECESSARY TO ESTABLISH AND MAINTAIN AN AIR FORCE VEHICLE CORROSION PREVENTION AND CONTROL PROGRAM AND COORDINATE WITH VEHICLE PROCUREMENT AGENCIES IN OTHER SERVICES.

FUTURE EMPHASIS

- REVIEW AND IMPROVE THE COLLECTION OF MAINTENANCE DATA (MDC, AFM 66-1) ON AIR FORCE WEAPON SYSTEMS

- PERFORM COST ANALYSES TO SUPPORT FACILITIES, EQUIPMENT, FUNDS, AND MANPOWER REQUESTS

FUTURE EMPHASIS

- DIRECT A CONCERTED EFFORT TOWARD DEVELOPMENT OF NDI METHODS/PROCEDURES WHICH WILL RESULT IN THE CAPABILITY TO EVALUATE CORROSION DAMAGE IN ADDITION TO DETECTING SUCH DAMAGE

SUMMARY

- PROGRAM MANAGEMENT TRANSFER
- MAJOR MANAGEMENT TOOLS
- FUTURE EMPHASIS

AIR FORCE CORROSION PROGRAM

MAJOR LARRY McCOURRY

Biography

Name: Larry G. McCourry, Major, USAF

Present Affiliation: Warner Robins Air Logistics Center/MMETC, Robins AFB GA 31098

Title: Air Force/Air Force Logistics Command Corrosion Programs Manager

Field of Interest/Responsibilities:
- Chief of Material Corrosion Section
- AFLC Corrosion Program Manager
- Air Force Corrosion Program Manager

Previous Affiliations/Titles:
- Officer in Charge, Programs & Mobility (Aircraft Maintenance), Military Airlift Command, Rhein Main Air Base Germany, 1975-1979
- Maintenance Programming Officer, Headquarters Military Airlift Command, 1972-1975
- Aircraft Maintenance Officer, Charleston AFB SC, 1970-1972

Academic Background:
- B.S. Mechanical Engineering, Univ of Tennessee, 1968
- M.A. Executive Development for Public Service, Ball State Univ, 1978
- Aircraft Maintenance Officer Course, Chanute AFB IL(USAF) 1969

Society Activities/Offices: Air Force Association

CORROSION OF NAVAL SEA SYSTEMS
AN OVERVIEW

by

George A. Wacker

CORROSION OF NAVAL SEA SYSTEMS - AN OVERVIEW

by

George A. Wacker

INTRODUCTION

The Naval Sea Systems Command (NAVSEA) is responsible for combatant and non-combatant systems with ocean related missions. As shown in Figure (1) the envelope of cognizance includes ship systems and ocean engineering systems. Naval submarines and submersibles vary in size, shape and design characteristics to suit mission requirements. Some examples are presented in Figure (2).

Even greater variations exist in the surface ships of the modern Navy. Here we have two important categories-- conventional hull vessels and high performance ships. Some examples, which demonstrate the variety of surface ships, are illustrated in Figure (3).

Examples of traditional displacement hulled ships are shown in the lower portion of Figure (3). In these vessels the hull floats on the surface as it is propelled through the water.

To reduce drag and thus improve efficiency, the planing hull craft is designed to skim across the surface of the water.

Carrying the lift principle a step further, the surface effect ship is supported on a cushion of air above the surface of the water to minimize drag.

In the hydrofoil, lift is accomplished in a different way. The ship "flies" through the water supported on foils which function analogously to the wings of an airplane.

In addition to ship systems, NAVSEA has cognizance over the Navy's ocean engineering systems. Included in this category are diver related equipment and research submersibles.

In this conference we are interested in the corrosion related aspects of NAVSEA systems or, putting it another way, the effect of the operating environment on the performance of component hardware items. Hardware components can be conveniently illustrated in the categories shown in Figure (4). A ship's hull is the obvious example for structural hardware. Propulsion and auxiliary machinery include the power plant (it can be steam, gas turbine or nuclear), fluid handling

systems and propulsors (propellers and water jet). In the weapons category are torpedos, missiles and guns. Ancillary equipment includes items such as deck mounted hardware and antennae.

One important mission responsibility of the Naval Sea Systems Command is to apply corrosion engineering principles in the acquisition and maintenance of ship and ocean engineering systems as illustrated in Figure (5). In today's Navy, the ever increasing refinements in mission objectives impose the need for increasingly complex and costly systems. This evolution in hardware sophistication, coupled with today's spiraling inflation, has magnified the importance of corrosion control. We need only to review the now famous NBS study on corrosion costs to realize the payoff potential from corrosion control efforts. In this regard, the Navy has identified as a new thrust area, the extension of system life cycle and time between overhauls.

An important goal in life cycle control is to provide a vehicle for easy transfer of R&D program results to acquisition and maintenance activities via the life cycle managers, as shown in Figure (6).

This new emphasis on life cycle and cost has stimulated the implementation of a continuing program to allow introduction of new corrosion technology for shipboard corrosion control. In the initial phase, this plan emphasizes maintenance with special attention given to technologies that are on the verge of practical fleet implementation because of prior R&D work. An excellent example of a corrosion control technology which is ready for widespread fleet application is the use of flame spray aluminum on deck hardware and machinery components and for the application of non-skid coatings.

NAVSEA implements the management of corrosion engineering activities through its RDT&E organizational elements as shown in Figure (7). The Office of Naval Research is not a part of the formal NAVSEA organizational structure but it plays an important role in the development of corrosion technology. The interrelationship of ONR with NAVSEA and the R&D laboratories is an essential element in "flow through technology", a concept that I will discuss later. In addition to in-house expertise, NAVSEA and the field activities support RDT&E program efforts by contracts.

A very important contract facility which supports NAVSEA corrosion R&D programs is the LaQue Center for Corrosion Technology at Wrightsville Beach, N.C., shown in Figure (8). Here, natural marine environment exposures are carried out on specimens, components and entire system mock-ups. All of the corrosion processes encountered in NAVSEA Systems can be reproduced at LCCT. Exposure conditions can be carefully

controlled over a broad range of parameters, relating to material, environment and service application. These capabilities provide NAVSEA project engineers with maximum flexibility in the design of marine corrosion experiments.

Figure (9) lists important corrosion processes which can be encountered when engineering materials are exposed in the marine environment. In terms of specific NAVSEA applications, each of these processes can exert a detrimental influence on the performance of component hardware. Localized corrosion, for example, can penetrate heavy section structural or machinery components rapidly in susceptible materials. Accelerated corrosion due to galvanic influences occurs in mixed metal systems and is probably the most frequently encountered process in failure analyses. The serious effect of selective phase attack is evident in dealloying of aluminum bronze. Environment induced cracking involves the conjoint action of stress and a corrosive environment and is of particular concern in critical, high strength structural components. Corrosion fatigue is analogous, but here the stress is cyclic in nature rather than static. With these processes, catastrophic failure can occur without warning. In many of the Navy's improved performance ships and propulsion systems, corrosion resistance over a broad range of seawater flow velocities has become a specific requirement. Polluted seawater can cause rapid corrosion of otherwise corrosion resistant materials. High temperature corrosion is encountered primarily in marine gas turbine engines and shipboard waste disposal systems. These elevated temperature applications challenge the corrosion engineer with the most severe marine operating environment yet encountered.

The specific examples that I will present later to demonstrate "flow through technology" will feature several of the corrosion processes listed in Figure (9).

Now that we have identified the types of corrosion processes which can occur, let's look, for a moment, at how we deal with them. The aim of NAVSEA corrosion control activities is to develop practical solutions to corrosion problems encountered in existing systems and to anticipated problem areas in new systems, as shown in Figure (10). In both cases, emphasis is being placed on extension of life cycle and time between overhauls.

The corrosion control options or solutions for the corrosion processes encountered are shown in Figure (11) to fall under three major headings. These are the corrosion engineer's tools. One or more of these may be considered a practical means of getting the job done.

Design modification can be a viable approach for a flow enhanced corrosion problem or one intensified by galvanic interaction of dissimilar metals.

A material change may be in order to circumvent a stress corrosion cracking problem or to eliminate a galvanic problem.

The modification of metallurgical structure can be especially effective in dealing with selective phase attack.

Environment modification can be employed to neutralize the accelerating effects of harmful pollutants by adding inhibitors or stripping agents.

The two most frequently employed corrosion control solutions involve the use of coatings (both organic and inorganic) and cathodic protection. These methods are used, for the most part, to control general corrosion and to minimize galvanic effects from dissimilar metal couples.

FLOW THROUGH APPROACH TO TECHNOLOGY

Up to this point, my discussion has not referred to specific programs or corrosion problems.

I would like now to illustrate, with several examples, the "flow through" technology approach as it is used to develop practical corrosion engineering solutions to current and anticipated problems. In these examples, I will try to show how the elements of technological methodology, shown in Figure (12) are applied in specific program areas.

Fundamental corrosion research is managed, for the most part by ONR. Programs are carried out in Navy laboratories such as the Naval Research Lab and by contractors. In many cases, ONR programs are designed to respond to specific current or anticipated Navy needs. After the fundamental research category comes the exploratory development phase. In this overview, I will subdivide exploratory development into two parts. The first is applied corrosion research which leads into the development of corrosion engineering solutions. These activities are carried out in large part at David Taylor Naval Ship Research and Development Center. The Naval Surface Weapons Center contributes in the weapons related areas of corrosion technology.

The advanced development efforts are often cooperative lab/shipyard programs. The final step is implementation where labs, shipyards and maintenance/repair facilities all interact to accomplish the transfer of technology.

One can see clearly from Figure (12) that the mechanism exists in the NAVSEA organization for applying the "flow through" approach in addressing corrosion related requirements. In the real world there are no sharp boundaries as indicated in the chart, but instead, overlap in the phases of emphasis as the program progresses.

At this point I would like to briefly discuss several different program areas to illustrate the mechanics of "flow through" technology.

DEVELOPMENT OF HIGH STRENGTH COPPER-NICKEL ALLOYS

The first program area that I have selected is the development of higher strength copper-nickel alloys for shipboard seawater piping systems. Figure (13) shows, schematically, the flow of the entire program from research to implementation. A need was anticipated in the early 60's for a piping material which was capable of withstanding greater pressure than the currently used 70/30 copper-nickel alloy, CA715. In early planning, it was decided to consider only copper base alloys because of their inherent antifouling properties.

Initially, third element modifications of 70/30 copper nickel compositions were selected to provide strengthening by solution hardening, precipitation hardening and by a spinodal decomposition process. At the same time fundamental research was carried out to characterize the spinodal decomposition and other strengthening processes. Experimental alloys were screened and alloy CA719 was selected as the most promising candidate. This 70/30 copper nickel alloy contains about 2.6% chromium which provides for strengthening by spinodal decomposition. This alloy is unique because the strengthening process does not require post-fabrication or post-weld heat treatments to achieve high strength. The next phase of development involved detailed characterization of CA719 in terms of strength and fatigue properties, corrosion behavior and fabricability.

Laboratory efforts also established that the alloy was practically weldable and welding parameters were developed. The R&D work on alloy CA719 revealed no problems which would discourage proceeding with the program. The next phase involved the development of production technology through procurement of full-sized piping and fitting components from a commercial source. Welding procedures were developed at Charleston Naval Shipyard and fabricated components were produced for burst and fatigue testing at DTNSRDC. The next step of development will be the installation of CA719 piping in a non-critical shipboard system. Finally, this program will culminate after approximately 15 years with the availability of a new alloy certified for improved performance

shipboard piping systems. Now that we've gone through the "flow through" diagram, I would like to illustrate some of the program highlights. Figure (14) illustrates candidate alloys which were screened in the early phases of the program. The iron, columbium and beryllium modifications to 70/30 and the 60/40 alloy were either solid solution hardened, precipitation hardened or combinations of these. All required special heat treatments to obtain desired strength levels. The selection of the chromium modified alloy circumvented the requirement for heat treatment.

Corrosion tests of CA719 included piping mockup studies, as shown in Figure (15). The mockups simulate shipboard piping systems to the extent that typically fabricated piping and fitting components conduct once through natural seawater over a range of seawater velocities.

Figure (16) shows that the new chromium-modified alloy is superior to CA715 under conditions of seawater flow. This illustration shows the results of a 1 year piping mock-up exposure at a sea water velocity of 20 fps.

Figure (17) makes a comparison of the same two alloys exposed in quiet seawater for 2 years. CA719, under these conditions is susceptible to a localized type of surface corrosion. However, the CA715, as we would expect from service experience, is essentially immune to corrosion. This corrosion susceptibility of CA719, when first discovered, generated concern as to the usefulness of the alloy for shipboard piping applications. However, subsequent long term exposure revealed that penetration decreased to a low linear corrosion rate. This characteristic permitted the establishment of a practical corrosion allowance. Figure (18) compares 1 and 4 year quiet seawater exposures of CA719, and shows that attack tends to broaden rather than penetrate deeper into the specimen.

After characterization of the new alloy, the next series of steps taken is shown in Figure (19). A 12 ton procurement of full size components, up to 16-inch diameter, demonstrated that alloy CA719 can be fabricated commercially. No serious problems were encountered in the development of welding procedures and in the weld fabrication of CA719 pipe and fittings. Component assemblies, that were fabricated in the naval shipyard, were then burst and fatigue tested at DTNSRDC.

The next example of "flow through" technology addresses, again, an anticipated requirement.

HIGH STRENGTH/WEIGHT RATIO TITANIUM ALLOYS

Figure (20) describes the program to develop high strength to weight ratio titanium alloys for deep depth submersibles. The potential of titanium for structural and machinery

components was recognized in the late 50's to early 60's time frame.

Specific alloy requirements for the research submersible, ALVIN included good weldability, corrosion and stress corrosion resistance and fracture toughness. Alpha titanium alloys seemed to fill the bill to meet these requirements.

Laboratory studies began with the screening of α alloys and selection of 7 Al-2Cb-1Ta as an early prime candidate. Conventional corrosion testing included long term U-bend stress corrosion exposures in natural seawater. From the results of these tests it was concluded that this titanium alloy was immune to all forms of deterioration in the marine environment. About this same time a new test method was developed at the Naval Research Laboratory which used a precracked specimen and measured the susceptibility to stress corrosion crack propagation only. Under these conditions, where the initiation phase was circumvented, alloy 7-2-1 was found to be highly susceptible to stress corrosion cracking. This discovery led to a period of intense fundamental research in Navy and non-government laboratories. This research revealed that the observed SCC susceptibility was associated with high aluminum content. We also learned that addition of sufficient molybdenum to produce some β phase in the microstructure improved stress corrosion resistance. Out of this fundamental research grew an alloy development effort which resulted in the identification of a composition with improved resistance to stress corrosion cracking, Ti alloy 6 Al-2Cb-1Ta-1-Mo. The follow-on characterization studies found this alloy to be a suitable candidate marine alloy. Successful development of fabrication and welding technology were carried out in the next phase of the development program.

Prototype studies followed which were designed to evaluate 6-2-1-1 in terms of material requirements for the deep diving research submersible, ALVIN. In this phase of the program, component size sections were fabricated and joined by arc welding. Large sections were tested to evaluate application related parameters including corrosion, stress corrosion and corrosion fatigue behavior. Two ALVIN pressure spheres were then designed and fabricated from Ti alloy 6-2-1-1 and proof tested beyond the design pressure for the submersible. The ALVIN vehicle was constructed in the early 70's.

Performance in Project Famous, its first assignment, confirmed that ALVIN had given deep ocean exploration a new and much needed capability - mobility at depth.

The next series of figures will illustrate some of the interesting aspects of this titanium alloy development program.

Figure (21) illustrates the precracked cantilever stress corrosion test method. The notched and precracked beam specimen is dead weight loaded in a seawater environment. As mentioned earlier, this test format revealed susceptibility to stress corrosion cracking in 7-2-1 titanium alloy. This susceptibility was not observed in conventional U-bend tests because no localized corrosion occurred to initiate the process.

Figure (22) is a crosssection view of a typical failed precracked specimen. Clearly visible boundaries separate the machined notch, the fatigue precrack, the zone of crack growth by stress corrosion and finally the failure by tensile overload.

After the alloy development and characterization phase of the program yielded stress corrosion resistant alloy 6-2-1-1, development and evaluation proceeded on component size sections.

Figure (23) illustrates a step in the development of welding procedures to be used in the construction of ALVIN. Welding is performed out-of-chamber, under shipyard conditions.

Figure (24) shows a large welded plate which was prepared for corrosion fatigue testing. The purpose of this test is to demonstrate the corrosion fatigue performance of heavy-section weldments, such as those used to construct ALVIN.

In Figure (25), the actual ALVIN pressure sphere is being lowered into the DTNSRDC pressure chamber. It was subjected to three pressure runs to verify its structural predictions. These cycles demonstrated successful performance beyond the planned operating depth for the vehicle. No cracking or surface flaws were observed as a result of the pressure test.

The next step in proof testing was a manned simulated dive. In Figure (26) the ALVIN is being boarded by its crew before it enters the deep submergence test chamber at DTNSRDC. This exposure certified ALVIN for operation.

Figure (27) shows the ALVIN operating below the surface at an eastern Pacific Ocean site off the coast of South and Central America during Galapagos II.

The next subject area addresses corrosion of 90-10 CuNi.

SULFIDE-INDUCED CORROSION

Figure (28) describes the program which was carried out to provide corrosion control for accelerated corrosion in seawater piping systems on ships under construction.

Initial failure analyses identified pollutants in shipyard harbor water as the cause of abnormal corrosion rates observed in pipe sections. Sulfide was singled out as the most probable agent responsible for the problem. Fundamental studies, sponsored by ONR, were carried out concurrently with applied research programs at DTNSRDC. The corrosion behavior characterization phase of the investigation included reproducing the attack under controlled laboratory conditions at LCCT and evaluation of influencing parameters such as seawater velocity, sulfide level and time of exposure. Studies were also conducted to evaluate the effect of sulfide altered seawater on other materials normally used in seawater piping systems. Other laboratory experiments were performed to evaluate practical corrosion control methods. These exposures were conducted both at the LCCT marine laboratory and in piping mockups at a shipyard site. It was concluded, from these studies, that the most promising approach for corrosion control was controlled addition of ferrous ions to the flowing, polluted seawater environment. It was determined that benefit was derived in two ways. First, harmful sulfides react with ferrous ions to form an innocuous product. Ferrous ion also modifies the films on pipe surfaces to provide resistance to sulfide induced corrosion. The two methods evaluated for introducing ferrous ions were: a) injection of ferrous sulfate solution to water flowing in shipboard piping systems and b) electrochemical stimulation of an iron waster piece to produce a controlled level of ferrous ions in the flow stream (sacrificial iron anode).

The next series of Figures will serve to illustrate some of the important aspects of this program.

Figure (29) shows localized corrosion which could penetrate pipe walls in 4 months. The pattern of attack suggests that turbulence contributed to the attack because deterioration is most severe downstream of elbows or other turbulence forming elements. Another important feature of sulfide induced corrosion is that surface films are modified by the environment to be loose, flaky and easily removed.

Figure (30) shows schematically the process believed to be operating in sulfide induced corrosion. In normal seawater 90/10 copper-nickel forms an adherent protective film of cuprous oxide which has a velocity tolerance of about 10 fps. When seawater is polluted by the presence of sulfide, a modified surface film is formed which is different in two ways: a) it becomes electrochemically more noble and b) it also loses adherence and is easily removed. Downstream of an elbow, the turbulent seawater removes film locally and exposes a small area of nascent metal surface which is

anodic to the relatively large area of modified film covering the remaining pipe surface. Attack is vigorous at areas of film rupture because of the significant galvanic driving force generated from the large cathode/anode area ratio.

Figure (31) shows schematically the design of a prototype stimulated iron anode. It is a heavy-walled iron pipe which replaces a copper-nickel pipe section located upstream of the affected parts of the piping system.

The next corrosion program that I will discuss relates to high temperature corrosion of shipboard gas turbine engines.

HIGH TEMPERATURE CORROSION/MARINE GAS TURBINES

Marine gas turbine engines are used to power several types of ships in the modern fleet. Large LM 2500 engines, for example, propel the new DD 963 class ships, shown in Figure (32).

The deterioration of hot section components, as shown in Figure (33), can occur rapidly to inflict catastrophic degradation in engine performance.

Figure (34) shows that the marine gas turbine material development program has involved two distinct phases. The first problem was recognized in the late 50's to early 60's time frame. Initial problem-scoping efforts, by the British and the U.S. Navys, revealed that accelerated corrosion occurred above 1550°F. This form of attack is presently referred to as "high temperature" hot corrosion. It occurs by the reaction of molten sodium sulfate with nickel and cobalt base superalloys used to fabricate gas turbine hot section components.

The other process causes severe deterioration of components at lower temperatures, approximately 1300°F. This process, referred to as "low temperature" hot corrosion, was only recently recognized as serious in terms of limiting the performance of naval systems.

Let's first take a look at the program for "high temperature" hot corrosion. R&D activity was vigorous in the mid-sixties. Navy and industrial laboratories conducted fundamental mechanism studies and concurrent alloy development efforts. Much of the fundamental work in this program was supported and managed by ONR. Alloy development studies, aimed at optimizing material compositions, yielded guidelines which producers subsequently used to make superalloys and coatings with improved hot corrosion resistance for marine gas turbines. In this same time frame, the Navy designed and installed a burner rig test facility at DTNSRDC. This

equipment is used to evaluate hot corrosion performance of candidate gas turbine materials. In the alloy development phase of this program burner rigs were used to screen laboratory heats.

The burner rig test was also used in the final selection processes to qualify commercially produced experimental alloys for further evaluation in service-simulating engine tests. By the program format described, optimum hot section alloys and coatings were commercially produced. Some of these materials are still in use today by the Navy for "high temperature" hot corrosion resistance in marine gas turbine engines.

The NAVSEA program relating to "low temperature" hot corrosion became active in 1975, after it first emerged as a potential Navy problem that occurred during extended low power operation of a shipboard gas turbine engine. Fundamental studies by NRL and engine manufacturers indicated that deterioration occurs by the action of low melting eutectic systems that form on blade surfaces. SO_3, a combustion product of fuel sulfur, reacts with metal surface oxides to produce cobalt sulfate and nickel sulfate. These, together with sodium sulfate, form low melting eutectics.

Soon after the recognition of "low temperature" hot corrosion, DTNSRDC developed a 1300°F burner rig test which accurately simulated shipboard conditions. This test now serves as a standard in NAVSEA contracts for development of corrosion resistant alloys and coatings. Contracted efforts, now in progress, involve alloy improvement by development of directionally solidified and single crystal components made from corrosion resistant superalloy compositions. Coating improvements are being pursued by optimizing compositions. As in the "high temperature" programs, the burner rig is used as a screening tool.

SUMMARY

The program examples that I have featured were selected to demonstrate the use of the "flow through" approach to accomplish technology transfer from laboratory R&D and serve to illustrate the variety and complexity of corrosion problems encountered in NAVSEA systems. From the standpoint of environment, NAVSEA corrosion problems are unique and do not relate directly to the corrosion activities of the other services.

When looked at from other aspects, however, there does exist commonality among the problems encountered by NAVSEA and the other services. Consider for example, the various

corrosion processes that were discussed earlier. Regardless of environment or application many of the same corrosion processes operate. I hope that this presentation has served to illustrate some of the unparalled expertise in marine corrosion research and engineering which exists within the Naval Sea Systems Command.

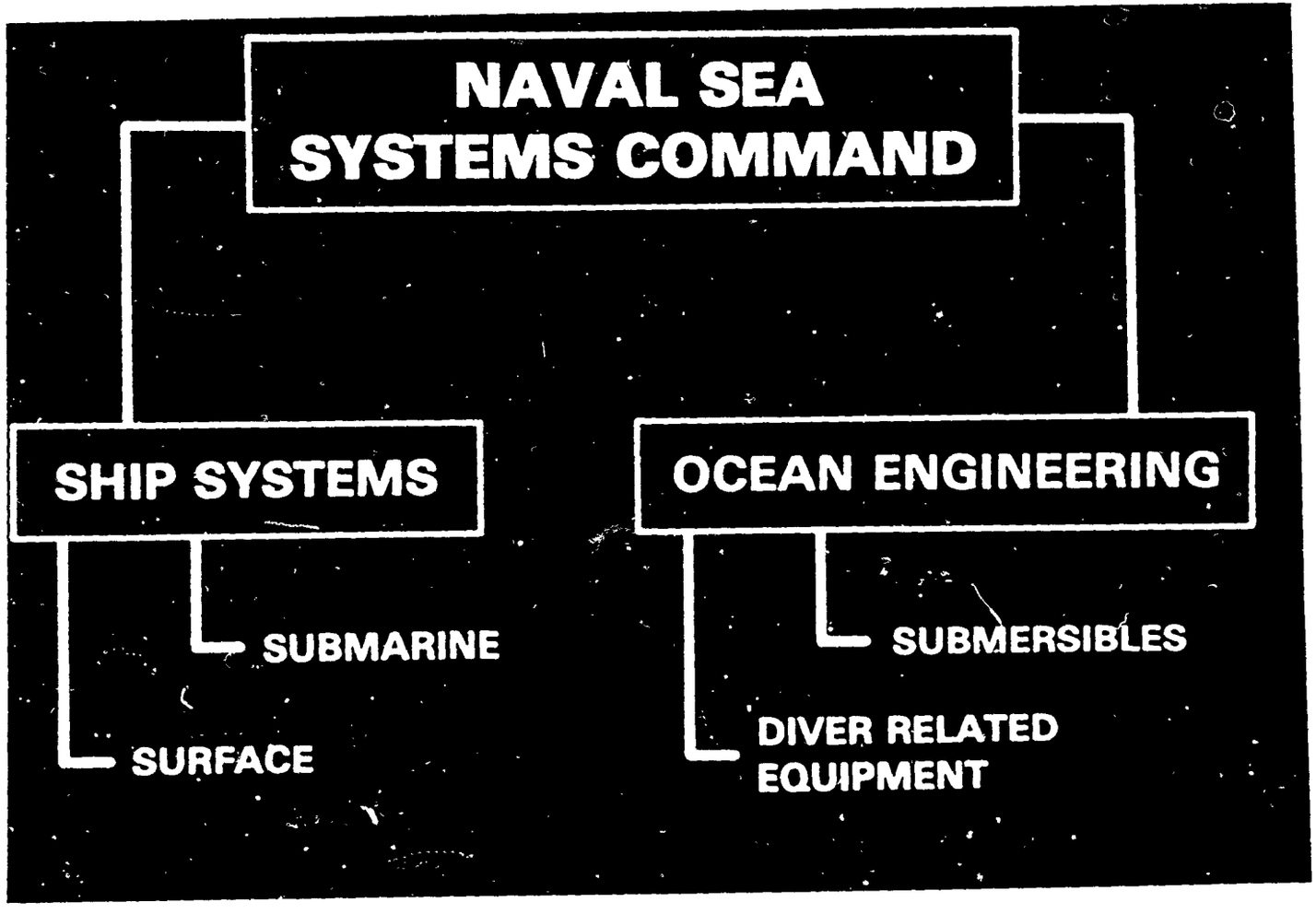

NAVAL SEA SYSTEMS COMMAND
SHIP SYSTEMS
OCEAN ENGINEERING
SUBMARINE
SURFACE
SUBMERSIBLES
DIVER RELATED EQUIPMENT

Figure (1)

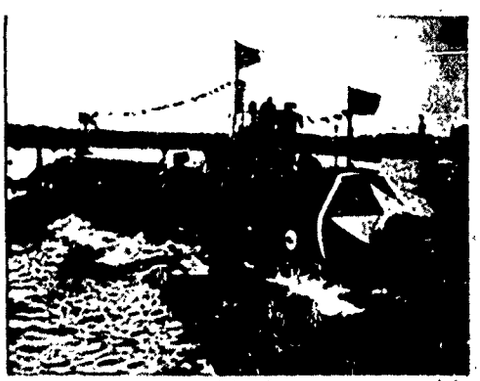
SUBMARINES

COMBATANTS

USS OHIO (SSNB-726)

USS LOS ANGELES (SSN-688)

SPECIAL PURPOSE

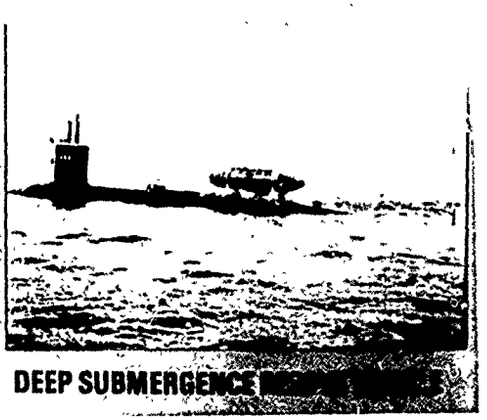


NR-1

DOLPHIN

SUBMERSIBLES

ALVIN



DEEP SUBMERGENCE

Figure (2)

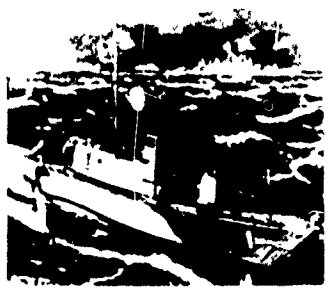
SURFACE SHIPS

AEROSTATIC LIFT

SES

ACV

HYDRODYNAMIC LIFT



HYDROFOIL

PLANING HULL

DISPLACEMENT

SWATH

CATAMARAN

DESTROYER

CARRIER

Figure (3)

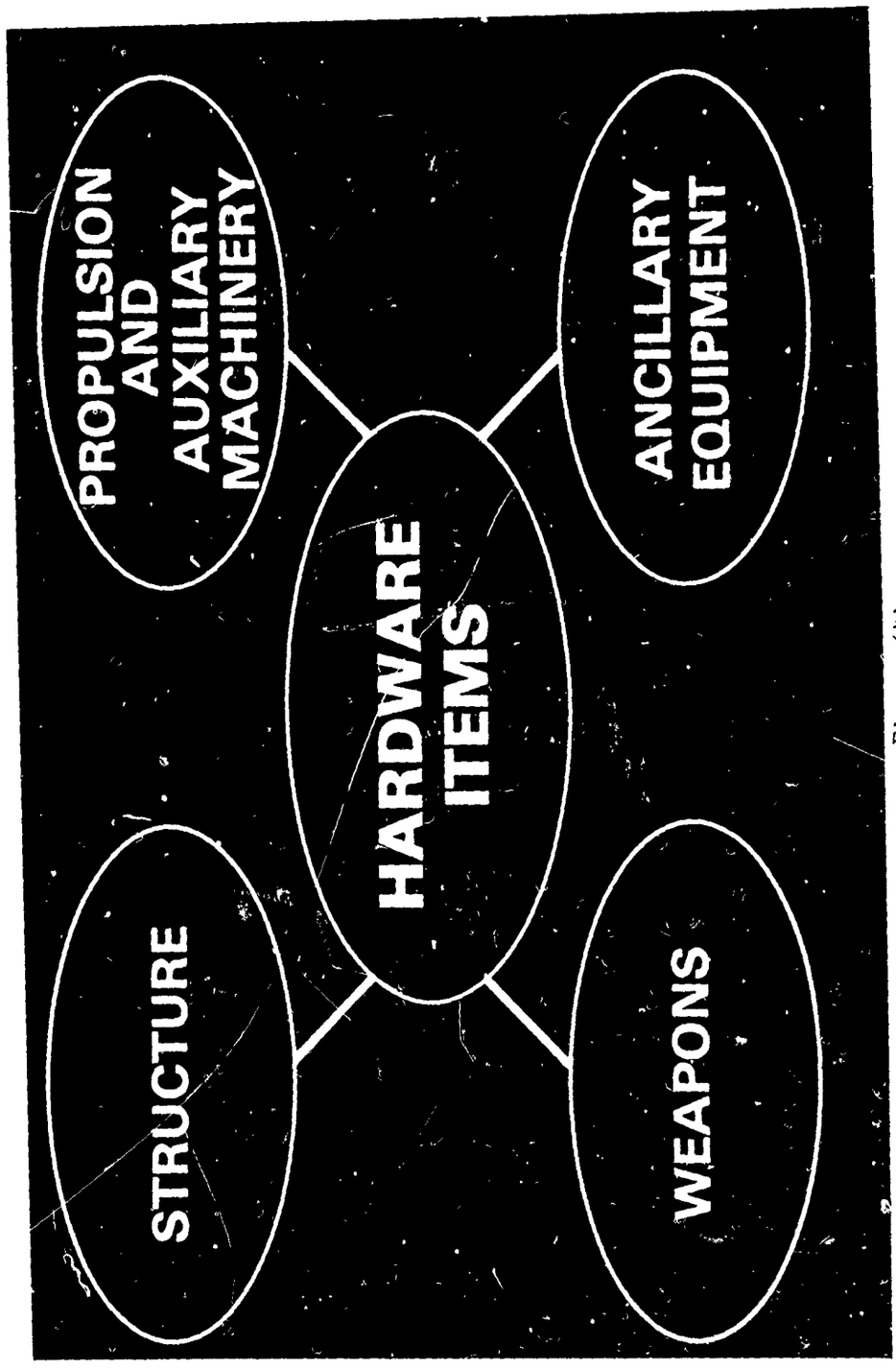

PROPULSION AND AUXILIARY MACHINERY
ANCILLARY EQUIPMENT
HARDWARE ITEMS
STRUCTURE
WEAPONS

Figure (4)

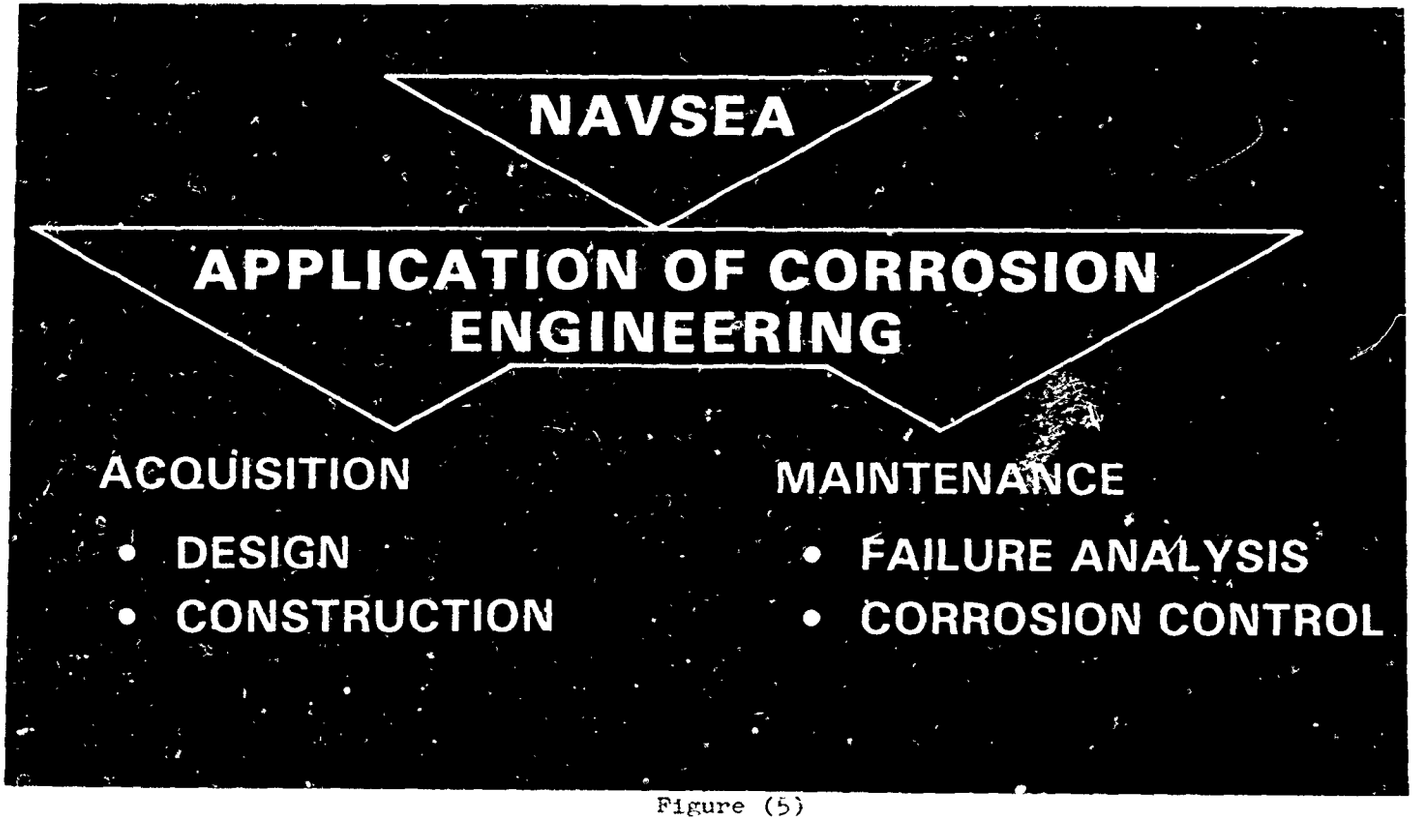

NAVSEA
APPLICATION OF CORROSION ENGINEERING
ACQUISITION
• DESIGN
• CONSTRUCTION
MAINTENANCE
• FAILURE ANALYSIS
• CORROSION CONTROL

Figure (5)

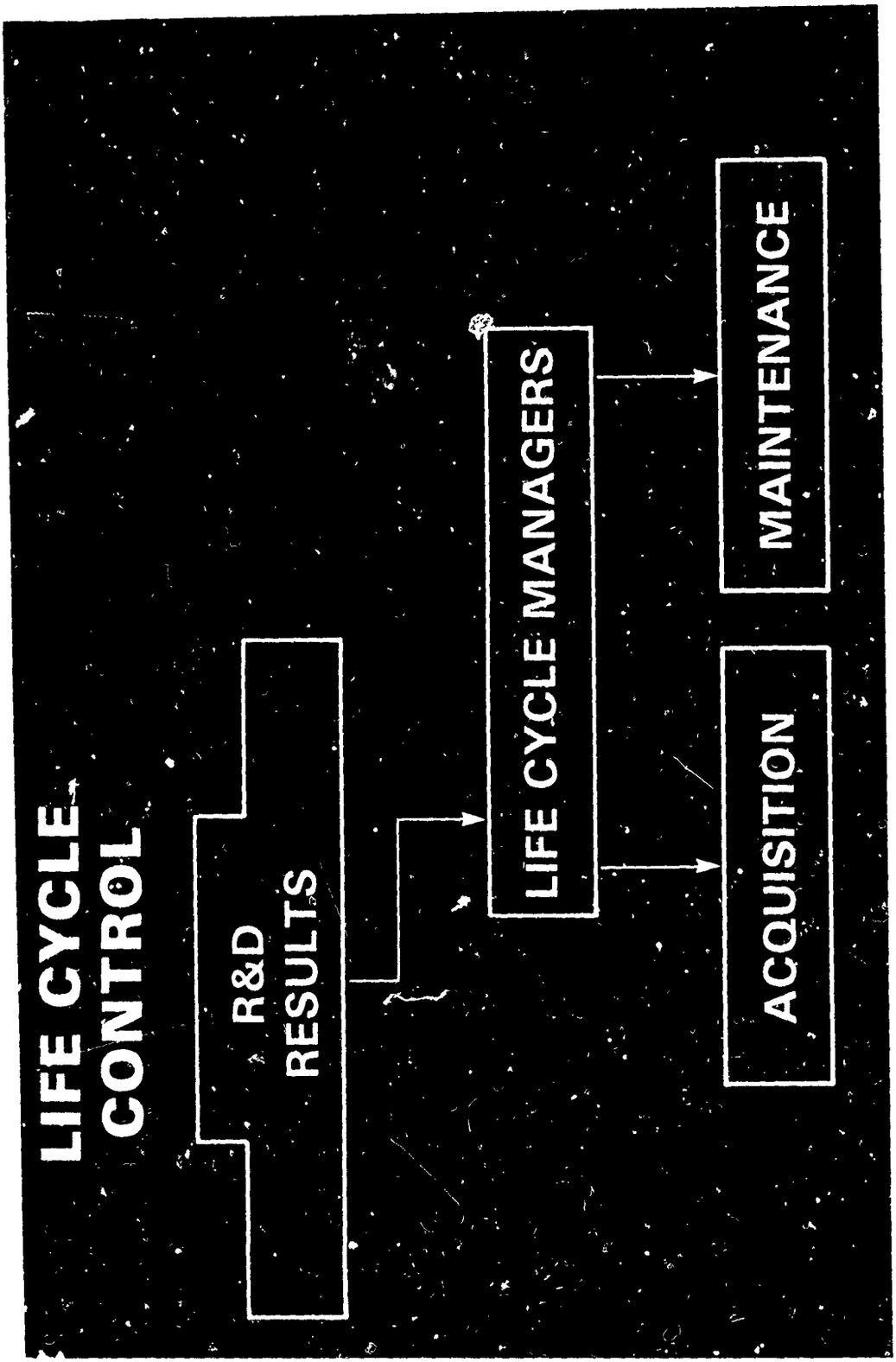

LIFE CYCLE CONTROL
R&D RESULTS
LIFE CYCLE MANAGERS
ACQUISITION
MAINTENANCE

Figure (6

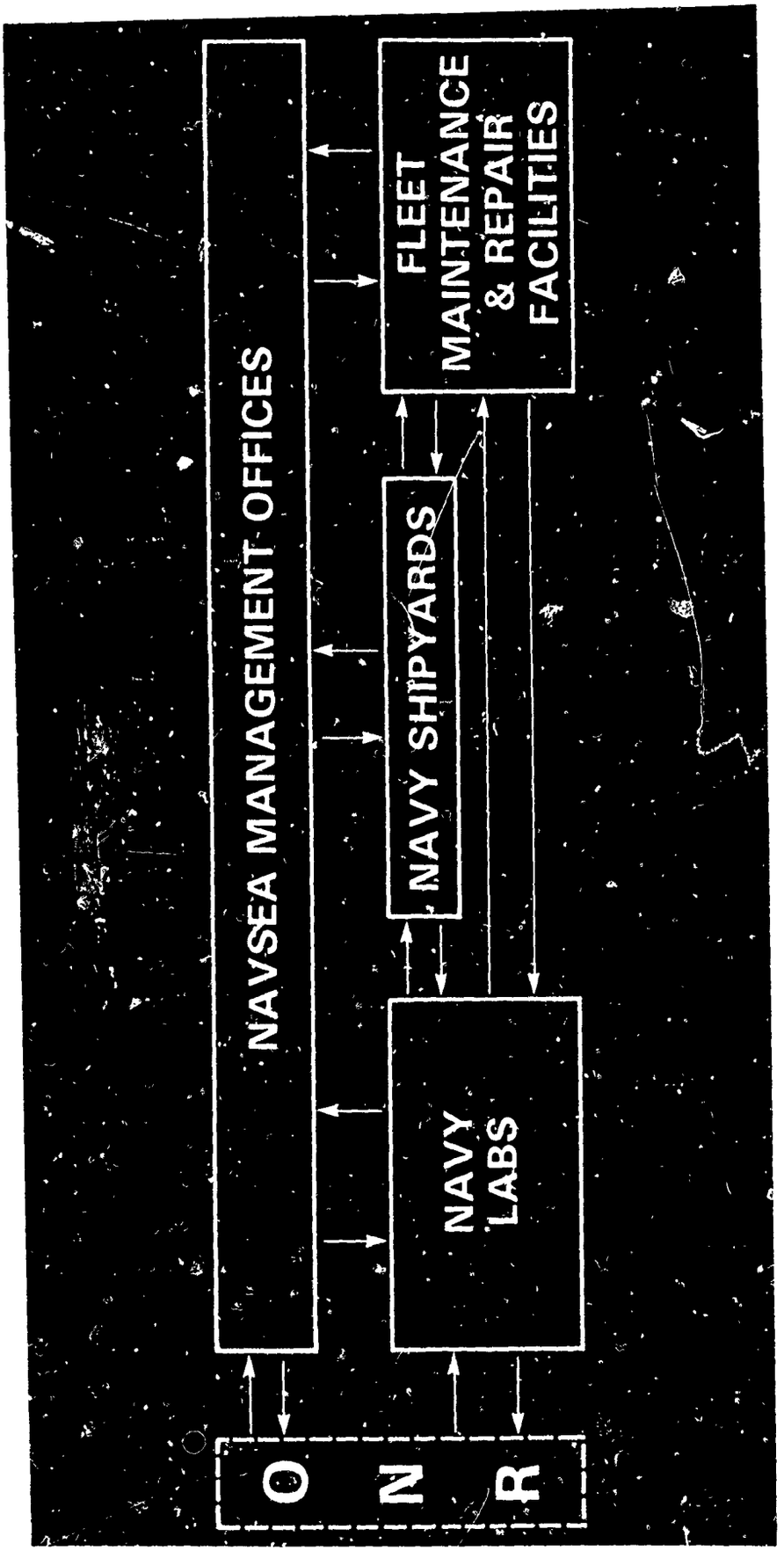

NAVSEA MANAGEMENT OFFICES
FLEET MAINTENANCE & REPAIR FACILITIES
NAVY SHIPYARDS
NAVY LABS
O N R

Figure (7)

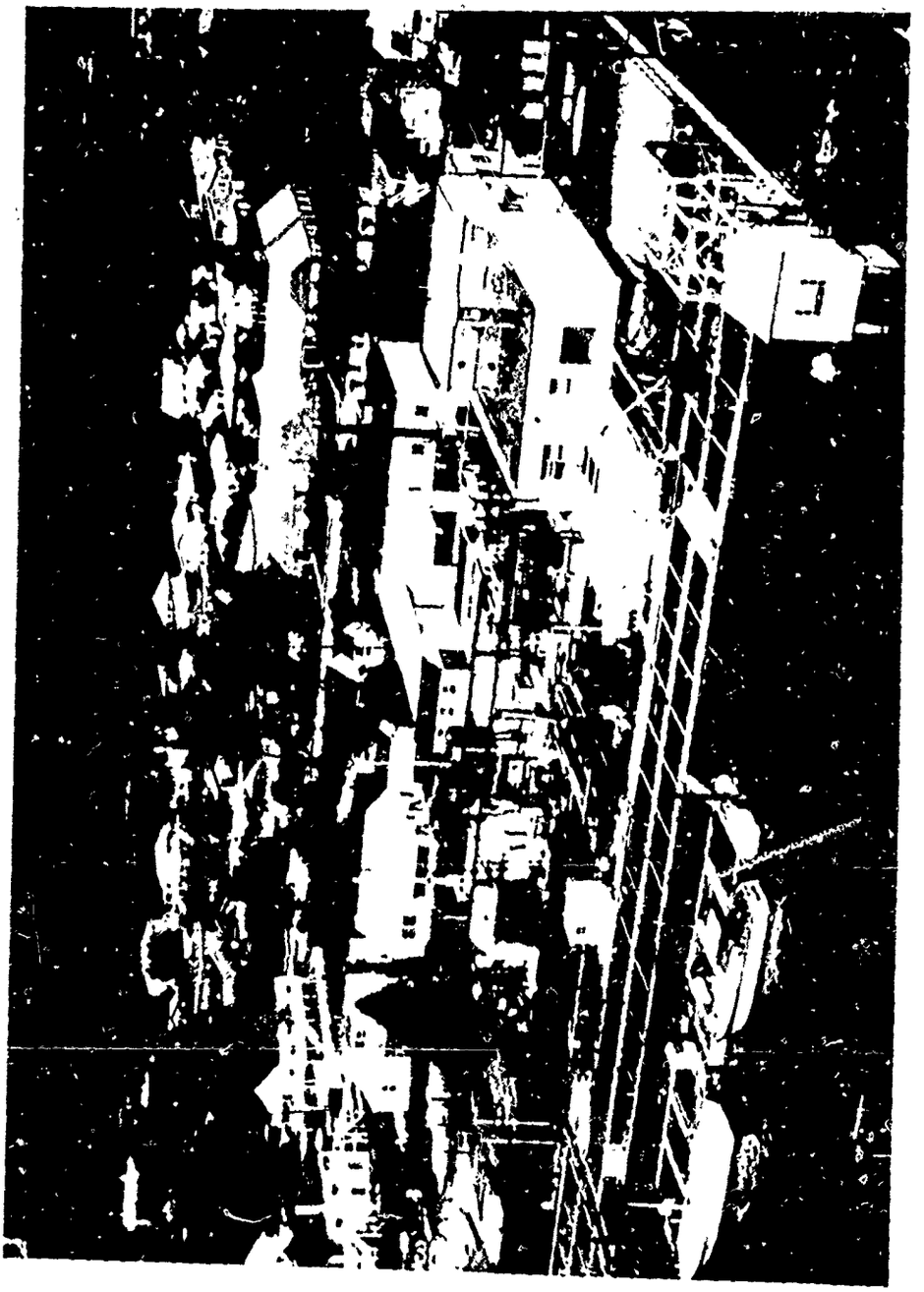


Figure (8)

IMPORTANT CORROSION PROCESSES

- GENERAL CORROSION
- LOCALIZED CORROSION
  - PITTING
  - CREVICE CORROSION
- GALVANIC CORROSION
- SELECTIVE PHASE ATTACK
- STRESS CORROSION CRACKING
- CORROSION FATIGUE
- FLOW ENHANCED CORROSION
  - CORROSION EROSION
  - IMPINGEMENT
  - CAVITATION
- CORROSION ACCELERATED BY POLLUTED ENVIRONMENTS
- HIGH TEMPERATURE CORROSION

DTNSRDC

Figure (9)

OBJECTIVE
DEVELOP PRACTICAL
CORROSION ENGINEERING SOLUTIONS
CURRENT
• EXISTING HARDWARE
ANTICIPATED
• FUTURE HIGH PERFORMANCE SYSTEMS

Figure (10)

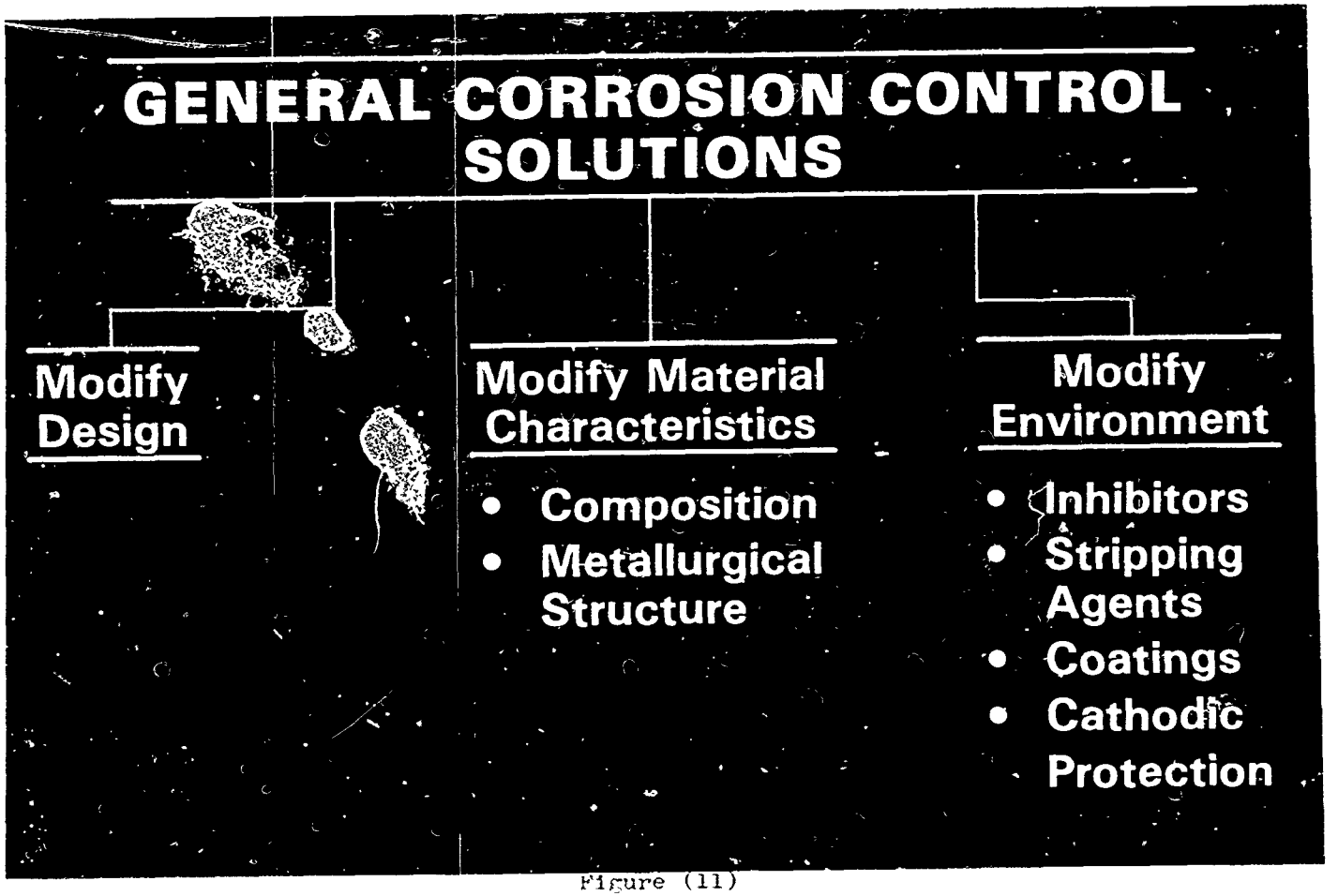

GENERAL CORROSION CONTROL SOLUTIONS
Modify Design
Modify Material Characteristics
• Composition
• Metallurgical Structure
Modify Environment
• Inhibitors
• Stripping Agents
• Coatings
• Cathodic Protection

Figure (11)

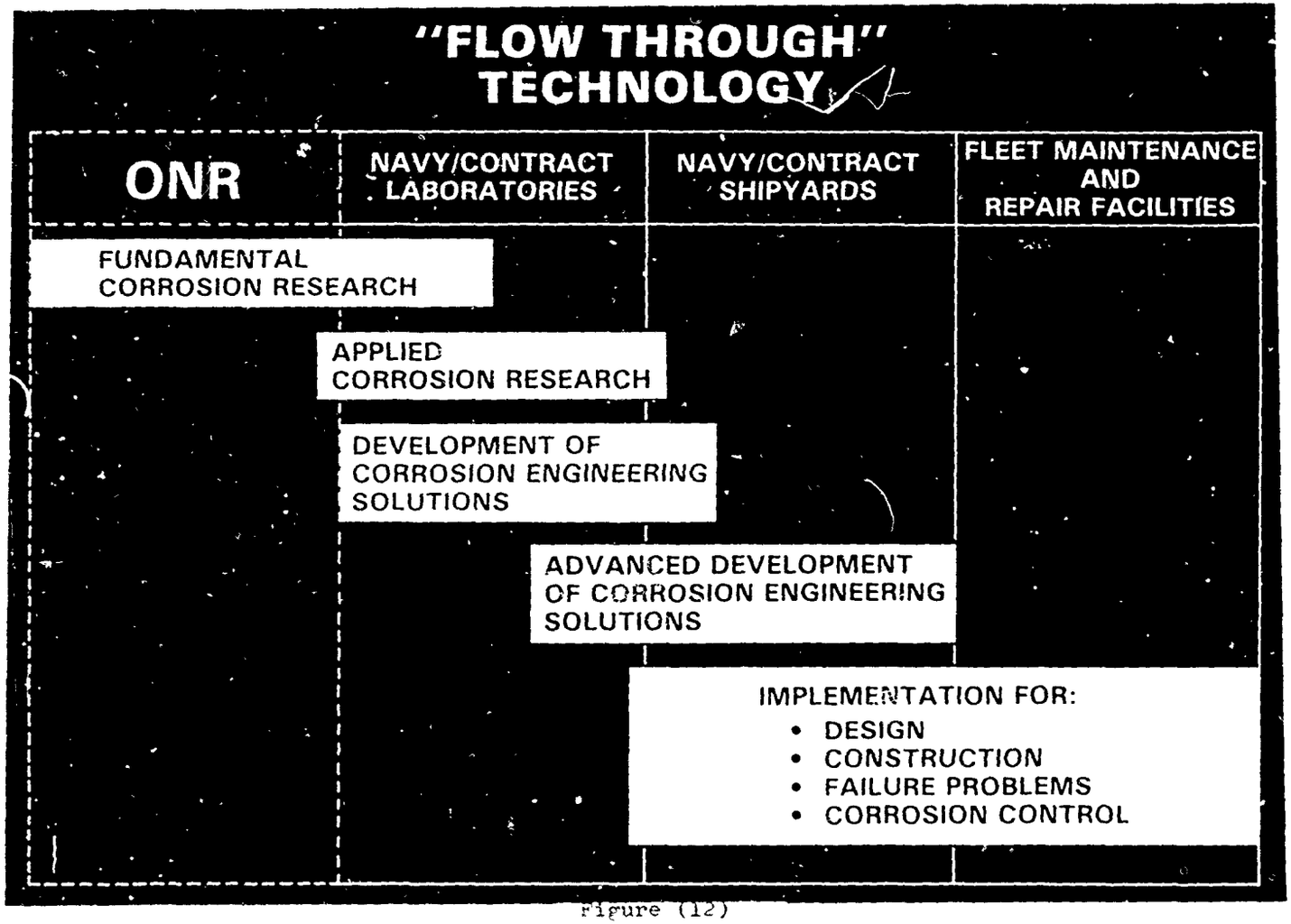

"FLOW THROUGH" TECHNOLOGY
ONR
NAVY/CONTRACT LABORATORIES
NAVY/CONTRACT SHIPYARDS
FLEET MAINTENANCE AND REPAIR FACILITIES
FUNDAMENTAL CORROSION RESEARCH
APPLIED CORROSION RESEARCH
DEVELOPMENT OF CORROSION ENGINEERING SOLUTIONS
ADVANCED DEVELOPMENT OF CORROSION ENGINEERING SOLUTIONS
IMPLEMENTATION FOR:
• DESIGN
• CONSTRUCTION
• FAILURE PROBLEMS
• CORROSION CONTROL

Figure (12)

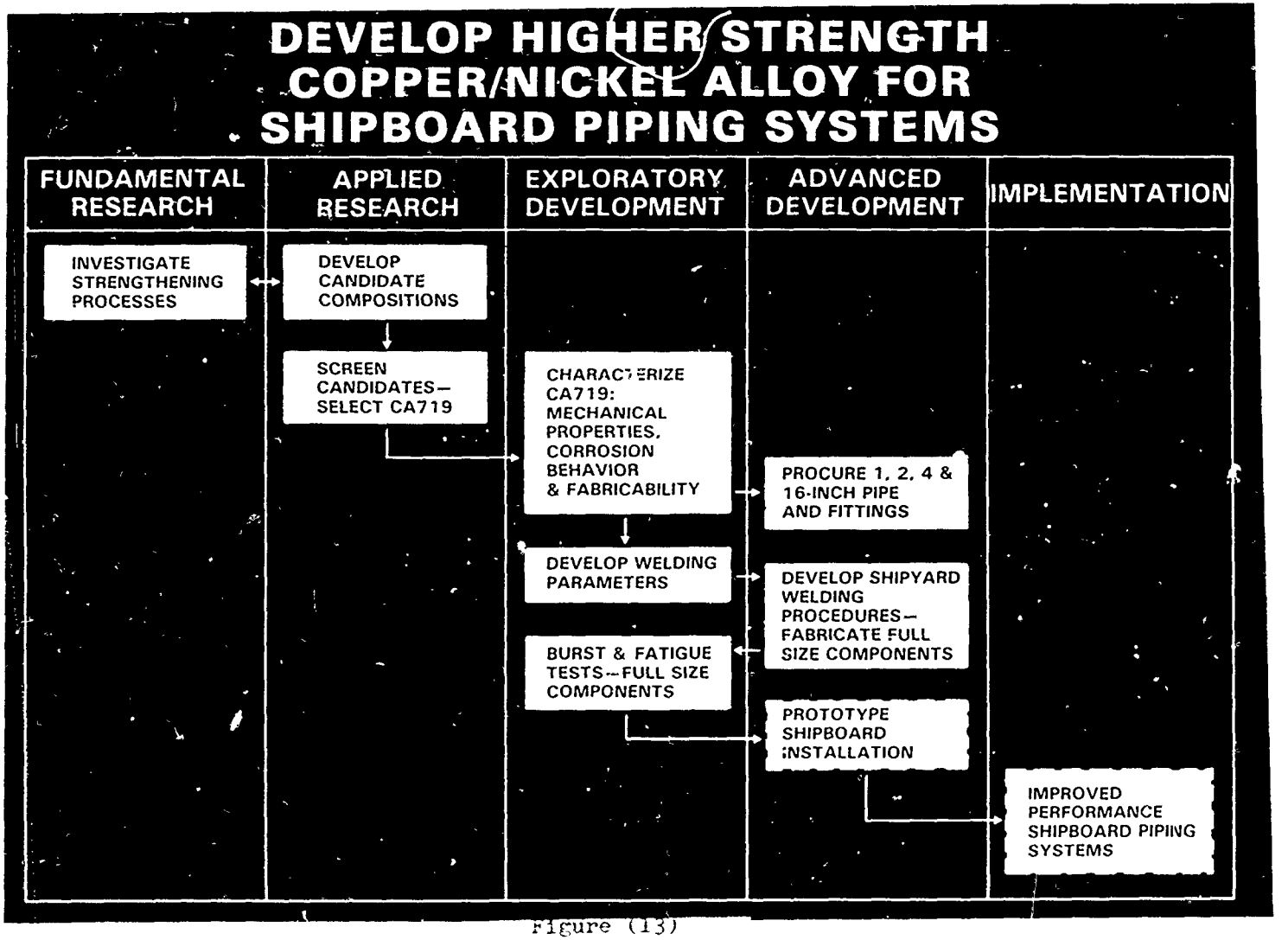

DEVELOP HIGHER STRENGTH COPPER/NICKEL ALLOY FOR SHIPBOARD PIPING SYSTEMS
FUNDAMENTAL RESEARCH
APPLIED RESEARCH
EXPLORATORY DEVELOPMENT
ADVANCED DEVELOPMENT
IMPLEMENTATION
INVESTIGATE STRENGTHENING PROCESSES
DEVELOP CANDIDATE COMPOSITIONS
SCREEN CANDIDATES— SELECT CA719
CHARACTERIZE CA719: MECHANICAL PROPERTIES, CORROSION BEHAVIOR & FABRICABILITY
DEVELOP WELDING PARAMETERS
BURST & FATIGUE TESTS—FULL SIZE COMPONENTS
PROCURE 1, 2, 4 & 16-INCH PIPE AND FITTINGS
DEVELOP SHIPYARD WELDING PROCEDURES— FABRICATE FULL SIZE COMPONENTS
PROTOTYPE SHIPBOARD INSTALLATION
IMPROVED PERFORMANCE SHIPBOARD PIPING SYSTEMS

Figure (13)

Modification of 70/30 Cu-Ni
NSRDC
70/30+Cr
70/30+Be
70/30 + Cr
70/30+Cb
60/40

Figure (14)

Figure (15)

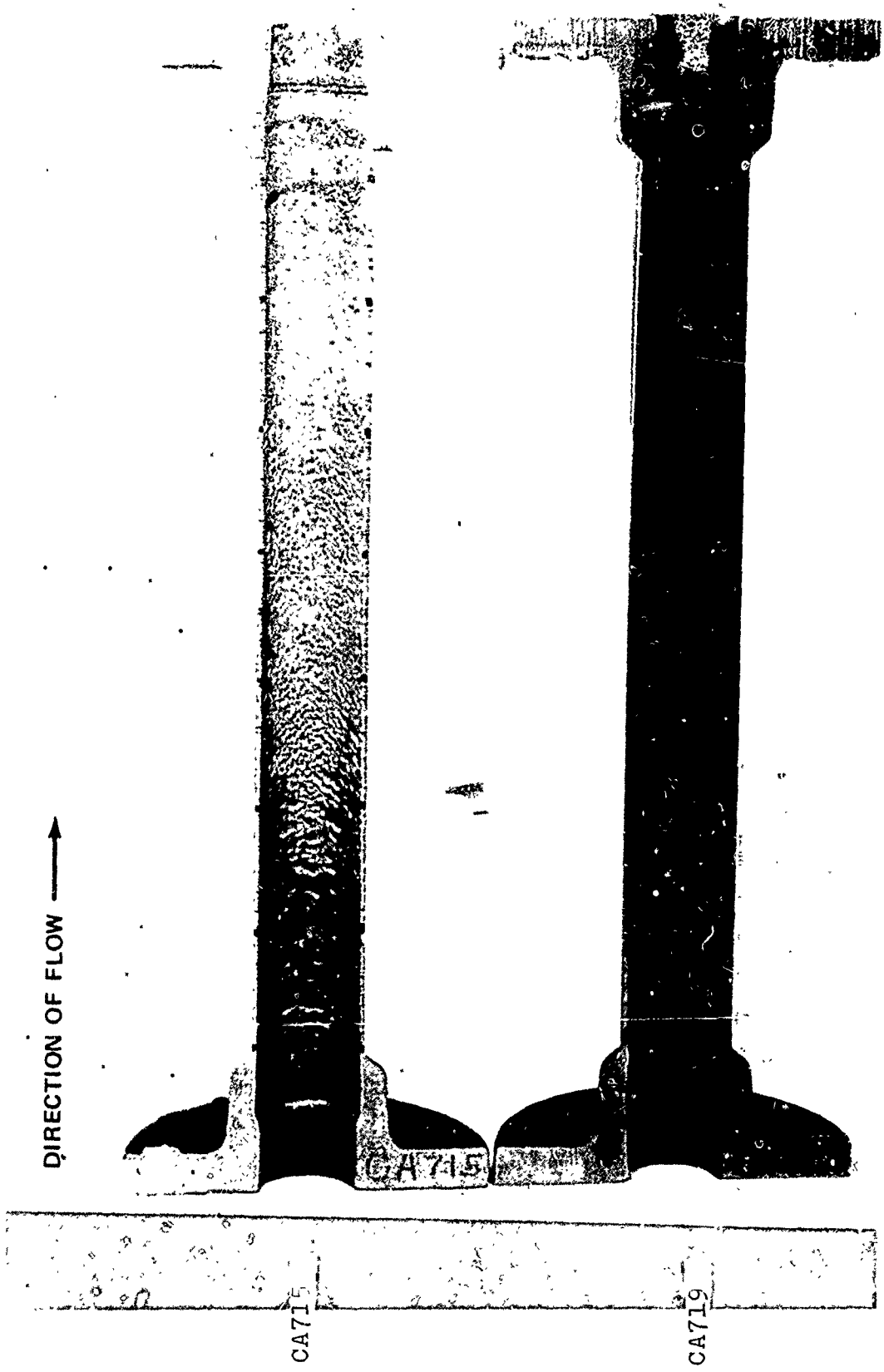


Figure (16)

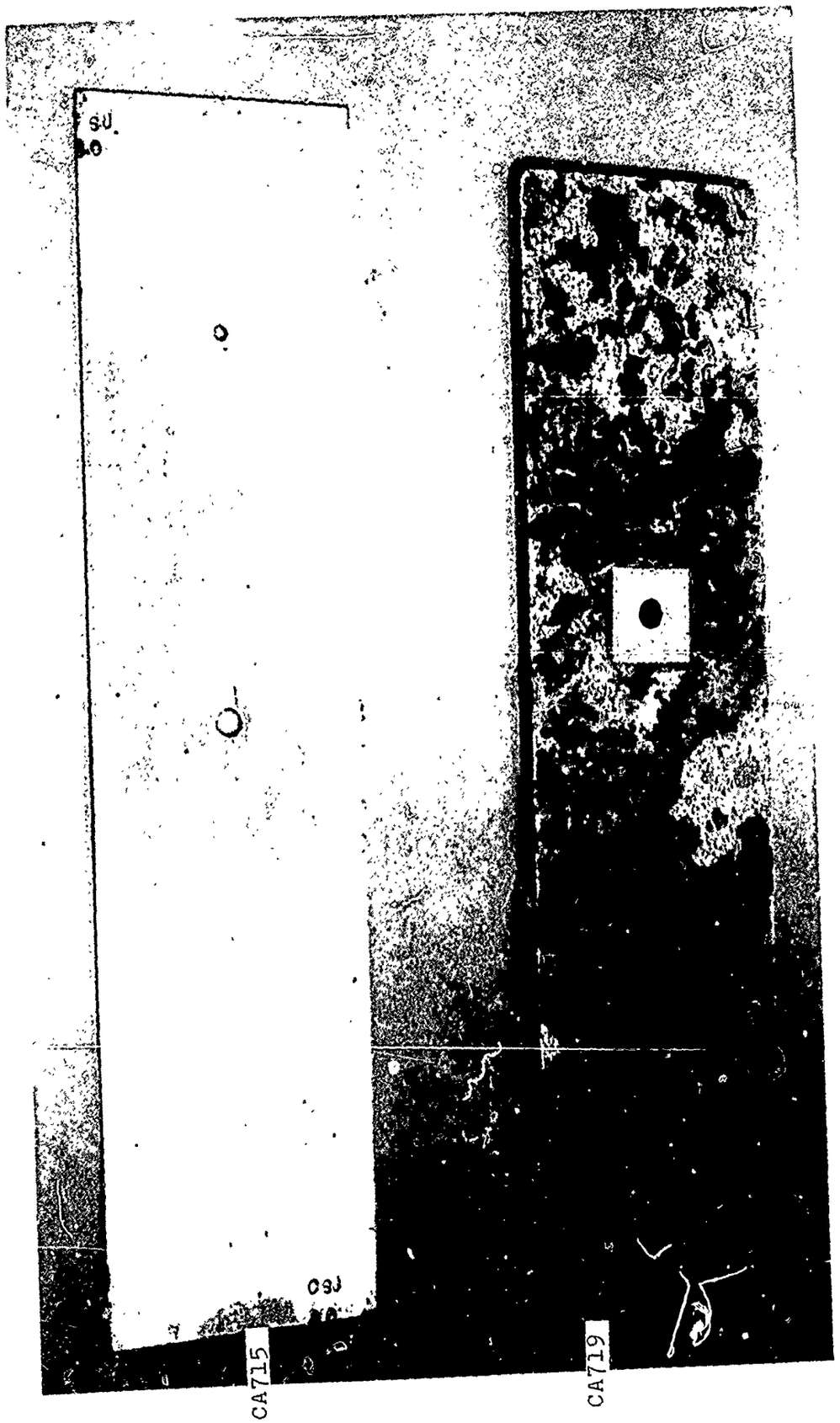
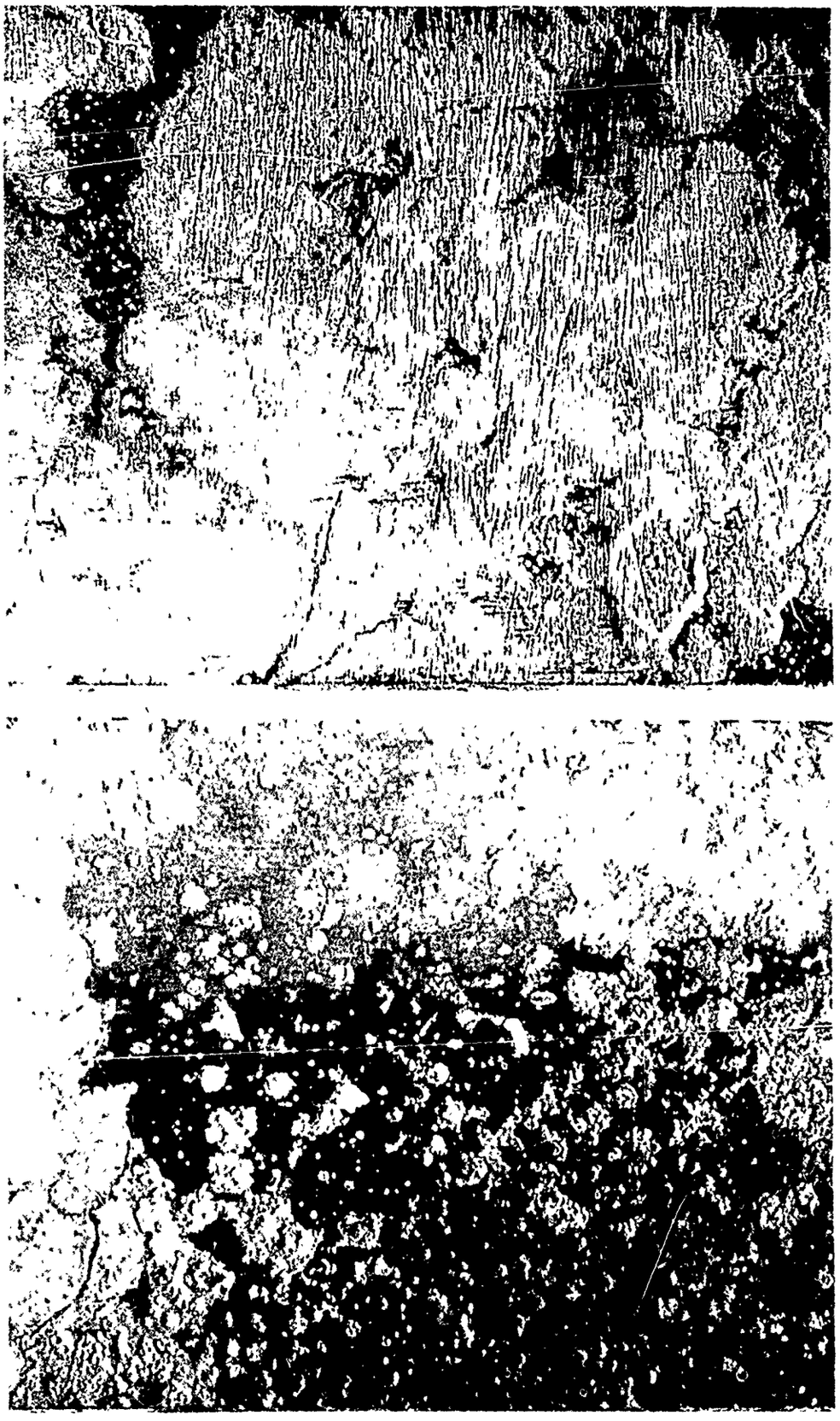


Figure (17)



(4 Yrs)
CA719

(1 Yr)
CA719

Figure (18)

Fleet Readine
COMMERCIAL PRODUCT
SHIPYARD FABRICATION
COMPONENT TESTING
NSRDC

Figure (19)

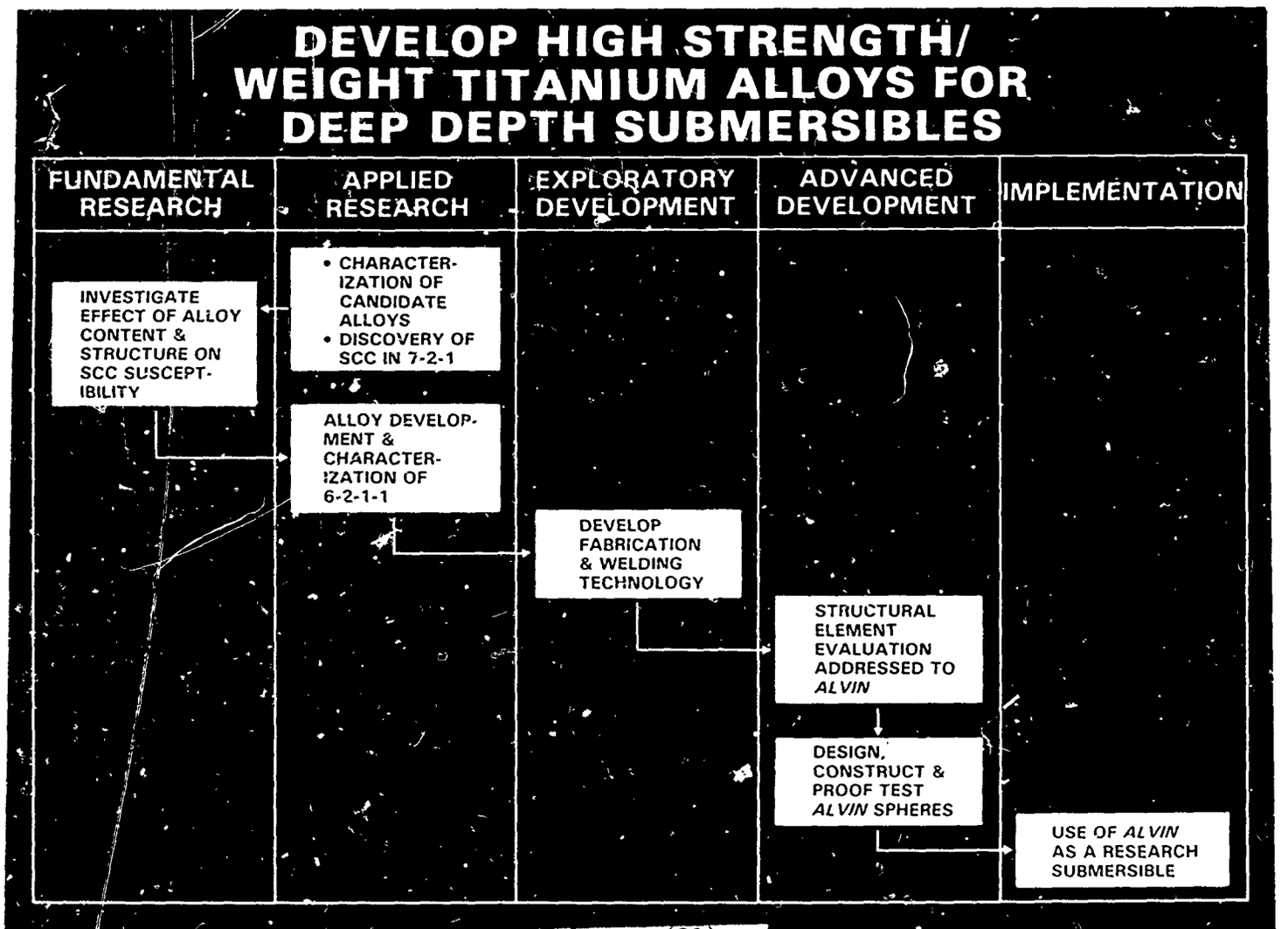

DEVELOP HIGH STRENGTH/ WEIGHT TITANIUM ALLOYS FOR DEEP DEPTH SUBMERSIBLES
FUNDAMENTAL RESEARCH
APPLIED RESEARCH
EXPLORATORY DEVELOPMENT
ADVANCED DEVELOPMENT
IMPLEMENTATION
INVESTIGATE EFFECT OF ALLOY CONTENT & STRUCTURE ON SCC SUSCEPT-IBILITY
• CHARACTER-IZATION OF CANDIDATE ALLOYS
• DISCOVERY OF SCC IN 7-2-1
ALLOY DEVELOP-MENT & CHARACTER-IZATION OF 6-2-1-1
DEVELOP FABRICATION & WELDING TECHNOLOGY
STRUCTURAL ELEMENT EVALUATION ADDRESSED TO ALVIN
DESIGN, CONSTRUCT & PROOF TEST ALVIN SPHERES
USE OF ALVIN AS A RESEARCH SUBMERSIBLE

Figure (20)

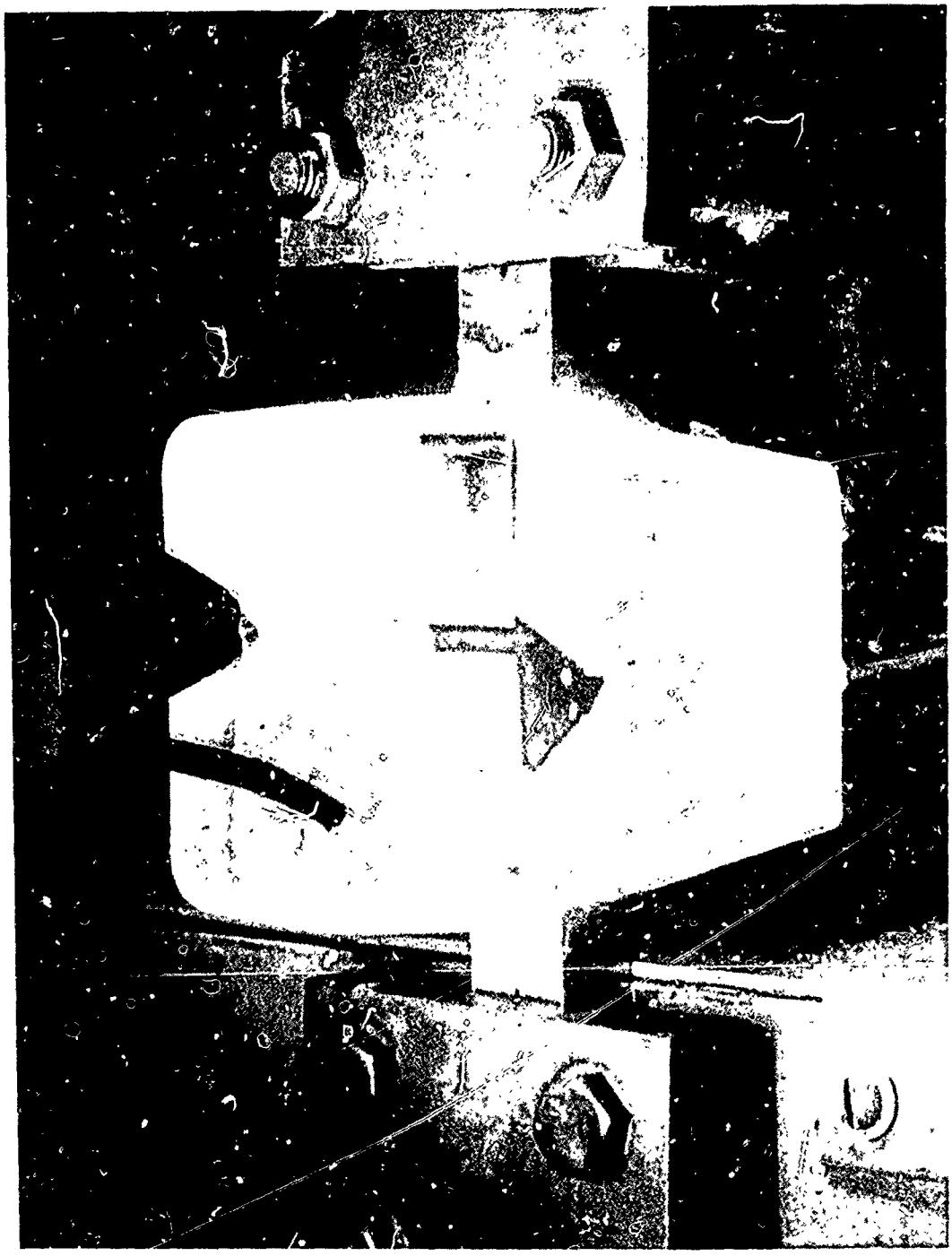


Figure (21)

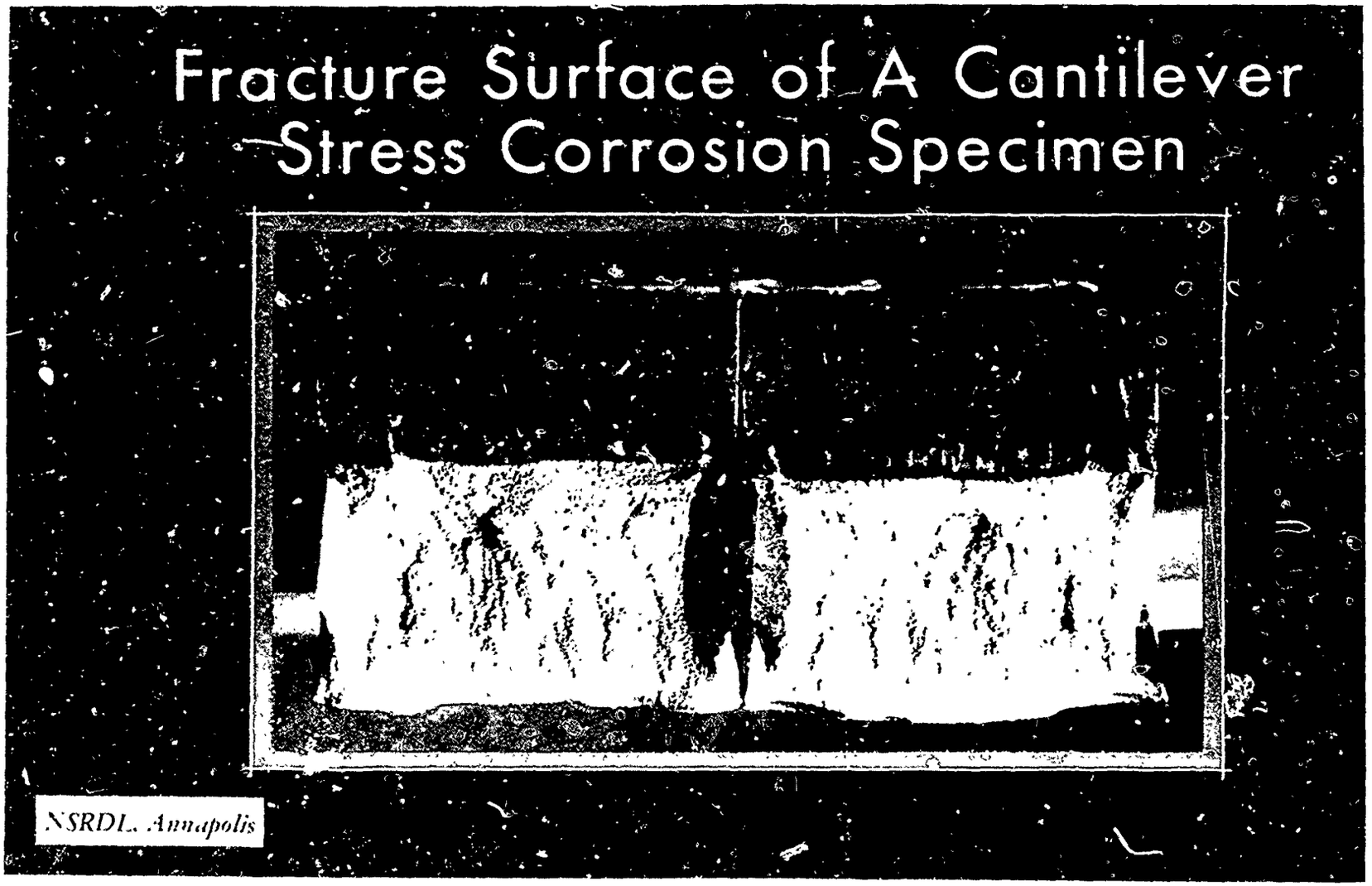
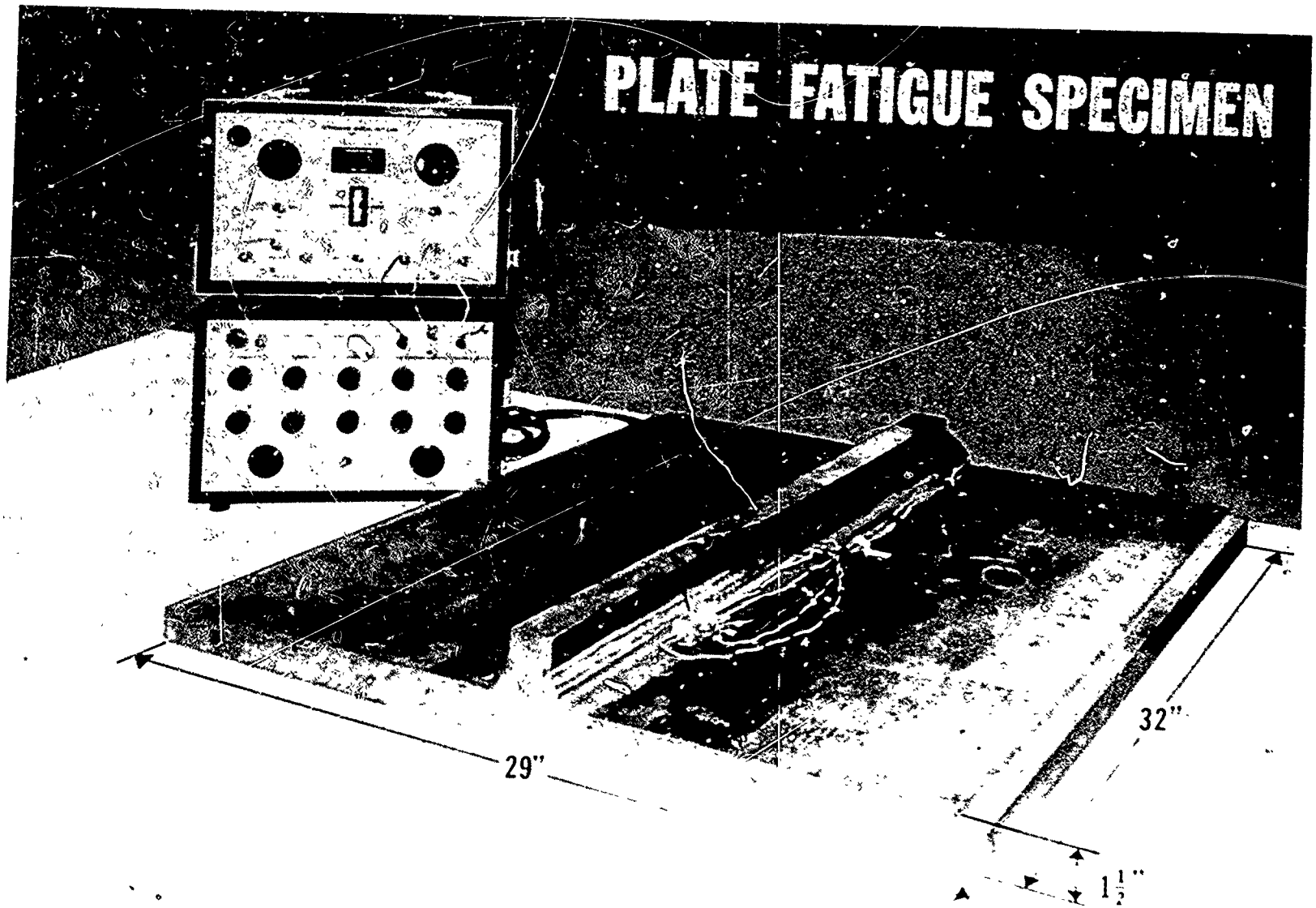

Fracture Surface of A Cantilever
Stress Corrosion Specimen
NSRDL Annapolis

Figure (22)

Figure (23)



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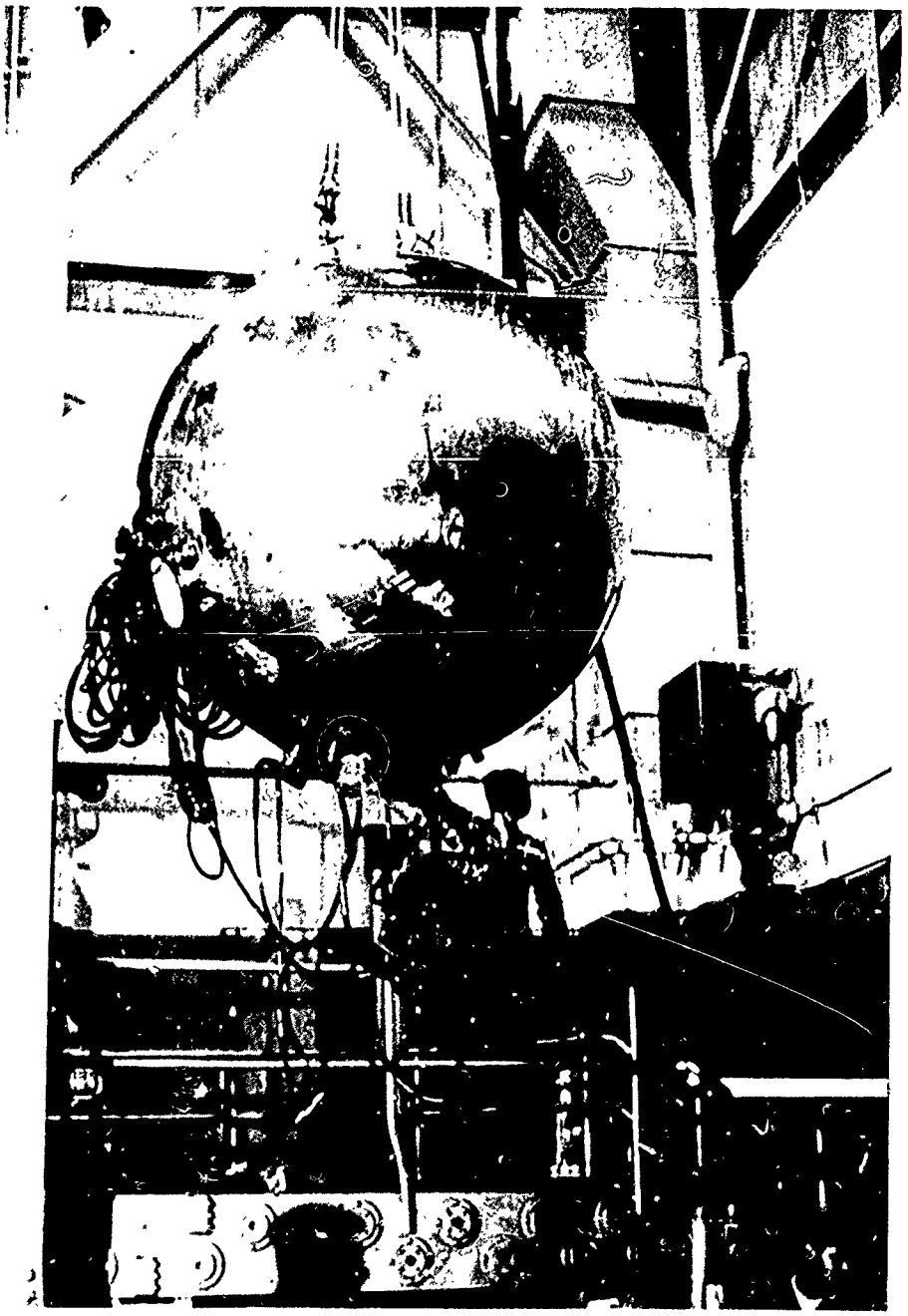

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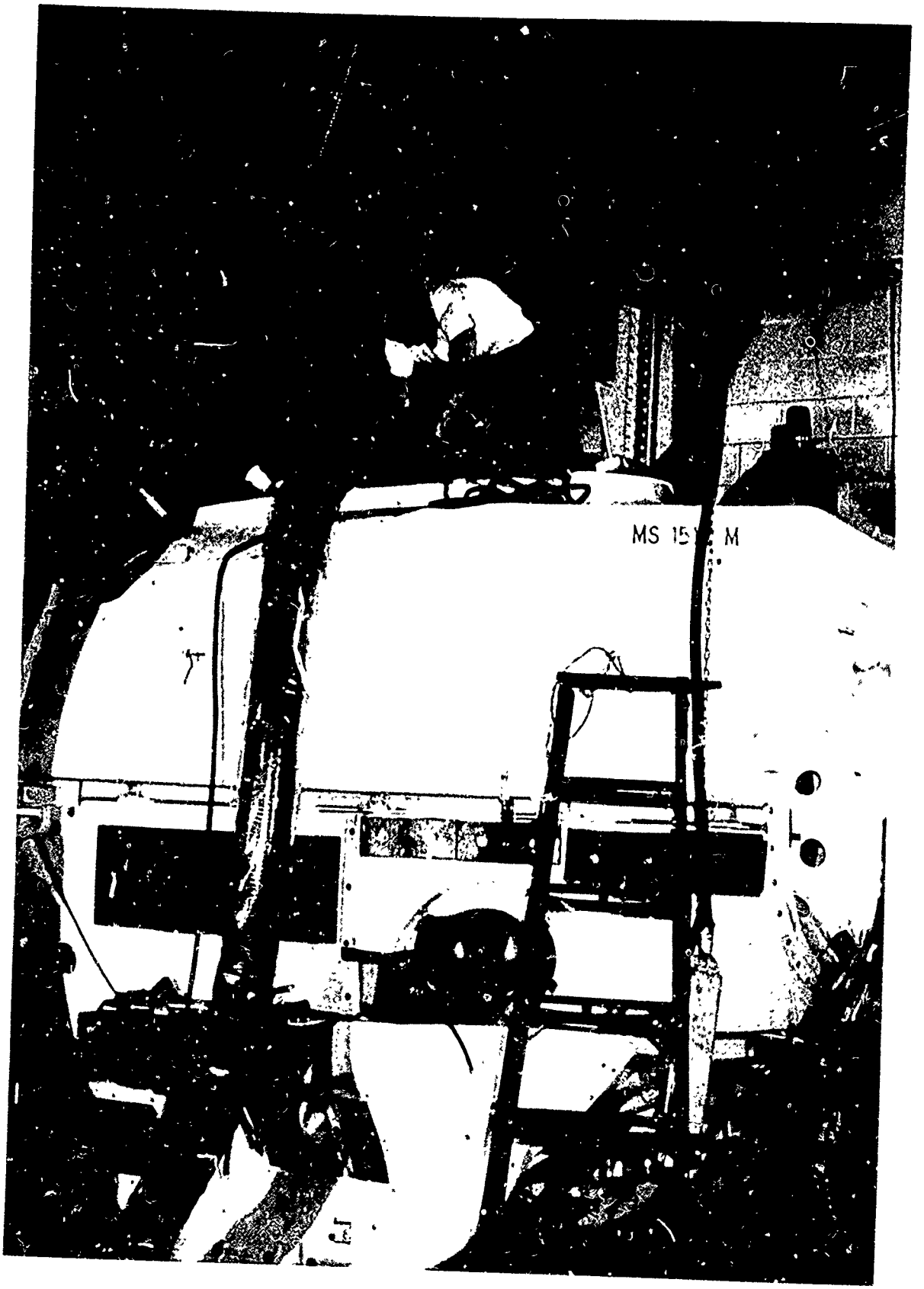

Figure (26)

Figure (27)

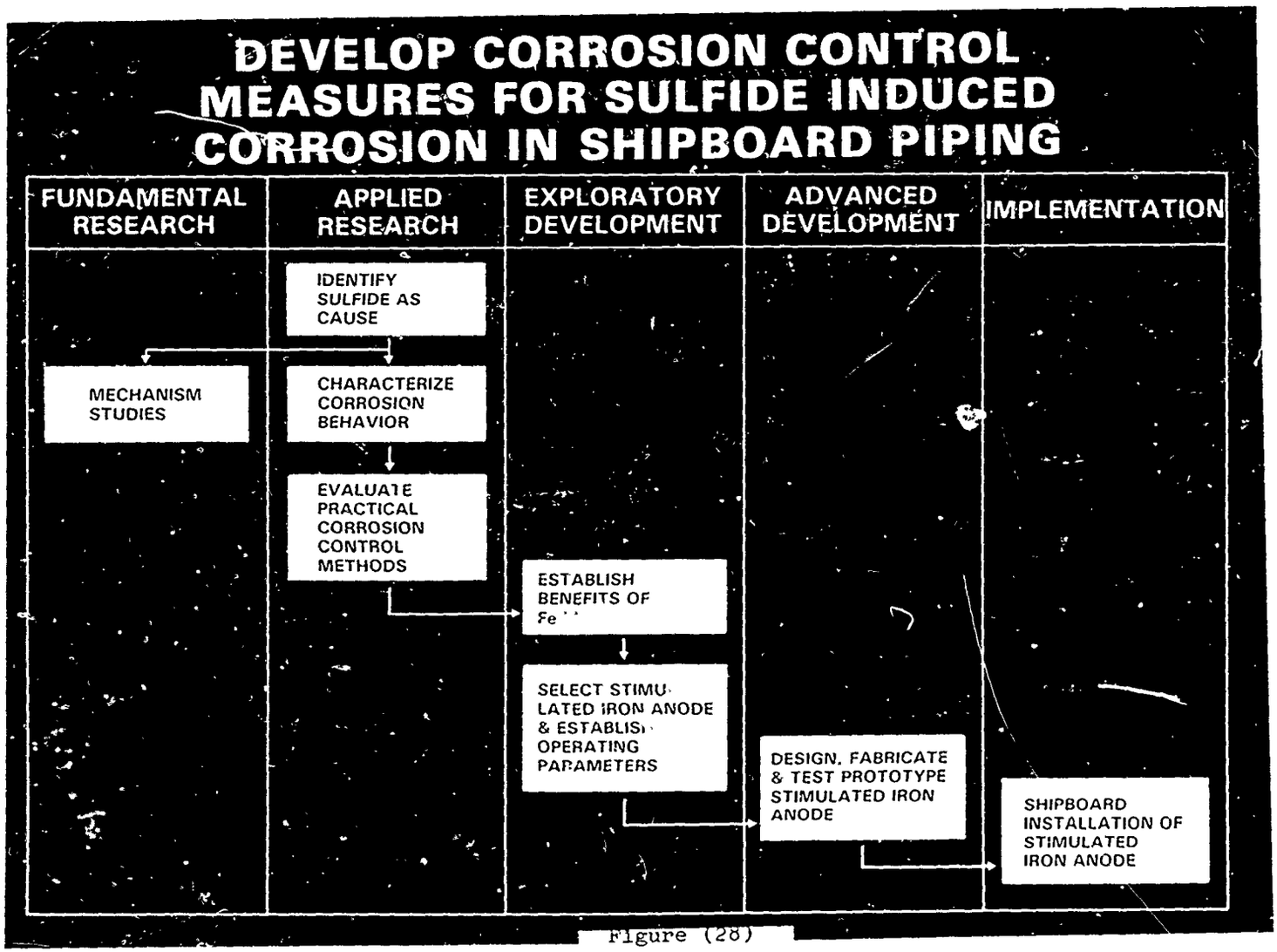
DEVELOP CORROSION CONTROL MEASURES FOR SULFIDE INDUCED CORROSION IN SHIPBOARD PIPING
FUNDAMENTAL RESEARCH
APPLIED RESEARCH
EXPLORATORY DEVELOPMENT
ADVANCED DEVELOPMENT
IMPLEMENTATION
IDENTIFY SULFIDE AS CAUSE
MECHANISM STUDIES
CHARACTERIZE CORROSION BEHAVIOR
EVALUATE PRACTICAL CORROSION CONTROL METHODS
ESTABLISH BENEFITS OF Fe
SELECT STIMULATED IRON ANODE & ESTABLISH OPERATING PARAMETERS
DESIGN, FABRICATE & TEST PROTOTYPE STIMULATED IRON ANODE
SHIPBOARD INSTALLATION OF STIMULATED IRON ANODE

Figure (28)

Figure (29)

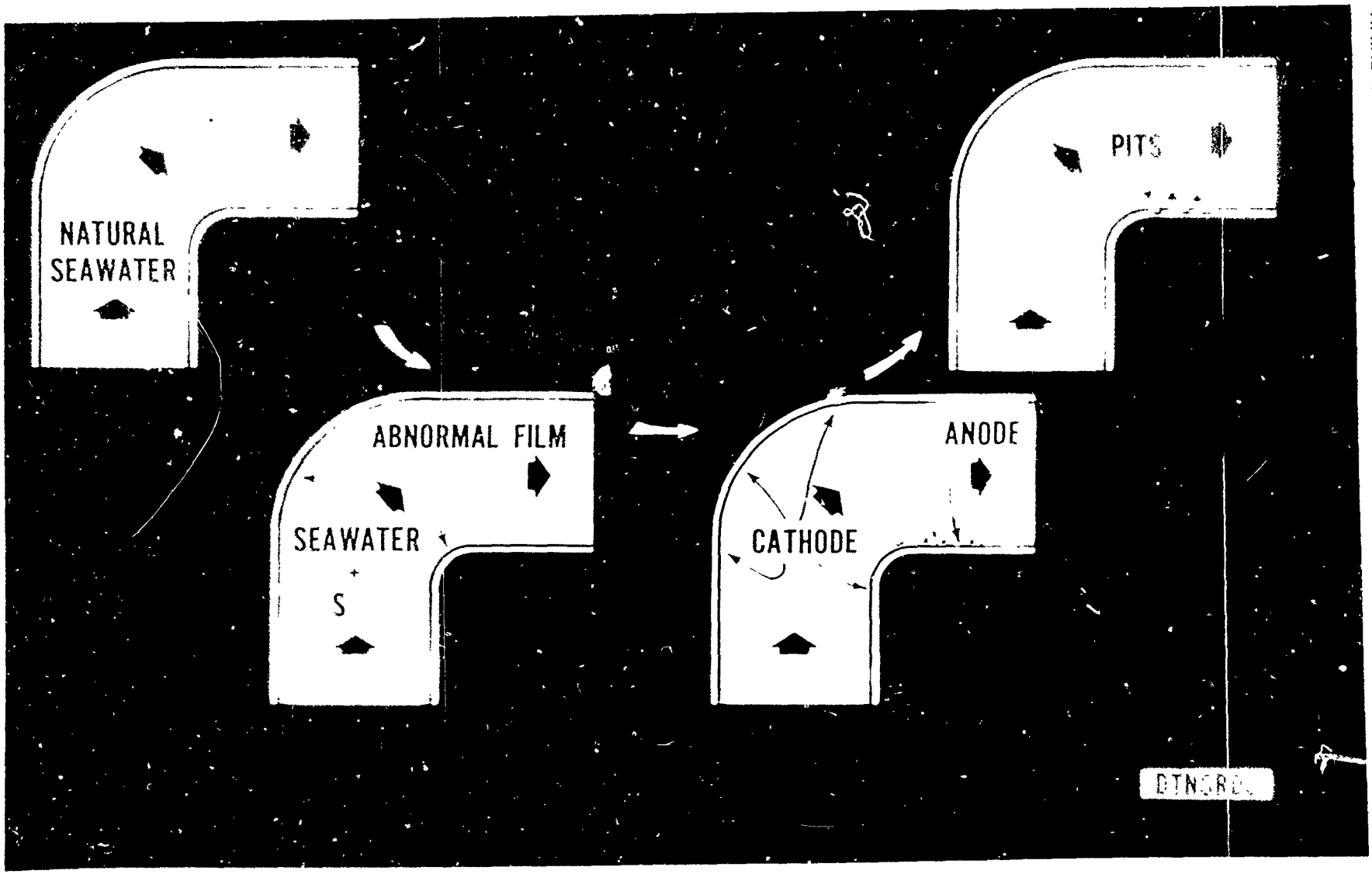
NATURAL
SEAWATER
PITS
ABNORMAL FILM
SEAWATER
S
CATHODE
ANODE

Figure (30)

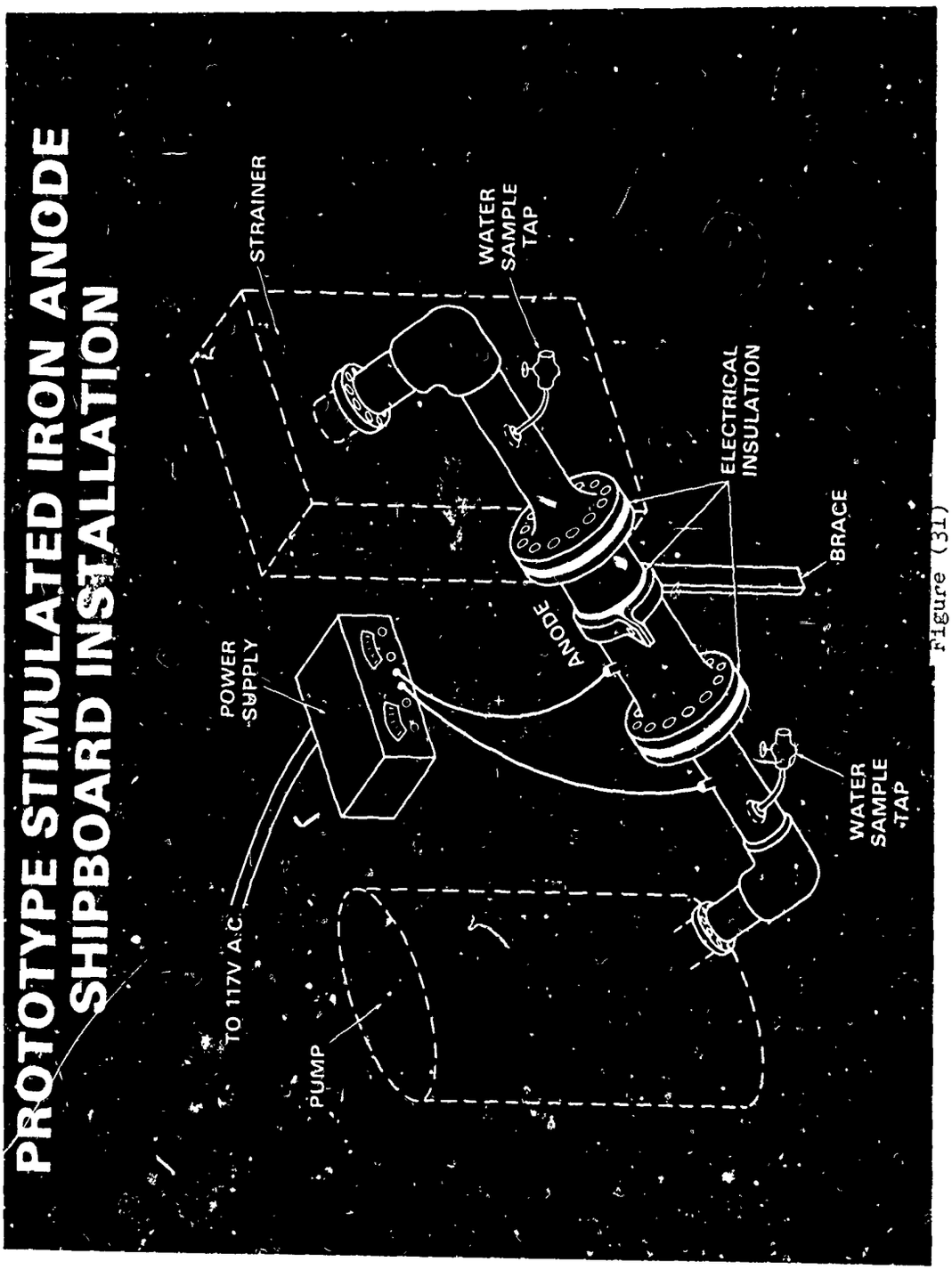
PROTOTYPE STIMULATED IRON ANODE
SHIPBOARD INSTALLATION
STRAINER
WATER SAMPLE TAP
ELECTRICAL INSULATION
BRACE
ANODE
POWER SUPPLY
TO 117V A.C.
PUMP
WATER SAMPLE TAP

Figure (31)

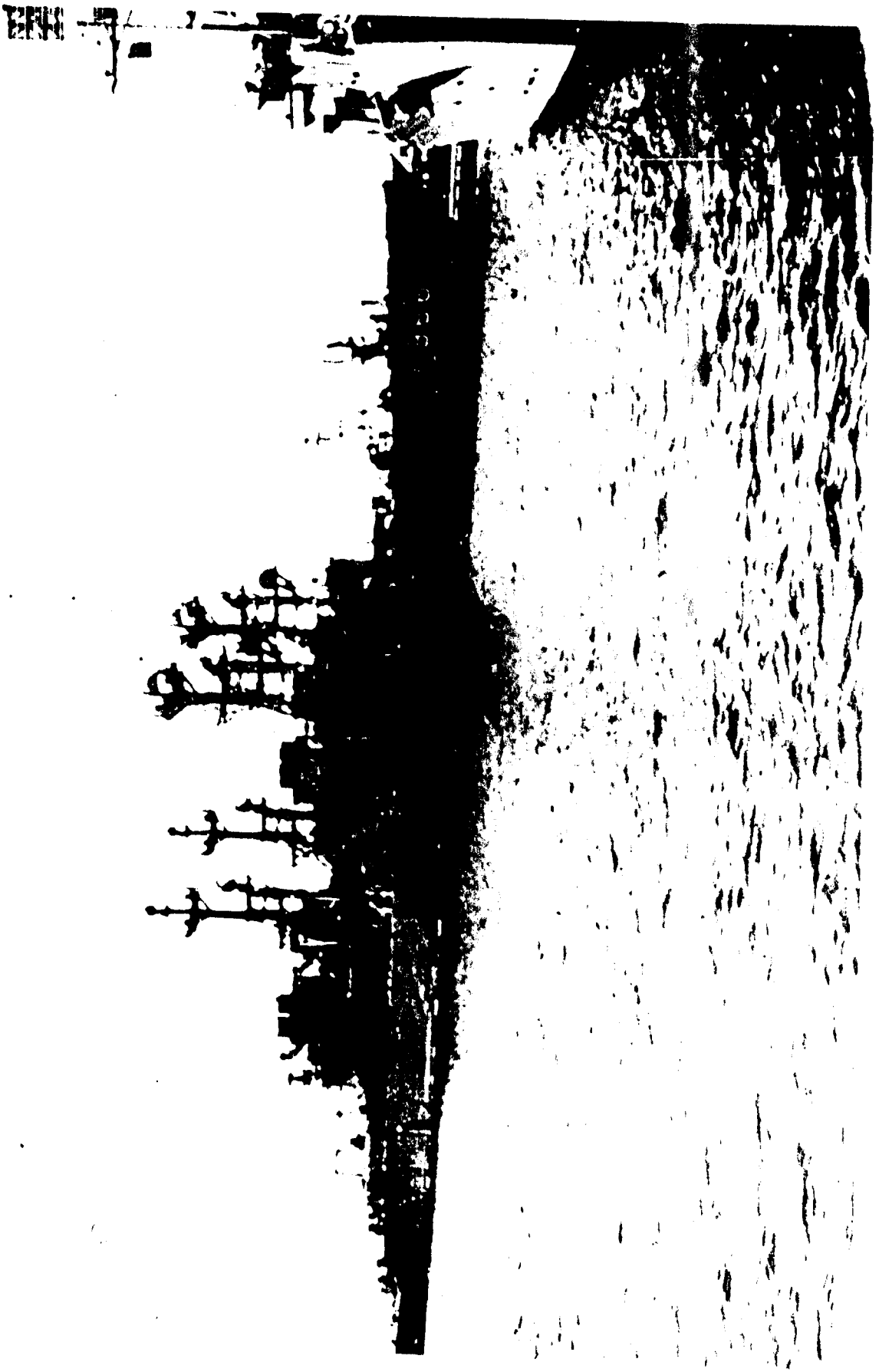

Figure (32)

Figure (33)

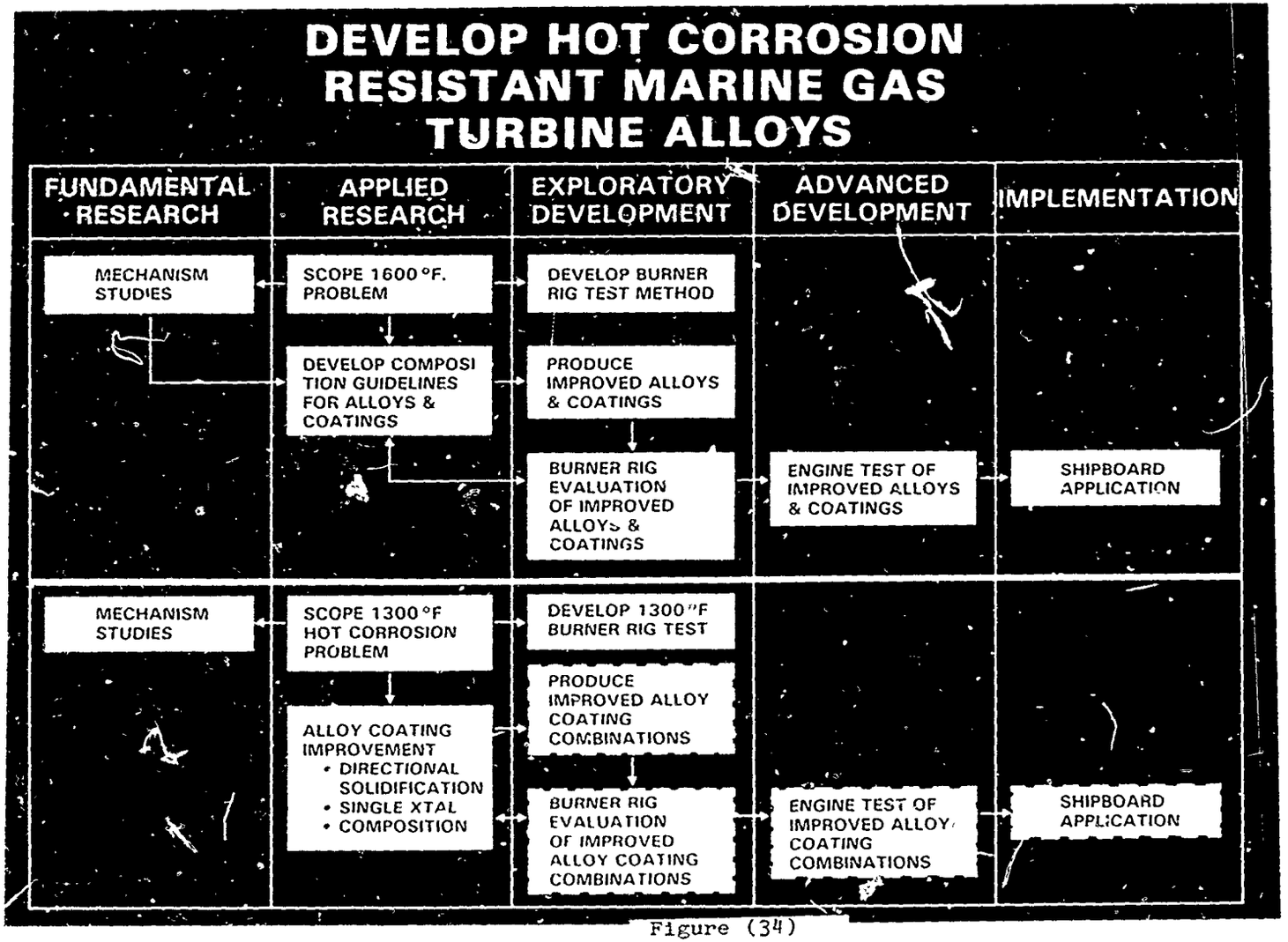
DEVELOP HOT CORROSION RESISTANT MARINE GAS TURBINE ALLOYS
FUNDAMENTAL RESEARCH
APPLIED RESEARCH
EXPLORATORY DEVELOPMENT
ADVANCED DEVELOPMENT
IMPLEMENTATION
MECHANISM STUDIES
SCOPE 1600 °F. PROBLEM
DEVELOP BURNER RIG TEST METHOD
DEVELOP COMPOSITION GUIDELINES FOR ALLOYS & COATINGS
PRODUCE IMPROVED ALLOYS & COATINGS
BURNER RIG EVALUATION OF IMPROVED ALLOYS & COATINGS
ENGINE TEST OF IMPROVED ALLOYS & COATINGS
SHIPBOARD APPLICATION
MECHANISM STUDIES
SCOPE 1300 °F HOT CORROSION PROBLEM
DEVELOP 1300 °F BURNER RIG TEST
PRODUCE IMPROVED ALLOY COATING COMBINATIONS
ALLOY COATING IMPROVEMENT
• DIRECTIONAL SOLIDIFICATION
• SINGLE XTAL
• COMPOSITION
BURNER RIG EVALUATION OF IMPROVED ALLOY COATING COMBINATIONS
ENGINE TEST OF IMPROVED ALLOY COATING COMBINATIONS
SHIPBOARD APPLICATION

Figure (34)

BIOGRAPHY

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AFWAL-TR-81-4019

CORROSION CONTROL USING WIRE SPRAYED ALUMINUM IN THE U.S. NAVY

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Netherlands

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The Hague, Netherlands

Secretariat
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INTRODUCTION

The primary mission of United States Navy ships is combat. The combat readiness of a ship is directly related to the material condition of the ship and the training of the crew. Crew manning is based on the number of individuals required to operate and maintain the ship. Any non-productive work by ship's force (S/F) is time taken away from training and operating the ship, thereby resulting in a reduction in operational readiness.

Marine corrosion degrades the performance and operability of shipboard equipment, machinery, and the ship structure itself. S/F is routinely, i.e., continually cleaning and represerving (chipping and painting) to control the marine corrosion (a never ending task). This chipping and painting is non-productive labor. The ship designer and the ship constructor are now in a position to use corrosion-control technology which can reduce chipping and painting time. This reduction in maintenance time can be achieved through use of Integrated Logistic Support (ILS) concepts and practices to enhance the operability of the ship while at the same time reduce the maintenance load for S/F, especially the non-productive work of preservation.

The Commander Naval Surface Force, U.S. Pacific Fleet, is most concerned with reducing non-productive S/F work load and instead use this time to do the real thing --- operate the ship and train the crew to maximize their combat readiness. Failure of our conventional preservation coating systems is a major source of non-productive labor. In search of a better solution, the literature pointed to the success of using wire-sprayed alumimum (WSA) to protect steel in the marine environent. The WSA preservation system consists of a properly prepared substrate (material to be protected), at least five-mils (thousands of an inch) of wire-sprayed aluminum, and sealed and/or color-topped with an organic paint. The procedings of the Eight International Symposium on Thermal Spray[1] amply summarize the methods for successful use of both oxygen-fuel and electric-arc wire sprayed alumimum for the protection of ferrous materials and structures and thus will not be

repeated here. Aircraft carriers have been using wire-sprayed aluminum since 1974 to protect launch and recovery systems[2]. This paper will summarize the test and evaluation leading to the implementation of WSA preservation in ships of the Naval Surface Force, U.S. Pacific Fleet. As a result, the Navy is currently extending such corrosion control to all surface ships of the United States Navy.

TEST AND EVALUATION

The WSA preservation system has been selectively used on NAVSURFPAC ships since 1974. A test and evaluation program was initiated in December 1977 on one guided missile frigate, USS SCHOFIELD (FFG 3), three guided missile cruisers, USS WILLIAM H. STANDLEY (CG 32), USS FOX (CG 33), and USS BAINBRIDGE (CGN 25), and two Spruance class destroyers, USS HEWITT (DD 966) and USS DAVID R. RAY (DD 971).

USS SCHOFIELD (FFG 3): During the period December 1977 to February 1978, corrosion-prone items, ranging from propulsion-plant components to weather-deck hardware, were preserved with oxygen-fuel WSA. This preservation was done by the Shore Intermediate Maintenance Activity (SIMA), San Diego and Flame Spray Inc. (a San Diego based thermal-spray service contractor). Test items in the engineering spaces include: steam valves with ambient to 525°C (975°F) operating temperatures located in bilge to upper levels in the engineroom and fireroom, boiler skirts, ladders, and instrument stands. Items on the topside weather decks include lifeline stanchions, diesel exhaust stacks, TARTAR missile exhaust deflector, helicopter deck tiedowns, fire applicators, ladders, and steam riser valves/ piping.

The design goal in December 1977 was to lay on the WSA four- to six-mils thick with at least two crossing passes on a 24-mesh aluminum oxide grit blasted substrate sealed with METCO Inc. silicone aluminum (SA) high temperature sealer for steam valves and components with operating temperatures higher than 55°C (125°F). (METCO Inc is a supplier of thermal-spray equipment and materials). The SA sealer was also used for ambient temperature; however, conventional Navy paint primers and color topping could be used for ambient temperature

applications. The four- to six-mil WSA thickness was predicated (a) on the 19-year corrosion-control study report wherein three- to five-mils aluminum gave complete base-metal protection[3] and (b) to mimimize the potential delamination failure from expansion-contraction cycles of the heated components. The result of the preservation was that all WSA-preserved items were completely protected for over one and one-half years. Components chosen for WSA preservation had been proven to require extensive "chipping and painting". No further preservation work was needed on WSA-preserved steam valves during that time. However, some of the items showed areas of degradation due primarily to "too thin a coat". Of the some 40 stanchions preserved with WSA, about five had rusted through on small areas. The diesel exhaust stack had three one-inch diameter thin rust spots. There was rust on the abraded "fingers" of the lifeline stanchion. Aluminum is soft, will abrade, but will not blister and exfoliate from the substrate as will paint systems. In addition helicopter tiedowns were preserved with WSA and are continuing to be effectively protected from February 1978 until this presentation. The diesel exhaust stack which operate at about 205°C (400°F) has needed no re-preservation since December 1977.

The lessons learned from the USS SCHOFIELD (T&E):

a. Minimum WSA-coating thickness must be at least five mils and applied with at least two-crossing passes. Manual application cannot control the crossing-pass to a minimum thickness of four mils as was done mechanically in the American Welding Society 19-year evaluation[3].

b. No delamination was observed on heated components (up to 525°C (975°F)) at WSA thickness up to 24 mils.

c. Rusting was observed on four stanchions and three one-inch square areas on the diesel exhaust stack topside. This can be attibuted to insufficient initial coating thickness.

d. Capstan drum working area preserved with four-mils oxy-aceclyene WSA for a corrosion-

control coat topped with three-mils plasma-sprayed tungsten carbide failed after about four-months service. This was attributed to frictional loading by the wire-rope on the aluminum and fracturing the tungsten carbide-coating. After all, the aluminum coating is "soft" when compared to the wire rope. Note: This coating system has been replaced with five- to seven-mils plasma-sprayed alumina-titania coating in October 1978. It has performed effectively through July 1979 (last observed measurement by the author) with only minor degradation in the capstan-drum curvature area where the wire rope is forced onto the cylindrical area of the drum.

The USS SCHOFIELD T&E results were the first large-scale demonstration of the suitability of WSA-preservation in COMNAVSURFPAC.

The operational payoff, reported by the Commanding Officer of the USS SCHOFIELD, was that the time saved from non-productive chipping/painting labor was redirected to readiness training and constructive preventive maintenance. The percentage of enlisted personnel successfully passing rating examinations rose from 35% to above 90% in the three following calender quarters, which was attributed to the additional training time. Reenlistment increased from 40% to 80%. The material condition of engineering and topside spaces were at their peak because personnel were doing "constructive" maintenance and not wasting time (e.g., two hrs per stanchion every 6-wks, and 16 hrs every 6-wks on diesel exhaust stacks).

USS WILLIAM H. STANDLEY (CG 32): The first full-scale service demonstration of WSA-preservation of propulsion-plant steam valves was made on the USS WILLIAM H. STANDLEY (CG 32) by Puget Sound Naval Shipyard[4]. Some 350 steam valves along with some flanged steam piping were preserved and installed during May-November 1978. A Service Test Plan was formulated to track these valves and steam piping components for six years[5]. The initial inspection was in August 1978 followed a second inspection in December 1978 and again in July 1979. No degration was found in the WSA preservation, save one 3/4-inch by 3/16-inch area on a valve bonnet. This degraded area was repaired

and could be attributed to inadequate surface preparation and/or contamination between grit blasting and flame spraying.

None of the other WSA-preserved valves have required preservation since installation. The non-WSA valves have required up to two paintings with heat resistant paint since August 1978.

Analysis of "literature" supported by interim approval to use WSA to preserve steam valves by the Naval Sea Systems Command in January 1978 lead COMNAVSURFPAC to service test aboard the USS SCHOFIELD and USS WILLIAM H. STANDLEY. The results of these tests lead to the policy to preserve steam valves and similar propulsion-plant components with WSA vice heat-resistant-aluminum paint in January 1979[6]. The Naval Sea Systems Command adopted the use of WSA preservation for steam valves in May 1979 and is expanding the use of WSA preservation for other shipboard corrosion-prone items and spaces.

METALLIZED NON-SKID HELICOPTER FLIGHT DECK COATING

The Naval Air Engineering Center, Lakehurst, NJ, has pioneered the development of metallized non-skid flight-deck coatings first for jet blast deflectors on aircraft carriers (conventional non-skid coatings could not stand up to the jet aircraft exhaust heat) followed by helicopter flight-deck applications. Conventional non-skid flight-deck coverings last from one-half to two years depending upon quality of product, its application, and upon the wear received. Once the coating is damaged or worn through to the substrate, the coating blisters and exfoliates.

The metallized non-skid systems are designed to give corrosion protection and a high profile abrasive surface. The corrosion protection comes from arc-wire spraying on a five- to eight-mil coat of aluminum over the substrate to give a barrier with no "through porosity". The aluminum corrosion-control coat will provide galvanic protection if cut through to the substrate.

The Navy is currently evaluating three metalized non-skid coating systems. These non-skid coating systems include: (1) spraying or rolling on the

conventional non-skid over five- to eight-mil arc-WSA corrosion-protection or cover coat; (2) arc-wire spraying on an aluminum non-skid coating 10- to 25-mil thick over an arc-WSA cover coat; and (3) a one-coat arc-WSA 15- to 45-mil thick and coarse enough to give both barrier protection (no through porosity) and a non-skid surface. These metallized non-skid systems typically have a bond of around 175 kgs/cm^2 (2500 pounds per square inch).

The first system, i.e., conventional non-skid over a five- to eight-mil arc-WSA cover or corrosion-control coat, is being service tested on the USS DONALD B. BEARY (FF 1085) by the Commander Naval Surface Force U. S. Atlantic Fleet, the Naval Sea Systems Command and the Naval Air Engineering Center. This system is expected to last at least three to five years with only minor repairs to replace worn or damaged conventional non-skid areas. The WSA corrosion-control coat is expected to last overhaul-to-overhaul.

System 2 above, the double coat arc-WSA, has been applied to the helicopter flight decks of the USS HEWITT (DD 966) and the USS FOX (CG 33). The USS FOX deck coating was applied in June 1979 and is "running" .

The USS HEWITT's flight deck was applied in September 1978. It had a 1.1-0.9 coefficient of dry static friction. However, it was covered over with a spray-on conventional non-skid coating making it equivalent to System 1 because of lack of sufficient technical and safety service test data, e.g., no data on wear qualities compared to conventional non-skid decks vs time and use conditions and friction degradation with cosmetic painting and fuel/oil spills. No degradation to date. Mechanically damaged or chipped conventional non-skid coating more easily repaired because the WSA precludes corrosion of the substrate.

System 3 above, one coat arc-WSA 15- to 45-mil thick has been laid down on the walkways and ASROC-launcher work area on the forecastle deck of the USS BAINBRIDGE (CGN 25) in May 1979. This non-skid coating has survived ASROC and TERRIER missile launchings but which destroyed adjacent conventional paint-preserved areas.

The Naval Sea Systems Command is implementing the use of WSA preservation, both as a metallized primer for organic preservation systems and as a preservation system in its own right. All naval shipyards, ship repair facilities, and intermediate maintenance activities are being outfitted with a production capability and capacity for all their repair and overhaul work. Technical data such as technical manuals, Military Standards, technical repair standards, corrosion control handbook, and fully proceduralized job performance aids for the "deck plates" are being developed and promulgated.

POLICY AND PRACTICES

The United States Navy is now implementing as a routine procedure, the use of WSA preservation to reduce fleet working hours and/or increase the service life of shipboard items and spaces. Planning for and use of WSA is of course dependent on (a) having a production capability and production capacity in the naval shipyards, shore intermediate maintenance activities and destroyer tenders, and among industrial contractors and service companies; and (b) having adequate time in the ship's construction, repair and overhaul schedule.

Cost data is being compiled by various activities. For WSA preservation of steam valves, one naval shipyards reported about one to one and one-half man-hours per valve (labor + material costs) on a data base of over 5,000 valves in three ship overhauls since May 1978; second naval shipyard, a projected one and one-half man-hour per valve on a data base of 150 valves on one ship overhaul since January 1979; and a third naval shipyard, about three-quarters man-hours per valve as measured on a 500-valve sample since October 1978; and the Shore Intermediate Maintenance Activity San Diego, about one man-hour per valve on a data base of several thousand valves since 1977.

It is noted that the lead shop for WSA preservation in one naval shipyard is the paint shop. In that shipyard, there has been no additional cost for WSA-preservation over the preservation cost using heat resistant aluminum paint.

SUMMARY

The use of wire sprayed aluminum (WSA) preservation coating for the control of shipboard corrosion has proven highly effective. A number of COMNAVSURFPAC ships have had a wide range of items/spaces preserved with WSA such as propulsion-plant steam valves and piping, boiler skirts, deck hardware and machinery, topside deck surfaces, helicopter deck tiedowns, non-skid flight-deck and weather-deck walkways. These applications have demonstrated a reduction in repetitive non-productive ship's force preservation work. The potential exists for additional significant reduction in repetitive non-productive ship's force work by the widespread use of WSA preservation on topside, well decks, machinery space and other shipboard corrosion-prone areas. The Naval Sea Systems Command is implementing a program for WSA preservation in the acquisition, repair, and overhaul of U.S. Navy ships.

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Manuscript cutoff date: September 1979.

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DTNSRDC ANNAPOLIS MD
USS ALBERT DAVID
COMCRUDESGRU ONE
NAVSEACENPAC SAN DIEGO CA
NAVSHIPYD PEARL HARBOR HI
NAVSWC SILVER SPRING MD

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METAL/PLASMA SPRAY APPLICATIONS

A. NAVSHIPYD LONG BEACH CA 071605Z SEP 79
B. NAVSEACENPAC SAN DIEGO CA 241902Z SEP 79
C. NAVSEASYSCOM WASHINGTON DC 281728Z SEP 79
D. NAVSHIPYD PEARL HARBOR HI 251959Z APR 79 NOTAL
E. USS BADGER 021200Z MAY 79 NOTAL
F. USS RATHBURNE 110501Z MAY 79 NOTAL
G. USS ROBERT E. PEARY 292345Z APR 79 NOTAL

1. SUMMARY. DUE TO RECENT FAILURE OF A FORCED DRAFT BLOWER METALLIZED BEARING AREA DURING A ROUTINE SHOP BALANCING OF THE ROTATING ASSEMBLY, NAVSEASYSCOM REAFFIRMED ITS PROHIBITION AGAINST USING "SPRAY METALLIZING" AS A REPAIR FOR STEAM TURBINE ROTATING/SLIDING/STATIONARY MACHINED PARTS. BASED ON RECENT SATISFACTORY TEST RESULTS AND ANTICIPATED COST BENEFITS NAVSEASYSCOM IS HEREIN REQUESTED TO RECONSIDER THE ABOVE AND CONTINUE SERVICE TESTING WITH THE ULTIMATE RESULT BEING THE ISSUANCE OF A SPECIFIC THERMAL-SPRAY PROCESS INSTRUCTION FOR USE BY IMA AND DEPOT LEVEL ACTIVITIES.

2. NAVSEACENPAC INVESTIGATED THE ABOVE NON-SERVICE FAILURE AND RE-

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PORTS IT WAS CAUSED BY USE OF A 3/4-IN. CROWNED ROLLER WHICH PRODUCED HIGH LINE LOADING OF THE CERAMIC COATING. REF B APPLIES. A HORSE-SHOE OR JOURNAL-TYPE BEARING SHOULD HAVE BEEN USED. NAVSEACENPAC REPORTS NO OBSERVATION OF THERMAL-SPRAY IN-SERVICE FAILURES IN PAST FOUR YEARS.

3. COMNAVSEASYSCOM IN REF C REAFFIRMS THE 20-YR. PROHIBITION OF USING "SPRAY METALLIZING (METAL/PLASMA) AS A REPAIR FOR STEAM TURBINE ROTATING/SLIDING/STATIONARY PARTS". THIS PROHIBITION IS BASED ON MUCH UNSAT PAST EXPERIENCE AND CONTINUING PROBLEMS AS REPORTED BY REF A. HOWEVER, NAVSEA AUTHORIZED ONE EXCEPTION IN 1977 TO SPRAY SEVERAL FF 1052 CLASS MAIN FEED PUMPS (MFP) AND FDB SHAFTS USING CONTROLLED PROCESSES FOR EVALUATION PURPOSES.

4. NAVSHIPYD PEARL HARBOR INSTALLED SIX TURBINE SHAFTS WHOSE DIMENSIONS WERE RESTORED TO SPECIFICATION AND INSTALLED IN USS BADGER (FF 1071) IN LATE 1976, USS ROBERT E. PEARY (FF 1073) IN MID 1977, AND USS RATHBURNE (FF 1057) IN LATE 1977:

SHIP	ITEM	THERMAL SPRAY SYS (SEE NOTE)	FINISHING (SEE NOTE)
USS BADGER (FF 1071)	1A FDB	1	A
USS ROBERT E. PEARY	1B FDB	2	A
(FF 1073)	1A FDB	2	A
	1C FDB	2	B
USS RATHBURNE (FF 1057)	1B MFP	2	B
	1C MFP	2	B

NOTE: 1 - COMBUSTION WIRE; NICKEL ALUMINIDE BOND COAT TOPPED WITH AUSTENITIC LOW CARBON STAINLESS STEEL.
2 - PLASMA SPRAYED SELF BONDING NICKEL CHROMIUM/ALUMINUM (6% ALUMINUM, BALANCE NICKEL CHROMIUM).
A - MACHINED TO DIMENSIONS W/CARBIDE TOOL.
B - GROUND TO DIMENSION. THIS IS THE PREFERRED FINISHING MODE RETAINING THE DENSE & SMOOTH CERAMIC FINISH WITHOUT PARTICLE PULLOUT WHICH OCCURS IN MACHINING PROCESS.

5. NAVSHIPYD PEARL HARBOR REQUESTED SHIPS TO REPORT ANY STEAM LEAKAGE AND DISCREPANCIES TO THESE SHAFTS (REF D). NO STEAM LEAKAGE OR OTHER DISCREPANCIES NOTED BY SHIPS (REFS E, F AND G).

6. IN VIEW OF THE GREAT POTENTIAL FOR INCREASED RELIABILITY AND COST EFFECTIVENESS OF REPAIR BY I&A AND NAVY DEPOT ACTIVITIES USING REPAIR AND COATING APPLICATIONS BASED ON ACCEPTANCE AND USE OF THERMAL-SPRAY TECHNOLOGY IN AVIATION AND MACHINERY REPAIR INDUSTRIES, REF B RECOMMENDATION FOR REEVALUATION IS SUPPORTED FULLY.

7. COMNAVSEASYSCOM REQUESTED TO CONDUCT TIMELY AND COMPREHENSIVE SERVICE TEST OF ARC-PLASMA AND ARC/COMBUSTION-WIRE METAL REPAIR AND COATING SYSTEMS DURING RUN OF SURFACE COMBATANT AT NAVSHIPYD PUGET SOUND. THE CONCEPT OF THE SERVICE TEST WOULD BE TO IDENTIFY MULTIPLE SIMILAR ITEMS SOME OF WHICH COULD BE REPAIRED WITH PLASMA/

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IRE-SPRAYED COATING SYSTEMS. APPLICATIONS OF LOW TECHNICAL RISK BASED ON INDUSTRY PRACTICES AND PAST NAVY IN-SERVICE TESTING, WOULD BE SELECTED. TYPICAL ITEMS WOULD BE MOTOR END BELLS; MOTOR SHAFTS; DECK-MACHINERY HOUSING BORE AREAS AND LINKAGES; AND TURBINE GLAND SEAL HOUSING AREAS. SPECIFIC THERMAL-SPRAY PROCESS INSTRUCTIONS WOULD BE DEVELOPED AND VALIDATED PRIOR TO COMPONENT REPAIR TO INCLUDE METALLOGRAPHIC, TENSILE, AND HARDNESS ANALYSES ALONG WITH REQUISITE QUALITY CONTROL, HANDLING, AND INSTALLATION INSTRUCTIONS.

A. TECHNICAL DIRECTION AND ASSISTANCE:

(1) NAVY SCIENCE ASSISTANCE PROGRAM (NSAP) FOR AN INDEPENDENT STATE-OF-THE-ART SURVEY, IDENTIFICATION AND RANKING OF CRITICAL PARAMETERS, AND DEVELOPMENT OF THE SERVICE TEST PLAN.

(2) DTNSRDC (ANNAPOLIS) AND NAVSSES FOR TECHNICAL GUIDANCE AND IMPLEMENTATION OF THE SERVICE TEST PLAN; DTNSRDC BECAUSE OF THEIR RDT&E MISSION AND WORK IN PLASMA-SPRAY TECHNOLOGY, NAVSSES BECAUSE THEY ARE THE IN-SERVICE ENGINEERING AGENT FOR MANY OF THE POTENTIAL TEST ITEMS.

B. FUNDING REQUIREMENTS:

(1) MINIMAL ADDITIONAL ROH FUNDING REQUIREMENTS ANTICIPATED; SCHEDULE-AND DOLLAR-COST REDUCTIONS EXPECTED IN THE LONG TERM.

(2) NSAP FUNDING SUPPORT REQUIRED FOR THE NAVY LABORATORY COMMUNITY TO CONDUCT THE INITIAL LITERATURE EVALUATION AND DEVELOP SERVICE TEST PLAN.

(3) NAVSEA DIRECTION AND FUNDING SUPPORT REQUIRED FOR:

(A) DTNSRDC (ANNAPOLIS) TO IMPLEMENT NSAP SERVICE TEST PLAN.

(B) NAVSSES TO OBSERVE AND IMPLEMENT FINDINGS AND RECOMMENDATIONS IN THE MANUFACTURE AND REPAIR OF APPLICABLE HME SYSTEMS (E.G., PROMULGATE AND MAINTAIN TECHNICAL REPAIR STANDARDS (TRS) AND DEVELOP EQUIPMENT AND SHIP ALTERATION PACKAGES).

(C) PSNSY TO (1) DEVELOP AND VERIFY THERMAL-SPRAY PROCESS INSTRUCTIONS AND (2) ISSUE SERVICE TEST REPORT FOR THE SELECTED SURFACE COMBATANT.

8. USS ALBERT DAVID (FF 1050), ROH 7/7/80 TO 5/8/81, NOMINATED SUBJECT TO CONCURRENCE NAVSHIPYD PUGET SOUND.

9. NAVSURFPAC POC IS N43A R SULIT, FORCE ENGINEERING ADVISOR, AVN 958-9221.

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U U N C L A S S I F I E D U

COMMANDER NAVAL SURFACE FORCE
UNITED STATES PACIFIC FLEET
SAN DIEGO, CALIFORNIA 92155

COMNAVSURFPACINST 9630.1
Code N43A/WPC 693
06 November 1979

COMNAVSURFPAC INSTRUCTION 9630.1

Subj: Shipboard Preservation with Wire Sprayed Aluminum (WSA)

1. Purpose. This instruction promulgates COMNAVSURFPAC policy for the use of Wire Sprayed Aluminum (WSA) preservation; guidance for selecting and prioritizing shipboard items and spaces; implementation procedures; and equipment procurement.

2. Discussion. Wire Sprayed Aluminum (WSA) preservation has been used selectively in NAVSURFPAC ships since 1972. A test and evaluation program was initiated in December 1977 in USS SCHOFIELD (FFG 3), USS WILLIAM H. STANDLEY (CG 32), USS HEWITT (DD 966), and USS FOX (CG 33). Results to date indicate that the WSA preservation system is more effective than conventional paint preservation systems. This is due to the WSA process introducing a "metallized primer" mechanically bonded to the substrate giving both barrier and galvanic protection. The WSA-preservation system consists of a properly prepared substrate (material to be protected), five to eight mils of wire-sprayed aluminum, and sealed and color-topped with organic paint. Surface preparation is the most demanding element of the WSA preservation process. The feasibility and cost of off-ship versus on-ship preservation and its compatibility and/or interference with concurrent work must be considered.

3. Policy. COMNAVSURFPAC policy is to use WSA for the preservation of shipboard corrosion-prone items and spaces where paint preservation systems have not been effective. Identification and prioritization of items and spaces designated for WSA preservation should be based on maximizing the reduction of fleet working hours and/or increasing the service life of the item or space. Planning for and use of WSA must be consistent with:

a. Available funding;

b. Production capability and capacity of the naval shipyard (NAVSHIPYD), afloat and ashore Intermediate Maintenance Activities (IMA) and industrial contractors; and

c. Time allocated for the various availabilities and overhauls.

4. Action

a. Implementation Guidance. In the repair, maintenance, and overhaul of ships, WSA preservation should be called out for corrosion-prone components and spaces and screened for implementation in Current Ship Maintenance Plans (CSMP) and Ship Alterations and Repair Packages (SARP) for Regular Overhauls (ROH) to get the most out of allocated resources within scheduled availabilities. Commanding Officers and Group and Squadron Commanders must take a common-sense approach in calling out WSA preservation and trading off its payoff versus other alteration and repair work. The screening process must include NAVSHIPYD, Supervisor of Shipbuilding (SUPSHIP), and IMA evaluation of feasibility and cost effectiveness of the item and space nominated for off-ship or in-place WSA preservation. The Work Definition Conference is the major forum for trade-off discussions to specify what WSA preservation will in fact be accomplished during the ROH. The Type Commanders Representative is the final screening authority for ROH and RAV.

b. Prioritization. Two precedence and three categories within each precedence are designated for categorizing and prioritizing WSA-preservation work items:

PRECEDENCE	CATEGORY
1 - Items removed from ship or installed space for repair or replacement.	A - Topside spaces
	B - Propulsion-plant and machinery spaces
2 - Items and spaces preserved in place.	C - Interior "wet" spaces and items in wet spaces.

The priority order shall normally be 1A, 1B, 1C, 2A, 2B, and 2C (see paragraph 4d below).

c. Performing Activities. Activities and their technicians performing WSA-preservation services must be certified in accordance with current directives. Six activities capable of performing WSA preservation are defined:

1 - NAVSHIPYD or Master Ship Repair (MSR) contractor during ROH.

2 - NAVSHIPYD or MSR contractor during restricted and technical availabilities.

3 - Commercial Industrial Services (CIS) for Shore Intermediate Maintenance Activities (SIMA) and tender availabilities.

4 - SIMA.

5 - Tender/Repair Ship.

6 - Ship's Force (S/F) during ROH (given proper training, certified S/F personnel, and facilities).

d. Item and Space Priority Listing.

(1) Precedence Number 1: Items Removed from Ship or Installed Space for Repair or Replacement.

CATEGORY		PERFORMING ACTIVITY PREFERENCE
1A - Topside Spaces		
1A.1	Deck and UNREP hardware/machinery: Large items as boat davits, winches, booms, and piping that can't be removed/replaced by S/F.	1, 2, 3
1A.2	Deck and UNREP hardware/machinery: Small items as stanchions, Baxter bolts, valves, piping, and watertight doors/scuttles that can be removed/replaced by S/F.	6, 4, 5, 3, 1, 2
1A.3	Helo-deck tiedowns.	1, 2
1A.4	Steam riser vlvs/piping.	4, 5, 6, 3, 1, 2
1A.5	Diesel exhaust stack/covers.	4, 5, 6, 3, 1, 2
1A.6	TASS reel hardware/foundations.	1, 2, 3

1A.7	Fire station hardware.	4, 5, 6, 3, 1, 2
1A.8	Bow ramp and gear on amphib ships/craft.	1, 2, 3, 4
1A.9	Lighting fixtures/brackets.	4, 5, 6, 3, 1, 2
1B - Propulsion-Plant and Machinery Group		
1B.1	Steam vlvs/reducers/stops/strainers/piping.	1, 2, 3, 6, 4, 5
1B.2	Bottom-blow vlvs/piping.	1, 2, 3, 6, 4, 5
1B.3	Pumps/machinery foundations.	1, 2, 3
1B.4	Boiler skirts.	1, 2, 3, 6, 4, 5
1B.5	Electrical/mechanical casings/shields incidental to equipment repair.	1, 2, 3, 4, 5
1B.6	Diesel headers & exhaust system components incidental to repair of the diesel engine.	6, 4, 5, 3, 1, 2
1B.7	Hanger, brackets, and supports.	6, 4, 5, 3, 1, 2
1C - Interior Ships Spaces		
1C.1	Watertight doors/scuttles.	6, 4, 3, 1, 2
1C.2	Equipment in wet spaces as mounting-racks and brackets.	6, 4, 5, 3, 1, 2

(2) Precedence Number 2: Items and Spaces Preserved in Place.

CATEGORY		PERFORMING ACTIVITY PREFERENCE
2A - Topside Spaces		
2A.1	Equipment foundations.	1, 2, 3
2A.2	Deck areas/walkways contigious to ordnance and UNREP stations.	1, 2, 3
2A.3	Masts and booms.	1
2A.4	Piping.	1, 2, 3
2A.5	Stanchions and stanchion foundations.	6, 4, 3, 1, 2
2A.6	Helo tie downs.	6, 4, 3
2A.7	Combing and 1-ft width around watertight doors/scuttles.	1, 2, 3
2A.8	Other deck areas especially where water collects/stands.	1, 2, 3

2A.9	Gun mounts.	1, 2, 3
2A.10	Missile houses.	1, 2, 3
2B - Propulsion-Plant and Machinery Group		
2B.1	Pump rooms.	1, 2
2B.2	Refrigeration, air-conditioning, and fan rooms.	1, 2
2B.3	Boiler airside casing and condenser heads.	1, 2
2B.4	RAM rooms.	1, 2
2B.5	Hot-water-heater rooms/components.	1, 2
2B.6	Sewage treatment rooms.	1, 2
2C - Interior Ships Spaces		
2C.1	Heads.	1, 2, 3
2C.2	Scullery.	1, 2, 3

e. Implementation Procedures.

(1) For ROH's. WSA should be initially identified at the Pre-Overhaul Test and Inspection (POT&I) and included in the Ship Alteration and Repair Package (SARP); cost estimates obtained from NAVSHIPYD and/or SUPSHIP; screened and prioritized at the Work Definition Conference (WDC) within the ship's budget for preservation work; and specified in the final ROH package for accomplishment.

(2) For NAVSHIPYD/IMA Availabilities. WSA preservation should be called out in 2 KILO work requests, listed in the CSMP, and prioritized for accomplishment in accordance with paragraph 4a. Note: If a corrosion-prone component is removed from the ship for repair, manufacture, and/or replacement, WSA preservation should be called out in the 2 KILO.

f. WSA Equipment-Procurement Guidance. WSA-equipment is classified as Industrial Plant Equipment (IPE). Procurement of WSA equipment with O&MN/O&MNR (OPTAR) funds is no authorized. However, WSA equipment can be leased with O&MN/O&MNR (OPTAR) funds.

5. Reports. No special reports required. However, ship's Commanding Officers will report WSA services requested in the CSMP and report WSA services received in their normal message SITREP's for ROH, RAV, and TAV.

6. Exception. WSA preservation is not authorized for items and systems under the cognizant of NAVSEA-08.

J. H. MORRIS
Deputy

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SUSCEPTIBILITY OF 17 MACHINERY ALLOYS TO SULFIDE-INDUCED CORROSION IN SEAWATER

by

Harvey P. Hack

Approved for public release, distribution unlimited.

SHIP MATERIALS ENGINEERING DEPARTMENT
RESEARCH AND DEVELOPMENT REPORT

September 1979 DTNSRDC/SME-79/56

SUSCEPTIBILITY OF 17 MACHINERY ALLOYS TO SULFIDE-INDUCED CORROSION IN SEAWATER

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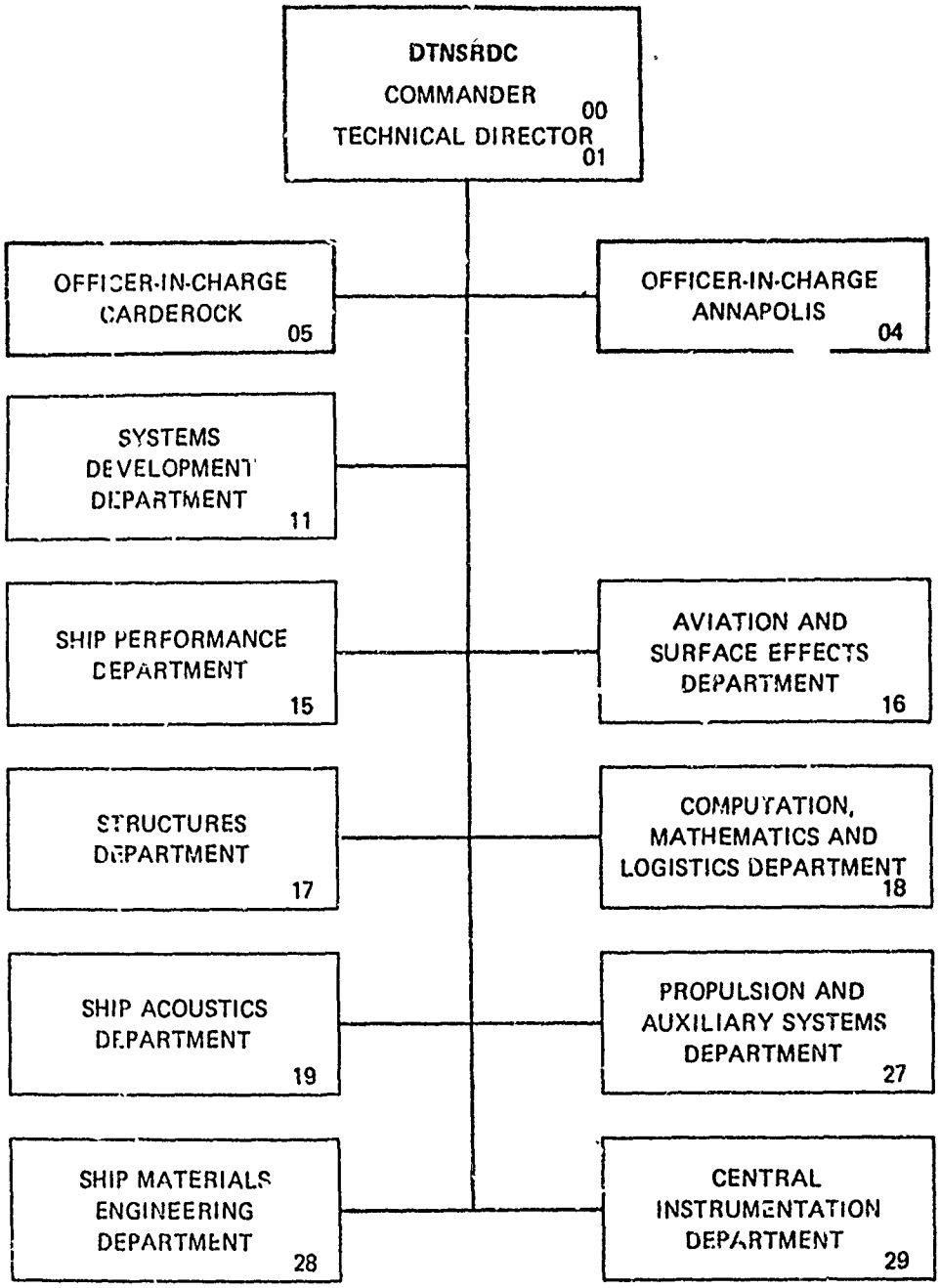

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Copper-Nickel
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Bronze
316 Stainless Steel

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

Corrosion exposures were conducted on 17 Naval machinery alloys in seawater containing sulfide pollutants. Sulfide concentrations of 0, 0.01, 0.05 and 0.02 milligrams per liter with exposure durations of 30, 60 and 120 days were used. Flow velocity was 2.4 metres per second. Minor alloy variations, such as the difference between cast and wrought nickel-copper, sometimes made large differences in corrosion behavior in sulfide-containing seawater.

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Sulfide-modified corrosion product films were generally black and loosely adherent. All alloys tested except 316 stainless steel were susceptible to sulfide-induced corrosion, usually at the 0.01 milligrams per liter sulfide level.

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LIST OF ABBREVIATIONS

mg/l	Milligram per liter
mm	Millimetre
m/s	Metre per second
MSWTL	Main seawater test loop
rms	Root mean square
µm/y	Micrometre per year

ABSTRACT

Corrosion exposures were conducted on 17 Naval machinery alloys in seawater containing sulfide pollutants. Sulfide concentrations of 0, 0.01, 0.05 and 0.2 milligrams per liter with exposure durations of 30, 60 and 120 days were used. Flow velocity was 2.4 metres per second. Minor alloy variations, such as the difference between cast and wrought nickel-copper, sometimes made large differences in corrosion behavior in sulfide-containing seawater. Sulfide-modified corrosion product films were generally black and loosely adherent. All alloys tested except 316 stainless steel were susceptible to sulfide-induced corrosion, usually at the 0.01 milligram per liter sulfide level.

ADMINISTRATIVE INFORMATION

This work was funded under the Submarine Materials Block Program (Program Element PE 62761N, Task Area SF 54-500-591) sponsored by Dr. H.H. Vanderveldt of the Naval Sea Systems Command (SEA 05R). It is a part of the machinery corrosion task (Work Unit 2803-149-40).

INTRODUCTION

The occurrence of accelerated corrosion of copper-nickel alloys and brass exposed to flowing seawater containing sulfide pollutants has been of concern to both the Navy[1,2*] and to industry.[3-5] Most experimental studies in the past have been directed toward defining the corrosion behavior of copper-nickel alloys in sulfide-containing seawater[6-10] although one paper also addressed the corrosion of nickel-copper.[1] It is of interest to the Navy to determine whether other machinery alloys, particularly those containing large amounts of copper, are susceptible to sulfide-induced corrosion and to what extent. Therefore, a study was undertaken to quantify the sulfide-induced corrosion of 17 machinery alloys presently used or proposed for use in seawater systems of Naval ships.

*A list of references is given on page 51.

MATERIAL

Seventeen different materials which have been used or are proposed for use in seawater systems were obtained. These materials are listed in Table 1 along with their product forms. Blanks were cut from these materials and machined to 19 x 138 mm* x thickness, with the thickness as indicated in Table 1. All surfaces were ground to a 32 rms finish. The chemical composition of all materials tested in listed in Table 2.

TABLE 1 - TEST MATERIALS, PRODUCT FORMS AND SPECIMEN THICKNESS

Material	Form	SAE/ASTM Unified Numbering System	DTNSRDC Code	Specimen Thickness mm
Ni-Al Bronze	Forged Disc	C63200	FLA	3.2
Ni-Al Bronze	Cast Plate	C95800	FHE	3.2
Mn-Ni-Al Bronze	Cast Bar	C95700	EEU	1.6
Mn Bronze	Propeller	C86500	EMD	1.6
Bronze Comp M	Cast Bar	C92200	ECZ	1.6
Bronze Comp G	Cast Bar	C90300	ECY	1.6
90/10 Cu-Ni	Rolled Sheet	C70600	001GS	1.6
90/10 Cu-Ni + Sn	Rolled Sheet	-	DV	1.6
70/30 Cu-Ni	Rolled Sheet	C71500	702°A	1.6
70/30 Cu-Ni + Cr	Rolled Plate	C71900	EUH	3.2
Monel 400	Rolled Plate	N04400	M	1.6
Monel 411	Cast Plate	-	DZA	1.6
K-Monel	Forged Bar	N05500	K	1.6
316 Stainless Steel	Rolled Sheet	S31600	EVJ	1.6
Al-Bronze D	Pipe*	C61400	P	3.2
P Bronze + 5% Sn	Rolled Sheet	C51000	FV	1.6
P Bronze + 10% Sn	Rolled Sheet	C52400	TN	1.6

*Cut into quarters and flattened before machining.

*A list of abbreviations is given on page viii.

TABLE 2 - COMPOSITIONS OF TEST MATERIALS, WEIGHT PERCENT

	Wrought Ni-Al Bronze	Cast Ni-Al-Bronze	Mn Ni-Al-Bronze	Mn Bronze	Bronze Comp M	Bronze Comp G	90-10 Cu-Ni	90-10 Cu-Ni +S	70-Cu Cu-Ni	70-30 Cu-Ni +Cr	Wrought Monel	Cast Monel	Monel K-500	316 SS	Al Bronze D	Phos Bronze +5% Sn	Phos Bronze +10% Sn
Cu	80.0	81.8	72.8	55.4	87.5	86.5	88.6	82.7	68.5	58.7	30.8	26.2	28.0		90.6	85.6	Bal
Fe	3.90	3.74	2.83	0.86	0.09	0.04	1.06	0.04	0.50	0.05	1.47	0 77	1.01	Bal	2.77	0.01	0.01
Mn	1.50	1.09	13.3	0.82	-	-	0.37	0.08	0.74	0.89	0.85	0.93	0.71	1.75	0.06	-	-
Ni	4.81	4.73	2.18	-	0.53	0.49	9.63	9.30	30.07	29.95	66.7	54.3	65.2	12.9	-	-	-
P	-	-	-	-	0.003	0.010	0.011	0.000	0.009	0.026	-	-	-	-	0.000	0.048	0.112
Pb	0.00	0.00	0.00	0.33	-	0.21	0.01	0.01	0.01	0.01	-	-	-	-	0.00	0.01	0.01
S	-	-	-	-	-	-	0.007	0.007	0.014	0.007	0.02	0.002	0.00	0.02	-	-	-
Sn	-	-	-	0.7	5.86	8.2	-	7.7	-	-	-	-	-	-	-	4.2	9.71
Zn	-	-	-	40.9	3.32	4.47	0.33	0.01	0.02	-	-	-	-	-	0.05	0.05	0.16
Al	9.06	8.72	7.94	0.78	-	-	-	-	-	-	-	-	-	-	6.62	-	-
C	-	-	-	-	-	-	-	-	-	0.013	0.10	0.13	0.18	0.05	-	-	-
Si	0.08	0.09	0.04	-	-	-	-	-	-	0.06	0.07	1.49	0.00	0.71	-	-	-
Ti	-	-	-	-	-	-	-	-	-	0.02	-	-	-	-	-	-	-
Zr	-	-	-	-	-	-	-	-	-	0.16	-	-	-	-	-	-	-
Cr	-	-	-	-	-	-	-	-	-	2.85	-	-	-	17.8	-	-	-
Others	-	-	-	-	-	-	-	-	-	-	-	1.7 Cb	1.6 Cb	2.8 Mo	-	-	-

APPARATUS

All exposures in sulfide-modified seawater were carried out in the modified seawater test loop (MSWTL) illustrated in Figure 1. Exposures of control specimens in normal seawater were carried out in the seawater test loop illustrated in Figure 2. Both loops were located at the F.L. LaQue Corrosion Laboratory at Wrightsville Beach, North Carolina. They both were nonrecirculating loops made of nominal 2-in. polyvinyl chloride pipe with removable sections for housing sample holders and taps for sampling water near each removable section. The modified seawater loop was fitted with a series of injection pumps for adding controlled amounts of sodium sulfide and chlorine generator units at the exits to oxidize any remaining sulfide before discharge. Each removable pipe section housed three cylindrical Delrin specimen holders. Each holder had a square slotted hole through its length which supported four or eight specimens (depending on thickness) parallel to each other and to the water flow. The specimen edges were not tapered so that some turbulence would be generated at the leading edges. Various sulfide ion levels were established in each test section independently by means of the injection pumps.

EXPERIMENTAL PROCEDURE

Exposures of duplicate specimens of each material were conducted in seawater containing sulfide concentrations of 0, 0.01, 0.05 and 0.2 mg/l. Exposure durations were 30, 60 or 120 days for all sulfide levels except 0.2 mg/l, which was run for only 30 days. Due to limited material certain materials were not tested at all sulfide concentration/duration combinations. These exceptions are noted in the "Results and Discussion" section of this report on a case-by-case basis.

Sulfide concentrations were measured daily using the p-phenylenediamine colorimetric technique with a turbidity correction. Water temperature was monitored and flow velocity was maintained at 2.4 m/s. Ambient sulfide concentrations in the seawater entering the MSWTL were less than 0.001 mg/l. No detectable pH shift was noted during injection of either constituent. Dissolved oxygen content of seawater entering the MSWTL ranged from 5 to 9 mg/l.

After exposure, corrosion rate and maximum thickness loss data were obtained by weight loss and pit depth measurements, respectively. Reported average corrosion rate is an average of the rates of duplicate specimens. Reported maximum depth of attack is the deepest pit found on the two specimens.

RESULTS AND DISCUSSION

Results of the exposures are tabulated in Table 3. Since the relative performance of the alloys was usually a function of sulfide concentration and exposure duration, no attempt will be made to compare the alloys except in a few instances where the comparisons held true throughout the exposure regime. The alloys will be discussed in groups according to type.

In evaluating the data presented in Figures 3-36 it should be noted that corrosion rate data is normalized with respect to time. The usual behavior of copper-base alloys is a parabolic decrease in corrosion rate with increasing time. Thus, steady or increasing rates can be considered as acceleration of the usual process of corrosion. The normalizing process, although assuming linearity of corrosion rate, is a standard design practice. Conversely, maximum depth of attack data is not normalized with respect to time. This data would therefore be expected to remain steady if no additional localized attack were occurring, or would increase at a rate proportional to the additional attack.

CAST AND WROUGHT Ni-Al BRONZES

Results of the exposures of wrought nickel-aluminum bronze are presented in Figure 3, while the specimens are shown in Figure 4. With no sulfide present, corrosion rate decreases and the depth of attack data increases only slightly with increasing exposure time. The addition of as little as 0.01 mg/l sulfide causes an increase in corrosion rate after 60-days exposure and large increases in the depth of attack with increasing exposure times of 60 days or longer. This is an indication of sulfide corrosion susceptibility after 60-days exposure at even this low sulfide level. A sulfide concentration of 0.05 mg/l was sufficient to cause large increases in corrosion rate, which did not decrease with time. Also, deep localized attack occurred earlier at this concentration. When 0.2 mg/l

TABLE 3 - RESULTS OF SULFIDE EXPOSURES

Alloy	30-Days Exposure							
	0.0 mg/l		0.01 mg/l		0.05 mg/l		0.2 mg/l	
	Corrosion Rate µm/yr	Depth of Attack mm	Corrosion Rate µm/yr	Depth of Attack mm	Corrosion Rate µm/yr	Depth of Attack mm	Corrosion Rate µm/yr	Depth of Attack mm
Ni-Al-Bronze(Wrought)	157.8	0.11	122.5	0.09	572.6	0.42	1668.1	0.96
Ni-Al-Bronze(Cast)	158.0	0.10					1654.0	1.27
Mn-Ni-Al-Bronze(Cast)	41.0	0.09	76.3	0.24	251.2	0.27	484.1	0.20
Mn Bronze	140.6	0.31	195.5	0.32	445.4	0.30	803.9	0.26
Bronze Comp M	129.8	0.13	253.2	0.22	291.8	0.40	1037.0	1.01
Bronze Comp G	95.9	0.07	196.5	0.21	375.2	0.47	1694.2	0.50
90-10	95.9	0.09	170.1	0.18	231.3	0.25	664.0	0.58
90-10 + Sn	74.9	0.05					558.8	0.29
70-30	207.9	0.12	214.5	0.38	467.0	0.78	836.9	1.02
70-30 + Cr(CA719)	84.9	0.06	175.6	0.36	587.5	0.41	1480.3	0.53
Monel 411(Cast)	6.7	0.07	257.0	0.22	865.5	0.39	1362.5	0.27
Monel 400(Wrought)	2.5	0.04	14.4	0.05	10.6	0.15	59.7	0.18
K-Monel	1.7	0.07	3.3	0.16	3.4	0.20	41.2	0.29
316 Stainless Steel	0	0	0	0	0.2	0	0.7	0
Al-Bronze D	184.3	0.09	181.4	0.28	300.2	0.46	1314.2	1.13
Ph-Bronze + 5% Sn	70.6	0.08	286.6	0.15	415.5	0.23	629.5	0.41
Ph-Bronze + 10% Sn	75.5	0.06	279.1	0.17	265.7	0.28	409.0	0.30

TABLE 3 (Continued)

Alloy	60-Days Exposure						120-Days Exposure					
	0.0 mg/l		0.01 mg/l		0.05 mg/l		0.0 mg/l		0.01 mg/l		0.05 mg/l	
	Corrosion Rate µm/yr	Depth of Attack mm	Corrosion Rate µm/yr	Depth of Attack mm	Corrosion Rate µm/yr	Depth of Attack mm	Corrosion Rate µm/yr	Depth of Attack mm	Corrosion Rate µm/yr	Depth of Attack mm	Corrosion Rate µm/yr	Depth of Attack mm
Ni-Al-Bronze(Wrought)	130.4	0.10	241.2	0.49	602.4	1.23	106.3	0.24	202.3	1.27	517.1	1.17
Ni-Al-Bronze(Cast)							101.0	0.51	223.4	1.12	381.1	1.39
Mn-Ni-Al-Bronze(Cast)	16.9	0.09	53.6	0.15	179.4	0.42	18.1	0.08 (0.94)	27.7	0.10	84.1	0.37
Mn Bronze	144.6	0.63	119.2	0.56	483.2	0.82	87.6	1.06	91.7	0.67	301.9	0.64
Bronze Comp M	152.0	0.20	212.2	0.69	363.1	0.76	160.6	0.49	185.2	0.66	351.6	1.18
Bronze Comp G	95.4	0.13	230.5	0.36	436.4	0.79	124.1	0.52	205.2	Perf	474.7	Perf
90-10	96.5	0.14	174.4	0.39	221.2	0.50	91.9	0.24	126.6	0.56	268.7	1.20
90-10 + Sn							79.0	0.12	143.8	0.39	220.2	0.86
70-30	209.9	0.32	245.2	0.80	517.7	1.25	190.0	0.39	137.9	0.55	569.2	1.49
70-30 + Cr(CA719)	68.8	0.06	258.5	0.45	640.6	0.68	53.1	0.28	302.2	0.87	610.7	1.74
Monel 411(Cast)	11.3	0.19	298.3	0.55	678.1	0.67	10.0	0.52	344.5	1.08	839.8	Perf
Monel 400(Wrought)	3.4	0.10	14.1	0.21	23.1	0.28	2.8	0.40	25.9	0.49	44.7	0.44
K-Monel	3.4	0.38	14.7	0.40	51.5	0.35	3.3	0.48	22.5	0.84	40.5	0.88
316 Stainless Steel	0.2	0	0.3	0	0.5	0	0	0	0.5	0.12	0.1	0

sulfide was added, the corrosion rate became extremely high, while very deep localized attack was evident after only 30-days exposure. In summary, susceptibility of this alloy to sulfide induced corrosion begins at exposures of 60 days with 0.01 mg/l sulfide, and the corrosion severity increases with increasing exposure time or sulfide concentration.

The cast nickel-aluminum bronze was exposed only for 30 days to 0.2 mg/l sulfide and for 120 days at lower sulfide concentrations, along with suitable controls (0 sulfide). This limited data, presented in Figure 5, and the specimen appearance in Figure 6 indicate that this material behaves similarly to the wrought version, with sulfide-induced pitting and general corrosion indicated clearly after 120 days at 0.01 mg/l sulfide.

CAST MANGANESE NICKEL-ALUMINUM BRONZE

Results of exposures of this alloy are illustrated in Figures 7 and 8. Corrosion rate increases are apparent at the 0.01 mg/l sulfide level and become greater with increasing sulfide concentration. Corrosion rates decrease with increasing exposure duration, indicating that the majority of the general corrosion occurs in the first 30 days of exposure. Increases in depth of attack data can be seen at the lowest sulfide concentration and become pronounced in the 120-day, 0.05 mg/l sulfide exposure. The great depth of attack and low corrosion rate of this specimen indicates that the attack is very localized. Thus, for manganese nickel-aluminum bronze, sulfide attack appears at the 30-day, 0.01 mg/l sulfide exposure and becomes an intense localized attack for the 120-day, 0.05 mg/l sulfide exposure.

CAST MANGANESE BRONZE

Attack of the manganese bronze specimens, illustrated in Figures 9 and 10, is not affected by 0.01 mg/l sulfide. Corrosion rate increases are apparent at 0.05 mg/l sulfide, indicating greater general corrosion. Thus, alloy begins to exhibit sulfide corrosion susceptibility at the 0.05 mg/l level, and the attack remains general even at higher sulfide concentrations.

CAST BRONZE (COMPOSITIONS M AND G)

Results of the exposures of composition M bronze are presented in Figures 11 and 12. Sulfide-induced corrosion begins at the lowest sulfide

concentration and exposure duration and increases with increasing sulfide levels. Although corrosion rates remain relatively constant with increasing exposure durations, the depths of attack become greater, indicating that the corrosion process does not taper off with time.

Bronze composition G behaves similarly to composition M, except for higher depths of attack in long-term, low concentration sulfides. This can be seen in Figures 13 and 14. Thus, this alloy also is susceptible to sulfide attack, starting at 30 days at 0.01 mg/l sulfide and increasing with increasing exposure duration or sulfide concentration.

WROUGHT COPPER-NICKELS

Exposure results of 90-10 copper-nickel, presented in Figures 15 and 16, indicate that both corrosion rate and maximum depth of attack increase with increasing sulfide concentration. The effect is noticeable even at 0.01-mg/l sulfide. Corrosion rates remained constant with exposure duration, and the depth of attack increased in proportion to exposure duration, which indicates a rate of penetration that was constant with time. Corrosion appeared fairly uniform. This is in contrast with earlier data, where 90-10 copper-nickel experienced much more intense, localized pitting attack.[1,10,11] However, susceptibility to sulfide-induced corrosion at sulfide levels as low as 0.01 mg/l was found in both instances.

Adding about 6% tin to 90-10 copper nickel decreased slightly the depths of attack but otherwise did not significantly affect the alloy's performance in sulfide. This can be seen in Figures 17 and 18. The 70-30 copper-nickel performed similarly to 90-10 copper-nickel, except for generally slightly higher corrosion rates and depths of attack, as seen in Figure 19. Previous experiments with these alloys had shown greater corrosion of the 90-10 copper-nickel in sulfide-containing seawater.[1,10,11] These differences may be due in part to temperature variations at the test site. The 70-30 copper-nickel also experienced localized corrosion at the crevices along the specimen edges created by the specimen holder, as seen in Figure 20. Thus, 70-30 copper-nickel experienced more corrosion and more localization of corrosion in these exposures than did 90-10 copper-nickel.

Additions of chromium to wrought 70-30 copper-nickel had little effect on its corrosion in low-sulfide environments but had a tendency to increase localized attack in high-sulfide environments (Figures 21 and 22). Overall susceptibility to sulfide-induced corrosion was present.

CAST AND WROUGHT NICKEL-COPPERS

Corrosion of wrought nickel-copper was lower than most alloys in the test. As seen in Figure 23, the corrosion rates and maximum depths of attack increased with increasing sulfide concentration or duration. The effect was noticeable even in the 30-day, 0.01-mg/l sulfide exposure. Corrosion tended to take the form of pitting, as seen in Figure 24. Although the amount of corrosion of this alloy was low, the factor of increase in corrosion of specimens exposed to sulfide over the controls was large.

Although the corrosion rate of cast nickel-copper without sulfide was similar to its wrought analog (Figure 25) and the maximum depth of attack was slightly greater than wrought material, behavior of cast material in sulfide was much different than that of the wrought alloy. Corrosion rates and depths of attack of cast material in sulfide were several orders of magnitude greater than those for wrought material. Thus, cast nickel-copper was the material most susceptible to sulfide attack in these tests, on the basis of its factor of increase in corrosion over control specimens. Generally, attack took the form of uniform etching, as seen in Figure 26. A comparison of Figure 26 with Figure 24 shows the difference in behavior of cast and wrought material.

Nickel-copper alloy K-500 (a wrought material) behaved similarly to wrought nickel-copper, with the exception of slightly greater depths of attack. This can be seen in Figures 27 and 28. The depths of attack of control specimens were also large; thus, the effect of sulfide concentration on this parameter was small.

Corrosion rates of all nickel-copper alloys tested tended to increase with exposure duration, particularly in the presence of sulfides.

WROUGHT 316 STAINLESS STEEL

Figures 29 and 30 illustrate that 316 stainless steel did not experience significant corrosion at any sulfide concentration or exposure duration in these exposures. Under all exposure conditions, this material performed better in this study than any other material tested.

WROUGHT ALUMINUM BRONZE D

Although not presently used in ship piping or machinery systems, this alloy was included because of its proposed use for oil-water separators. Since it was a special-interest alloy, only 30-day exposures were conducted. Results of these exposures are presented in Figures 31 and 32. Accelerated corrosion is present even at the 0.01 mg/l sulfide level, and the attack increases with increasing sulfide.

WROUGHT PHOSPHOR BRONZES WITH TIN

The phosphor bronzes were also included as special-interest alloys and were exposed for only 30 days. Results of exposures of phosphor bronze with 5% tin are presented in Figures 33 and 34. Sulfide-induced corrosion susceptibility is apparent at the lowest sulfide concentration. The amount of corrosion increases with increasing sulfide.

Results of exposures of phosphor bronze with 10% tin (presented in Figures 36 and 36) indicate similar behavior to the 5% tin alloy. Thus, the additional 5% tin had little effect on the corrosion behavior of the phosphor bronze.

GALVANIC CORROSION

Although the influence of sulfide on the galvanic behavior of materials was not studied here, it has been reported[12] that significant changes in corrosion potential and galvanic corrosion behavior of some of these alloys take place when even small amounts of sulfide are present. Materials which are normally compatible may not be compatible in seawater containing even 0.01 mg/l sulfide. Therefore, possible galvanic interactions, as well as susceptibility to general corrosion and localized attack, should be reappraised when considering material performance in seawater, if the presence of sulfide is suspected.

CORROSION PRODUCT FILMS

Many of the copper-based alloys exhibited coppery-colored, brown, or reddish-brown corrosion product films in seawater without sulfide. Exceptions to this were cast nickel-aluminum bronze, 90-10 Cu-Ni, 70-30 Cu-Ni with Cr, and aluminum bronze D. These alloys exhibited black corrosion product films.

All of the copper-bearing alloys displayed black corrosion product films when exposed to sulfide. These films were usually evident at the lowest sulfide concentration and shortest time and tended to increase in thickness with increasing sulfide exposure. These films were generally loosely adherent. The exception to this behavior was phosphor bronze with 5% tin. Although no black film was present on these specimens, there was evidence that a black film had once existed but had been stripped away by the flow. Portions of this film remained in crevice areas caused by specimen identification markings or the specimen holder.

The stainless steel specimens did not display any corrosion product film except at the 0.2 mg/l sulfide level where a black film was evident.

CONCLUSIONS

All alloys tested, except 316 stainless steel, were susceptible to sulfide-induced corrosion in seawater at the 0.05 mg/l sulfide level, and most were susceptible at the 0.01 mg/l level.

Minor variations within an alloy class such as the difference between cast and wrought nickel-copper can make very large differences in corrosion behavior in sulfide-containing seawater, with the observed corrosion rates being several orders of magnitude higher for the former.

In seawater, the copper alloy corrosion product films were brown or black depending on the alloy. Films in sulfide containing seawater were always black and loosely adherent.

Selection of an alloy for seawater service should involve consideration of the amount of sulfide pollution likely to be encountered.

ACKNOWLEDGEMENT

The author gratefully acknowledges the assistance of Mr. T.S. Lee of the Francis L. LaQue Corrosion Laboratory in Wrightsville Beach, North Carolina, in the design and conduct of these exposures.

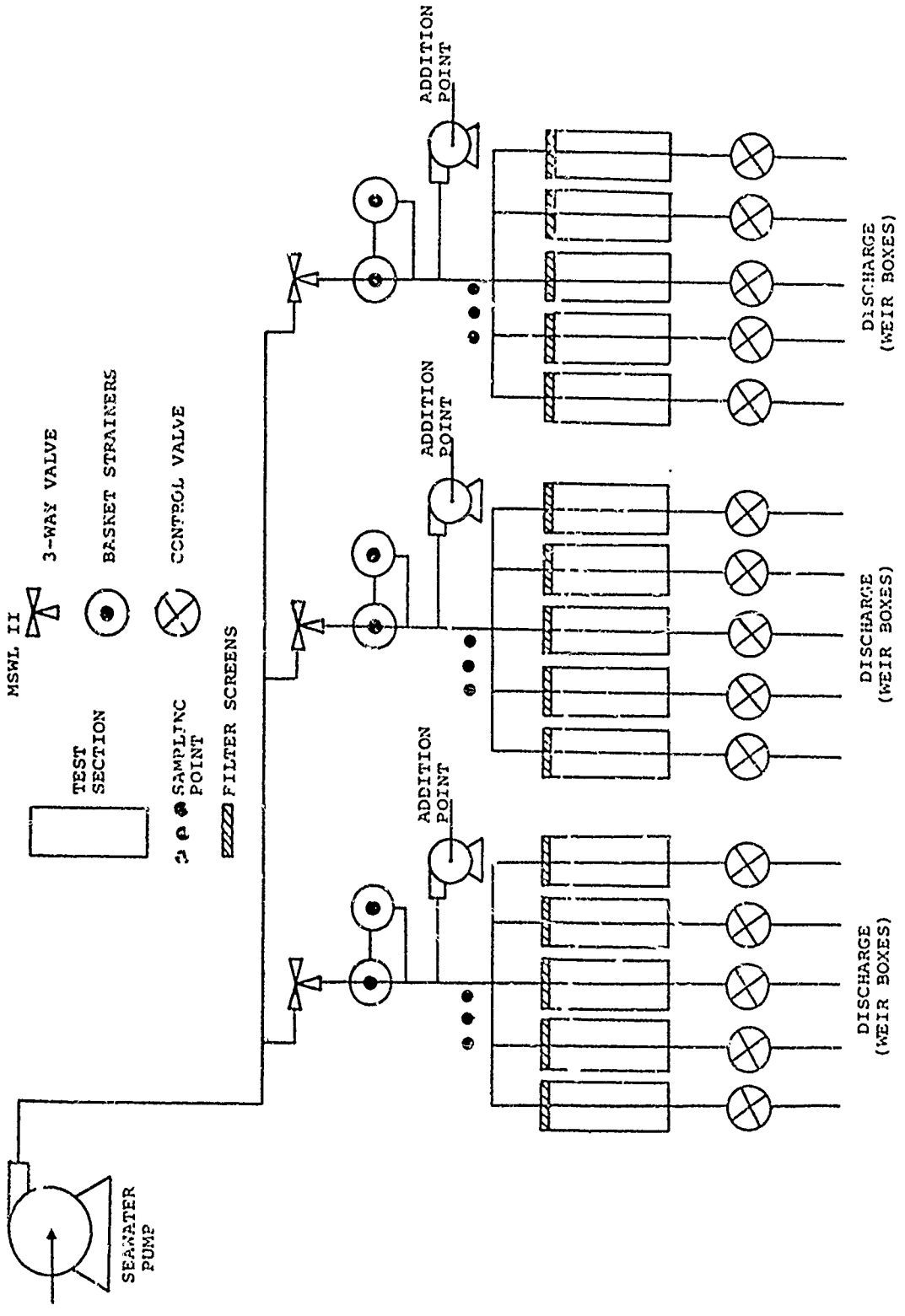


Figure 1 - Modified Seawater Test Loop

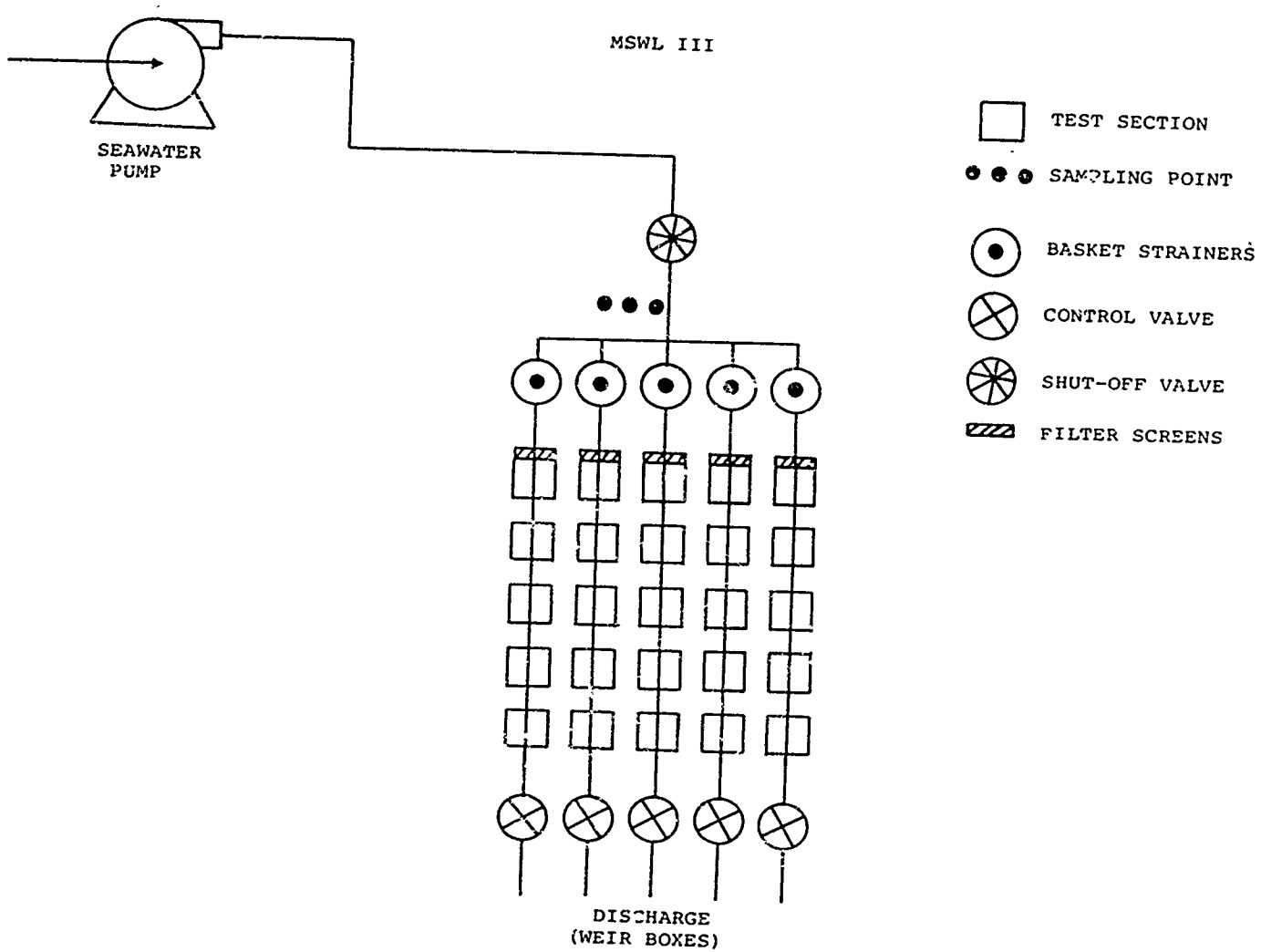


Figure 2 - Seawater Test Loop for Control Specimens

AFWAL-TR-81-4019

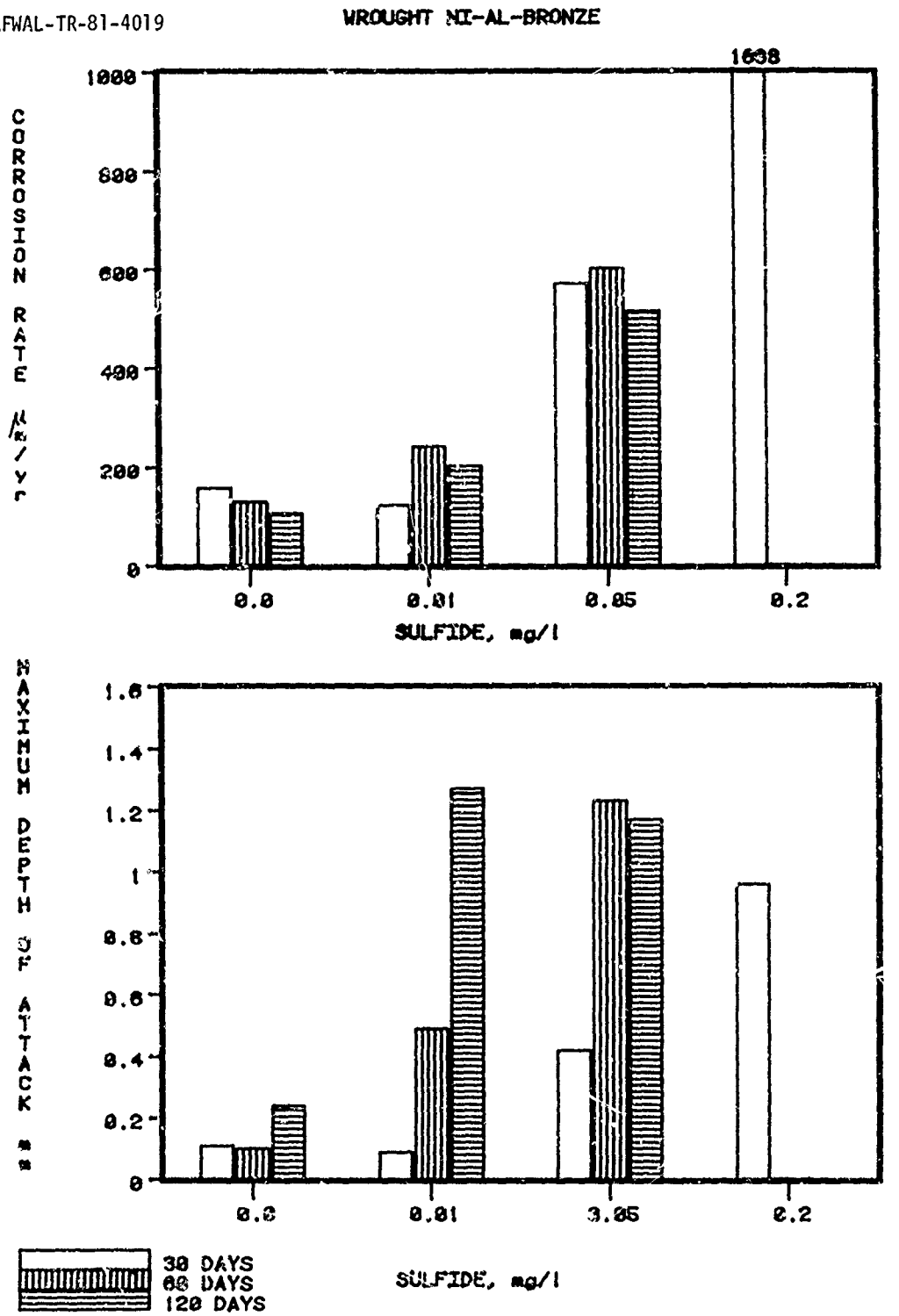


Figure 3. Corrosion of Wrought Ni-Al Bronze in Sulfide-Containing Seawater

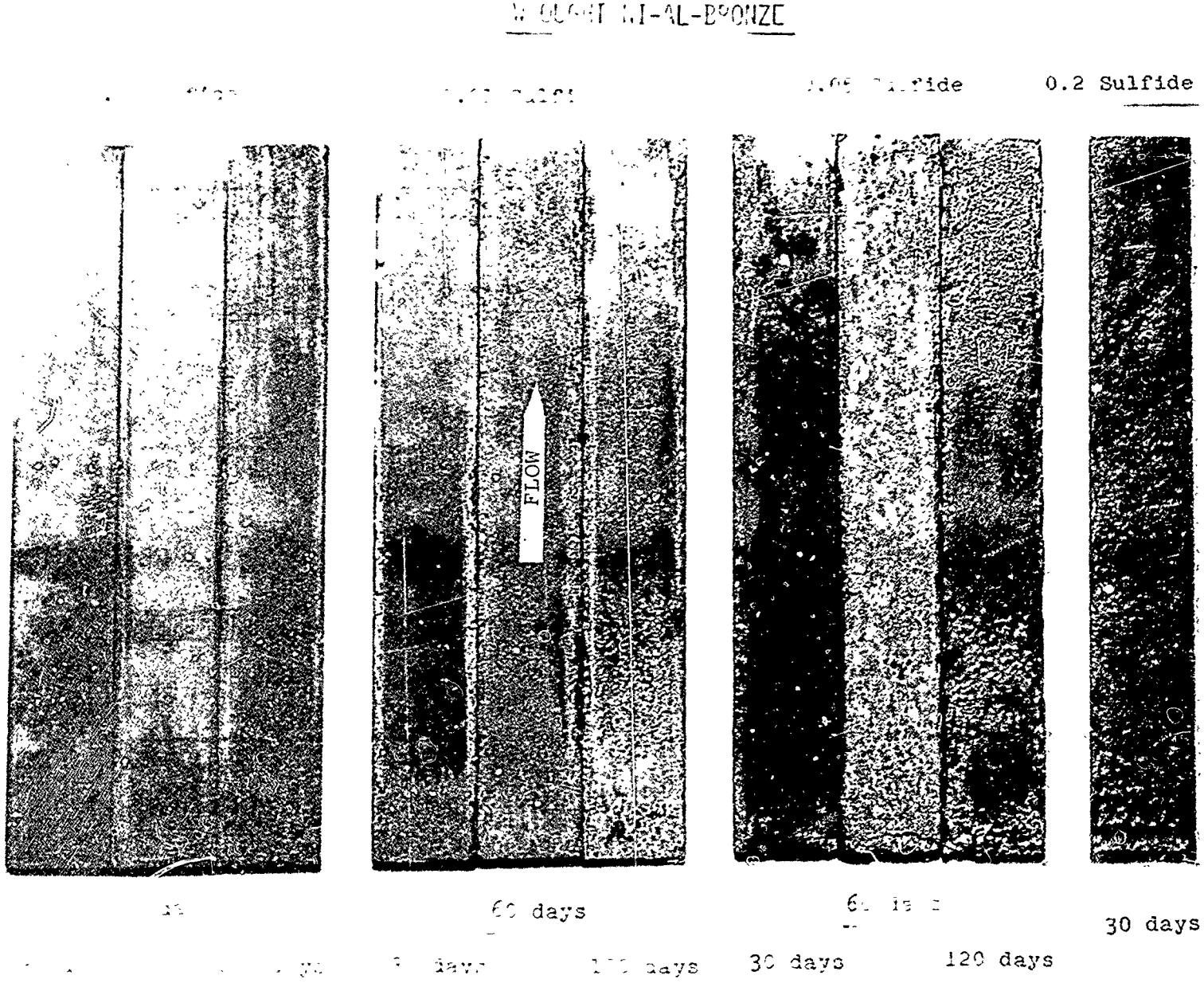
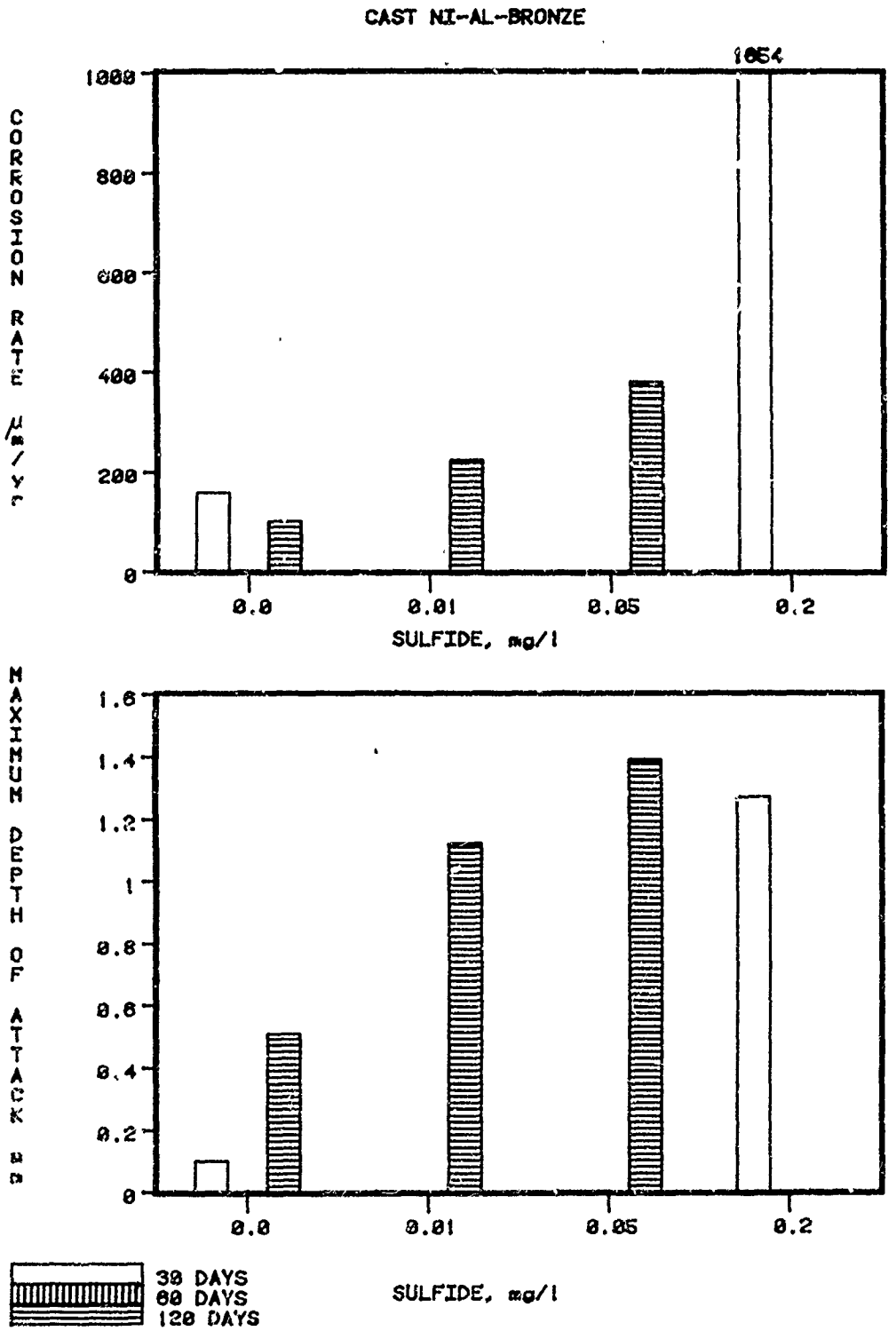


Figure 4. SME-79/56


CAST NI-AL-BRONZE
1054
CORROSION RATE µm/yr
1000
800
600
400
200
0
0.0
0.01
0.05
0.2
SULFIDE, mg/l
MAXIMUM DEPTH OF ATTACK µm
1.6
1.4
1.2
1
0.8
0.6
0.4
0.2
0
0.0
0.01
0.05
0.2
SULFIDE, mg/l
30 DAYS
60 DAYS
120 DAYS

CAST NI-AL-BRONZE

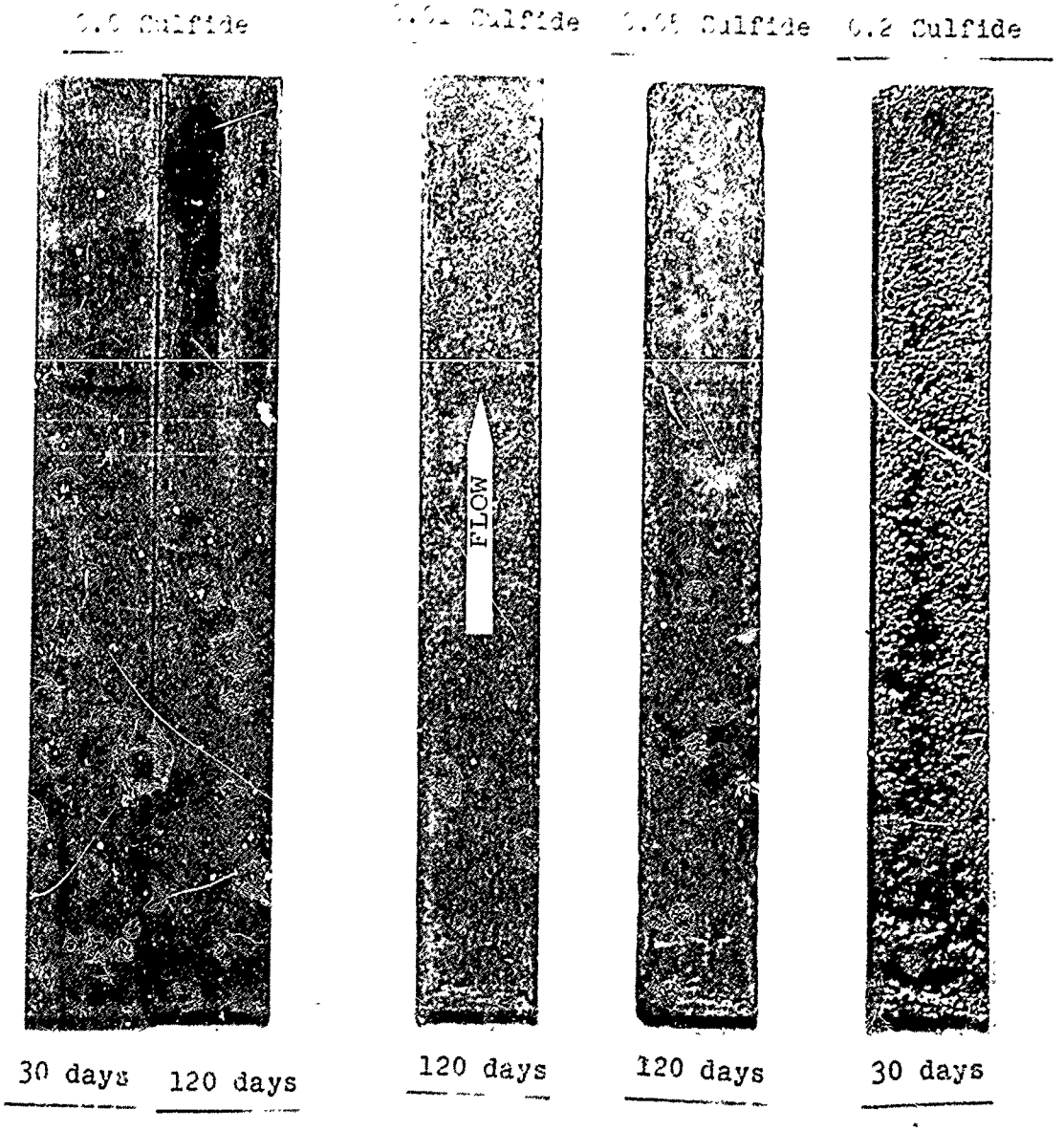
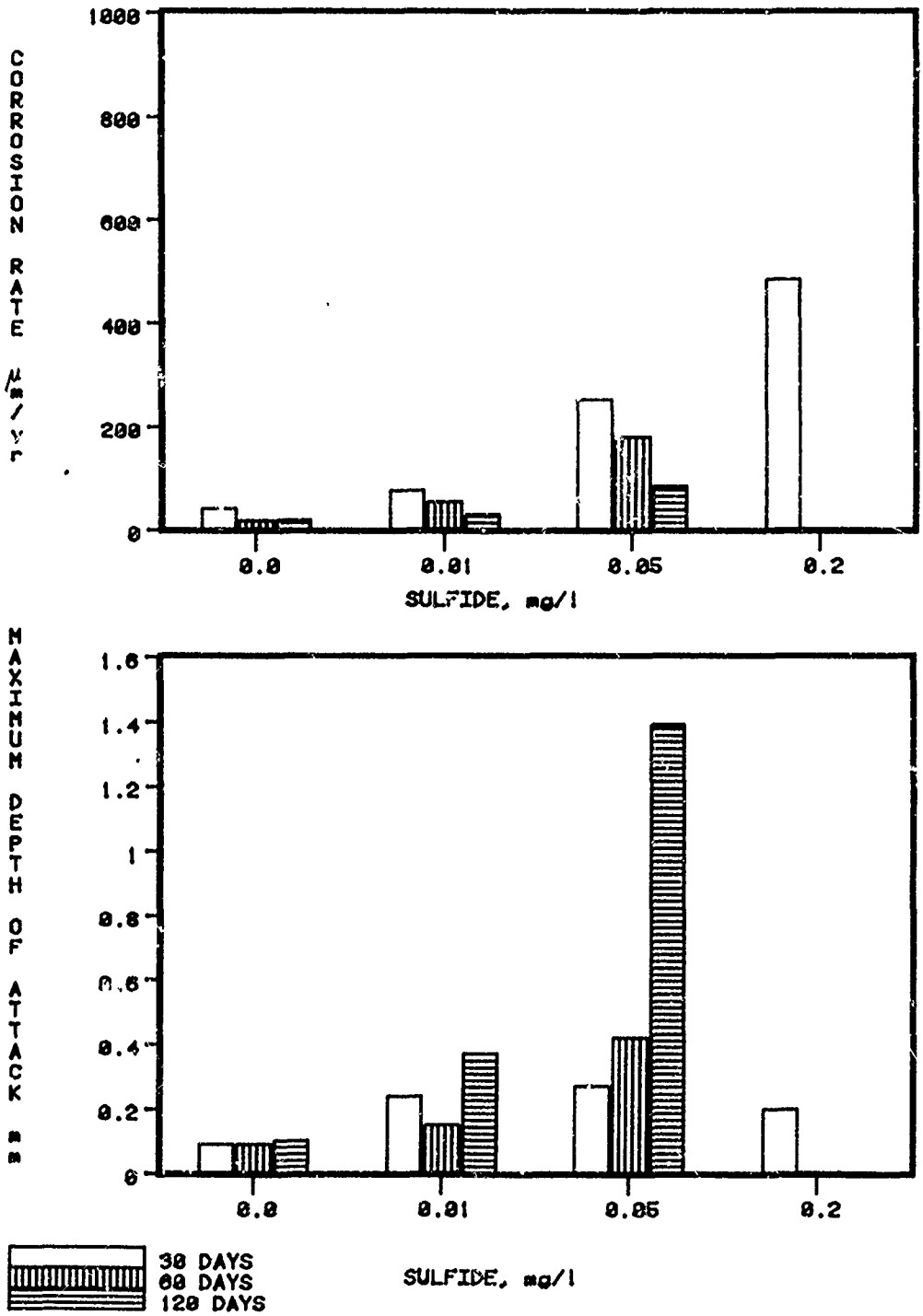


Figure 6. SME-79/56

MANGANESE NI-AL BRONZE



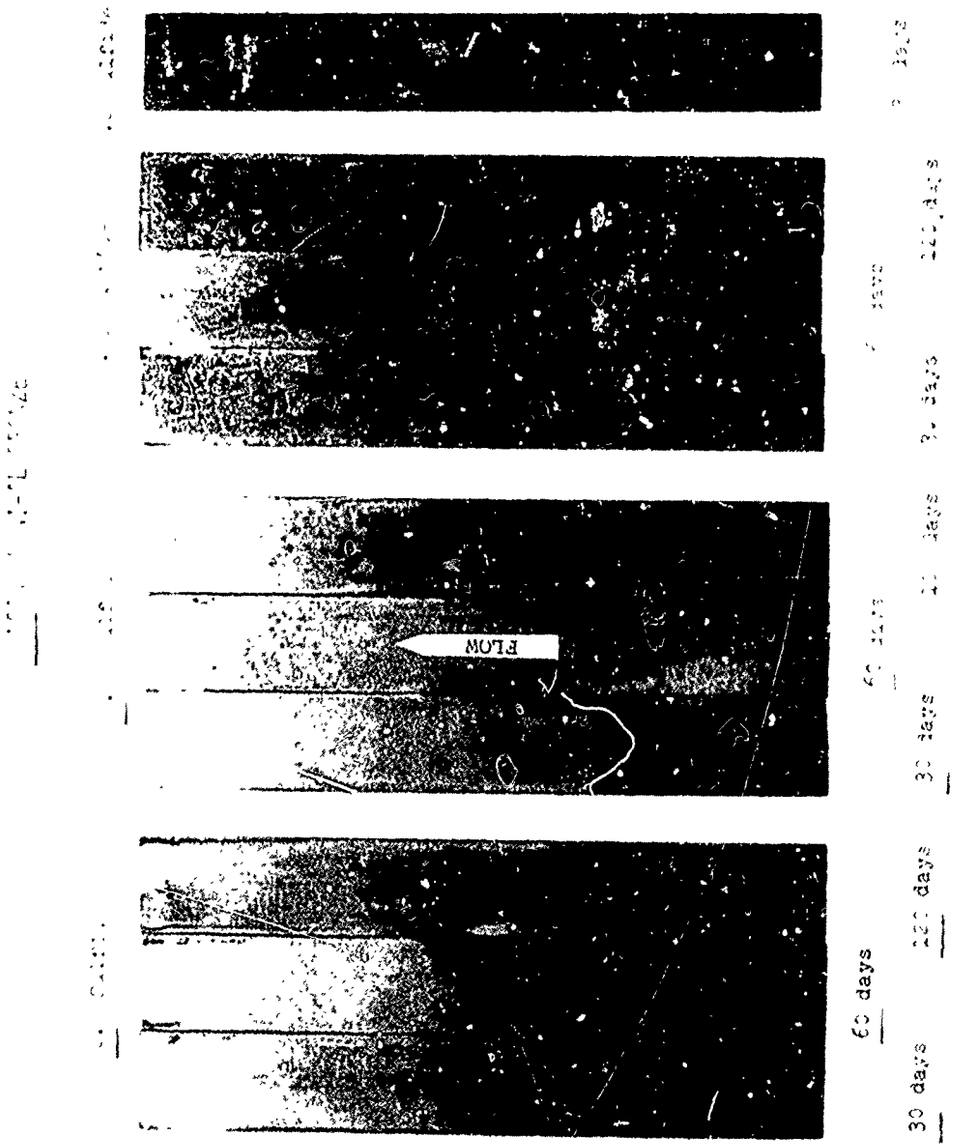
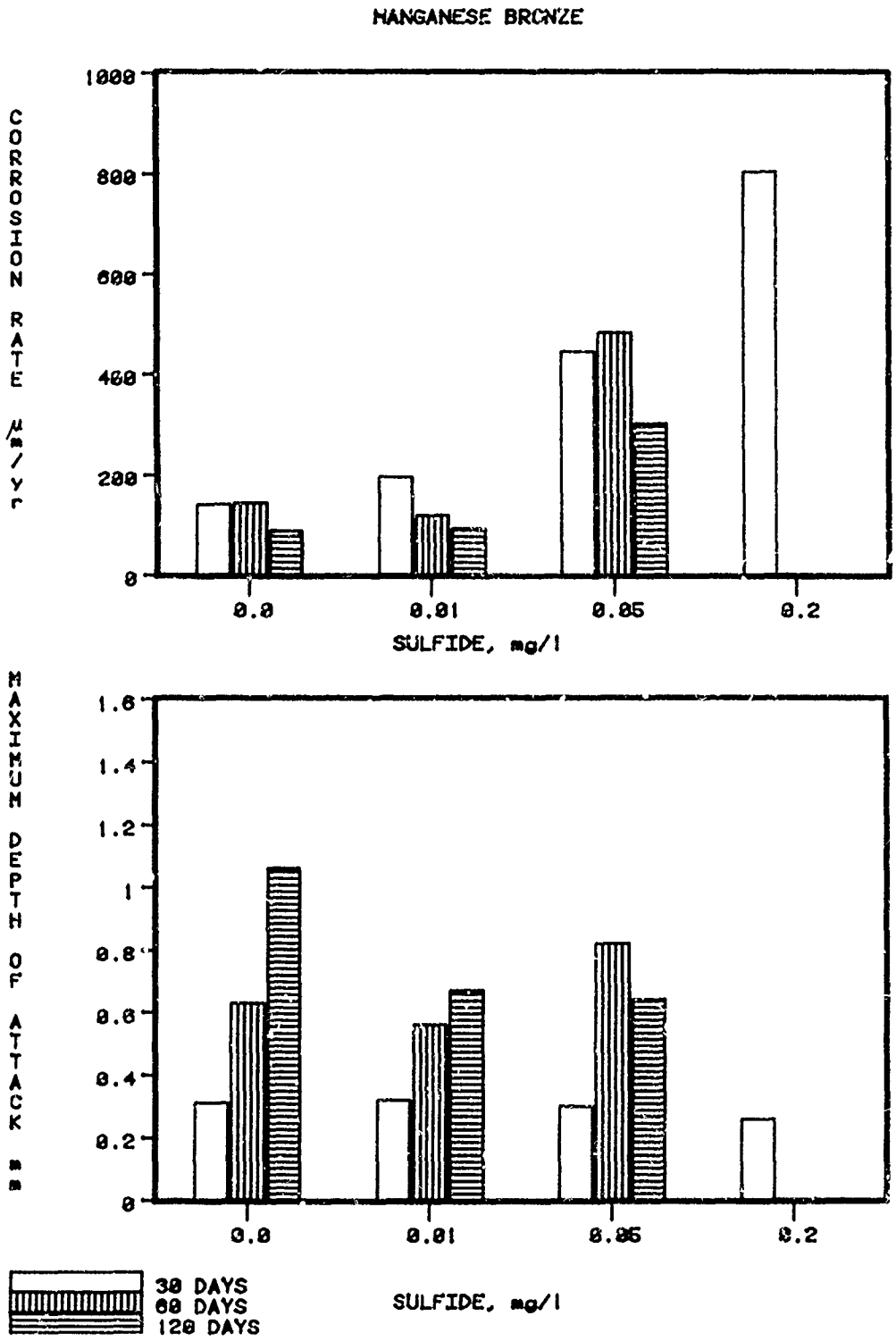


Figure 8. SME 79/56


MANGANESE BRONZE
CORROSION RATE MM/YR
1000
800
600
400
200
0
0.0
0.01
0.05
0.2
SULFIDE, mg/l
MAXIMUM DEPTH OF ATTACK mm
1.6
1.4
1.2
1
0.8
0.6
0.4
0.2
0
0.0
0.01
0.05
0.2
SULFIDE, mg/l
30 DAYS
60 DAYS
120 DAYS

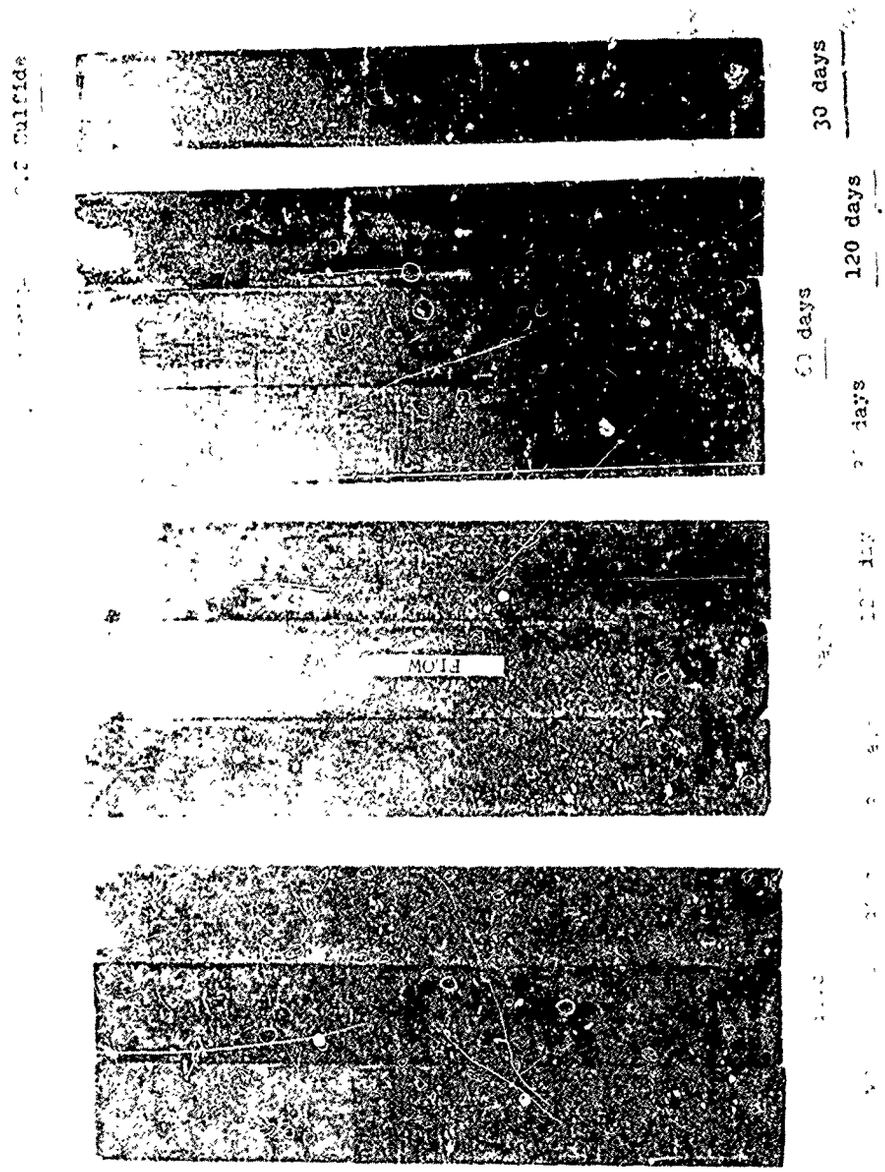
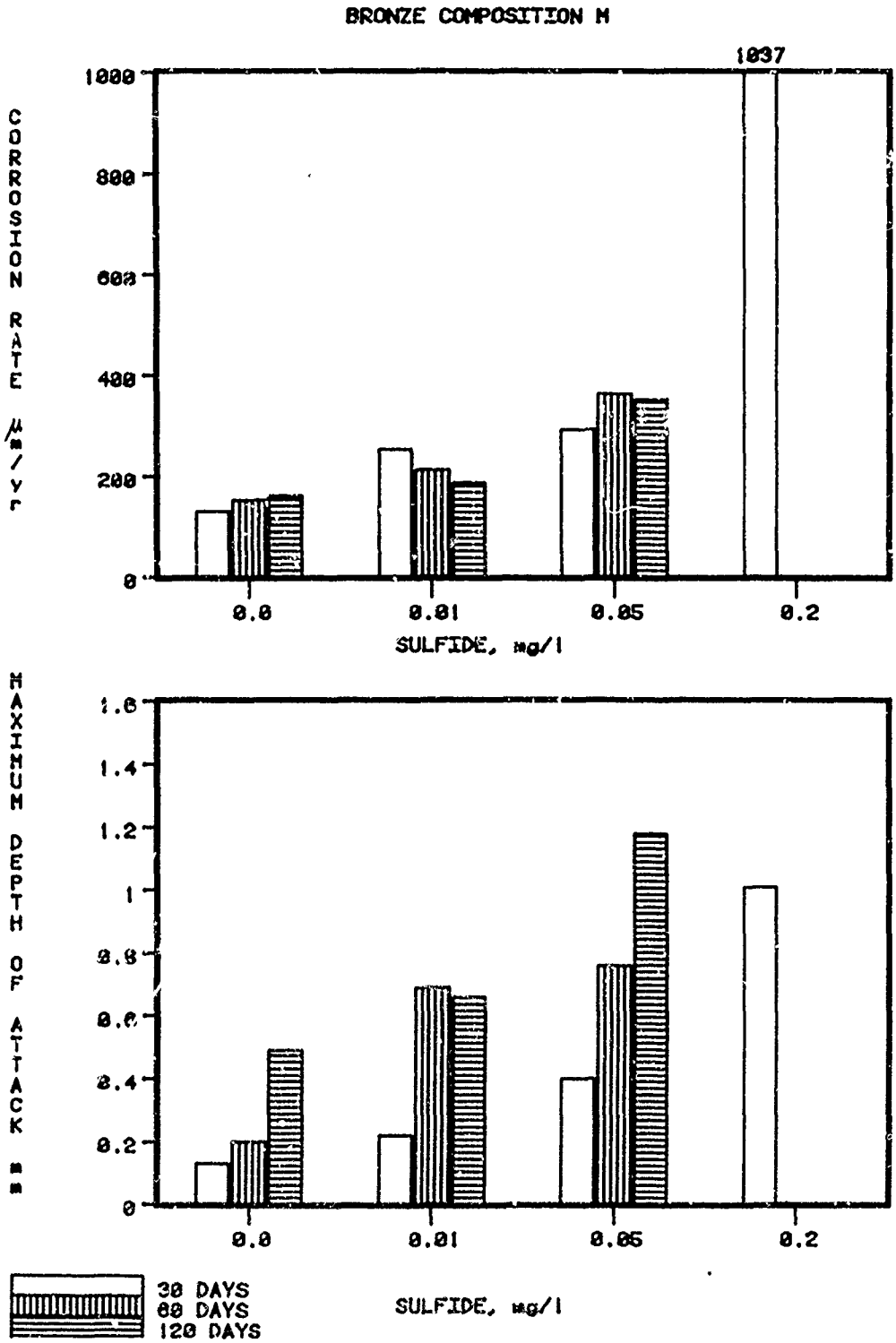


Figure 10. SME 79/56


BRONZE COMPOSITION M
1037
1000
800
600
400
200
0
CORROSION RATE MM/YR
0.0
0.01
0.05
0.2
SULFIDE, mg/l
MAXIMUM DEPTH OF ATTACK MM
1.6
1.4
1.2
1
0.8
0.6
0.4
0.2
0
0.0
0.01
0.05
0.2
SULFIDE, mg/l
30 DAYS
60 DAYS
120 DAYS

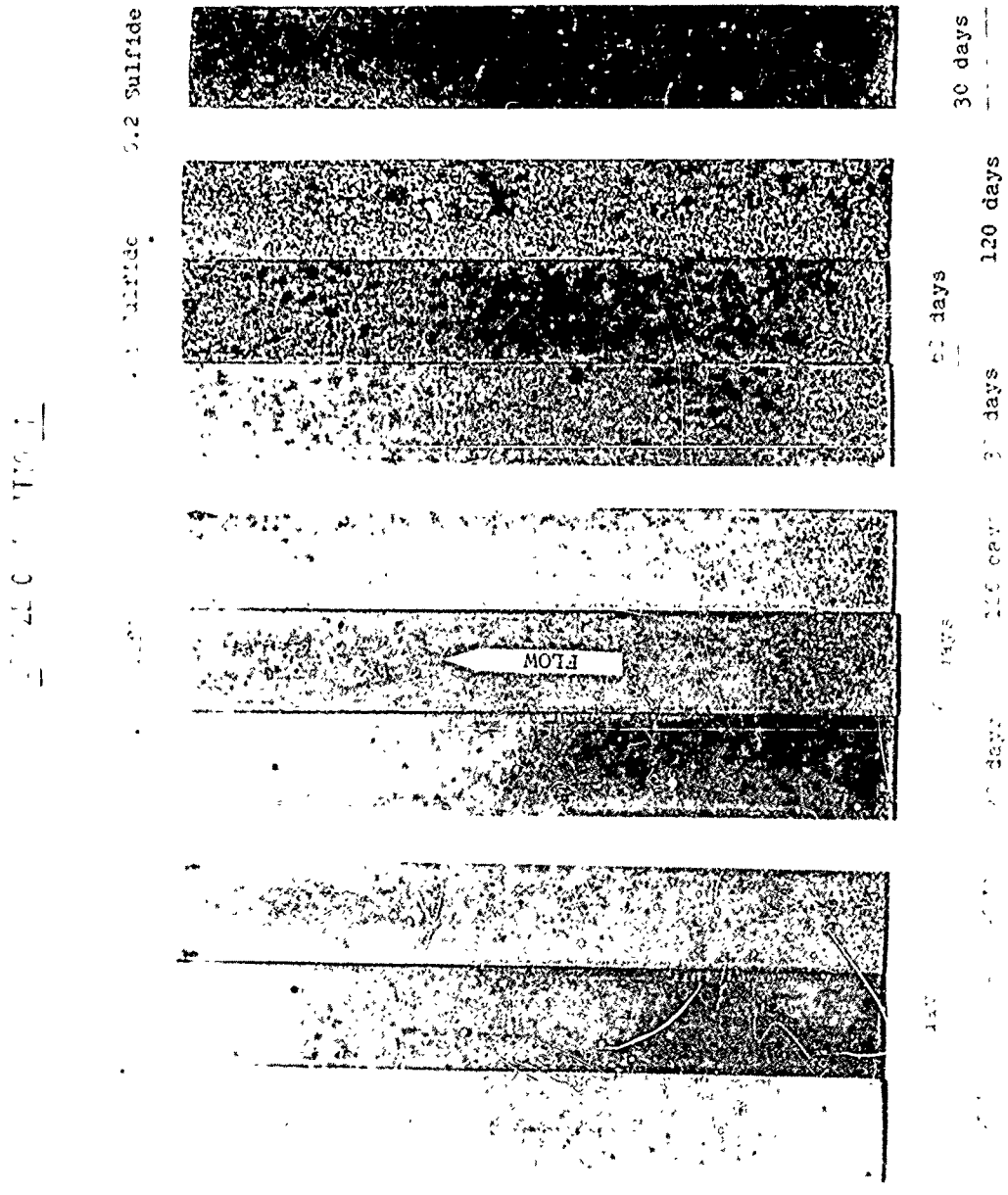
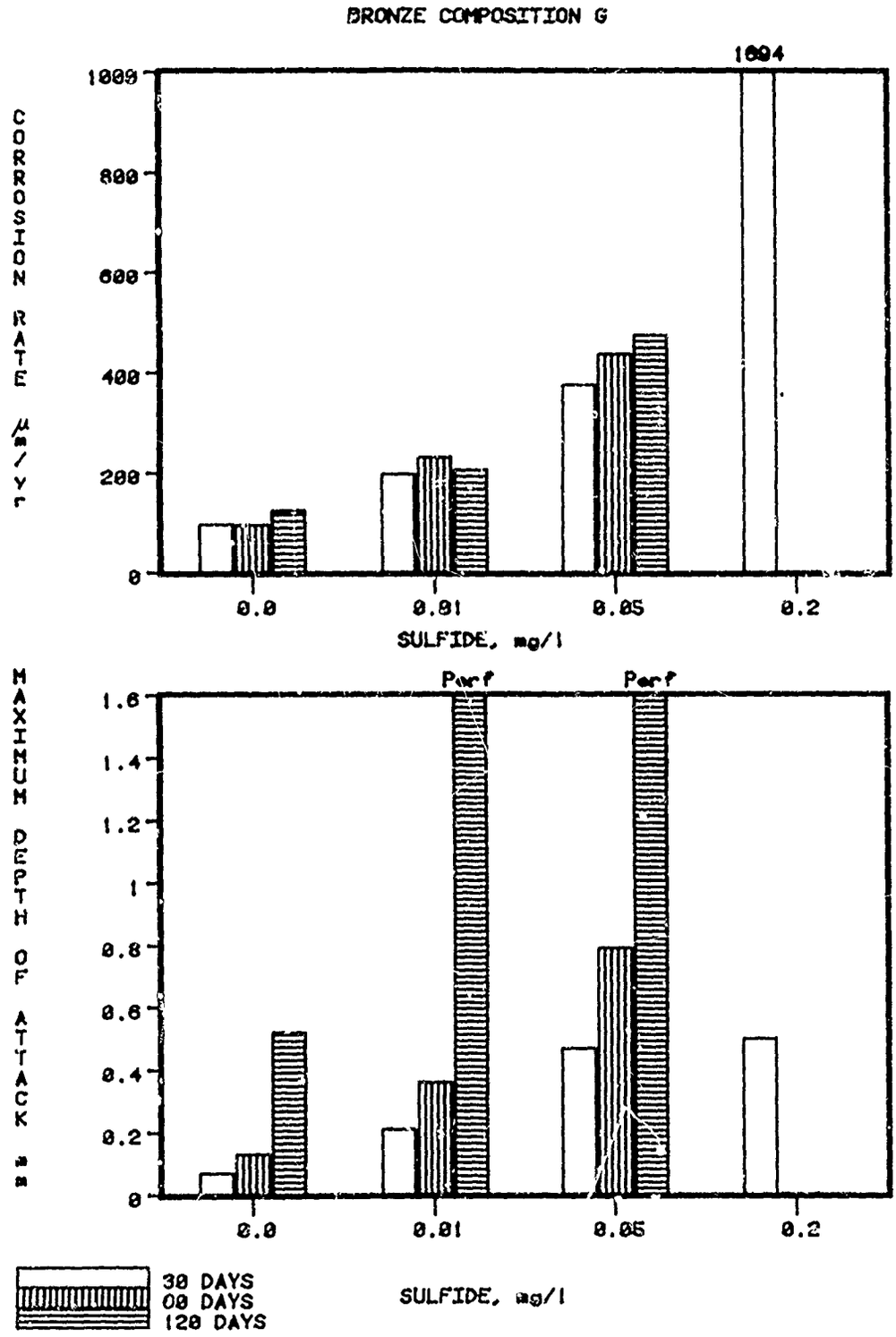


Figure 12. SME 79/56


BRONZE COMPOSITION G
1694
1000
800
600
400
200
0
CORROSION RATE μm/yr
0.0
0.01
0.05
0.2
SULFIDE, mg/l
Perf
Perf
1.6
1.4
1.2
1
0.8
0.6
0.4
0.2
0
MAXIMUM DEPTH OF ATTACK mm
0.0
0.01
0.05
0.2
30 DAYS
90 DAYS
120 DAYS
SULFIDE, mg/l

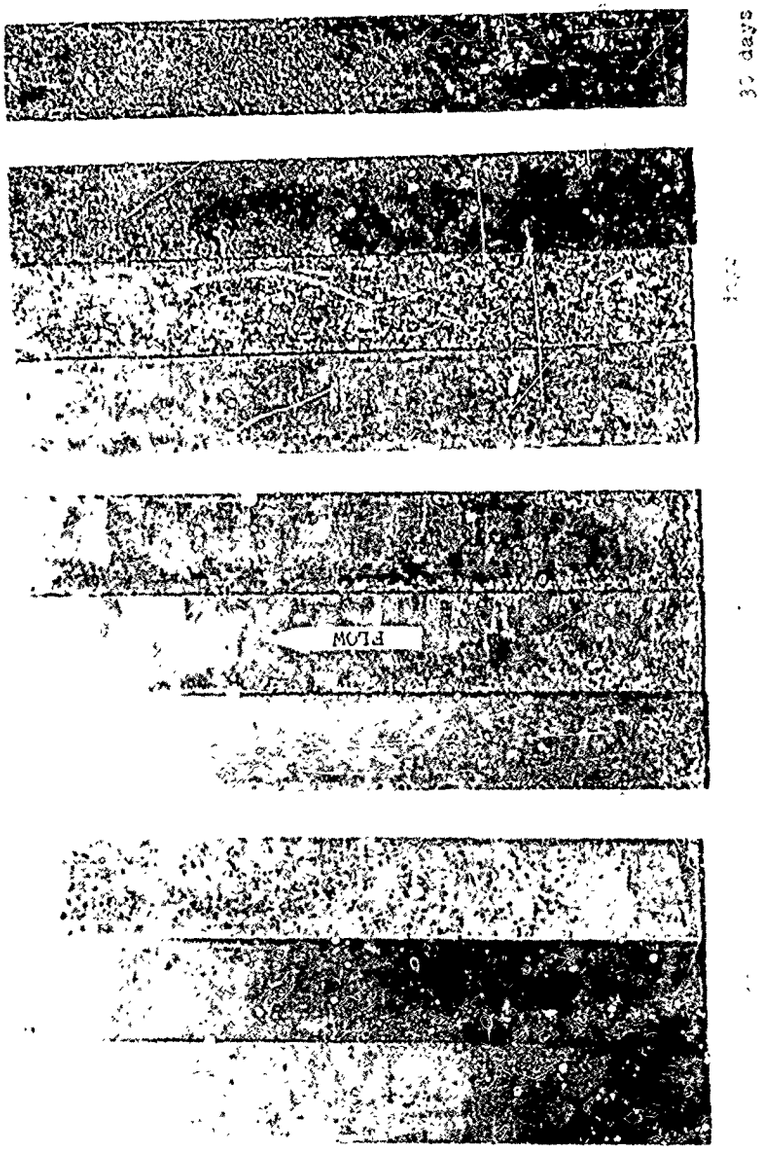


Figure 14. SME-79/56

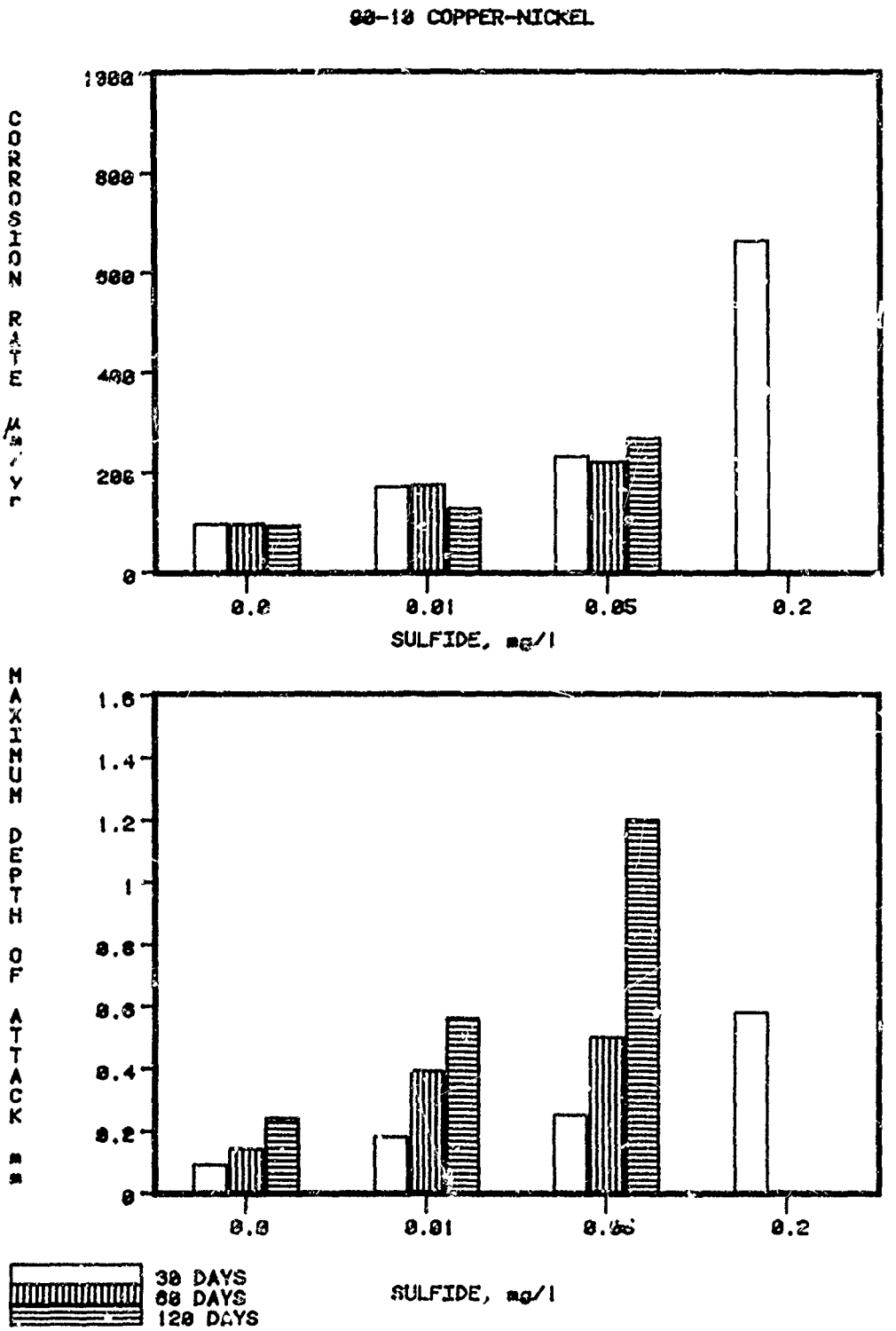
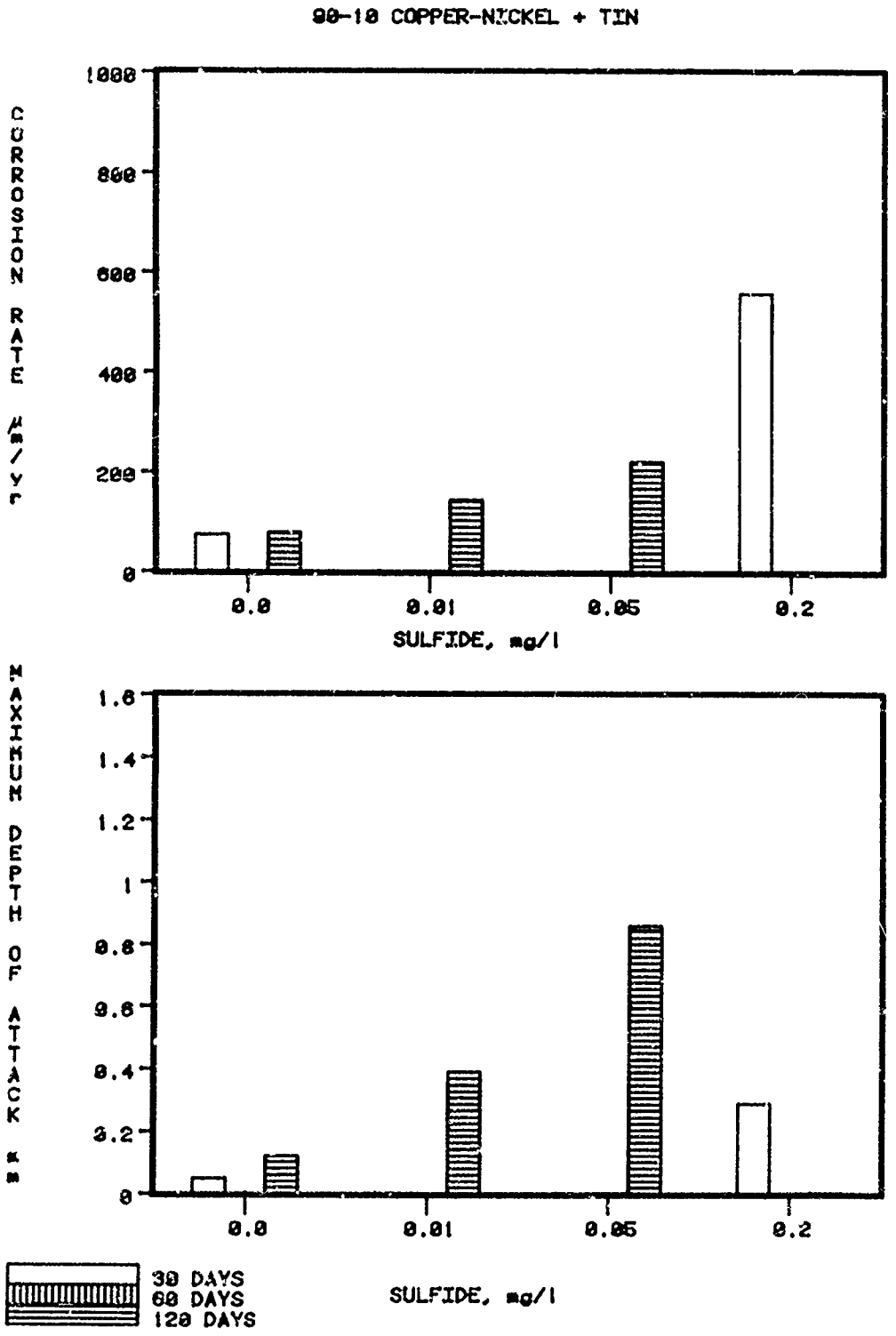
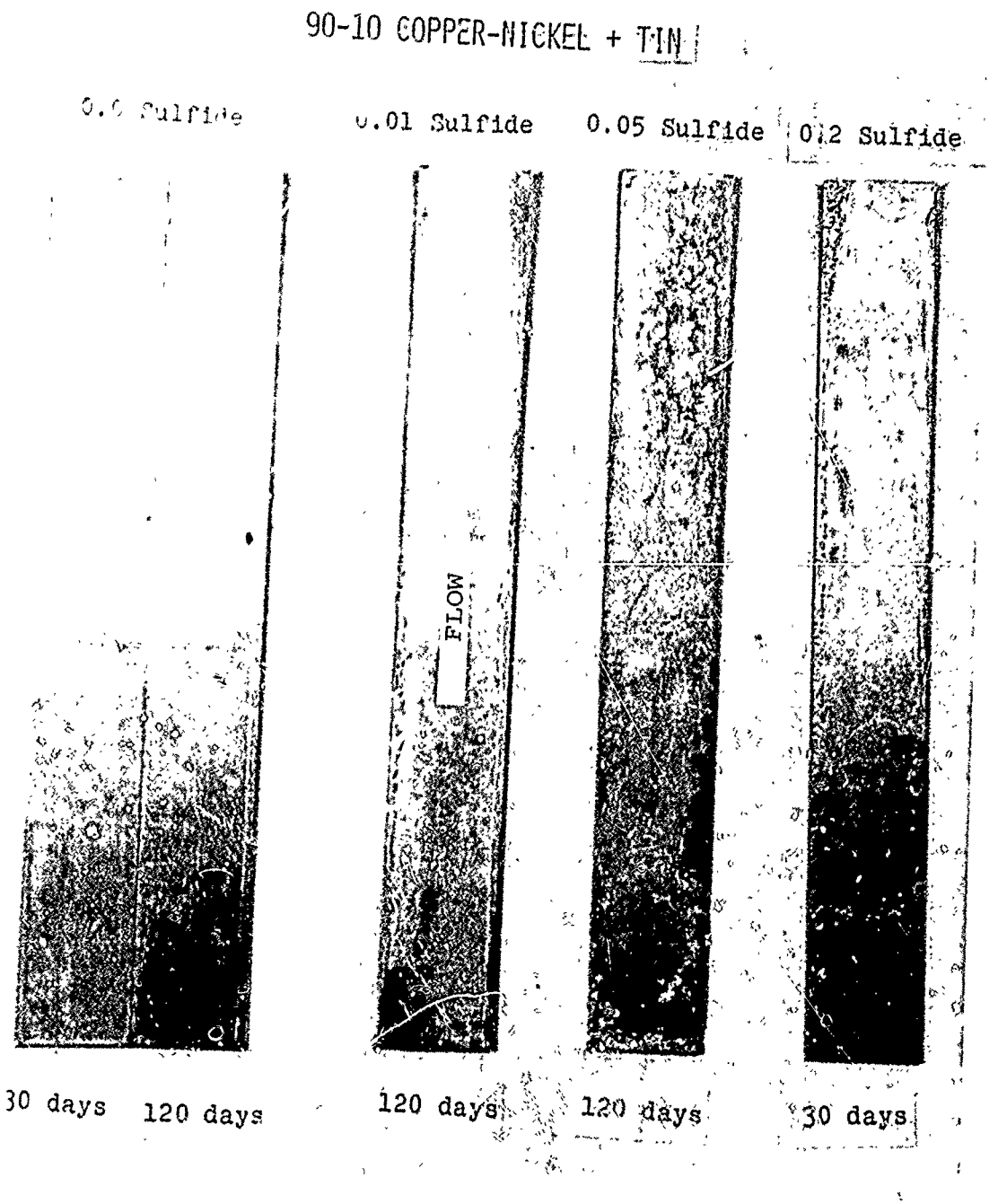

90-10 COPPER-NICKEL
CORROSION RATE μm/yr
1000
800
600
400
200
0
0.0
0.01
0.05
0.2
SULFIDE, mg/l
MAXIMUM DEPTH OF ATTACK mm
1.6
1.4
1.2
1
0.8
0.6
0.4
0.2
0
0.0
0.01
0.05
0.2
SULFIDE, mg/l
30 DAYS
60 DAYS
120 DAYS

Figure 16. SME-79/56


90-10 COPPER-NICKEL + TIN
CORROSION RATE μm/yr
1000
800
600
400
200
0
0.0
0.01
0.05
0.2
SULFIDE, mg/l
MAXIMUM DEPTH OF ATTACK μm
1.6
1.4
1.2
1
0.8
0.6
0.4
0.2
0
0.0
0.01
0.05
0.2
SULFIDE, mg/l
30 DAYS
60 DAYS
120 DAYS



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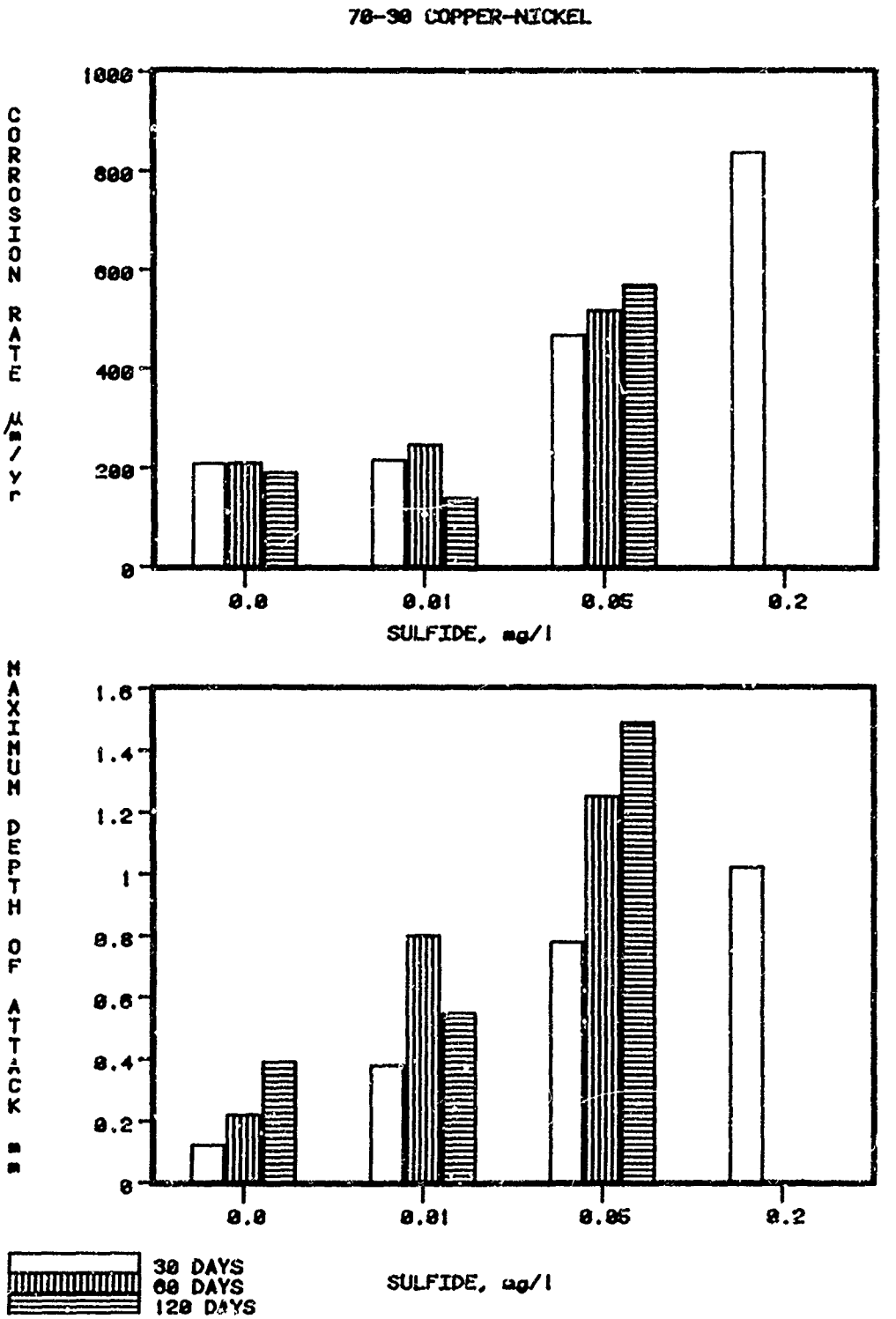
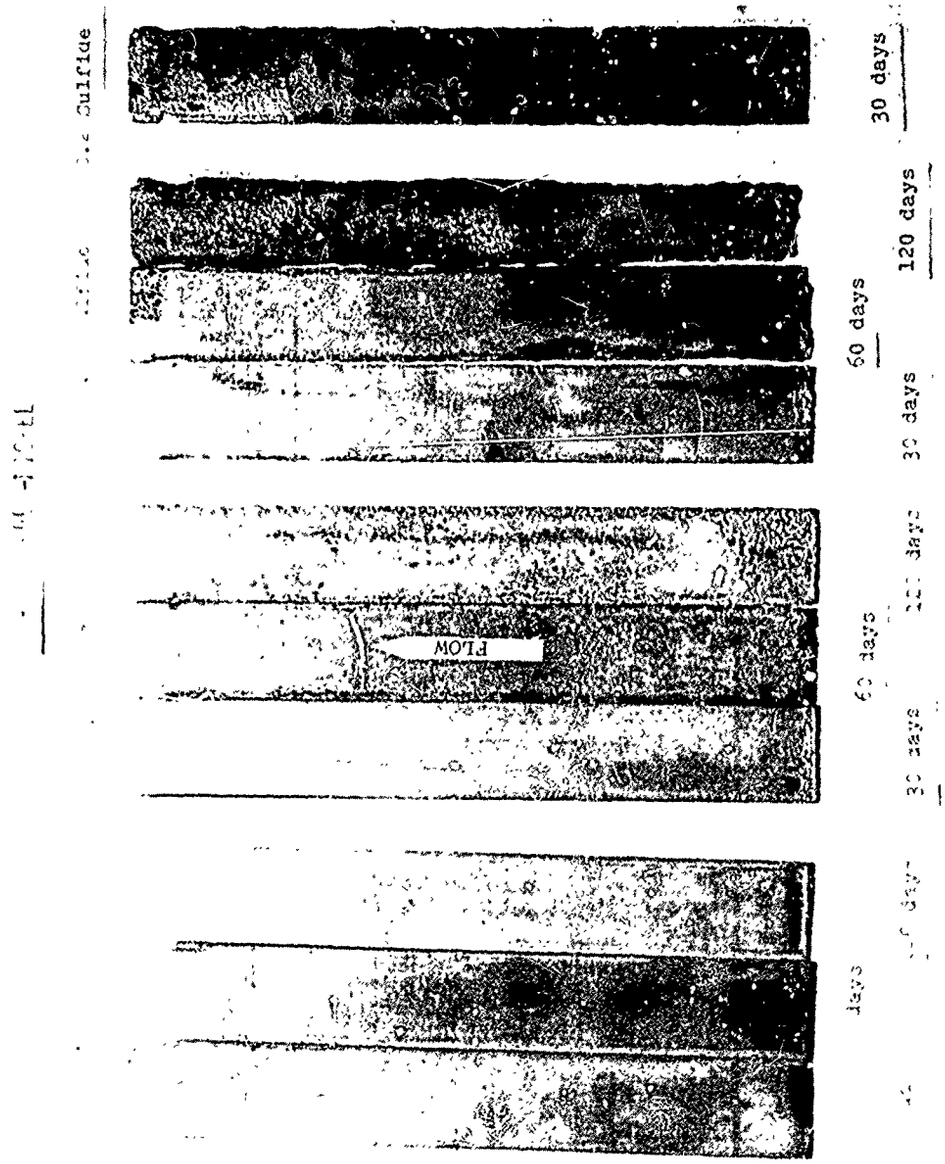

70-30 COPPER-NICKEL
CORROSION RATE µm/yr
1000
800
600
400
200
0
0.0
0.01
0.05
0.2
SULFIDE, mg/l
MAXIMUM DEPTH OF ATTACK mm
1.6
1.4
1.2
1
0.8
0.6
0.4
0.2
0
0.0
0.01
0.05
0.2
SULFIDE, mg/l
30 DAYS
60 DAYS
120 DAYS



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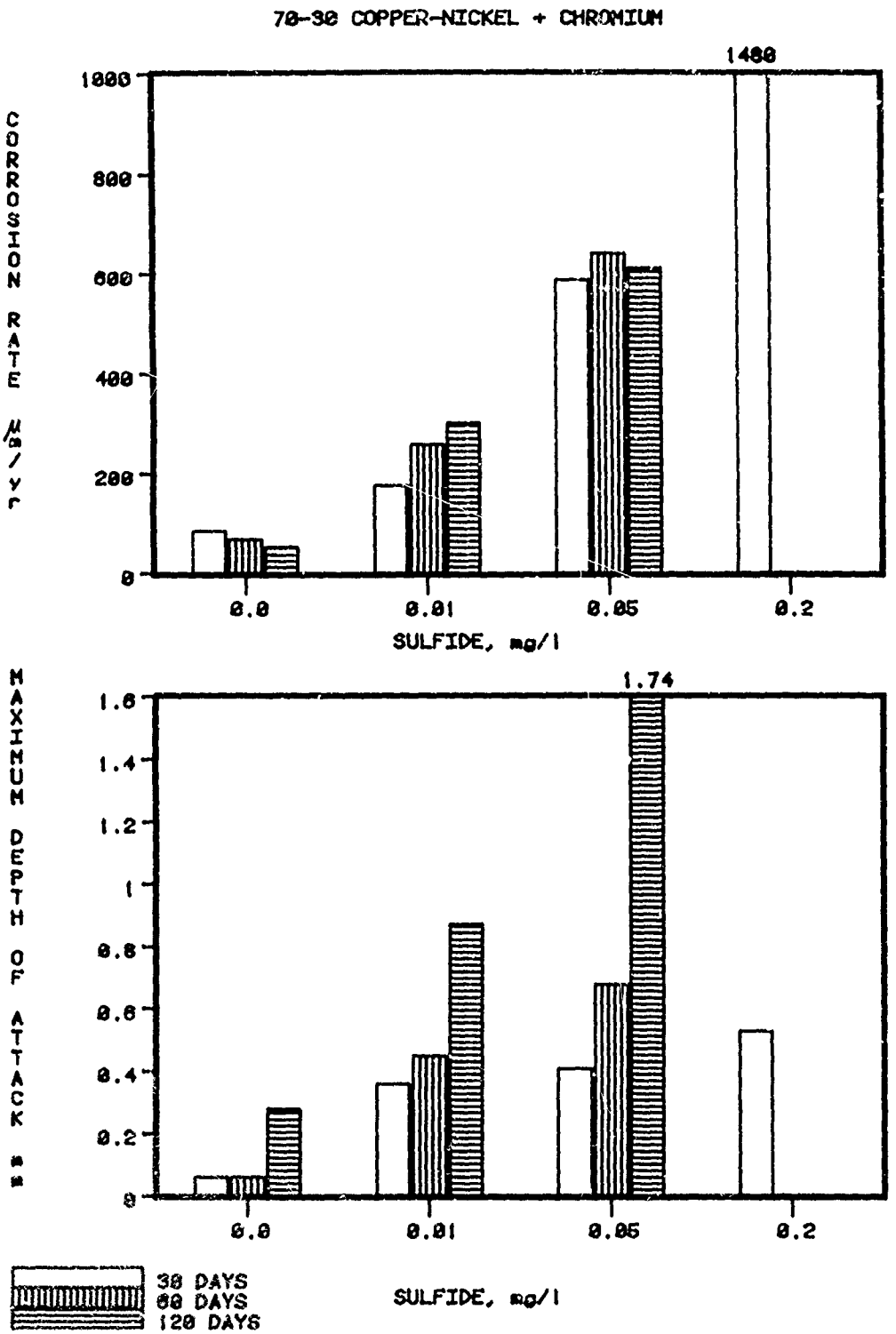
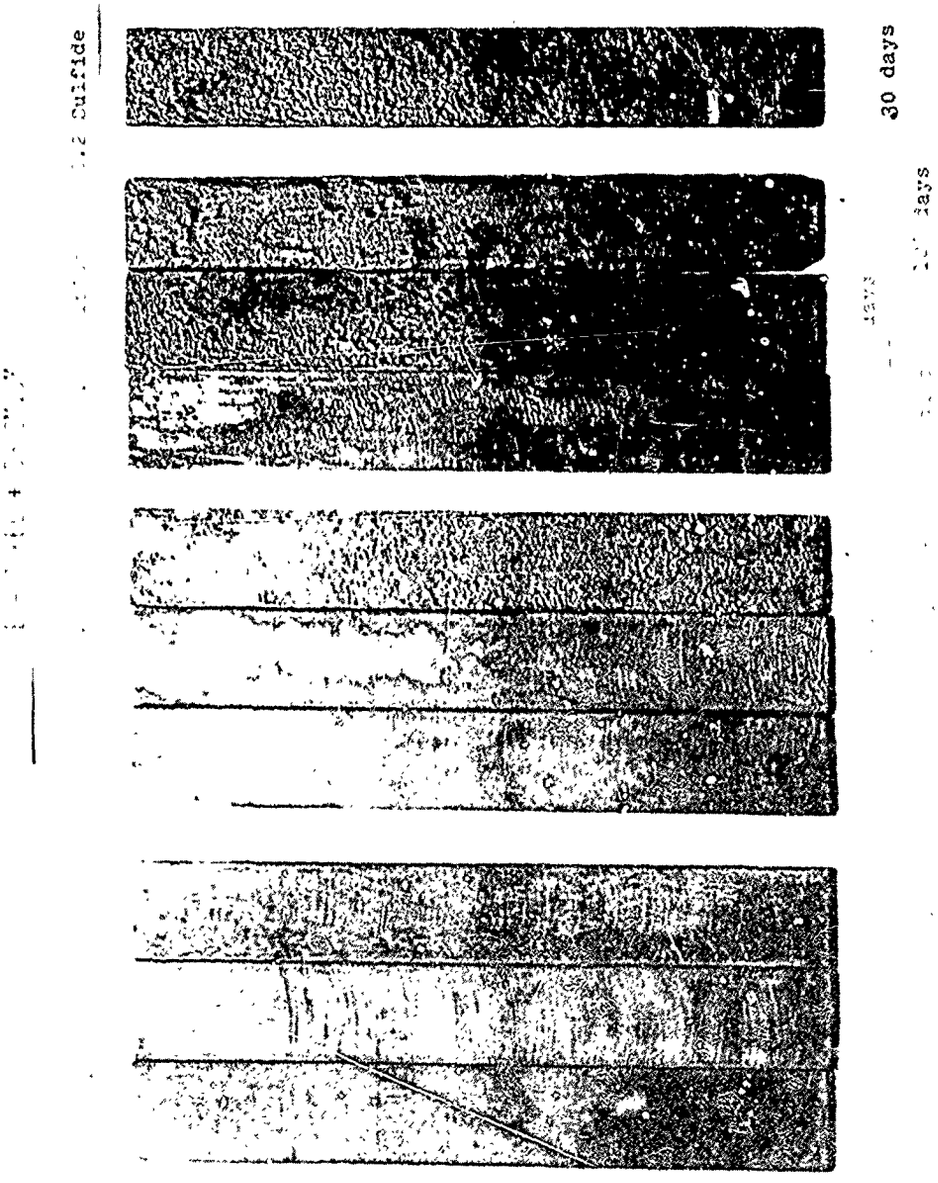

70-30 COPPER-NICKEL + CHROMIUM
CORROSION RATE MG/YR
1000
800
600
400
200
0
1480
0.0
0.01
0.05
0.2
SULFIDE, mg/l
MAXIMUM DEPTH OF ATTACK MM
1.6
1.4
1.2
1
0.8
0.6
0.4
0.2
0
1.74
0.0
0.01
0.05
0.2
SULFIDE, mg/l
30 DAYS
60 DAYS
120 DAYS



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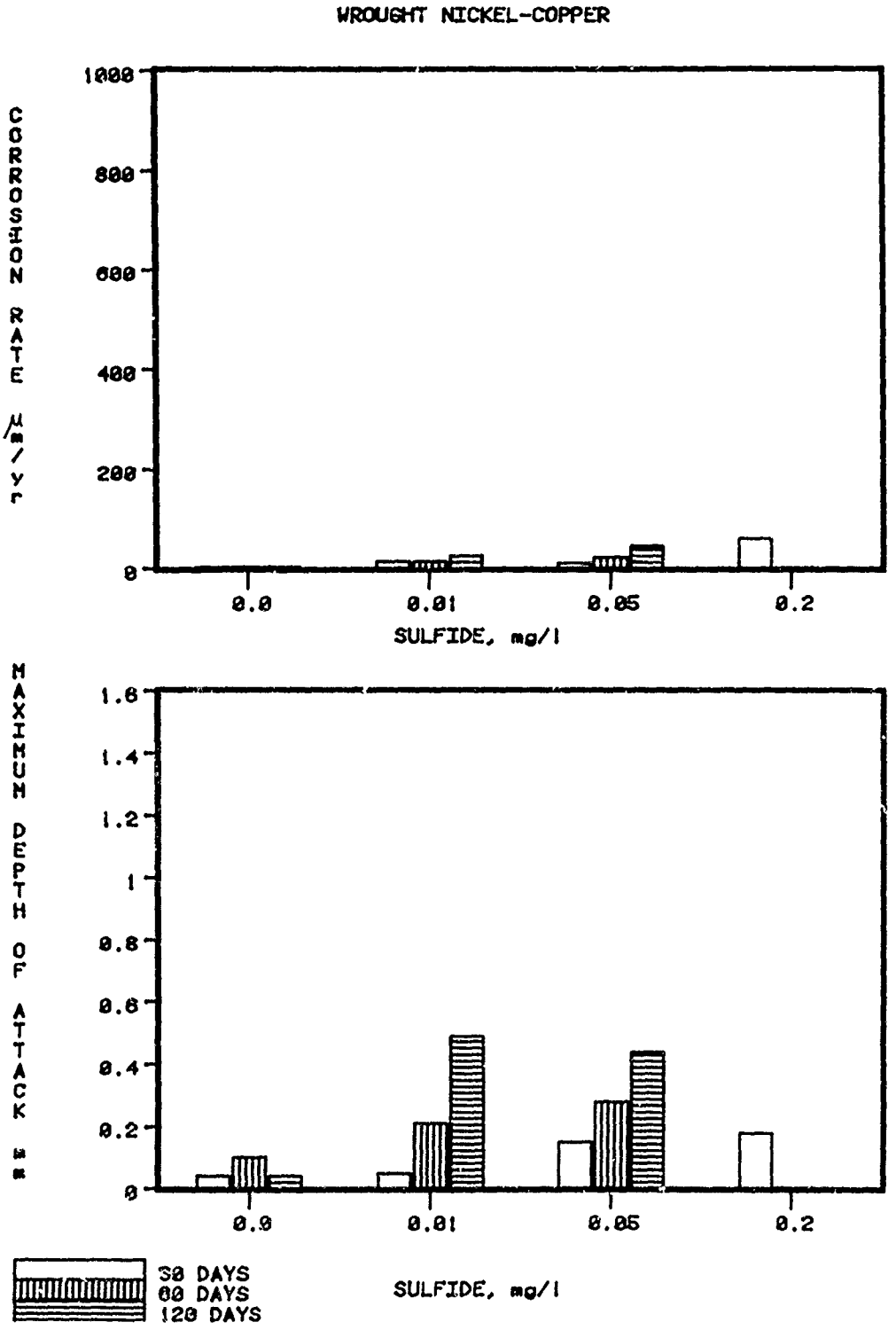
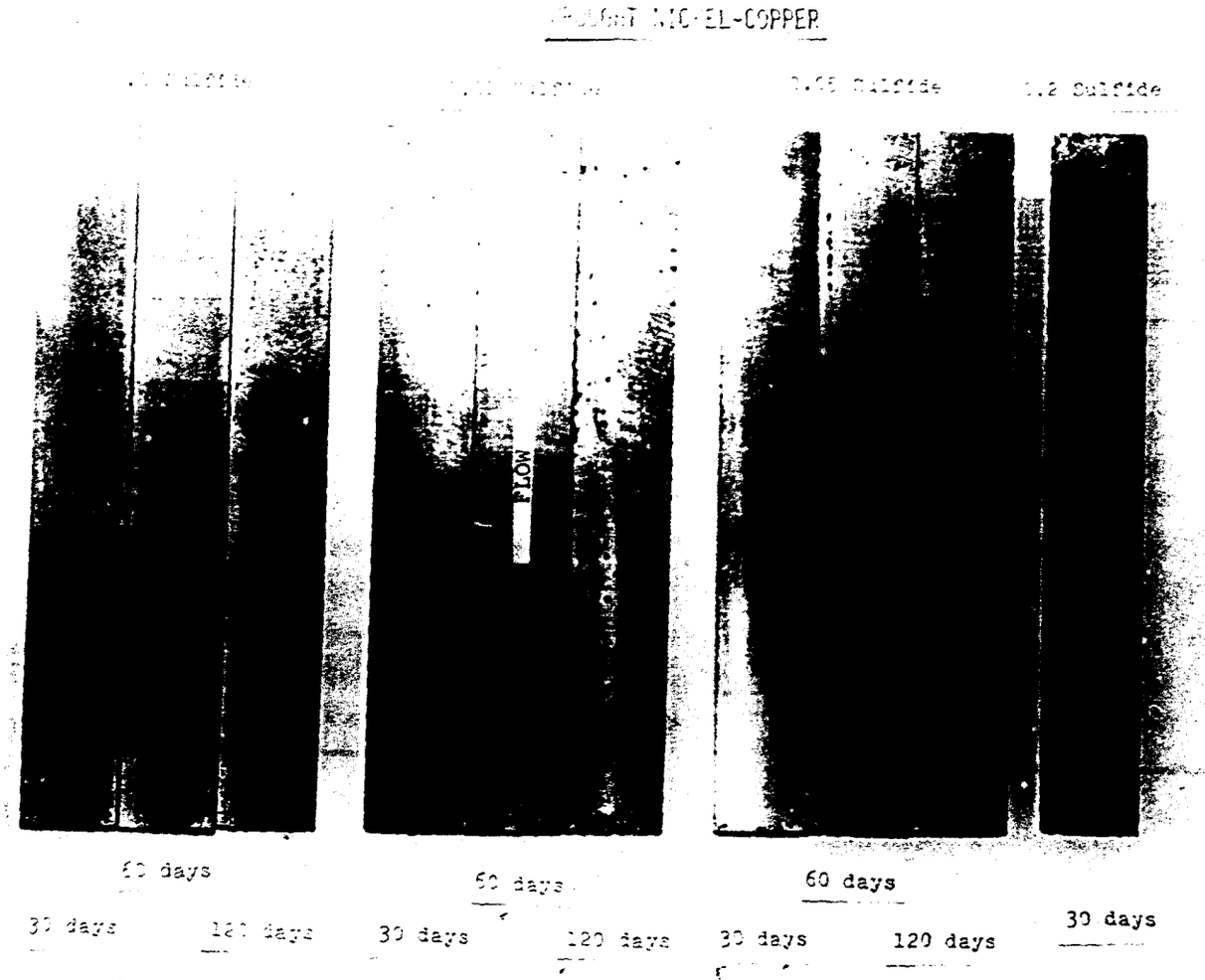

WROUGHT NICKEL-COPPER
CORROSION RATE μm/yr
1000
800
600
400
200
0
0.0
0.01
0.05
0.2
SULFIDE, mg/l
MAXIMUM DEPTH OF ATTACK
1.6
1.4
1.2
1
0.8
0.6
0.4
0.2
0
0.0
0.01
0.05
0.2
SULFIDE, mg/l
30 DAYS
60 DAYS
120 DAYS



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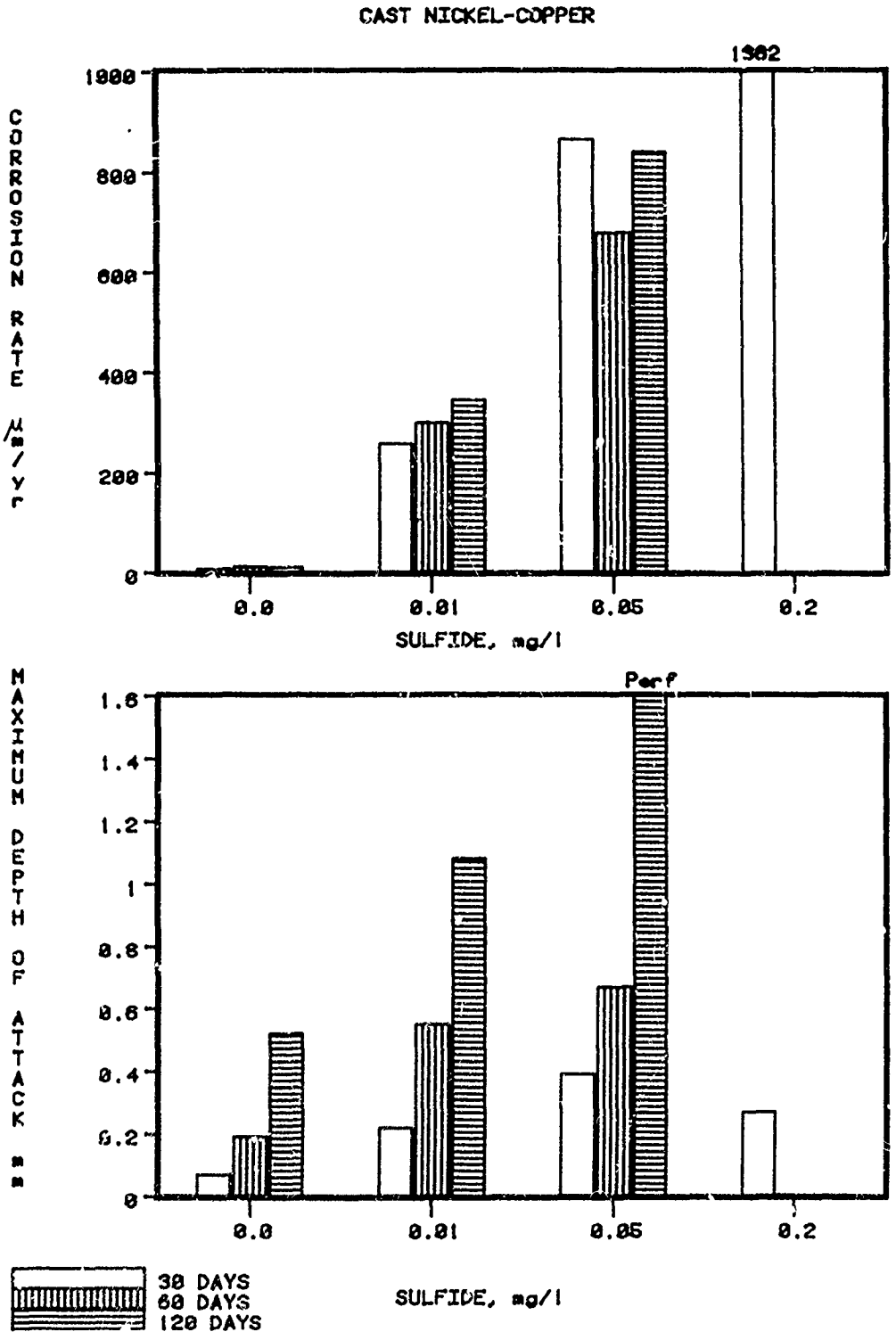

CAST NICKEL-COPPER
1362
1000
800
600
400
200
0
CORROSION RATE MM/YR
0.0
0.01
0.05
0.2
SULFIDE, mg/l
Perf
1.6
1.4
1.2
1
0.8
0.6
0.4
0.2
0
MAXIMUM DEPTH OF ATTACK mm
0.0
0.01
0.05
0.2
SULFIDE, mg/l
30 DAYS
60 DAYS
120 DAYS

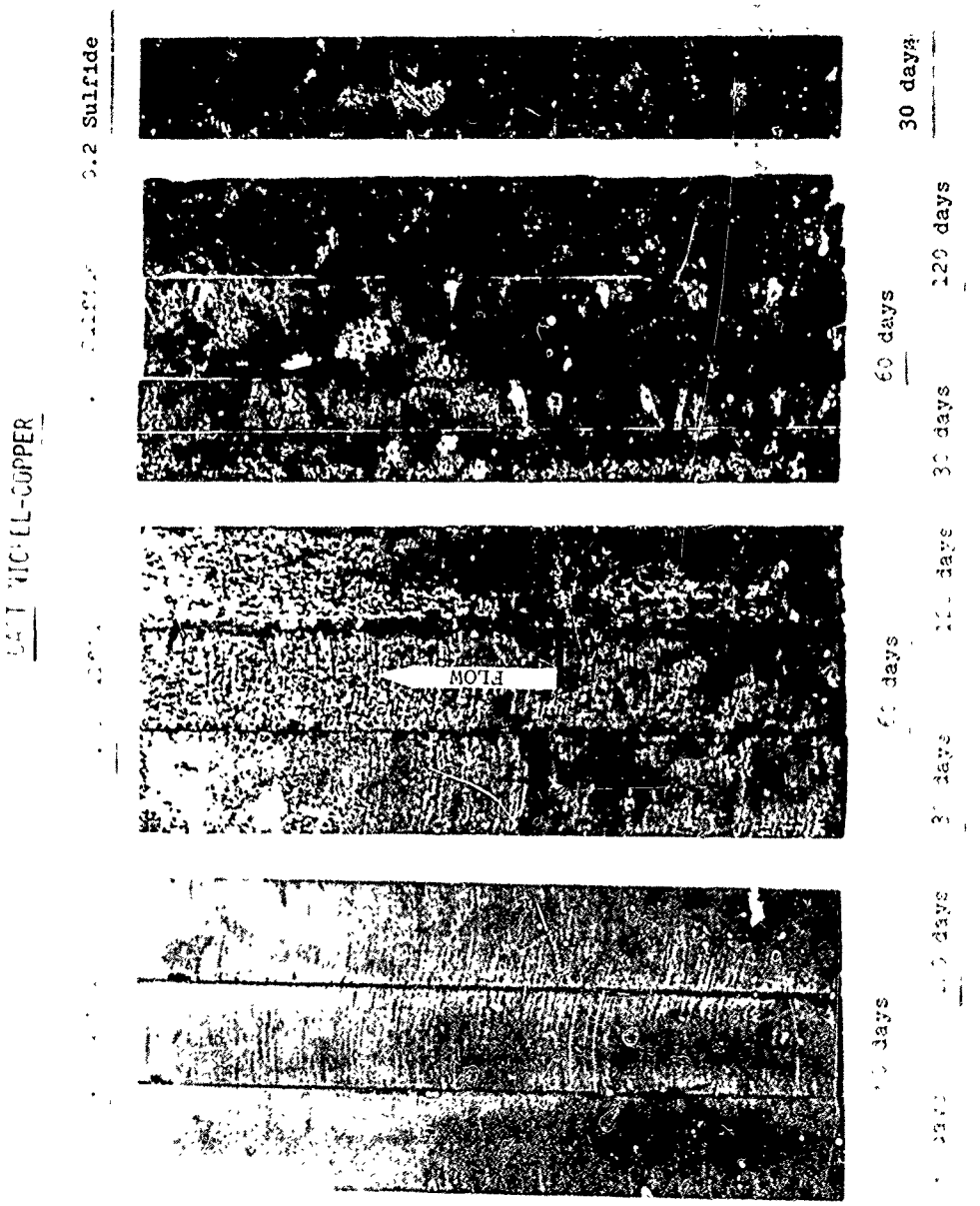
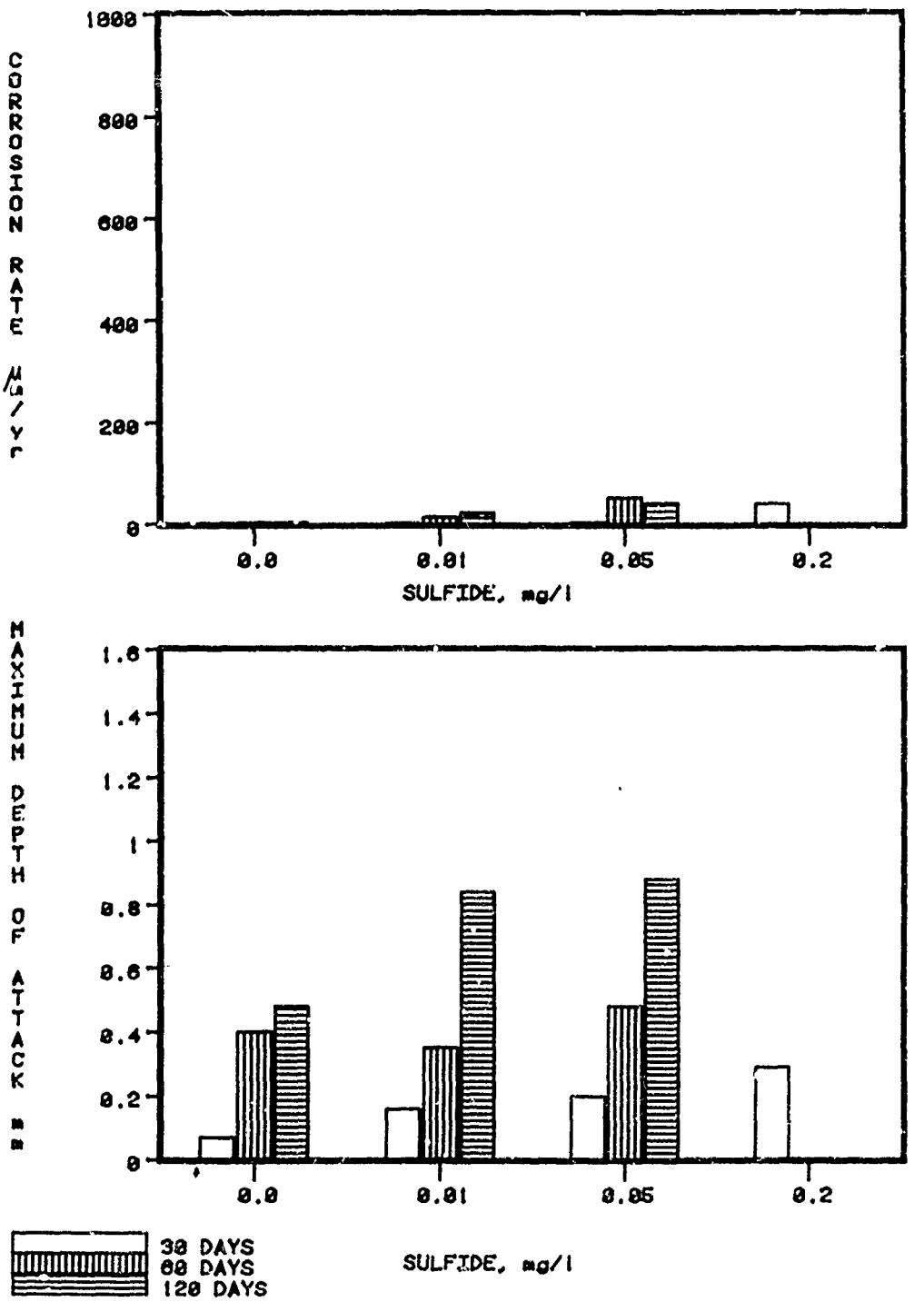


Figure 26. SME 79/56

NICKEL-COPPER K-500



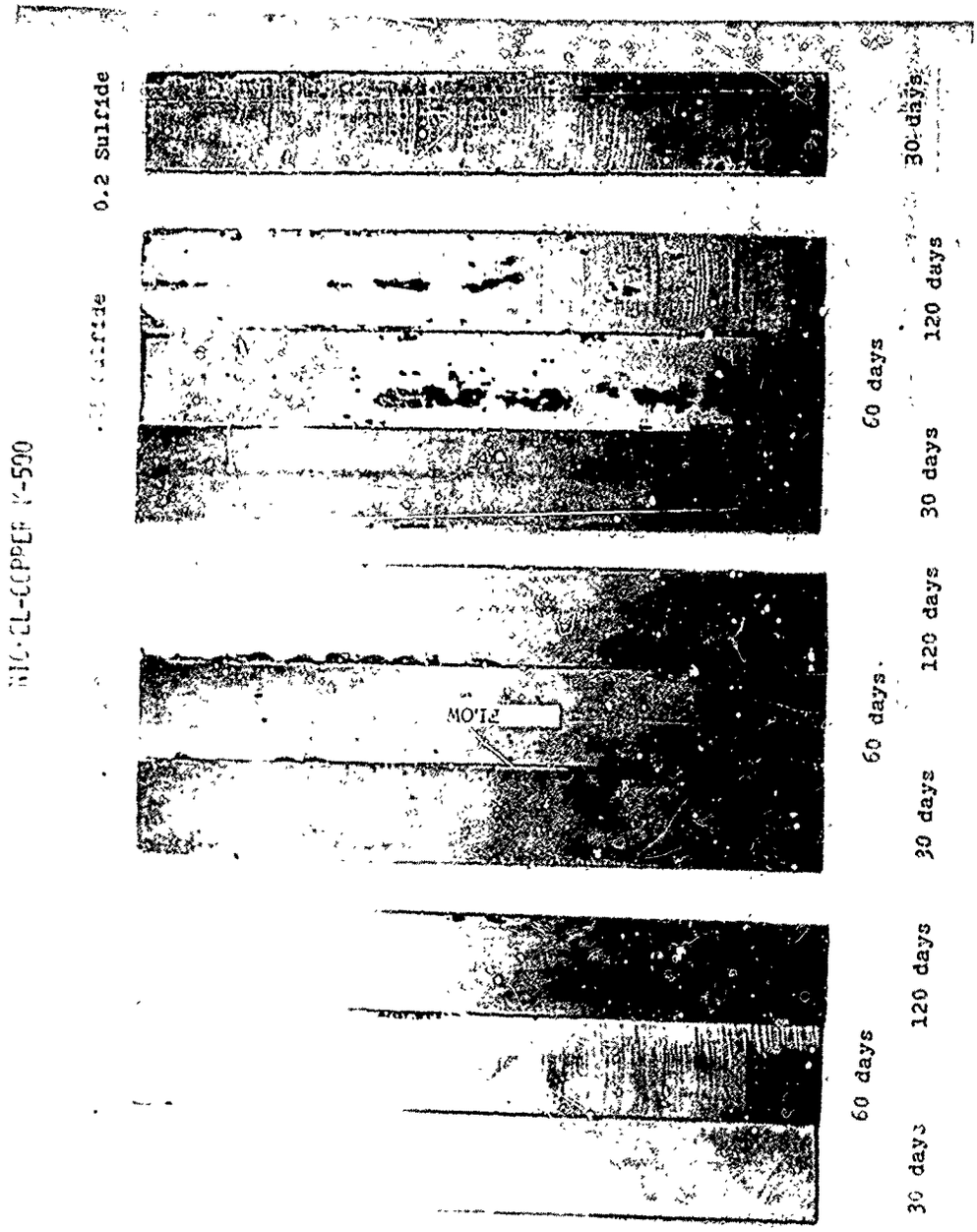
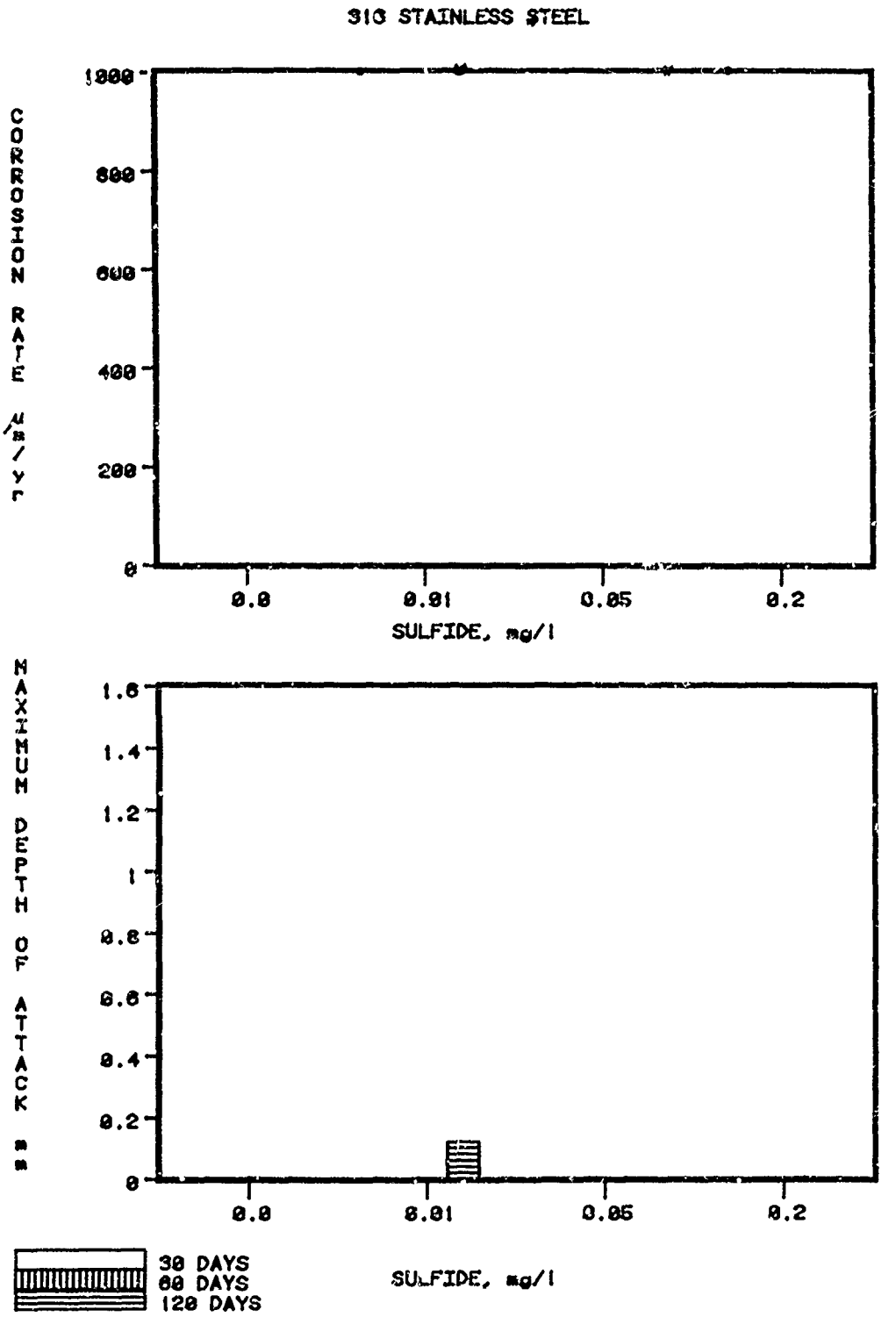


Figure 28. SME 79/56


316 STAINLESS STEEL
CORROSION RATE MM/YR
1000
800
600
400
200
0
0.0
0.01
0.05
0.2
SULFIDE, mg/l
MAXIMUM DEPTH OF ATTACK mm
1.6
1.4
1.2
1
0.8
0.6
0.4
0.2
0
0.0
0.01
0.05
0.2
SULFIDE, mg/l
30 DAYS
60 DAYS
120 DAYS

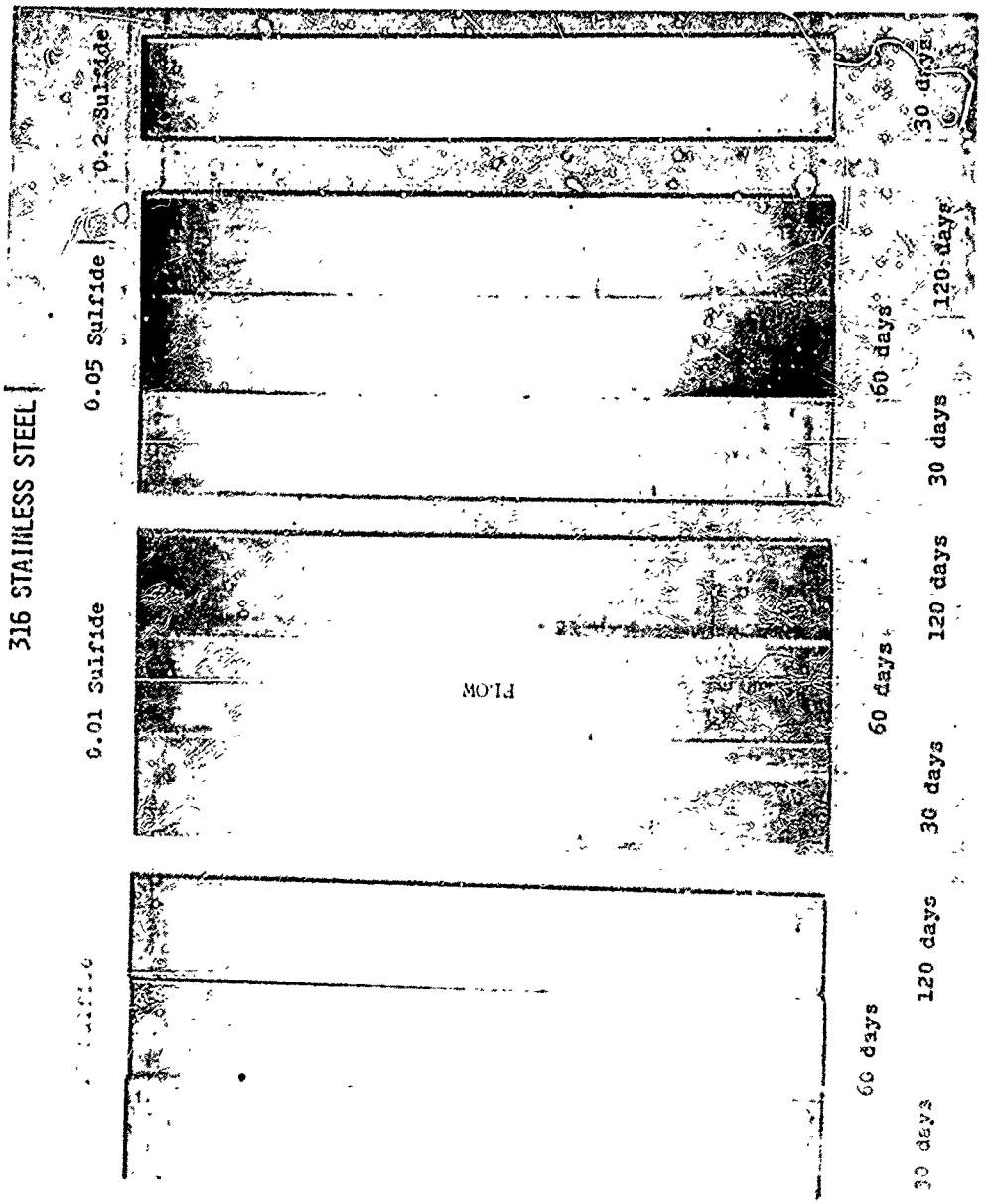
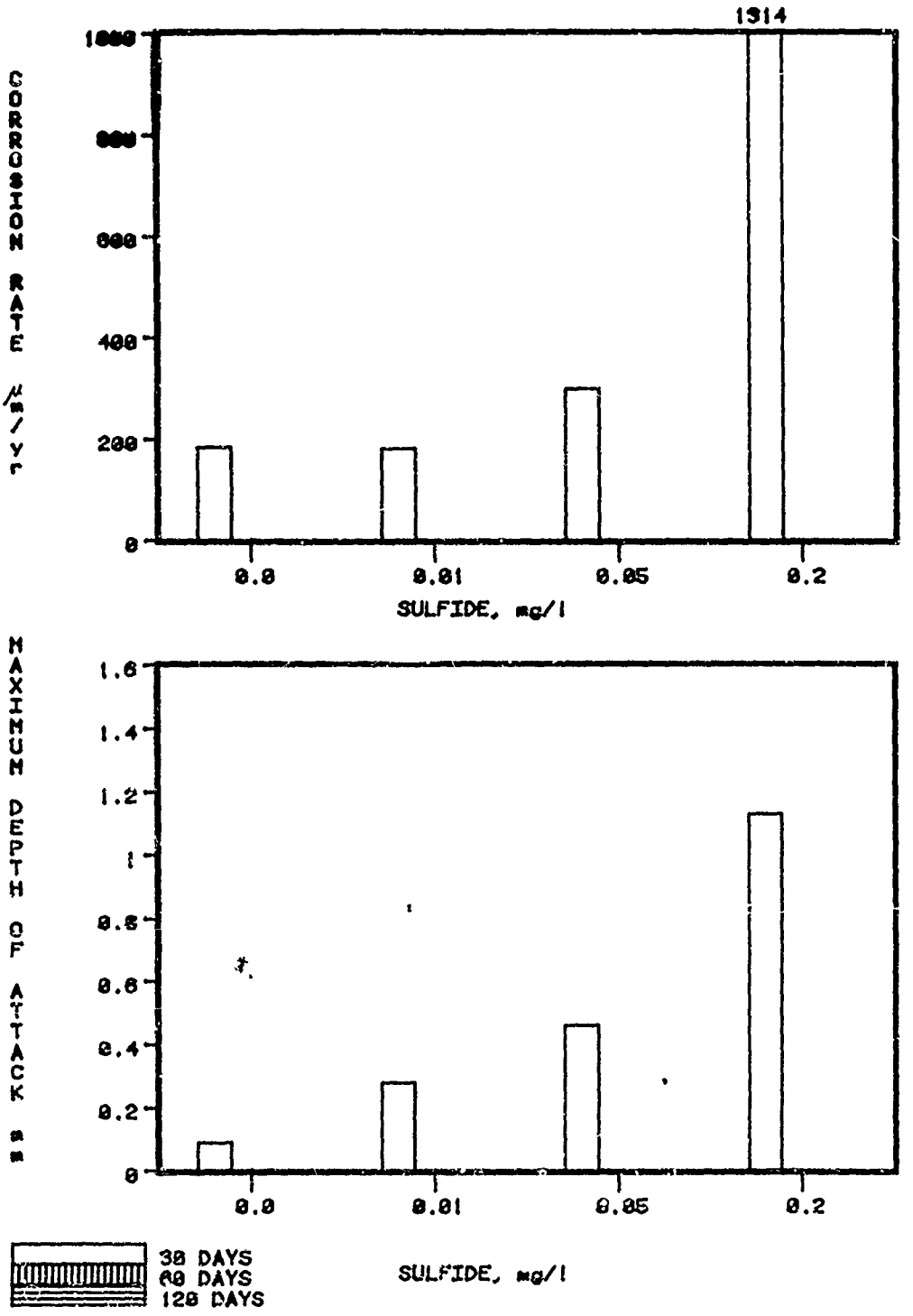


Figure 30. SME 79/56


ALUMINUM BRONZE D
1314
CORROSION RATE µm/yr
1000
800
600
400
200
0
0.0
0.01
0.05
0.2
SULFIDE, mg/l
MAXIMUM DEPTH OF ATTACK µm
1.6
1.4
1.2
1
0.8
0.6
0.4
0.2
0
0.0
0.01
0.05
0.2
SULFIDE, mg/l
30 DAYS
60 DAYS
120 DAYS

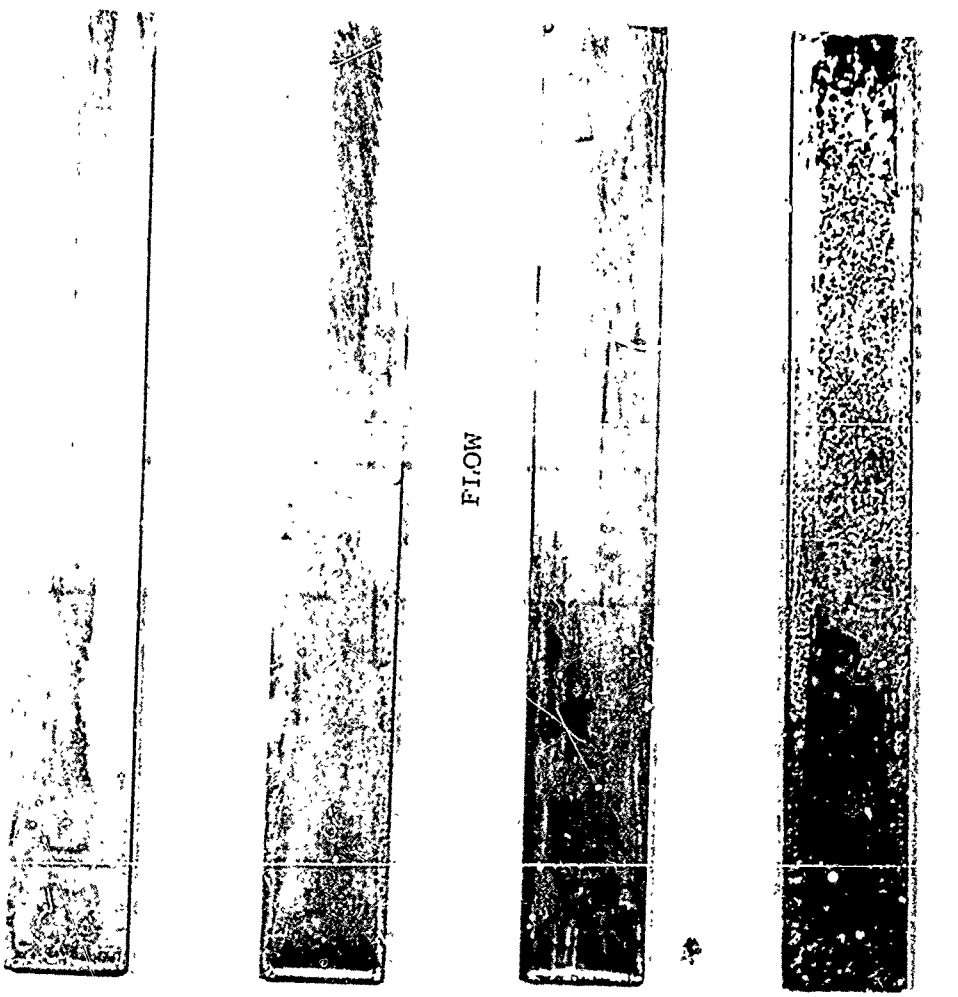
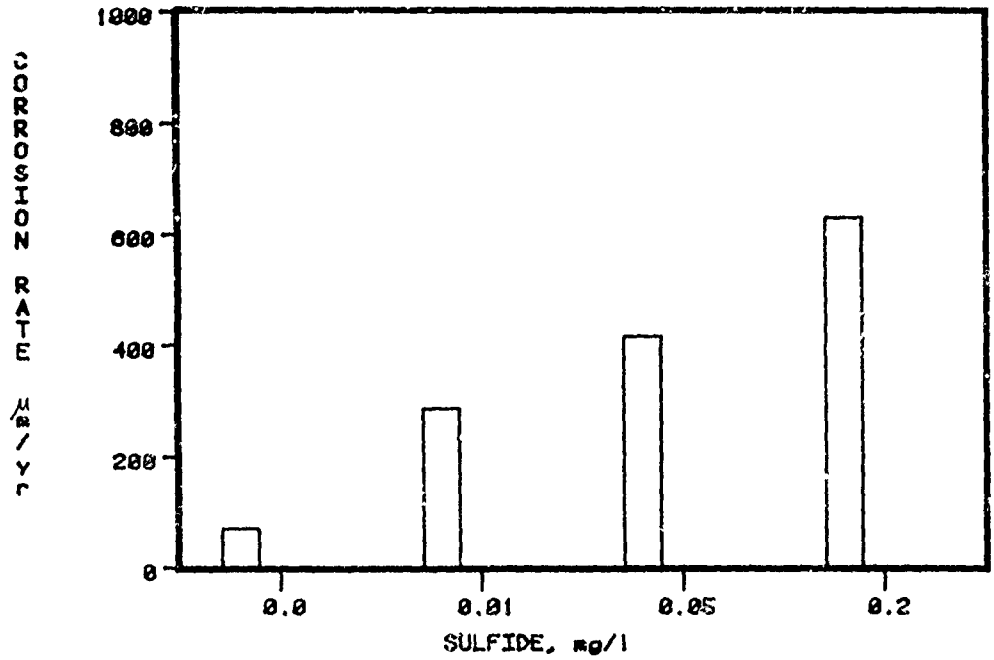
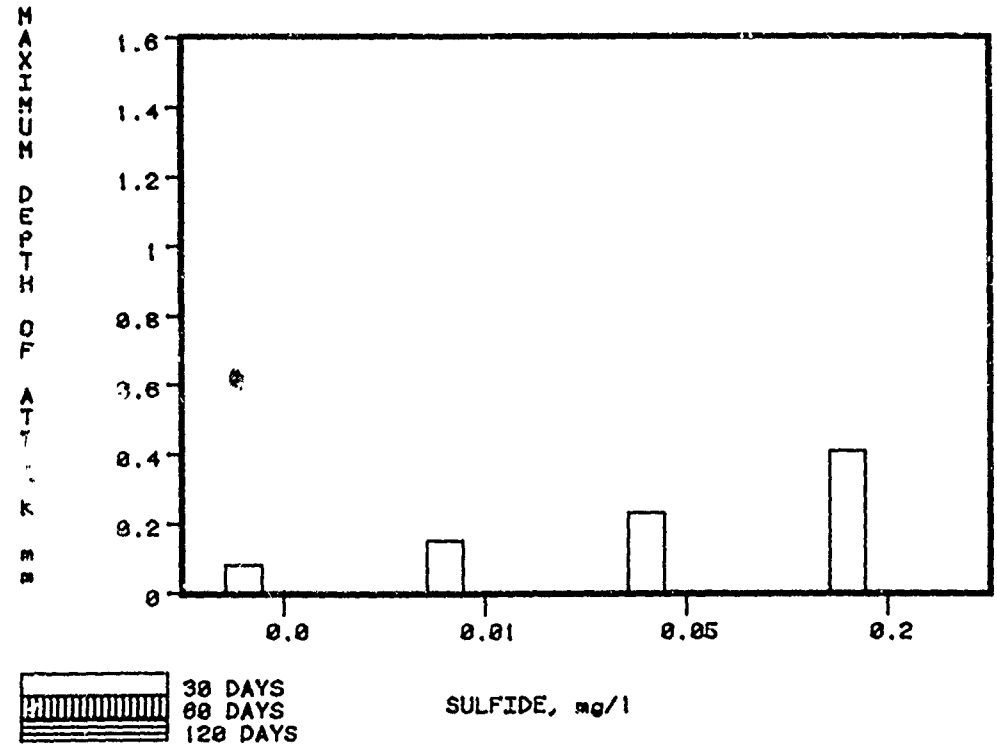


Figure 32. SME 79/56

PHOSPHOR BRONZE + 5% TIN





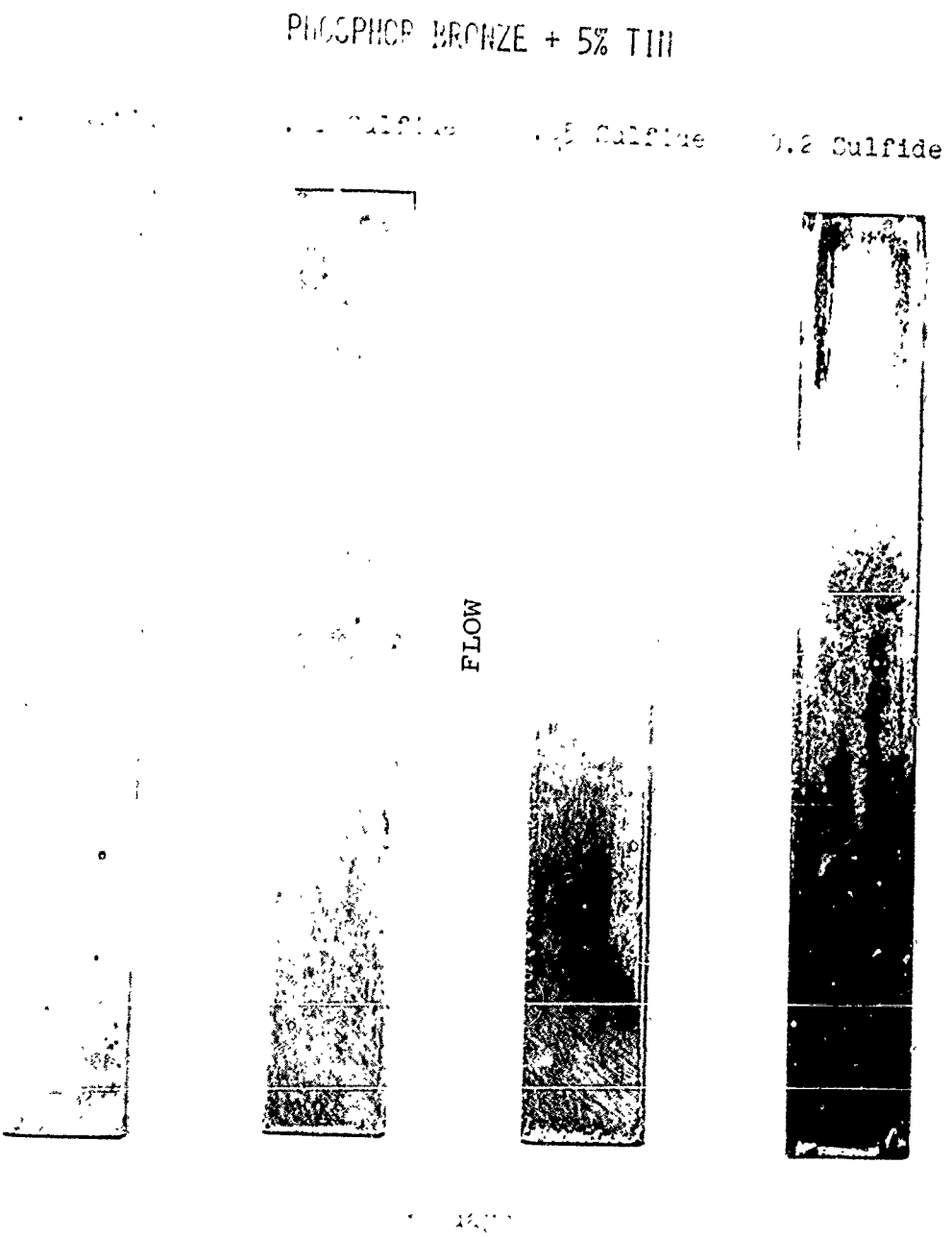
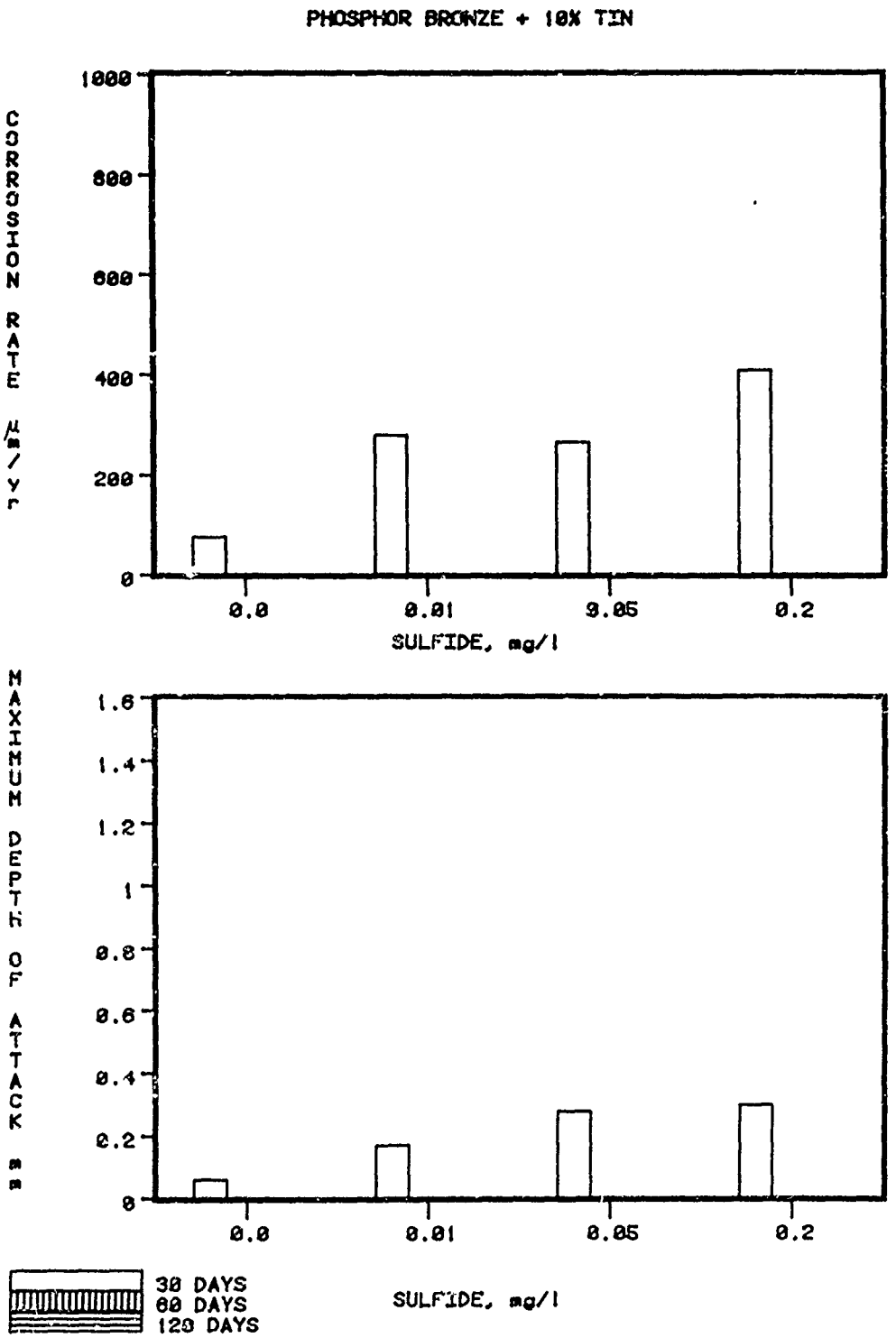


Figure 34. SME 79/56


PHOSPHOR BRONZE + 10% TIN
CORROSION RATE μm/yr
1000
800
600
400
200
0
0.0
0.01
0.05
0.2
SULFIDE, mg/l
MAXIMUM DEPTH OF ATTACK m
1.6
1.4
1.2
1
0.8
0.6
0.4
0.2
0
0.0
0.01
0.05
0.2
SULFIDE, mg/l
30 DAYS
60 DAYS
120 DAYS

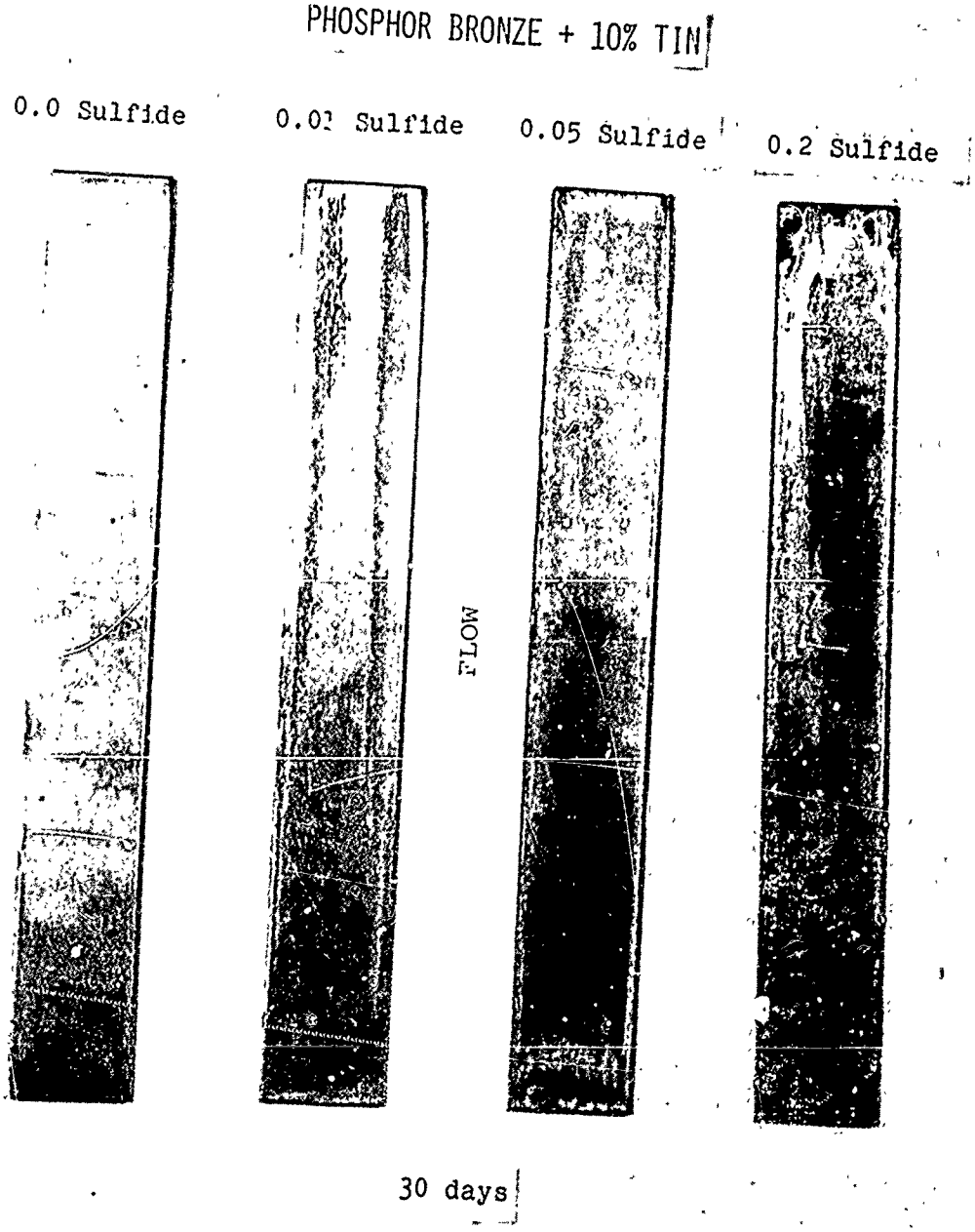


Figure 36. SME 79/56

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12. Hack, H.P., "Galvanic Corrosion of Piping and Fitting Alloys in Sulfide-Modified Seawater," Presented at Symposium on Galvanic Corrosion (ASTM), San Francisco, California (22 May 1979).

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DEALLOYING OF ALUMINUM BRONZE AND NICKEL ALUMINUM BRONZE CASTINGS IN SEAWATER

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ABSTRACT

A review of dealloying of aluminum-bronze (AB) and nickel-aluminum bronze (NAB) castings used by the U.S. Navy is provided. Relationships among dealloying, alloy composition and microstructure are discussed. The use of an eddy-current test method to determine dealloying depth is discussed and an assessment of an existing nondestructive inspection procedure is provided. The results of 6-months and 24-months seawater corrosion tests on four cast NAB alloys are reported. All four alloys displayed varying degrees of dealloying in the as-cast condition depending on alloy composition and microstructure. Heat treatment at 700°C (1300°F) for 8 hours practically eliminated susceptibility to dealloying in all four alloys and changed the predominant mode of corrosion attack to pitting or surface wastage. Dealloying depth measurements obtained from numerous castings with varying lengths of service time were compiled. Results indicate that dealloying in NAB castings containing a minimum of 4-percent nickel is limited to a penetration depth of 6mm (1/4 in.) for service times of up to fifteen years. Dealloying in AB castings however was a more serious problem with penetration depths in excess of 13mm (1/2 in.) being observed.

INTRODUCTION

Corrosion of both aluminum-bronze (AB) and nickel-aluminum bronze (NAB) alloys by the process of "dealloying" in seawater has been well documented.[1-2] Over the years this intriguing phenomenon has been described by the use of a variety of terms such as dealuminization or dealuminification, selective or preferential phase corrosion, parting corrosion, as well as dealloying. Dealloying seems a good description of the phenomenon in both AB and NAB as illustrated by comparing the bulk compositions of both sound metal and dealloyed metal shown in Table (1). The percentage of aluminum, iron and

nickel, the major alloying constituents, all are lower in the dealloyed metal. Still the use of terms such as dezincification to describe the phenomenon in Cu-Zn alloys is an apt descriptor, therefore the use of one term or another is largely a matter of personal preference or general acceptance. The mechanisms of the dealloying phenomenon have been described by Heidersbach,[3] and the most frequently cited explanations with reference to AB and NAB alloys has been stated.[1,2,4] This paper will present a review of dealloying in cast AB and NAB alloys as related to their use by the U.S. Navy. In addition, the results of two-year seawater corrosion tests of four cast NAB alloys will be presented. These alloys were part of an earlier investigation on the effect of alloy composition and "temper-anneal" heat treatment on the seawater corrosion behavior of cast NAB, and 6-month results were reported in reference (5). A compilation of the dealloying depths measured on numerous castings having seawater service times of up to 15 years is presented and the implications discussed.

REVIEW OF DEALLOYING

Work in the early 1960s focused attention on the potential seriousness of "dealuminization" or "selective phase corrosion" in both cast and wrought aluminum bronze alloys being used for seawater service, and the effects of heat treatment and compositional adjustments aimed at minimizing or eliminating the dealloying problem were examined.[1] This work resulted in a shift to the use of the more corrosion resistant nickel-aluminum bronze alloys containing a minimum of 4-percent nickel. The cast NAB alloys were known to exhibit some susceptibility to dealloying in the as-cast condition, and the possible adverse effects of unfavorable galvanic interactions and welding on dealloying also were recognized. In the mid-1960s the use of a 700°C (1300°F) temper-anneal heat treatment was recommended for butt-welded and weld repaired NAB castings in consideration of the potential corrosion problem. Guidelines set forth during 1965-1968 on the use of butt-welded and weld repaired NAB castings reflected this concern over corrosion. However, the "temper-anneal" heat treatment on castings not subjected to welding operations was not considered essential as the as-cast NAB alloys conforming to the more restrictive composition required by MIL-B-23921 (issued in 1963) were shown to be highly resistant (if not immune) to dealloying in the as-cast condition.[1] This view was essentially correct; however, there arose a general belief that NAB castings simply containing a minimum of 4-percent nickel were practically immune to dealloying.

In the early 1970s dealloying was observed on NAB castings containing 4-percent minimum nickel. The first and (as later learned) most serious case occurred on a several hundred pound casting exhibiting dealloying to a depth of approximately 6mm (1/4 in.). An extensive investigation of dealloying in cast NAB was initiated under the sponsorship of the Navy. Numerous castings having varying lengths of seawater service were examined for dealloying. Microstructural examinations indicated that dealloying had occurred due to the presence of interconnected regions of non-equilibrium beta plus the alpha and gamma-2 eutectoid. The presence of these microconstituents was attributed to non-equilibrium cooling and microsegregation normally associated with large castings. An intensive study examined the effects of composition, foundry variables and heat treatment on the microstructure and dealloying susceptibility of NAB castings.[2,4,5] For the Navy

there were two significant results of this work:

(1) A revised specification (MIL-B-24480, issued in 1973) for NAB castings with tightened composition limits and a 675°C ± 10°C (1250°F ± 50°F) six hour heat treatment requirement.
(2) An inspection procedure utilizing an eddy-current and a silver nitrate spot test for determining the presence and depth of dealloying on AB and NAB castings in contact with seawater.

This concluded the Navy effort on cast NAB, and while resistance to dealloying was now believed to be optimized for the cast alloy in the new specification, it was also recognized that complete immunity for all casting sizes and under variable service conditions including detrimental galvanic effects would be practically impossible to achieve.[2,5] In addition, since many of the castings had been produced to earlier specifications, continued occurrences of dealloying were inevitable. The alloy compositions included in the major specifications covering AB and NAB castings used by the Navy over the years are shown in Table (2).

The reliability of cast NAB was now viewed with misgivings, and the requirement for continual monitoring for dealloying expensive and cumbersome. Dealloying became an issue again in 1978 as the result of an analysis of a valve body and associated cast component removed from seawater service. The analysis revealed that these parts had suffered from extensive dealloying as shown on the fracture surfaces in Figure (1) with depths of dealloying greater than 13mm (1/2 in.) in some locations. Chemical analysis and microstructural examination revealed that these castings, although identified as NAB, were in fact aluminum bronze conforming to the Class 3 composition of MIL-B-16033 as shown in Table (3).

This event was in itself nothing more than a restatement of the findings of the early 60s regarding the susceptibility of aluminum-bronze alloys to dealuminization.[1]

Nonetheless, due to some questionable results obtained using an eddy-current inspection method that is part of the inspection procedure to measure the depth of dealloying, a new investigation was initiated. The purpose of the investigation was to determine the reliability of the inspection procedure for the detection and measurement of dealloying in AB and NAB castings and to recommend improvements or changes.

ASSESSMENT OF DEALLOYING INSPECTION PROCEDURE

Briefly, the dealloying inspection procedure involves the use of an eddy-current test for non-destructive dealloyed metal depth measurements up to 2.54mm (0.100 in.). Verification or measurement beyond 2.54mm (0.100 in.) is accomplished by an excavation/spot testing procedure utilizing a ten percent silver nitrate solution. The silver nitrate reacts with the dealloyed metal leaving a demarcation line between the dealloyed and non-dealloyed metal interface within the excavation. Evaluation of the inspection technique was accomplished by comparing the eddy-current and silver nitrate/excavation methods for measuring dealloying depths with measurements made on fracture surfaces. The evaluation procedure is illustrated in Figure (2). Microstructural examinations were also conducted to determine the microconstituents present and to identify which were being attacked.

The results of this evaluation showed that dealloyed depth measurements using the eddy-current method were variable in accuracy and unreliable when compared with the silver nitrate/excavation method or direct measurement of dealloying on a fractured cross-section. It has been determined that the eddy-current method of measuring dealloying depends on the ability to detect differences in magnetic permeability between sound metal and dealloyed metal and that differences in the electrical conductivity of sound and dealloyed metal on a given casting are not significantly different. It has also been determined that magnetic permeability can vary in sound metal from casting to casting. These variations are a function of alloy composition, casting size, cooling rate and thermal history. Since the calibration procedure for the present eddy-current equipment depends on the use of "dealloyed standards," these variations in permeability are largely responsible for the inconsistent results with the present eddy-current method. Solutions to this problem are being sought and involve the use of superior eddy-current instrumentation and modified test procedures. In addition, other nondestructive techniques such as ultrasonic inspection and strict magnetic property measurements (as compared with eddy-current, which measures both electrical conductivity and magnetic permeability) are being investigated. Results will determine the direction of near term and longer range solutions to the problem of measuring dealloying depths in AB and NAB castings.

SEAWATER CORROSION TESTS

The results of 6-months seawater corrosion tests on the four cast alloys identified in Table (4) were reported in an earlier study.[5] Results after two-years exposure of these same four alloys under freely corroding conditions are presented here for both as-cast and heat treated (700°C[1300°F] for 8 hours) conditions. As reported previously, all four alloys were subject to dealloying in the as-cast condition with attack concentrated on the intergranular network of retained beta and kappa phases.[5] In addition, minor pitting and surface wastage was evident. A comparison of maximum dealloying depths recorded for the as-cast alloys is provided in Figure (3). The 700°C (1300°F) 8 hour heat treatment eliminated the dealloying susceptibility of these four alloys. Corrosion attack on the four heat treated alloys was manifested by increased pitting or surface wastage with little or no sub-surface penetration. A comparison of the corrosion performance of as-cast and heat treated specimens is shown in Figures (4) to (7). The change from dealloying to pitting and surface wastage is illustrated by the photomicrographs in Figures (8) to (11). Note the dramatic improvement in corrosion resistance for Alloy A1 from as-cast to heat treated conditions. Alloy C1, on the other hand, had suffered least from dealloying so that the difference in corrosion performance between as-cast and heat treated conditions was less significant. Figure (12) shows the depth of pitting on the four heat treated alloys after six-months and two-years in seawater. While the results suggest that proper heat treatment can eliminate dealloying susceptibility, it must be kept in mind that other factors, as mentioned previously, may make heat treatment less effective. Large castings may require unacceptably long heat treating times to completely transform non-equilibrium constituents to the alpha plus kappa structure.[2] Furthermore, adverse galvanic effects may result in dealloying

along alpha plus kappa networks as shown in reference (5), particularly if coarse interconnected kappa networks are present. Thus proper heat treatment, while beneficial to corrosion behavior, may not eliminate corrosion problems with NAB.

EXAMINATION OF CASTINGS DEALLOYED IN SERVICE

The Navy-sponsored dealloying studies have resulted in the examination of first AB and more recently NAB castings that have been used in seawater service to gage the magnitude of the dealloying problem.

The estimated service time for some of these castings is 15 years or more. Dealloying of aluminum-bronze alloys, considered here to be the duplex or multi-phase copper-aluminum alloys, including those containing up to 5-percent iron and less than 4-percent nickel, has repeatedly been shown to be a problem. Dealloying depths in excess of 13mm (1/2 in.) have been observed. The microconstituents responsible for the most serious cases of dealloying are generally believed to be the alpha plus gamma-2 eutectoid. The photomicrographs in Figure (13) show the microstructure of both sound metal and dealloyed metal from a MIL-B-16033 Class 3 casting. Identification of the microconstituents present in this alloy is provided in Figure (14).

Numerous nickel-aluminum bronze castings (alloys containing a minimum of 4% Ni) of various configurations were examined. Microstructures of these castings exhibited anticipated differences due to cooling rate variations from component size differences. It was observed that in all alpha plus kappa phase microstructures, the Ni-kappa and Fe-kappa phases appear to have been selectively attacked in the absence of retained beta or other more anodic constituents (Figure 15). These observations confirm earlier evidence that the Ni-kappa and Fe-kappa phases can be selectively attacked by seawater.[5] However, it became quite clear as this investigation proceeded that alloys with a minimum of 4-percent nickel (NAB), while not immune, are more resistant to dealloying than the binary Cu-Al (AB) alloys. As more castings were examined it appeared that dealloying in NAB castings was limited in depth. The maximum depth of dealloying measured in over 400 nickel-aluminum bronze components was compiled (Figure 16). Some of the components had been in seawater service as long as 15 years. The compilation indicates that in 4-percent nickel alloys, dealloying is limited to an approximate penetration depth of 6mm (1/4 in.). Since penetration as deep as 3mm (1/8 in.) has been observed in NAB castings having service time of 5 years and less, it is postulated that dealloying in nickel-aluminum bronze castings exposed to seawater becomes rate limited and decreases to no graphic (measurable) significance as a penetration depth of 6.3mm (1/4 in.) is approached. To date the U.S. Navy has not found a NAB casting with dealloying in excess of this value. Microstructural inspections have indicated that the depth of attack is strongly influenced by the size and distribution of microconstituents, and that coarser microstructures can result in deeper attack. The effect of environment is also reflected in these results since the NAB castings are often galvanically coupled to more noble alloys such as Monel which tend to aggravate dealloying, or coupled to slightly less noble alloys such as 70/30 Cu-Ni which can provide some cathodic protection (depending on relative area ratios).[5] Since the castings included in this study experienced a broad

spectrum of galvanic interaction, and a large sample was taken, it appears that even when unfavorable galvanic conditions exist, dealloying penetration depths may be limited to about 6mm (1/4 in). Under extremely unfavorable galvanic conditions, however, excessive surface corrosion would occur as has been shown previously.[5]

SUMMARY

The experience of the U.S. Navy with dealloying in seawater of aluminum bronze and nickel-aluminum bronze (4% minimum nickel) castings, and the most recent findings may be summarized as follows:

(1) Dealloying of duplex phase (alpha plus gamma-2) aluminum-bronze (AB) castings has repeatedly been shown to be a problem and is often undetectable by visual inspection. Dealloying depths in excess of 13mm (1/2 in.) have been observed on some AB castings.

(2) Dealloying has been diminished in cast components by the use of NAB alloys containing a minimum of 4-percent nickel. However, the microstructure of as-cast NAB will often contain non-equilibrium microconstituents (mixtures of retained beta and gamma-2) that are susceptible to dealloying attack.

(3) The use of a temper-anneal heat treatment in the range of 650-700°C (1200-1300°F) can further diminish susceptibility to dealloying in cast NAB by effecting a more complete transformation to an all alpha plus kappa structure, but the response of castings to heat treatment is also variable. It appears that heat treatment is highly effective on smaller castings having fine and uniformly distributed microconstituents, but large castings having coarser and more segregated microstructures are less responsive.

(4) Large NAB castings having nearly complete alpha plus kappa microstructures still exhibit susceptibility to dealloying along the alpha plus kappa eutectoid network. The effectiveness of heat treatment on the dealloying resistance of such castings is uncertain. Work is in progress to establish whether any significant improvement in dealloying resistance will occur.

(5) Dealloying in NAB castings containing a minimum of 4-percent nickel appears to be limited to a maximum penetration depth of approximately 6mm (1/4 in.) for service times of up to fifteen years. It is postulated that dealloying becomes rate limited and decreases to no graphic significance as a penetration depth of 6mm (1/4 in.) is approached.

(6) The dealloying inspection procedure currently used, which incorporates an eddy-current test method for non-destructive depth measurement, was found to be unreliable. An evaluation of an alternate eddy-current inspection procedure and assessment of other NDT approaches is currently underway.

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4. Zanis, C. A. and R. J. Ferrara, "Selective Phase Corrosion of Cast Nickel-Aluminum Bronze," Proceedings of Fourth Internaval Conference on Marine Corrosion, NRL (1972).

5. Zanis, C. A. and R. J. Ferrara, "Seawater Corrosion of Nickel-Aluminum Bronze," Transactions AFS (1974).

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TABLE 1 - COMPOSITIONS OF SOUND METAL AND DEALLOYED METAL FROM TYPICAL CAST COMPONENTS

IDENTIFICATION	CONDITION	COMPOSITION, WEIGHT %							
		Cu	Ni	Al	Mn	Fe	Si	Pb	Sn
CASTING I	SOUND METAL	84.8	0.00	9.20	0.30	4.97	0.12	0.00	0.03
	DEALLOYED METAL	86.7	0.00	7.13	0.26	2.50	0.08	0.00	0.03
CASTING II	SOUND METAL	79.3	5.10	8.70	2.18	5.50	0.00	0.00	—
	DEALLOYED METAL	84.7	3.03	7.10	1.82	2.50	0.00	0.00	
CASTING III	SOUND METAL	81.4	4.72	8.40	1.20	4.20	0.00	0.00	
	DEALLOYED METAL	86.3	3.02	7.11	0.48	2.10	0.05	0.00	

TABLE 2 - MILITARY SPECIFICATIONS COVERING CAST ALUMINUM BRONZE AND NICKEL-ALUMINUM BRONZE ALLOYS USED BY THE U.S. NAVY

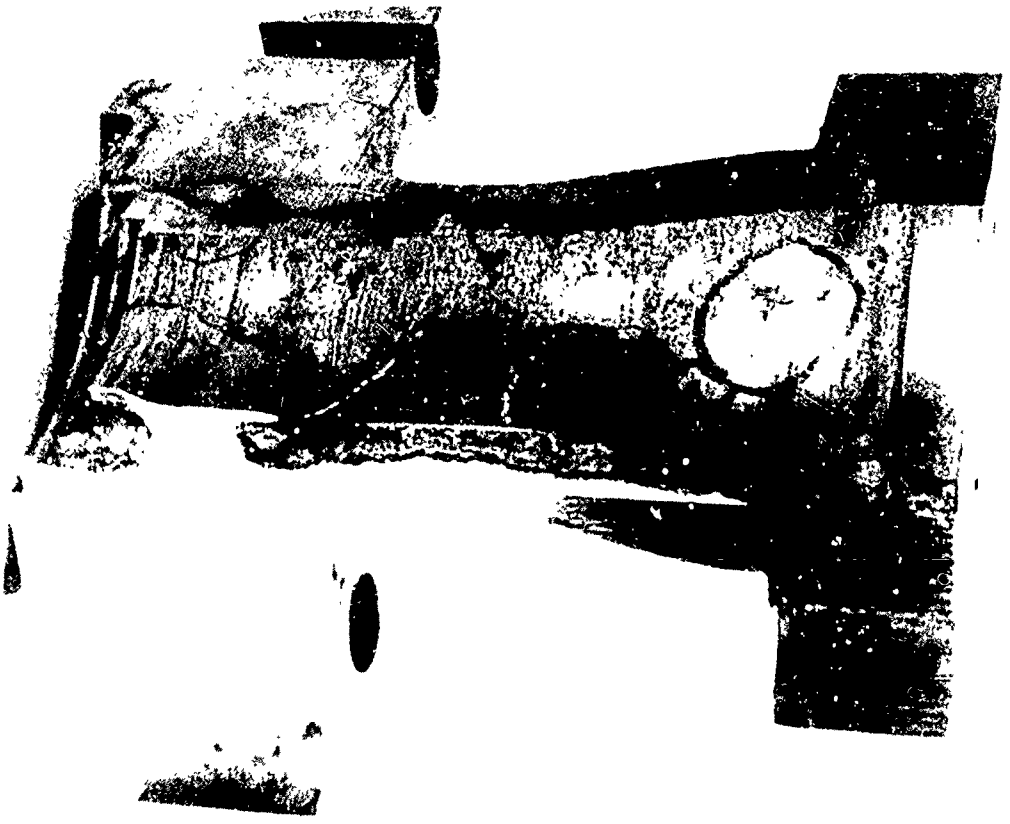
SPECIFICATION	YEAR ISSUED	COMPOSITION, WEIGHT %							
		Cu	Mn	Ni	Fe	Al	Si	Pb	OTHERS
MIL-B-16033	1951								
CLASS 1		86.0 MIN.	–	–	2.50/4.00	8.50/9.50	–	–	0.50 MAX.
CLASS 2		86.0 MIN.	–		0.75/1.50	9.00/11.00	–	–	0.50 MAX.
CLASS 3		83.0 MIN.	0.50 MAX.	2.50 MAX.	3.00/5.00	10.00/11.50	–	–	0.50 MAX.
CLASS 4		78.0 MIN.	3.50 MAX.	3.00/5.50	3.00/5.00	10.00/11.50	–	–	0 50 MAX.
MIL-B-21230A ALLOY 1	1960	78.0 MIN.	3.50 MAX.	3.00/5.50	3.00/5.00	8.50/11.00	–	0.03 MAX.	0.50 MAX.
MIL-B-23921	1963	78.0 MIN.	3.50 MAX.	4.00/5.50	3.00/5.00	8.50/9.50	0.10 MAX	0.02 MAX.	0.50 MAX.
MIL-B-24480	1973	79.0 MIN.	0.75/1.50	4.00/5.00	3.50/4.50	8.50/9.50	0.10 MAX.	0.03 MAX.	0.50 MAX.

TABLE 3 - CHEMICAL ANALYSES OF ALUMINUM BRONZE CASTINGS DEALLOYED IN SEAWATER SERVICE

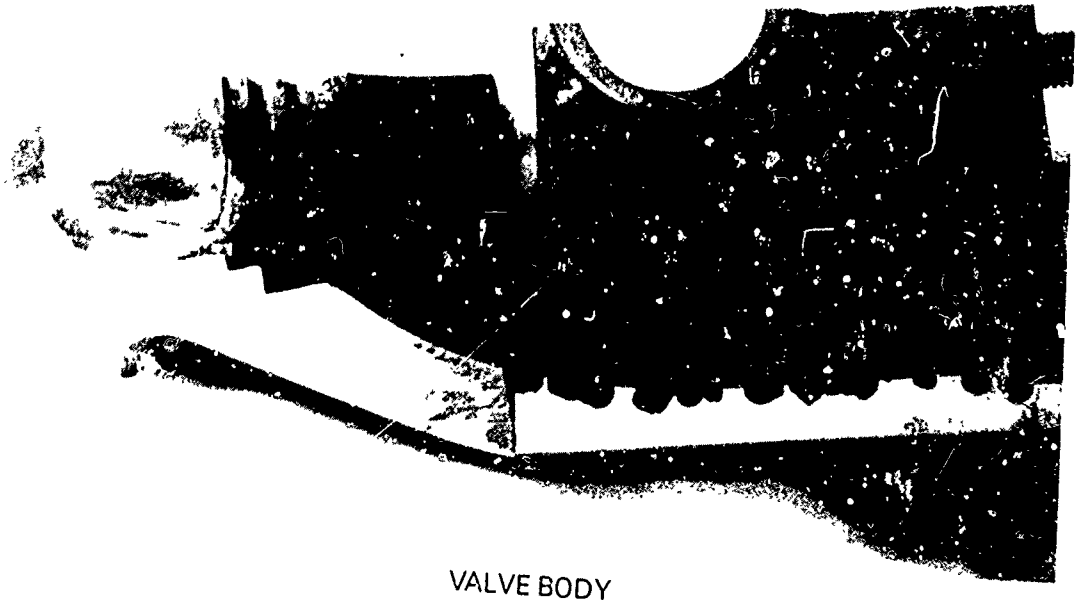
ITEM	COMPOSITION, WEIGHT %					
	Cu	Al	Fe	Mn	Ni	TOTAL OTHERS
SPECIFICATION MIL-B-16033 CLASS 3	86.0 MIN	10.00 / 11.50	3.00 / 5.00	0.50 MAX	2.50 MAX	0.50 MAX
VALVE BODY	83.3	11.6	3.6	0.20	0.05	1.25
TAILPIECE	83.4	11.2	4.9	0.26	0.02	0.22

TABLE 4 - CHEMICAL COMPOSITIONS OF CAST NICKEL-ALUMINUM BRONZE ALLOYS USED IN SEAWATER CORROSION TESTS

	COMPOSITION, WEIGHT %						
ALLOY	Cu	Al	Fe	Ni	Mn	Si	Pb
A1	81.93	9.27	3.80	4.17	0.71	0.03	0.03
A2	80.95	9.07	3.93	4.12	1.83	0.03	0.03
C1	79.68	9.00	5.00	5.24	0.90	0.03	0.03
C2	78.66	9.16	4.50	5.38	2.09	0.04	0.03
SPECIFICATION MIL-B-23921	78.0 MIN	8.50 / 9.50	3.00 / 5.00	4.00 / 5.50	3.50 MAX	0.10 MAX	0.02 MAX

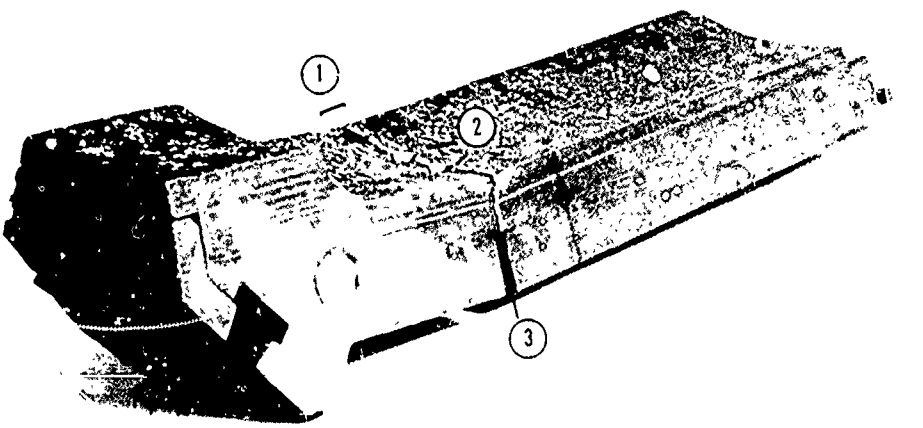


VALVE TAILPIECE

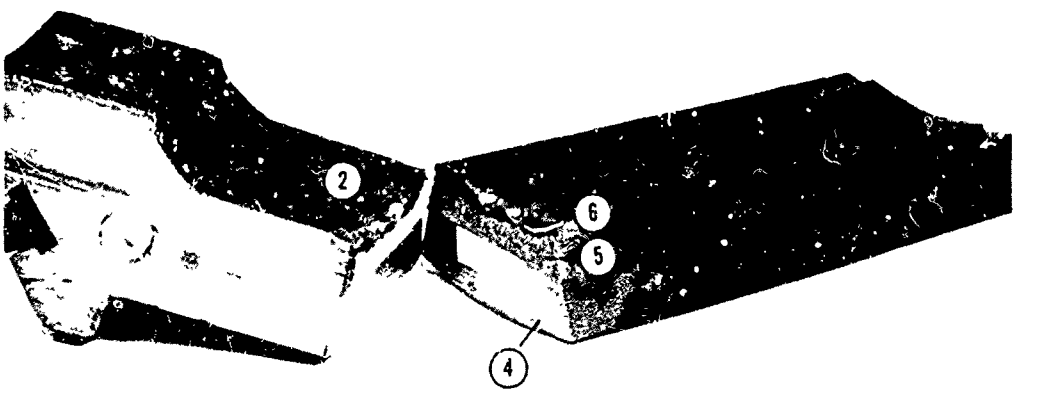


VALVE BODY

Figure 1- Appearance of Dealloying on Fracture Surgaces of MIL-B-16033 Class 3 Alloy Components



EDDY CURRENT AND SUBSURFACE SILVER NITRATE ON TEST SECTION



FRACTURE OF TEST SECTION TO REVEAL DEALLOYING ON FRACTURE SURFACE

Description

1. Area inspected by eddy current
2. Excavations for subsurface silver nitrate test
3. Saw cut to define plane of fracture
4. Saw cut area
5. Fracture area
6. Dealloying revealed on fracture face

Figure 2- Inspection Procedure Evaluation Method

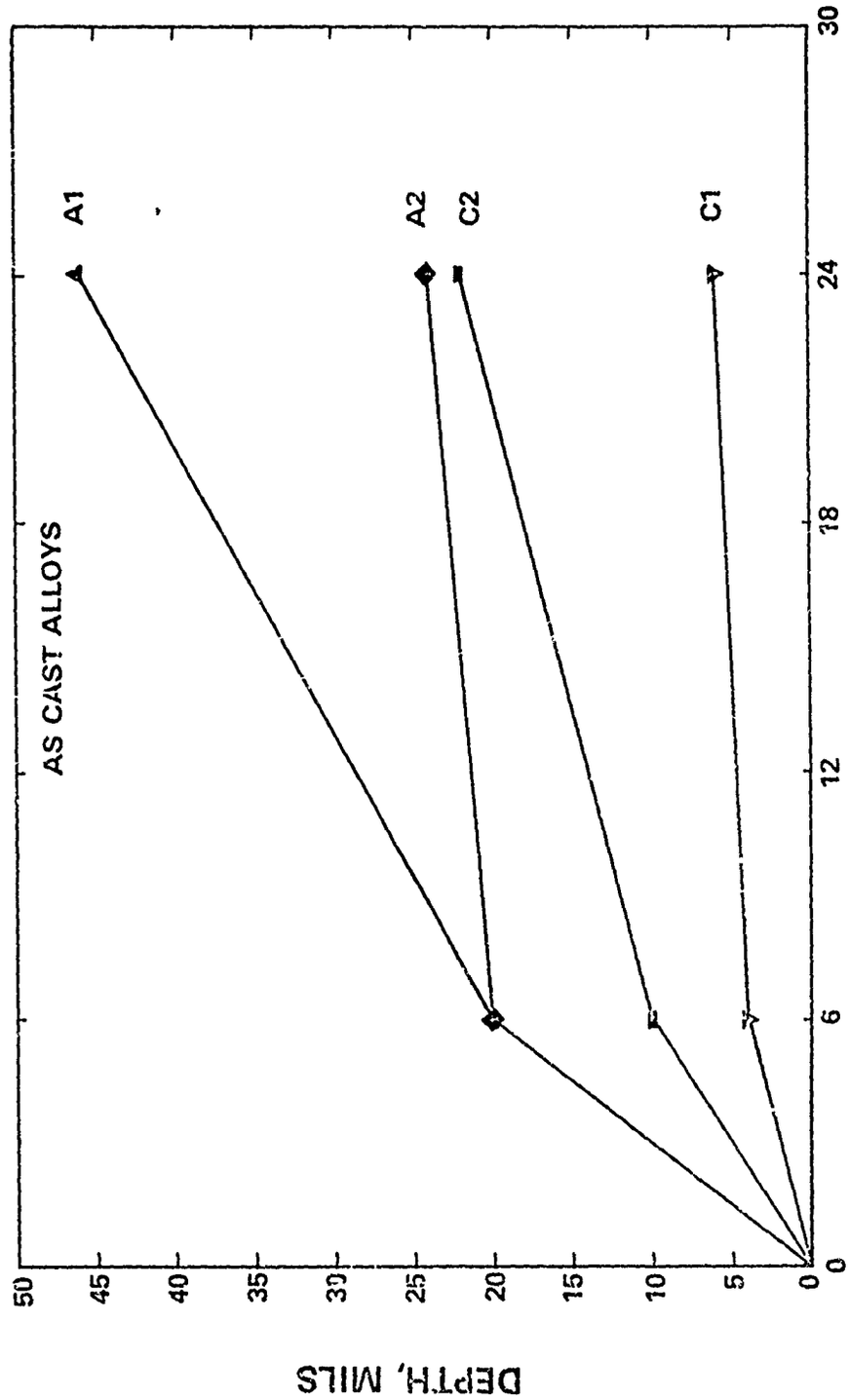


Figure 3 - Dealloying Depths Measured on As-Cast NAB Alloys After Six-Months and Twenty-Four-Months Immersion in Seawater

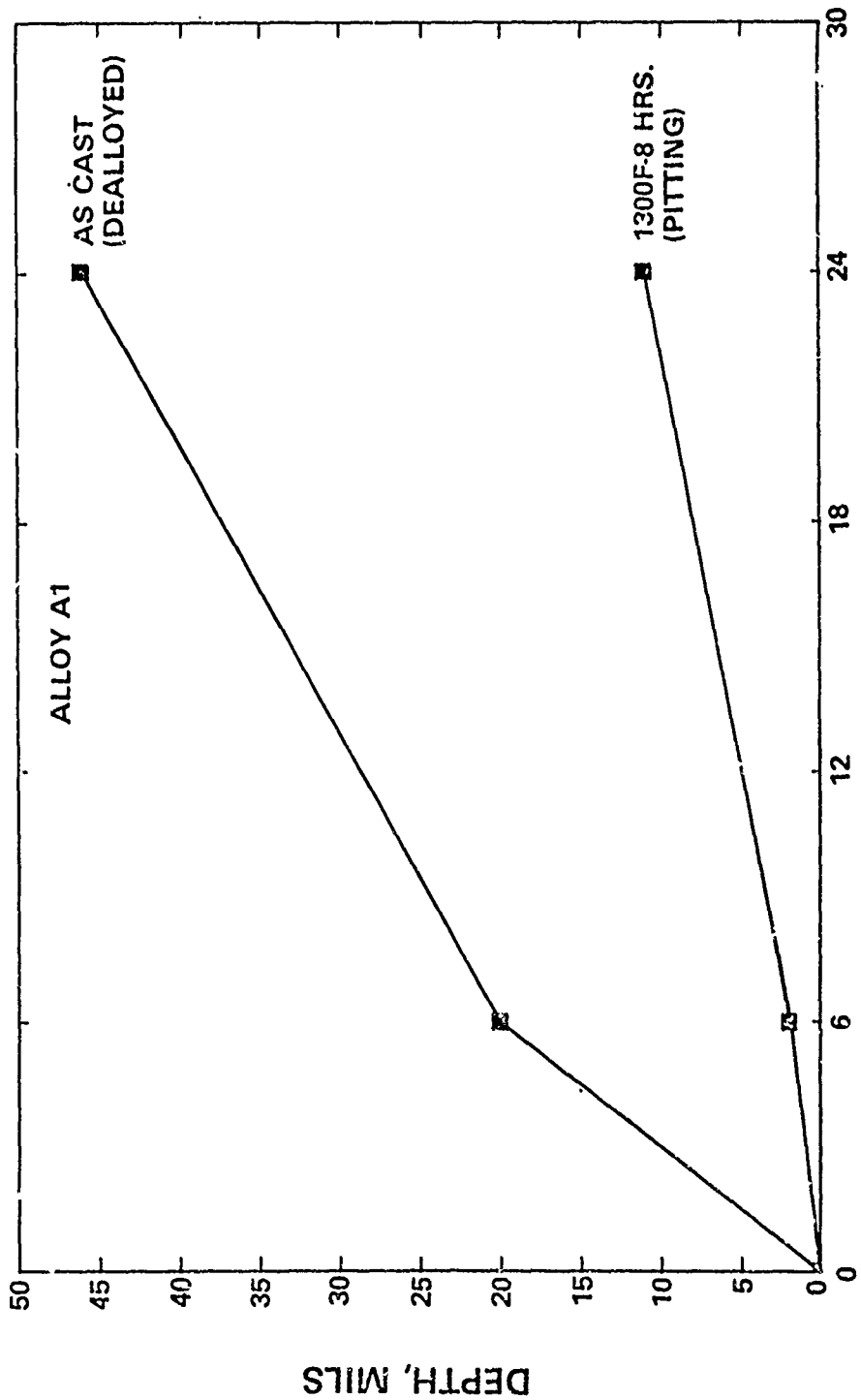


Figure 4 - Effect of Heat Treatment on the Seawater Corrosion Behavior of Alloy A1

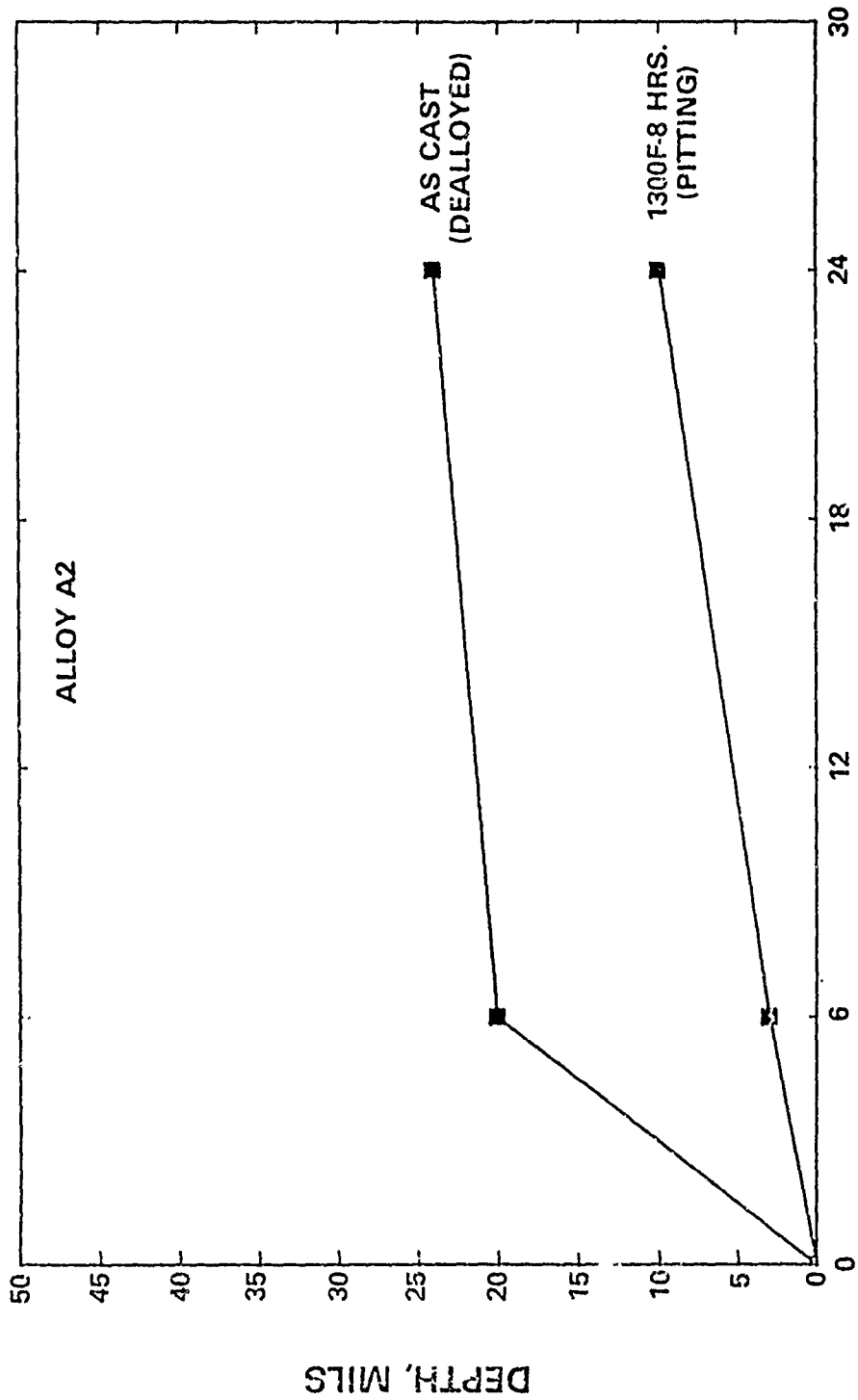


Figure 5 - Effect of Heat Treatment on the Seawater Corrosion Behavior of Alloy A2

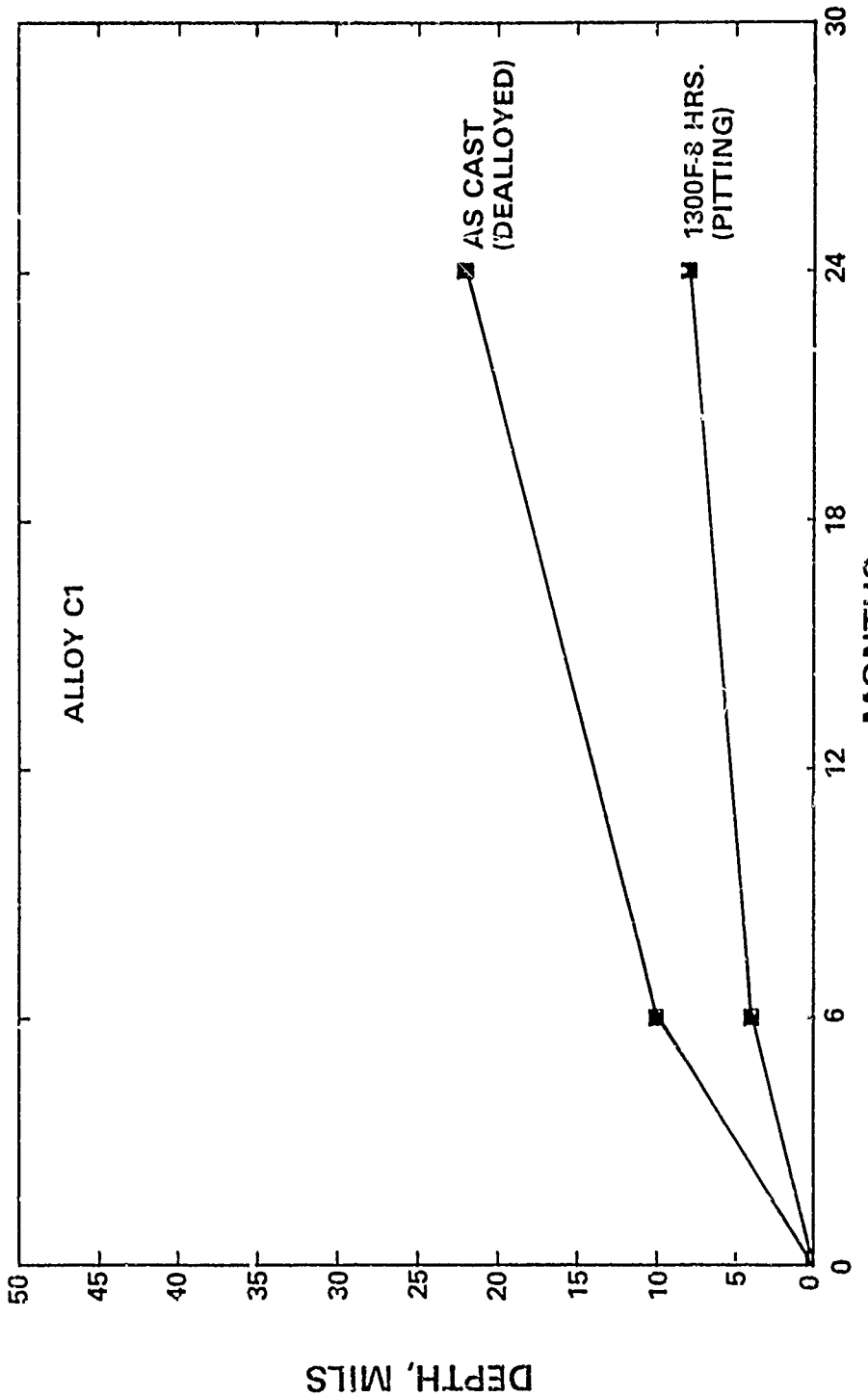


Figure 6 - Effect of Heat Treatment on the Seawater Corrosion Behavior of Alloy C1

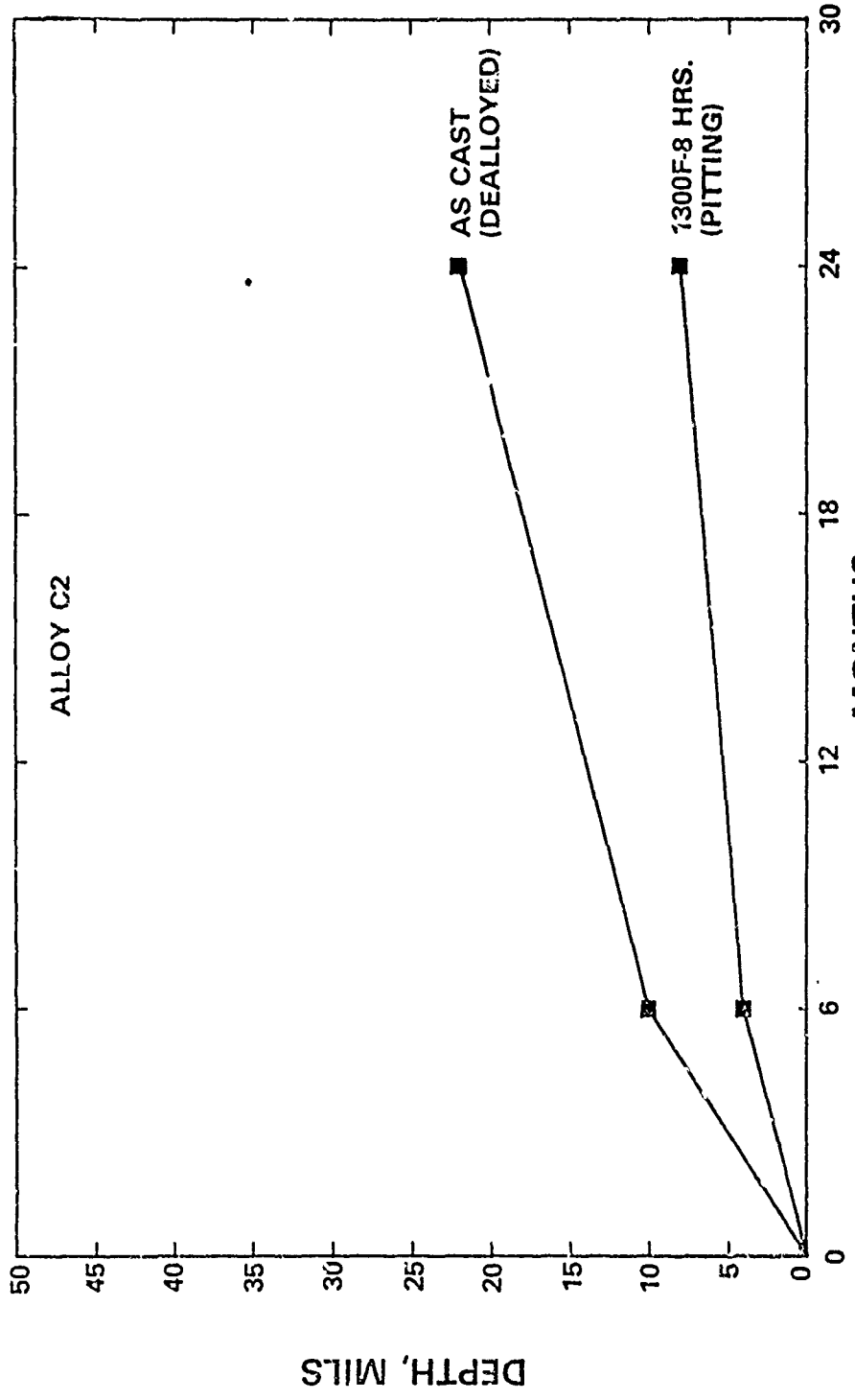


Figure 7 - Effect of Heat Treatment on the Seawater Corrosion Behavior of Alloy C2

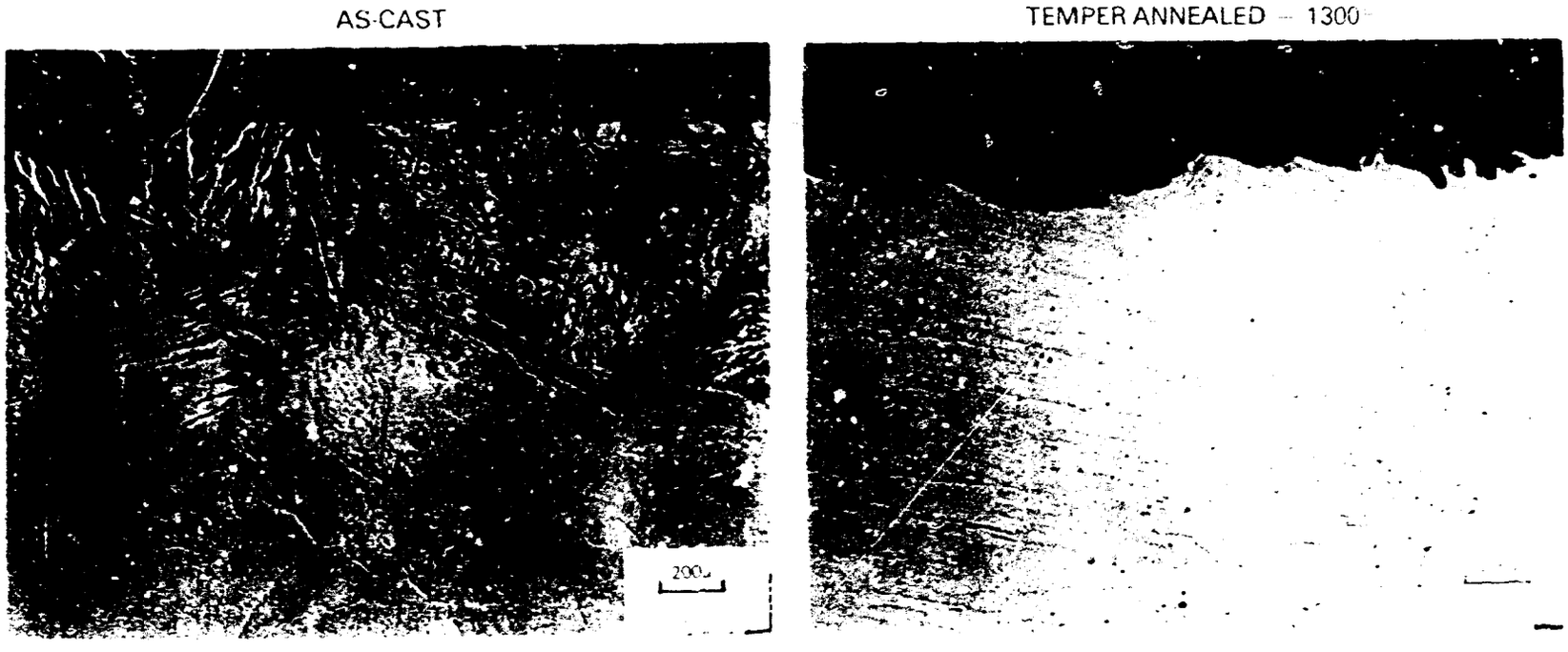


Figure 8- Corrosion of As-Cast and Temper Annealed Nickel-Aluminum Bronze Alloys After 24-Months Immersion in Seawater, Alloy A1

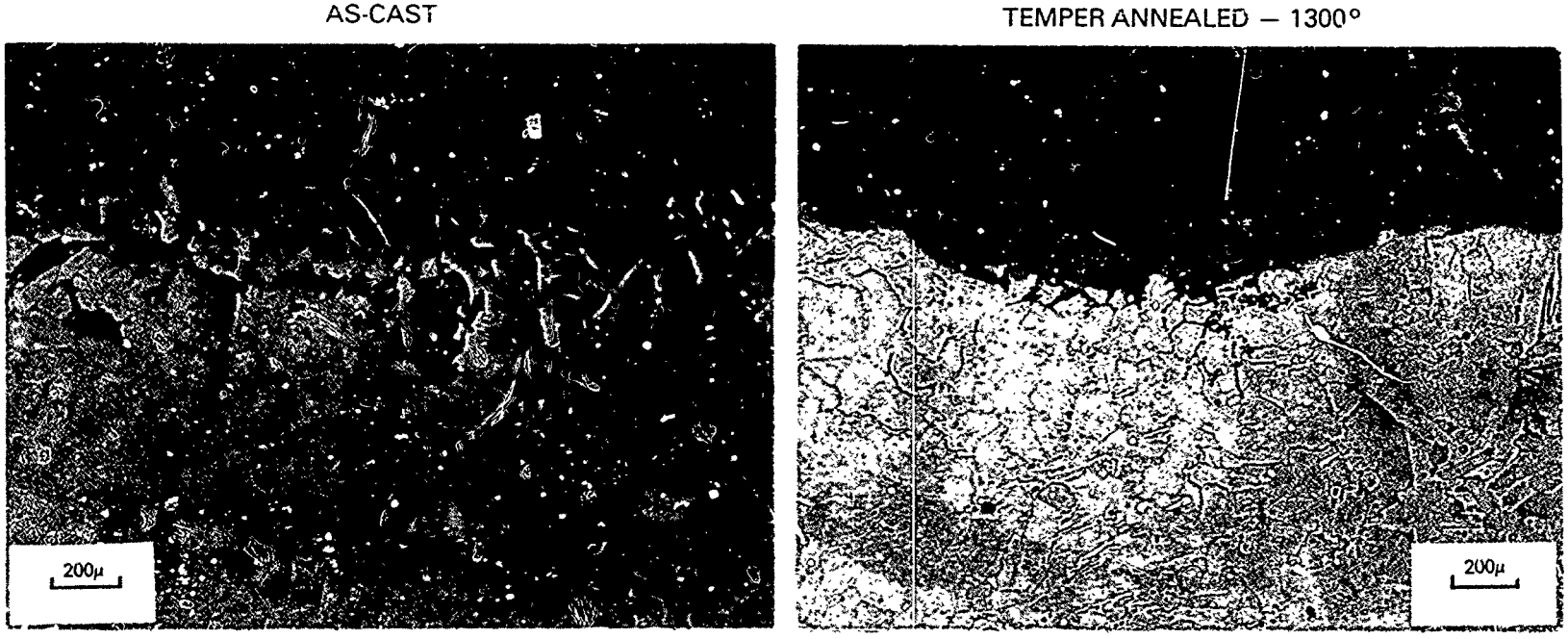


Figure 9- Corrosion of As-Cast and Temper Annealed Nickel-Aluminum Bronze Alloys After 24-Months Immersion in Seawater, Alloy A2

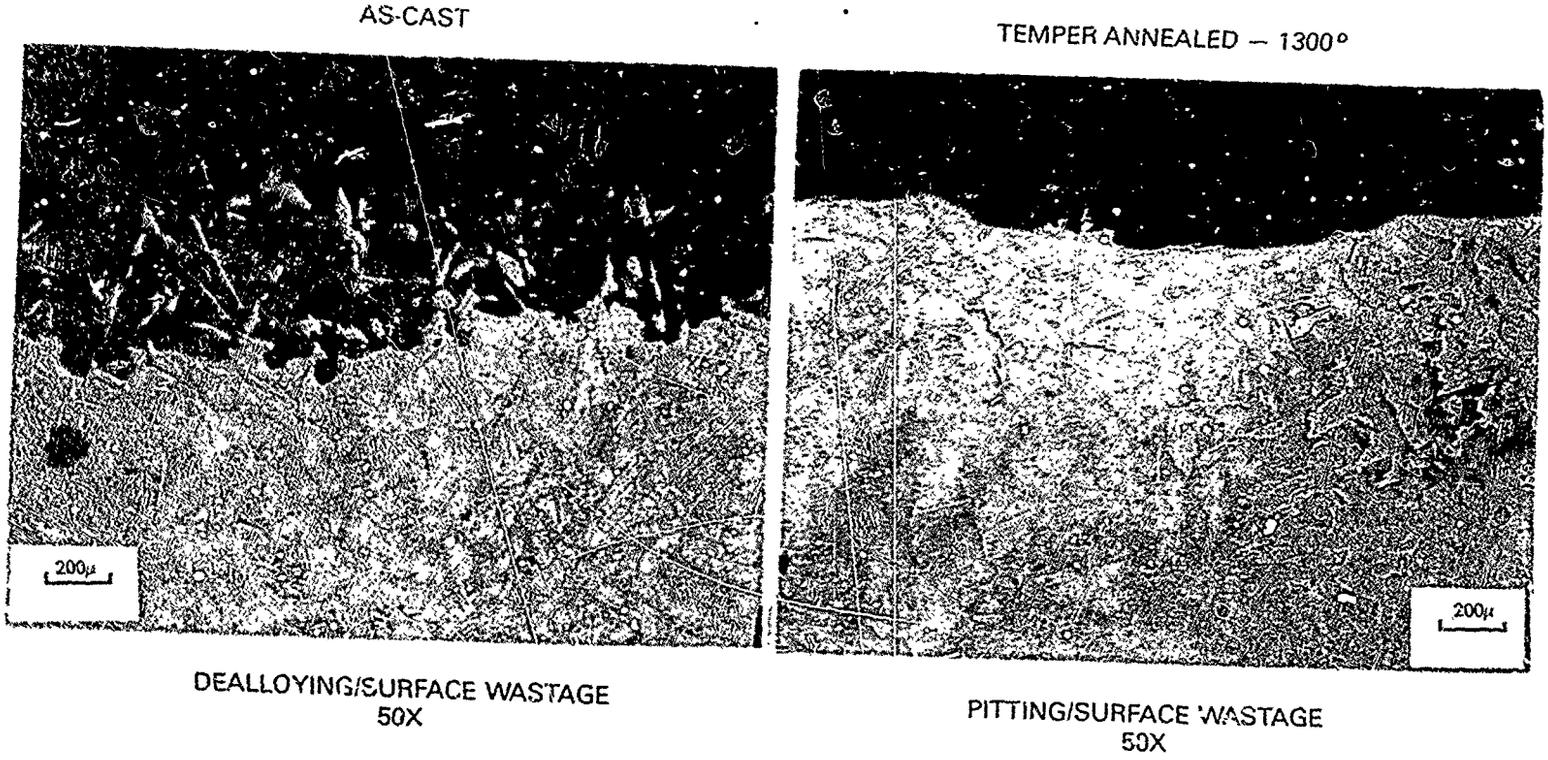


Figure 10- Corrosion of As-Cast and Temper Annealed Nickel-Aluminum Bronze Alloys After 24-Months Immersion in Seawater, Alloy C1

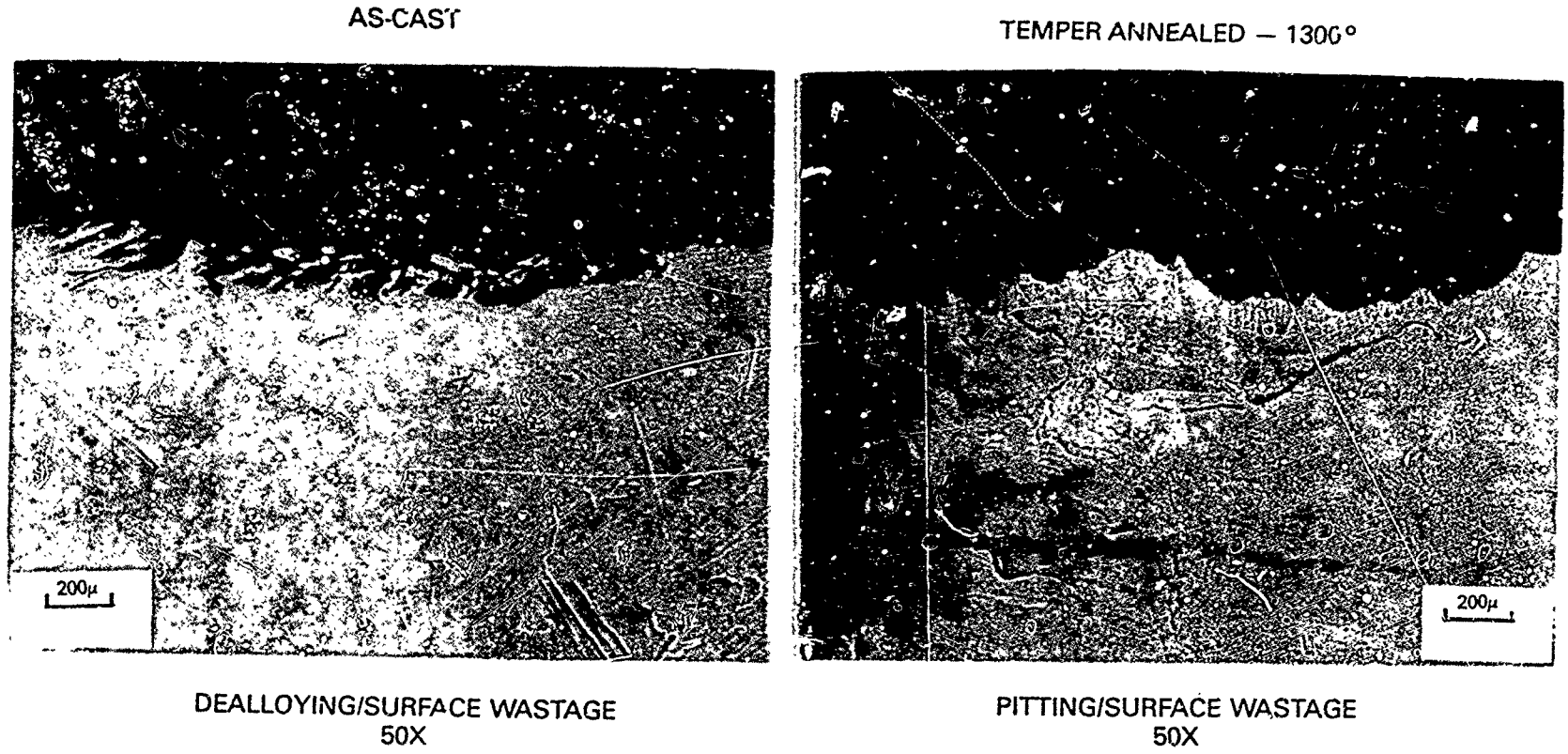


Figure 11- Corrosion of As-Cast and Temper Annealed Nickel-Aluminum Bronze Alloys After 24-Months Immersion in Seawater, Alloy C2

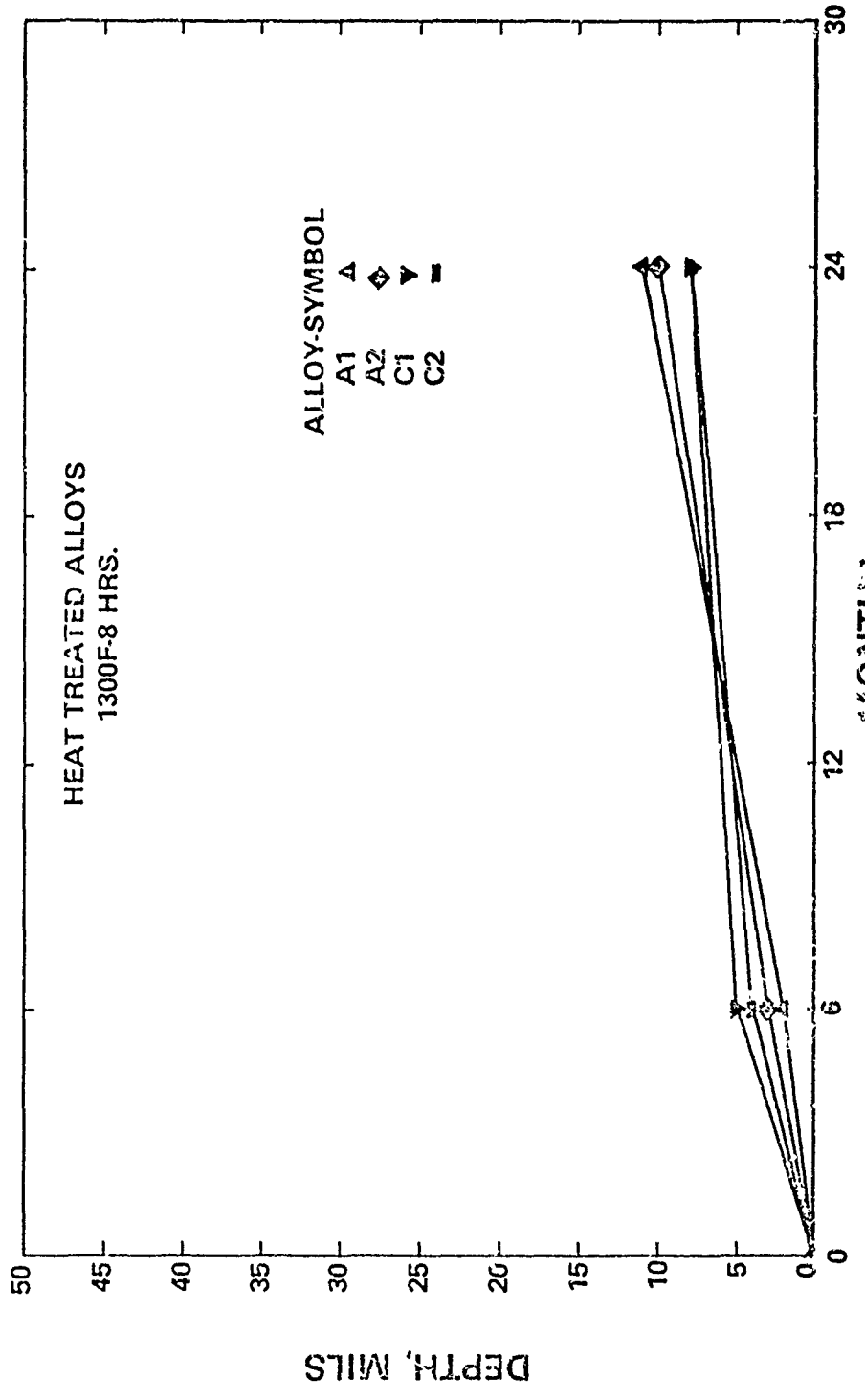
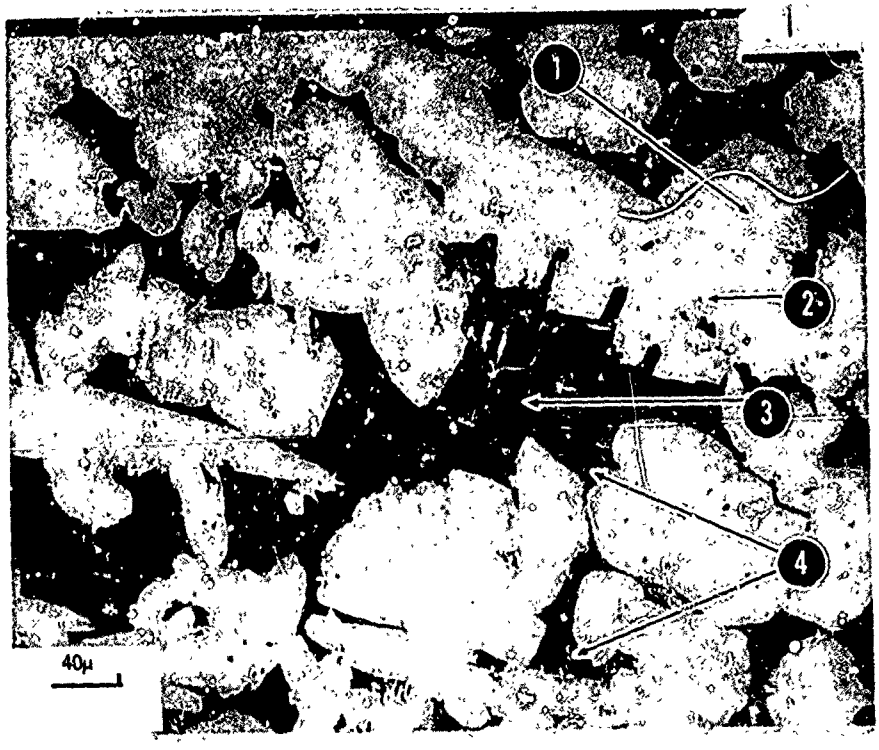


Figure 12 - Pitting Depths Measured on Heat Treated Alloys After Six-Months and Twenty-Four-Months Immersion in Seawater

Figure 13- Aluminum-Bronze Casting: Microstructural Comparisons of Dealloyed Metal and Sound Metal



1 ALPHA PHASE
2 IRON-KAPPA PHASE
3 RETAINED BETA
4 ALPHA + GAMMA-2 EUTECTOID

Figure 14- Microstructural Features of Aluminum-Bronze (MIL-B-16033, Class 3 Alloy) (250X)

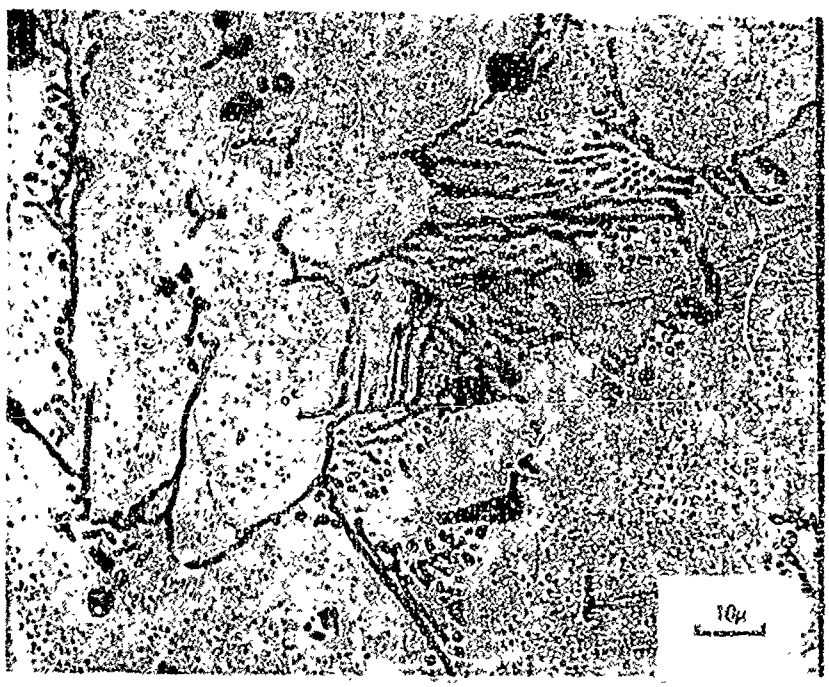


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Figure 15- Corrosion Attack of Ni-Kappa and Fe-Kapp Phases on NAB Casting Used for Seawater Service

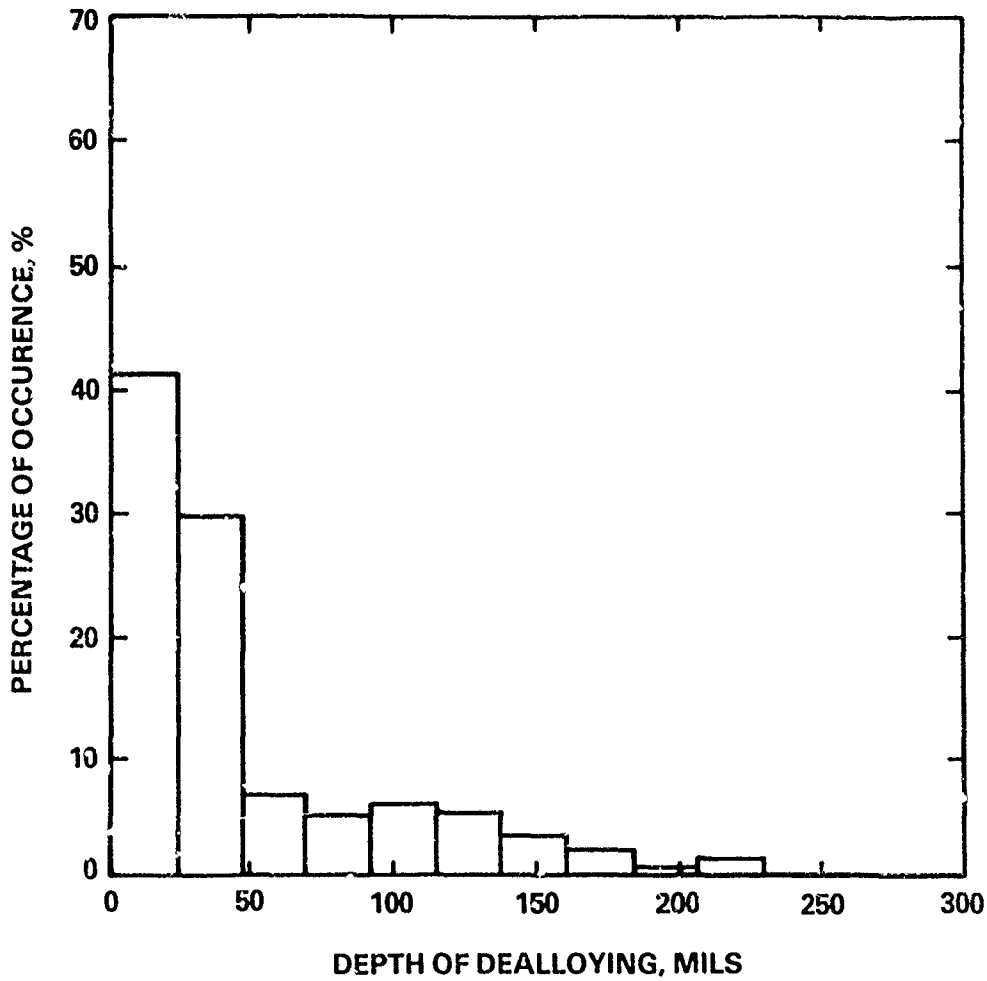

Figure 16- Maximum Depth of Dealloying in 402 NAB Castings

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80 OCT 1980

TESTING OF EXTERNAL COATING SYSTEMS FOR THE CORROSION CONTROL OF STEAM VALVES

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Enclosure (1)

DEPARTMENT OF THE NAVY
NAVAL SEA SYSTEMS COMMAND
WASHINGTON, D.C 20362

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ABSTRACT

Accelerated corrosion tests were performed on wire sprayed aluminum coatings and on coatings containing aluminum flakes in inorganic binders in order to assess capabilities of preventing service corrosion of shipboard steam valves. Simulated valve-shaped specimens and associated stud and nut hardware were coated with different protective systems and subjected to controlled alternate high temperature and salt spray mist corrosion cycles. The paper describes the coating systems studied, the method of test, the assessment techniques employed, and the results obtained from the evaluations. Discussion is given to conclusions reached from this program which are being incorporated into applicable standards and corrosion advisories for Fleet-wide use.

BACKGROUND

In recent years the Navy significantly has increased its efforts to minimize corrosion problems within the Fleet. A major stimulus for this effort is the decreased manning levels aboard modern ships with less time available for unnecessary maintenance. One major area of concern has been the continuous corroding of high temperature steam valves. Steam valve preservation is a chronic problem in surface ships because the heat resistant aluminum paint utilized for this service (per current specifications) does not hold up for more than a few months. Excessive amounts of work hours are wasted in the preparing and repainting of corroded valves because of the failure of the paint system. In this regard, industrial literature and several Naval applications indicated that coatings such as wire sprayed aluminum (WSA) and aluminum flakes in inorganic binders have the capability of decreasing corrosion on shipboard items. One of the first reports of satisfactory results using WSA in the Navy was in preserving of selected items onboard aircraft carriers. Using the same techniques, the Commander of Naval Surface Forces Pacific (COMNAVSURFPAC) satisfactorily coated various items on several ships (including the USS WILLIAM H. STANDLEY (CG-32) and the USS SCHOFIELD (FFG-3)) with wire sprayed aluminum. COMNAVSURFPAC has also studied coatings which are basically aluminum flakes in an inorganic binder.

In general, the advantages of coating systems containing aluminum were evident; however, prior to promoting implementation on a Navy-wide basis, it was considered advisable to evaluate the serviceability of different coating systems under closely controlled laboratory conditions. Laboratory testing permitted side-by-side comparisons of various promising coatings. In this way, untoward systems could be discarded and sensitive variables in promising systems could be identified and better controlled.

APPROACH

Test specimens representative of the candidate systems were exposed to controlled corrosive environments and then examined for coating deterioration. The coatings used for testing included (but were not limited to) material coatings used aboard the USS SCHOFIELD and the USS WILLIAM STANDLEY and the presently-used heat resistant paint. The particular coating systems tested were:

(1) Wire sprayed aluminum (WSA), oxyacetylene, plus SA sealer.

(2) Wire sprayed aluminum (WSA), oxyacetylene, plus DOD-P-24555 paint.

(3) Wire sprayed aluminum (WSA), electric arc plus SA sealer.

(4) Wire sprayed aluminum (WSA), electric arc plus DOD-P-24555 paint.

(5) DOD-P-24555 paint on wire brushed surface.

(6) DOD-P-24555 paint on grit blasted surface.

(7) Sermetel 725.

(8) Sermetel 249 plus 737 A sealer.

(9) Alseal 500.

(10) Sermetel 725 fastener formulation.

(11) Ion vapor deposited aluminum

Best Available Copy

Systems 1 through 9 are systems pertaining to preservation of valves. Systems 10 and 11 pertain to coating of valve hardware (Nuts and Studs).

For testing purposes, a high temperature salt spray test chamber was designed and constructed so that coated specimens could be exposed for prolonged periods at elevated temperatures as well as to a corrosive environment. The test specimens were heated intermittently to 925° ± 25° F and sprayed (at room temperature) with 5% salt solution. The testing cycles were highly agressive in order to simulate accelerated service use.

For the evaluation, visual examination and thickness measurements were performed before, during, and after the testing cycles. Metallurgical examinations were performed on the various test specimens following the full test period. Evaluation of the effectiveness of the different coatings was made based on comparisons of obtained results.

DESCRIPTION OF COATINGS EVALUATED

The coating products used in the test program included:

Wire sprayed aluminum, oxygen fuel gas: Layer of pure aluminum which is deposited onto a substrate by spraying small drops of melted aluminum. The aluminum wire is melted within a thermal spray gun by a high temperature flame produced from oxygen and a fuel gas. For the test specimens, acetylene was used as the fuel gas, the abrasive grit was aluminum oxide of 20-50 grit, the wire was 1/8" diameter and the time between blasting and spraying was 2 hours maximum.

Wire sprayed aluminum, electric arc: Layer of pure aluminum applied using a thermal spray gun whose heat source is an electric arc struck between two aluminum wires. The molten material is atomized by high velocity compressed air jet. For the test specimens the abrasive grit was aluminum oxide of 20-50 grit and the wire was 14 gauge and the time between blasting and spraying was 2 hours maximum.

SA sealer: Silicone-alkyd sealer with aluminum flakes specifically produced by METCO Co. for sealing WSA coatings used at elevated temperatures.

Sermetel 725: Two coat system with Sermetel W as basecoat and Sermaseal 570A as topcoat produced by Sermetel Co. Sermetel W is an inorganic water-base material containing aluminum powder which is cured at 650°F. Sermetal 570A is an inorganic water-based chromate/phosphate coating which acts as sealer for Sermetel W.

Sermetel 249 plus 737A sealer: Sermetel 249 is an aqueous paint-on inorganic metallic coating which is air dried. The coating is primarily high purity aluminum and zinc powder. The 737A sealer is a proprietary sealer designed for Sermetel 249 by Sermetel INC.

Alseal 500: Coating consisting of aluminum powder in an organo-inorganic binder. Coating is final cured at 1000°F. Coating on test specimens were baked at 300°F for 20 minutes between two coats and cured at 1000°F. Coating is produced by "Coatings for Industry, Inc."

DOD-P-24555: Heat resisting, low emissivity aluminum pigmented paint for use up to 1200°F.

Sermetel 725 fastener formulation: A "modified" Sermetel 725 coating with finer grained aluminum for applying onto fasteners.

IVD Aluminum: Ion vapor deposited aluminum is aluminum which has been vaporized, partially ionized, and then allowed to condense onto the surface. Coating was used only for fasteners. Coating is typically 0.0003 - 0.0015 in. thick.

CORROSION TESTING

A. Test Specimens

The test specimens used in the elevated temperature salt spray test consisted of (1) valve-shaped specimens to evaluate various coating systems, (2) straight pipe sections to test various thicknesses of WSA coatings and (3) studs/nuts to test coatings on steam valve hardware. All materials were alloy steels which are rated for 1000°F and which are similar to actual shipboard materials.

Valve-Shaped Specimens: The valve-shaped specimens were 15" long tee shaped assemblies fabricated by welding together two flanges, a pipe tee straight pipe section and a plug. A typical uncoated assembly is shown in Figure 1. The valve-shaped specimen was selected rather than the use of actual valves or solely straight pipe sections because this configuration:

(1) provided a complex shape (similar to a valve) to which the coatings had to be applied.

(2) provided a means of easily joining (bolting) the specimen together.

(3) provided a relatively large surface area which could be evaluated.

(4) was less costly than actual flanged valves.

B. Construction/Design of Test Set-Up

Test set-up consisted of the test specimen assembly, the heating system, and the salt spray system.

Test specimen assembly: The valve-shaped specimens were bolted together in three series with each series containing seven specimens. The three series were then bolted to the two manifolds which were connected to the plant boiler and the condenser. The resulting assembly contained three parallel paths of valve-shaped specimens with a common inlet and common outlet. The assembly was housed in a spray chamber. The completed assembly is shown in Figure 2. A schematic of the respective positions of the valve-shaped specimens is shown in Figure 3.

In the assembly, each joint made up of two mating flanges contained one "sermeteled" stud/nut assembly, one IVD stud/nut assembly, one stud/nut assembly coated with DOD-P-24555 and one stud/nut assembly coated with SA sealer. The DOD-P-24555 paint and SA sealer were applied after the studs and nuts were tightened.

The types of coatings, the number of specimens used for each coating and the sample identification for the valve-shaped specimens were as follows:

	No. of Specimens	Sample I.D.	Notes
WSA using oxy-acetylene, no sealer	1	No. 14	(a)
WSA using oxy-acetylene, SA sealer	2	Nos. 13, 17	(a)
WSA using oxy-acetylene, DOD-P-24555	2	Nos. 5, 16	(a)
WSA using electric arc, no sealer	1	No. 8	(a)
WSA using electric arc, SA sealer	2	Nos. 9, 10	(a)
WSA using electric arc, DOD-P-24555	2	Nos. 15, 18	(a)
Sermetel 725	2	Nos. 1, 2	
Sermetel 249 plus 737	2	Nos. 3, 4	
Alseal 500	2	Nos. 6, 7	
DOD-P-24555 on wire brushed surface	1 1/2	Nos. 11, 19	(b)
DOD-P-24555 on grit blasted surface	1 1/2	Nos. 20, 19	(b) (c)
Uncoated	1	No. 12	

(a) Metcolite C grit used, (12-35 mesh).
(b) To increase number of samples 1/2 of sample was wire brushed, 1/2 was grit blasted.
(c) Al_2O_3 grit size 30 was used.

Studs and Nuts To evaluate coating systems for steam valve hardware, the 1"-8 UNC 2A studs and UNC 1"-8 2B nuts used in the bolting of the valve-shaped specimens were coated with candidate systems. 16 studs and 32 nuts were coated with 0.0010-0.0015 in. of IVD aluminum; 24 studs and 48 nuts coated with 0.001-0.003 in. of Sermetal 725 fastener formulation; the remaining stud and nuts were coated with either DOD-P-24555 paint or SA sealer. The IVD and Sermetel coatings were applied by facilities experienced in these coatings; the painting was performed by NAVSSES.

Other 1"-8 stud/nut assemblies were used to evaluate the effort needed to remove nuts from studs which end threads had been WSA coated. This condition occurs when completely assembled valves are sprayed. For the test, nuts were threaded onto the stud until 2, 4, or 6 threads were exposed. The exposed threads were then coated with approximately 0.010-0.015 in. thick WSA (oxyacetylene). These stud/nut assemblies were hung from the cross beams inside the chamber. Unlike the stud/nuts used in the construction, the hung assembly only experienced the corrosive environment and not the elevated temperatures.

Ancillary Piping Specimens

The assembly of valve-shaped specimens were connected to the boiler and condenser by means of an inlet and outlet manifold. The manifolds were constructed by welding together tees, elbows and straight pipe sections, and were located within the spray chamber. Construction of the manifold assembly at one end of the test loop is illustrated in Figure 4. The straight pipe sections (ranging from 6 to 18 in. long) were used as ancillary test specimens for determining whether spalling would occur when thick layers of WSA (oxyacetylene) coatings were exposed to elevated temperatures. For the test, the various sections were sprayed with thicknesses ranging from 0.004 to 0.024 in. in increments of 0.004 in. (approx.), sealed and then welded to form the manifold. The system was P-1 rated; therefore, to ensure satisfactory weld joints, the coating in the area of the weld was removed on a lathe prior to welding.

Unintentionally AP (air dried phenolic) sealer was used in lieu of SA sealer on all but two of the prepared samples. Those two coated sections contained three distinct zones; one zone sealed with SA sealer, one zone with AP sealer, and one zone with no sealer. Comparison of the three zones was performed at the termination of the test.

Also, for the test, the pipe tees and elbows of the manifold were either coated with SA sealer, painted with DOD-P-24555 or unpainted after construction. None of these components were wire sprayed. The data was to be used in evaluating touch-up method for steam valves.

C. Heating System

The plant boiler to which the assembly was connected was capable of producing 1200 lb steam at 950°F. To check actual specimen temperature, thermocouples were attached to the common inlet and outlet legs, and also on each of the parallel runs. During the heating cycles insulation pads were placed on each of the flanged shaped specimens. The pads which were made of 2 in. of fiberglass felt and fiberglass cloth were used to provide more uniform heating and to facilitate obtaining the desired elevated temperature. Photograph of the insulated specimen is shown in Figure 5.

D. Spray System

System consisted of six spray nozzles (one positioned above each end of the three parallel legs), a PVC header to maintain constant solution level for nozzles, a 55 gal drum acting as large resevoir in which solution could be mixed, a pump and a timer. The nozzles were Type H601, air operated brass nozzles produced by Monarch; the pump was a polypropylene magnetic drive. During the spray cycle, the timer activated a solenoid valve and pump. The pump transferred the 5% salt solution from the large tank to the header while simultaneously air pressure caused a suction within the nozzle. The suction resulted in an atomization of the solution from each nozzle. The header provided a constant solution level which was necessary for a uniform spray pattern. Spray was applied while metal was at room temperature and with the insulation pads removed. A photograph of the valve-shaped specimens being sprayed with the 5% salt spray is shown in Figure 6.

E. Heating and Spraying Cycles

The 7 day schedule generally consisted of exposing the flanged-shaped specimens and manifolds to two eight hour heating periods, a weekly total of 32 hours of cool down time (925°F to ambient) and 120 hours of ambient environmental exposure. During the ambient environmental testing, high humidity salt environment was maintained continually by injecting the 5% salt spray into the cabinet 2-3 minutes every hour. A typical spraying and heating schedule is shown below. The schedule was altered occasionally to accommodate use of boiler for other in-house tests.

	1st 8 hr. Period	2nd 8 hr. Period	3rd 8 hr. Period
1st day	(1) Heat at 900 ± 25°F, No Spray	CP, (2) No Spray	CP, No Spray
2nd day	Heat at 900 ± 25°F No Spray	CP, No Spray	CP, No Spray
3rd day	AT, (3) Salt Spray	AT, Salt Spray	AT, Salt Spray
4th day	AT, Salt Spray	AT, Salt Spray	AT, Salt Spray
5th day	AT, Salt Spray	AT, Salt Spray	AT, Salt Spray
6th day	AT, Salt Spray	AT, Salt Spray	AT, Salt Spray
7th day	AT, Salt Spray	AT, Salt Spray	AT, Salt Spray

(1) Insulation pads were applied before heating on the first day, and removed prior to spraying.

(2) CP - Cool Down Period, boiler turned off and specimens allowed to cool from 925°F to ambient.

(3) AT - Ambient Temperature.

F. Information from Elevated Temperature Tests

During the elevated temperature salt spray test the specimens were exposed to 190 hours (30 cycles) at elevated temperature (925°F ± 25°F) 475 hours of cool down (925°F down to ambient), 1430 hours of high humidity (maintained by 2-3 min. spray every hour), and 600 hours of ambient temperature, no spray. Information obtained from this testing follows.

Thickness Measurements

Thickness measurements were performed using an Elcometer prior to exposure, several times during exposure and following the complete exposure period. Readings initially were taken at 24 locations to determine thicknesses and uniformity of coating; subsequent readings were performed at 6 of these locations to monitor any changes in thicknesses.

Visual Examination and Photographic Documentation

Visual examination and photographic documentation were performed periodically throughout the testing cycle.

Valve-Shaped Specimens

Photographic and descriptions of the surface conditions of each of the valve-shaped specimens were prepared. Typical photographs of the valve-shaped specimens after the complete exposure cycles are shown in Figures 7 through 11. Comparisons of the various types of coatings made based on the general appearances are presented below.

Comparison Between	Comment
WSA oxyacetylene, SA Sealer and WSA oxyacetylene, DOD-P-24555	Very little difference between coatings
WSA oxyacetylene, No Sealer and WSA oxyacetylene, SA Sealer or WSA oxyacetylene, DOD-P-24555	Specimen with no sealer showed more white deposits on all surfaces and was slightly more rusty around holes than either of sealed coatings
WSA Electric Arc, SA Sealer and WSA Electric Arc, DOD-P-24555	SA sealed specimen appeared slightly better. More white deposits on DOD-P-24555 sealed specimens. Some flaking of paint on painted specimen
WSA Electric Arc, No Sealer and WSA Electric Arc, SA Sealer or WSA Electric Arc, DOD-P-24555 Sealed	Specimen with no sealer showed more corrosion (particularly on flanges) than sealed specimens; however, original coating was thinner on "No Sealer" specimen than on other specimens
WSA oxyacetylene, Sealed and WSA Electric Arc, Sealed	Slightly more rust on flanges of WSA electric arc than on WSA oxyacetylene; however original coatings were thinner on WSA electric arc specimen
WSA oxyacetylene, Sealed vs Sermetel 725	The WSA specimens showed less rusting around bolt holes and on the flanges
Sermetel 725 vs Alseal 500	Alseal 500 specimens were slightly more corroded on flanges particularly near bolt holes. Some rust spots were evident on the horizontal pipe of one of the Alseal 500 specimens

Manifold Sections (Ancillary Piping)

Visual examination of the manifold sections showed that during the test program the WSA oxyacetylene sections became light brown in color; however, no corrosion was evident. The discoloration was apparently due to the effects of heat on the AP sealer. No spalling was found in any of the manifold WSA sections. Neither the SA sealer nor the DOD-P-24555 paint used to coat the base pipe tees and elbows withstood the elevated temperature salt spray tests; however, the DOD-P-24555 paint performed better than the SA sealer. The SA coating was completely depleted after 17 days; whereas, the same portions of the DOD-P-24555 paint lasted up to 54 days.

Bolt/Stud Specimens

Only the stud/nuts coated with "Sermetel 725 fastener formulation" showed good corrosion resistance during the test. The stud/nuts coated with the SA sealer and the DOD-P-24555 showed rusting after 17 days; the IVD studs/nuts showed significant corrosion at the 52 day inspection. The Sermeteled stud/nuts were only slightly rusted at the completion of the test (146 days). Photographs showing comparison of hardware is shown in Figure 12. The Sermeteled coating on the nuts beneficially slowed down the "sacrificing" action of the aluminum spray on the flanges. In many of the specimens, the flange surface around the nuts coated with the other methods were corroded; however, the areas around the Sermeteled nut was still protected.

G. Metallographic Examinations

Transverse cross sections were cut from the vertical leg, horizontal leg and flange area of the valve-shaped specimens, mounted metallographically and examined microscopically to determine the condition of the coatings following test exposure. Both optical and scanning electron microscopes were used in the examination. Thickness measurements made microscopically were in agreement with the ranges recorded by the elcometer. The bond between the coating and the substrate appeared good in all samples, showing little or no cracking at the interface. An oxide layer, which was not detected in the unheated specimens, was present at the interface of most of the samples. The oxide was highly adherent and was considered to be a high temperature oxide rather than a corrosion product.

Elemental mapping by energy dispersive x-ray analyses (EDXA) was performed on several of the transverse cross sections to determine if any diffusion of aluminum into the steel had occurred during the elevated-temperature salt spray test. Based on the elemental maps, no diffusion had occurred.

H. Bend Tests

As part of the evaluation, transverse cross sections from the manifold and from the valve-shaped specimens were bent intencionally to cause flaking of the coating. The exposed surface was then examined under low magnification (20X) to determine the condition of the substrate-coating interface. All the exposed surfaces contained a dull gray layer which was apparently an oxide layer which had formed during the elevated temperature exposure. Some of the surfaces were marked with small, sparsely distributed, specks of rust. In general, the rust specks appeared in the AP sealed manifold sections, but not in the SA or DOD-P-24555 sealed valve-shaped specimens nor the SA sealed manifold sections. In the AP sealed manifold sections the specks were evident even in the 0.025 in. thick coating. The rust specks were considered indications of through coating porosity.

I. Nut Removal Test

Photographs of the 1"-8 stud/nut assembly for the nut removal (backing-off test) are shown in Figure 13. Severe corrosion had occurred in the uncoated central portion of the stud; however, the WSA end threads showed no rusting. Upon backing-off of several of the studs, the coating flaked off and offered little resistance to the travel of the nut; however, other nuts (approx 2/3) became bound and could not be removed. The problem of binding increased as the number of exposed threads increased. Also the studs from which the nuts could be removed would have to be cleaned-up of remnant aluminum if the studs were to be reused.

CONCLUSIONS

Based on examinations of the valve-shaped specimens and the nut and stud appurtenances, the following conclusions were drawn:

1. WSA oxyacetylene with SA sealer, WSA oxyacetylene with DOD-P-24555 paint, WSA electric arc with SA sealer and WSA electric arc with DOD-P-24555 paint, Sermetel 725 and Alseal 500 all performed satisfactorily in the elevated temperature-salt spray test by significantly reducing the amount of corrosion.

2. The Alseal 500 specimens corroded slightly more than the Sermetel 725 samples; and. the WSA coatings provided slightly more corrosion resistance than the Sermetel 725 coatings, particularly around scratches or grooves.

3. The DOD-P-24555 paint and the Sermetel 249 plus 737 system provided only short term corrosion protection in an elevated temperature-salt spray environment. In addition, preparing the substrate by grit blasting (in lieu of wire brushing) provided little to no benefit when the standard heat resistant paint was applied.

4. Little or no difference was evident in the performance of the WSA coating applied by oxyactylene and that applied by electric arc. Also little or no diffference was noted between the WSA specimens sealed with SA sealer or with the DOD-P-24555 paint.

5. The WSA coatings proved to be more durable than the Sermetel 725 or the Alseal 500 coatings as evidenced during the grooving, machining and handling of the specimens.

6. Spalling of the coatings did not occur in any of the valve-shaped specimens or the manifold sections (up to 0.024 in. thick).

7. No diffusion of the coating was observed in any of the WSA, Sermetel or Alseal 500 specimens.

8. The DOD-P-24555 paint provided more protection of the bare steel components than the SA sealer; thereby, indicating that the DOD-P-24555 paint should be used for touch-up of any minor scratches or surface defects.

9. Sermetel 725 fastener formulation was the only coating which performed satisfactorily on the studs and nuts. Not only did the Sermetel coating reduce corrosion of the stud and nuts; but, by acting as a barrier coating between the nuts and coated flanges, it drastically slowed the sacrificing of the coating of the flanges.

10. Too heavy a Sermetel coating on fasteners caused problems with assembly and disassembly of joints. No problems were experienced with the IVD aluminum coated stud/nuts.

11. WSA spraying of assembled valve hardware will effectively minimize corrosion.; however, difficulty upon removal of the nut should be anticipated. In any instance, no more than three exposed threads should be WSA coated.

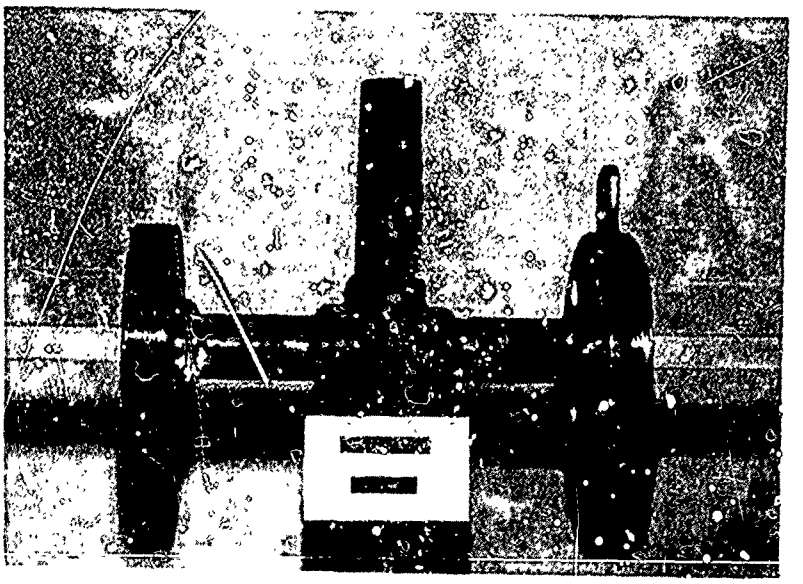

FIGURE 1 - UNCOATED FLANGE-SHAPED SPECIMEN;
15 in. LONG WITH 7 in. DIAMETER FLANGE

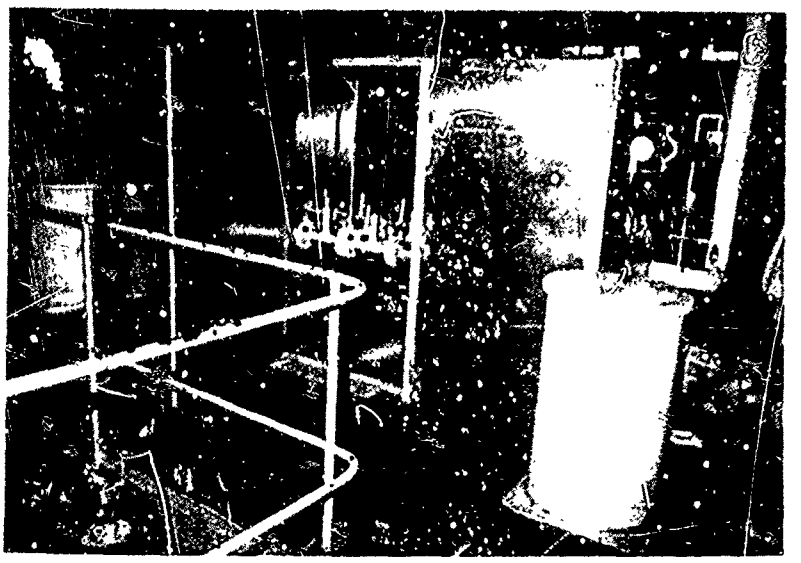

FIGURE 2 - ASSEMBLED SPRAY CAPSULE

FIGURE 3 - POSITIONS OF FLANGED-SHAPED SPECIMENS

SPECIMEN IDENTIFICATION

1. Sermetel 725
2. Sermetel 725
3. Sermetel 249 plus 737
4. Sermetel 249 plus 737
5. WSA, oxy-acetylene, DOD-P-24555
6. Alseal 500
7. Alseal 500
8. WSA, electric arc, no sealer
9. WSA, electric arc, SA sealer
10. WSA, electric arc, SA sealer
11. DOD-P-24555, wire brushed
12. Uncoated
13. WSA, oxy-acetylene, SA sealer
14. WSA, oxy-acetylene, no sealer
15. WSA, electric arc, DOD-P-24555
16. WSA, oxy-acetylene, DOD-P-24555
17. WSA, oxy-acetylene, SA sealer
18. WSA, electric arc, DOD-P-24555
19. DOD-P-24555, grit blasted/wire brush
20. DOD-P-24555, grit blasted
21. Uncoated

ENCLOSURE (1)

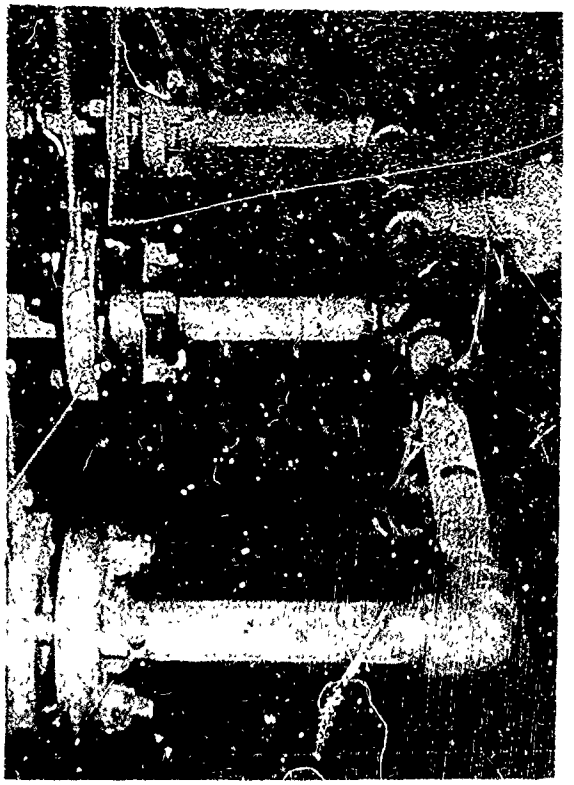

FIGURE 4 - ASSEMBLED INLET MANIFOLD

FIGURE 5 - VALVE-SHAPED SPECIMENS INSULATED FOR HEATING CYCLE

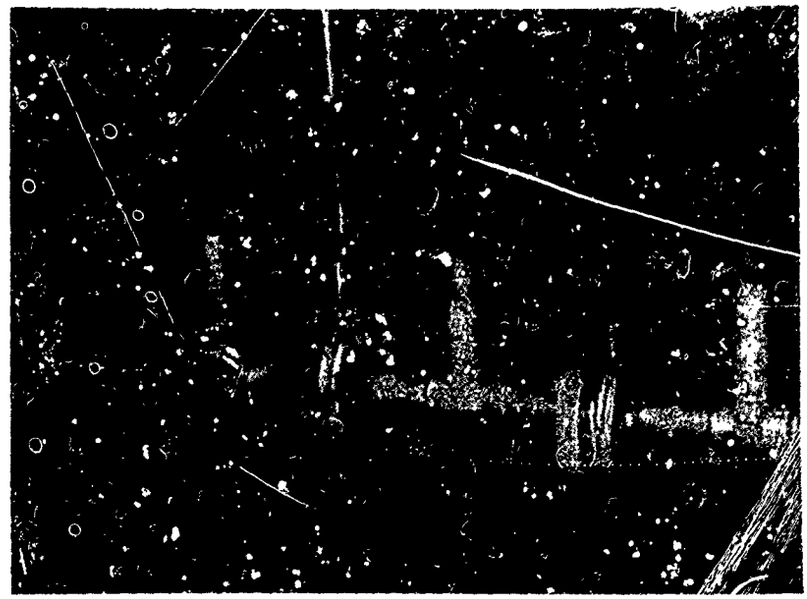

FIGURE 6 - SPRAY CYCLE DURING TEST PROGRAM:
5% SALT SPRAY 2-3 MINUTES EVERY HOUR

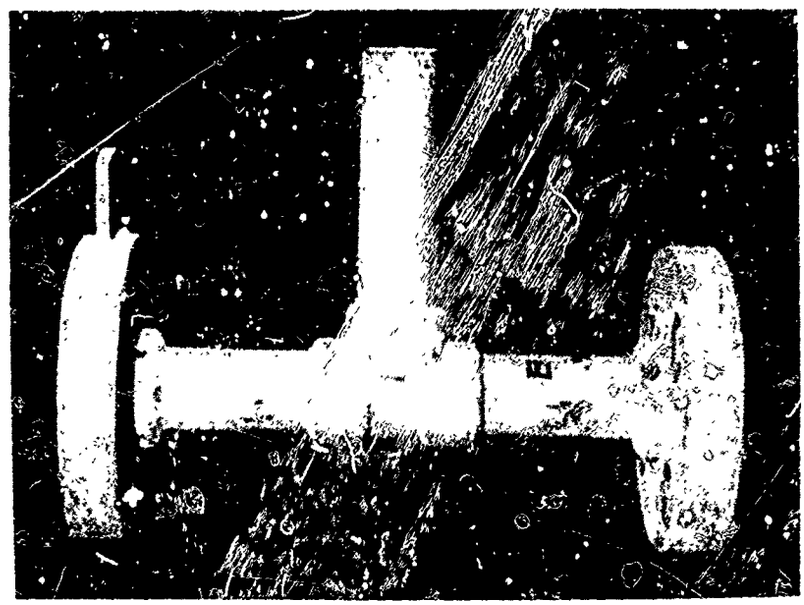

FIGURE 7 - FLANGED-SHAPED SPECIMENS COATED WITH
VSA (OXY-ACETYLENE) PLUS SA SEALER

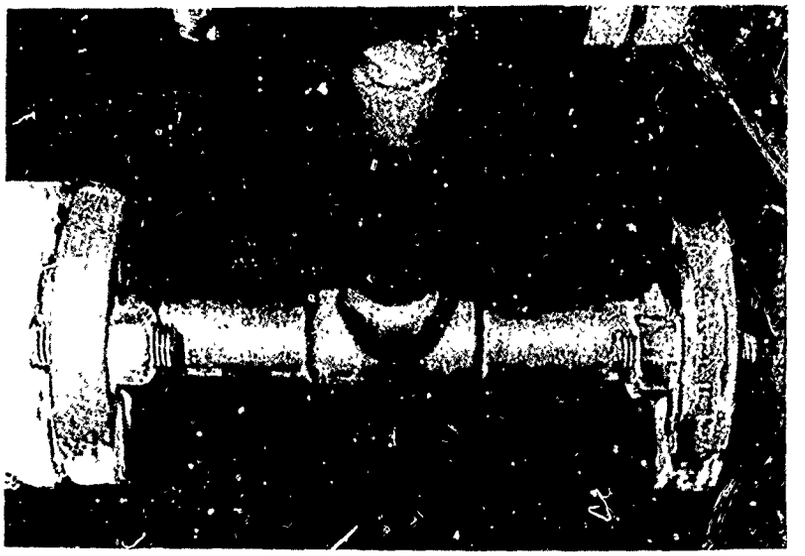

FIGURE 8 - FLANGED-SHAPED SPECIMEN COATED WITH SERMETAL 725

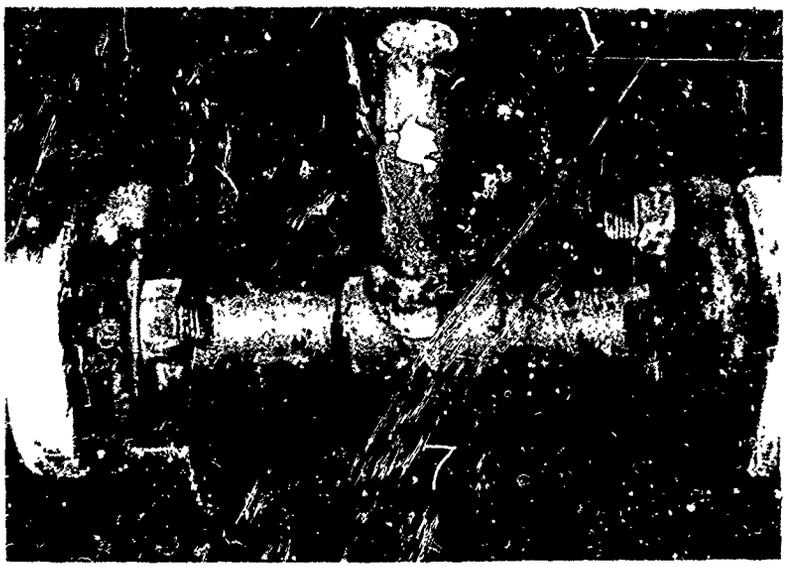

FIGURE 9 - FLANGED-SHAPED SPECIMEN COATED WITH SERMETAL 240 PLUS 737 SEALER

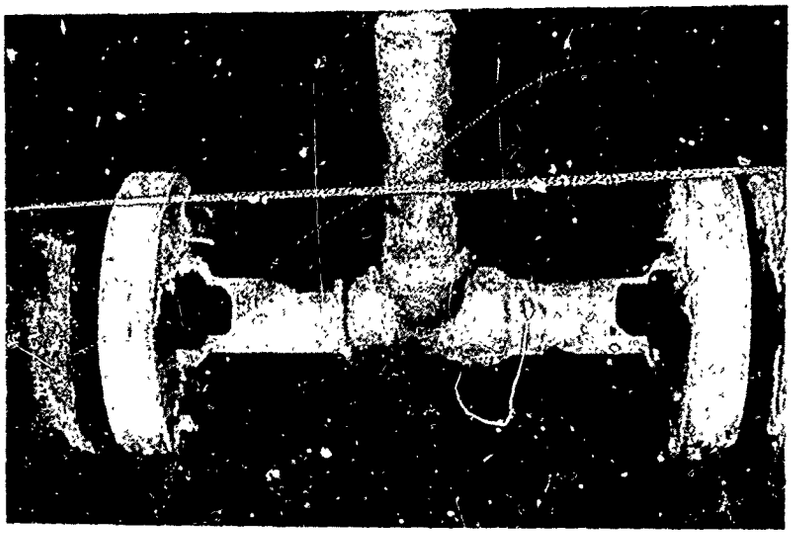

FIGURE 10 - FLANGED-SHAPED SPECIMEN COATED WITH WSA (OXY-ACETYLENE) PLUS DOD-P24555 PAINT

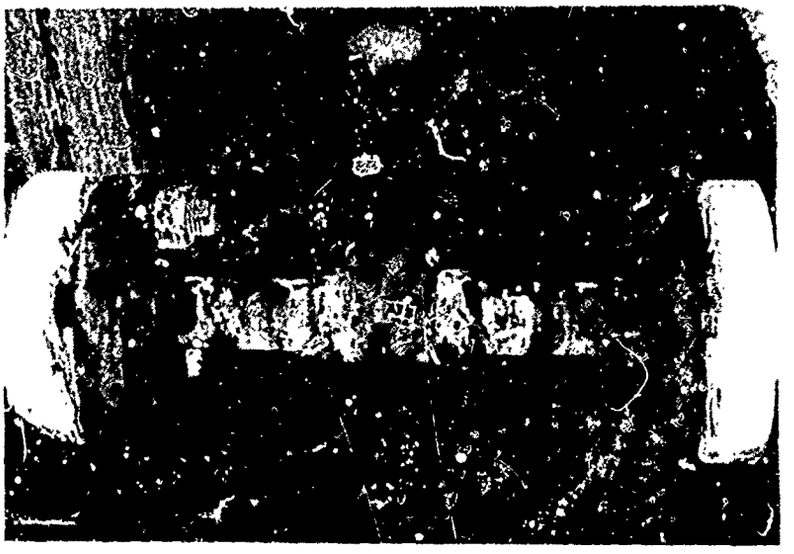

FIGURE 11 - FLANGED-SHAPED SPECIMEN COATED WITH DOD-P-24555 PAINT APPLIED ON GRIT BLASTED SURFACE

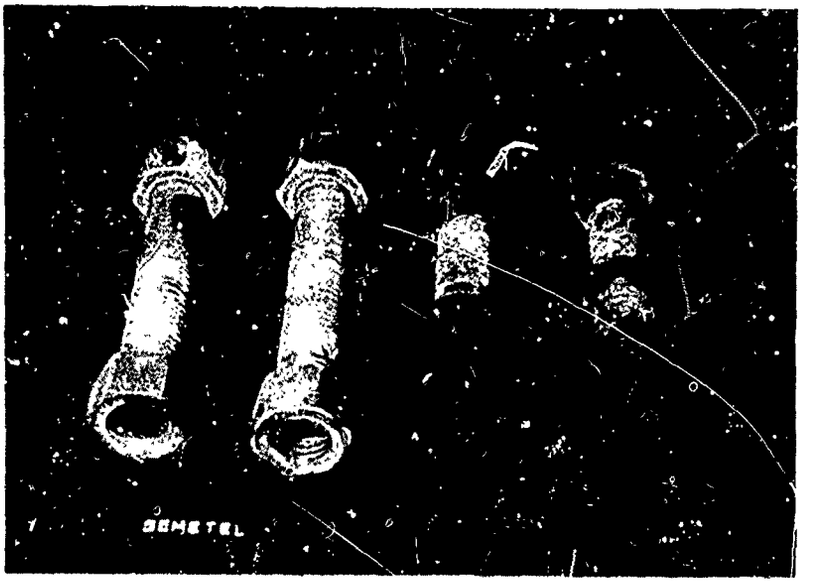

FIGURE 12 - COMPARISON OF SERMETAL 725 COATED HARDWARE WITH STUD ASSEMBLIES PREVIOUSLY COATED WITH DOD-P24555 PAINT AND SA SEALER

FIGURE 13 - STUD/NUT ASSEMBLIES USED IN NUT REMOVAL TEST

COATINGS TO CONTROL TITANIUM COMBUSTION

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INTRODUCTION

Rapid developments in high performance aircraft gas turbine engines have necessitated corresponding advances in material technology, including titanium alloys for fan and compressor components. These alloys contribute to gains in performance and efficiency because of their high strength and low density, resulting in favorable strength-to-weight ratios. Titanium alloys have gained wide acceptance in operating environments up to 480°C (900°F). Typical titanium components in current use include static structures, such as fan and compressor vanes and cases, and rotating components, such as fan and compressor disks and blades.

Titanium, like several other metals, can be made to ignite and react in a rapid oxidation (exothermic) process. In the specific case of titanium, a unique combination of thermophysical properties, including high heat of combustion, low thermal conductivity, and a spontaneous ignition temperature below its melting point, enhance this reactivity. This latter property favors ignition rather than melting, thus producing additional rapid local temperature increases and rapid propagation of the resultant combustion, once ignition occurs.

Several instances of titanium blade and vane ignition and combustion have occurred in gas turbine compressors over a wide range of ambient pressures and temperatures. Initiating conditions may include blade tip rubbing on adjacent casing or blade/structure rubbing as a result of compressor stalls where blades deflect into the casing, rotor imbalance, entrapment of broken airfoil elements, and aircraft maneuver. Aerodynamic heating of compressor components during a stall also contributes to ignition of titanium gas turbine components. Improved compressor seals help reduce the blade tip rubbing problem. However, the high-velocity airstream in axial flow compressors enhances the continued combustion of any titanium blade or vane that does ignite, causing burning particles and molten metal to be sloughed off. These particles can be entrained in the airstream and impinge on downstream components, thereby spreading combustion. The results and extent of this spreading depend largely on the

environmental conditions prevalent at the time of ignition, and can vary from burning the tips of a few compressor blades to the catastrophic destruction of an entire engine.

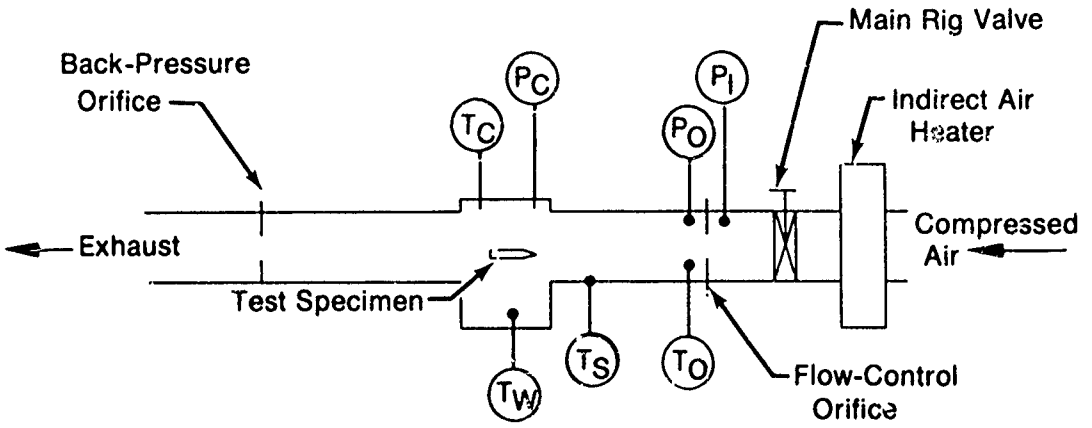
This paper is based on studies funded by NASA under Contract NAS3-21815, conducted to determine the effect of coatings on titanium ignition and/or combustion.

TEST EQUIPMENT

Combustion Rig — Laser Ignition

The Pratt & Whitney Aircraft Group (P&WA) titanium combustion test rig consists of a small wind tunnel driven from a 2.4 MPa (350 psi) compressed air supply. Ancillary conditioning equipment permits the simulation of a wide range of environmental combinations of air pressure (up to 15 atmospheres), temperature (up to 550°C), and velocity (up to 350 m/sec). Small test specimens are mounted in a rectangular test chamber. Installed instrumentation provides a vehicle to determine pressure and temperature at strategic locations in and around the rig.

Air, supplied from a large compressor, passes through a gas-fired indirect heater and a flow-measuring orifice prior to entering the test section. The test section, shown schematically in figure 1, consists of a 2 by 5 cm (0.75 by 2.0 in.) rectangular channel with a bellmouth and 7.5 cm (3.0 in.) of straight section upstream of the test specimen leading edge. The test specimen mounts in a carrier which is inserted into the test section. Orifice plates, upstream and downstream of the test section, provide control of flowrate and pressure level. Thermocouples provide temperatures at the flow-measuring orifice, in the specimen test chamber, on the rig skin, and on the laser and camera windows. Airstream flow is determined by calculation using the pressure differential (ΔP) across the orifice.



P_I = Orifice Upstream Pressure
P_O = Orifice Downstream Pressure
P_C = Test Chamber Pressure
T_O = Orifice Air Temperature
T_S = Rig Skin Temperature
T_C = Test Chamber Temperature
T_W = Window Temperature

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Figure 1. Titanium Combustion Test Rig-Laser Ignition

The test section contains two windows: one for laser irradiation of the specimen and one for photographic viewing of the test specimen. These windows mount in a port on the side of the rig approximately 20 cm (8 in.) from the test specimen. The window for the camera is optically flat fused quartz which is 6.4 cm (2.5 in.) in diameter by 1.3 cm (0.5 in.) thick. The laser beam window is zinc selenide 3.8 cm (1.5 in.) in diameter by 6.4 cm (0.25 in.) thick. Zinc selenide offers excellent transmissivity for the 10.6μ wavelength emission of the CO_2 laser beam. This window has an antireflective coating on both faces to minimize reflection and beam scatter. The quartz window exhibits excellent optical clarity for visible light, but will not transmit the CO_2 laser light, thus protecting the camera lens from scattered reflections of the laser beam. A water jacket to absorb conducted heat in the metal housing, and an air injection system to film the optical surfaces protect the windows from the high-temperature test environment.

The arrangement of the test section and other supporting test equipment appear in figures 2 and 3. Because of environmental restrictions, the laser equipment is located in the air-conditioned control room and the beam passed through a port in the concrete blast wall. A high-speed Hycam motion picture camera and a video camera with a tape recording/playback system permit, through the use of a beamsplitter, simultaneous photographic recording and real-time video observation.

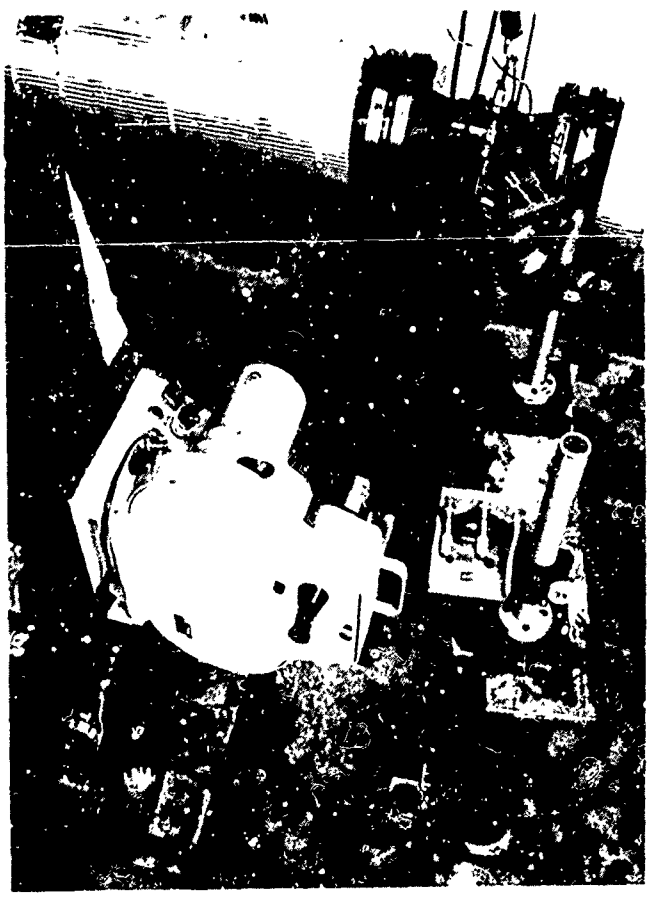

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Figure 2 Titanium Combustion Test Rig Setup

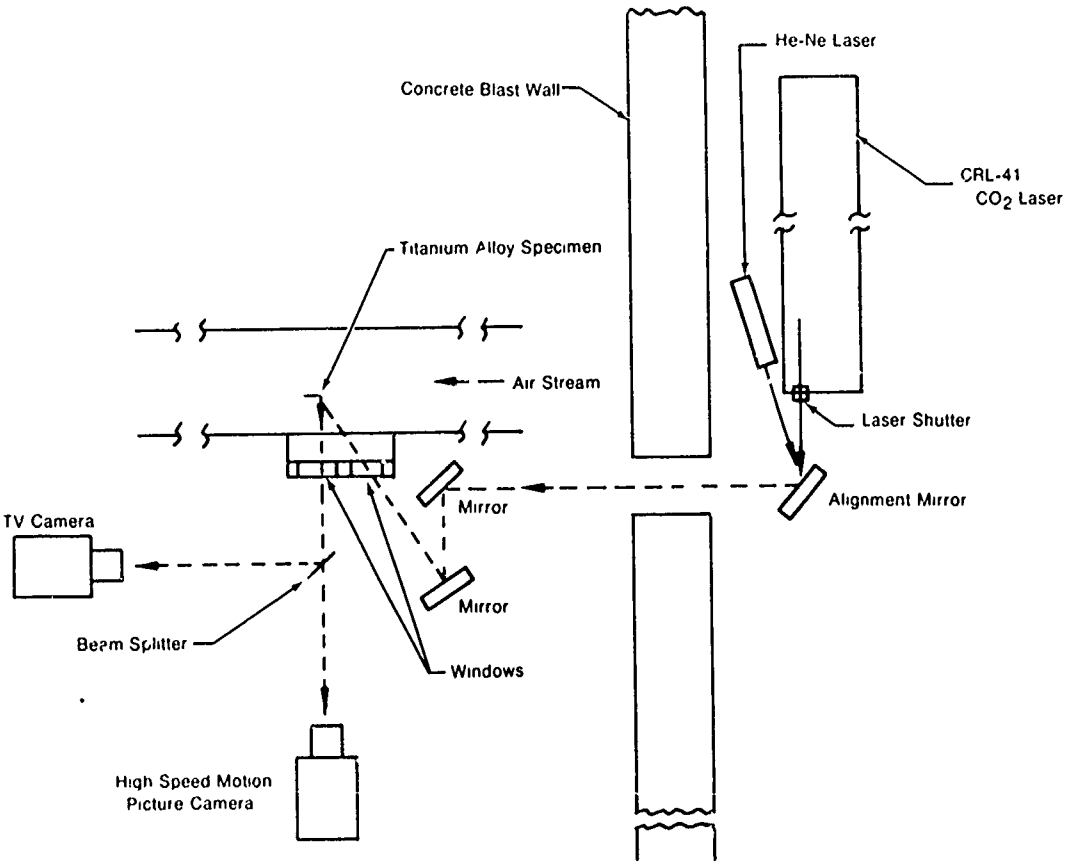


Figure 3. Arrangement of Laser Ignition and Photographic Recording Systems

A CRL Model 41 laser provides the energy required for specimen ignition. This electric-discharge, water-cooled CO_2 laser system is capable of providing an output of 250 watts in the TEM 00 mode at a transmission frequency of 10.6μ. The beam defocuses at the specimen to diameter of approximately 0.3 cm (0.12 in.) to yield an incident average power density of approximately 1.25 kw/cm^2 absorbed by the specimen. A coincident helium-neon laser provides a visible red beam for alignment of the hot CO_2 laser beam on the titanium test specimen. The videotape system enables observation of this red alignment beam.

Laser Ignition Specimen

Test specimens were prepared for combustion tests in the configuration shown in figure 4. The dimensions of each machined specimen were measured and recorded; specimens which did not meet the specifications noted in figure 4 were rejected. An average of micrometer readings taken at the seven points shown in figure 5 determined specimen thickness.

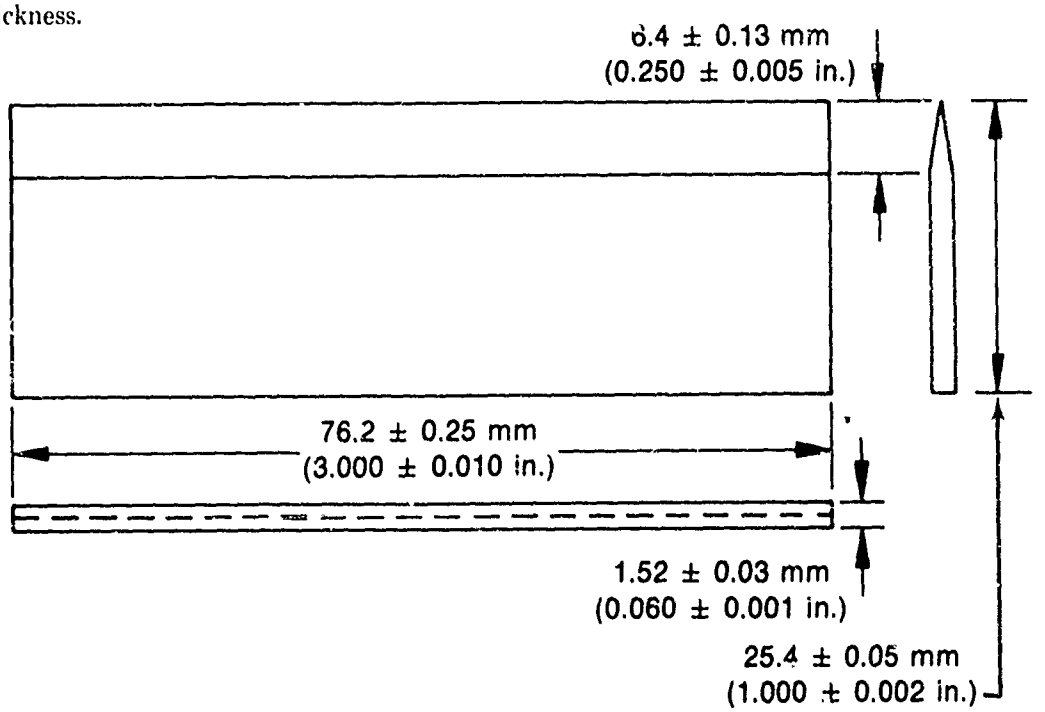


Figure 4. Specimen Configuration — Laser Ignition

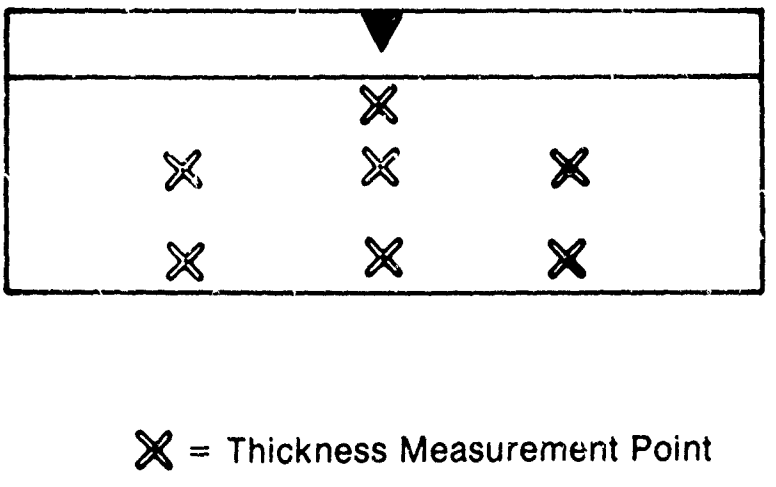
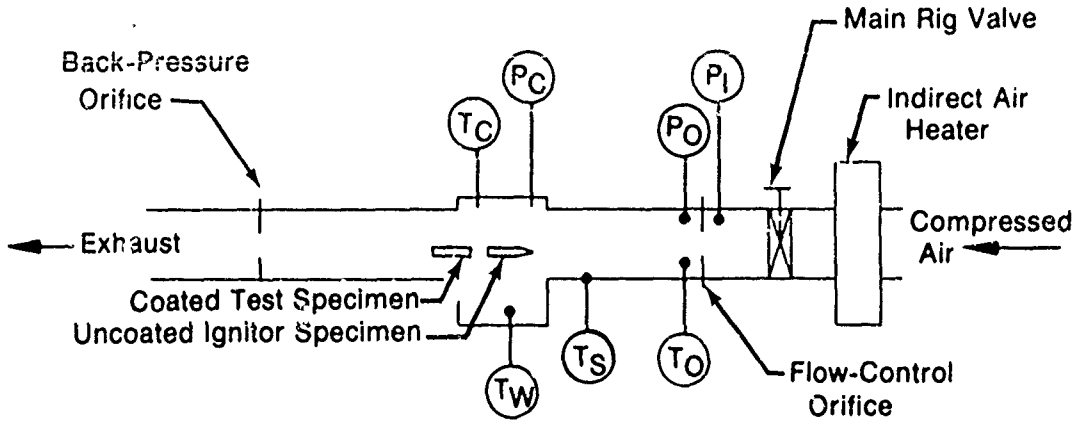


Figure 5. Specimen Thickness Measurement Points

Prior to testing, the coated and uncoated specimens received a coating of electroplated black nickel or black chromium in the shaded triangular area shown in figure 5. The nonreflective black coating served to maximize the coupling of the laser energy to the specimen by eliminating variations caused by reflectivity differences among the various coatings.

Combustion Rig — Cascade Ignition

In later combustion tests, modification of the combustion rig permitted molten metal ignition (cascade), as shown in figure 6. Enlargement of the specimen holder to a capacity where two specimens could be held is shown in figure 7. The upstream specimen, composed of anodized Ti 8Al-1Mo-1V, ignites by use of the laser (as described earlier), thereby subjecting the downstream specimen to molten metal impingement.



P_I = Orifice Upstream Pressure
P_O = Orifice Downstream Pressure
P_C = Test Chamber Pressure
T_O = Orifice Air Temperature
T_S = Rig Skin Temperature
T_C = Test Chamber Temperature
T_W = Window Temperature

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Figure 6 Titanium Combustion Rig — Cascade Ignition

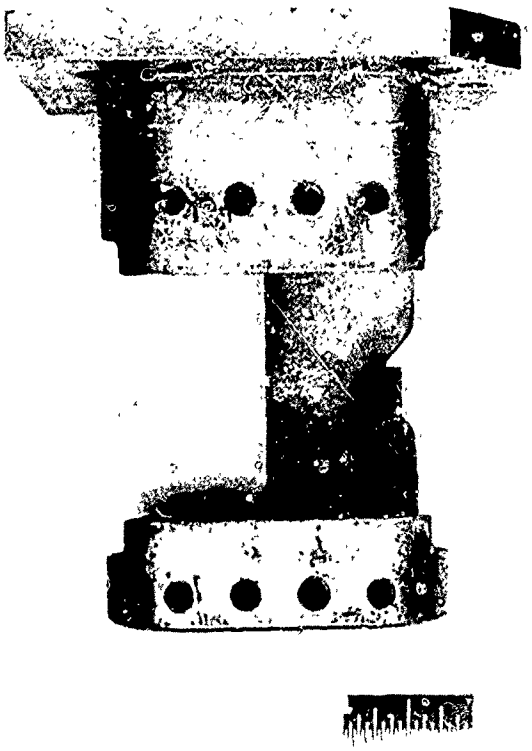

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Figure 7 Combustion Rig Specimen Holder – Cascade

Cascade Ignition Specimen

Test specimens were prepared for cascade combustion tests in the configuration shown in figure 8. The dimensions of each sheared specimen were measured and recorded; specimens which did not meet the specifications noted in figure 8 were rejected. Specimen thickness was recorded as the average of micrometer measurements taken at the seven points shown in figure 5.

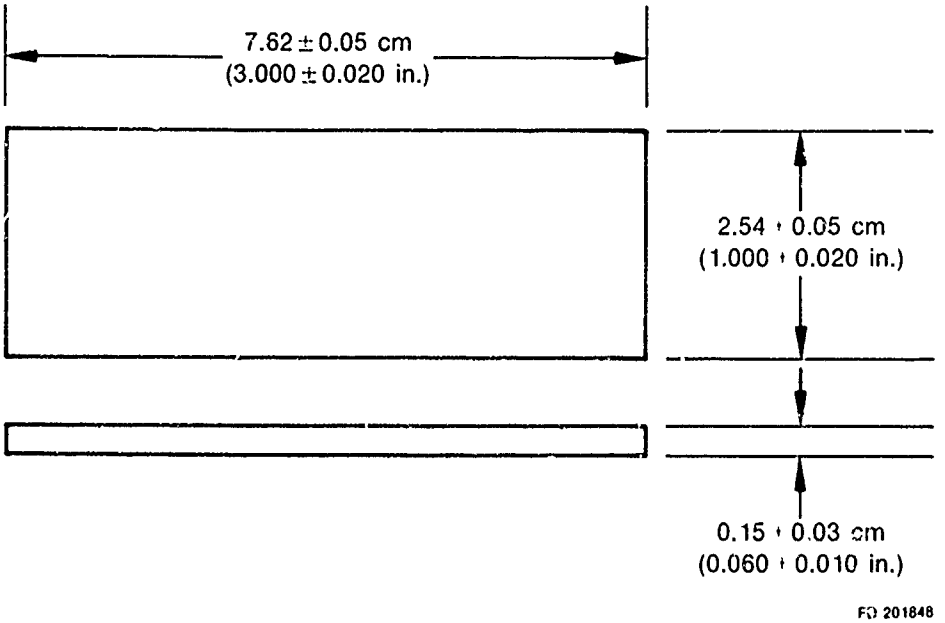

Figure 8. Cascade Combustion Specimen

The upstream specimen for cascade combustion tests was sheared in accordance with the configuration shown in figure 9 from AMS 4916 (Ti 8Al-1Mo-1V) sheet stock. Prior to testing, the ignitor sample was anodized to a blue or violet color to maximize the coupling of laser energy to the specimen.

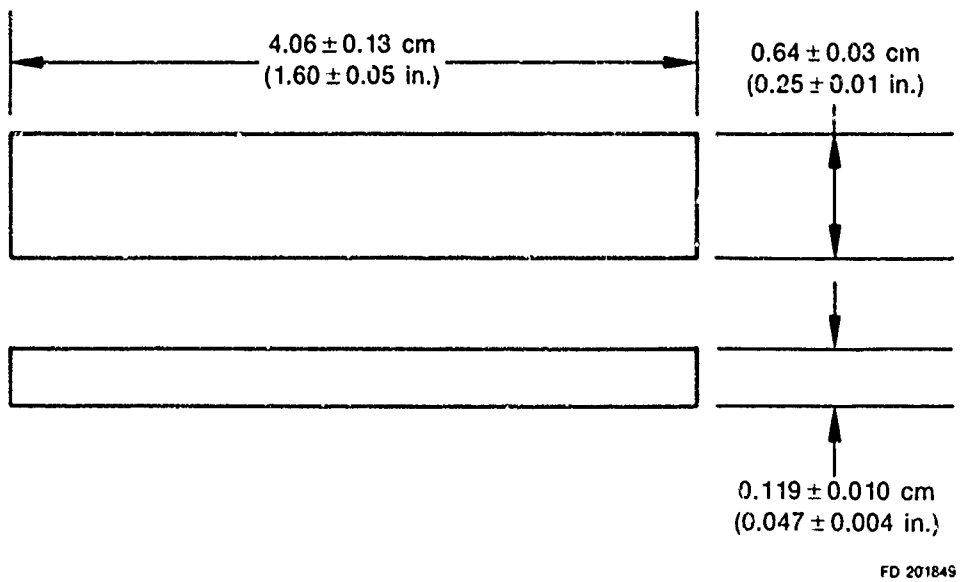

Figure 9. Igniter Combustion Specimen

TEST PROCEDURE

Prior to the test run, test specimens are placed in the specimen holder which is then mounted in the test chamber. Installing a specific combination of flow-measuring and back-pressure orifices in the test rig establishes individual run values of air velocity and chamber pressure. After setting the heater to the desired temperature, airflow is introduced into the system and the test chamber allowed to reach a thermal equilibrium. Once thermal equilibrium has been reached, the laser optics are aligned using the visible helium-neon laser beam and the videotape system. A high-intensity light transmitted from its source by fiber optics provides specimen illumination during alignment. For high-speed photographic coverage, the camera is focused on the specimen at all times during the test run. Sufficiently intense light from the specimen ignition and burning permits photodocumentation of burn propagation and movement of the melted material. An event marker (light pulse) recorded on the side of the film on all runs annotates the start and finish of the laser action during the run. Light pulses from a 1 kHz timing generator also mark the high-speed films to provide an absolute time reference for event sequences.

Just prior to the start of a particular run, the following sequence occurs: (1) final temperature and pressure adjustments are made by judicious throttling of the hot air valve and a cold air bleed input valve, (2) final adjustment is made, as necessary, to laser alignment, and (3) final run parameters are then recorded. A time-sequenced switch initiates the test by starting the high-speed camera. Approximately 2 sec after camera start, the sequencer opens the laser shutter to irradiate the specimen, thereby starting the run. The laser remains on for 5 sec before the sequencer closes the shutter. This time can be overridden manually when ignition occurs before the 5 sec have elapsed. The camera runs until it is out of film (about 16 sec) and is sequenced off at approximately 20 sec. The video system remains on at all times in the CCTV mode. Videotape recording is controlled manually during a run sequence. The instant replay and slow-motion/stop-action capability of the color video recording permits immediate review of the test run for its potential impact on the next test run

COATINGS

The following 15 coating systems underwent combustion testing utilizing laser ignition:

Single Coating Systems

Chromium (electroplate and diffuse)

Chromium-molybdenum (electroplate and diffuse)

Chromium-molybdenum (sputtered)

Aluminum (IVD)

Aluminum-manganese (electroplate)

Platinum (ion-plated)

Cermet plate of chromium with occluded TiC

Duplex Coating Systems

Chromium-molybdenum (electroplate and diffuse plus IVD aluminum)

Chromium-molybdenum (electroplate and diffuse) plus aluminum-manganese

Chromium-molybdenum (electroplate and diffuse) plus copper

Chromium-molybdenum (electroplate and diffuse) plus nickel

Ion-plated platinum plus IVD aluminum

Ion-plated platinum plus aluminum-manganese

Ion-plated platinum plus copper (electroplate) plus nickel (electroplate)

Ion-plated platinum plus nickel (electroplate)

These coatings were selected based upon the following rationale.

Electrodeposited Coatings

Chromium — Electroplated chromium was selected since it represents a simplified cost-effective variation of the chromium-molybdenum coating and has demonstrated some fire resistance. It was applied as a single coating by a conventional chromium electrodeposition process.

Chromium Cermet — A chromium cermet coating was included in the preliminary combustion screening tests. The chromium cermet coating consisted of an electroplated chromium with occluded titanium carbide.

Chromium-Molybdenum — Chromium-molybdenum was selected for evaluation as an electroplated coating due to the degree of fire control demonstrated in previous tests. In addition, this coating was believed to not adversely affect titanium mechanical properties.

Copper — Copper electrodeposits applied to either electrodeposited chromium-molybdenum or ion-plated platinum were evaluated in this program based on its established fire protection capability. This coating was applied from a conventional Rochelle copper-cyanide plating bath.

Aluminum-Manganese — Aluminum-manganese coating, applied by electrodeposition from a molten salt bath directly on the titanium alloy or as an overcoat to electrodeposited chromium-molybdenum, was evaluated in this program.

Nickel — Electroplated nickel over chromium-molybdenum was selected to provide data on the mechanism of how coatings affect the combustion characteristics of titanium. Also, a thin nickel coating was applied over copper to provide oxidation resistance from the normal gas turbine compressor environment. The coating was applied utilizing a conventional high-speed, nickel-sulfamate plating bath.

Sputter Coatings

Chromium-Molybdenum — Sputtered chromium-molybdenum was selected as a variation of the electroplated chromium-molybdenum that has demonstrated a degree of fire control in previous tests. Also, without a requirement for diffusion heat treatment, this coating should not adversely affect titanium mechanical properties.

Ion-Plating and Ion Vapor Deposition

Ion-plating and ion vapor deposition are terms defining essentially the same method of coating application. Two materials were selected for use with this process:

Platinum — Platinum, applied by ion-plating, was selected primarily for its favorable effects on titanium mechanical properties and, although it did not provide a significant degree of fire protection, it found application as a base or barrier coat for other coatings.

Aluminum — Aluminum, applied directly onto the titanium by ion vapor deposition (IVD), as an overcoat to chromium-molybdenum, and as an overcoat to ion-plated platinum, was evaluated during this program. IVD aluminum can be used alone as a coating without mechanical property degradation because the application temperature of the aluminum is low enough to prevent intermetallic formation. The combination coatings were used to provide fire resistance and minimize the effects on mechanical properties.

TEST RESULTS

Each coating system was applied to Ti 8Al-1Mo-1V and subjected to laser-initiated combustion testing. The initial test conditions were 700°F — 110 psia — 800 ft/sec. The specimens that did not experience sustained combustion were further tested at conditions of 850°F — 110 psia — 800 ft/sec. The results of these tests are summarized in table 1 and shown pictorially in figure 10a, b, c. After these tests, there were six specimens that did not burn; also the Cr-Mo/IVD Al burned minimally at the milder test condition. These seven coating systems

were combustion tested at environmental conditions of 850°F — 140 psia — 800 ft/sec. All coating systems experienced sustained combustion. The results are shown in table 2. To preclude the selection of a coating system which would degrade substrate mechanical properties, high cycle fatigue (HCF) screening tests were conducted concurrently with the screening combustion tests. The most favorable coating from the HCF test results was IVD aluminum followed by Pt/Cu/Ni. Based on combustion and HCF testing, IVD aluminum and Pt/Cu/Ni were selected as the "best" coating systems.

Table 1. Screening Test Results

Coating Tested	*Burn Severity (%) 700°F — 110 psia — 800 ft/sec*	*Burn Severity (%) 850°F — 110 psia — 800 ft/sec*
Chromium	67%	
Cr — 1% Mo	0	37%
Sputtered Cr — 5% Mo	0	18%
IVD Aluminum	0	~1%
Aluminum-Manganese	0	55%
1μ Platinum	100%	
Cr-TiC Cermet	0	~1%
Cr-Mo + IVD Al	13%	
Cr-Mo + Al-Mn	0	0
Cr-Mo + Cu + Ni	0	0
Cr-Mo + Ni	0	0
Pt + IVD Al	0	38%
Pt + Al − Mn	56%	
Pt + Cu + Ni	0	0
Nickel-Phosphorus	No Test	25%

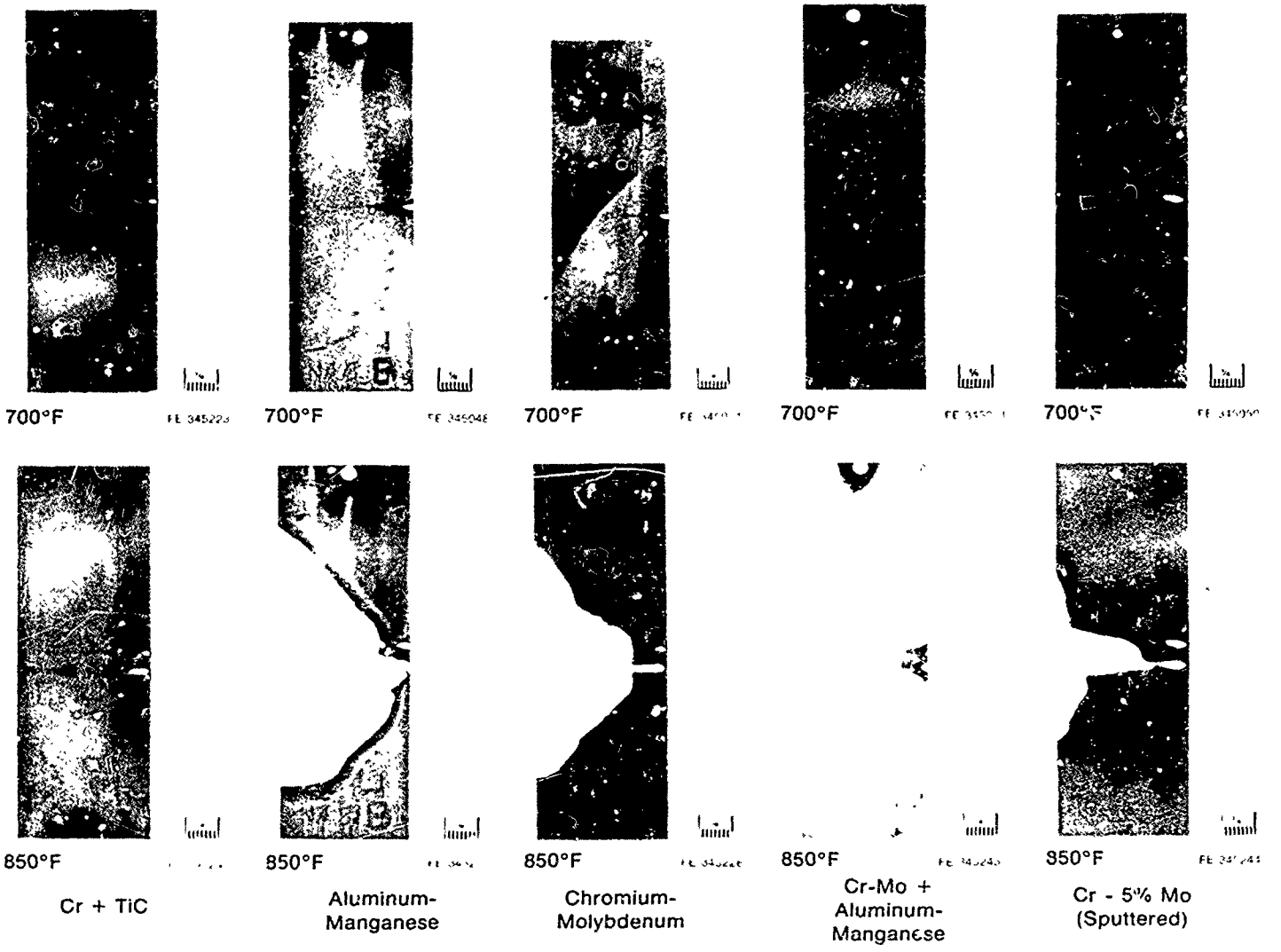

Figure 10a. Screening Combustion Test Results

Figure 10b. Screening Combustion Test Results

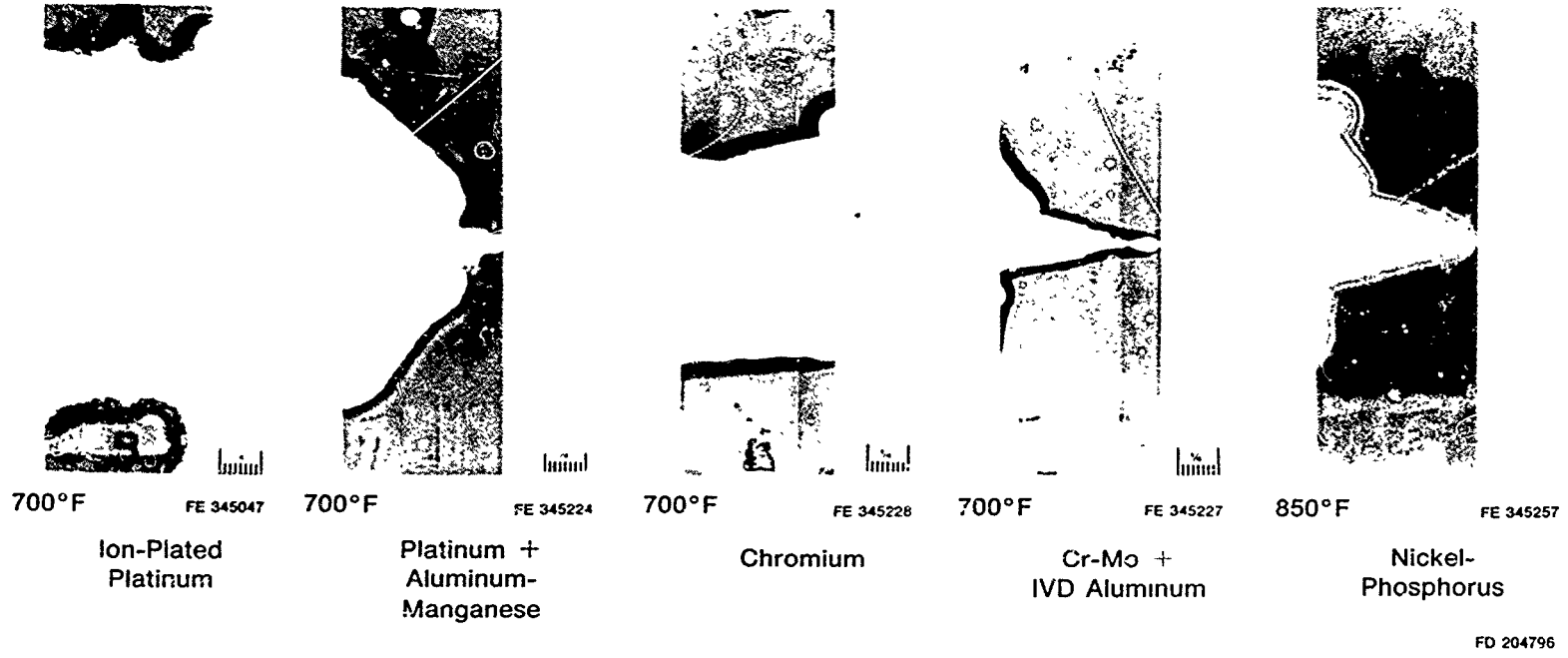

Figure 10c. Screening Combustion Test Results

Table 2. Task II Combustion Results

Coating System	*Pressure (psia)*	*Temperature (°F)*	*Air Velocity (ft/sec)*	*Burn Severity (%)*
IVD Aluminum	110	900	800	47.5
Pt/Cu/Ni	140	850	800	47.0
Chrome-moly/Cu/Ni	140	850	800	44.6
Chrome-moly/Ni	140	850	800	58.8
Chrome-moly/IVD Aluminum	140	850	800	60.0
Chrome-moly/Al-Mn	140	850	800	64.7
Chromium Cermet	140	850	800	100.0

The effects of these two coating systems were characterized by mechanical property testing. A listing of the mechanical property tests and results are summarized in table 3.

Table 3. Summary of Test Results

	Pt/Cu/Ni	*IVD Al*
Combustion	+	++
HCF	0	0
Tensile	0	0
Creep Rupture	0	0
HSSC	0	0
Stress Rupture	+	0
Erosion	+	+
Adhesion	Good	Good
Static Ox.	–	–
Diffusion	0	0
Thermal Shock	0	0
Stress Analysis	0	0

where: 0 = No significant influence due to coating
– = Coating had degrading effect on baseline
+ = Coating appeared to provide improvement over baseline.

From table 3, the difference between the effects of IVD aluminum and Pt/Cu/Ni mechanical properties is small. To complement these tests, cascade combustion testing was conducted on these two "best" coating systems.

Cascade combustion testing was conducted according to an experimental matrix employing three pressures (40 psia, 60 psia, 80 psia), three temperatures (600°F, 725°F 825°F) and three air velocities (600 ft/sec, 800 ft/sec, 1000 ft/sec). Both coating systems tested were applied to Ti 8Al-1Mo-1V and Ti 3Al-6Cr-8V-4Mo-4Zr. The cascade combustion test results are shown pictorially in figures 11 to 16. After statistical analysis the following equations were generated:

Burn Severity Equations

Coating System	Equation	Correlation Coefficient (R^2)	Standard Deviation
Ti 8-1-1 (Baseline)	$B = -1410.5 + 0.31P + 2.59T - 1.12 \times 10^{-3}T^2$	0.41	11.6
Pt/Cu/Ni on Ti 8-1-1	$B = -1416.6 - 4294.8C + 6.87 \times 10^{-3}P^2 + 2.41T - 1.01 \times 10^{-3}T^2 + 3.35 \times 10^{-5}V$	0.53	17.6
Al on Ti 8-1-1	$B = -421.9 - 8834.4C + 0.58P + 3.03 \times 10^{-5}T^2 + 0.99V - 5.55 \times 10^{-4}V^2$	0.67	16.3
Ti 3-6-8-4-4 (Baseline)	$B = -131.2 + 0.23P + 4.13 \times 10^{-1}T + 0.46V - 3.33 \times 10^{-4}V^2$	0.46	11.8
Pt/Cu/Ni on Ti 3-6-8-4-4	$B = -138.3 - 5958.3C + 4.37P - 3.03 \times 10^{-2}P^2 + 3.80 \times 10^{-2}T$	0.56	14.0
Al on Ti 3-6-8-4-4	$B = -22.8 + 0.46P + 3.25 \times 10^{-2}T$	0.45	9.1

where: B = Burn severity, %
C = Coating thickness, in.
P = Pressure, psia
T = Temperature, Rankine
V = Air velocity, ft/sec

Chordwise Burn Velocity Equations

Coating System	Equation	Correlation Coefficient (R^2)	Standard Deviation
Ti 8-1-1 (Baseline)	$CBV = -1.042 + 2.129 \times 10^{-4}P^2 + 1.945 \times 10^{-3}V$	0.95	0.121
Pt/Cu/Ni on Ti 8-1-1	$CBV = -5.215 + 2.207 \times 10^{-4}P^2 + 1.151 \times 10^{-3}T + 9.019 \times 10^{-3}V - 4.58 \times 10^{-6}V^2$	0.86	0.215
Al on Ti 8-1-1	$CBV = -3.137 - 100C + 2.625 \times 10^{-2}P + 6.095 \times 10^{-3}V - 2.9 \times 10^{-6}V^2$	0.86	0.198
Ti 3-6-8-4-4 (Baseline)	$CBV = -1.835 + 3.08 \times 10^{-2}P + 6.2 \times 10^{-7}T^2 + 1.06 \times 10^{-6}V^2$	0.90	0.206
Pt/Cu/Ni on Ti 3-6-8-4-4	$CBV = -1.233 + 2.98 \times 10^{-2}P + 8.3 \times 10^{-7}V^2$	0.64	0.404
Al on Ti 3-6-8-4-4	$CBV = 0.409 - 144.9C + 2.62 \times 10^{-2}P + 1.348 \times 10^{-3}T - 7.246 \times 10^{-3}V + 5.85 \times 10^{-6}V^2$	0.88	0.192

where: CBV = Chordwise burn velocity, in/sec
C = Coating thickness, in.
P = Pressure, psia
T = Temperature, Rankine
V = Air velocity, ft/sec

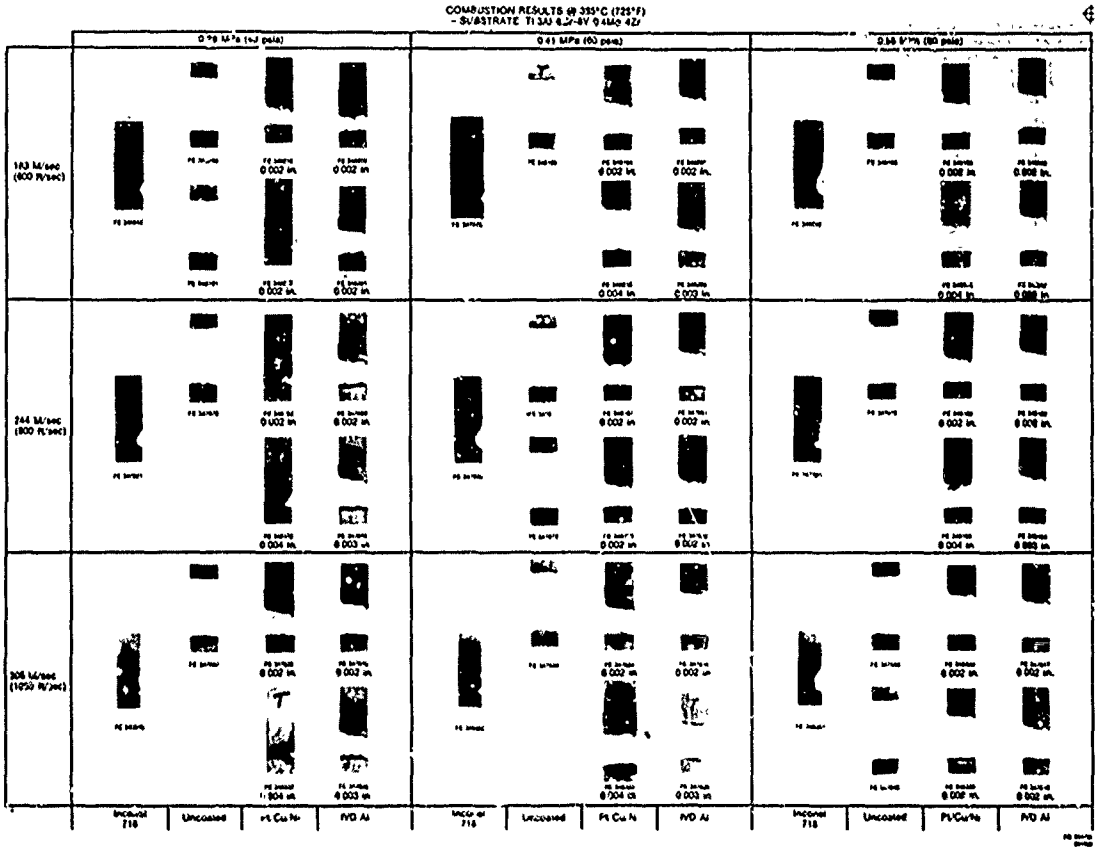

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Figure 11. Cascade Combustion Test Results

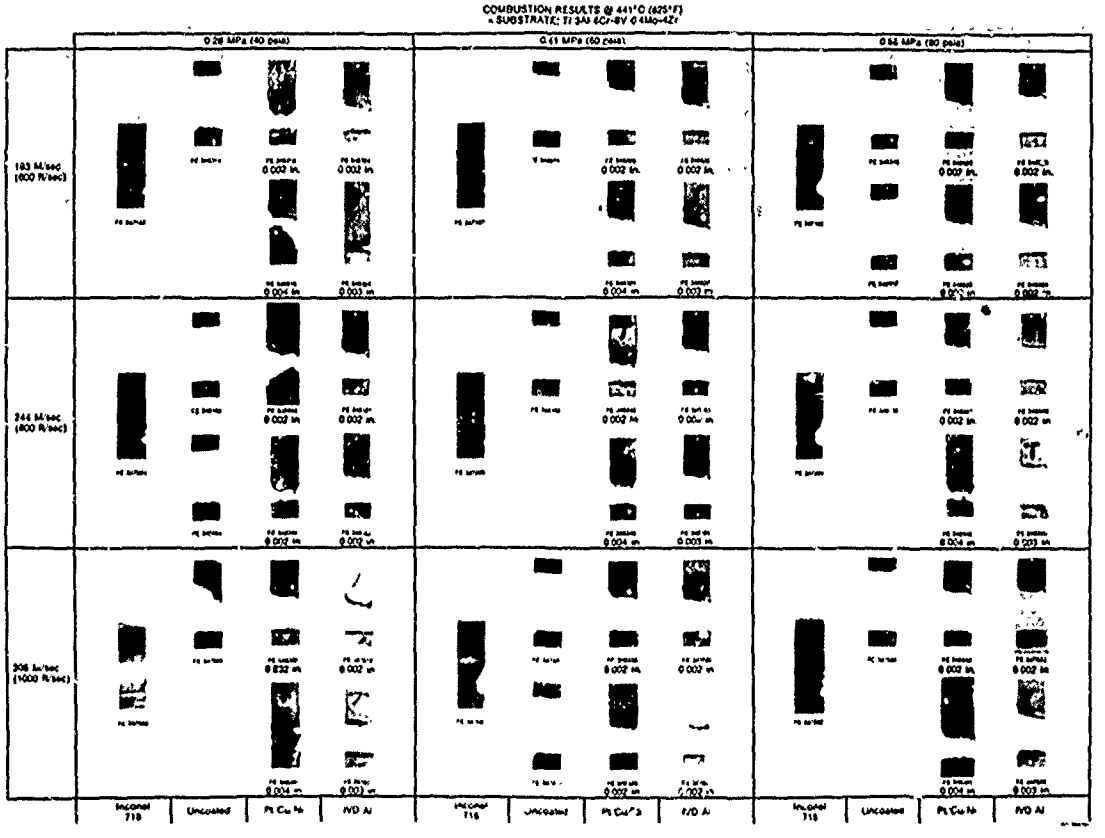

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Figure 12. Cascade Combustion Test Results

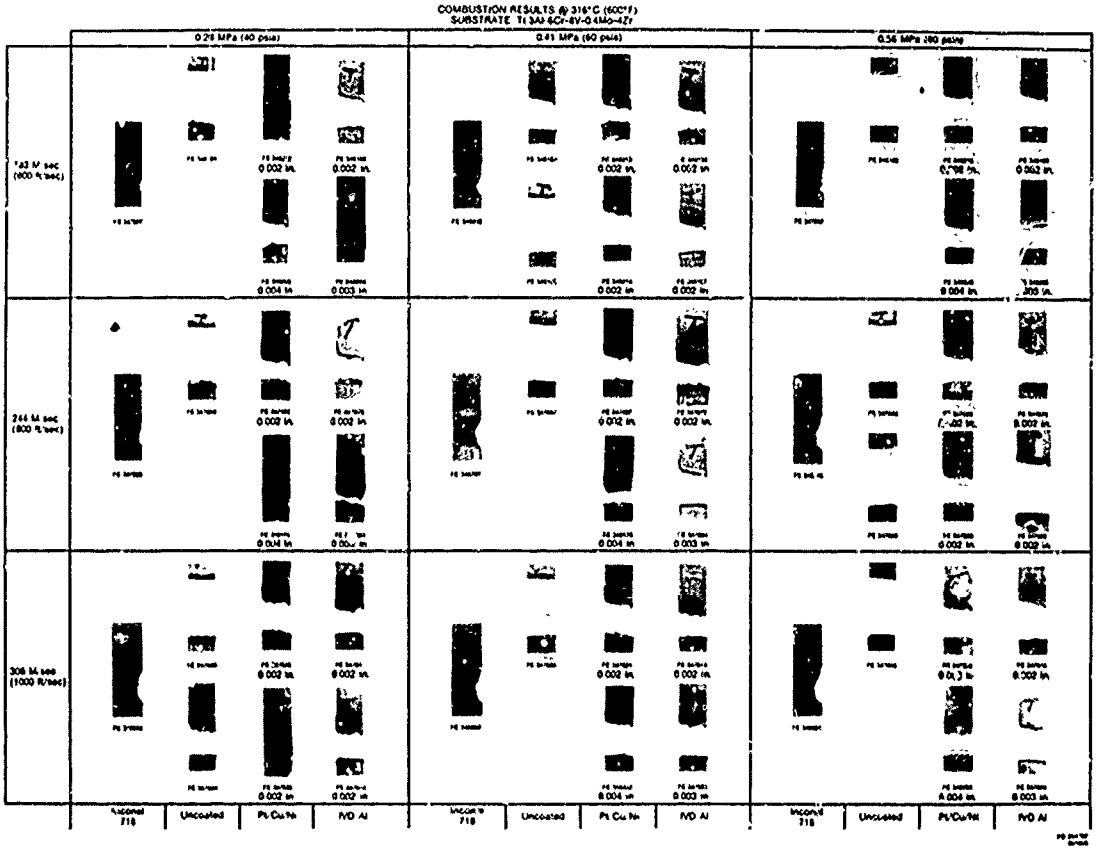

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Figure 13. Cascade Combustion Test Results

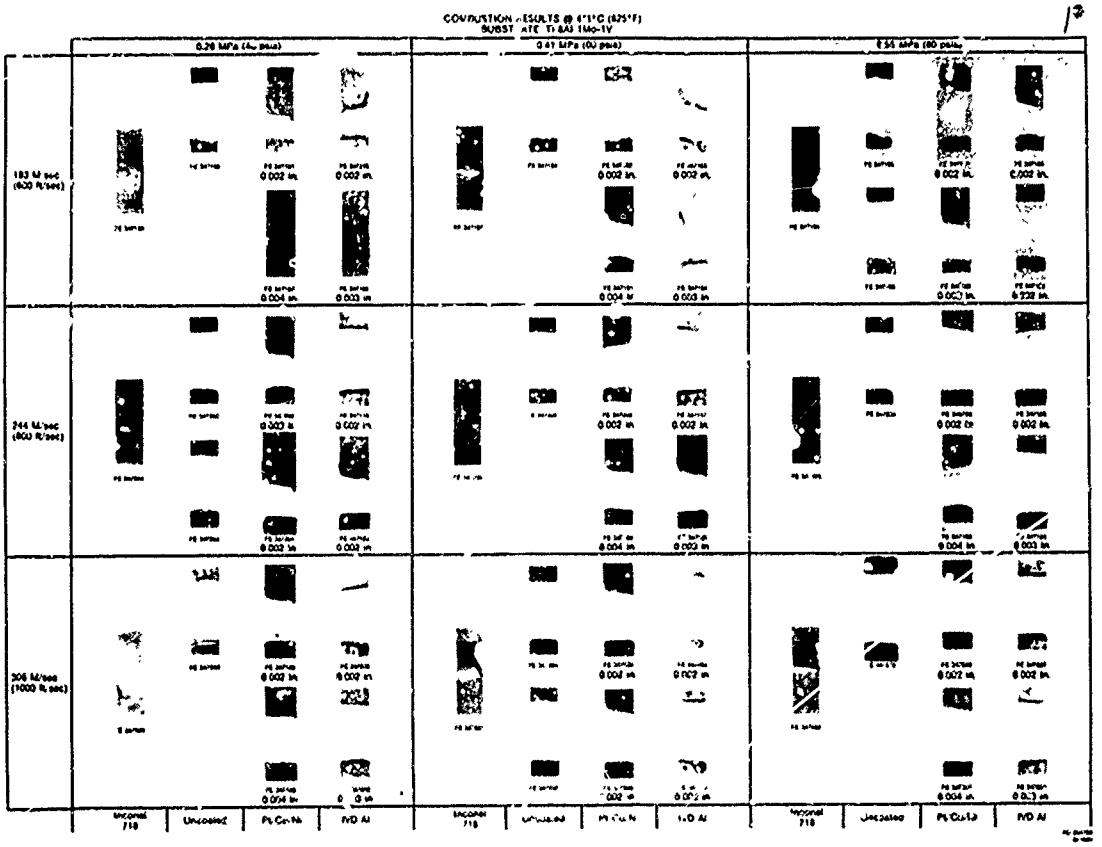

Figure 14. Cascade Combustion Test Results

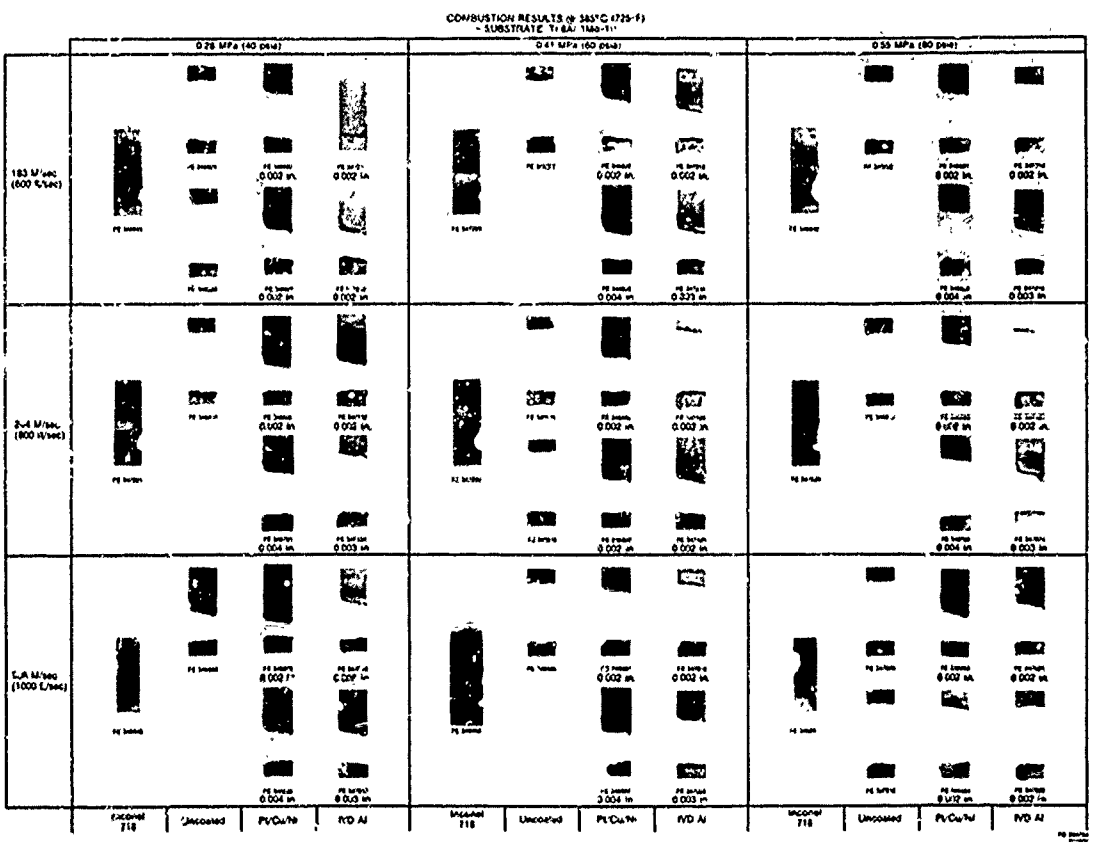

Figure 15. Cascade Combustion Test Results

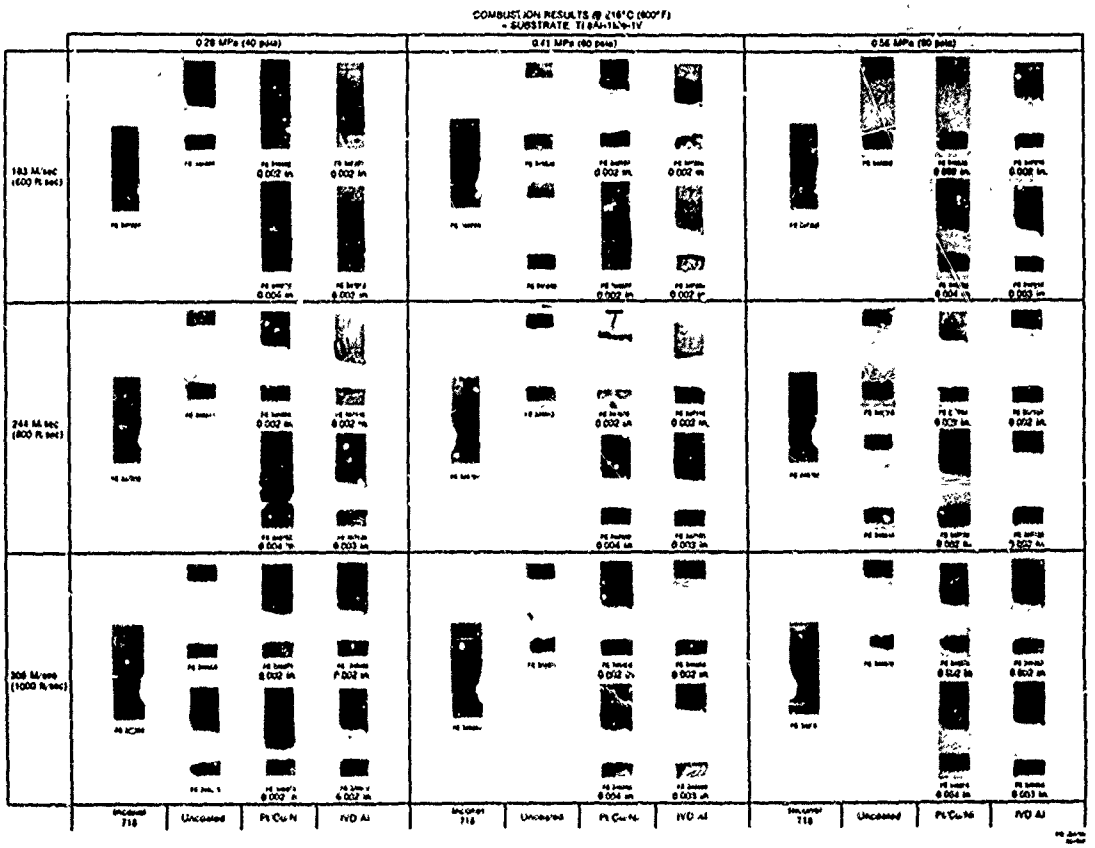

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Figure 16. Cascade Combustion Test Results

While the correlation coefficients for the chordwise burn velocity equations are relatively very high, the burn severity equations correlation coefficients were relatively low. Thus any value calculated from the burn severity equations should be used with caution.

CONCLUSIONS

From the statistical analysis the following conclusions were drawn:

Burn Severity

Burn severity data exhibited a large scatter, thereby yielding low correlation coefficients for equations expressing the influence of the independent variables. However, the following variables were shown to be significant in their influence on burn severity:

1. Test chamber air pressure was shown to be the most significant variable. In all cases, an increase in pressure produced an increase in burn severity.

2. The presence of a coating on the specimen resulted in a decrease in burn severity.

3. As coating thickness increased, the burn severity decreased.

Chordwise Burn Velocity (CBV)

Equations for the expression of CBV consistently produced significantly high correlation coefficients of 0.80 to 0.95. Based on the analysis of these equations, the following preliminary conclusions can be reached:

1. An increase in pressure results in an increase in CBV.

2. An increase in velocity results in an increase in CBV.

3. Temperature effect on CBV appears to be very minor or negligible.

4. On a Ti 8Al-1Mo-1V substrate, coating type does not affect CBV.

5. On a Ti 3Al-6Cr-8V-4Mo-4Zr substrate, the Pt/Cu/Ni coating produces CBV values significantly lower than the IVD aluminum coating.

6. An increase in coating thickness results in a low CBV.

FATIGUE-CRACK INHIBITORS FOR ALUMINUM ALLOYS

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Marietta, Georgia

Presented at the

TRI-SERVICE CONFERENCE ON CORROSION

United States Air Force Academy
Colorado

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FATIGUE-CRACK INHIBITORS FOR ALUMINUM ALLOYS

Robert N. Miller
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Marietta, Georgia

Abstract

The use of crack-growth inhibitors in paint systems to extend the useful life of aircraft is being investigated. The emphasis is on vapor phase compounds because they provide a mechanism for getting the inhibitor into the cracks.

Thirty-four compounds were evaluated for their effect on the corrosion resistance, surface energy, and crack propagation rates of 7075-T6 aluminum. Crack growth rates were obtained on center-cracked fatigue specimens cycled at 0.1 Hz in air at both high and low humidity conditions.

A number of inhibitors retarded the rate of crack propagation in a moist environment but were detrimental in dry air. There was no correlation between the results of the potentiostatic polarization and surface energy tests and the ability of the test compounds to retard the rate of fatigue cracking of 7075-T6 aluminum.

The most effective inhibitors were incorporated in MIL-P-23377 epoxy-polyamide primers. Substantial reductions in the rate of crack growth were achieved through use of the special primer.

Introduction

A major limitation in the life of modern aircraft is the development and growth of fatigue cracks in the airframe structure. Aircraft are designed so that cracks in structural parts will not grow to a critical length during the life of the aircraft. These designs are based on data obtained by testing precracked specimens under controlled laboratory conditions. Typically, this would be at room temperature and at a relative humidity of approximately 50 percent.

Marine environments accelerate the rate of crack propagation. Aircraft which operate in coastal regions have a shortened life span unless the environmental effects are neutralized. This is accomplished, in part, by protecting all structural parts with paint systems which contain corrosion inhibitors and which are relatively impermeable to the diffusion of moisture.

Lockheed-Georgia has been investigating the possibility of extending the life of aircraft by incorporating into the paint system chemical compounds which not only minimize corrosion, but also retard the rate of crack propagation in high strength aluminum alloys.

Background

The development of inhibitors for fatigue crack growth in aluminum alloys requires an understanding of the mechanisms of crack growth. Gest and Troiano[1] report that environmentally enhanced cracking of aluminum involves hydrogen embrittlement. Hartman[2], from thermodyamic considerations, shows that the reduction of water by aluminum is possible and suggests that water molecules are adsorbed on the surface oxide and are readily available to oxidize any fresh aluminum exposed during fatigue cycling. This results in the liberation of hydrogen ions in the vicinity of the crack tip.

Beacham[3] is of the opinion that hydrogen enhances dislocation glide and thus aids microplasticity failure mechanisms. Heady[4] mathematically describes the effect of dissolved hydrogen on the energy of a dislocation. His formulas indicate that dissolved hydrogen embrittles metal by interacting with the dislocation network. As the energy of edge dislocations decreases, dislocation generation and dislocation coalescence become easier. Wei[5] concludes that moisture in the air accelerates fatigue cracking because hydrogen diffusing into the metal contributes a stress component and lowers the external stress required to produce a given crack increment.

Inhibitor combinations which are effective in slowing the rate of crack propagation in high strength steel have been developed. Lynch, Bhansali and Parrish[6] have shown that crack growth in high strength, low alloy steels may be retarded by the presence of reactive inhibitors such as hydrazine or by the presence of nitrite ions. They also demonstrated that combinations of borax and nitrite are more effective than single inhibitos in controlling crack propagation in high strength steels. Experimental results showed this system to be equally effective in the presence of sodium chloride and in both sustained load stress-corrosion and cyclic load corrosion-fatigue conditions.

The literature also contains data on the use of inhibitors to slow crack growth in aluminum alloys. Stoltz and Pelloux[7] report that the addition of nitrate ions drastically reduces the corrosion fatigue crack growth rates of peak-aged 7075-T6 aluminum tested in sodium chloride solution. The nitrite ions displace the chloride ions from the crack tip and change the fracture morphology from brittle to ductile. Khobaib[8] retarded the rate of crack growth in high strength aluminum alloys exposed to distilled water and to 0.1M sodium chloride solutions through the use of borax-nitrite and piperazine inhibitors.

Program Plan

Lockheed-Georgia has been investigating the use of inhibitors in paint systems to control crack growth. Most of the work reported

in the literature on the use of inhibitors to control crack growth rate has been done by exposing the crack path to solutions which contain the inhibitors. In the studies reported in this paper the normal aircraft environment, air containing varying amounts of moisture, was used.

The use of inhibitors to minimize crack growth, at first consideration, appears to be a promising approach. However, inhibitors in paint systems would have little or no effect on crack propagation rates unless the inhibitors are available at the tip of the advancing crack. Therefore, it was decided to concentrate on the evaluation of vapor-phase inhibitors because they provide a mechanism for introducing the inhibitor into the crack and onto the fracture surface. If such inhibitors were incorporated into special primers for stress-critical areas, they would volatilize and be available for reaction with the fresh surface of any crack which might form. These primers could be overcoated with a low-permeability polyurethane to prevent the loss of the inhibitor to the atmosphere.

The object of this program is to establish a sound theoretical basis for the effective use of inhibitors in controlling the growth of cracks in aluminum alloys.

Experimental

Selection of Inhibitors

The selection of potential inhibitors for slowing the rate of crack propagation in high strength aluminum alloys is a complex problem because of the many modes of inhibitor action in retarding crack growth. These include the following possible mechanisms[9]:

1. The inhibitor forms a barrier film which slows or prevents the reaction between aluminum and atmospheric moisture.

2. The compound acts as a buffer and brings the pH of the crack into a neutral range which is not conducive to crack propagation.

3. The compound changes the surface energy of the crack in such a manner that there is interference with the normal metal slip and deformation processes.

4. The inhibitor reacts with the hydrogen formed by the corrosion reactions and prevents it from diffusing to the zone of maximum stress.

5. The inhibitor shifts the rest potential of the alloy to a range where corrosion is minimized.

Other considerations in the selection of an inhibitor which will be incorporated into a paint system are the effect of the compound on the curing of the paint and the vapor pressure of the inhibitor. A compound which reacts with the catalyst in a paint formulation

will cause incomplete curing and a sticky paint layer. A compound which is highly volatile may cause the paint to blister or may prevent proper adhesion of the top coat.

On the basis of a comprehensive literature survey and a consideration of the factors described above, 20 inhibitors and compounds were selected for evaluation in this program. The compounds were subjected to preliminary tests to evaluate the properties of the surface film formed when they react with, or are adsorbed by, aluminum.

Potentiostatic Polarization Tests

Corrosion resistance tests were conducted with cylindrical specimens of 7075-T6 aluminum 1/4 inch in diameter and 3/4 inches long. The specimens were cleaned by degreasing, washing and drying, and then abrading the surfaces with 600-grit emery paper to remove the oxide film. They were then placed in a sealed container and exposed to the vapor from the volatile experimental inhibitors for a 16-hour period. Following this, potentiostatic polarization curves were determined with the specimens immersed in 3-1/2 percent NaCl solution. The non-volatile inhibitors were dissolved in the 3-1/2 percent NaCl solution in a concentration of 200 ppm. the results are summarized in Table I. The specimens with the lowest corrosion currents at 500 millivolts were benzotriazole, sodium borate, sodium vanadate, and Amlguard. The corrosion currents are inversely proportional to the electrical resistance of the film which is formed when the inhibitor reacts with, or is adsorbed by, the surface of the aluminum specimen.

TABLE I. SUMMARY OF POTENTIOSTATIC CATHODIC POLARIZATION TESTS

	Inhibitor	$I_{Corrosion}$ ($\mu a/cm^2$)
1.	control	.130
2.	thiourea	.043
3.	sodium aleate	.046
4.	1,3 phenylene diamine	.039
5.	3,5 hydroxybenzoic acid	.044
6.	ammonium acetate	.040
7.	diphenylamine	.041
8.	Quadrol	.032
9.	L5 inhibitor	.069
10.	mercaptobenzotriazole	.033
11.	hydrazinothiazole	.037
12.	polyoxypropylene diamine	.073
13.	Amlguard	.016
14.	zinc phosphate complex (200 ppm)	.052
15.	magnesium azealate (200 ppm)	.042
16.	polyacyrlic acid (200 ppm)	.056
17.	benzotriazole (200 ppm)	.015
18.	sodium vanadate (200 ppm)	.013
19.	sodium borate (200 ppm)	.029

Surface Energy Tests

The surface energy of aluminum specimens which had been exposed to vapor phase inhibitors was determined by placing 0.5-microliter drops of distilled water on the test surface, measuring the drop diameter with a calibrated microscope, and converting the drop diameter to surface-energy units. The readings obtained by this test method give the "surface energy of wetting" of the metal surface. This is the surface tension of a solution which will just wet the test surface and, in consequence, is a measure of the surface energy of the specimen[10]. The results are summarized in Table II. Aluminum stearate, sodium vanadate and benzotriazole produced the greatest drop in surface energy. Palmitic acid produced the greatest increase.

TABLE II. SURFACE ENERGIES OF INHIBITOR-TREATED ALUMINUM PANELS

	Inhibitor	Surface Energy (dynes/cm)
1.	control	51.3
2.	lauric acid	62
3.	aluminum stearate	35
4.	stearic acid	73
5.	palmitic acid	72.4
6.	vinytriacetooxysilane	64
7.	sodium vanadate	32
8.	thiourea	70
9.	sodium oleate	68
10.	1,3 phenyl diamine	72.4
11.	3,5 dihydroxybenzoic acid	69
12.	Quadrol	71
13.	diphenylamine	71
14.	benzotriazole	32
15.	L5 inhibitor*	58
16.	L8 inhibitor*	64.7
17.	mercaptobenzothiazole	68.8

*Proprietary Amines

Fatigue Test Specimen Configuration and Procedure

Fatigue tests with and without the inhibitors were conducted on center-cracked 7075-T6 aluminum fatigue specimens 4.0 inches wide, 0.10 inch thick, and 28 inches long. The selected temper is the one most susceptible to stress corrosion cracking. Tests with the 7075-T6 alloy readily differentiated among the various inhibitors.

To obtain the maximum amount of useful data with the minimum amount of machine and operator time, triple slot specimens of the configuration shown in Figure 1 were machined from 7075-T6 aluminum plate. Three through-the-thickness center slots were cut in each specimen by the electrical discharge machining (EDM) process. The use of the triple-crack fatigue specimen enabled three times as much data to be obtained per hour machine time. This was especially important at lower cycling

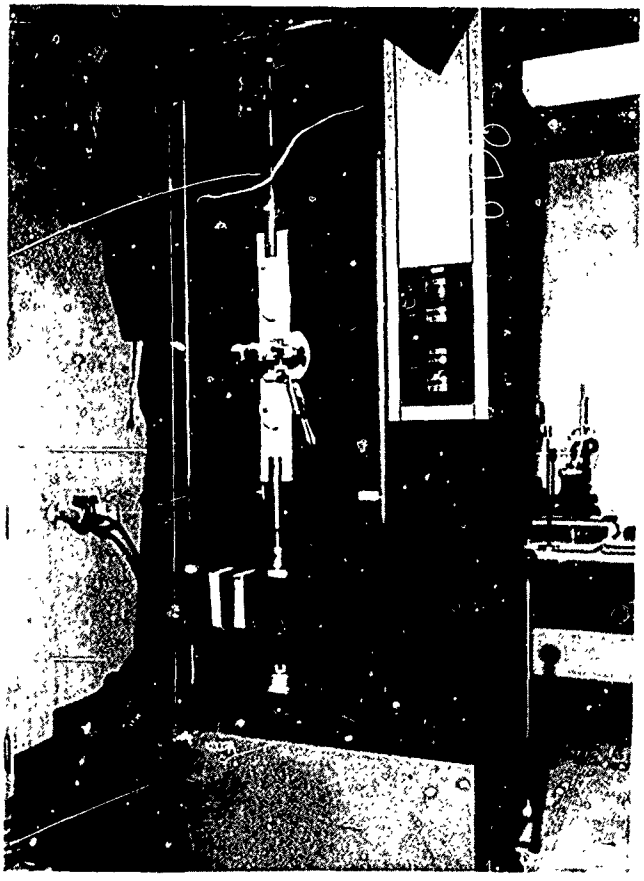

FIGURE 1. TRIPLE SLOT 7075-T6 ALUMINUM FATIGUE SPECIMEN IN INSTRON UNIVERSAL TEST MACHINE

rates, where several days are required just to precrack a specimen. Another important advantage of the triple-crack specimen is that the control tests can be run on the same specimen with the inhibitor tests and all chance of experimental error due to variation in metal structure is eliminated.

The crack path adjacent to the EDM slots was polished to a mirror finish to provide a scratch-free and uniform background which facilitated crack observation and tip location. After polishing, a fine grid was lightly engraved on the specimen surface and subsequently used as a reference for tracking crack growth. The spacing of the grid times was approximately 0.010 inch. The specimens were precracked by fatigue-cycling until a precrack of 0.03 inch was present on each side of the slot.

The vapor phase inhibitors were tested by placing them in Petri dishes sealed against the crack path on both the front and back of the specimens as illustrated in Figure 2. The specimens were cycled at a rate of 0.1 Hz at loads of 1000 to 4000 pounds in an Instron Universal Test Machine. The growth of the cracks was optically monitored with the aid of a Nissho Optical Company 20 power microscope.

Fatigue Test Results

The inhibitors were evaluated for their effectiveness in retarding the fatigue cracking of 7075-T6 aluminum in both high and low humidity environments.

Figure 3 is a plot of stress cycles vs crack length. It illustrates the great effect of moisture on the rate of crack growth. After 40,000 fatigue cycles the crack in the 100% humidity environment had grown to a length of 0.83 inches while the crack in the dehumidified atmosphere grew only 0.31 inches.

Figure 4 shows that boric acid, mercaptobenzothiazole and the L8 inhibitor are suitable for retarding crack growth of 7075-T6 aluminum at 100% relative humidity. In the absence of moisture, however, many of the inhibitors accelerated the rate of crack growth. Figure 5 shows that hexadecylamine and thiourea are deterimental in a low humidity environment.

Table III summarizes the results of the fatigue tests with the potential crack growth inhibitors in a moisture saturated atmosphere. It gives the length of the crack (1/2a) at 40,000 load cycles.

The tests with the inhibitors alone showed two of the more effective crack growth inhibitors to be the L5 and the L8 amine complexes.

In subsequent tests, the L5 inhibitor was added to an epoxy-polyamide primer formulation which contained no other inhibitor. Fatigue tests in a 100% moisture environment were conducted on a bare control specimen

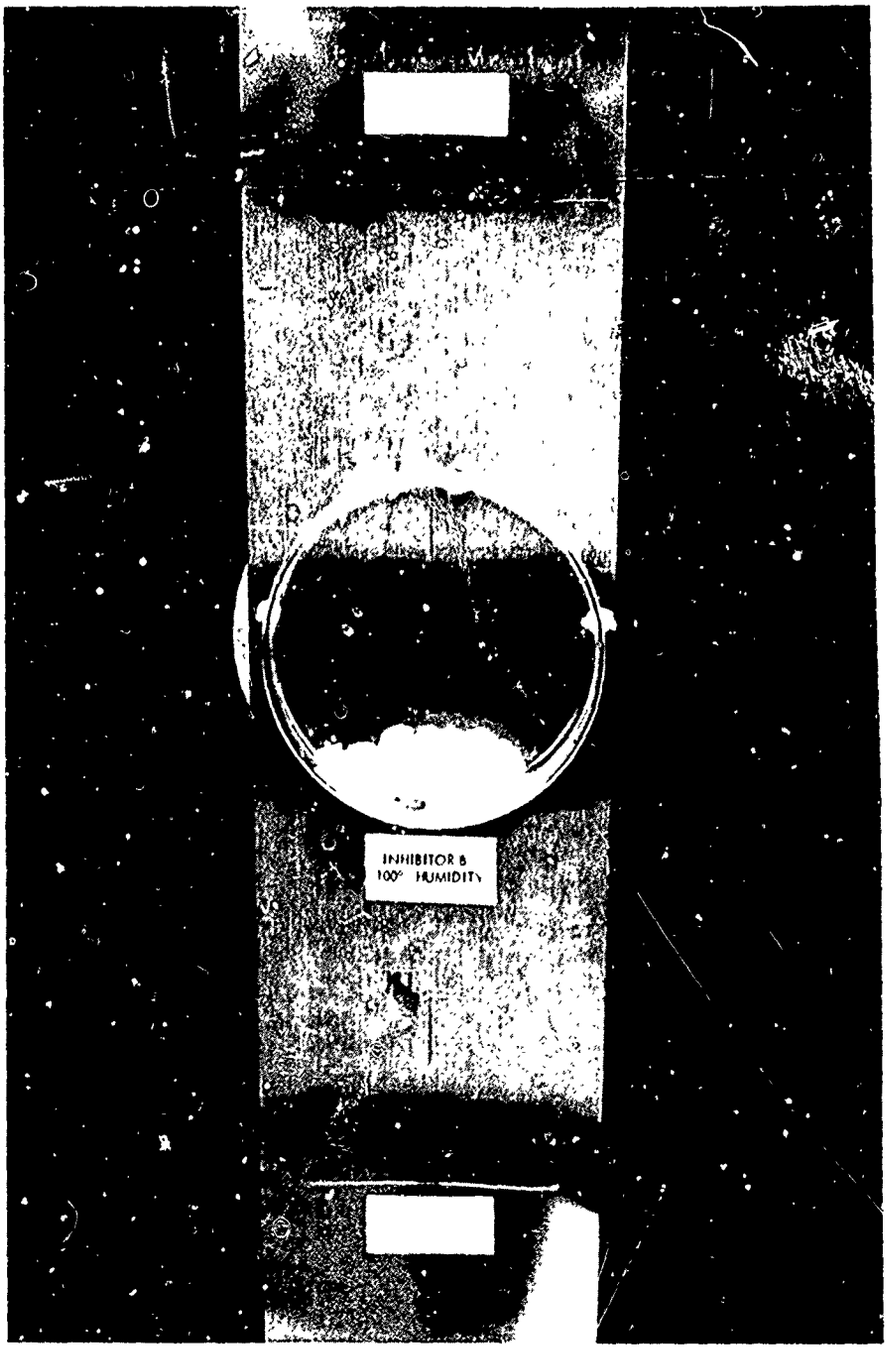

FIGURE 2. PETRI DISH CONTAINING THE VAPOR PHASE INHIBITOR IS SEALED AGAINST THE CRACK PATH.

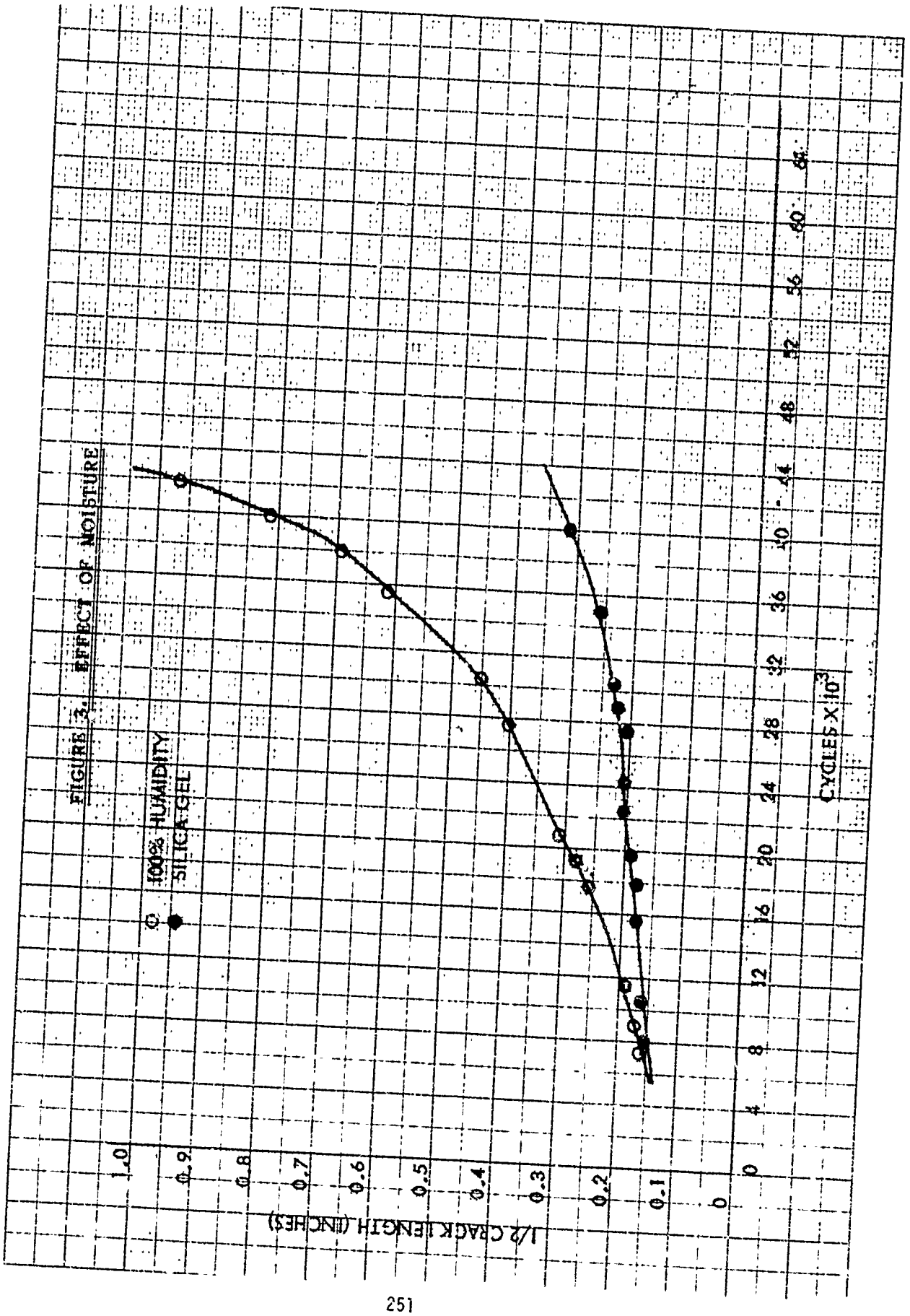
FIGURE 3. EFFECT OF MOISTURE
100% HUMIDITY
SILICA GEL
1/2 CRACK LENGTH (INCHES)
CYCLES X 10^3
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
0
4
8
12
16
20
24
28
32
36
40
44
48
52
56
60
64

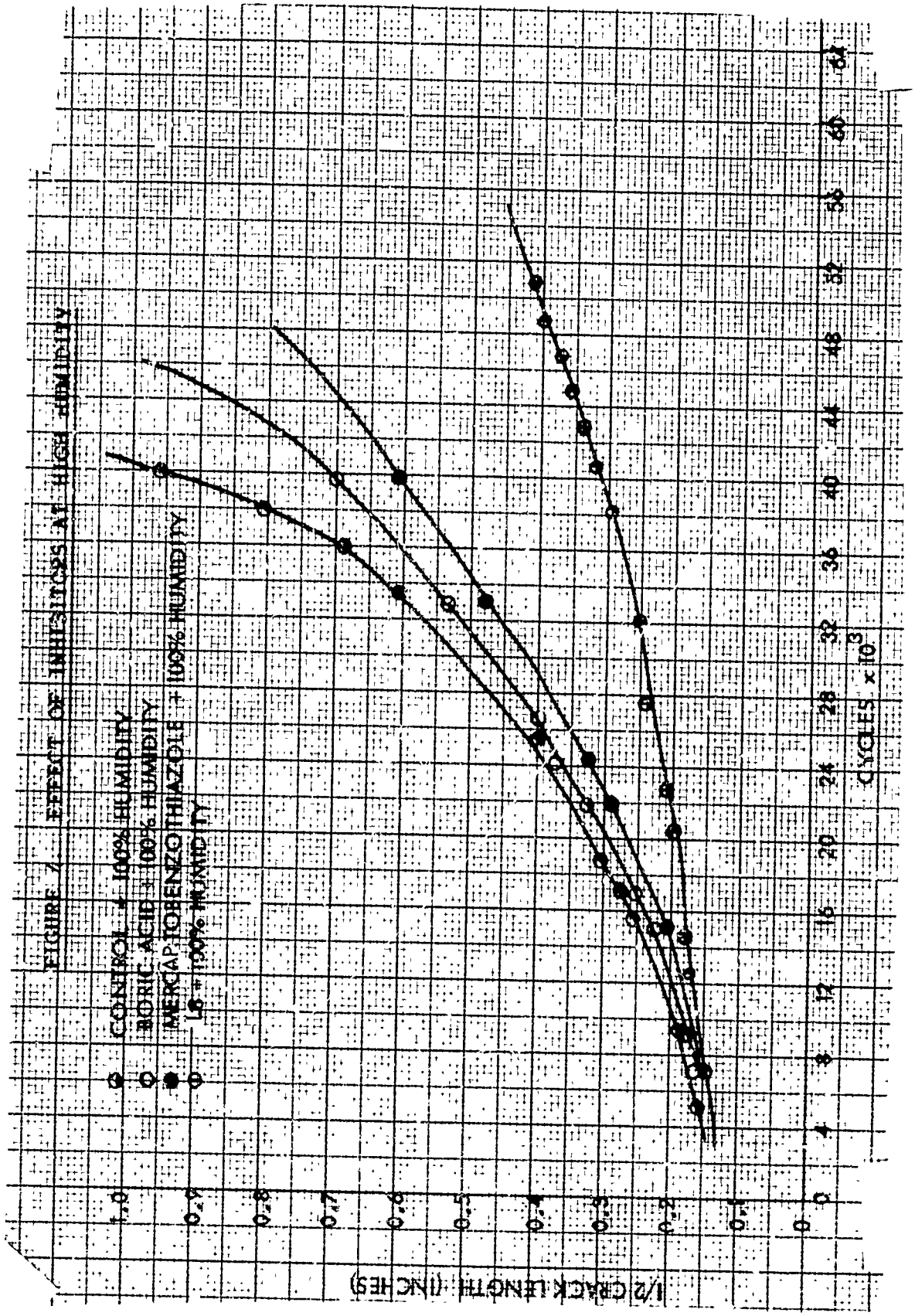

FIGURE 7 EFFECT OF INHIBITORS AT HIGH HUMIDITY

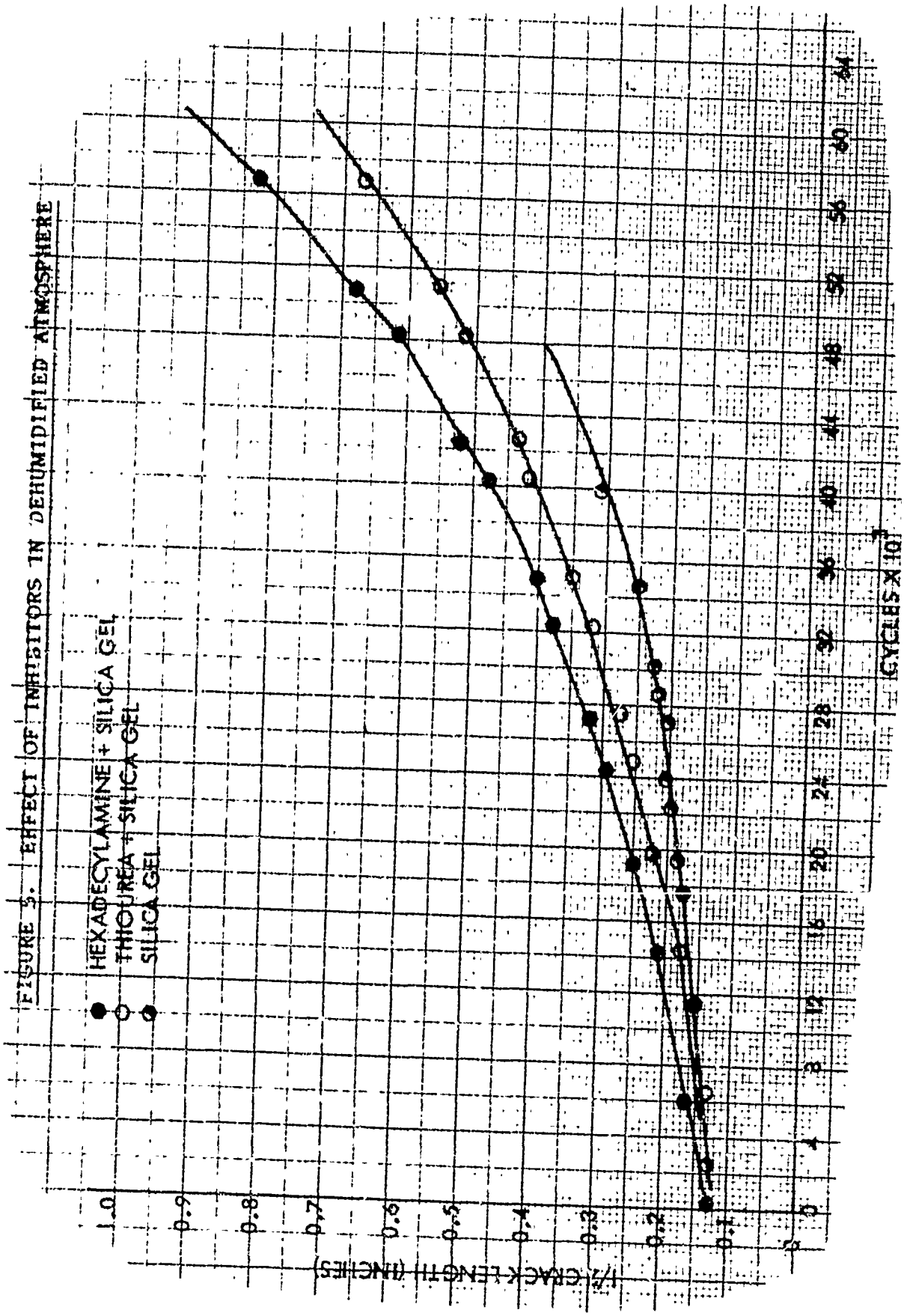

FIGURE 5. EFFECT OF INHIBITORS IN DEHUMIDIFIED ATMOSPHERE

and a specimen coated with primer which contained 5% of the L5 inhibitor. The specimens were cycled at 0.1 Hz at ambient temperature and 100% relative humidity. Figures 6 and 7 show the fracture surfaces of the test specimens. In both figures, the photograph was taken at points the same distance from the center of the crack. In the bare control specimens. shown in figure 6, the distance between striations was 1.43×10^{-5} inches. The specimen in Figure 7 was protected with primer which contained 5 percent of the L5 inhibitor. the crack growth/cycle, as indicated by the distance between striations, was 0.926×10^{-5} inch.

TABLE III. SUMMARY OF FATIGUE TESTS AT 100% HUMIDITY

Inhibitor	1/2 Crack Length at 40,000 Cycles (Inches)
control	0.83
thiourea	1.2
dicyclohexylamine nitrite	0.81
boric acid	0.70
sodium borate	0.66
mercaptobenzothiazole	0.74
magnesium azealate	0.8
L5 inhibitor	0.75
L8 inhibitor	0.31

Table IV gives the da/dN values for a bare specimen which was cycled in a 100% humidity atmosphere and one cycled in 100% humidity atmosphere saturated with the L5 inhibitor vapor. Also shown are data for specimens coated with MIL-P-23377 primer, with and without the L5 inhibitor. The data show that MIL-P-23377 primers alone, without the vapor phase inhibitor, will substantially reduce the crack growth rate of 7075-T6 aluminum. The presence of the L5 inhibitor makes the primers even more effective in reducing crack growth rate.

TABLE IV. EFFECT OF VAPOR PHASE INHIBITOR ON CRACK GROWTH

Type Coating	Without L5 Inhibitor	With L5 Inhibitor	Percent Difference
Bare	1.43×10^{-5}	1.126×10^{-5}	21.2
MIL-P-23377 with no chromates	1.04×10^{-5}	$.926 \times 10^{-5}$	11.0
MIL-P-23377 with chromates	$.788 \times 10^{-5}$	$.622 \times 10^{-5}$	21.1

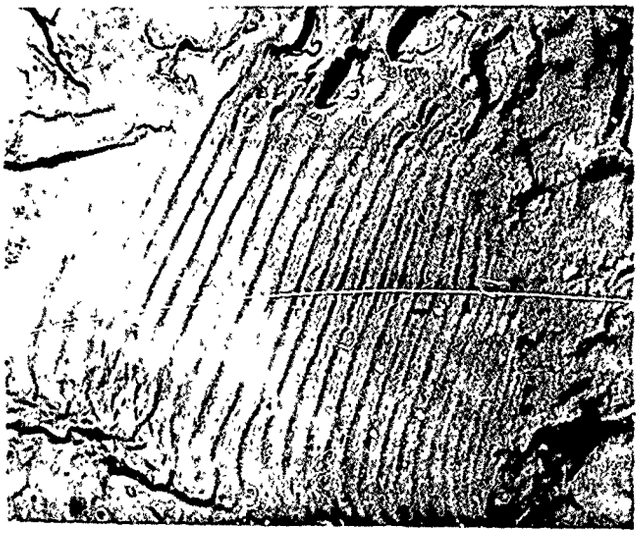

FIGURE 6. STRIATIONS IN FRACTURE SURFACEOF CONTROL SPECIMEN. CRACK GROWTH WAS 1.43×10^{-5} INCHES PER CYCLE

(10,000X)

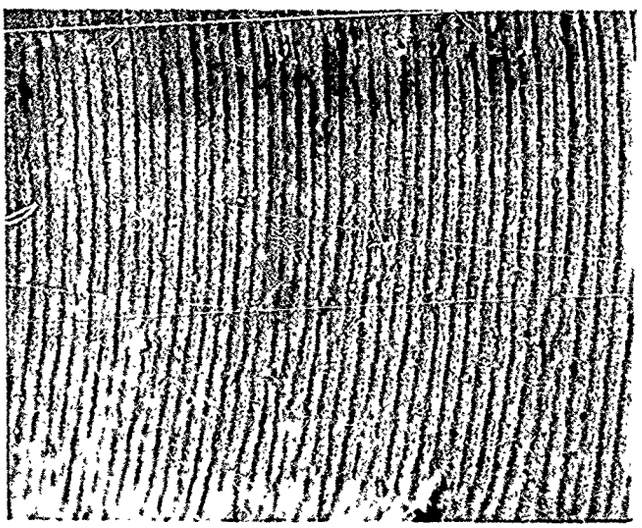

FIGURE 7. FRACTURE SURFACE OF SPECIMEN PROTECTED WITH SPECIAL PRIMER. CRACK GROWTH WAS $.926 \times 10^{-5}$ INCHES PER CYCLE.

(10,000X)

Figure 8 is a da/dN vs Δ K plot for a bare control specimen, a specimen protected with primer only, and a specimen protected with primer which contained 5 percent of the L5 inhibitor compound. The tests were conducted a a 100 percent relative humidity, 0.1 Hz, and a stress ratio of 0.1. Comparing the two primer-coated specimens, the addition of the inhibitor to the primer resulted in a 26.5 percent decrease in da/dN at $\Delta K_I = 7$ and a 15.4 percent decrease at $\Delta K_I = 10$.

A similar set of tests were conducted using a triple-crack 7075-T6 aluminum specimen. The back side of the top slot was painted with a 1 mil coating of the MIL-P-23377 epoxy polyamide primer. The back side of the middle slot was painted with the same primer formulated with 5% by weight of the L-8 vapor phase inhibitor. The bottom slot was bare and served as a control. A Petri dish containing a water saturated swab of cotton was sealed around each slot to assure a 100 percent relative humidity atmosphere. Table V shows the crack lengths after 25,000 stress cycles.

These results show that the crack exposed to the primer which contained the L8 inhibitor grew 1/4 as much as the control crack and only 1/3 as much as the crack exposed to the standard MIL-P-23377 epoxy polyamide primer. Similar results were obtained when the MIL-P-87112 polysulfide primer was used.

TABLE V. CRACK LENGTHS AFTER 25,000 CYCLES
MIL-P-23377 PRIMER WITH AND WITHOUT L8 INHIBITOR

Slot	Crack Length (In.)
Bottom (Control)	0.24
Middle (MIL-P-23377 Plus 5% L8)	0.06
Top (MIL-P-23377)	0.19

Discussion of Results

The potentiostatic polarization tests and the surface energy tests on aluminum specimens which had been treated with the inhibitors were conducted to establish data which, hopefully, could be correlated with the results of the fatigue tests and given an indication of the mechanism by which fatigue crack growth was retarded.

The inhibitors which gave the best results in the 100% humidity fatigue tests were boric acid, sodium borate, mercaptobenzothiazole and L5 inhibitor. The mercaptobenzothiazole gave a low corrosion current in the potentiostatic polarization test but the other two inhibitors were not especially effective in minimizing corrosion currents.

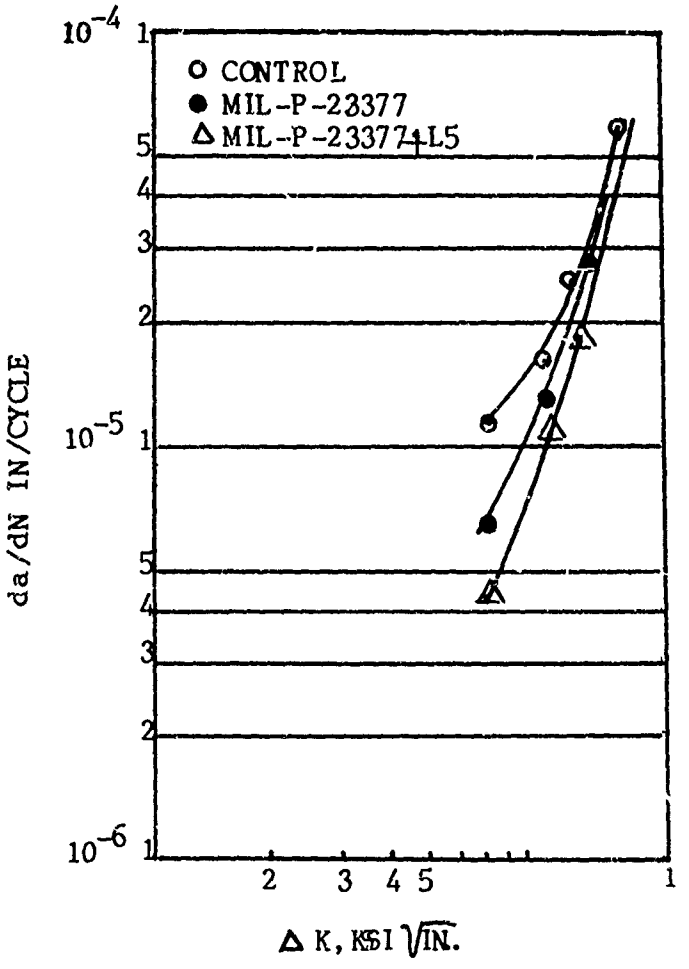

FIGURE 8. EFFECT OF MIL-P-23377 PRIMER WITH AND WITHOUT L5 INHIBITOR (100% HUMIDITY, 0.1 HZ, R = 0.1)

The surface energy data shows that the mercaptobenzothiazole and the L5 inhibitor created a film with a high surface energy but the remaining effective crack growth inhibitors formed medium and low energy films.

On the basis of these limited tests there is no correlation between the performance of the inhibitors in the potentiostatic polarization tests and surface energy tests and their ability to retard the rate of fatigue cracking in 7075-T6 aluminum.

The results of the fatigue tests illustrate the great effect of moisture on the rate of crack propagation. They also show that a number of compounds, mercaptobenzothiazole, L5 inhibitor, dicyclohexylamine nitrite, sodium borate and inhibitor L8, are effective in retarding crack growth at 100% humidity. In the absence of moisture, most of these compounds accelerate the rate of crack growth.

The tests with primer coated specimens, with and without L5 inhibitor in the primer, demonstrate the validity of the concept that cracking of aluminum can be retarded by mixing suitable inhibitors into the primer.

Conclusions

1. In the group of compounds evaluated, there was no apparent correlation between the results of the potentiostatic polarization tests and their ability to retard crack growth in 7075-T6 aluminum.

2. There was no correlation between the results of the surface energy tests and the ability of the inhibitors to minimize crack growth.

3. The inhibitors which were most effective in retarding the rate of crack propagation in 7075-T6 aluminum under 100 percent humidity conditions were boric acid, sodium borate, mercaptobenzothiazole, inhibitor L5 and inhibitor L8.

4. The cracking of 7075-T6 aluminum under high humidity conditions may be minimized by incorporating selected inhibitors into the primer used to protect the metal.

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Biography

Name: Dr. Robert N. Miller

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Plans, directs and conducts research programs relating to corrosion prevention, protective coatings, fatigue fracture and electrochemistry.

Previous Affiliations/Titles:

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Academic Background:

B.S. in Chemical Engineering, Ohio State University, 1936
M.Sc. in Chemical Engineering, Ohio State University, 1942
Ph.D. in Chemical Engineering, Ohio State University, 1949

Society Activities/Offices:

Tau Beta Pi
Mensa
National Association of Corrosion Engineers

Publications/Papers:

Has presented or published more than 40 papers in the fields of corrosion, protective coatings, surface chemistry, cryogenics, radiation effects and electrochemistry. Has been granted 4 United States patents.

PRESSURE SENSITIVE PROTECTION FILMS AND JOINING SYSTEMS AUTOMOTIVE INDUSTRY RELATED APPLICATION

R. J. Olson and D. F. Brown
Industrial Specialties Division, 3M Company

ABSTRACT

This presentation will cover pressure sensitive attachment and protective film systems with primary as well as secondary surface protection capability.

Automotive Industry corrosion prevention by the use of pressure sensitive adhesive products will be reviewed. We will concentrate specifically on vehicle surface protection, dissimilar metal insulation, as well as the elimination of mechanical fasteners, studs, and holes in the sheet metal as a means of corrosion reduction.

This information will be of value to each of you whether your field is aerospace, marine, or ground support as another tool to resolve design, assembly. and functional problems.

INTRODUCTION

Illustration 1.

The Automotive Industry has in recent years given increased attention to corrosion prevention. Their concern is not unfounded.

Illustration 2.

Corrosion menaces most vehicles in the U.S. and Canada. The worst car body and chassis damage occurs in a "salt belt" as shown on this map. In this international zone nearly thirteen million tons of salt is liberally applied to our streets and roads each winter. This is nearly a tenfold increase over 1955 usage.

Vehicle corrosion results when lower body panels and undercarriage components are exposed to road slush containing de-icing chemicals. Corrosion, however, is not limited to vehicles driven in this "salt belt".

The development of light weight, more fuel economy vehicles has caused severe galvanic corrosion problems where dissimilar metal structural parts are mated together.

Protective Coatings

Illustration 3.

The Automotive Industry is concerned and is actively pursuing corrosion prevention by using protective coatings that are being applied both before and after sheet metal forming. This diagram shows a cross section of an outer door assembly where a total of nine coatings or treatments are used to protect against corrosion. These coatings range in thickness from less than 0.5 mil to 14 to 16 mils vinyl of plastisol or polyurethane abrasion resistant film tape.

Polyurethane Abrasion Resistant Film Tape

The first protective product I would like to discuss is a transparent polyurethane abrasion resistant film tape with a pressure sensitive adhesive.

Illustration 4.

Its primary function in automotive related applications is surface protection as illustrated here on these Chevrolet fender sections which had been subjected to a GM proving grounds test. The fender on the left, protected with abrasion resistant film, is relatively free of corrosion while the unprotected fender on the right has suffered stone chip damage resulting in severe corrosion.

Before showing other applications, let's first review the construction, features, and physical properties of the polyurethane abrasion resistant film tape.

CONSTRUCTION

Illustration 5.

The Polyurethane Abrasion Resistant Film Tape consists of either 6 or 12 mils of a transparent, thermoplastic polyurethane film coated with 2 mils of a permanent acrylic pressure sensitive adhesive which is protected with a 3 mil thick silicone treated paper liner.

FEATURES

Transparent and Weatherable

Illustration 6.

Both the pressure sensitive acrylic adhesive and the polyurethane film exhibit excellent resistance to outdoor aging.

Illustration 7.

This accelerated aging panel indicates the consistent improvement in resistance to discoloration that has been achieved over the last few years.

Other illustrations of accelerated and outdoor aging will be shown later.

Abrasion Resistance

Illustration 8.

The abrasion resistance of the polyurethane film is best illustrated by a SAE-J400 gravelometer test which consists of one pint of a specified gravel to be projected under pressure at a test panel. Both of the painted panels were subjected to the gravelometer test. The panel on the left, protected with abrasion resistant film, is not damaged while the unprotected panel is severely damaged. The paint damage is more than an aesthetic problem.

Illustration 9.

After completion of five consecutive gravelometer blasts, these panels were subjected to a salt spray chamber. Again, the protected panel shows little damage or subsequent corrosion hile the unprotected panels are severely corroded.

Physical Properties - Comparison

Illustration 10.

This graph illustrates the balance of physical properties exhibited by the Polyurethane Abrasion Resistant Film as compared to other films such as polyethylene and polyester.

Accelerated Aging - Physical Properties

Illustration 11.

One accelerated weathering test used throughout the Automotive Industry is a QUV test exposure. It consists of a repetitive cycle of eight hours UV light at 160°F. and four hours of condensation at 120°F. The test is usually terminated after a maximum exposure of 1,000 hours.

Illustration 12.

As you can see, tensile and elongation properties are unchanged as are the tear strength and taber abrasion even after 1,000 hours of exposure. Many films such as vinyl and polyethylene are too deteriorated to test after 250 hours.

Natural Aging - Physical Properties

Illustration 13.

While accelerated aging is widely accepted, the true test remains natural aging in Florida and Arizona. Although Florida's hot/humid climate is the most demanding, the abrasion resistant film physical properties are not adversely affected.

Current Automotive Applications

The next series of slides illustrate some of the current automotive applications.

Dissimilar Metal Separator

Illustration 14.

Bumper and hinge assemblies are likely areas for galvanic corrosion to occur when two dissimilar metals are combined with an electrolyte (a salt, acid, or alkali solution) to complete an electric circuit. As illustrated, the abrasion resistant film is a permanent barrier or insulator between the dissimilar metal bumper components.

Weld Joint Seam Protection

Illustration 15.

Concentration corrosion occurs when a single type of metal in contact with an electrolyte having different compositions or concentrations will cause a current flow between the two areas. A common location for this type of corrosion is in the cracks and crevices of a welded door frame as shown in the black areas.

Illustration 16.

Conformability of the Abrasion Resistant Film Tape is necessary to a tight seal preventing moisture and road salt penetration.

Stone Chip Protection

Road debris such as stones, sand, and grit will abrade the surface protection leaving the metal vulnerable to oxidation.

Illustration 17.

Unprotected rear wheel fender areas will receive stone chip damage as shown in the following illustrations.

Illustration 18.

Chevrolet Pickup - No protection.

Illustration 19.

Chevrolet Pickup - Protected.

Illustration 20.

Jeep Cherokee - No protection.

Illustration 21.

Jeep Cherokee - Protected.

Illustration 22.

Chevrolet Van - Protected.

Exterior Surface Chafing Protection

As in stone chip protection, exterior surfaces are protected from mechanical chafing as shown in the following illustrations:

Illustration 23.

Front Bumper Filler Panel

Illustration 24.

Ford Bronco - Spare Tire Mount

Illustration 25.

Jeep Wagoneer - Door Edge Protection

Automotive requirements for these exterior surface protection applications are:

1. Conformability
2. Weatherability (unstable)
3. Abrasion (Gravel) Resistance
4. Permanent Pressure Sensitive Adhesive
5. Ease of Application - Wet Method

Fabricated Parts

Illustration 26.

The abrasion resistance film tape can be provided in standard rolls or as die cut and kiss cut parts to specified dimensions. This facilitates easy application at assembly line speeds.

Aircraft

At this point, I'd like to call your attention to aircraft applications that currently utilize the abrasion resistant film tapes.

Leading Edge Protection

Illustration 27.

Rain erosion protection of wing, horizontal, and vertical stabilizer leading edges is shown on this schematic of the P-3.

Illustration 28.

In addition to the P-3 this application is employed on the A-6, C-5A, C-130, C-1410, and the A/T-37.

Fuel Cell Bladder Protection

Fuel cell bladder protection is another application where the abrasion resistant film is applied over the fuel cell rivet patterns to protect the bladder from chafing. Current applications include the A-6, F-4, F-14, F-15, and F-18.

Radome Boots

Illustration 29.

The Navy pioneered the use of abrasion resistant film tape for Radome rain erosion protection several years ago. Today they use thermoformed boots on the P-3, A-6, EA-6B, A-7, and the S-3A. 3M provides preformed radome boots to the commercial aircraft industry for the 707, 727, 737, DC-9, Gulfstream G-2, Lockheed Jetstar, and Piper Cheyenne II.

Illustration 30.

Pictured is a Radome boot applied to a U.S. Air DC-9.

Protective Keyboard Boot

Illustration 31.

Another type of boot being fabricated is a protective keyboard boot. It's used on a produce scale to prevent contaminants such as grease, oil, moisture, and dirt from penetrating into the electrical circuitry. Custom boots can be made with or without the pressure sensitive adhesive.

The unique resiliency and toughness of the polyurethane film has allowed the boots to withstand, in test, nearly 5 million fatigue cycles without failure (keyboard failed).

NEOPRENE FOAM TAPE

Eliminating holes in exterior sheet metal for screws, bolts, studs, and other mechanical fasteners needed to attach trim is another technique used to reduce corrosion of the car body. Obviously a hole in the sheet metal will be a high probability site for corrosion because of two primary reasons: 1) greater surface area for moisture retention, and 2) chaffing of any coatings on the metal edge by the mechanical fastener inserted into the hole. The corrective action is to eliminate the holes and to attached the trim with adhesive.

The role of tape in reducing corrosion is to provide a pressure sensitive adhesive system for bonding trim to the exterior of the vehicle. An additional benefit of tape attachment is a substantial cost savings from eliminating drilling and piercing operations and the related tools and dies, reduction of sheet metal inventories for different models with different hole patterns, and improved assembly rates.

The primary tape system used throughout the world by automotive manufacturers for exterior trim attachment is a neoprene foam tape. A conservative estimate of 35 million vehicles have had exterior trim attached with neoprene tape in the past 12 years.

CONSTRUCTION

Illustration 32.

The neoprene foam is provided in three thicknesses and three densities to compensate for various degrees of mismatch between the trim and sheet metal. The pressure sensitive adhesive system is an acrylic coated on both sides of the neoprene foam. A protective release liner of paper or film is provided on one side. Specific performance characteristics and physical properties of the tape system will be presented after a review of some basic applications.

Attachment of Body Side Molding is a most common application.

BODY SIDE MOLDING APPLICATIONS

Illustration 33.

A vinyl extrusion is used to replace the metal molding. The foam tape is laminated to the vinyl at the time of extrusion.

Illustration 34.

Volkswagon

Body Side Molding

Illustration 35.

Honda

Body Side Molding

Illustration 36.

AMC Pacer

Body Side Molding around woodgrain

ORNAMENTATION APPLICATIONS

Illustration 37.

Chrysler Cordoba

Body Side Molding

Cordoba Die Cast Script

Cordoba Plastic Ornament

The script or ornaments represent another use of tape attachment of exterior trim.

Illustration 38.

Buick Le Sabre, Sport Coupe Script

Illustration 39.

Pontiac Body Side Molding

Phoenix Ornament

Illustration 40.

Oldsmobile Body Side Molding

Cutlass and Brougham Script

Illustration 41.

Buick Ornament

Buick Metal Trim (61 inch)

New applications for pressure sensitive tape attachment are:

Illustration 42.

Wheel Lip Moldings

Illustration 43.

Lower Body Molding

Illustration 44.

Reveal Moldings

Illustration 45.

Flexible bumper moldings on flexible urethane bumper systems. The flexible bumper system is being adopted to meet the Federal bumper impact requirements. In addition, the plastic components help eliminate corrosion. Twelve 1981 models will use tape attachment of the bright trim to the flexible bumper.

To provide permanent long-aging bonds for exterior applications, the tape system must demonstrate high holding at evaluated temperatures and resist degradation from exposure to fuels, as well as elements of the environment.

TEST METHODS

Four test method for characterization of tapes are:

1. Illustration 46.

   Peel Adhesion - Measure force required to break bond.

2. Illustration 47.

   Dynamic Shear - Measure force required to break bond.

3. Illustration 47.

   Static Shear - Differs from dynamic shear in that load is constant and time to failure is measured. Termination of test after 100 hours is typical.

4. Illustration 48.

   Tensile (T-Block) - Measure force required to break bond.

PERFORMANCE

The following three tests are selected to illustrate performance characteristics.

1. Illustration 49.

   Dynamic Shear - Effect of temperature.

2. Illustration 50.

   Dynamic Shear - Effect of fuel exposure.

3. Illustration 51.

   Static Shear - Effect of load and temperature.

Selected to illustrate physical properties and include minimum performance values is Chrysler Specification MS-CH51.

Illustration 52.

Tensile and Tear

Represent high internal strength of the neoprene foam.

Peel Adhesion

Immediate test but the values can triple within three days.

Humidity Test

The 50 psi is the result of a most severe 14 day continuous exposure to 100% relative humidity at 100°F. This may represent the very minimum performance level in the most severe environment.

Neoprene tapes also retain flexibility and high holding strength at low temperatures and are required to pass tests at -20°F. to include shock tests.

In summary, tape systems offer varying methods to combat corrosion. They have proven their effectiveness in the cost conscious Automotive Market for many years, and they are becoming more commonly used as familiarity with the tape systems increases.

Principle applications for tape systems reviewed are:

1. Exterior surface protection.
2. Dissimilar metal barrier.
3. Rain erosion.
4. Elimination of mechanical attachments.

REFERENCES

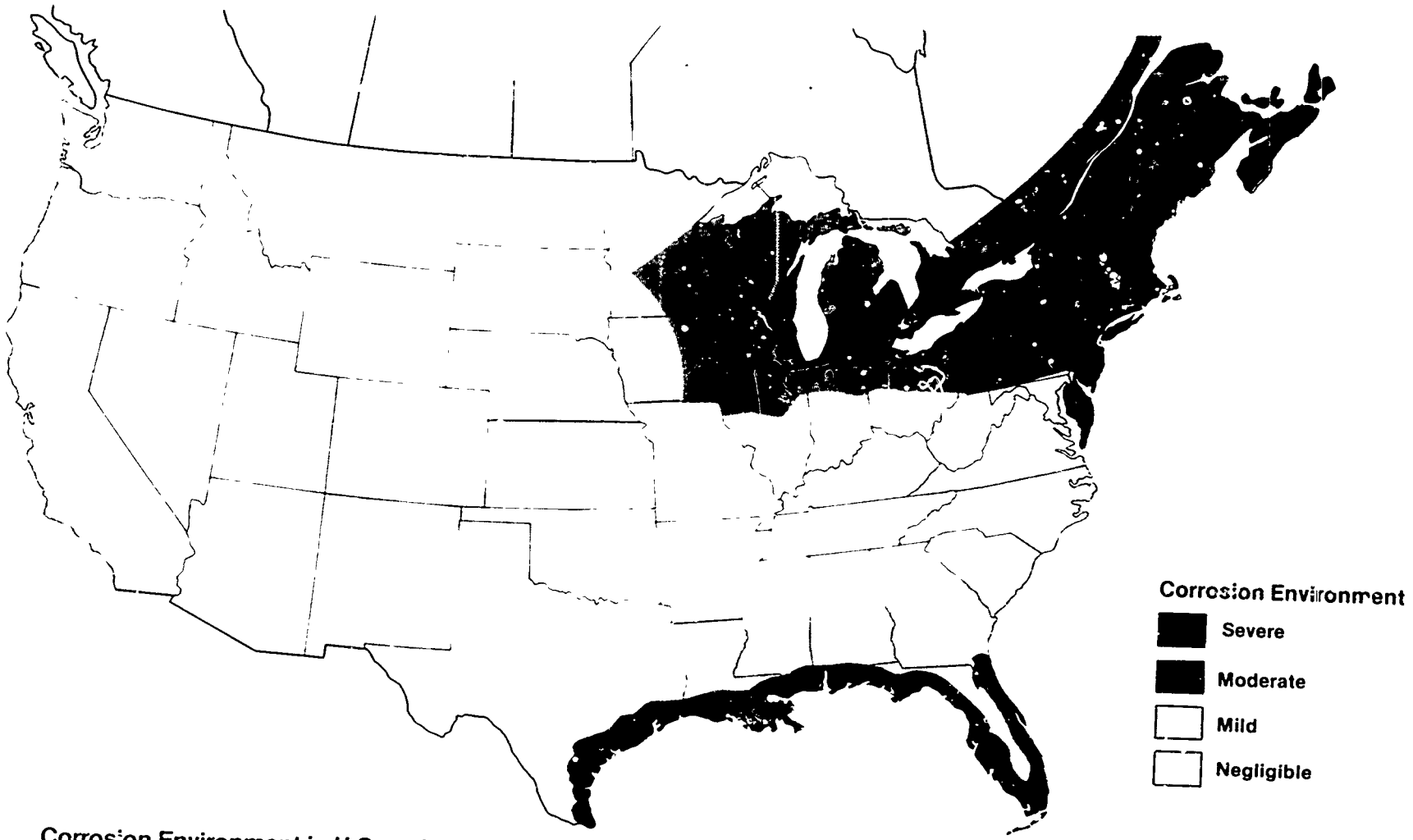
1. W. G. Patton, "What Are The Automakers Doing to Stem the Corrosion Tide?", Iron Age, April 29, 1971, page 53, map modified by C. Durbin, Chrysler Corporation, 1977, to include Canada.

2. American Public Works Association, "Vehicle Corrosion Caused by De-Icing Salts", Special Report #34, September, 1970.

3. N. D. Greene and G. Judd, "The Relationship Between Anodic Dissolution Kinetics and Resistance to Pitting Corrosion", Corrosion, Volume 21, January 1965, pages 15-18.

4. "Cracking Down on Corrosion", American Iron and Steel Institute, SG-731-1078-20M-SR.

Illustration 1.



Corrosion Environment in U.S. and Southern Canada

Illustration 2.

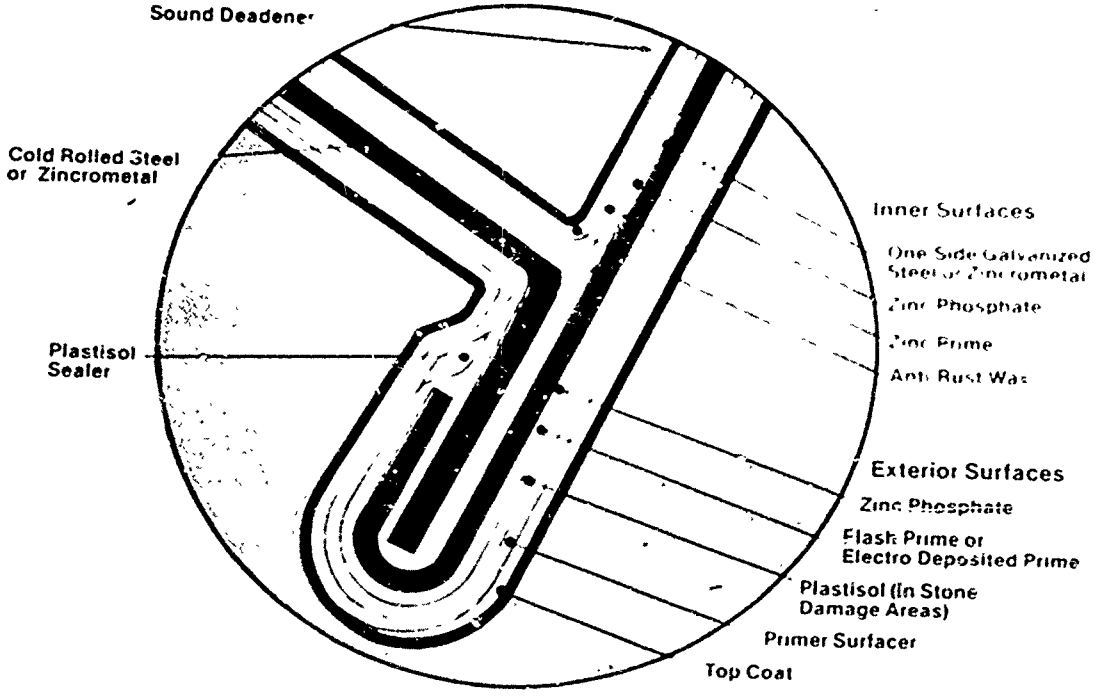


Figure 10:

Post assembly coatings provide improved protection against corrosion. Here, the door outer panel is of one side galvanized steel with three additional coatings on the inner surface and five, including topcoat, on the exterior surface. Deadener also is applied to the inner surface of the outer panel.

(Drawing adapted from *Machine Design*—IPC Penton-Nov. 1976)

Illustration 3.

Illustration 4.

Abrasion Resistant Film

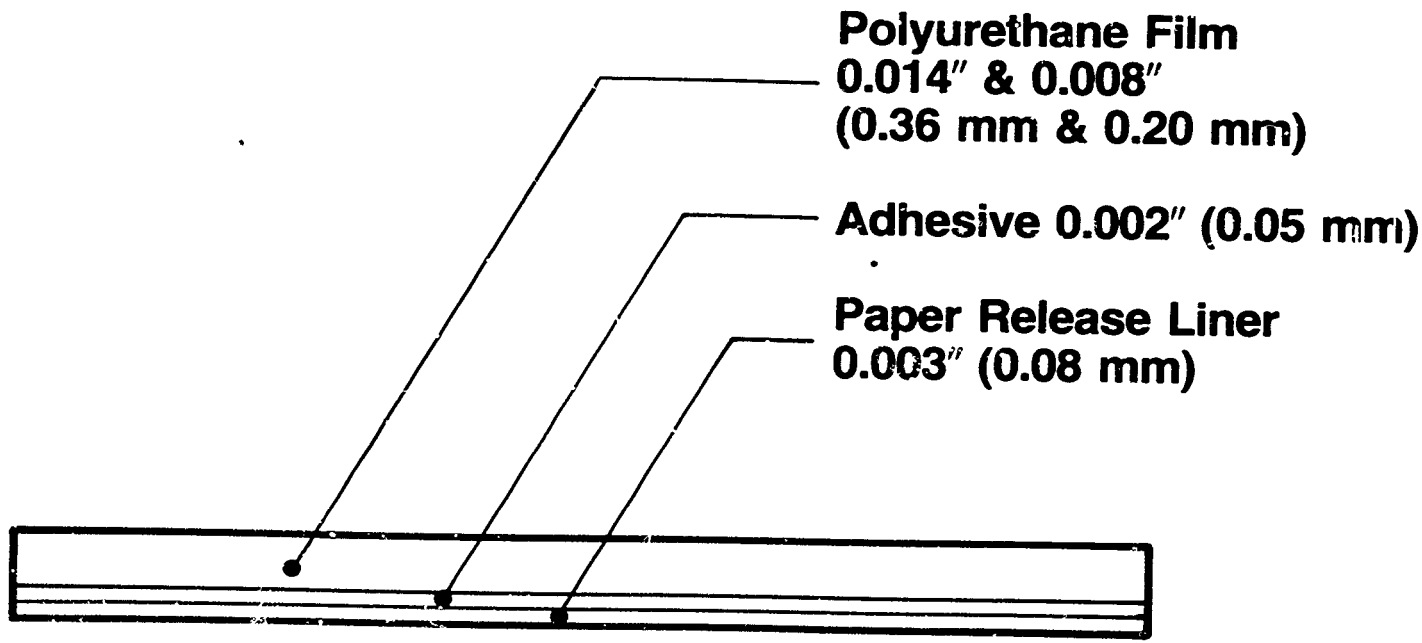


Illustration 5.

Abrasion Resistant Film Tape Features

Polyurethane Film

- Transparent
- Weatherable — UV Stable
- Abrasion Resistant
- Conformable

Adhesive — Pressure Sensitive Acrylic

- Permanent
- Exterior Grade

Illustration 6.

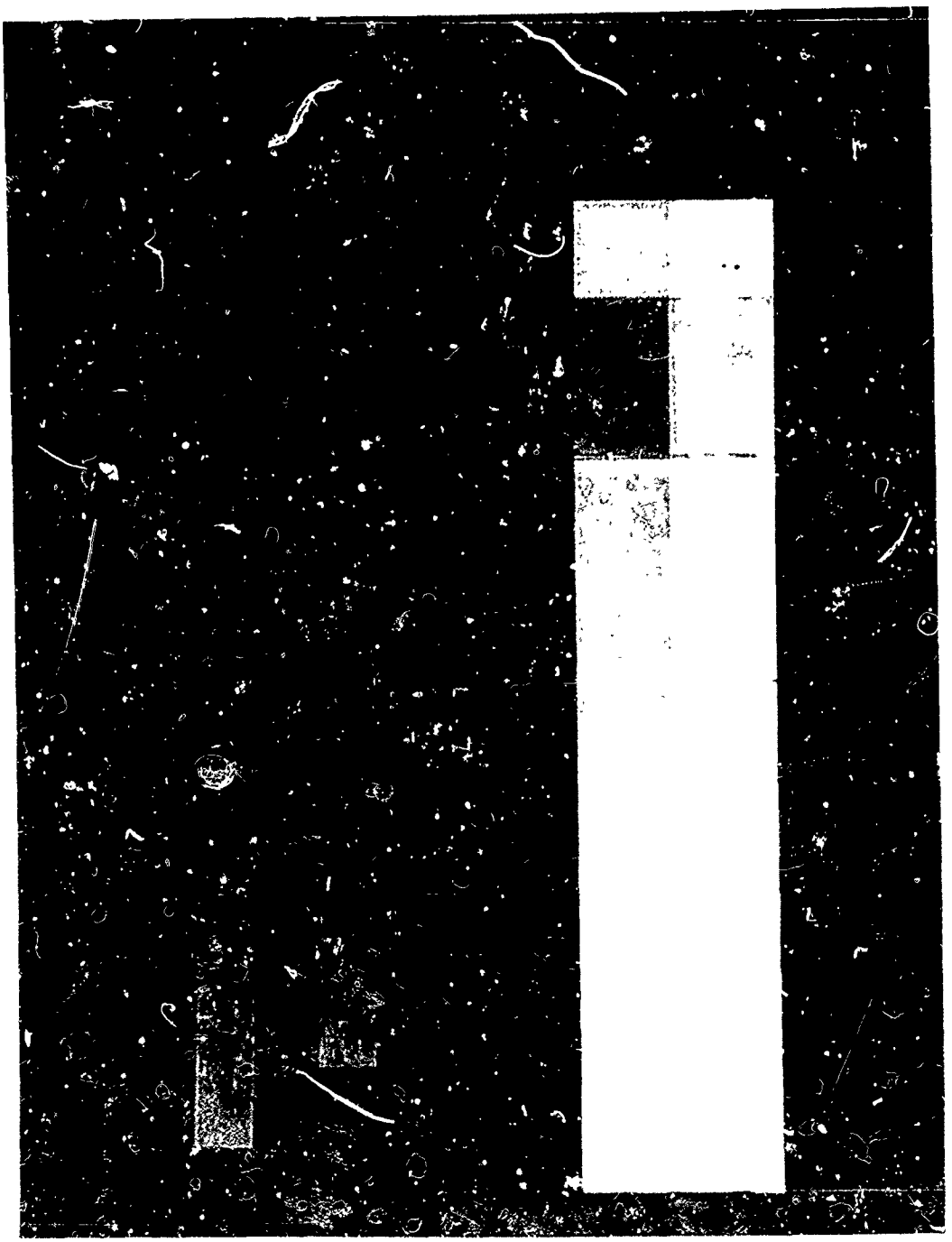
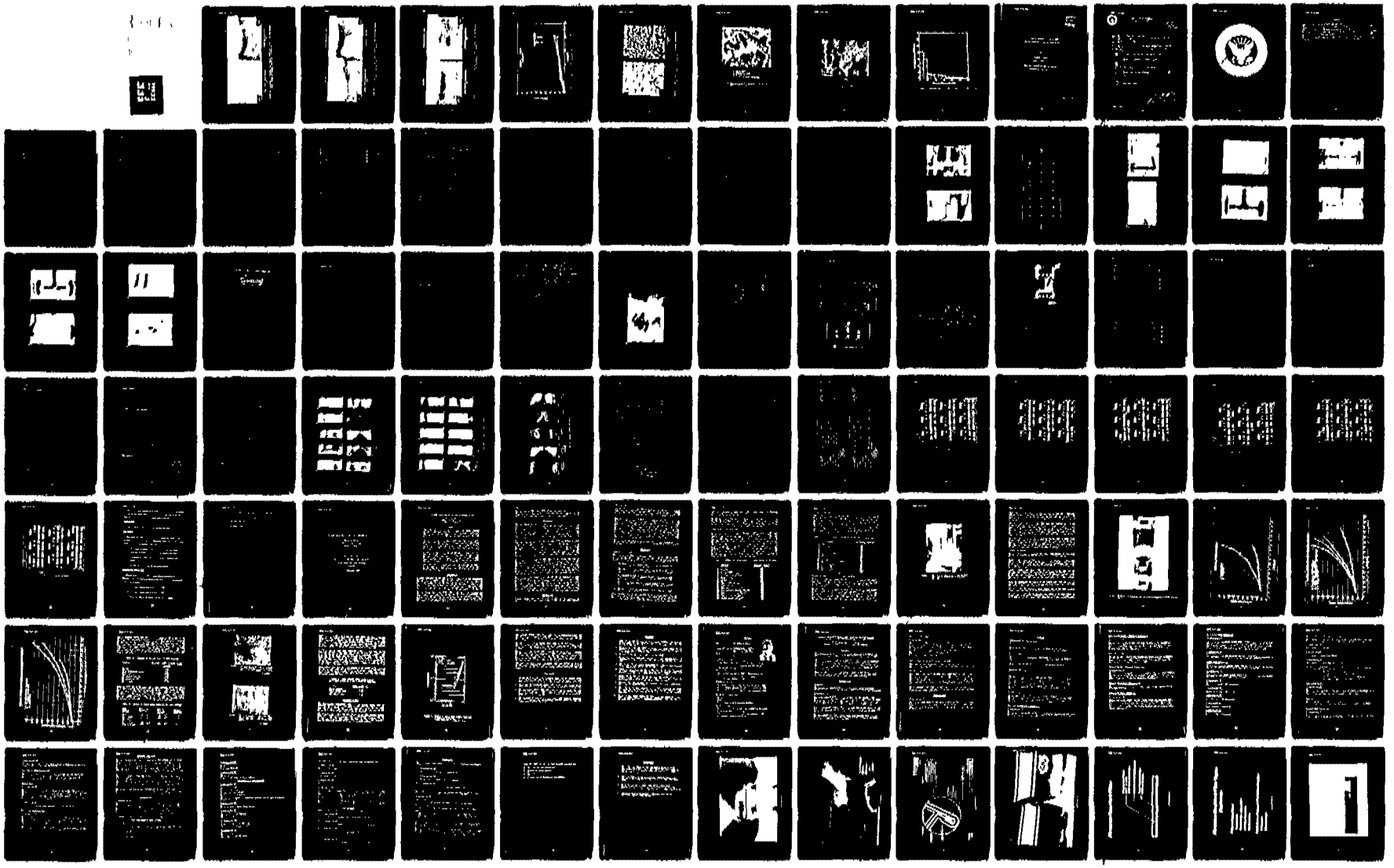


Illustration 7.

AD-A106 803 AIR FORCE WRIGHT AERONAUTICAL LABS WRIGHT-PATTERSON AFB OH F/G 13/8
PROCEEDINGS OF THE 1980 TRI-SERVICE CONFERENCE ON CORROSION, 5---ETC(U)
NOV 80 F H MEYER

UNCLASSIFIED AFWAL-TR-81-4019-VOL-1 NL



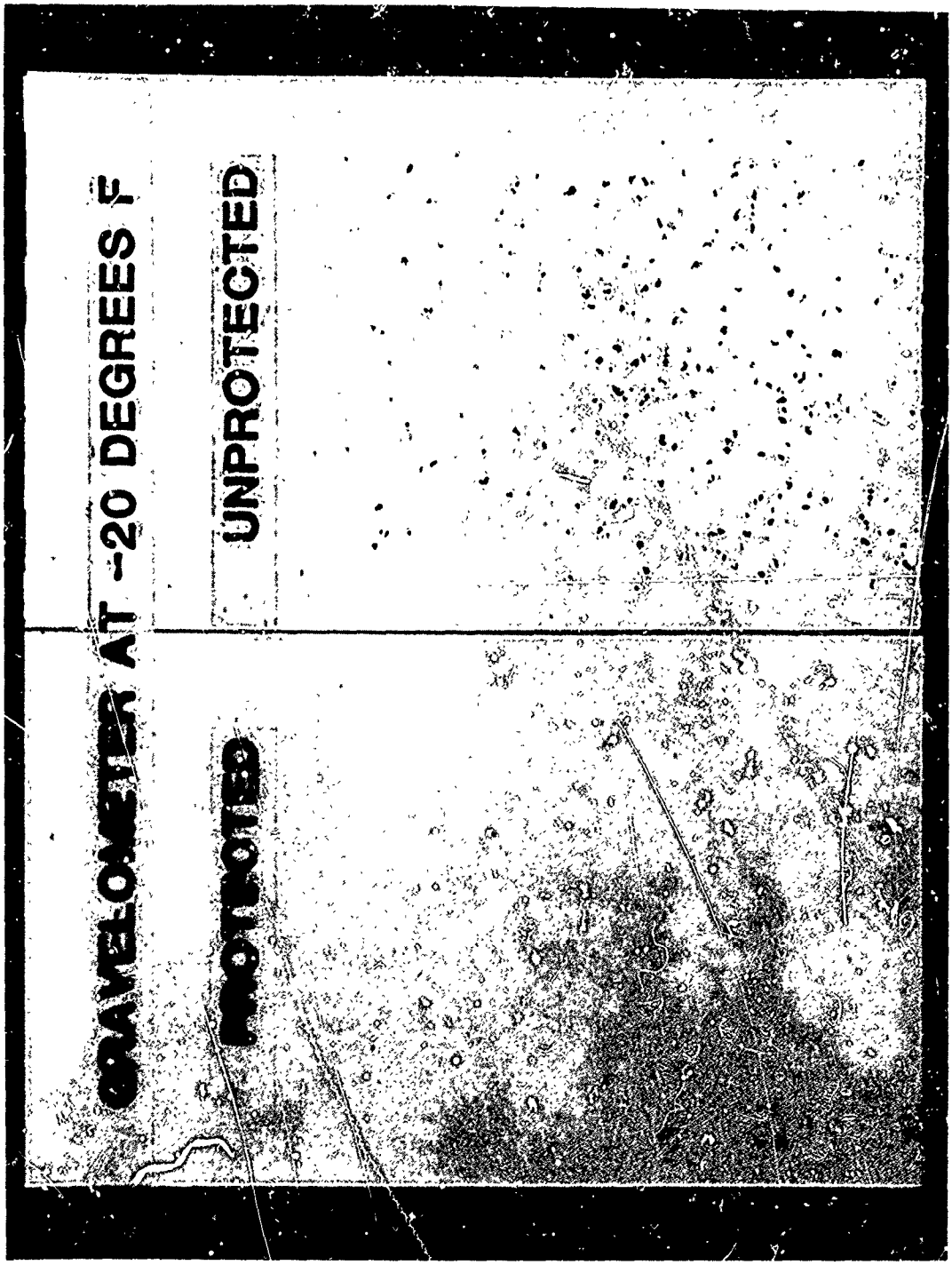


Illustration 8.

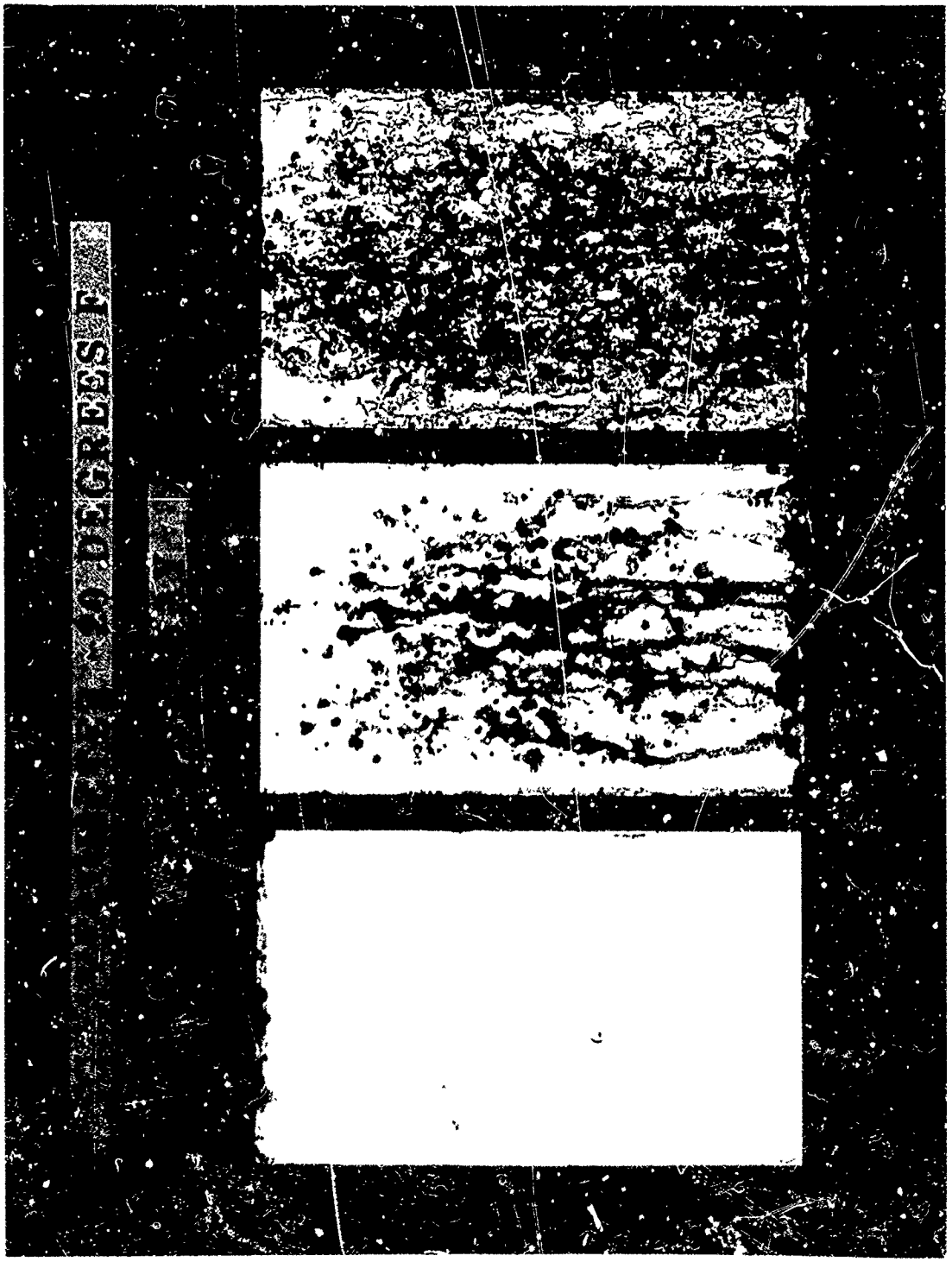


Illustration 9.

QUV Exposure

Abrasion Resistant Film

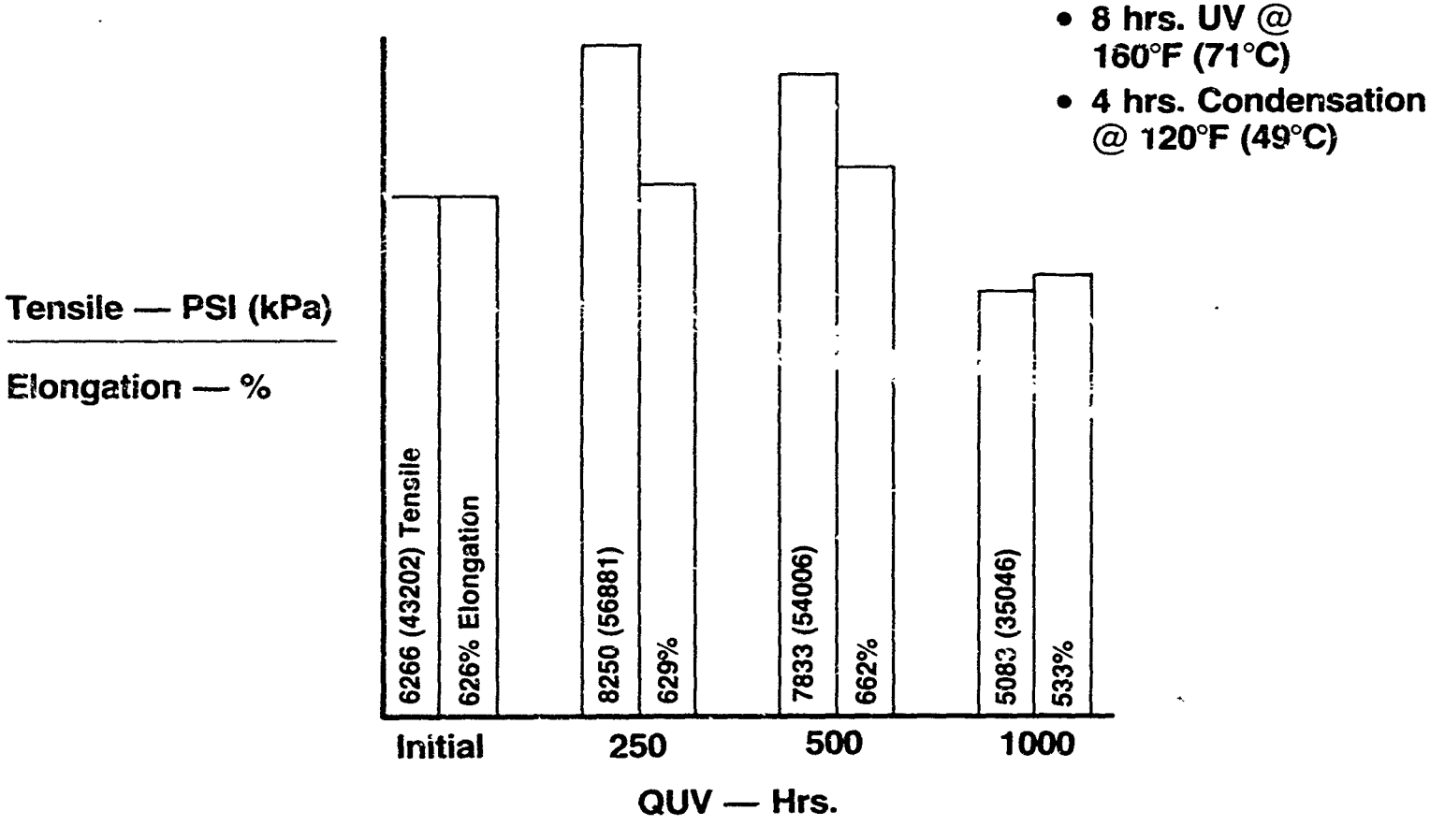


Illustration 11.

QUV Exposure
Abrasion Resistant Film

Tear Strength
Lbs. (Newtons)

Taber Abrasion
H-18 Whl, 1000 Gm. Wt.
1000 Cycle
Wt. Loss, Grams

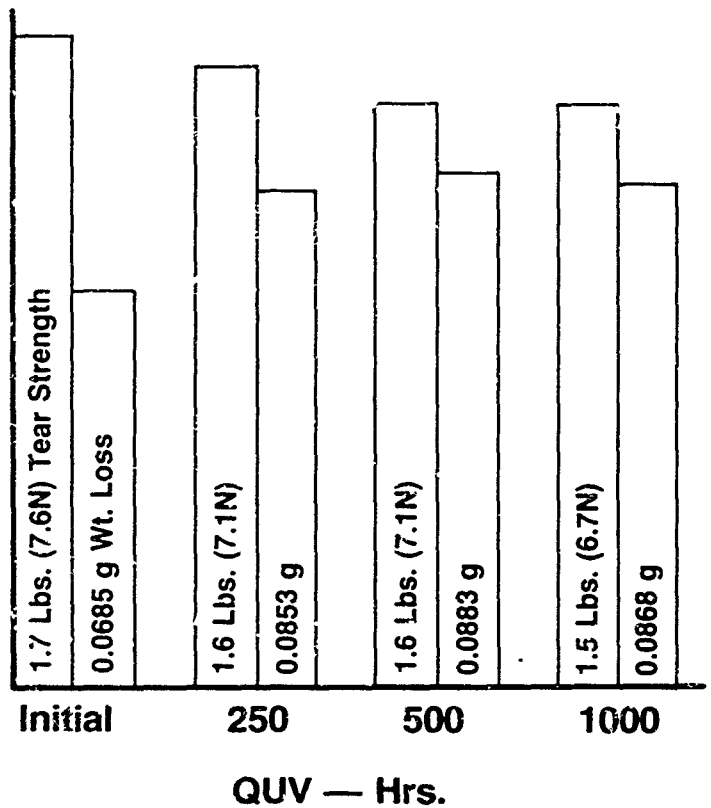


Illustration 12.

Natural Aging

Abrasion Resistant Film

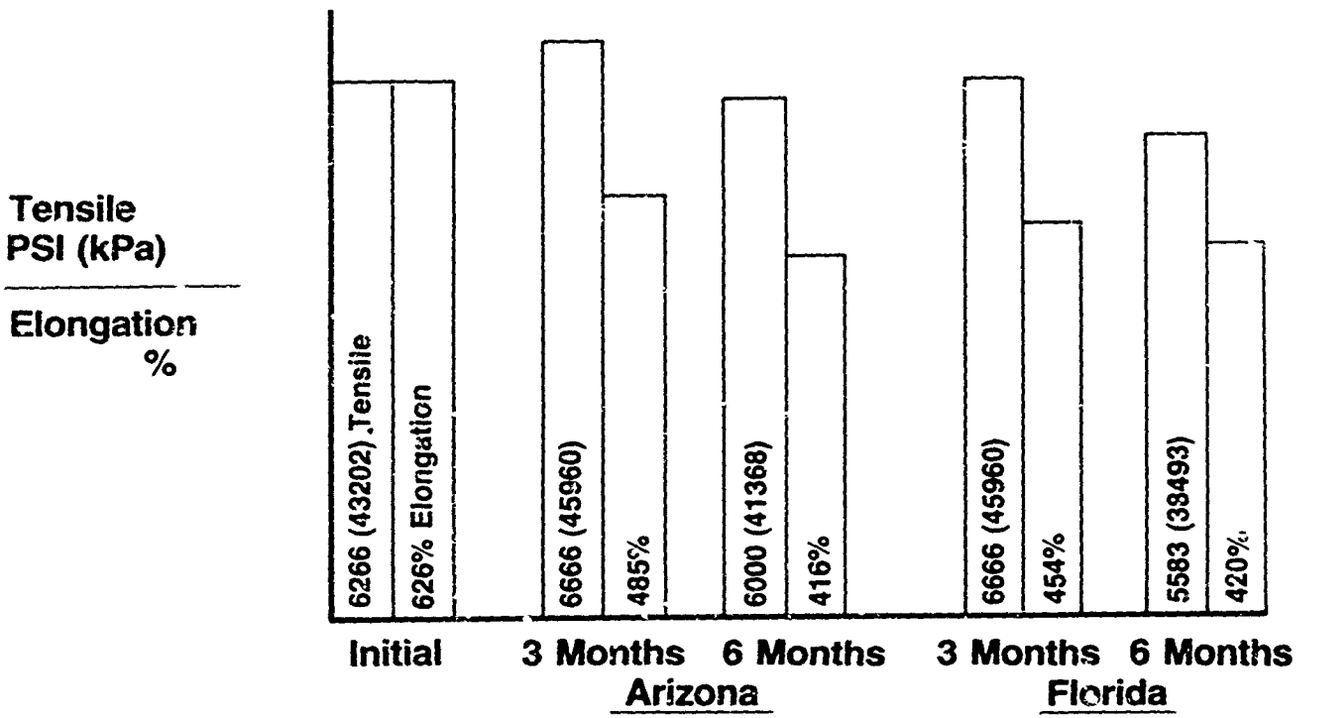
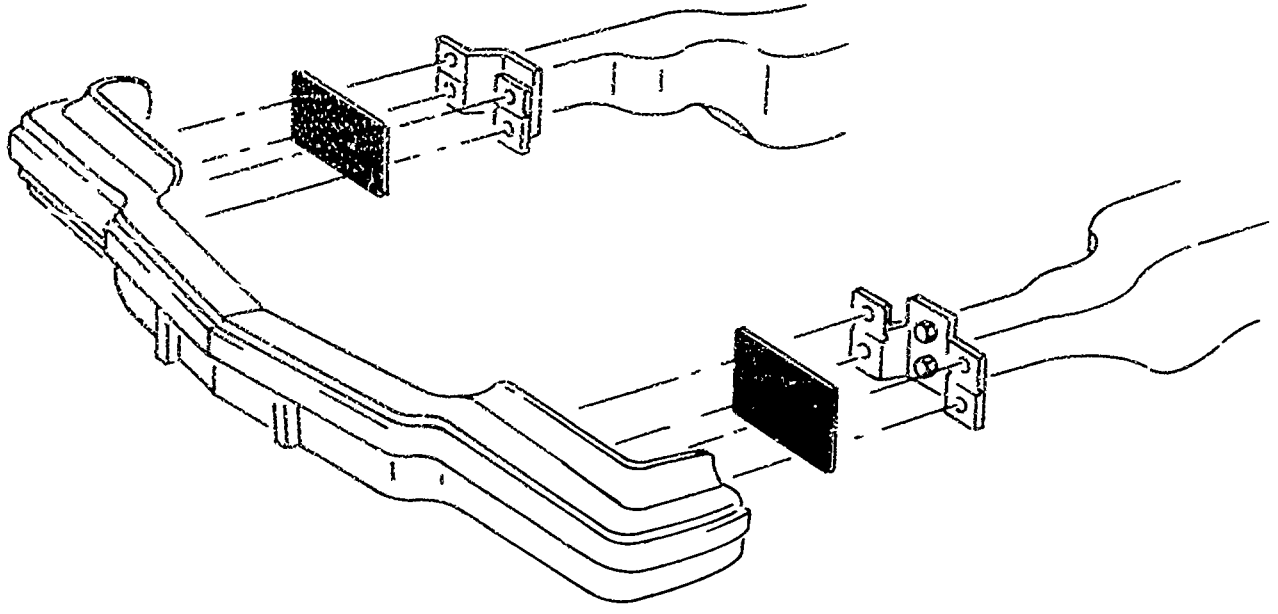


Illustration 13.

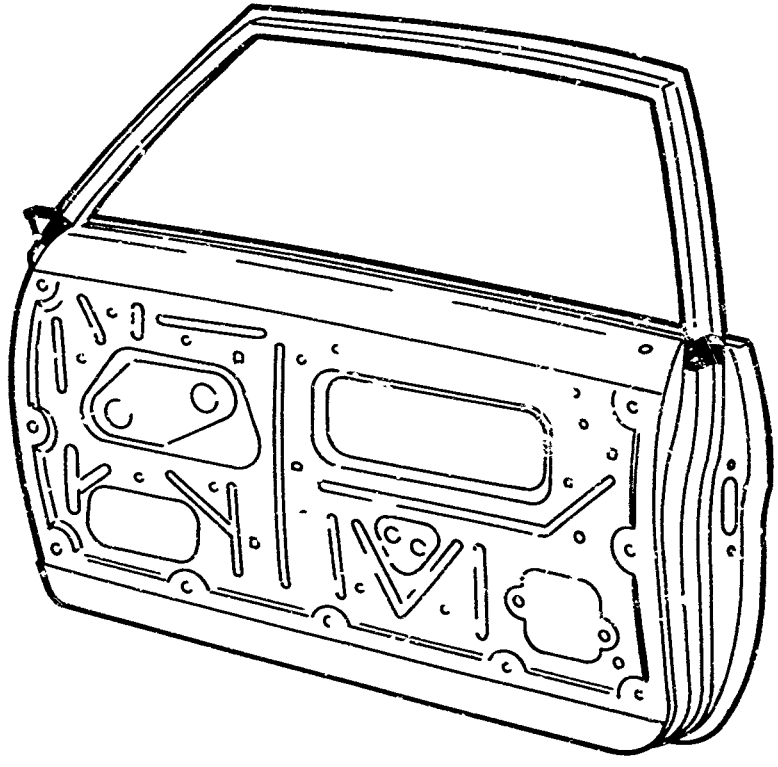
DISSIMILAR METAL SEPARATOR



Scotch Abrasion Resistant Film

Illustration 14.

WELD JOINT SEAM PROTECTION



Scotch Abrasion Resistant Film

Illustration 15.

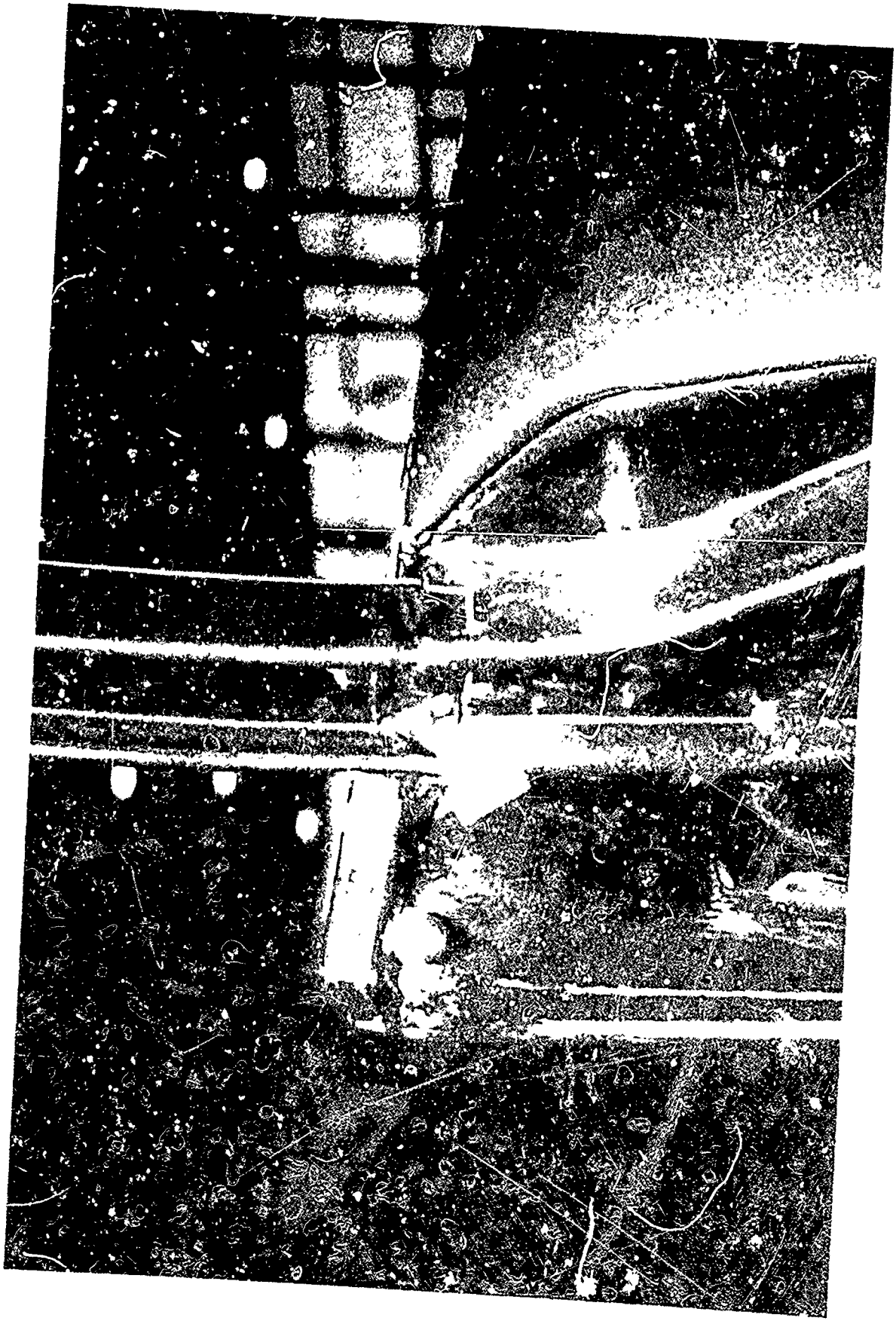
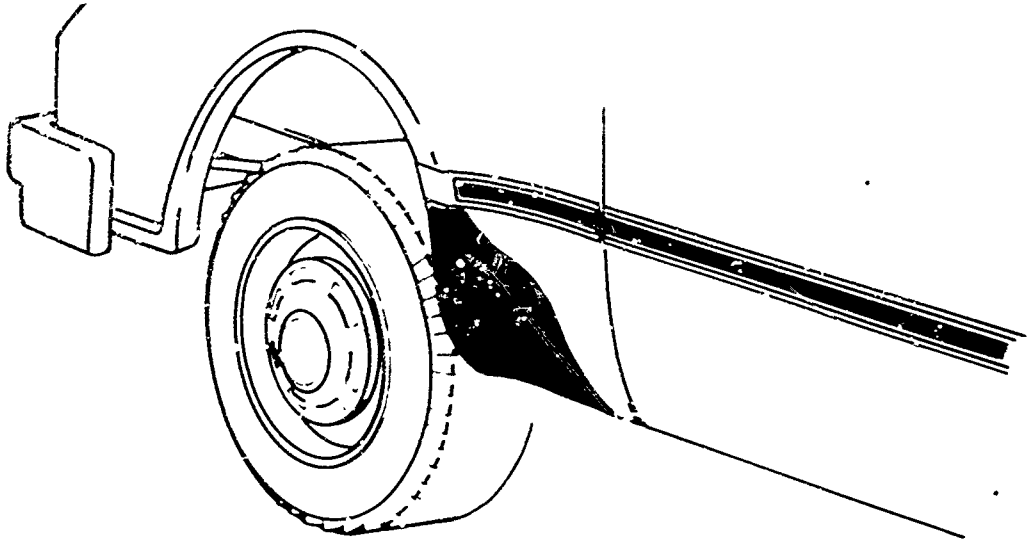


Illustration 16.

STONE SHIELD



Scotch Abrasion Resistant Film

Illustration 17.

Illustration 18.

Illustration 19.

Illustration 20.

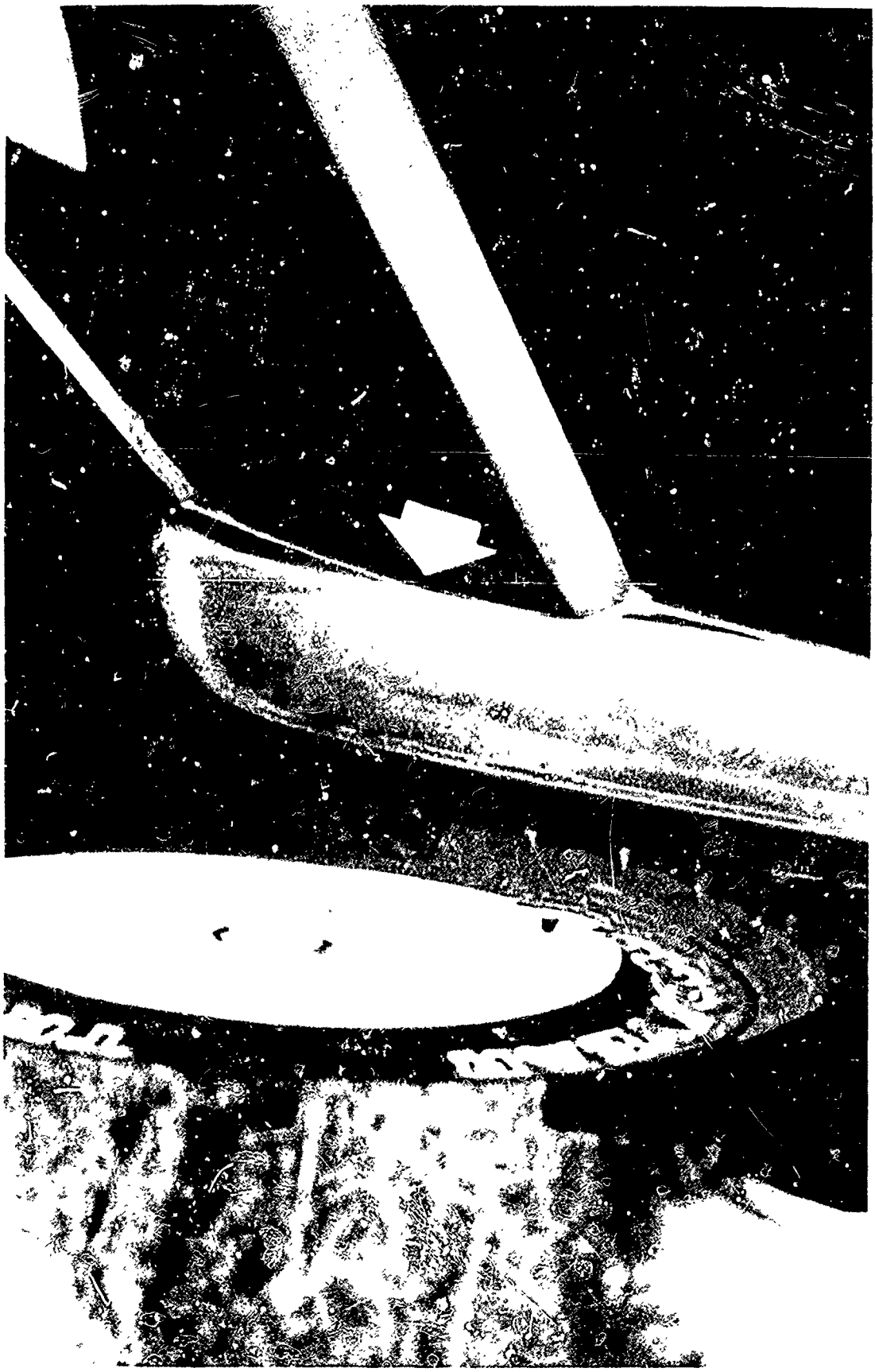
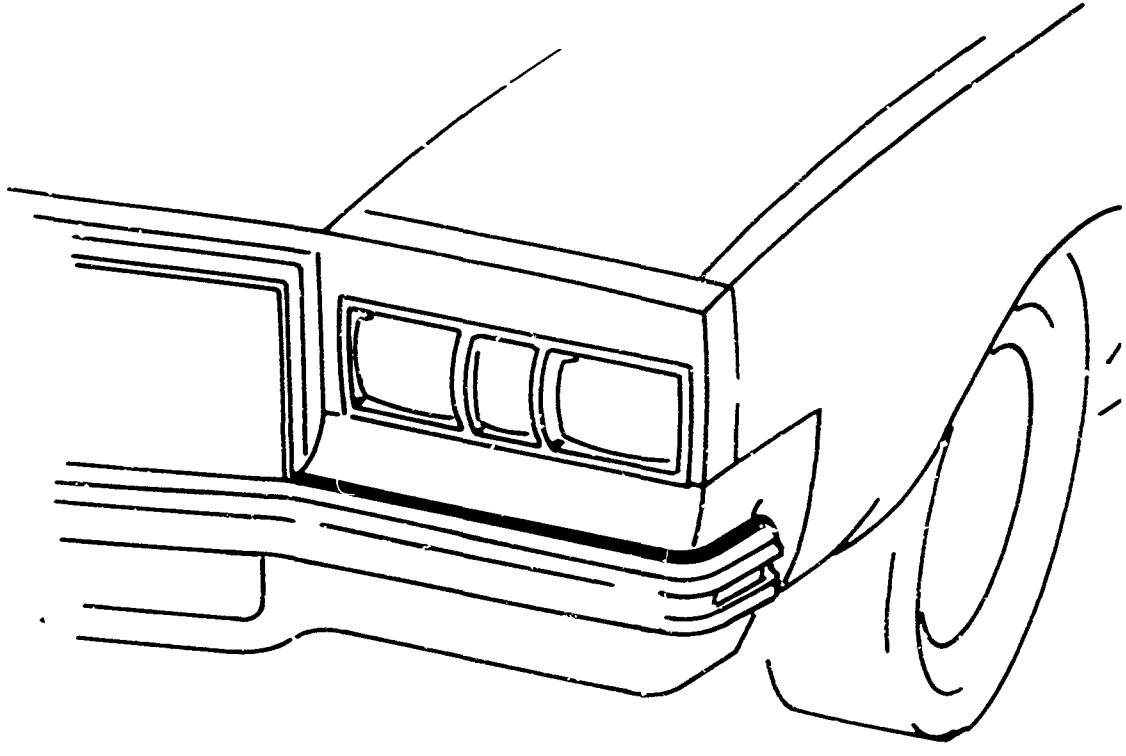


Illustration 21.

Illustration 22.

FILLER PANEL ABRASION PROTECTION

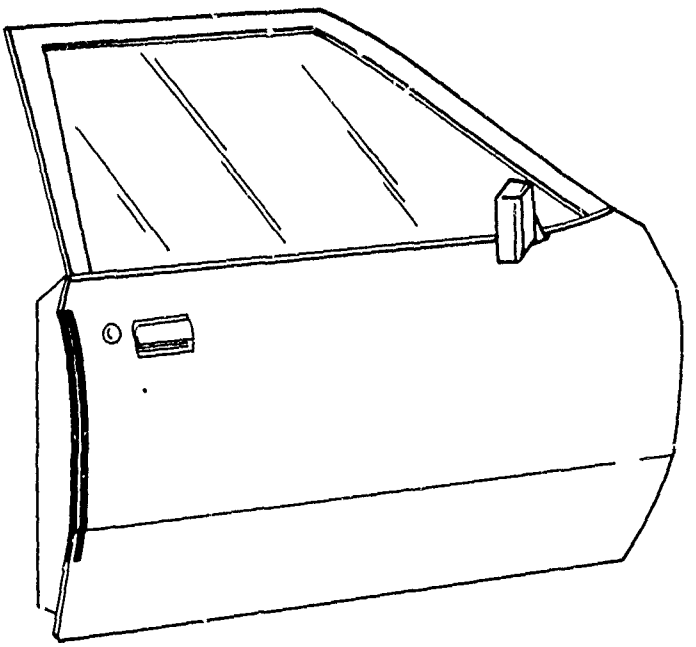


Scotch Abrasion Resistant Film

Illustration 23.

Illustration 24.

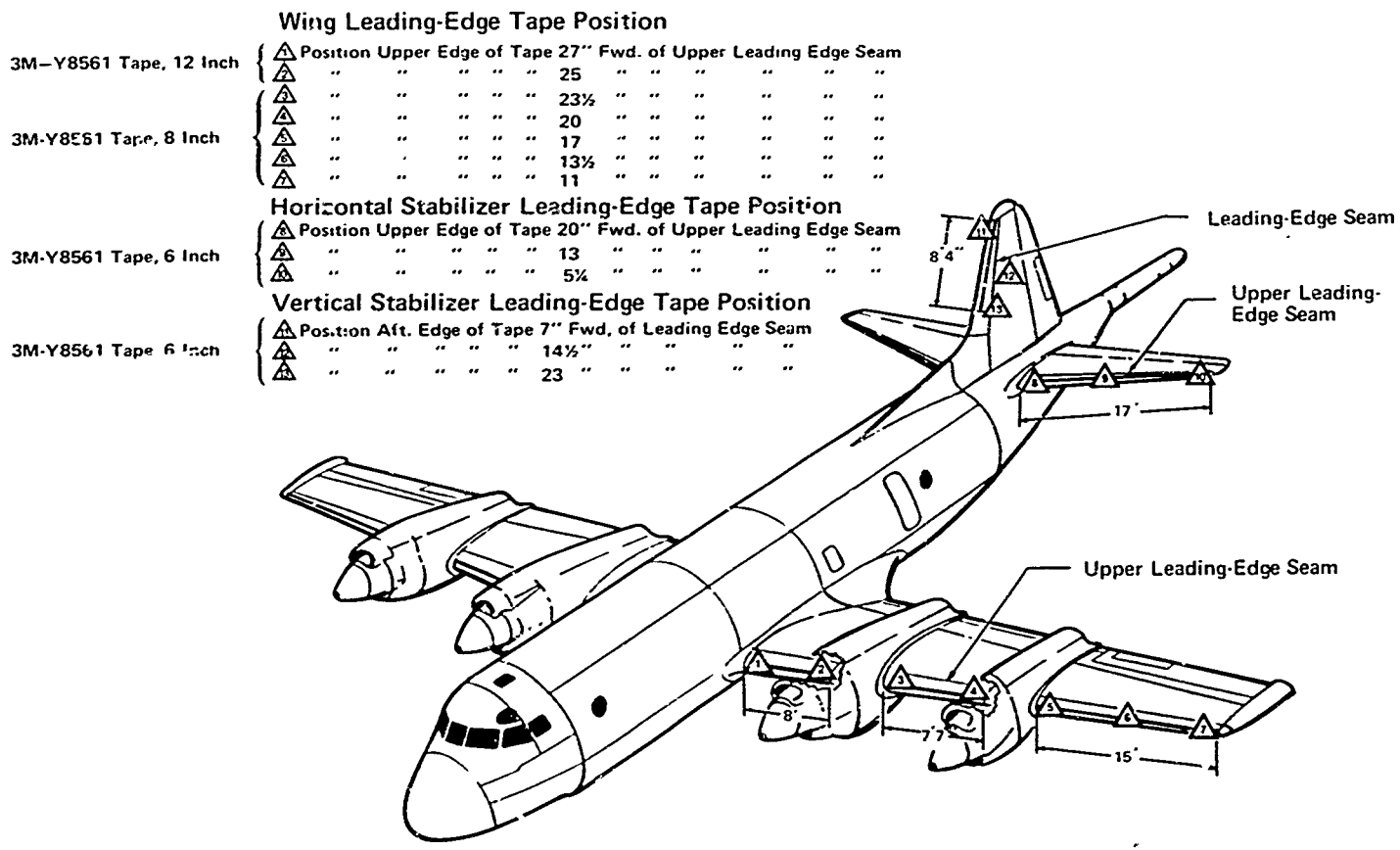
DOOR EDGE GUARD



Scotch Abrasion Resistant Film

Illustration 25.

Illustration 26.



P3 LEADING-EDGE TAPE INSTALLATION

Illustration 27.

Aerospace

Leading Edge Protection of Vertical & Horizontal Stabilizers on the:

P-3
A-6
C-5A
C-130
C-1410
A/T-37

Fuel Cell Bladder Protection

A-6
F-4
F-14
F-15
F-18

Illustration 28.

Aerospace

Radome Protection

Military Aircraft

P-3
A-6
EA-6B
A-7
S-3A

Commercial Aircraft

707, 727, 737
DC-9
Gulfstream G-2
Lockheed Jetstar
Piper Cheyenne II

Illustration 29.

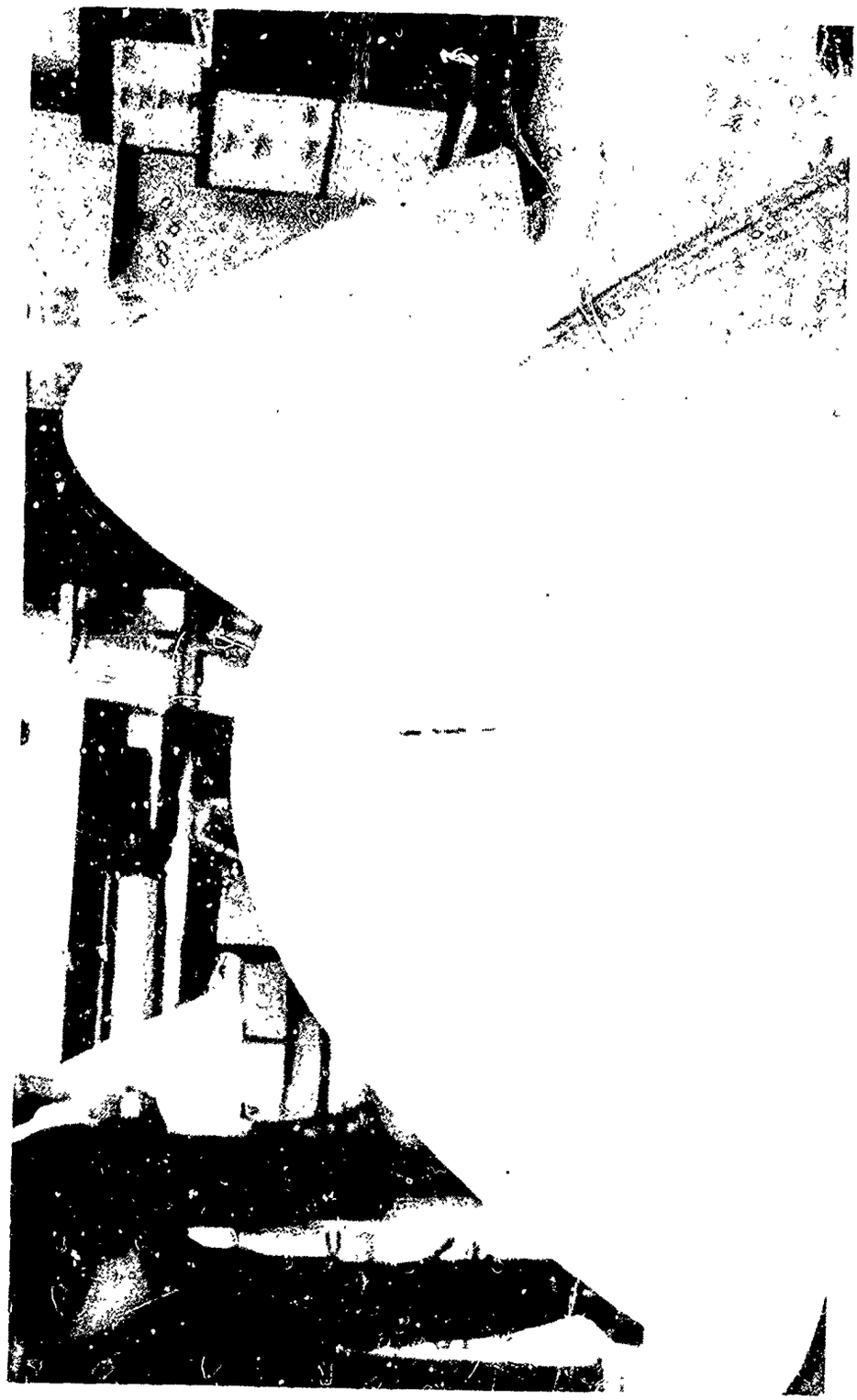


Illustration 30.

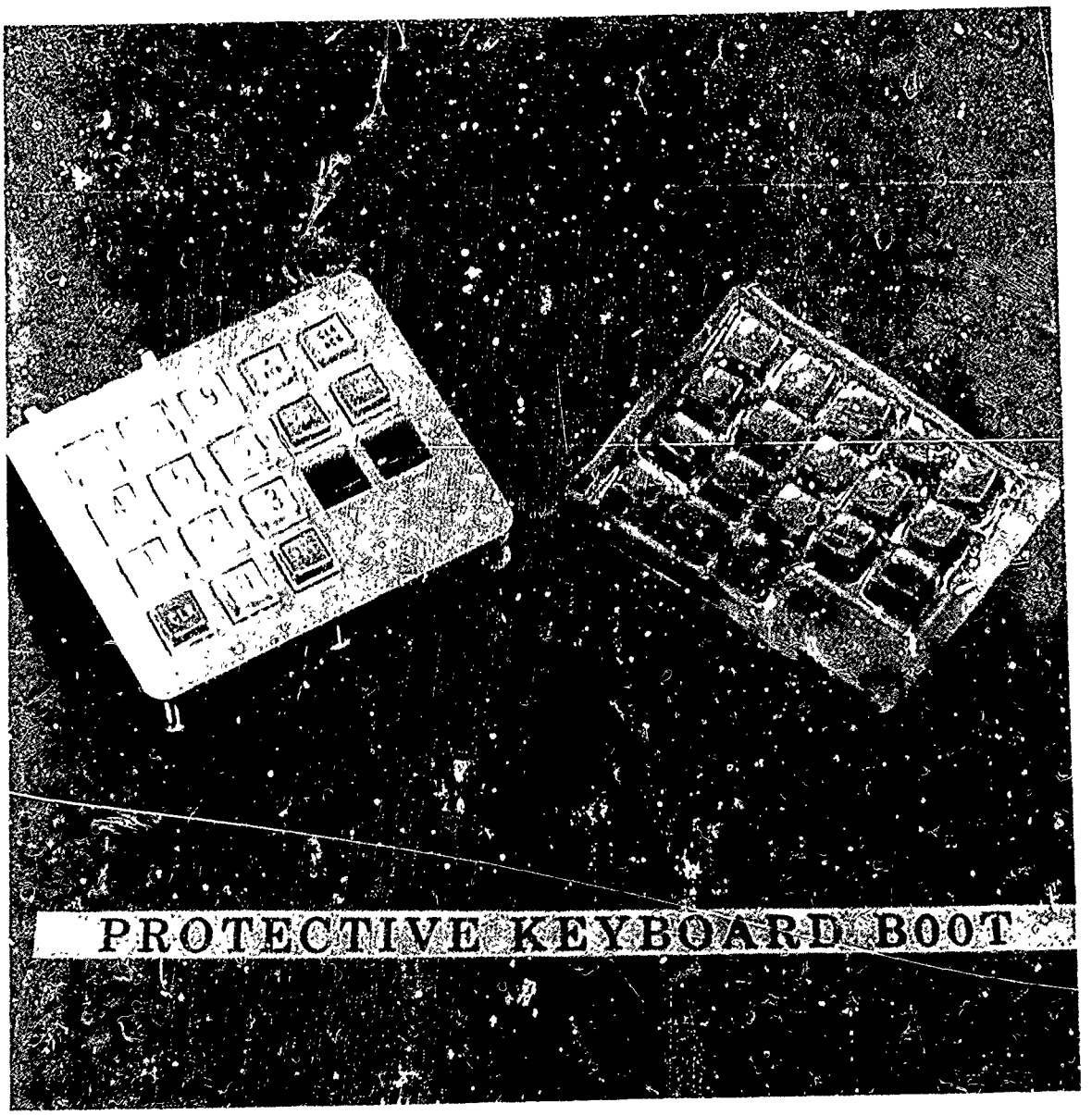
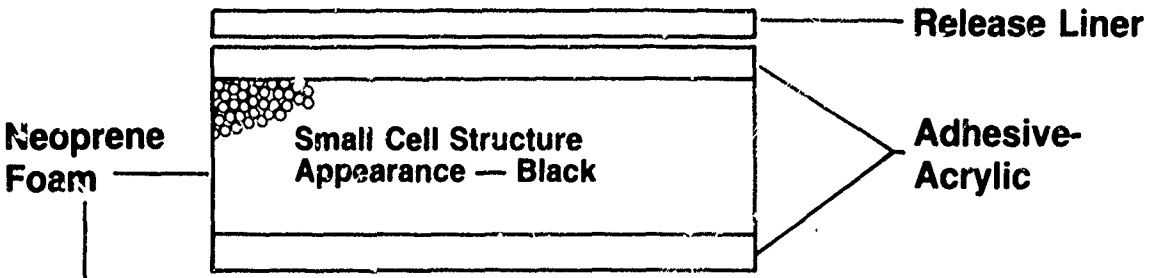


Illustration 31.

Neoprene Foam Tapes



Thickness	Density
0.030 Inch (0.78 mm)	55 lb/cu. ft. (881 kg/cu. m.)
0.045 Inch (1.14 mm)	45 lb/cu. ft. (721 kg/cu. m.)
0.060 Inch (1.52 mm)	40 lb/cu. ft. (641 kg/cu. m.)

Illustration 32.

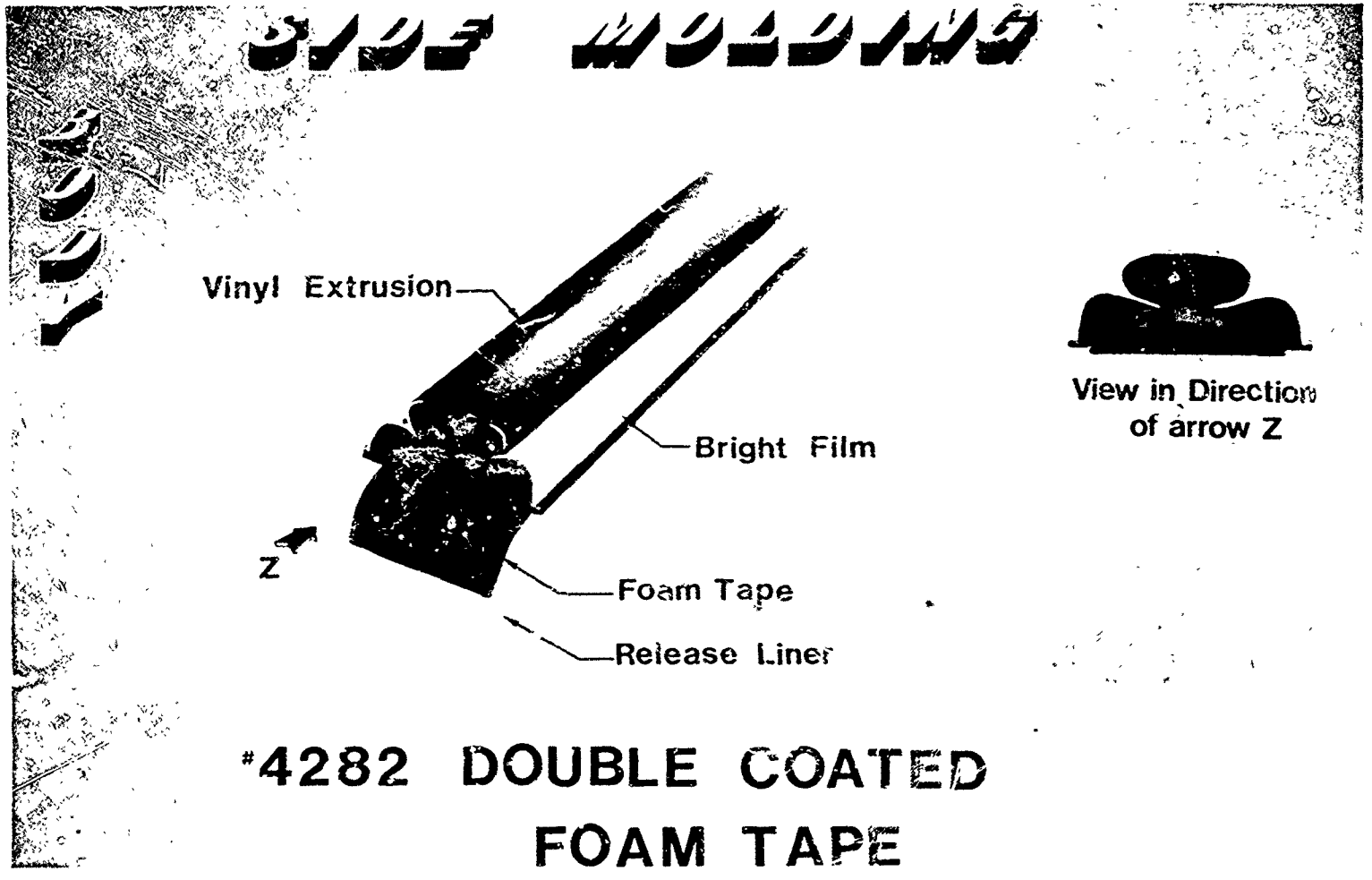


Illustration 33.

Illustration 34.

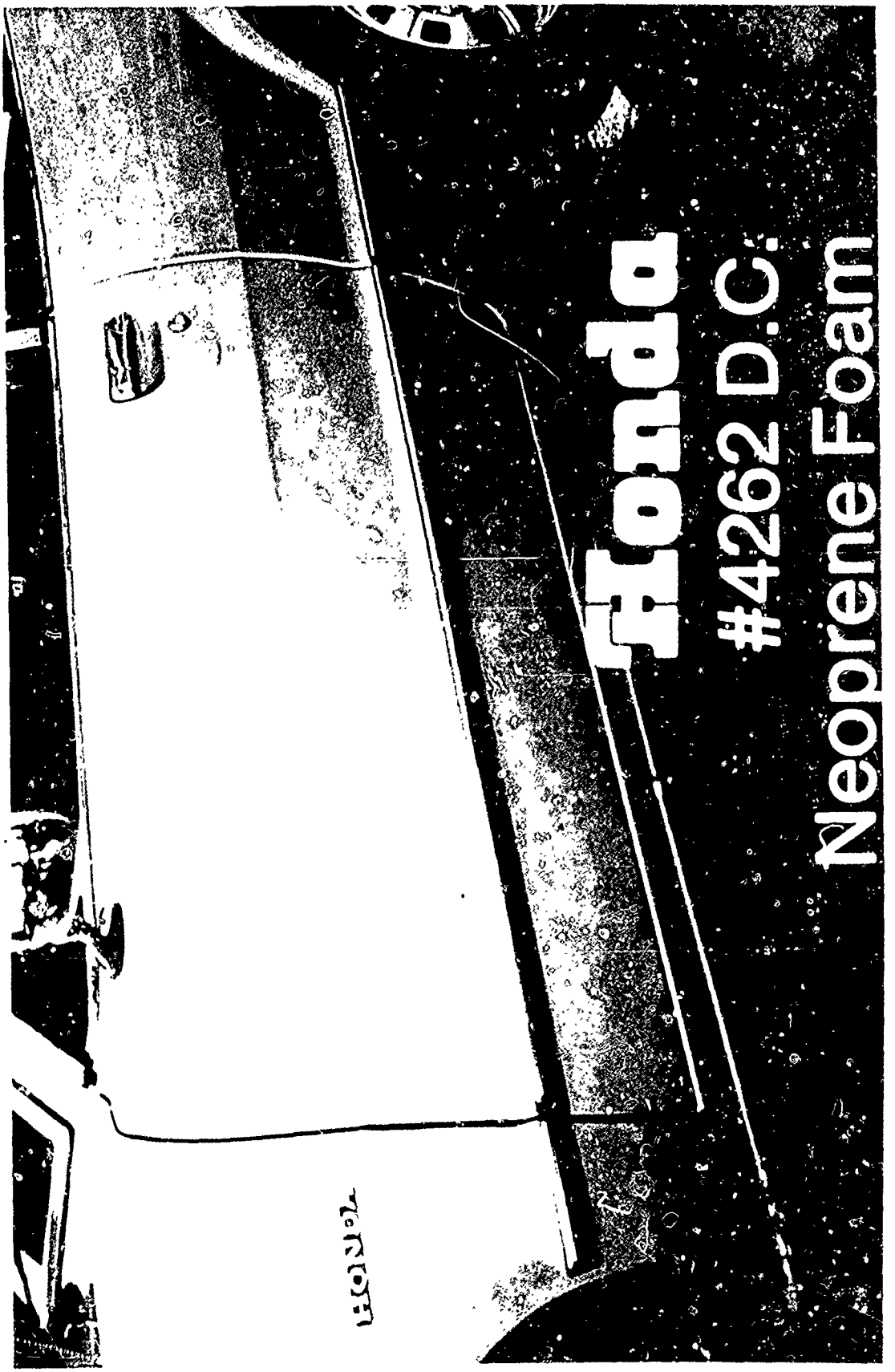


Illustration 35.

Illustration 36.

Illustration 37.

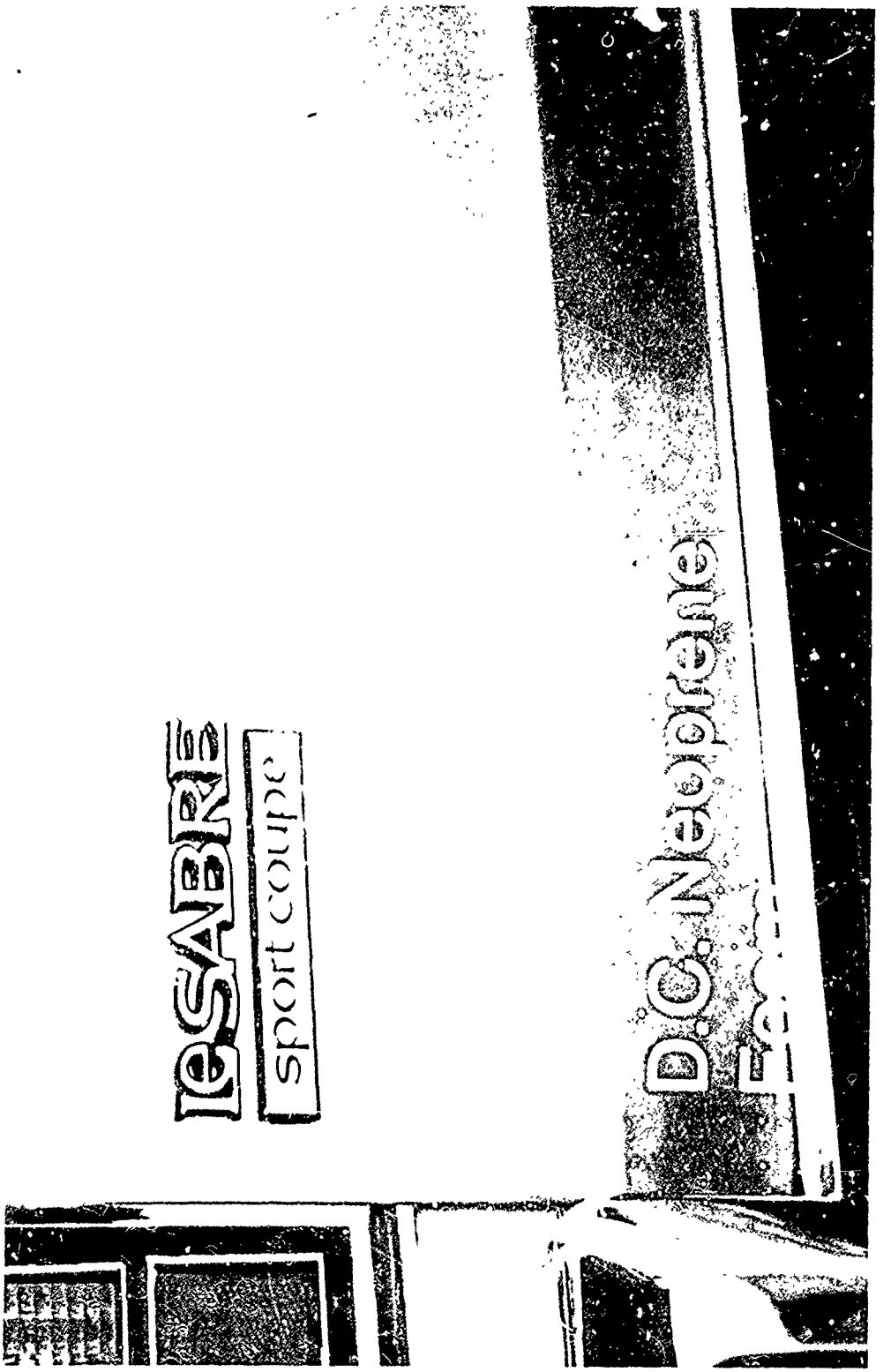


Illustration 38.

Illustration 39.

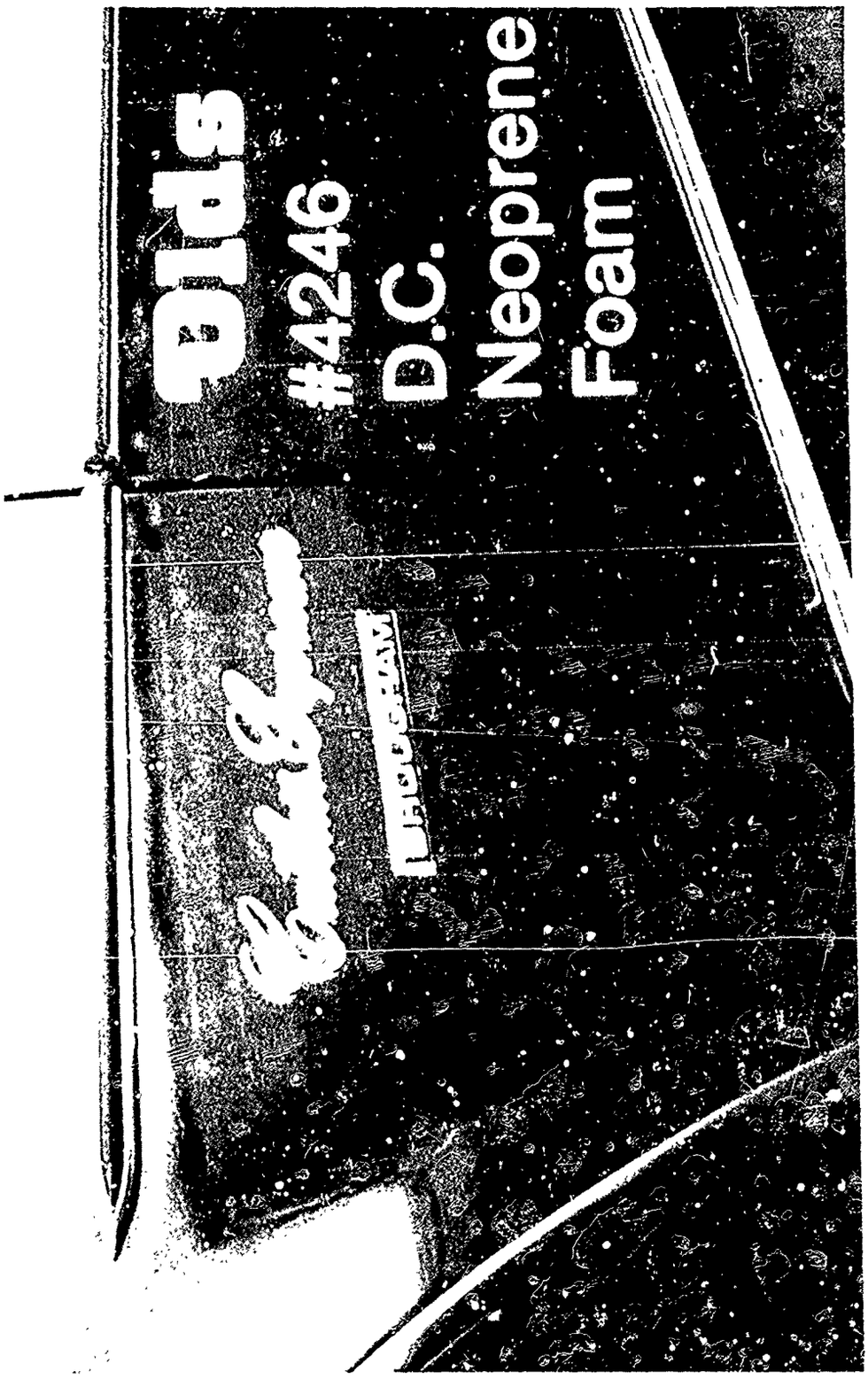


Illustration 40.

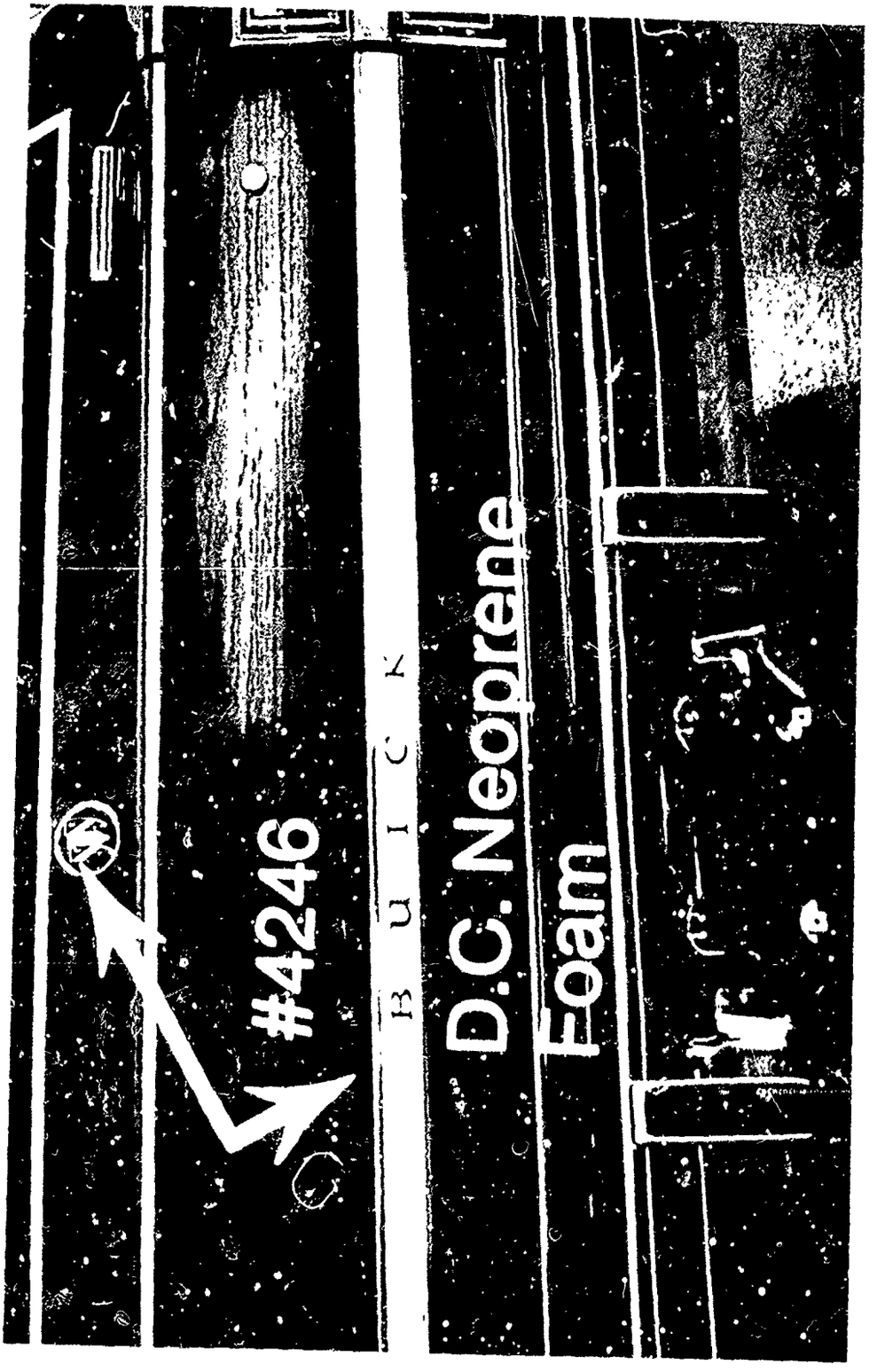


Illustration 41.

Wheel Lip Molding

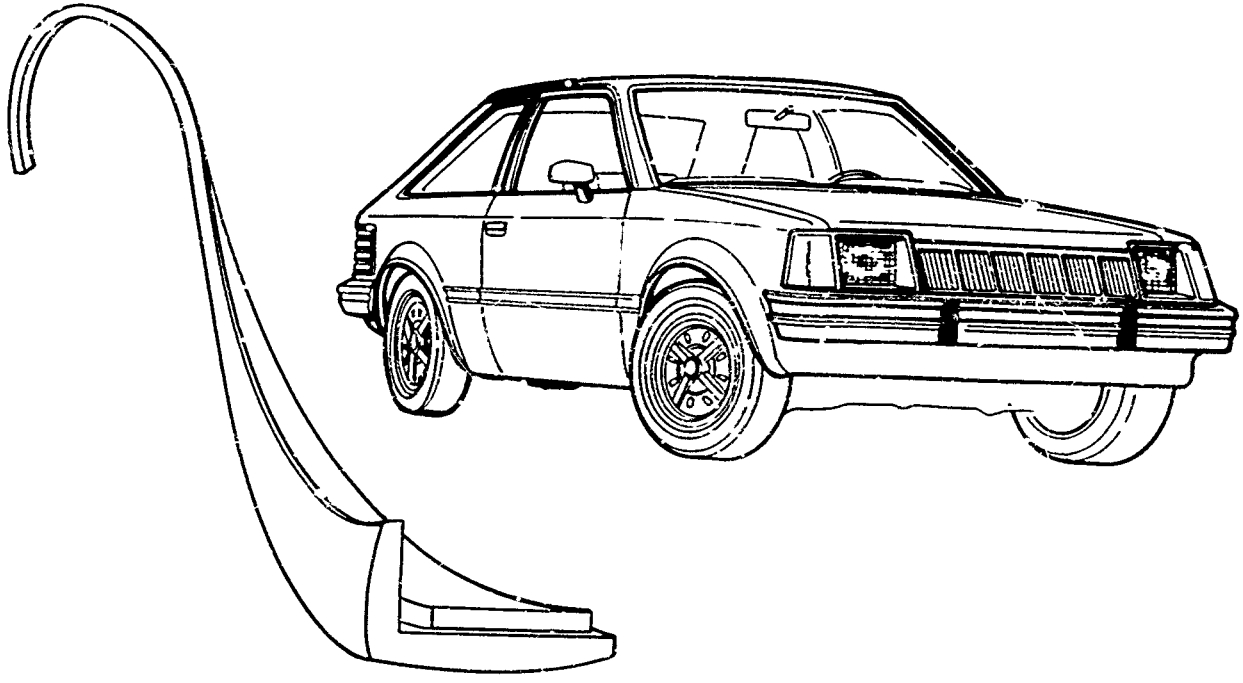


Illustration 42.

Lower Body Molding

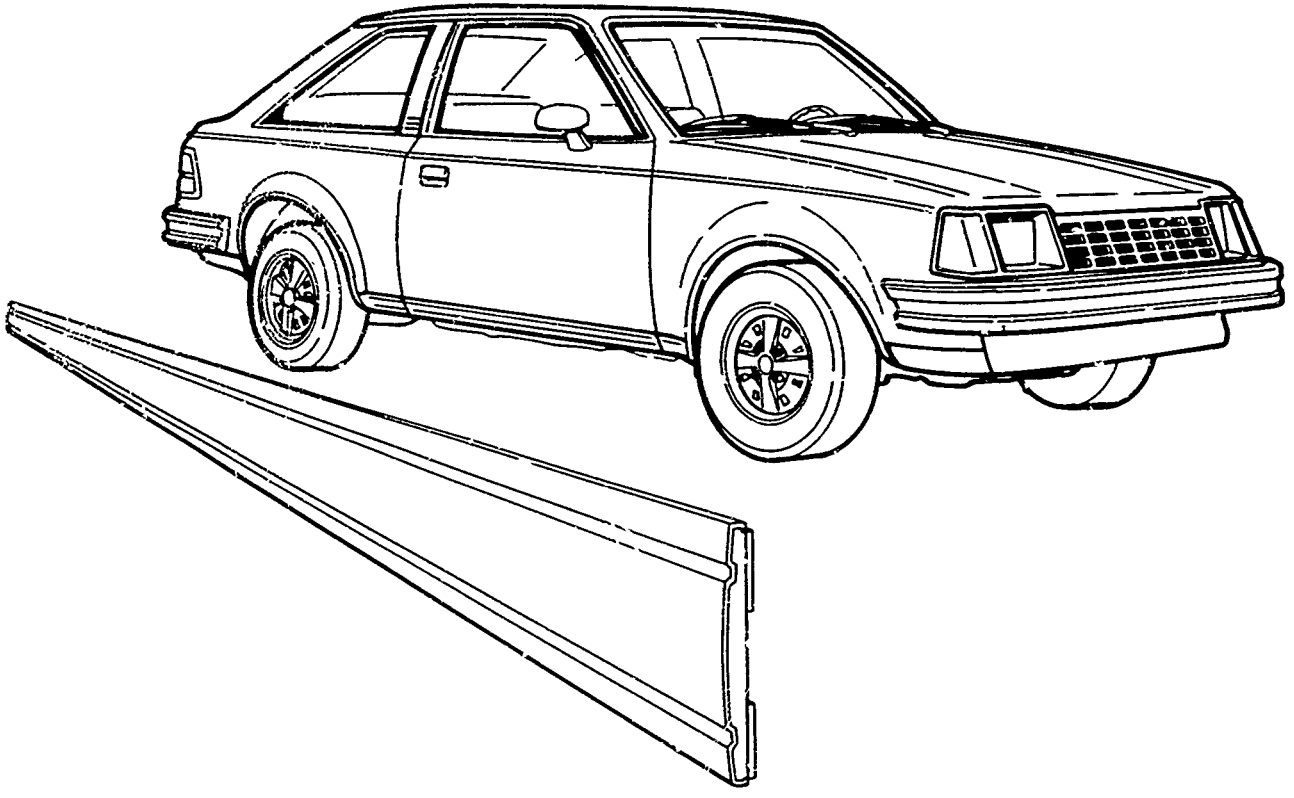


Illustration 43.

Reveal Moldings

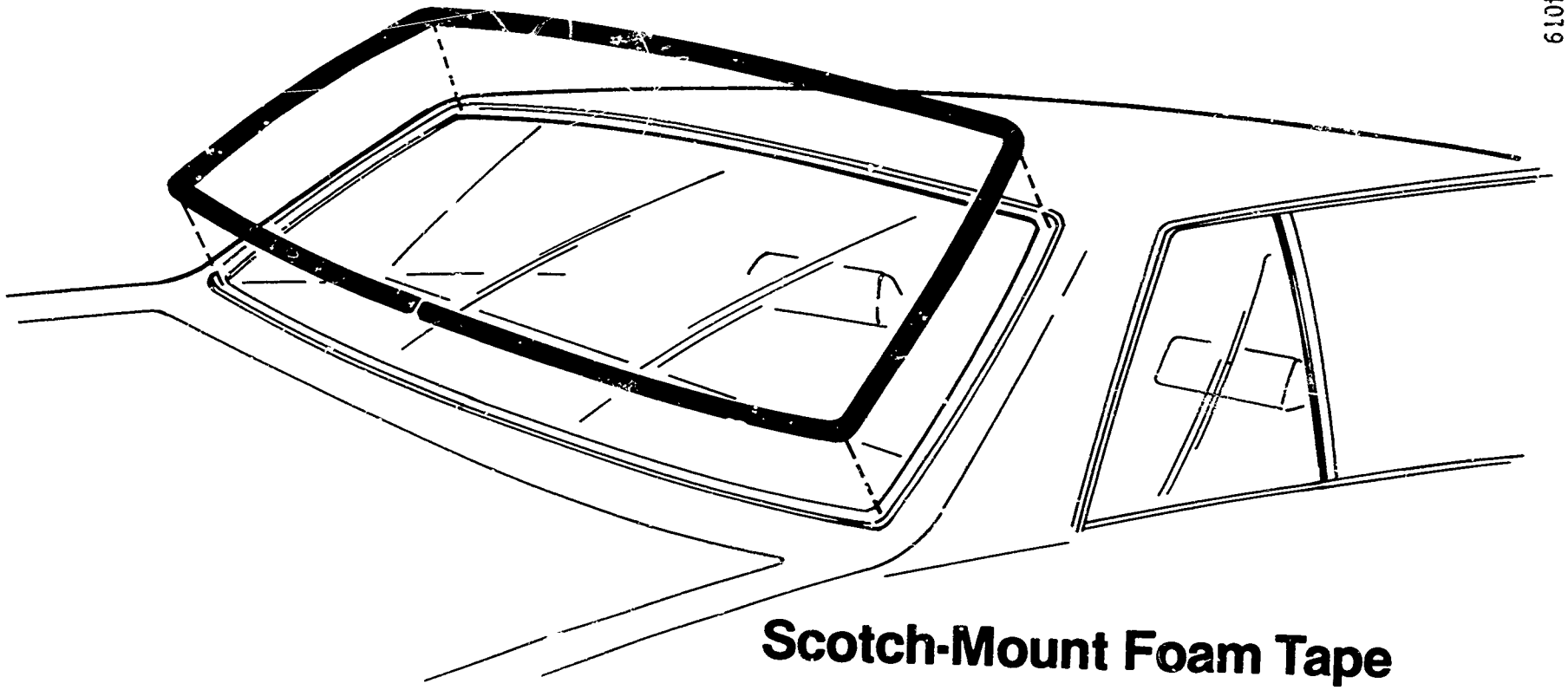


Illustration 44.

Adhesion Test

Peel

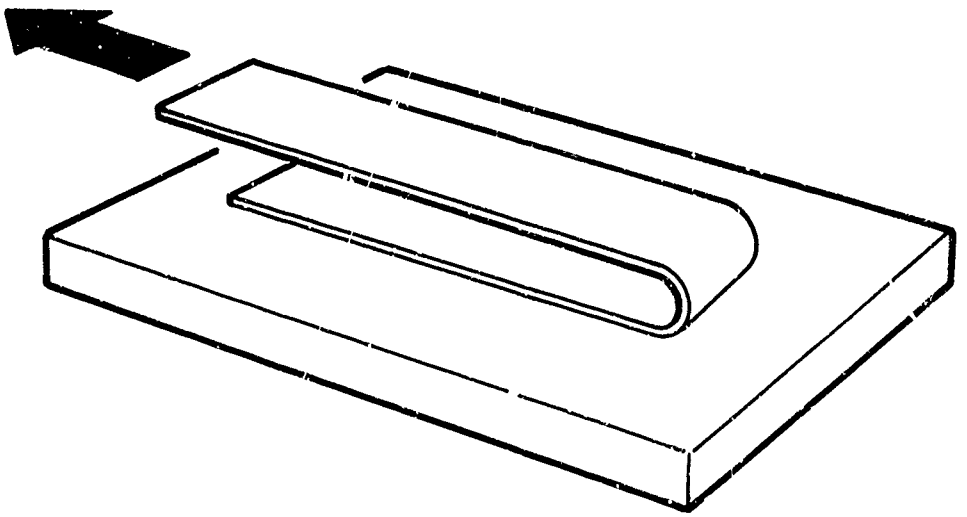


Illustration 46.

Adhesion Test

Dynamic Shear

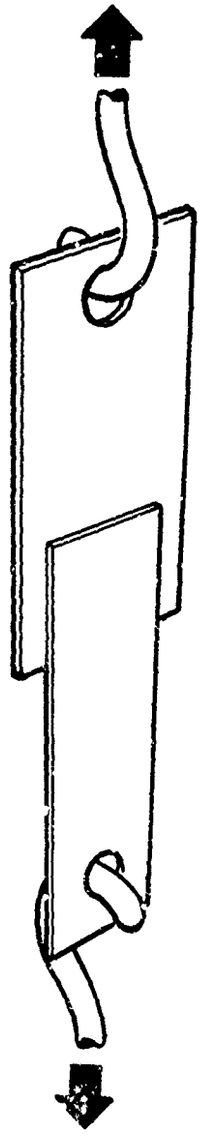


Illustration 47.

Adhesion Test

Tensile (T-Block)

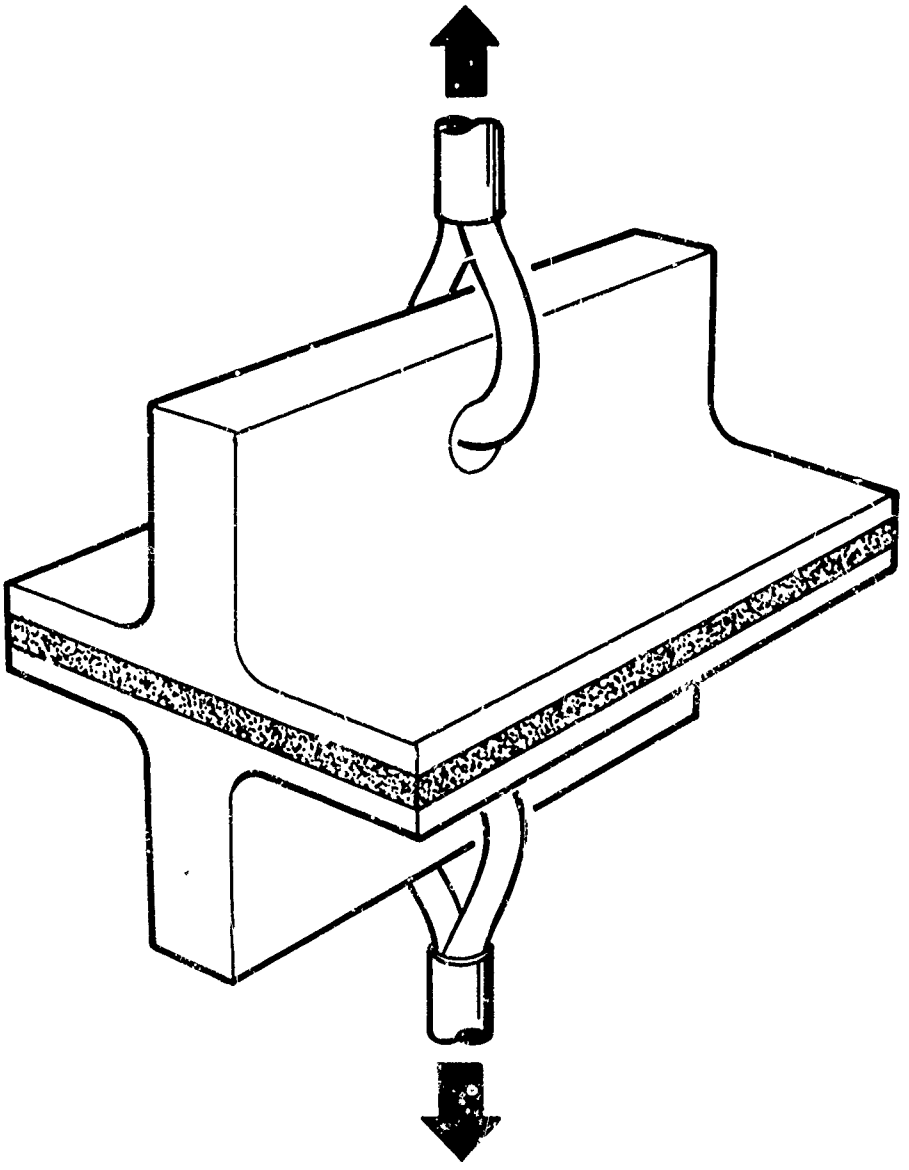
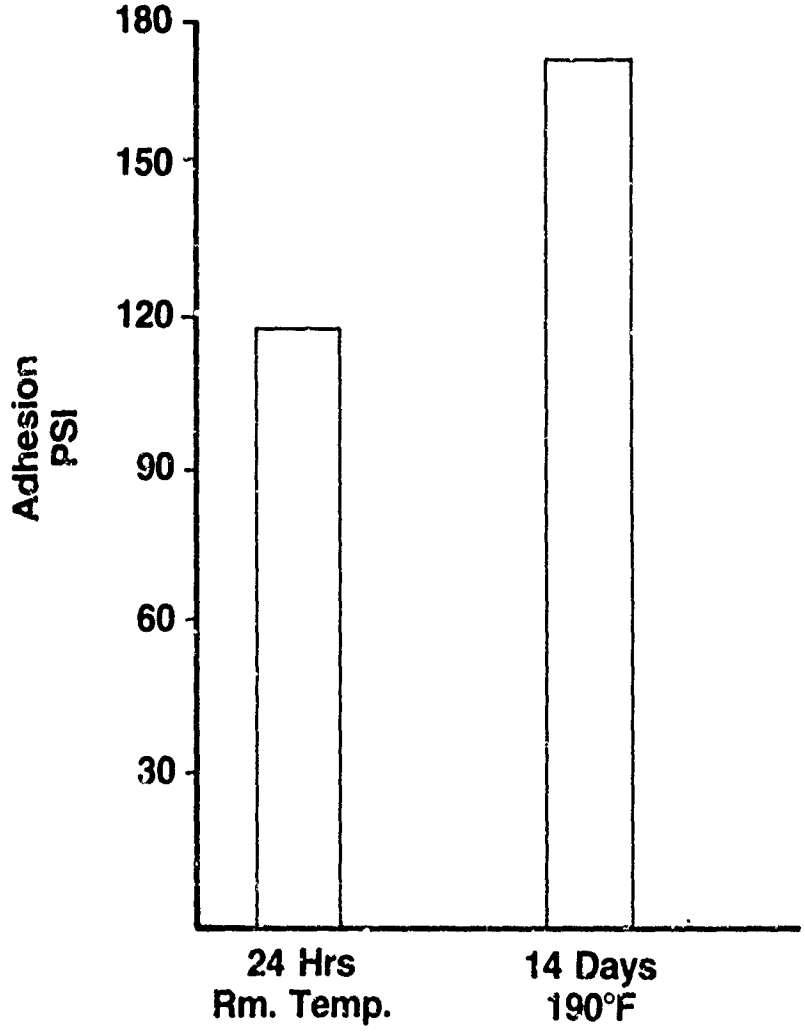


Illustration 48.

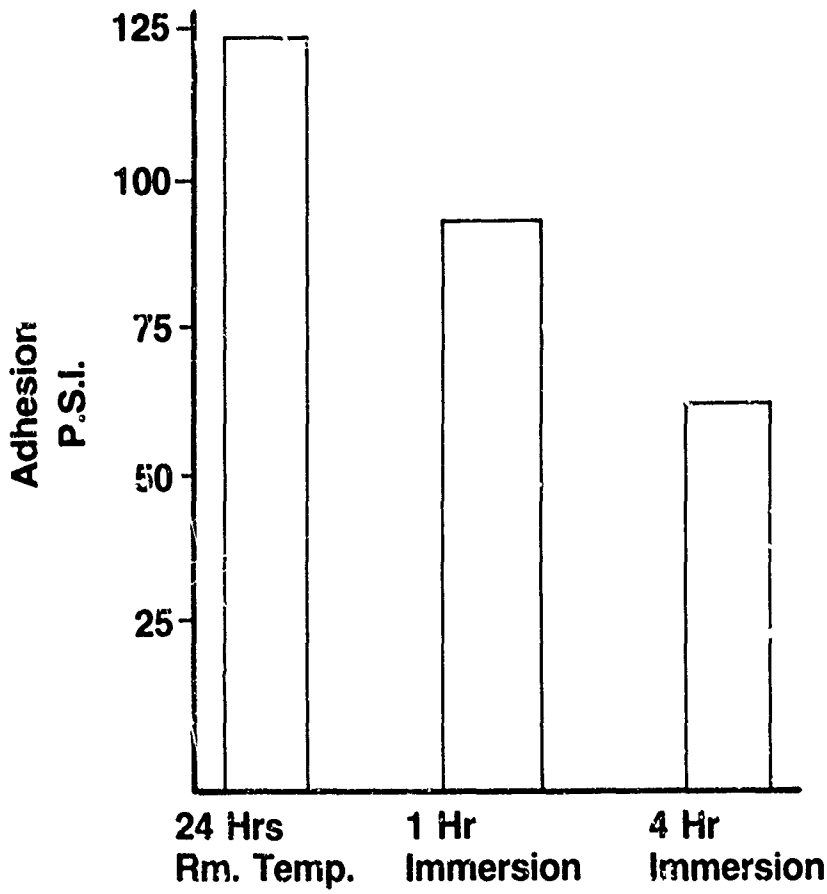
Dynamic Shear
.045" Neoprene



Surfaces: Aluminum to Enamel Paint

Illustration 49.

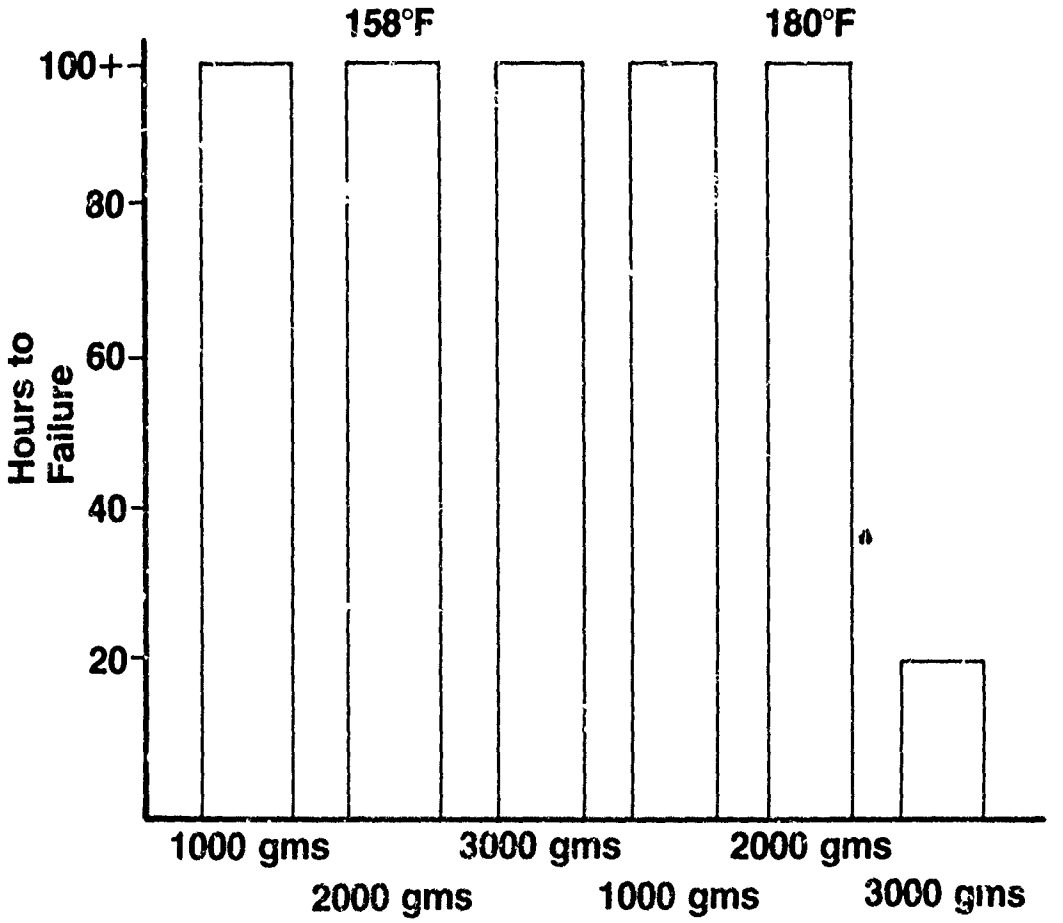
Dynamic Shear
.045" Neoprene
10% Gasohol Immersion



Surfaces: Aluminum to Enamel Paint

Illustration 50.

Static Shear
.045″ Neoprene



Surfaces: Aluminum to Enamel

Test Terminated at 100 Hours

Illustration 51.

Flexible Fascia System

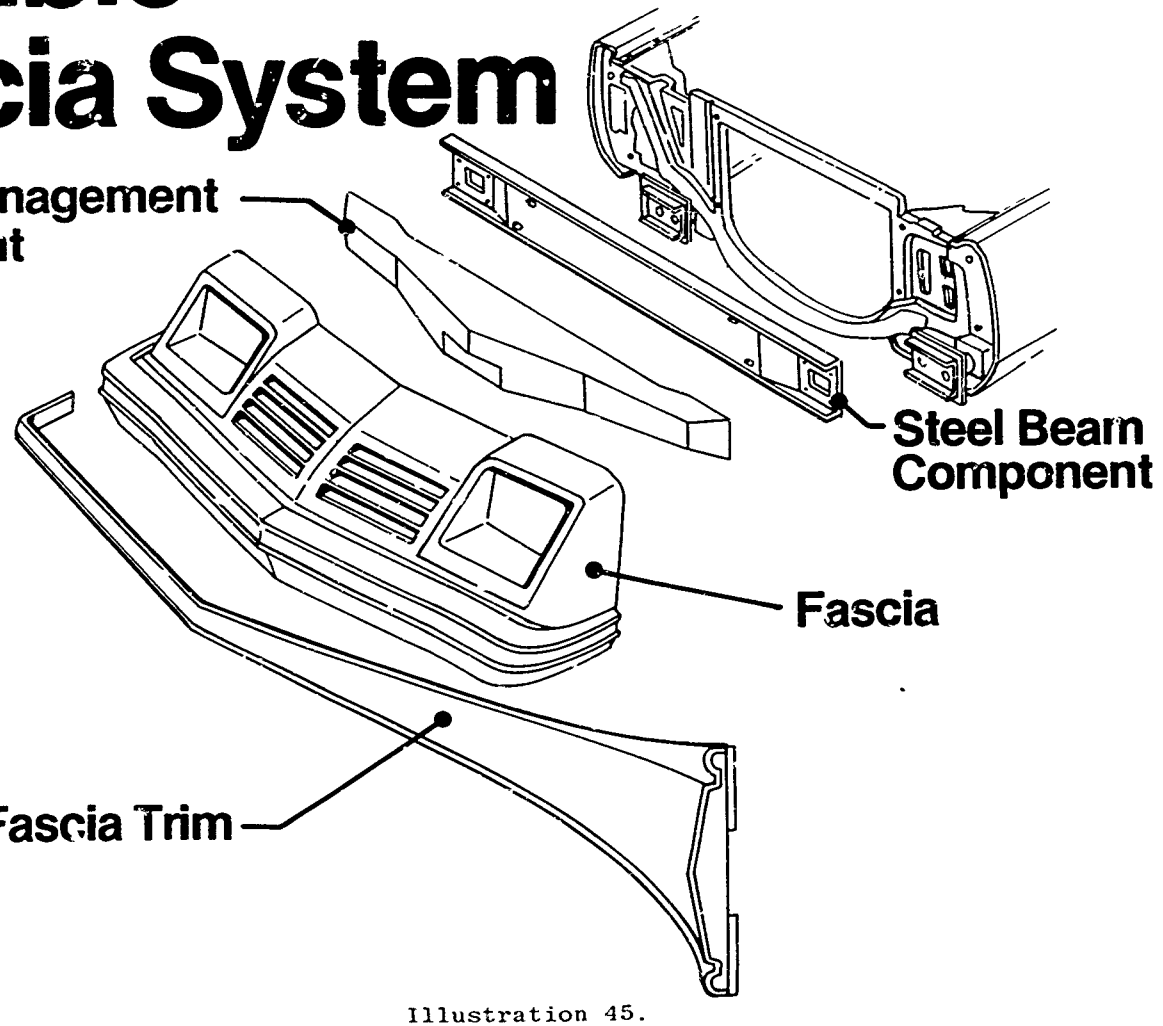


Illustration 45.

Neoprene Tapes

Minimum Specification Values
Chrysler MS-CH51

	.030" Neoprene	.045" Neoprene
1. Tensile Strength P.S.I.	500	300
2. Tear Strength Lbs./In.	100	50
3. Peel Adhesion Ozs./In.	36	36
4. Shear Adhesion P.S.I.		
As Received	80	80
Heat Aged	150	150
Environment Cycle	80	80
Humidity	50	50
Gasoline	80	80

Selected Performance Tests.

Illustration 52.

BIOGRAPHY

Name: Ronald J. Olson

Present Affiliation:

3M
Industrial Specialties

Title:

Technical Service Representative

Field of Interest/Responsibilities:

General Industry/Automotive/Aerospace as concerns surface protection and pressure sensitive bonding. Primary responsibilities include identifying new product opportunities, services and assuring product conformance to meet government, industry and 3M requirements.

Previous Affiliations/Titles:

Product Engineering and Development - 3M Industrial Specialties Div.

Academic Background:

University of Minnesota - Technical Course Study

HYDROGEN BEHAVIOR IN COATED AND UNCOATED LOW ALLOY STEELS

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INTRODUCTION

High strength steels have limited corrosion resistance, so they often are plated or given some other protective coating before use. During processing (e.g. pickling) and coating (e.g. electroplating), they absorb hydrogen and thus are susceptible to catastrophic failure through internal hydrogen embrittlement (HE) [1]. The problem of HE in metal finishing has received considerable attention [2]. Baking out at moderate temperatures (see for example MIL-STD-171 C (MR)) is employed for embrittlement relief; however, much evidence exists that indicates that the protective coating serves as a barrier for hydrogen egress during bake-out.

As early as 1956, Brown [3] was able to show that prolonged baking-out of plated components resulted in less brittle behavior, but that large amounts of H remained in steels even at bake-out times a factor of ten greater than those currently specified in the MIL-STD. Recently, Pickering and co-workers [4] have shown that even discontinuous plated coatings, which only cover about 20% of an alloy's surface, reduce hydrogen egress rates by a factor of ten or more. It is clear that conventional bake-out procedures cannot remove more than a fraction of the hydrogen dissolved in a coated steel.

It is well established that the composition, thermo-mechanical history and microstructure of a steel influence hydrogen motion and HE resistance [5]. Sandoz [6] has shown that small variations in C and Mo content of AISI 4340 steel greatly influence HE resistance. Also, Iino [7] has recently shown that H-egress from charged pipeline steels was noticeably influenced by S content. In addition, Kim and Loginow [8] and Sakamoto and Takao [9] have shown that hydrogen ingress and egress rates are strong functions of the microstructure and composition of high strength steels.

Three points emerge from this discussion relative to hydrogen up-take and bake-out processes in high strength steels.

1. The microstructure and composition (as established by method of production) of a steel have a strong influence on hydrogen ingress and egress, and embrittlement.

2. Coatings markedly decrease the rate of egress of hydrogen from a steel, even under supposedly acceptable bake-out conditions.

3. Quantitative correlations between microstructures, coating type and specified bake-out treatment have not been established.

Those three points must be clearly understood in order to assure high strength steel component reliability and to optimize the economics of component processing.

A two phase experimental program was devised to obtain this understanding. The goals of the first phase of the program were to determine:

1. Which microstructural forms of AISI Type 4340, one of the most commonly employed high strength steels, resist hydrogen ingress and/or allow most rapid hydrogen egress.

2. Which combinations of steel microstructure, and bake-out temperature and time, lead to most effective hydrogen outgassing from steels pre-charged to a fixed hydrogen level.

3. Whether the method of production of a steel (i.e. steel quality) effects hydrogen ingress or egress.

This information is useful in its own right, and it also provides the necessary baseline information for the second phase of the program. The goal of the second phase of the program will be to determine:

4. The extent to which Cd plating, one of the most common means of protective coating-production, retards the egress of hydrogen from precharged samples. The Cd plating effects will be determined for the various Type 4340 steel microstructures and compositions studied in phase one.

This paper describes the results of the first phase of the program in which H behavior was studied for uncoated Type 4340 steel. The second phase of the study, concerned with the H behavior in Cd coated Type 4340 steel, will be the subject of a later publication.

STEEL CHARACTERIZATION

Materials

The primary differences among AISI Type 4340 steels produced by the variety of steelmaking processes are gas contents, and minor element and inclusion contents. To determine to what extent these compositional variations affect H-ingress and egress, four materials that represent the complete range of commercial Type 4340 steel quality were acquired. The chemical analysis of each steel is given in Table 1.

The commercial quality (CQ), aircraft quality (AQ) and consummable vacuum melted (CVM) steels were obtained as 1-1/2 inch diameter hot rolled bar, while the electroslag remelted (ESR) steel was obtained in the form of 2 inch round corner square bar. Two of the steels represent air melted grades (CQ and AQ), and two represent remelted grades (CVM and ESR).

Inspection of Table 1 indicates that the primary chemical difference among the steels is their sulfur content. All four steels are, as expected, very similar in major element content. The chemical analyses indicated that any observed behavior differences cannot be attributed to major element differences. However, differences in minor element content, and S in particular, must be considered.

The dissolved gas contents of the Type 4340 steels also depend on steelmaking practice. Remelting generally reduces the gas content of Type 4340 steel. Typical gas contents for the air melted grades (CQ and AQ) are H_2 = 1.4 ppm, O_2 = 25 ppm and N_2 = 100 ppm, while the remelted grades (CVM and ESR) contain H_2 = 0.9 ppm, O_2 = 4 ppm

Table 1. Chemical Compositions of Type 4340 Steel Test Materials

Steel Grade	Element Content - Weight Percent									
	Ni	Cr	Mo	C	Mn	Si	P	S	Cu	Al
Commercial Quality (CQ)	1.73	.82	.20	.37	.72	.24	.008	.018	.13	.036
Aircraft Quality (AQ)	1.75	.84	.23	.42	.78	.28	.007	.021	--	--
Consumable Vacuum Melted (CVM)	1.80	.82	.25	.42	.84	.28	.009	.004	.20	--
Electroslag Remelted (ESR)	1.78	.83	.23	.40	.72	.26	.010	.002	--	--

and N_2 = 53 ppm [10].

The remelting processes also have been reported to reduce the size and number of non-metallic inclusions in Type 4340 steel [10]. Metallographic and scanning electron microscopic analyses were performed for each test steel to determine those and other microstructural differences.

Optical Metallography

The as received hot rolled Type 4340 steels were analyzed by optical metallography. The analysis indicated two primary differences among the steels:

1) The size, shape and number of non-metallic inclusions.

2. The degree of heterogeneity in the distribution of carbon, called carbon banding.

The differences in inclusion distribution among the steels are shown in the photomicrographs of as-polished samples in Figure 1. The observed differences were:

a) The CQ steel contained a high density of large inclusions. The inclusions were elongated in the steel bar's hot rolling direction.

b) The AQ steel contained a lower density of relatively large inclusions that were also elongated in the bar hot rolling direction.

c) The CVM steel contained a low density of quite large spherical inclusions. At higher magnification, the spherical inclusions appeared to be made up of two different components, which was suggested by differences in optical reflectivity.

d) The ESR steel contained a very fine dispersion of spherical particles.

Photomicrographs of the polished and etched samples, Figure 2, indicated that the steels varied considerably in their degree of carbon banding. The banding is

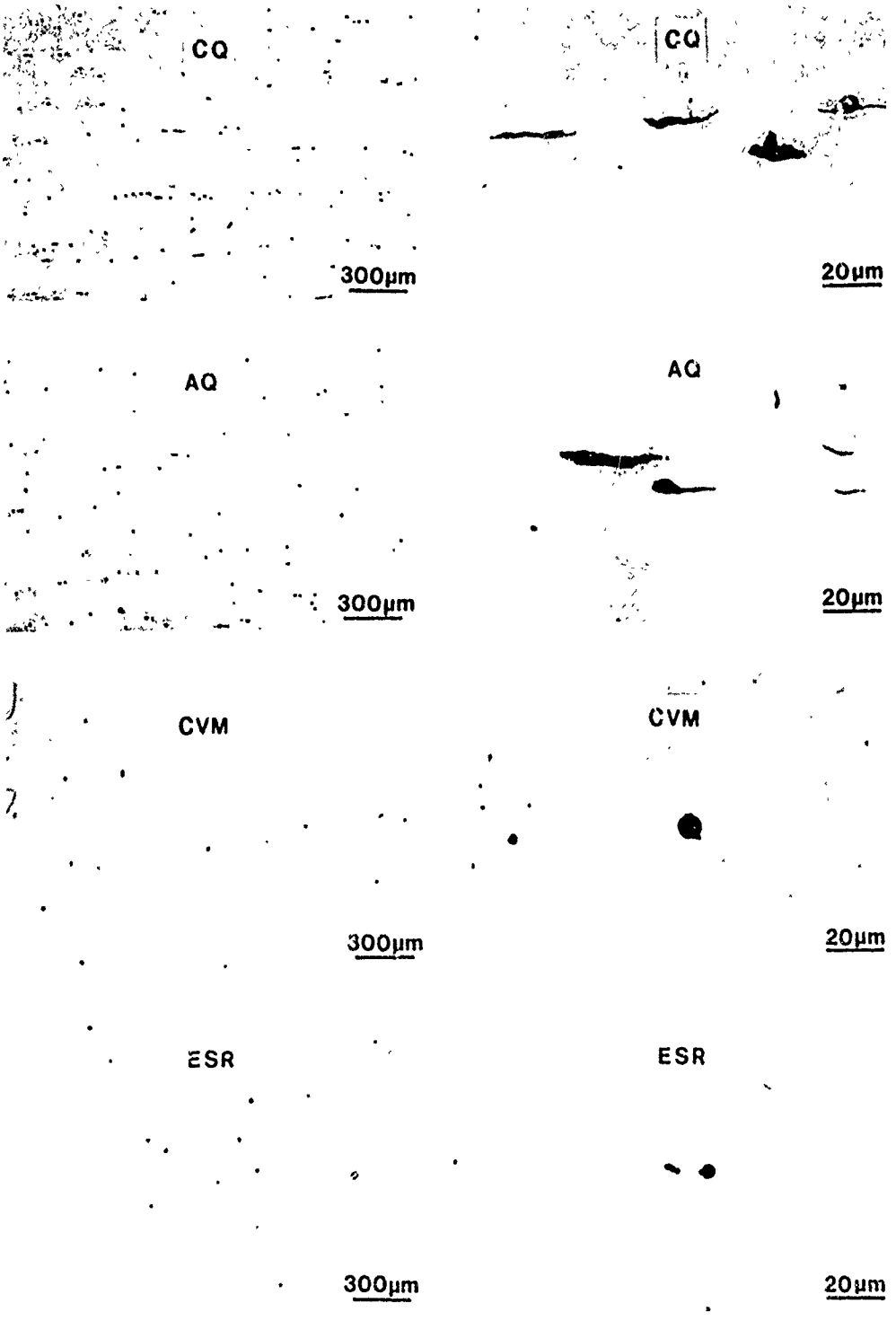


Figure 1. Optical Photomicrographs of Hot Rolled Type 4340 Steels, As Polished.

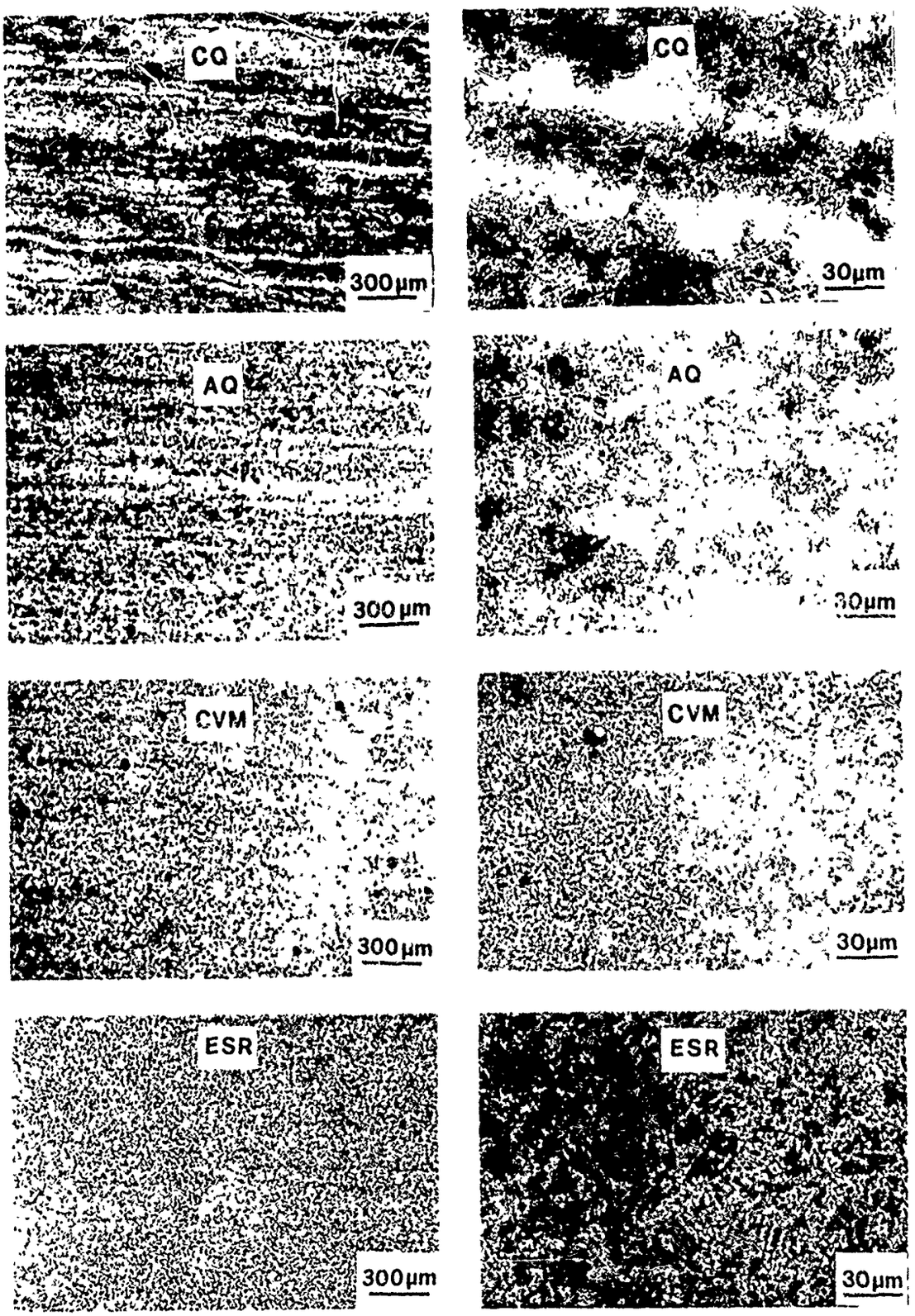


Figure 2. Optical Photomicrographs of Hot Rolled Type 4340 Steels, Nital Etch.

indicated by bands of high and low pearlite content. The degree of carbon banding for the four steels is in the order CQ>AQ>CVM≥ESR; indeed, no carbon banding of the CVM and ESR steels was observed optically. Absence of carbon banding in the CVM and ESR steels can be attributed to the homogenizing effect of the remelting processes by which the two steels were refined.

Scanning Electron Microscopy

The polished metallographic samples were also examined with an ISI* Model 60A Scanning Electron Microscope (SEM) equipped with a PGT† energy dispersive X-ray analyzer (EDX). The EDX analyzer was used to identify elements in and, thus, identify the non-metallic inclusions.

The SEM and EDX analyses indicated that non-metallic inclusions in the CQ and AQ air melted steel grades were predominantly (Mn,Fe)S_x type sulfides. A small number of entrained slag particles, consisting of (Al,Si,Ca)O_x oxide, were also observed.

The optical metallographic analysis had indicated that many of the spherical non-metallic inclusions in the CVM steel consisted of two components. The EDX analysis indicated that the inclusions most likely consisted of Al_2O_3 plus (Mn,Fe)S_x sulfide. The sulfide also contained a large Ca content; the Ca may have been intentionally added to the CVM steel during remelting to aid in desulfurization and refine sulfide size and shape.

No sulfide inclusions could be found in the ESR steel; only a fine dispersion of small oxide particles were evident. Large Al and Si peaks in the EDX spectra were indicative of (Al,Si)O_x oxide inclusions.

Steel Characterization Summary

Four grades of AISI Type 4340 steel were selected for the H behavior study. Two of the steels were air melted (CQ and AQ) and two were refined by remelting (CVM and ESR). All four steels were nearly identical in major element content; they differed primarily according to:

1) Sulfur content in bulk chemical analyses.

2) Heterogeneity of carbon distribution (i.e., carbon banding).

3) Non-metallic inclusion content, size, shape, and chemical composition.

The H behavior of each of the steels was studied to determine which, and to what extent, the above factors influenced H ingress and egress for the steels. The steels were studied at four different hardness levels to determine the role of microstructure on H behavior. The heat treatments, sample preparation, and H charging procedure are described in the next section of the paper.

H CHARGING EXPERIMENTS

Sample Preparation

Approximately 1/8 inch thick discs were cut from each hot rolled steel bar. The discs were austenitized at 850°C (1550°F), quenched, and tempered to one of four

*International Scientific Instruments, Mt. View, CA 94043.
†Princeton Gamma Tech, Princeton, NJ 08540.

hardness levels (R_c55, 50, 45 and 40) according to the tempering treatments listed in Table 2. The tempered discs were surface ground to a thickness of 1/16 inch.

Table 2. Tempering Temperatures for Type 4340 Steels Tempered for Two Hours

Steel Grade	As Quenched Hardness (R_c)	Tempering Temperature (°C) R_c55	R_c50	R_c45	R_c40
CQ	58	125	245	350	430
AQ	59	130	270	395	450
CVM	58	135	280	395	450
ESR	57	125	240	380	455

Both sides of each disc were ground to both assure removal of oxidized and decarburized layers, and to produce parallel surfaces.

The surface ground discs were cut into one gram, approximately 1.5 cm^2 surface area H-charging samples. A steel wire was spot welded to each sample, and the sample edges were coated with a polymeric electrochemical masking agent to assure that H-charging occurred only into the ground, parallel faces.

Cathodic H-Charging

Samples of each steel at the four hardness levels were cathodically H-charged for a fixed time of 2 hours according to the reproducible charging procedure developed at this laboratory [11,12]. The charging was conducted at a current density of 100 A/m^2 (10 mA/cm^2) in an electrolyte of 5 vol. % (1.8N) H_2SO_4 containing 2 g/l thiourea (NH_2CSNH_2) as a H-recombination poison. After charging, the protective polymer coating was removed from the samples by rinsing with acetone and then with ethanol.

That constant current charging procedure assured that all samples were charged under identical environmental conditions. However, the H^+ reduction process is quite complex and depends on the character of the metal surface on which it occurs. Therefore, differences observed in the steel characterization study and also microstructural variations among the four hardness levels of each steel were expected to influence the H^+ reduction process and, thus, the amount of H absorbed by the respective steels.

Total H-Content Measurements

The total H-content, M_H, was measured as a function of H egress time, t_e, for both room temperature (25°C) and elevated temperature (100°C) outgassing into air. The H-content measurements were made with a LECO* RH1 Hydrogen Determinator. Linear regression analysis indicated that the H egress behavior of each steel at a given hardness level obeyed, with correlation coefficients greater than 0.9, a power law relationship of the form $M_H = Kt_e^{-n}$ where K is a constant and n is less than one. That egress behavior is similar to what had previously been observed at this laboratory for several other alloy systems [11-13].

*LECO Corporation, St. Joseph, MI.

H EGRESS RESULTS

H Egress Plots

The H egress results are presented as log-log plots of M_H vs. t_c for each steel (CQ, AQ, CVM and ESR) at the four hardness levels, R_c55, R_c50, R_c45 and R_c40, in Figure 3 (25°C egress) and Figure 4 (100°C egress). The elevated temperature egress results for the CVM steel were not complete and, therefore were not included in Figure 4. The H egress results indicated that H behavior clearly depends on the steel grade (and thus chemistry) and hardness level (and thus microstructure).

In order that the degree of scatter in the egress data could be compared, a statistical analysis was made to determine the standard deviations for the two constants, K and n, in each power law relationship. For this study, the standard deviation for the power law exponents, σ_n, was of most interest because it reflects the uniformity of H outgassing rate for the various test steels. The calculated σ_n values for each n are shown in Table 3; also shown are the ratios σ_n/n, which provide for a direct comparison of egress rate scatter for each steel.

Table 3. Standard Deviations for H Egress Power Law Exponents for Type 4340 Steels.

Steel Grade	R_c	25°C Egress N*	n	σ_n	σ_n/n	100°C Egress N*	n	σ_n	σ_n/n
CQ	40	48	.196	.039	.20	23	1.07	.121	.11
	45	50	.224	.030	.13	29	1.43	.155	.11
	50	40	.341	.030	.09	27	0.97	.138	.14
	55	46	.279	.029	.10	32	1.10	.128	.12
AQ	40	39	.303	.023	.08	25	1.03	.152	.15
	45	18	.255	.018	.07	26	0.92	.108	.12
	50	26	.295	.018	.06	22	1.17	.085	.07
	55	23	.296	.022	.07	28	1.04	.127	.12
CVM	40	40	.291	.031	.10	--	--	--	--
	45	37	.354	.035	.10	--	--	--	--
	50	28	.331	.019	.06	--	--	--	--
	55	33	.338	.024	.07	--	--	--	--
ESR	40	48	.338	.032	.09	26	1.05	.096	.09
	45	48	.516	.030	.06	29	1.37	.067	.05
	50	35	.319	.024	.08	22	1.51	.128	.08
	55	47	.440	.028	.06	40	1.62	.103	.06

*N = number of data points.

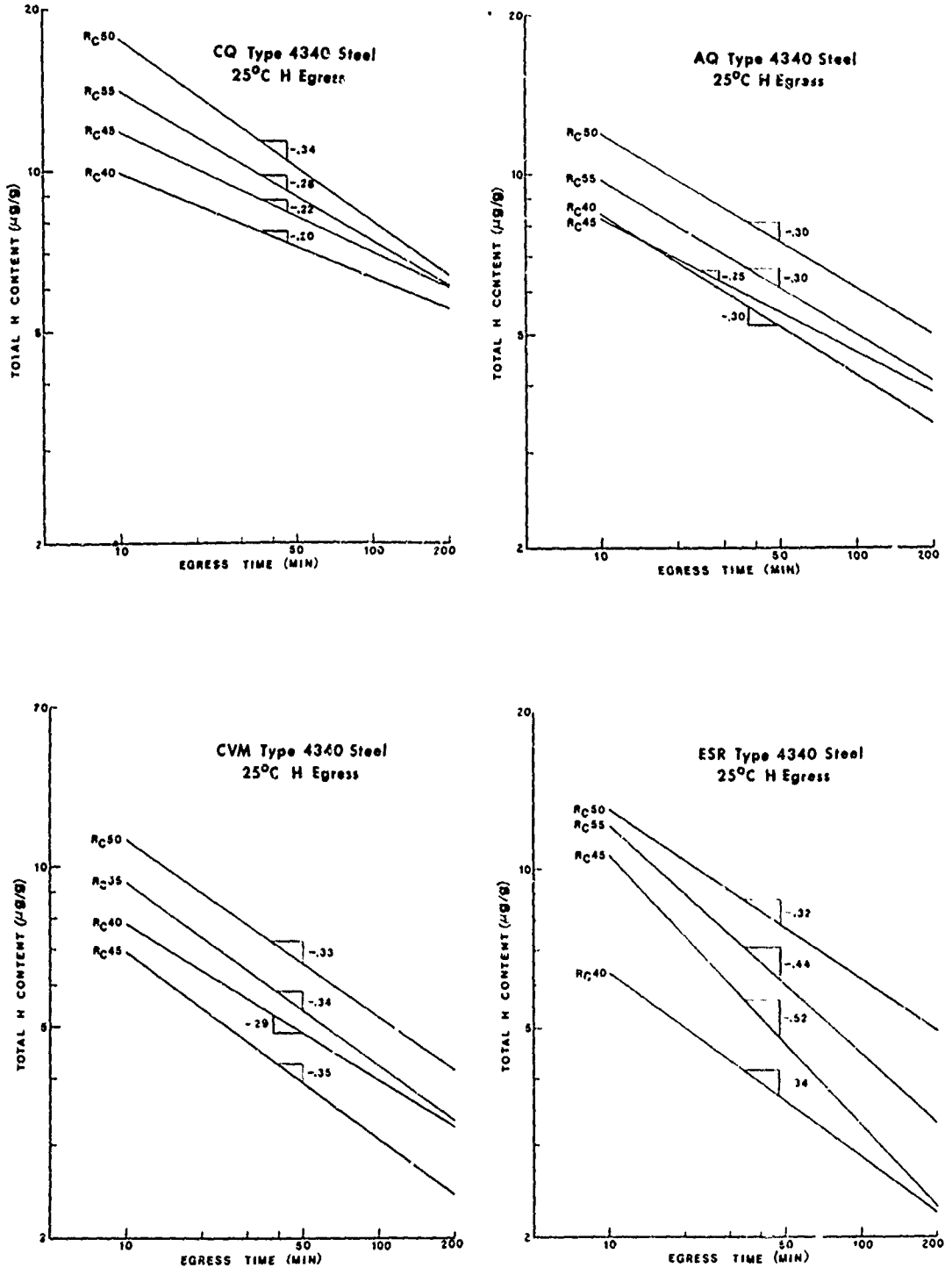
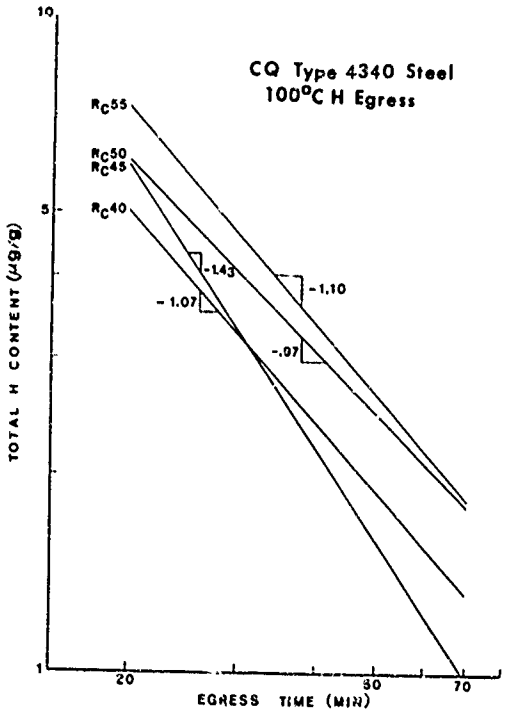


Figure 3. H Egress at 25°C from Cathodically Charged Type 4340 Steels.



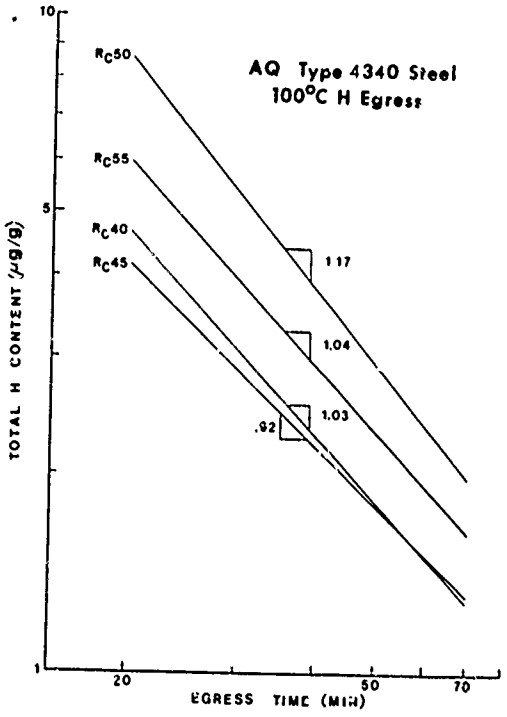
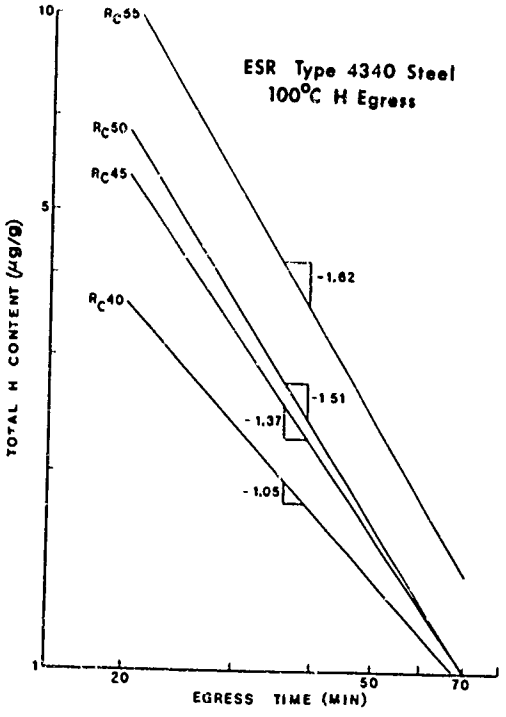


Figure 4. H Egress at 100°C from Cathodically Charged Type 4340 Steels.



H Egress Trends

A number of trends in H behavior are evident in the H egress results. First of all, the amount of H absorbed by each steel exhibits the same dependence on hardness, i.e., $M_H(R_c 50) > M_H(R_c 55) > (M_H(R_c 45) \geq (M_H(R_c 40)$. That trend is best indicated by comparing the M_H values obtained at the shortest egress time (t_e = 10 min) at the lower egress temperature (25°C) in Figure 3. Those values are plotted in Figure 5. In addition, the H content of the charged samples exhibits the same hardness dependence following 25°C egress (Figure 3). However, there is a reversal in $R_c 55$ and $R_c 50$ H content in the ESR and CQ steels following 100°C egress (Figure 4).

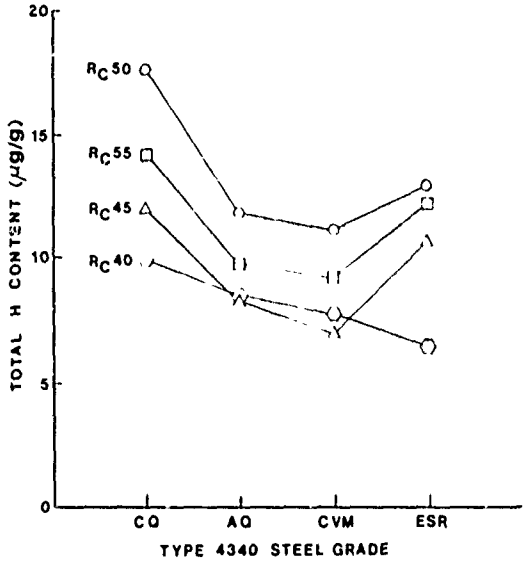


Figure 5. Total H Absorbed by Cathodically Charged Type 4340 Steels (Measured after 10 min. Egress at 25°C).

Another trend in H behavior is evident in Figure 5. The amount of H absorbed for a given hardness level was not the same for all the steel grades. At each hardness level, the H contained in the CQ steel was greater than that contained in the other three steels. The influence of steel grade was more pronounced after longer egress times. It is apparent in Figure 3 and, to a lesser degree, Figure 4, that after longer egress times, the H contained in the steels at each hardness level varied with steel grade according to the general trend: air melted grades (CQ and AQ)>remelted grades (CVM and ESR). That the trend is more pronounced at longer egress times suggests that it is the H egress rate, and not H absorption, that is most influenced by steel grade. The H egress rate dependence on steel grade is illustrated by comparing the 25°C and 100°C power law exponents, n (referred to as the H egress coefficients), for the steels as shown in Figure 6.

The final trend observed in the H egress results is with respect to the degree of scatter in the H content measurements. In particular, the scatter in the H egress coefficients, σ_n/n (Table 3) are greatest for the CQ steel, and least for the ESR steel.

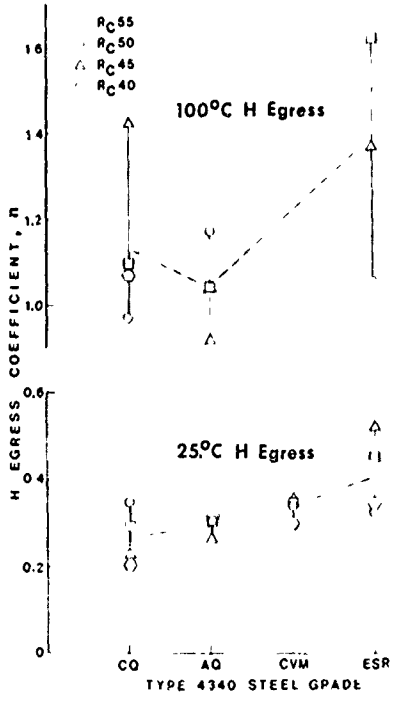


Figure 6. H Egress Coefficients at 25°C and 100°C for Cathodically Charged Type 4340 Steels.

H Egress Summary

The H egress results indicated that H behavior in quenched and tempered Type 4340 clearly varied with both hardness and steel grade.

H behavior variations with hardness included:

1. H absorption in each steel grade varied according to $M_H(R_c50)>M_H(R_c55)>M_H(R_c45)\geq M_H(R_c40)$.

2. Room temperature H egress exhibited the same hardness trend.

3. Elevated temperature H egress varied similarly, but a reversal in H contents for the highest hardnesses (i.e., $M_H(R_c55)>M_H(R_c50)$ was observed for the CQ and ESR steel grades.

H behavior variations with steel grade included:

1. The air melted grades (CQ and AQ) absorbed more H, and outgassed more slowly than the remelted grades (CVM and ESR).

2. More scatter in the calculated H egress rates (i.e., larger standard deviations for the power law exponents) was observed for the air melted grades than for the remelted grades.

The H egress results were compared with the steel characterization results and with information available in the literature in order to establish causal relationships that would explain the observed trends in H behavior. That analysis is described in the next section.

DISCUSSION

The H egress results established that H behavior in quenched and tempered Type 4340 steel was correlated to hardness and steel grade. Each of the observed trends in H behavior may be explained in terms of the steel characterization analysis and information available in the literature.

Hardness Effects on H Behavior

The H behavioral trends that were related to hardness may be explained in terms of the microstructural changes that occur during tempering of the Type 4340 steel. The first trend, that of increased H absorption with increased hardness up to R_c50, has previously been discussed by Kim and Loginow [8]. They also observed increased H absorption for a Ni-Cr-Mo steel at higher strength levels; the increase in H absorption was attributed to a higher concentration of H traps in the steel when it was heat treated to the higher strength levels. Although the traps were not clearly identified, carbide size was suspected to play a significant role. The smaller carbide size at the higher strength levels would result in greater carbide-ferrite interfacial area; the interfaces are likely to serve as traps [8].

The H trapping analysis for Kim and Loginow could explain the increase in H absorption at increased hardnesses between R_c40 and R_c50. However, H absorption was observed to decrease at the higher R_c55 hardness. A similar trend, $R_c40<R_c45<R_c50>R_c55$, was observed in room temperature H egress rate. An explanation for that trend has been offered by Sakamoto and Takao [9], who observed the same variations in H absorption and diffusivity in a similar Mo-Cr-Mo steel as a function of tempering

temperature. They explained the H behavior by considering each microstructural change that occurs during the first stages of tempering. In addition to carbide-ferrite interfaces, they considered lattice imperfections, which also vary with the degree of tempering, to be potential H trap sites.

Tempering was described to take place in four stages according to tempering temperature [9]:

Stage 1: This stage occurs at 80 to 160°C and corresponds to the R_c55 tempering treatment. Martensite begins to decompose and ε-carbide precipitation begins. More importantly with respect to H motion, residual microstrains, due to quenched-in lattice defects that serve as H traps, are relieved. As a result, apparent H diffusivity increases and H absorption decreases.

Stage 2: This stage occurs at 160 to 260°C and corresponds to the R_c50 tempering treatment. C continues to precipitate as ε-carbide, which is then converted to a defective form of cementite. During this stage, the carbide-ferrite interfactial area and, thus, the number of H traps increase. As a result, apparent H diffusivity decreases and H absorption increases.

Stage 3: This stage occurs at 260 to 360°C and corresponds to the R_c45 tempering treatment. Carbide precipitation proceeds to completion, leading to a maximum in carbide-ferrite interfacial area and resultant H traps. H diffusivity reaches a minimum, and H absorption reaches a maximum.

Stage 4: This stage occurs above 360°C and corresponds to the R_c40 tempering treatment. Cementite coarsening causes a decrease in carbide-ferrite interfacial area and decrease in the number of H traps. However, the coarsening occurs slowly and, therefore, the corresponding H diffusivity decrease and H absorption increase will not be dramatic at temperatures near 360°C.

The analysis of Sakamoto and Takao [9] clearly indicates that changes in H trap density which result from tempering induced microstructural changes explain the correlation between H behavior and hardness for the Type 4340 steels. The microstructure with the highest H trap density, R_c50 for Type 4340 steel, absorbs more H and outgasses more slowly than the other microstructures. The R_c50 hardness level is also one of the most susceptible microstructures to hydrogen embrittlement (HE) [5]. Increased H trapping may decrease HE by removing H from potential embrittlement sites. However, this analysis suggests that the increased absorption of H, and slower outgassing, for the more susceptible R_c50 microstructure may account for its greater HE tendency.

The analysis of Sakamoto and Takao explained the H absorption and room temperature egress results obtained in the present study. In particular, it explained the decrease in H contents at hardness levels above R_c50. However, after 100°C H egress, the H contents for two of the Type 4340 steels, CQ and ESR, were greatest for the R_c55, and not the R_c50 hardness level. An explanation for that apparent inconsistency is that the 100°C H bake-out treatment caused additional tempering of the R_c55 microstructures.

Sulfide Inclusion Effects on H Behavior

The H behavioral trends that were related to steel grade may be explained in terms of the compositional changes that occur during the remelting processes. The

primary differences between the air melted and remelted steel grades were in their sulfur content and non-metallic inclusion content, size and shape.

The air melted (CQ and AQ) Type 4340 steels absorbed more hydrogen and outgassed more slowly than the remelted grades (CVM and ESR) at both room and elevated temperatures. A likely explanation for that result is, of course, the greater sulfur content in the air melted grades. Iino [7] has reported a similar effect of S on H absorption into a medium carbon line pipe steel. He attributed the S effect to increased H trapping at manganese sulfide inclusion-ferrite matrix interfaces.

The analysis by Iino suggests that sulfide inclusions play a similar role in influencing H-behavior to that of carbide precipitates, i.e., the sulfide inclusions increase H absorption and decrease egress by serving as H trap sites. However, Craig [13] has suggested that sulfide inclusions at the steel surface may play a more important role by altering the H^+ reduction reaction during cathodic charging in such a way that H absorption increases. He postulated that reaction of sulfides with acid solutions leads to H_2S formation; the H_2S serves as a H recombination poison which causes the increased H absorption. According to Craig's analysis, not only the increased inclusion concentrations of the air melted Type 4340 steel grades, but also their more elongated inclusion shape (see Figure 1) leads to increased H absorption. The elongated inclusions have a greater exposed surface area, and thus a greater number of H absorption sites, at the steel surface.

The effect of sulfides on H absorption may not be manifested only in the massive sulfide inclusions in the steels. Joshi [14] has shown that grain boundary concentration of S and Mn, in the form of sulfides, are much greater than bulk levels in high strength steels. Those sulfides are likely to have the same accelerating H absorption effect, for grain boundaries that intersect the steel surface, as do the massive inclusions. The air melted Type 4340 steel grades, with their higher S contents, are likely to have higher grain boundary sulfide contents.

The air melted steel grades are more susceptible to HE than the remelted grades; this has been attributed to the detrimental effect of sulfide inclusions [13]. The results of the present study and Craig's analysis suggest that increased HE tendency may be related to the increased H absorption caused by their higher sulfide inclusion content and elongated inclusion shape.

Carbon Banding Effect on E Behavior

The final trend in H behavior previously noted was that there appeared to be greater scatter in the air melted steel grades' H egress results. That trend may be explained by the greater heterogeneity in carbon distribution (i.e., carbon banding) in the air melted steel grades (see Figure 2). The bands of high and low carbon content in the quenched CQ and AQ steels can be expected to temper at different rates and to varying carbide distributions. The non-homogeneous microstructures of the quenched and tempered CQ and AQ air melted steel grades would cause variations in H absorption and egress. A corresponding variability and, therefore, unpredictability in HE tendency could be expected for the air melted steel grades.

CONCLUSIONS

H absorption and egress from quenched and tempered AISI Type 4340 steel varies with hardness. The observed hardness dependence is related to H trap density which in turn depends on the degree of tempering. H traps are associated with carbide-

ferrite interfaces and with lattice defects. The hardness with the greatest trap density, R_c50, absorbed the most H and also contained more H after outgassing. The R_c50 hardness level steel is also one of the more susceptible microstructures to hydrogen embrittlement (HE).

The air melted grades of Type 4340 steel absorbed more H and outgassed more slowly than the remelted grades. That difference in H behavior was attributed to sulfide inclusions in the steels. The greater sulfide contents in the air melted grades act similarly to carbide particles by increasing the number of H trap sites. Additionally, sulfide inclusions at the steel surfaces may increase H absorption by suppressing H recombination. H absorption is increased for the air melted grades because of their greater sulfide contents and elongated sulfide shapes. Sulfide formation along grain boundaries may also increase H absorption. The increased HE tendency of the air melted Type 4340 steels may be related to the accelerated H absorption caused by the sulfides.

Greater variability in H absorption and egress was observed for the air melted than for the remelted Type 4340 steels. The variability was attributed to nonhomogeneous microstructures due to carbon banding in the air melted grades. That variability may partially account for the greater variability and, thus, unpredictability in HE tendency for the air melted steel grades.

The quantitative H absorption and egress results obtained in this study make it possible to predict H behavior for particular Type 4340 microstructures and steel grades. The results also confirmed previous studies which indicated that HE tendency in quenched and tempered high strength steels is closely related to H behavior in the steels. Therefore, the H behavior results may lead to reduced HE tendency by providing better control of H absorption and egress through the use of H outgassing methods that are tailored to specific microstructures and steel grades. The uncoated steel H behavior results also provide the necessary baseline information for the second phase of the program which is concerned with H behavior in cadmium coated Type 4340 steels.

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CORROSION CHARACTERISTICS AND CONTROL OF MIXED HYDRAZINE FUEL

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For Presentation at the Tri Service
Corrosion Conference, U.S. Air
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Abstract

This paper describes the use of mixed hydrazine fuel (70% hydrazine - 30% water) in the F-16 emergency power unit (EPU). When emergency power is needed to maintain hydraulic and electrical control, the hydrazine fuel is passed through a catalyst bed where it decomposes into nitrogen and ammonia gasses. These gasses drive a turbine to provide the emergency power. The corrosive properties of the hydrazine and its compatibility with aircraft materials and components are described. A hydrazine-resistant sealant has been developed to isolate spilled or leaking hydrazine in a single compartment thereby minimizing attack to components in adjacent areas.

CORROSION CHARACTERISTICS AND CONTROL OF MIXED HYDRAZINE FUEL

INTRODUCTION

The F-16, built by General Dynamics in Fort Worth, Texas, and co-produced in Denmark, Belgium, the Netherlands, and Norway is a single engine plane with an auxillary emergency power unit (EPU). The EPU provides up to ten minutes of hydraulic and electrical power so in case of engine failure the pilot can maintain control of the airplane until the engine is restarted or the plan is landed, (See Table I). The emergency power unit is powered by a liquid fuel comprised of 70% hydrazine and 30% water. The 70% hydrazine fuel (also known as H-70) is covered by military specification MIL-P-87930. Some physical properties of this material are shown in Tables II and III. Chemically the hydrazine mixture is highly reactive, acting as both an oxidizing and reducing agent. It is corrosive to a variety of materials, including some metals, plastics, and organic coatings. The corrosive effects of hydrazine on specific aircraft materials and components will be discussed in the following sections.

Operation of Emergency Power Unit

The manner in which the unit operates is described as follows (see Figure 1). The hydrazine fuel is pumped through a decomposition chamber containing a catalyst which converts the hydrazine into nitrogen and ammonia gasses ($3N_2H_4 \rightarrow 4NH_3 + N_2$). These gasses turn a turbine which drives an emergency hydraulic pump and a standby generator to provide the hydraulic and electrical power.

Characteristics of Hydrazine Leaks

The 70% hydrazine fuel is stored in a 7 gallon tank in a compartment in the fuselage, (See Figure 2). The decomposition chamber is located in an adjacent compartment and is connected to the storage tank by dismountable piping. The fuel tank and EPU are designed to be removed for servicing as required. During these operations some hydrazine may leak onto the surrounding area. These "minor" spills may be cleaned up immediately. Occasionally a major spill may occur

TABLE I

F-16 EMERGENCY POWER UNIT (EPU)

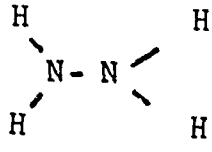
- PROVIDES UP TO TEN MINUTES OF HYDRAULIC/ELECTRICAL POWER

- POWERED BY MIXED HYDRAZINE FUEL (70% HYDRAZINE - 30% WATER)

TABLE II

DESCRIPTION OF HYDRAZINE

- CHEMICAL STRUCTURE



- PURE FORM VERY EXPLOSIVE - USED AS ROCKET FUEL

- DILUTED WITH 30% WATER - NON-EXPLOSIVE BUT VERY REACTIVE

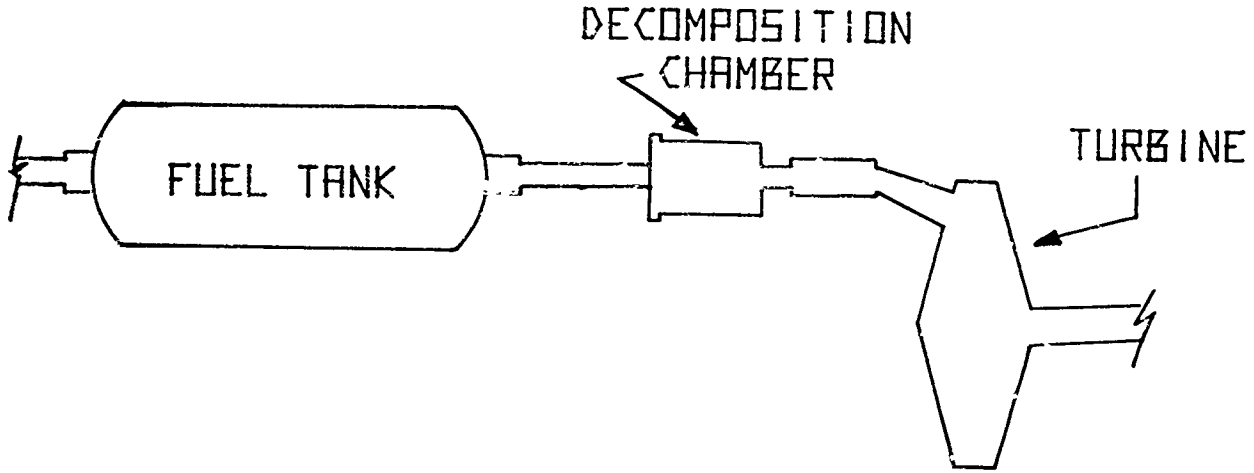
TABLE III

PROPERTIES OF H-70 FUEL

(70% HYDRAZINE - 30% WATER)

APPEARANCE	- -	CLEAR LIQUID
ODOR	- -	AMMONIACAL
SPECIFIC GRAVITY	- -	1.03
FREEZING POINT, ^{o}F	- -	-58
BOILING POINT, ^{o}F	- -	246
FLASH POINT, ^{o}F	- -	154

OPERATION OF EMERGENCY POWER UNIT



$$3N_2H_4 \rightarrow 4NH_3 + N_2$$

FIGURE 1

LOCATION OF HYDRAZINE COMPARTMENTS

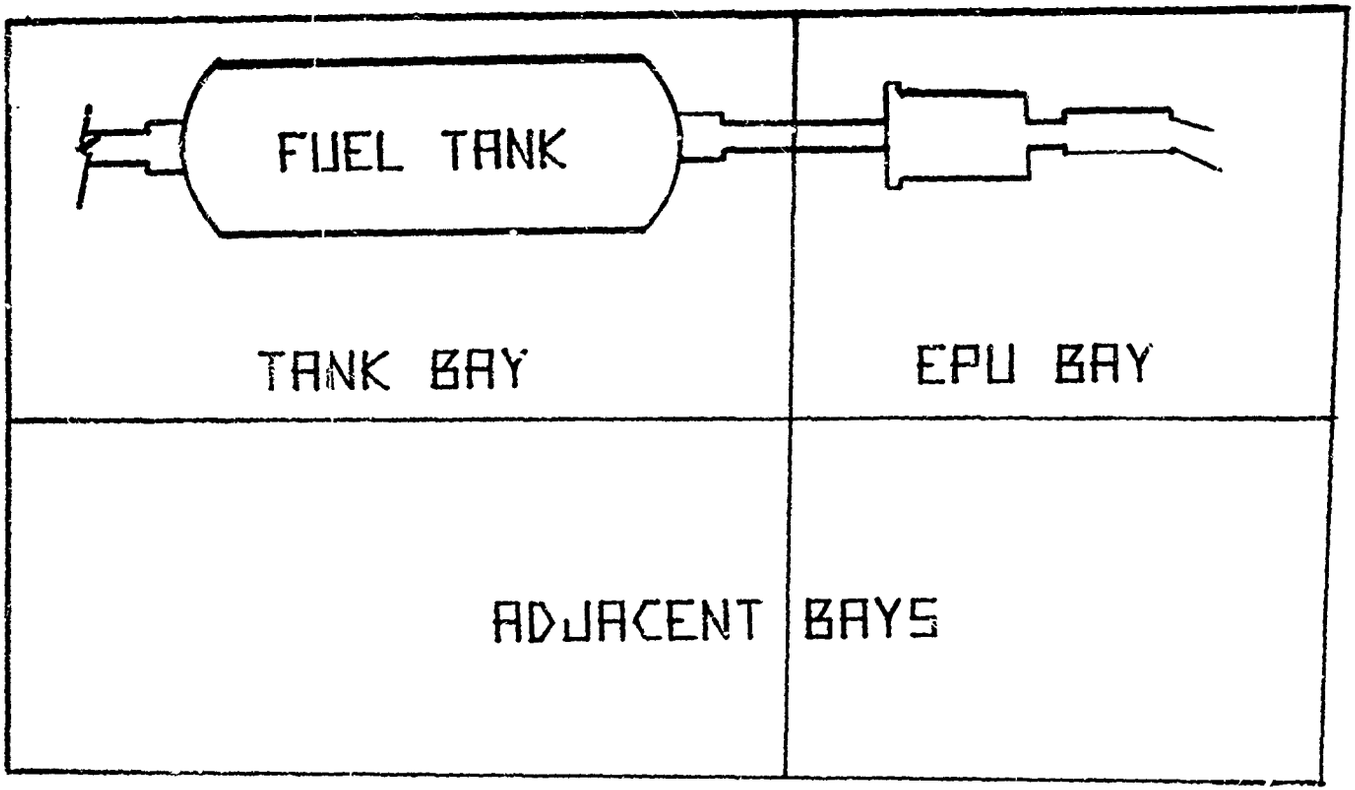


FIGURE 2

due to system leaks at the connections under high pressure. In this case, a considerable quantity of hydrazine may be involved and the spill may not be detected for several hours or even days. The spilled fluid may interact with components in the compartment at point of origin and in addition i may run into adjacent (usually lower) compartments.

Corrosive Effects of Hydrazine on Specific Aircraft Materials

The effects of hydrazine on various aircraft materials located in or near the hydrazine fuel tank or EPU compartment is described below.

Metals - Several metals were tested for corrosion characteristics in hydrazine. Some of these metals are present in the hydrazine compartment; others were tested for future reference. Table IV shows their weight and appearance change after 7 days of immersion at room temperature (listed in increasing order of corrosion). It is seen that no serious corrosion problem exists with metals in or near the hydrazine compartments. The 303 and 316 CRES fittings should be replaced with 321 or 304 if possible.

Finish Systems - The EPU and the hydrazine tank compartment walls are constructed from chromic acid anodized 2024 aluminum and are coated with MIL-P-23377 epoxy primer. Some areas have a topcoat of MIL-C-83286 urethane paint. Tests were conducted to determine the effect of hydrazine on these coated surfaces. Test panels were immersed in H-70 for seven days at room temperature. The results are shown in Table V. In the case of the epoxy primed panels, a few small blisters formed but no loss of adhesion or other significant effects were noted. The urethane painted panels showed a slight loss of adhesion (5% by dry tape tests).

Electrical Wiring - Electrical harnesses are located in the EPU compartment and in other adjacent compartments. Two types of wire insulation are used, Kapton (polyimide) and Teflon. Laboratory tests showed that the Teflon wires were not affected by hydrazine exposure. The Kapton wires, however, were heavily attacked, (Figure 3). The attack began on the dye used for color coding the wires. The dye was destroyed, exposing the copper-colored Kapton surface. At this point the wires looked like they were stripped to bare copper, but actually only the Kapton surface was exposed.

TABLE IV

EFFECT OF HYDRAZINE H-70 ON METALS

METAL	FUNCTION IN EPU COMPARTMENT	7 DAY IMMERSION AT RT WT CHANGE (MG/CM^2)	APPEARANCE CHANGE
2024 Alum. (chromic acid anodized)	Structural Wall	-.001	None
Nickel plated 4130	Tools	+.003	None
321 CRES	Fittings	-.007	None
304 CRES	Fittings	-.012	None
316 CRES	Fittings	-.042	Sl Discolored
303 CRES	Fittings	-.052	Sl Discolored
Copper	Not Present	-.057	Discolored
2024 Alum. (bare)	Not Present	+.066	Discolored
1100 Alum.	Not Present	+.086	Discolored
Iron	Not Present	-.090	Pitted
Cadmium	Not Present	-.094	Pitted
Lead	Not Present	-.096	Pitted

TABLE V

EFFECT OF HYDRAZINE ON COMPARTMENT FINISHES

2024 ALUMINUM (CHROMIC ACID ANODIZED)	EFFECT OF 7-DAY IMMERSION IN H-70
o COATED WITH MIL-P-23377 EPOXY PRIMER	FEW BLISTERS NO LOSS OF ADHESION
o COATED WITH MIL-P-23377 PLUS MIL-C-83286 URETHANE PAINT	SLIGHT LOSS OF ADHESION

ATTACK OF KAPTON WIRES BY HYDRAZINE

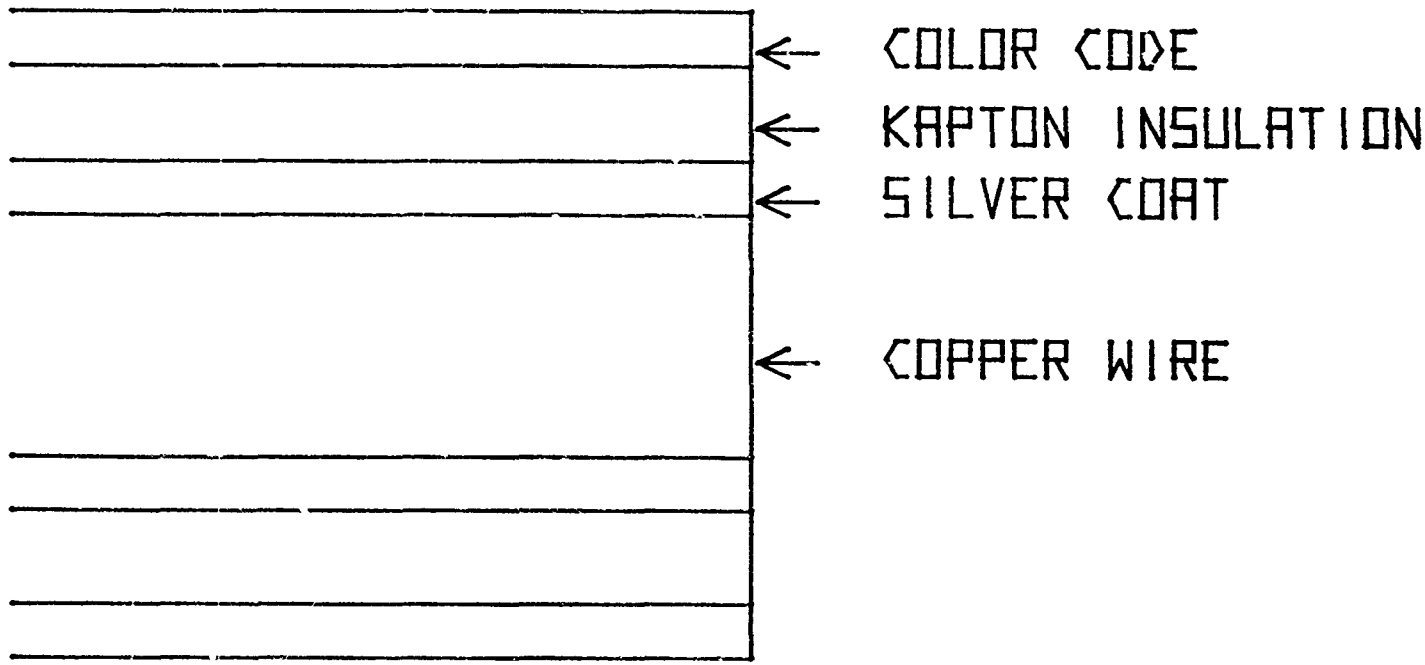


FIGURE 3

After a total of five hours of exposure the Kapton began to disintegrate, exposing bare silver-coated copper wires. In the presence of moisture, electrical shorts were created. It was also noted that once a wiring harness was contaminated with hydrazine, it was virtually impossible to flush out with water. (A water flush is the only accepted way of cleaning up hydrazine spills on the airplane). For this reason even a short term contact of the wires with hydrazine could lead to the damage described. Teflon wires cannot be substituted for Kapton in many instances due to other property requirements.

Other Electrical Components - Additional electrical components tested for hydrazine compatibility include silicone rubber connectors, irradiated polyolefin shrink tubing, harness braiding material (Stilan, Nomex, Tefzel), relays, and sockets. None of these materials was damaged by hydrazine contamination, (Table VI).

Control of Hydrazine Corrosion

Inside The EPU Compartments - From the foregoing discussion, we see that the only material inside the EPU and fuel tank compartments which is not compatible with hydrazine is electrical wiring. To solve this problem, it was decided to completely wrap those harnesses with Teflon tape, (Figure 4). Exposure tests confirmed that harnesses wrapped in this manner were resistant to hydrazine.

Outside The Epu Compartments - If hydrazine spills into adjacent compartments, there is no predicitng how many or which components would be affected. It was decided, therefore, to prevent such contamination by sealing the hydrazine compartments so that any spilled fuel would be contained therein. The program to select a sealing compound to make the compartments leak-proof is described below.

Hydrazine Compatibility Of Sealants - The sealing materials tested for resistance to hydrazine are shown in Table VII. It is seen that sealants made from polysulfides, polyurethanes, and viton were severely degraded by hydrazine. Although butyls and silicones were not apparently damaged by hydrazine, they did lose adhesion from the coated aluminum substrate following hydrazine immersion and therefore would not be an effective sealant. An amine cured epoxy exhibited excellent resistance to hydrazine and excellent adhesion following immersion. It had the disadvantage, however, of having a low

TABLE VI

EFFECT OF HYDRAZINE ON OTHER ELECTRICAL COMPONENTS

SILICONE RUBBER CONNECTORS	NO SIGNIFICANT DAMAGE
POLYOLEFIN SHRINK TUBING	
HARNESS BRAIDING MATERIALS (STILAN, NOMEX, TEFZEL)	
RELAYS/SOCKETS	

ELECTRICAL HARNESS WRAPPED WITH TAPE

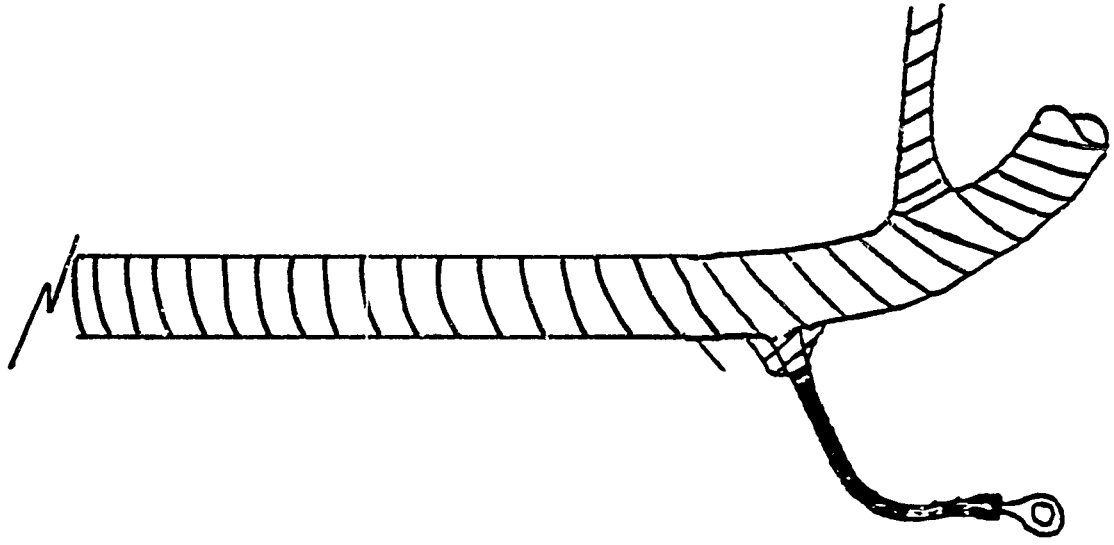


FIGURE 4

TABLE VII

EFFECT OF HYDRAZINE ON SEALANTS

SEALANT	SEVEN DAY IMMERSION AT RT (EXCEPT AS NOTED)
Pro-Seal 899[1] (polysulfide)	Heavy chalk on surface, spongy interior
PR 366[2] (one part polyurethane)	Spongy interior, high swell, low adhesion
Pro-Seal 799 (two-part polyurethane)	OK at RT, but depolymerized by hydrazine at 160°F for 8 hours
PR 1730 (Viton)	Large blisters, spongy, 100% swell
Butylite 712[3] (butyl)	Lost adhesion to coated aluminum
EC 3598[4] (amine cured epoxy)	Good resistance to hydrazine, low flexibility
DC 94-002[5] (fluorosilicone)	Poor adhesion
DC 3120 (methyl silicone)	Poor adhesion

(1) Essex Chem. Corp.

(2) Products Research & Chem. Co.

(3) Polymeric Systems, Inc.

(4) 3M Company

(5) Dow Corning Corp.

flexibility and might be subject to cracking under stress at low temperature. A modification of the epoxy formulation (reduced epoxy-to-amine ratio) was then tested, (Table VIII). This modified epoxy had satisfactory flexibility and was still resistant to hydrazine. This material was selected, therefore, for sealing the EPU and hydrazine tank for containment of spilled hydrazine.

CONCLUSION

The materials located in compartments where hydrazine spills might occur have been selected based on their resistance to the chemical mixture. An exception is electrical wires which may become severely damaged by hydrazine exposure. This problem was effectively solved by wrapping the wires in the hydrazine compartments with Teflon tape. A hydrazine-resistant sealant was selected to seal these compartments so as to contain any spilled hydrazine and prevent corrosive attacks on components in adjacent areas.

TABLE VIII

MODIFICATION OF EPOXY FORMULATION TO INCREASE FLEXIBILITY

o ORIGINAL FORMULATION	
40% EPOXY 60% AMINE	CRACKED AT -65°F UNDER STRESS
o MODIFIED FORMULATION	
30% EPOXY 70% AMINE	IMPROVED FLEXIBILITY NO CRACKS AT -65°F

JOINT SERVICE DESERT ENVIRONMENTAL TIRE PRESERVATION TEST PROJECT

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I. INTRODUCTION

This paper describes tests performed, results and conclusions in minimizing tire degradation caused by ozone attack experienced at the Marine Corps Logistics Base, Barstow, California.

The Logistics Base at Barstow is the West Coast Supply/Storage facility for the Marine Corps with a fifth echelon repair/maintenance facility. Barstow stores approximately 7,000 serviceable tracked and wheeled vehicles, and performs annual care-in-store maintenance.

Prior to 1977, all vehicles were in outside storage. Presently approximately 4,000 vehicles (with a goal of 7,500 by 1984) have been moved to inside or covered storage. As a result of providing improved storage protection, a dramatic decrease in tire degradation and vehicle maintenance costs has been realized.

Investigation into the problem of tire degradation began in 1977 prior to moving the vehicles to inside storage. The cost of applying LR-1588 preservative (manufactured by The Akron Paint and Varnish Company in accordance with specification MIL-P-11520) became prohibitive since it did not provide protection against ozone attack. The decision was made to investigate the problem to determine alternatives.

II. BACKGROUND

During the investigation, we consulted with TARADCOM, Warren, Michigan, and agreement was reached to conduct a joint service tire preservation test under desert environmental conditions. Funds were provided by both TARADCOM and Headquarters Marine Corps to plan and conduct a controlled test on various types of tire preservatives at MCLB, Barstow, California.

The purpose was to conduct a comprehensive controlled test in the desert environment to establish and implement adequate procedures for preventing tire deterioration of installed tires for the longest storage period possible and to provide answers to the following objectives:

a. Establish a deterioration rate variance to provide criteria for inside versus outside storage of vehicles with mounted tires.

b. Determine whether application of preservatives will maintain the service life of rubber to the degree of a new tire.

c. Determine whether the preservation will serve as a barrier, providing protection against ozone attack between the surface of the rubber and the environmental atmosphere.

d. Determine if there is a direct relationship between the age of a tire and the degree of deterioration and loss of useful tire life.

e. Determine if the current practice at MCLB, Barstow, California of topical application of preservatives during cyclic care-in-storage is cost effective for mounted tires.

Two testing procedures were used at Barstow: (a) Method D 518, Procedure B as detailed in the American Society for Testing and Materials (ASTM) - "Outdoor Exposure of Looped Test Specimens," and (b) Outdoor Exposure Test of Mounted Tires.

III. PROCEDURE

a. ASTM D 518, Procedure B (Outdoor Exposure of Looped Test Specimens).

We cut rubber specimens from standard laboratory slabs (without antiozonants incorporated in its formulation) into rectangular strips 3-3/4 in. in length by 1 in. wide with a thickness of .075 inches. The specimens were looped and mounted on a board. Duplicate tests were performed. The duration of the test was 360 days.

The following preservatives were used in this test:

Preservative	Manufacturer
ZR-2550 (Age Master No. 1)	Chem Pro Corp., Buffalo, N.Y.
Armor-All	Very Important Product, Newport Beach, California
LR-1588	Akron Paint & Varnish Company, Akron, Ohio
UOP-62	Universal Oil Products, E. Rutherford, N.J.
UOP-88	Universal Oil Products, E. Rutherford, N.J.
UOP-288	Universal Oil Products, E. Rutherford, N.J.
UOP-688	Universal Oil Products, E. Rutherford, N.J.

Each rubber specimen was cleaned with acetone and allowed to dry before application of preservatives.

Two methods of application were used for each preservative. One specimen was coated twice by spray application and another specimen was coated twice by brushing for each type of preservative. All preservatives were applied at 100% strength.

Spray application was accomplished by using Brinks Air-Spray Gun Model 18 (Nozzle 665D) at 110 psi.

The rubber specimens were mounted on a board at a 45° angle facing south in an open field which provided full exposure to all environmental conditions of the desert as shown in exhibit #1.

b. Outdoor Exposure Test of Mounted Tires

Twelve tires were used for the test. Six of the tires were new, four were used and two were unused. The two unused tires were new but had been in storage for approximately 18 months.

Types of tires used

#1 New - Mohawk Chief 9.00 x 20, NDCC.
#2 New - Mohawk Chief 9.00 x 20, NDCC.
#3 New - Mansfield Super Transport 9.00 x 20, Commercial Tire.
#4 New - Mansfield Super Transport 9.00 x 20, Commercial Tire.
#5 New - Goodyear Radial 9.50 x 16.5.
#6 New - Goodyear Radial 9.50 x 16.5.
#1 Used - Kelly Springfield 9.00 x 20, NDCC.
#2 Used - Goodyear 9.00 x 20, NDCC.
#3 Used - Firestone Transport 9.00 x 20, Commercial Tire.
#4 Used - Uniroyal Fleetmaster 9.00 x 20, Commercial Tire.
#5 Unused - Goodyear Radial 9.50 x 16.5.
#6 Unused - Goodyear Radial 9.50 x 16.5.

The same preservatives were used for this test as for Method D 518, Procedure B of ASTM. Exhibit #2 shows the type preservative applied to each section of each tire.

All tires were fully inflated and mounted on individual stands at a 45° angle facing south in an open field. Tires had full exposure to all the environmental conditions of the desert as shown in exhibit #3.

All preservatives were applied at full strength on both sides of the tire by spray application in the same manner as for Method D 518, Procedure B of ASTM.

c. Problems with Outdoor Exposure Test of Mounted Tires.

Tires were from different manufacturers with differing rubber compositions. Some had an antiozant in the rubber composition already built in. Therefore comparisons cannot be made between tires. Comparisons can only be made between the control section

and the preservatives on any one particular tire. Also comparisons/evaluations can be made between the side of the tire directly exposed to the sun and the reverse side of the tire which received indirect sunlight.

IV. RESULTS/FINDINGS

Exhibit #4 charts periodic findings during the 360 days of exposure for Method D 518, Procedure B of the ASTM.

Exhibit #5 shows number of days to initial cracking on the new tires for the Outdoor Exposure Test of Mounted Tires.

Exhibit #6 and 7 show the amount of cracking on both sides of the tires after 12 months exposure and shows the comparisons between the two sides of the tires for the Outdoor Exposure Test of Mounted Tires.

Exhibit #8 provides information on application characteristics of each preservative that were experienced during the test procedure.

Exhibit #9 provides weather information during the 12 month test period.

The initial test period was from November 1978 to November 1979 (12 months). However, we have informally continued the tests to achieve some more results to confirm our original findings and/or obtain new information that may alter our original conclusions.

Exhibit #10 - 25 show the results of the looped specimens after 18 months exposures. The results confirm our original findings. The most significant additional results are: (1) ZR-2550 (Age Master No. 1) did not hold up as well as expected and (2) the Universal Oil Products are still holding as well as they did at 12 months.

Exhibit #26 - 74 show the results of the exposed mounted tires after 18 months exposure. The additional results provide substantial evidence to verify our original findings and conclusions. The most significant supplemental information is the variance in degree of deterioration between the directly exposed side and the indirectly exposed side. Also, the variance in the rate of deterioration between the commercial tires and the military tires has continued to increase.

V. CONCLUSIONS

a. Objectives

(1) Establish a deterioration rate variance to provide criteria for inside versus outside storage of vehicles with mounted tires.

After 360 days exposure, results showed a very significant difference, or variance, in amount and rate of deterioration between tire sides directly exposed to sunlight and the reverse side (receiving indirect sunlight). After 18 months exposure, the original conclusions were confirmed. This provides clear evidence that if vehicles with mounted tires are stored out of direct sunlight the amount and rate of deterioration will correspondingly decrease.

(2) Determine whether application of preservatives will maintain the service life of rubber to the degree of a new tire. Several preservatives, when properly applied, will protect and extend the service life of tires to the degree of new tires for a limited time under desert environmental conditions. In addition, exhibit #5 gives evidence on the effectiveness of the various preservatives tested on the Loop Test. Also, the 18 month follow-up results provide more conclusive evidence from the Loop Test. The Loop Test shows that the Universal Oil Products are superior to the other preservatives tested and in relation to the control specimens. Results from the Mounted Tire Test are somewhat more ambiguous, although, when each tire is considered separately and the preservatives are compared on each particular tire, some conclusions can be drawn as can be observed from the following exhibits.

(3) Determine whether the preservative will serve as a barrier, providing protection against ozone attack between the surface of the rubber and the environmental atmosphere. The most effective candidate preservative coatings are not a barrier forming coating, but rather a chemical solution which is absorbed beneath the surface of the rubber to provide protection against ozone attack. Treatment does protect the rubber from ozone attack for a limited time in the desert environment as shown from the 18 month follow-up evaluations.

(4) Determine if there is a direct relationship between the age of a tire and the degree of deterioration and loss of useful tire life.

There is no direct relationship between the age of a tire, degree of deterioration and loss of useful tire life for tires produced by different manufacturers. This statement may be questioned when considering the results of the Military Non-directional Cross Country Tires when compared to Commercial Tires. More testing and evaluation is recommended for this problem.

The degree of deterioration and useful tire life is dependent on the original incorporation of effective antiozonants in the rubber at the time of manufacture. For the same type of tire, deterioration increases and the useful life decreases with age. This fact can be readily substantiated by comparing the results between the different types of tires.

(5) Determine if the current practice at MCLB, Barstow,

California of topical application of preservatives during cyclic care-in-storage is cost effective for mounted tires. The use of barrier forming (rubberized coating - LR-1588) preservative is not cost effective. On the Loop Test LR-1588 coated specimens deteriorated before and at a faster rate than the control (untreated) specimens. This preservative does not penetrate the rubber. The tires deteriorate under the coating. It is extremely difficult to apply LR-1588 (MIL-C-11520) without pinholes forming in the coating. LR-1588 has merely provided a cosmetic covering. In summary, the following are the most significant conclusions derived from the results of the tests:

a. The most satisfactory preservative coatings evaluated were UOP 62 and UOP 688 based on application characteristics results and overall cost effectiveness. This conclusion was substantiated in the 18 month follow-up evaluation.

b. The least effective preservatives tested were Armor-All and LR-1588. LR-1588 (MIL-C-11520) was being used at MCLB, Barstow, but has been discontinued because of the test results. Both of these preservatives deteriorated before and at a faster rate than the control specimens on the Loop Test.

c. After the 360 days and 18 months evaluation, of the three types of tires tested, commercial bias and radial tires had better resistance to ozone attack than military NDCC tires procured under specification MIL-T-12459.

d. The variance and rate of deterioration between the tire side directly exposed to the sun and the reverse side (receiving indirect sunlight) provides significant evidence to conclude that the rate of tire degradation due to ozone attack will be substantially reduced when vehicles with mounted tires can be stored inside a darkened warehouse.

e. The performance of preservative coatings is dependent on rubber formulation to be protected, surface preparation and cleanliness, workmanship and application of an adequate amount and type of antiozonant.

VI. RECOMMENDATIONS.

a. From the standpoint of cost and long term storage protection, the most desirable method of achieving good preservation protection of military tires is by incorporating a suitable quantity and type of antiozonant into the tire at the time of manufacture.

b. Procure NDCC military tires which meet all ozone resistance requirements specified in MIL-T-12459, titled Pneumatic Tires for Military Ground Vehicles.

c. It is recommended, in order to achieve the most effective ozone protection and extending the useful life of mounted tires, that (1) inside storage is as dark an area as possible be utilized

for long term storage and (2) tires be preserved with the most cost effective preservative for outside storage until tires can be procured with better antiozonants incorporated in the rubber.

This paper was prepared for presentation at the TRI-SERVICE CONFERENCE on CORROSION at the U.S. Air Force Academy, Colorado Springs, Colorado, on 5-7 November, 1980.

TABLE #I

APPLICATION CHARACTERISTICS COMPARISONS RATINGS

	ZR-2550	Armor-All	LR-1588	UOP-62	UOP-88	UOP-288	UOP-688
Spray Application							
Ease of Application	6	2	4	2	2	2	2
Overspray	8	3	4	2	2	2	2
Flashpoint	FP 60°-65° F	Unknown	FP 24° F	FP>270° F	FP 396° F	FP 325° F	FP 365° F
Irritable Fumes Toxicity	8	3	9	3	3	3	2
Staining Effect	8	2	3	5	5	4	3
Effect on Spray	8	2	4	3	3	3	3
Drying	3	4	9	3	3	3	3
Time between applications	5-10 min	5-10 min	12 hours	5-10 min	5-10 min	5-10 min	5-10 min
Finished Appearance	1	1	7	1	1	1	1
Brush Application							
Ease of Application	3	3	5	2	2	2	2
Stain Effect	8	2	3	5	5	4	3
Drying	3	4	9	3	3	3	3
Time between applications	5-10 min	5-10 min	12 hours	5-10 min	5-10 min	5-10 min	5-10 min
Finished Appearance	1	1	7	1	1	1	1
Total Comparison Scores	57	27	64	30	30	28	25

Assigned Ratings

0-2 Excellent
3-4 Good
5-6 Fair
7-8 Poor
9-10 Very Poor

TABLE #II

TEMPERATURE AND WEATHER DATA FOR DURATION OF TEST

	AVG. MONTHLY TEMPERATURE FOR SELECTED HOURS		AVG. MONTHLY REL. HUMIDITY FOR SELECTED HOURS		AVG. MONTHLY WINDSPEED (KNOTS FOR SELECTED HOURS		AVG. HIGH TEMPERATURE FOR MONTH DEGREES F.	AVG. MONTHLY OZONE LEVEL BASED ON HOURLY MAXIMA IN PARTS PER MILLION (PPM)
	0600	1500	0600	1500	0600	1500		
NOV 78	45	66	67	34	7	7	66	.03
DEC 78	36	56	63	36	6	6	56	.02
JAN 79	38	53	73	47	6	9	53	.02
FEB 79	41	62	74	36	7	11	62	.04
MAR 79	48	66	76	41	8	10	67	.05
APR 79	53	78	61	22	10	10	79	NO RECORD
MAY 79	62	88	52	19	13	12	86	.07
JUN 79	71	98	31	12	9	11	100	.09
JUL 79	74	103	45	19	8	8	104	.08
AUG 79	72	96	51	26	8	12	100	.08
SEP 79	73	99	34	16	8	7	100	.06
OCT 79	60	84	48	19	8	10	84	.05
NOV 79	45	68	41	19	8	9	68	.05

TABLE #III

RESULTS OF LOOPED TEST SPECIMENS

Time to Initial Cracking	ZR-2550 (Age Master #1) Brushed	ZR-2550 (Age Master #1) Sprayed	Armor-All Brushed	Armor-All Brushed	LR-1588 Brushed	LR-1588 Sprayed	UOP 62 Brushed	UOP 62 Sprayed	UOP 88 Brushed	UOP 88 Sprayed	UOP 288 Brushed	UOP 288 Sprayed	UOP 288 Brushed	UOP 688 Sprayed	Untreated	
14 Days	NC	NC	VLC	VLC	NC	NC	NC	NC	NC	NC	NC	NC	NC	NC	NC	
16 Days	NC	NC	LC	LC	LC	LC	NC	NC	NC	NC	NC	NC	NC	NC	NC	
17 Days	NC	NC	IC	IC	IC	IC	NC	NC	NC	NC	NC	NC	NC	NC	VLC	
23 Days	NC	NC	SC	SC	SC	SC	NC	NC	NC	NC	NC	NC	NC	NC	IC	
27 Days	NC	NC	SC	SC	SC	SC	NC	NC	NC	NC	NC	NC	NC	NC	IC	
30 Days	NC	NC	VSC	VSC	VSC	VSC	NC	NC	NC	NC	NC	NC	NC	NC	SC	
90 Days	NC	NC	Exceed 85% Decadence				NC	NC	NC	NC	NC	NC	NC	NC	Exceed 85% Decadence	
180 Days	VLC	NC	100% Decadence				NC	NC	NC	NC	NC	NC	NC	NC	100% Decadence	
270 Days	One Crack	NC	100% Decadence				NC	NC	NC	NC	NC	NC	NC	VLC	100% Decadence	
300 Days	One Crack	NC	100% Decadence				NC	NC	NC	NC	NC	NC	NC	One Crack	100% Decadence	
360 Days	One Crack	NC	100% Decadence				NC	NC	One Crack	One Crack	NC	NC	NC	One Crack	100% Decadence	

NC = No Cracking
VLC = Very Light Cracking
LC = Light Cracking
IC = Increased Cracking
SC = Severe Cracking
VSC = Very Severe Cracking

NOTE: 1. No apparent difference in rate of deterioration between brushed and sprayed specimens.

2. These results include the duplicate test since there was no significant difference between the two tests.

TABLE #IV TYPE PRESERVATIVE APPLIED TO NUMBERED SECTIONS

Type of Tire	1	2	3	4	5
New Tire #1 - NDCC	Untreated	UOP-62	Armor-All	LR-1588	UOP-288
*New Tire #2 - NDCC	Untreated	ZR-2550	UOP-88	UOP-688	
New Tire #3 - Commercial	Untreated	UOP-62	Armor-All	LR-1588	UOP-288
*New Tire #4 - Commercial	Untreated	ZR-2550	UOP-88	UOP-688	
New Tire #5 - Radial	Untreated	UOP-62	Armor-All	LR-1588	UOP-288
*New Tire #6 - Radial	Untreated	ZR-2550	UOP-88	UOP-688	
Used Tire #1 - NDCC	Untreated	UOP-62	Armor-All	LR-1588	UOP-288
*Used Tire #2 - NDCC	Untreated	ZR-2550	UOP-88	UOP-688	
Used Tire #3 - Commercial	Untreated	UOP-62	Armor-All	LR-1588	UOP-288
*Used Tire #4 - Commercial	Untreated	ZR-2550	UOP-88	UOP-688	
Used Tire #5 - Radial	Untreated	UOP-62	Armor-All	LR-1588	UOP-288
*Used Tire #6 - Radial	Untreated	ZR-2550	UOP-88	UOP-688	

*Tires were sectioned into quarters due to only three (3) preservatives.

TABLE V

COMPARISON TABLE OF AMOUNT OF CRACKING BETWEEN EXPOSED SIDE AND THE REVERSE SIDE OF TIRES

	1 Control	2 UOP 62	3 Armor-All	4 LR-1588	5 UOP-288	1 Control	2 ZR-2550	3 UOP 88	4 UOP 688
#1 New Tire-Exposed Side	4	4	4	4	3				
Reverse Side	3	2	3	3	1				
#2 New Tire-Exposed Side						4	3	3	3
Reverse Side						3	3	1	1
#3 New Tire-Exposed Side	3	2	4	2	4				
Reverse Side	1	1	1	1	1				
#4 New Tire-Exposed Side						3	3	3	3
Reverse Side						1	1	1	1
#5 New Tire-Exposed Side	2	2	4	1	1				
Reverse Side	1	1	1	1	1				
#6 New Tire-Exposed Side						1	3	2	1
Reverse Side						1	2	1	1
#1 Used Tire-Exposed Side	4	2	4	3	4				
Reverse Side	3	1	3	2	1				
#2 Used Tire-Exposed Side						4	3	3	3
Reverse Side						3	3	3	3
#3 Used Tire-Exposed Side	3	3	3	3	3				
Reverse Side	1	1	1	1	1				
#4 Used Tire-Exposed Side						4	4	4	4
Reverse Side						3	3	2	2
#5 Used Tire-Exposed Side	1	1	4	1	1				
Reverse Side	1	1	1	1	1				
#6 Used Tire-Exposed Side						1	1	1	1
Reverse Side						1	1	1	1

Numbers assigned according to severity of cracking.

1 = No cracking
2 = Light cracking
3 = Moderate to severe cracking
4 = Very severe cracking

TABLE VI

PERCENT CHANGE IN DETERIORATION BETWEEN DIRECTLY EXPOSED SIDE AND THE REVERSE SIDE - ASSIGNED NUMBERS FROM TABLE V USED FOR COMPARISON

	Standard Deviation Intervals Low Point	Mid Point	High Point	Midpoint % Change
#1 New Tire-Exposed Side	3.32	3.75	4.18	=66.7% more deterioration on exposed side.
Reverse Side	1.43	2.25	3.07	
#2 New Tire-Exposed Side	3.00	3.00	3.00	=79.6% more deterioration on exposed side.
Reverse Side	0.73	1.67	2.61	
#3 New Tire-Exposed Side	2.00	3.00	4.00	=200% more deterioration on exposed side.
Reverse Side	1.00	1.00	1.00	
#4 New Tire-Exposed Side	3.00	3.00	3.00	=200% more deterioration on exposed side.
Reverse Side	1.00	1.00	1.00	
#5 New Tire-Exposed Side	0.59	2.00	3.41	=100% more deterioration on exposed side.
Reverse Side	1.00	1.00	1.00	
#6 New Tire-Exposed Side	1.18	2.00	2.82	=50.4% more deterioration on exposed side.
Reverse Side	0.86	1.33	1.80	
#1 Used Tire-Exposed Side	2.42	3.25	4.08	=85.7% more deterioration on exposed side.
Reverse Side	0.92	1.75	2.58	
#2 Used Tire-Exposed Side	3.00	3.00	3.00	=0.0% no significant difference.
Reverse Side	3.00	3.00	3.00	
#3 Used Tire-Exposed Side	3.00	3.00	3.00	=200% more deterioration on exposed side.
Reverse Side	1.00	1.00	1.00	
#4 Used Tire-Exposed Side	4.00	4.00	4.00	=72.4% more deterioration on exposed side.
Reverse Side	1.85	2.32	2.80	
#5 Used Tire-Exposed Side	0.45	1.75	3.05	=75.0% more deterioration on exposed side.
Reverse Side	1.00	1.00	1.00	
#6 Used Tire-Exposed Side	1.00	1.00	1.00	=0.0% no significant difference.
Reverse Side	1.00	1.00	1.00	

TABLE #VII

DAYS TO INITIAL CRACKING OF NEW EXPOSED TIRES

TYPE PRESERVATIVES APPLIED TO CORRESPONDING SECTIONS

	1 Untreated (Control)	2 UOP-62	3 Armor-All	4 LR-1588	5 UOP-288	1 Untreated (Control)	2 ZR-2550	3 UOP-88	4 UOP-688
New Tire #1 Mohawk	120	240	90	180	150				
New Tire #2 Mohawk						150	240	240	240
New Tire #3 Mansfield	195	300	180	UNK	240				
New Tire #4 Mansfield						180	300	300	270
New Tire #5 Goodyear	300	300	210	NC	NC				
New Tire #6 Goodyear						NC	270	330	NC

UNK: Unknown when initial cracking occurred because of rubberized coating. See results of exposed tire test.

NC: No cracking occurred after 360 days exposure.

SURVEY OF RUST DAMAGE TO THE M880 SERIES, 1-1/4 TON TRUCK

DARCOM TASK 79-24A
AMSAA TR-291

JANUARY 1980

HAROLD T. LOOTENS
FIELD EQUIPMENT & TECHNOLOGY DIVISION
US ARMY MATERIEL SYSTEMS ANALYSIS ACTIVITY
ABERDEEN PROVING GROUND, MARYLAND

SURVEY OF RUST DAMAGE TO THE M880 SERIES, 1-1/4 TON TRUCK

SLIDE 1

INTRODUCTION

This paper presents the results of a survey to determine the severity of the rust problem on the M880 series, 1-1/4 ton truck. The adequacy and effectiveness of contractor applied rustproofing is assessed and actions that can be taken to reduce the rate of rusting are suggested. This survey was conducted by the Field Equipment and Technology (FEAT) Division, US Army Materiel Systems Analysis Activity (AMSAA) from April to June 1979.

SLIDE 2

BACKGROUND

In June 1978, at the direction of MG Hardin, TARCOM Commander, a team of personnel from TARCOM, FORSCOM, and AMSAA visited the 25th Infantry Division, Hawaii to assess the degree of rust on several types of vehicles including the M880 series. As a result of this visit, termed "Operation Rustproof", TARCOM initiated a three-phase effort to address the problem of rusting vehicles in the 25th Infantry Division. This three-phase effort, however, did not include any specific actions to remedy the rust problems with the M880 series vehicles.

Under the authority of DARCOM Regulation 70-7, AMSAA conducts periodic R&D Field Liaison visits to tactical units worldwide. The purpose of those visits is to maintain direct contact with Army materiel users in the field in order to surface equipment-related problems, and then provide quick response, low cost solutions to these problems. Since the M880 series vehicle was first fielded in 1976, AMSAA Field Liaison teams have had the opportunity to observe them in thirteen CONUS locations, as well as, in Hawaii, Panama, Alaska, Okinawa, Korea, and Germany.

SLIDE 3

AMSAA personnel were concerned about the fact that the vehicles were rusting. This condition was observed both by the TARCOM team and on the R&D Field Liaison visits. As a result, AMSAA proposed to DARCOM HQ that a survey of the M880 fleet be conducted to evaluate the present degree of rust and assess the adequacy of rustproofing vehicles. Data from this survey might also prove useful to the Vehicle Useful Life Assessment and Sample Data Collection plan being conducted on the M880 series vehicle. In April 1979, DARCOM formally tasked AMSAA to perform such a survey (DRCPA Task 24A, Equipment Rust and Corrosion), as one of a series of logistics tasks in support of the DARCOM materiel readiness responsibility.

SLIDE 4

OBJECTIVES

The objectives of this task were to survey a sample of the M880 vehicle fleet to determine:

(1) the specific areas of the vehicle that are damaged by rust and the severity of the damage,

(2) the adequacy of contractor-applied rustproofing and,

(3) corrective actions that could be taken to improve the situation and prevent similar occurrences in the future especially when commercial vehicles are procured.

SLIDE 5, SLIDE 6

APPROACH

It was decided to survey vehicles as a part of regularly scheduled R&D Field Liaison trips, and to make special trips to other locations only as required to augment these data. A special form was prepared to aid in the collection of data. Vehicles were surveyed on Field Liaision trips to Fort Knox, KY in April 1979 (Lightning and 194th Armor Brigades) and to Germany in June 1979 (3rd Infantry Division). Additional data were obtained in Hawaii in June 1979 (25th Infantry Division) and in Korea in May 1979 (8th Army) by AMSAA personnel on twelve-month assignments there. A special trip was made to Letterkenny Army Depot in June 1979 to gather data on new, unissued vehicles.

No attempt was made to examine all the vehicles at any location or to examine only those vehicles that were rusted. The selection of vehicles was completely random and based only upon availability. To assure consistency in the evaluation of the amount of rust on the vehicles examined, various degrees of rust were established and survey personnel were taught how to distinguish between them. Almost all the data were collected by AMSAA personnel and, in some cases, the same individuals examined vehicles at more than one location. In this way, the grading of the severity of rust was consistent from vehicle-to-vehicle and location-to-location.

To aid in the reduction of data, the information was transferred from the individual data sheets to punched cards and computerized. Once this was accomplished, it was an easy task to analyze and correlate the data in a variety of combinations.

SLIDE 7, SLIDE 8

VEHICULAR DESCRIPTION

The M880 series vehicle, the first vehicle purchased under the "WHEELS" study, is a commercial truck. It is basically the Dodge 1-1/4 ton, 4-wheel drive pickup truck, with only the paint distinguishing the Army truck from the commercial version. Both 4-wheel and 2-wheel drive are included in the M880/890 series. The vehicle cab comes equipped with a fiber floor mat covered by a thin rubber mat.

The M880 series is available in twelve models, all with the same basic chassis design. Its special uses include communications shelter carrier, ambulance, telephone maintenance, and general purpose cargo truck. The M880 was procured to be a less complex, less expensive companion truck to the M561 (GAMA GOAT). The M561 is designed for use as a highly mobile, multi-purpose vehicle operating forward of the brigade rear, while the M880 is meant to be used principally behind the brigade rear.

The various models available in the M880/890 series are as follows:

(1) M880 - a 4x4 cargo truck.

(2) M881 - A 4x4 cargo truck equipped with a 60 amp/24 V generating system kit, in addition to the vehicle's normal 12 V electrical system.

(3) M882 - A 4x4 cargo truck equipped with a 60 amp/24 V generating system kit and a communications kit, in addition to the vehicle's normal 12 V electrical system.

(4) M883 - A 4x4 cargo truck with a S250 shelter kit installed in the cargo box and a 60 amp/24 V generating system kit, in addition to the vehicle's normal 12 V electrical system.

(5) M884 - A 4x4 cargo truck with a S250 shelter kit installed in the cargo box and a 100 amp/24 V generating system kit, in addition to the vehicle's normal 12 V electrical system.

(6) M885 - A 4x4 cargo truck with a S250 shelter kit installed in the cargo box.

(7) M886 - A 4x4 ambulance.

(8) M888 - A 4x4 truck with a telephone maintenance body installed.

(9) M890 - A 4x2 cargo truck.

(10) M891 - A 4x2 cargo truck equipped with a 60 amp/24 V generating system kit, in addition to the vehicle's normal 12 V electrical system.

(11) M892 - A 4x2 cargo truck equipped with a 60 amp/24 V generating system kit and a communications kit, in addition to the vehicle's normal 12 V electrical system.

(12) M893 - A 4x2 ambulance.

SLIDE 9

VEHICLE TYPE

As indicated earlier, vehicles were examined at five locations. These locations will be referred to in this paper as follows:

Letterkenny Army Depot	LEAD
Fort Knox	KNOX
Korea	KREA
Germany	GERM
Hawaii	HWAI

The Depot Support Command (DESCOM), Chambersburg, PA furnished data to AMSAA on the worldwide distribution of M880 series vehicles. These data are classified; therefore, only percentages are used here when referring to quantities of vehicles. The size of the AMSAA sample is shown as a percentage of worldwide assets or a percentage of vehicles examined at a specific location. Data are shown as a percentage of vehicles in a specific column.

The total number of vehicles surveyed represent 3.3% of the worldwide assets. SLIDE 9 shows how many of each model were examined at the various locations. As far as the rust survey is concerned, the model designation is not of major importance since the entire M880 series is built on the same chassis. These data are given only to indicate the wide cross-section of vehicles surveyed, which represents many different conditions of use and varying potential for the formation of rust.

It should be noted that approximately 6.4 percent of the worldwide M880 series assets are still in depot storage as of December 1979 (2.6 percent CONUS, 3.8 percent OCONUS).

SLIDE 10

VEHICLE MILEAGE

SLIDE 10 shows the average mileage of the vehicles at each location and of vehicles at the four field locations, excluding Letterkenny Depot. The vehicles observed in Germany have the highest mileages, followed by those in Korea, Fort Knox, and Hawaii in that order. The high mileage in Germany is because of the large distance between bases there and the good roads, especially the AUTOBAHN. As far as the individual models are concerned, the M880 shows the most mileage of those vehicles at the field sites, except at Fort Knox where the M882 is higher. In Korea, Germany, and Hawaii, the M890 shows the second highest mileage. This is not surprising since the M880/890 models are the standard cargo truck, and these models would get more use than the specialized ones.

Predicted usage for the M880 series vehicle was 4000 miles per year. Using the average vehicle age of 33 months, the average expected vehicle mileage would be approximately 11,000 miles per year. The overall average (w/o LEAD) is 8997 miles, slightly lower than what would be predicted. This is because 59 percent of the sample (w/o LEAD) is made up of vehicles in Hawaii, the majority of which have relatively low mileage. In fact, 53 percent of this group (w/o LEAD) have traveled less than 5000 miles.

Mileage alone, however, is not truly representative of the amount of rust on a vehicle. Vehicular age must also be considered. Based on manufacturing date, the average age of all vehicles surveyed is 30.6 months while the average age of all vehicles (w/o LEAD) is 33.4 months. These values were computed using May 1979 as the current month, since the data for this survey were collected between April and June 1979. The actual date that these vehicles were delivered to the field was not obtained. If a constant time for each vehicle to move from the manufacturer through the depot to the field is assumed, however, then the manufacturing date, which is stamped on the vehicle data plate, can be related to time of use in the field. As expected, the older vehicles are in the field, while the newer ones are still in the depot. Hawaii, Germany, and Korea all received vehicles from the early production in 1976, and then Hawaii received another shipment of vehicles manufactured in 1977. Of the vehicles surveyed that were manufactured in 1977, 73.6 percent were at Letterkenny.

SLIDE 11

ASSESSMENT OF RUST DAMAGE

The primary objective of this survey was to determine the amount of rust on specific areas of the vehicle. The specific areas selected for inspection were the cab floor pan, tailgate, cargo bed, front fenders, air intake plenum, firewall gutter and the fender-firewall-plenum junction. These areas were considered significant from the standpoint of safety, usefulness and appearance of the vehicle. They were also areas that could be easily examined. Rust on the cab floor pan and tailgate was recorded only as YES or NO, while rust in the other areas was assessed as to severity and recorded as NONE, SLIGHT, MODERATE, HEAVY, or PERFORATED.

This SLIDE shows a summary of the most heavily rusted vehicle areas. Note that 87 percent of all the vehicles at the field sites had wet floor mats. Still worse is the fact that one-third of the vehicles at the depot had the same problem, and these are new vehicles not yet issued to troop units.

SLIDE 12

RUSTPROOFING

One of the objectives of this study was to determine the adequacy of the rustproofing that was applied to the vehicles by the manufacturer. Many of the areas that were rustproofed are hidden from view, and the quality of the treatment in these areas could not be assessed. One area that is essentially hidden but yet can still be easily examined is the reinforcing web under the hood. This web was closely examined on each vehicle as were the firewall and the underside of the fenders, cargo bed, and cab floor.

This SLIDE shows the absence of rustproofing in the areas mentioned (i.e., the percentage of vehicles that DID NOT show evidence of rustproofing). Note that 77 percent of all vehicles surveyed were not rustproofed under the hood web. This means that, even though the rustproofing spray tool was inserted into the small holes at the ends of the X-shaped web, the rustproofing compound covered only a small area adjacent to the holes.

The lack of rustproofing under the web will contribute to premature rusting of the web and hood section. Even more important, however, is the fact that this condition raises a question about the quality of the rustproofing throughout the rest of the vehicle, especially in the hidden areas not readily accessible to view. It is likely that the inner door panels, inner fender panels, and other inclosed vehicle areas may have been only partially rustproofed and will suffer premature damage.

SLIDE 13

WATER LEAKAGE

In an effort to determine how and where water was getting into the cab of the M880 series vehicles, a series of tests was conducted by AMSAA at Letterkenny Depot in October 1979. Six vehicles, previously identified in this survey as having wet floor mats and rusted floor pans, were chosen for the leakage test. All the test vehicles had been driven less than 50 miles.

To begin the test, the floor mats in the test vehicles were pulled back and the cab floor was allowed to dry. It might be noted here that several of the vehicles did not have the covers on the cab floor mounting bolt access holes, located under the floor mat on each side of the cab. Once the floor pan was dry, the windows and doors were all tightly closed.

Originally, it was planned to simulate rainfall by using hoses. On the afternoon the test was planned to start, however, it began to rain and continued to rain intermittently for the next 10-12 hours. During this period, 0.8 inches of rainfall was recorded at a local weather station. The next morning, the six test vehicles were examined and water was observed in each one on the floor pan adjacent to the side cowl and door sill junction.

The floor pans were again dried off and the vehicles were subjected to artificial rainfall by directing water high into the air from a hose and allowing it to fall on the vehicles. During this period, the wind was blowing at 10-20 mph and these conditions created an ideal simulation of windblown rainfall. During this part of the test, the vehicles were examined at 5-minute intervals. In some cases, test personnel remained inside the vehicles to observe exactly where the water was coming in.

SLIDE 14

WATER LEAKAGE RESULTS

It was determined that water enters the cab area via the door gaskets around the top of the door. As the water travels around the perimeter of the door, it gets under the gasket seat and leaks into the cab at the bottom of the door, where it collects on the cab floor near the door sill. This leakage is the result of a defective or improperly fitted gasket. In some of the test vehicles, the gasket did not appear to be installed with adhesive and could be easily pulled away from the cab door frame.

Water also enters the inner door panel via the door glass. Water runs down the outside of the glass into the inside of the door panel and enters the cab along the lower edge of the interior vinyl trim panel. This is apparently caused by improper positioning of the water deflector

inside the door panel. Instead of diverting the water toward the outside of the door panel, the deflector is allowing the water to run along the inside of the panel and leak through at the bottom edge of the vinyl trim panel. In addition, the vent windows do not fit correctly, allowing water to enter the cab.

During the water leakage test, several holes were observed in each vehicle located in the area where the door hinges are mounted to the cab body. Some of these holes were taped over; others were not covered in any way. Water which flows down the door jam in this area can enter these holes and flow to the bottom of the inside lower cab panel. Here the water may enter the cab or else collect inside the lower edge of the cab panel near the door sill and lower door hinge, where it can cause premature rusting. There was no rustproofing in the area of the holes in the door jam.

On these six test vehicles, as on almost all of the vehicles surveyed, the fiber mat underneath the rubber floor mat was soggy and beginning to rot. This fiber mat serves as a sponge and soaks up any water that collects on the cab floor. There is very little chance for the mat to dry out under normal use, and consequently, the cab floor pan is constantly wet and soon begins to rust.

SLIDE 15

CONCLUSIONS

Rust Damage

There is a significant problem with rust in the M880 series fleet. It is especially serious in Hawaii and it will get progressively worse unless some corrective actions are taken immediately. As shown earlier, 87 percent of the vehicles surveyed had wet floor mats and 56 percent had rusted floor pans. If only those vehicles manufactured during 1977 are considered (less than 30 months old), 90 percent have wet mats and 63 percent have rusted floor pans. In the majority of these vehicles, the fiber floor mat has already begun to deteriorate and rot. Since this soggy mat is in constant contact with the floor pan it is causing a serious rust problem there, which will result in the floor pan rusting through. When this occurs, the vehicle cannot be driven until the floor pan is repaired.

In the other areas of the vehicle, considering only those conditions of Moderate, Heavy, or Perforated rust, there are serious problems in the firewall gutter (35 percent of the sample) and the fenders (17 percent). In most vehicles, there was standing water in the firewall gutter, which is creating the rust observed even though the gutter has been rustproofed.

If this situation continues, the gutter seam will rust through and allow water to enter the cab area underneath the upper part of the floor mat.

Rustproofing

Rustproofing of the M880 fleet was not thoroughly done. More than 75 percent of the vehicles examined had no rustproofing under the hood reinforcement web, and approximately 13 percent were not rustproofed under the fenders, cargo bed, or cab floor. Furthermore, although this survey did not examine hidden areas, it is reasonable to assume that some of these areas were not completely rustproofed, based on the condition of the hood web.

This lack of adequate rustproofing may be the result of poor workmanship or failure of the manufacturer to properly inspect the vehicles after rustproofing. In either case, some action is required to improve the rustproofing treatment and prevent further damage. This is especially necessary if the vehicles are used in areas having a salt-air environment or in areas where salt is used extensively during the winter on the highways.

Water Leakage

Water is entering the cab around the door gaskets and through the inner door panel via the glass, because the deflector inside the door panel is not positioned correctly. There is also evidence that water may be coming into the cab through miscellaneous holes located where the door hinges are mounted to the cab body.

SLIDE 16, SLIDE 17

RECOMMENDATIONS

To improve the condition of the vehicles still in depot storage and those already issued to field units, the following actions are recommended:

(1) For all vehicles:

a. Remove and discard all fiber and rubber floor mats.

b. Repair and repaint rusted cab floor pans.

c. Repair or replace defective door gaskets and inner door panel water deflectors, and plug miscellaneous holes in the door hinge mounting area.

(2) Those vehicles that are in use where there is a salt-air environment or where salt is used extensively during the winter on the roads should be re-rustproofed. This can be accomplished either by unit maintenance personnel or by a commercial rustproofing contractor in the local area.

To complete this presentation, the following slides show rusted M880 vehicles. These pictures were all taken in Hawaii, and attest to the fact that the rust and corrosion problem is extremely severe in that area.

(SLIDES 18-33, referred to above, are not included in this paper).

SURVEY OF RUST DAMAGE TO THE M880 SERIES, 1-1/4 TON TRUCK

DARCOM TASK 79-24A

AMSAA TR-291
JANUARY 1980

SLIDE 1

BACKGROUND

- TARCOM / AMSAA / FORSCOM VISIT TO HAWAII IN JUNE 1978 TO ASSESS RUST DAMAGE TO VEHICLES.

- AMSAA FIELD LIAISON VISITS WHERE M880 VEHICLES WERE OBSERVED (13 CONUS SITES PLUS HAWAII, PANAMA, ALASKA, OKINAWA, KOREA AND GERMANY)

AFWAL-TR-81-4019

BACKGROUND (CON'T)

- AMSAA PROPOSED RUST SURVEY OF M880 VEHICLES TO DARCOM IN DEC 78. DATA ALSO APPLICABLE TO VEHICLE USEFUL LIFE ASSESSMENT AND SAMPLE DATA COLLECTION STUDY.
- DARCOM TASKED AMSAA IN APRIL 79 TO PERFORM SURVEY AS ONE OF LOGISTICS TASKS.

OBJECTIVE

CONDUCT SURVEY OF M380 SERIES VEHICLE TO DETERMINE EXTENT OF RUST DAMAGE AND ADEQUACY OF RUSTPROOFING.

SLIDE 4

APPROACH

- SURVEY VEHICLES AS PART OF AMSAA FIELD LIAISON VISITS.
- SURVEY VEHICLES IN KOREA AND HAWAII USING ON-SITE AMSAA ANALYSTS.
- SPECIAL VISIT TO SURVEY VEHICLES AT LETTERKENNY DEPOT.
- COMPUTERIZE AND ANALYZE DATA.
- FORMULATE CONCLUSIONS AND RECOMMENDATIONS.

SLIDE 5

VEHICULAR SURVEY SCHEDULE

		NO. OF VEHICLES
• FORT KNOX, 9-13 APR 1979	(KNOX)	21
• KOREA, 1-20 MAY 1979	(KREA)	97
• LETTERKENNY AD, 6-9 JUN 1979	(LEAD)	402
• HAWAII, 1-15 JUN 1979	(HWAI)	418
• GERMANY, 1-16 JUN 1979	(GERM)	168
TOTAL VEHICLES SURVEYED		1106

DESCRIPTION OF VEHICLE

- DODGE 1-1/4 TON COMMERCIAL PICKUP TRUCK, FIRST VEHICLE BOUGHT UNDER "WHEELS" STUDY.
- TWELVE MODELS ALL WITH SAME CHASSIS DESIGN.
- M880 SERIES 4-WHEEL DRIVE.
- M890 SERIES 2-WHEEL DRIVE.
- USED AS CARGO TRUCK, TELEPHONE MAINTENANCE, COMMUNICATIONS SHELTER, AMBULANCE.

SLIDE 7

DESCRIPTION OF VEHICLE (CON'T)

- KITS FOR BLACKOUT LIGHTS, REAR SUSPENSION, ALTERNATOR, CARGO BOX COVER, TROOP SEAT, MILITARY RADIO SUPPRESSION, CARGO TIE DOWN, ARCTIC USE, TOW BAR, TOW PINTLE REINFORCEMENT, HOOD LOCK, STEERING WHEEL LOCK.
- COVERED UNDER 12 MONTH / 12,000 MILE WARRANTY WHICH HAS EXPIRED FOR ALL VEHICLES.

SLIDE 8

TYPE OF VEHICLES

	ALL LOCATIONS	LEAD	KNOX	KREA	GERM	HWAI
M880	27.4*	12.9*	28.6*	31.9*	25.0*	41.9*
M881	0.7	0.5	–	–	–	1.4
M882	35.4	69.4	42.8	12.4	14.9	15.8
M883	3.6	–	–	4.1	8.9	5.0
M884	4.0	0.2	–	8.2	5.4	6.2
M885	12.1	6.5	–	31.9	26.8	7.6
M886	8.8	2.1	28.6	2.2	19.0	12.0
M888	1.1	1.7	–	–	–	1.0
M890	5.7	5.5	–	9.3	–	7.7
M891	0.5	1.2	–	–	–	–
M893	0.5	–	–	–	–	1.4

*PERCENT OF VEHICLES IN THIS COLUMN

SLIDE 9

AVERAGE MILEAGE OF VEHICLES

	ALL LOCATIONS	ALL W/O LEAD	LEAD	KNOX	KREA	GERM	HWAI
M880	11775	14164	105	13239	23465	28650	9071
M881	630	823	50	-	-	-	823
M882	2667	9269	17	15035	11104	18370	4701
M883	3687	3687	-	-	1409	7258	1554
M884	2171	2221	41	-	1208	4693	1676
M885	3212	3965	84	-	5207	4723	1695
M886	5306	5770	85	2685	7766	11794	2205
M888	333	879	22	-	-	-	879
M890	7652	11722	68	-	20435	-	9271
M891	44	-	44	-	-	-	-
M893	3142	3142	-	-	-	-	3142
ALL VEHICLES	5740	8997	37	10993	12755	14307	5891

SLIDE 10

RUST SUMMARY

	ALL W/O LEAD	0-2500 MI. W/O LEAD	<30 MO. OLD W/O LEAD	LEAD ONLY
SAMPLE SIZE	63.6*	34.0	18.6	36.4
FLOOR MAT WET	87**	82**	90**	33**
FLOOR PAN RUSTED	56	49	63	13
TAILGATE RUSTED	17	14	13	1
CARGO BED RUST (M, H, P)	8	5	2	0
FENDER RUST (M, H, P)	17	21	0	0
FIREWALL GUTTER RUST (M, H, P)	35	34	16	7

*PERCENT OF TOTAL SAMPLE
**PERCENT OF VEHICLES IN THIS COLUMN

SLIDE 11

ABSENCE OF RUSTPROOFING ON SPECIFIC AREAS OF THE VEHICLE

	ALL LOCATIONS	ALL W/O LEAD	LEAD	KNOX	KREA	GERM	HWAI
SAMPLE SIZE	(31.4/ 9.6)*	(29.3/ 6.2)	(2.1/ 57.5)	(0.8/ 7.7)	(4.0/ 7.2)	(23.6/ 2.1)	(1.0/ 98.7)
UNDER HOOD WEBS	77**	65**	99**	78**	75**	78**	54**
ON FIREWALL	2	2	1	10	1	2	2
UNDER FRONT FENDERS	13	22	0	19	0	3	32
UNDER REAR FENDERS	13	23	0	10	0	4	33
UNDER CARGO BED	13	22	0	5	10	5	29
UNDER CAB FLOOR	14	25	0	5	11	5	32

*PERCENT OF WORLDWIDE ASSETS AT THIS LOCATION/ PERCENT OF VEHICLES EXAMINED AT THIS LOCATION

**PERCENT OF VEHICLES IN THIS COLUMN

SLIDE 12

WATER LEAKAGE TEST

OBJECTIVE:
- DETERMINE WHERE AND HOW WATER ENTERS VEHICLE CAB.

PROCEDURE:
- SELECT SIX VEHICLES AT LETTERKENNY DEPOT THAT HAVE WET FLOOR MATS & RUSTED FLOOR PANS.
- SPRAY WITH HOSES AND OBSERVE LEAKAGE.

SLIDE 13

RESULTS OF WATER LEAKAGE TEST

- WATER ENTERS AROUND DOOR GASKET AND THROUGH INNER DOOR PANEL.
- WATER ENTERS CAB PANEL THROUGH MISCELLANEOUS HOLES IN CAB BODY/ DOOR HINGE AREA.
- FLOOR MAT SOGGY AND DETERIORATING ON ALL VEHICLES.

SLIDE 14

RECOMMENDATIONS

FOR ALL VEHICLES:

- REMOVE AND DISCARD ALL FIBER AND RUBBER FLOOR MATS.
- REPAIR AND REPAINT RUSTED CAB FLOOR PANS.
- REPAIR OR REPLACE DEFECTIVE DOOR GASKETS AND INNER DOOR PANEL WATER DEFLECTORS, AND PLUG MISCELLANEOUS HOLES IN THE DOOR HINGE MOUNTING AREA.

SLIDE 16

RECOMMENDATIONS (CON'T)

- THOSE VEHICLES IN USE WHERE THERE IS A SALT-AIR ENVIRONMENT OR WHERE SALT IS USED EXTENSIVELY ON THE ROADWAYS IN WINTER SHOULD BE RE-RUSTPROOFED. THIS CAN BE ACCOMPLISHED EITHER BY UNIT MAINTENANCE PERSONNEL OR BY A COMMERCIAL RUSTPROOFING CONTRACTOR IN THE LOCAL AREA.

SLIDE 17

CORROSION OF REDEYE FUSE COMPONENTS

ABSTRACT

Two springs in the REDEYE fuse are steel music wire with a gold plate. This is a classic example of corrosion, a large cathode and a small anode due to the porosity of the gold plate.

This paper then covers the requirement for gold in electronic applications for missile systems. Cost cutting methods and the use of alternate materials are discussed.

This report is about corrosion of gold plated parts used in the electronics of missile systems. First, I will discuss the classic corrosion problem, that is gold plating a steel spring. Second, why is gold used in electronic components and how the amount of gold used may be reduced.

The requirement for gold on two switch springs in the REDEYE fuse is analogous to the TVA dams along the Tennessee River. The dams were designed to control flooding that had been prevalent for years. The desire to generate electric power was added; so on one hand you have a need to keep the water level low and for the second requirement you need to impound the maximum amount of water. The REDEYE boost and impact switch springs were made from steel music wire for the force constant needed. Also, a small current was required for activation of the fuse; therefore, the spring was gold plated for conduction.

The material callout was for steel music wire per ASTM A 228 and the finish note was for gold plate per 1.11.2.1 of MIL-STD-171. That is fifty micro-inches of 99 per cent pure gold. As we all know fifty micro-inches of electroplated gold is going to have pores. All that was needed then for the classic corrosion problem of a large cathode and small anode was an electrolyte. Although the REDEYE fuse was considered a hermetically sealed component, experience has shown that during long storage periods, moisture will invariably enter any component, thus the electrolyte was added. This first figure is one of the impact springs at 20X magnification from a REDEYE fuse that had been in storage. There was corrosion on each coil of the spring. This is typical of each of ten sets of springs examined. The second figure is of two end coils at 100X magnification. The third figure shows one of those coil areas at 500X magnification. The next three figures, 4, 5, and 6, are x-ray maps of this same area at

500X magnification. This first map is for gold, each white dot represents gold. The second shows copper, this indicates the plater applied a copper strike on the steel before plating with gold. The last x-ray map is for iron. Now, if we compare the gold and iron maps (figure 7), you can see the iron shows strongest where the gold is missing.

In the example cited, the recommendation made was to nickel plate the steel wire per QQ-N-290, Type IV, Class I (400 micro-inches thick), then gold plate per MIL-G-45204, Type II, Class I (50 micro-inches of 99 per cent gold). Similar corrosion to that shown in the second view graph has been noted on gold plated connector pins of thermal batteries.

Gold is used in the electronics industry because it is resistance to tarnishing and corrosion at all operating temperatures and in any environment. It is one of the best electrical conductors and can be readily deposited by electroplating, thermal evaporation, or sputtering. Gold is unequalled for contact applications because of its low contact resistance particularly with light loads and low voltages. Thin gold films are extensively used to carry remarkably high currents in the tiny integrated circuits which are the stock in trade of the electronics industry today. Lets look for a moment how the use of gold varied during the early seventies. Table I, an excerpt from Gold Bulletin, Vol 9, 1976, shows three countries that were the major users of gold. You will note that the metric tons of gold used peaked in 1973. The two probably causes, other than cost, for the decline in the amount of gold used may be attributed to the introduction of integrated circuits and the determination that excess gold caused solder joint failures. The first involves improved technology of micro-circuits in electronics that I will not discuss. The second resulted from the brittle solder joints when made with a thick plate of gold. Many

years ago when gold was $36 per ounce its required thickness for protection and wide spread use was not a significant cost of electrical applications in missiles. With the increase of electronic devices incorporated in the current missile systems, the use of gold at about $600 per ounce is a significant cost driver of the missiles.

There are several approaches to reducing the cost of gold in the missile and electronics industries. An article in Product Finishing, March 1980, indicated that controlling the overplating above thickness specifications could reduce costs by $375 to $750 per month in a plating shop using 15 to 30 ounces per month to meet specifications. At MICOM there are some on-going evaluations of other metals and alloys such as palladium, tin-nickel, and nickel either with of without tin or indium as a lubricant for a direct replacement of gold used on printed wiring board edge contacts and cable connector pins. Another area of considerable use, gold is the preferred metal coating for component leads, as it does not corrode under normal conditions. Gold forms extremely brittle alloys with tin in low percentages. The presence of gold-tin alloy in solder joints can cause failure. This is the reason gold must be removed from component leads before soldering. The current industry practice for removal of excess gold is dipping in a solder bath and then wiping prior to either machine or hand soldering. This procedure is not only labor intensive but leads to gold loss or the expense of recovery from the dipping bath. In addition to replacement alloys or metals investigations are being made into the application of high speed pulse plating and other suitable high production plating techniques to edge board contacts and cable connector pins. Cost savings may be realized by improved plating techniques, automatic measurement of gold plating thickness and production machinery to remove excess gold from

leads at high rates and low costs.

At this point, I would like to digress and regress. While looking through old reports for corrosion problems relating to the use of gold, I looked at a copy of the "Missile Overview" presented at the Tri-Service Meeting on Corrosion at the US Naval Academy, November 1969. Two areas of that report impressed me. One of the examples cited by Mr. Edmund Wheelahan related to current corrosion problems. That is, missile systems develop corrosion problems during long term storage that are not found when tested per MIL-STD-810 or MIL-STD-202. Ed's point here was that laboratory tests are of short duration and do not offer the exposure time needed for the external environment to penetrate the "sealed" internal surfaces of components.

The second area was a proposed approach to set up a model or models that would predict what will happen when a weapon system is exposed to a complex environment. That proposal was to define the environment, including such things as pressure, temperature, time,composition; define the variables of the materials and geometry, such as surface conditions, thermal, mechanical, and physical properties, and internal conditions and state of stress; and define the reactions, chemical and electrochemical, that can occur.

Using these parameters, a mathematical model can be constructed using thermodynamics to define equilibrium conditions and reaction rates (including diffusion through protective systems) to define the kinetics. If successful, the benefits include a systematic and rapid analysis of complex corrosion problems, corrosion-free deisgn, and of considerable importance, the use of a language that design personnel understand and have faith in. I believe that statement is of most importance because until we begin having corrosion-free designed systems, we are doomed to correcting problems after-the-fact.

The question I would put to this group today is whether any of the Services represented here have initiated an effort to develop corrosion models? If so, what has been accomplished and are copies of reports on such efforts available?

TABLE I

GOLD (Metric Tons) Used in Electronics

	1970	1971	1972	1973	1974	1975
United States	44.8	42.8	41.2	61.6	44.0	20.4
Japan	18.1	20.1	22.5	26.0	15.0	17.1
Germany	10.0	8.0	11.0	15.0	12.0	8.0
All Other Nations	18.6	17.4	33.3	25.3	23.1	19.7
TOTAL	91.5	88.3	108.0	127.9	94.1	65.2

From Gold Bulletin, 1976

REFERENCES

1. Corrosion Examination of REDEYE Fuse Components, Technical Report E-78-5

2. Gold Bulletin, Volume 9, 1976

3. Product Finishing, March 1980, Saving Gold by Gerry Bush

4. Missile Overview, Presentation at the Tri-Service Meeting on Corrosion at the US Naval Academy, November, 1969

Figure 1. 20X impact switch spring.

Figure 2. 100X higher magnification view of the lower portion of Figure 1.

Figure 3. 500X higher magnification of the impact switch spring shown in Figure 2.

Figure 4. 500X gold x-ray map of Figure 3 (the white dots represent gold).

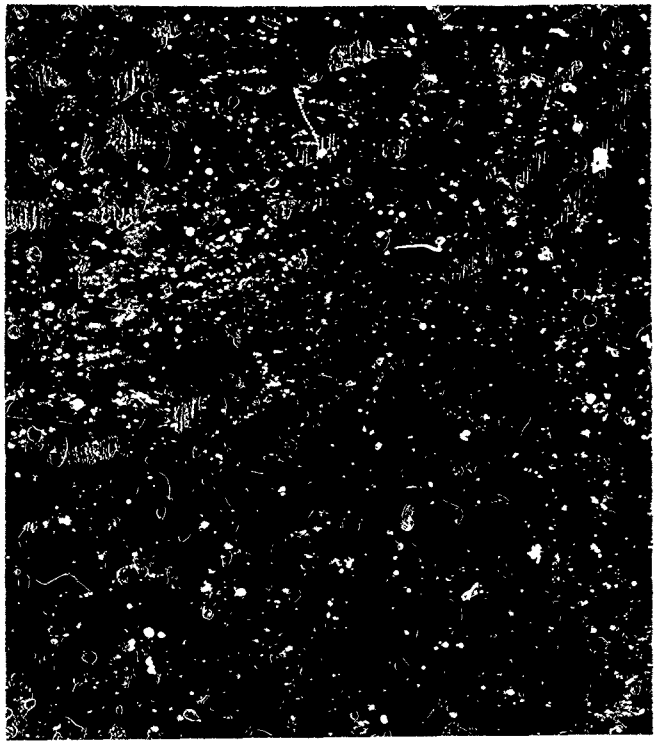

Figure 5. 500X copper x-ray map of Figure 3 (the white dots represent copper).

Figure 6. 500X iron x-ray map of Figure 3 (the white dots represent iron).

Figure 7. 500X iron x-ray map of Figure 3 (the white dots represent iron).

Figure 7. 500X gold x-ray map of Figure 3 (the white dots represent gold).

Biography

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Paint Compatibility with Double Base Propellant

TRI-SERVICE CORROSION CONFERENCE 5-7 November 1980

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TITLE: "Corrosion problems in the US Army BLACK HAWK Helicopter"

ABSTRACT: This paper describes several corrosion-related problems observed on a US Army BLACK HAWK helicopter at Ft. Rucker, Alabama. Descriptions of the BLACK HAWK, the corrosion prevention plan for this helicopter, and the specific types of corrosion involved in the situations noted at Ft. Rucker are presented.

Both environmental and design defects are the general causes of the recorded BLACK HAWK corrosion problems. These defects have been minimized through application of the procedures described in the corrosion prevention plan for the BLACK HAWK.

None of the problems described in this paper, with exception of the main landing gear drag strut failure, are serious. Resolutions to these defects have been developed by the manufacturer of the BLACK HAWK for all of the problems described.

Overall effectiveness of the BLACK HAWK in maintaining a reliable readiness posture has not been compromised by these corrosion problems, primarily due to application of contemporary corrosion control procedures through the corrosion protection plan that has been developed for this helicopter system.

1. DESCRIPTION OF THE BLACK HAWK

The BLACK HAWK helicopter, model number UH-60A, is a US Army transport system manufactured by the Sikorsky Aircraft Division of United Technologies Corporation. This system is designed to convey a fully-equipped squad of eleven men with a three-man crew (1). Primary missions of the BLACK HAWK include tactical transport of Army troops and necessary supplies and equipment for combat and combat-support operations (2). Combat support, in the primary BLACK HAWK mission, includes re-positioning of troops to reinforce, as well as replacing and resupplying units in contact with enemy forces. The BLACK HAWK also is designed to complete secondary missions, such as aeromedical evacuation and administrative transport of command personnel and troop units.

Drawings of the BLACK HAWK are presented in Figures 1 and 2.

II. THE BLACK HAWK CORROSION CONTROL PLAN

Within AVRADCOM, the effort for corrosion control in the BLACK HAWK includes active monitoring of this helicopter system to assure strict compliance to the "Finishes and Coatings Specification and Corrosion Control Plan" (3). Since AVRADCOM's implementation of this plan for the BLACK HAWK, problems due to corrosio have been minimal. The original plan was written in 1972 and was revised in 1978.

The corrosion control plan provides a specific framework for the prevention and control of corrosion and materiel deterioration in the BLACK HAWK. The bulk of the plan consists of generalized requirements for the protection of the overall helicopter system's internal and external surfaces, as well as instructions for pro tection of specific parts. For example, the general system requirements for paint coatings recommend the utilization of an epoxy-polyamide primer meeting MIL-P-2337 (4). Several topcoats, including those conforming to either MIL-L-19538 (5), an acrylic nitrocellulose lacquer, MIL-C-22750 (6), an epoxy polyamide-based coating, or MIL-L-46159 (7), an acrylic lacquer, are specified in the plan. The Army is pr ently using the acrylic applications for topcoat protection of exterior surfaces o the BLACK HAWK. For the application and control of all organic finishes applied i manufacturing and maintenance of the BLACK HAWK helicopter, the plan states that MIL-F-18264 (8) is the governing specification.

The plan for prevention of deterioration in the BLACK HAWK includes a thorough section dealing with the protection of specific parts. Specifications that outlin procedures for preserving these components are cited throughout this section of th plan. Some of the processes dealt within this section of the plan include metal finishing, cleaning, and surface treatment. A general military specification for the protection of aerospace weapons systems components and spare parts (MIL-F-7179 (9) is prescribed within this plan and is applicable to specific, as well as gener system, components.

The implementation of corrosion protection procedures is covered in depth in the latter portion of the corrosion control plan. This phase of the plan designates requirements for assembly and installation of BLACK HAWK components, and it outlines and describes various insulation techniques for corrosion protection under various degrees of corrosive conditions. One of these methods, for example, covers the utilization of corrosion-protective compounds for the insulation of moving parts and frequently-disassembled parts

In summary, the corrosion control plan has contributed significantly to the maintenance of reliability and mission readiness in the BLACK HAWK. The plan was revised in 1978 in order to include state-of-the-art corrosion prevention technology within the design of the system, as well as to delete either outdated or ineffective corrosion control techniques. Continuous review of the plan, both by AVRADCOM and Sikorsky engineers, has made a positive contribution to the gradual improvement of the overall reliability and mission-oriented readiness posture of the BLACK HAWK.

Revision and monitoring of the plan also has been an important contribution toward averting repetitive catastrophic mechanical failures while the BLACK HAWK has been in service.

III. THE FT. RUCKER INVESTIGATION

The importance of the BLACK HAWK corrosion control plan in averting serious materiel deterioration problems was illustrated during a recent inspection of one of these helicopters at Ft. Rucker, Alabama. Photographs were taken of areas indicating either initiation or propagation of corrosion on a BLACK HAWK helicopter with 1,000 hrs. of flying time.

None of the Ft. Rucker observations on BLACK HAWK materiel deterioration were considered serious. That is, the general reliability and mission readiness of this helicopter system were not adversely affected because of these problems. Most of the corrosion-related shortcomings, including the drag strut failure, either have been or are in the process of being rectified through design technology improvements and by application of product assurance procedures within the framework of the corrosion prevention and control plan for the BLACK HAWK.

IV. REVIEW OF BLACK HAWK CORROSION PROBLEMS

A. Ft. RUCKER OBSERVATIONS:

Cadmium-plated steel screws in the lower portion of the BLACK HAWK's windshield wiper blades indicated slight corrosion. The degree of brownish discoloration, due to formation of iron oxides on these parts, did not reflect a severe corrosive tendency.

Because these parts are situated on the external surface of the helicopter, they are exposed continuously to the ambient environment and sometimes must endure adverse weather conditions.

The solution to this problem is to increase the thickness of cadmium plating on these parts.

2. Paint Coating Deficiencies:

Peeling and cracking of the acrylic paint coating system was observed during examination of the 1,000-hr BLACK HAWK at Ft. Rucker. This was noted on the cargo door on a section of the upper cowling of the helicopter body and on the main rotor tip caps. For example, on the surfaces of some of the tip cap bodies, cracking of the applied coating was observed.

For corrosion protection on these parts, an epoxy primer coating in conformance with MIL-P-23377 and an infrared (IR) acrylic lacquer topcoat (MIL-L-46159) are applied.

In this situation, as in the case of the windshield wiper blade corrosion, we are dealing with environmental factors. Exposure to extreme weather conditions and foreign objects (sand, dirt, etc.) are definite factors to be considered in connection with the deterioration of these coatings.

This problem can be resolved only by conversion to a better paint system. The Army is considering the application of polyurethane-based topcoats for its helicopters.

These coatings have been shown to be more durable than presently-used acrylic systems. If adopted by the Army, polyurethane paints will significantly enhance the external surface corrosion protection required for the BLACK HAWK. This is substantiated by a report (10), published in a 1979 study by Arthur D. Little, Inc. In this document, a review of the comparative field performace of polyurethane systems meeting MIL-C-81773 (11) and acrylic lacquers conforming to MIL-L-81352 (12) is presented. One of the conclucions of this report was that MIL-C-81773 polyurethane paints require less touchup and, therefore, less maintenance than MIL-L-81352 acrylics. The study also indicated that polyurethane coatings conforming to MIL-C-81773 confer better weathering and cleaning properties on exterior surfaces in comparison to MIL-L-81352 acrylic lacquers.

3. Surface Deterioration of the Main Rotor Tip Cap:

The area between the leading edge and body of the BLACK HAWK's tip cap indicated surface deterioration near the nickel erosion strip leading edge. One of the causes of this problem is erosion of the fairing material of the tip cap. This is because the maximum main rotor blade rotation is 725 ft/sec. Particle impingement upon the the blades at or near this speed contributes to the gradual wearing of the fairing surface.

Another contribution to this instance of deterioration is erosion of the sealant material between the leading edge of the tip cap and the tip cap body.

The tip caps, which are made of Kevlar, have two holes drilled into them. The purpose of these holes is to drain any water within the blades through the centrifugal force of the rotating blades. However, the process of drilling the holes exposes Kevlar fibers that swell in the presence of water and close the holes. Consequently, water accumulates, and the main rotor blades could become unbalanced. Also, excessive vibratory effects would develop in the blades. This problem can be

eliminated by sealing the Kevlar material to prevent water adsorption to the fibers.

4. CORROSION IN THE DROOP STOP HARDWARE

In the vicinity of the main rotor section of the BLACK HAWK, the droop stop bolts and springs showed some oxidation. The steel bolts on these components are cadmium plated, and they serve as an attachment for the droop stop springs. This problem is still under review.

5. MAIN ROTOR PITCH LINK AND DAMPER BOOT CORROSION

The polymeric boots on the main rotor pitch link were found to be collecting water. This induced corrosion on the bearings that are covered by the boots. An identical problem exists in the main rotor damper boots, in which an accumulation of water and tearing of the boots were observed (Fig. 3).

Boots are used on these parts for the purpose of preventing moisture and dirt from accumulating in the vicinity of the bearing surface. This design was expected to minimize corrosive deterioration of the pitch link and damper bearings. Field observation of the BLACK HAWK, however, indicated that the boots produced the opposite effect. Moisture was entering and remaining inside the boots. Elimination of these boots on the BLACK HAWK's pitch link and damper is the solution to this problem.

6. THE MAIN LANDING GEAR DRAG STRUT FAILURE

The drag strut assembly (Fig 4) of the BLACK HAWK main landing gear failed through one of two brake line holes within the strut. Stress corrosion cracking (SCC) is the primary cause of this failure.

The strut consists of 300M steel hardened to Rockwell C 53 to 56. The design also includes shot peening over the entire length of the drag strut, as well as vacuum cadmium plating, for corrosion protection.

This failure developed because water collected on the strut, on top of the lower brakeline hole, to a depth of about one inch. SCC originated at the lower brakeline hole from a corrosion pit of approximately 0.010 inch depth. Also, the plugs used to seal the brakeline holes did not fill the entire cavity in the strut, permitting water to attack the poorly protected metal surface on the sides of the opening.

A solid plug for the brakeline holes (a plug that completely fills the brakeline hole) is one modification that has been implemented for prevention of similar strut failures.

Another solution includes designation of the drag strut as a critical part, which means that the strut would be inspected completely on a specific requirement, such as shot peening, during the manufacturing process.

This problem also can be avoided through application of a better cadmium plate, and by addition of a resin coating over the cadmium plating. In the future, installation of the brakeline outside of the strut will eliminate the need for holes in this part.

V. CONCLUSIONS:

With exception of the main rotor blade droop stop hardware, all of the problems illustrated here have been resolved through application of current corrosion control measures of the BLACK HAWK helicopter. The corrosion control plan has assumed a significant role in the application of these corrective procedures.

Most importantly, the plan for averting corrosion in the BLACK HAWK system has minimized incidences of serious failure in the helicopter. This has enhanced the overall effectiveness of the BLACK HAWK in completing its primary and secondary missions for the Army.

The process of combating corrosion in the BLACK HAWK is a continuous one. As new techniques for preventing materiel deterioration in this helicopter are developed, they will supersede outdated methods for corrosion control in the helicopter design. Therefore, the corrosion control plan for the BLACK HAWK helicopter is expected to continue to be important in helping to maintain this system in a reliable readiness posture.

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12. Military Specification MIL-L-81352 (AS) and Amendment 1, "Lacquer, Acrylic (for Naval Weapons Systems)", Navy-AS, 31 Jan 73.

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The auther expresses his appreciation to Messrs. Bill Schlenk, Tom Murphy, Pete Konieczny, Frank Canzolino, Bob Tynan, and Bill Reinfelder of Sikorsky Aircraft and Messrs. Bill McClane, Philip Haselbauer, Al Winn, Jim Fay, Larry Doyle, Bill Brunson, Ken Nelson, Windel Baker, Jack Walkenhorst, and Jim Wilson of AVRADCOM for their generous technical asssitance during the preparation of this paper.

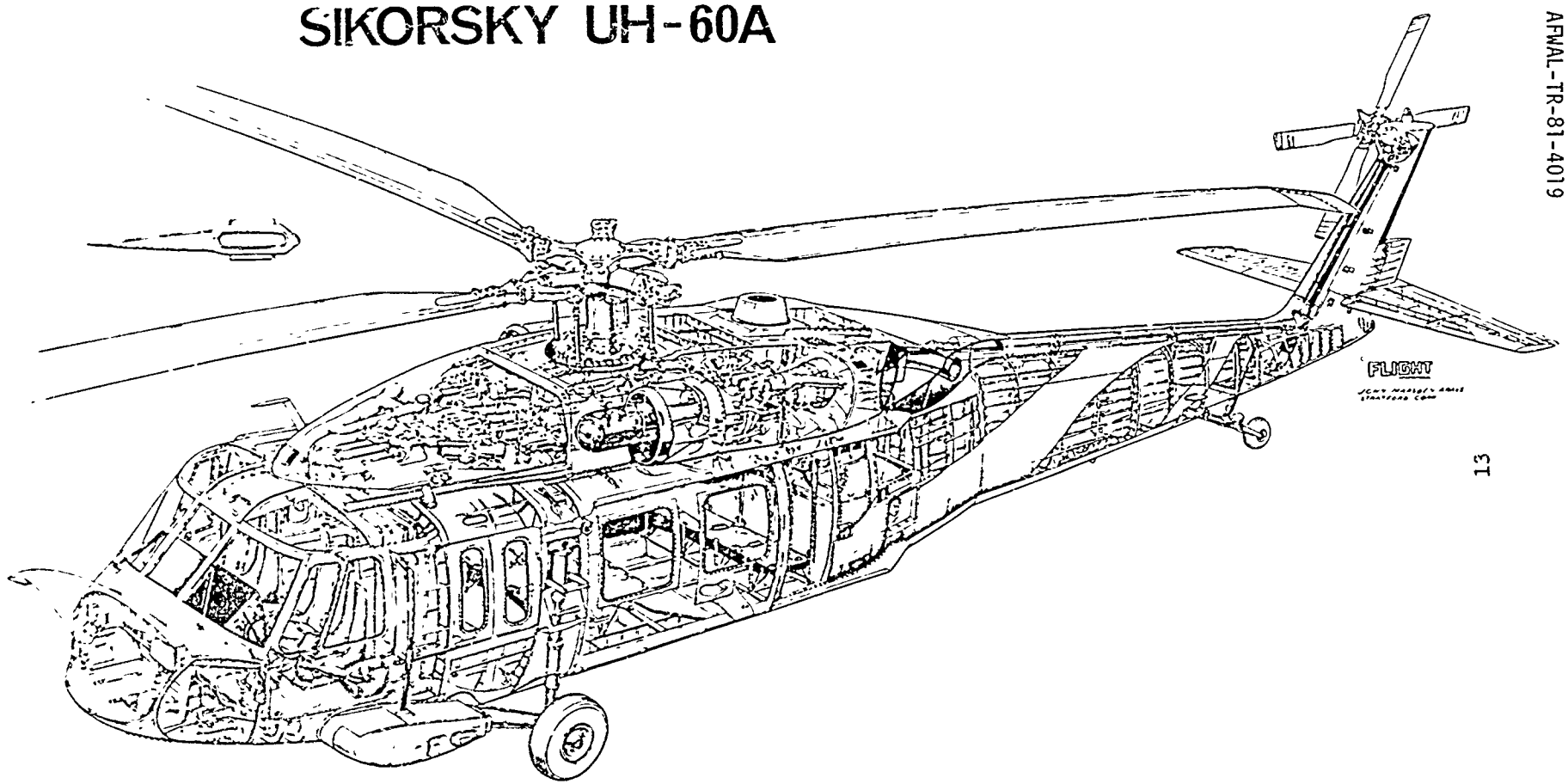

Fig. 1. The UH-60A BLACK HAWK helicopter.

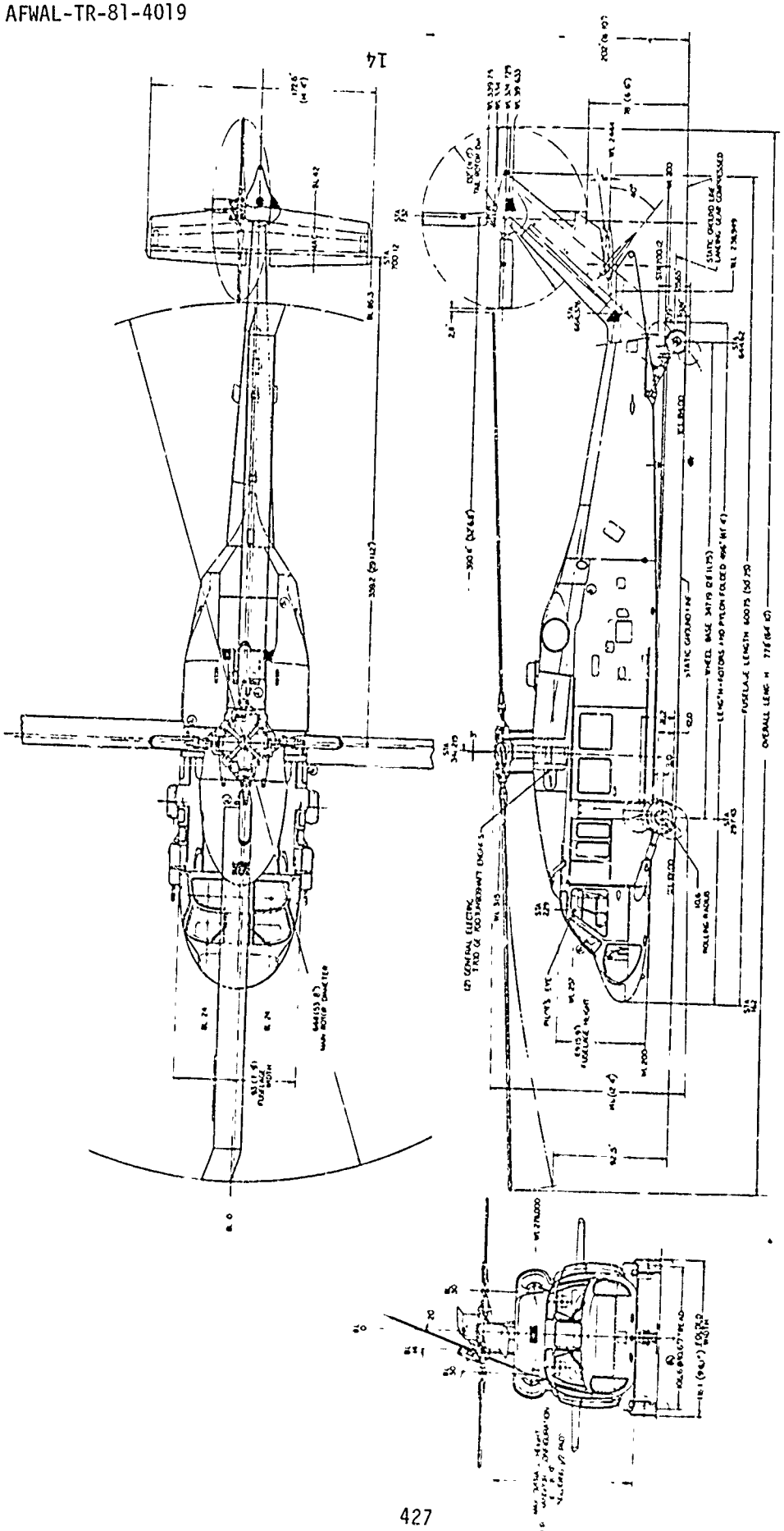

Fig. 2. Engineering diagrams of the BLACK HAWK helicopter.

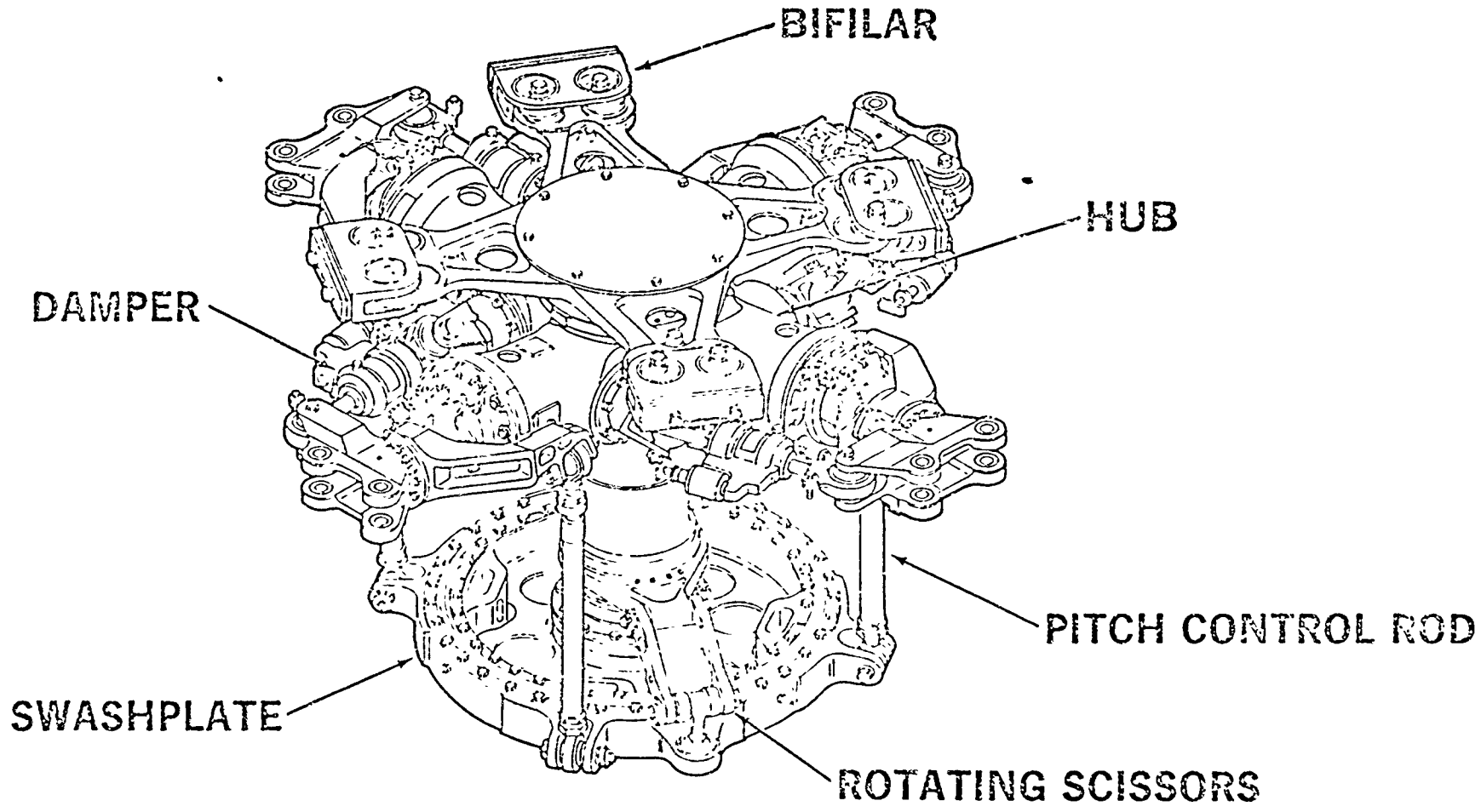

Fig. 3. The main rotor head assembly of the BLACK HAWK helicopter.

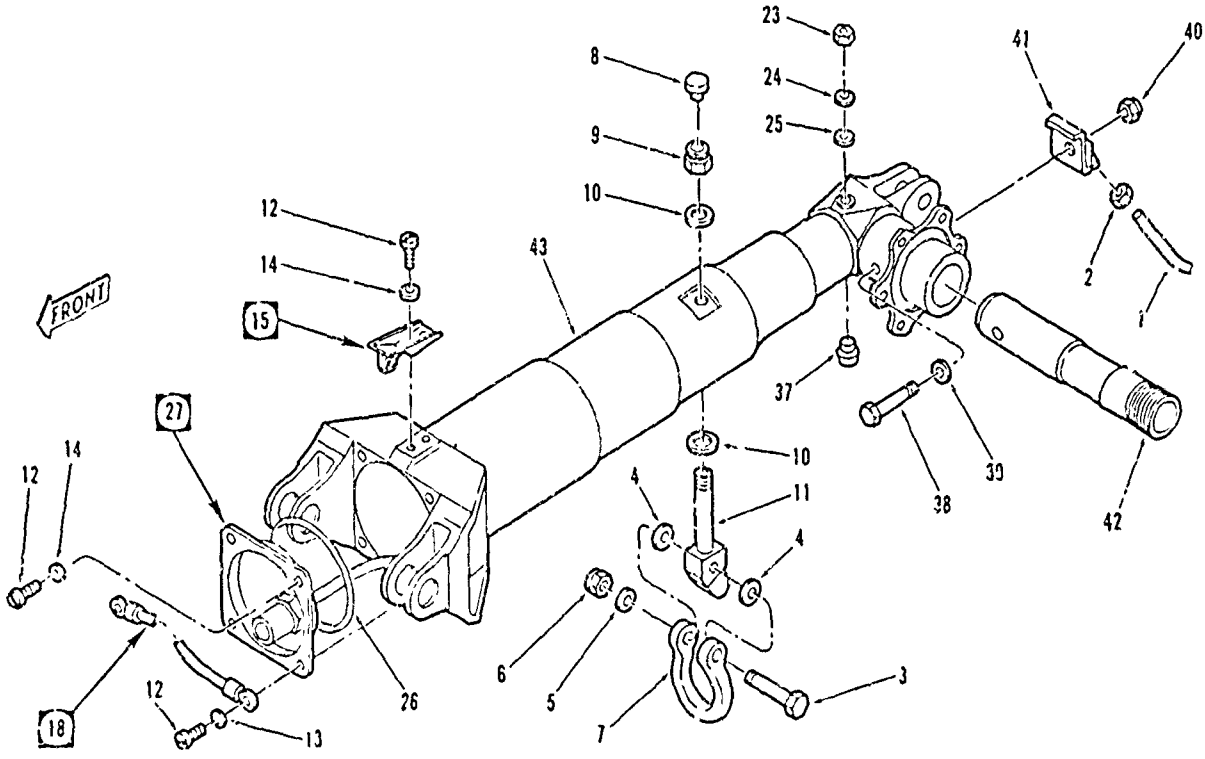

Fig. 4 The BLACK HAWK helicopter main landing gear assembly.

ARMY EXPERIENCE WITH SILICONE BRAKE FLUIDS

BY
JAMES H. CONLEY

ABSTRACT

A program to evaluate silicone brake fluids for use in military vehicles operating in various climatic conditions was begun in 1967. After 6 years of laboratory testing and numerous improvements in the characteristics of these fluids, a vehicle field test was initiated in the spring of 1973. Three candidate silicone fluids were selected and installed in M151 1/4-ton cargo vehicles, and M-715 1 1/4-ton vehicles operating at the Tropical Test Center (TTC), Panama Canal Zone, the Yuma Proving Ground (YPG), Arizona, and the Arctic Test Center (ATC), Fort Greeley, Alaska. Brake parts were inspected after 1 year of operation, and all parts were removed and inspected after 2 years of operation. After 2 years of service at TTC and YPG, the two water intolerant silicone fluids were significantly better than the water tolerant silicone fluid and the conventional VV-B-680 fluid. At ATC, the water intolerant silicone fluids were removed from test after 8 months due to possible crystallization at temperatures below -50°F, and two new silicones were installed. The new low temperature silicones were superior to the MIL-H-13910 arctic brake fluid after 1 year of service.

INTRODUCTION

The U. S. Army for many years has used three types of automotive hydraulic brake fluids. These fluids are covered by specifications VV-B-680, "Brake Fluid Automotive,"(1), for operations ranging from plus 55°C to minus 30°C; MIL-H-13910, "Hydraulic Fluid, Polar Type, Automotive, All-Weather" (2), for operation to minus 55°C; and MIL-P-46046, "Preservative Fluid, Automotive Brake System and Components" (3), for brake systems of vehicles in storage and as a packaging fluid for wheel and master cylinders. Vehicle brake fluid must be changed if a vehicle is sent from one climatic extreme to the other. The brake system must be drained and refilled with the preservative fluid when it is to be in storage for periods over 6 months, then serviced again when the vehicle is to be used.

The water sensitivity of these fluids and commercial type poly-glycol base hydraulic fluids has been recognized for many years as the major factor in brake system failures. Because brake systems contain hoses and diaphragms using rubber seals and gaskets, large amounts of water may be absorbed by the brake fluid. This absorbed water adversely affects the performance of these fluids by lowering the boiling point and the vapor lock point, and by increasing the low temperature viscosity.

A previous Army report (4) has shown that small percentages of water drastically reduce the boiling point of brake fluids. Data in Table I shows that the higher the initial boiling point, the greater the effect. Addition of 1 percent water to a brake fluid with an initial boiling point of 558°F dropped to 384°F, a drop of 174°F. A fluid with a boiling point of 322°F only drops 16°F upon addition of 1 percent water. Six percent water brings the boiling points of almost all fluids to between 240°F to 250°F.

A SAE round robin test to evaluate the Markey Vapor Lock Tester confirmed that the vapor lock points of wet brake fluids were considerably lower than the reflux boiling points. A typical 550°F type fluid with a water content of 1 percent boils at 430°F but has a vapor lock point at 334°F. As the water content increases the difference between the boiling point and the vapor lock point decreases until with 6 percent water the two values are very close.

Viscosities of conventional brake fluids are affected by moisture in a similar manner. As these fluids pick up water, the low temperature viscosities increase drastically. A fluid that has a viscosity at minus 40°C of 1089 c.s. increases to 1897 c.s. when it picks up 6.57 percent water. A fluid with an initial viscosity at minus 40°C of 844 c.s. increased to 1470 c.s. with a 5.38 percent water pickup. Increases of this magnitude could cause the brake system to be sluggish or even inoperable at these temperatures.

Silicone fluids, on the other hand, do not exhibit these properties. Silicones are nonhygroscopic; in fact, they are hydrophobic in that they repel water. The boiling points and vapor lock points remain the same after humidification. Viscosities are virtually unchanged. Furthermore, the viscosities are not affected by temperature change to the extent conventional brake fluids are. Table 2, published by Dow-Corning (5), confirms this.

Therefore, in 1967, because of the success of silicone fluids in other hydraulic applications, the Army became interested in developing a single all-purpose fluid to overcome the water sensitivity of current fluids as well as to provide all-weather and preservative properties. Silicone producers were encouraged by the Army to develop such a fluid since it would reduce maintenance and logistics costs substantially by providing increased brake system reliability, eliminate the need to change fluids for CONUS, Arctic, or storage conditions; and would replace the three existing fluids with one. The increased use of disc brakes presents another problem that will be resolved by the use of silicones. Fluids in disc brake systems reach higher temperatures,and consequently the boiling points and vapor lock points become critical factors. Silicones boil above 500°F and are virtually unaffected by moisture.

During the next 6 years, laboratory tests of various critical fluid properties were conducted. Deficiencies such as poor lubricity and rubber incompatibility which surfaced in laboratory testing were minimumized by the incorporation of small amounts of additives to these fluids. Laboratory evaluation, including stroking tests and storage tests for packaging and preservative properties, established that a silicone brake fluid could be formulated to provide heavy-duty and arctic-type performance and the preservative properties required by the current brake fluids and preservative fluid. The remaining question of suitability under all operating conditions required field testing. During March and

April 1973, tests were initiated to obtain experience with silicone brake fluids in operational vehicles. Three silicone fluids and a conventional fluid were installed in vehicles operated by Army units in three areas representing climatic extremes: tropical (Tropical Test Center, Panama Canal Zone), extreme cold, (Arctic Test Center, Fort Greeley, Alaska), and desert (Yuma Proving Ground, Arizona).

VEHICLE FIELD TEST

Three silicones (two water-intolerant and one water-tolerant) and a conventional VV-B-680 "Brake Fluid Automotive" were selected for a 2-year field test. Each fluid was placed in the brake system of two M151, 1/4-ton cargo vehicles, and two M715 1 1/4-ton vehicles at each test location. New brake cylinder sets were cleaned and filled with the test fluids in the laboratory and shipped together with new brake hoses to the appropriate area for installation.

At the time of installation, the wheel cylinders on the vehicles were removed and the systems were flushed with alcohol and allowed to air dry. The master cylinder and rubber brake hoses were then removed, the new packed cylinders and rubber brake hoses were installed and filled with test fluid, and the vehicles were placed in operation.

After 1 year, half of the cylinders from Panama and Yuma were torn down and examined. Brake fluid was taken from each wheel cylinder and master cylinder and sent to the laboratory for examination. The cylinders were then re-installed and brought back to the proper level with fresh fluid, and the vehicles were placed back in operation. The other half of the vehicles were left undisturbed for the additional year's test. All cylinders from Alaska were returned to the laboratory for examination. Testing was discontinued for the two water-intolerant fluids after 8 months because of possible crystallization at low temperatures below minus 50°F. Two new low temperature water-intolerant silicones were put into service in Alaska at the beginning of the second year with one M151 containing MIL-H-13910 Arctic brake fluid as the control fluid.

RESULTS AFTER 1 YEAR OF OPERATION. MERADCOM Report No. 2132 (7) tabulates the results of the first year

results in this period. It was determined that due to limited accumulated mileage, it would be advisable to continue the test for an additional year to determine if any difference would surface with further testing

RESULTS AFTER 2 YEARS OF OPERATION. U. S. Army Mobility Equipment Research and Development Command Report No. 2164 (8) tabulates the final results of the 2-year silicone brake fluid field test . In Panama, three of the four vehicles using the VV-B-680 fluid completed the second year of operation without a brake malfunction even though the cylinders were severely corroded. The fourth vehicle was reported missing in February 1975. During examination of the brake parts, a strong odor of gasoline and swelling of the secondary cup were noted in the master cylinder from the two 1 1/4-ton vehicles. Water pickup in the fluid ranged from 2.5 to 15 percent by weight.

The vehicles using the silicone fluids continued to operate trouble free during the second year. The cylinders with the two water intolerant fluids were satisfactory, with one fluid showing a tendency to stain and have slightly more corrosion of metal parts. The cylinders with the water tolerant silicone showed considerably more corrosion than those with the other silicones but were substantially better than those with the VV-B-680 fluid. The odor of gasoline and swelling of the secondary cup in the master cylinder were also noted in the 1 1/4-ton vehicles using the water intolerant silicones. It was not present in the vehicles using the water tolerant silicone. The rubber cups had a slight-to-moderate scoring and scuffing with all the fluids under test.

At Yuma Proving Ground, Arizona, all vehicles except one containing a water intolerant silicone completed the second year of operation without a brake malfunction. Those brake parts were discarded inadvertently and the cause of the malfunction could not be determined. Fluid performance was comparable to the Panama portion of the test.

At Fort Greeley, Alaska, the vehicle containing MIL-H-13910, Arctic Brake Fluid, showed heavy corrosion of the wheel cylinders and scoring of the pistons. All of the vehicles with the two new low temperature silicones gave comparable results, showing only slight stain of the cylinders, and with the exception of one vehicle showed no piston scoring.

Photographs illustrating representative cylinders from Panama, the most severe portion of the test, are shown in figures 1 through 3.

CONCLUSIONS

This program has shown that silicone brake fluid will equal or exceed the performance obtained from current Army Specification fluids in conventional hydraulic brake systems. The water-intolerant silicones show considerably less corrosion than either the conventional fluids or the water-tolerant silicone fluid after the 2-year period. After 1 year in the Arctic, both the water-intolerant and the water-tolerant silicones were comparable in performance.

The odor of gasoline and swelling of the secondary cups were found to be attributed to the use of the deep water fording kit. These kits vent the master cylinder into the air breather which, in turn, allows gasoline vapors to enter the master cylinder and cause the rubber cup swelling that was noted. Swelling of the master cylinder cups in vehicles equipped with the deep water fording kit can produce brake failure regardless of the fluid used.

Based on the study and previous laboratory evaluations, silicone brake fluids have demonstrated their potential use in the bulk of the Army fleet, which is composed of vehicles under 10,000 pounds gross weight and equipped with conventional hydraulic brake systems.

However, during this test period, laboratory tests conducted by a brake parts manufacturer indicated a potential problem with silicone brake fluids in vacuum-over-hydraulic brake systems used on some larger vehicles. Since the Army fleet includes some vehicles with this type of hydraulic brake system, further studies were conducted to resolve the problem. The Army set up a vacuum-over-hydraulic test stand and evaluated several new formulations. Two silicones subsequently passed this test along with the normal stroking test.

As a final result, a new specification, MIL-B-46176, was published, 27 March 1978, covering the Silicone Brake Fluid. Two products have been qualified to date. Use of this fluid will allow the Army to replace the three presently used brake fluids with one fluid, greatly reducing logistic and maintenance costs and increasing the Army's combat readiness.

REFERENCES

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3. Military Specification MIL-P-46046, Preservative Fluid, Automotive Brake System and Components.

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5. E. R. Jakubczak and G. W. Hollbrook, "Silicone Brake Fluids, A Non-Conventional Solution to a Conventional Problem," Dow-Corning Corporation. Presented at the Chemical Specialties Manufacturer Association, December 1973.

6. J. H. Conley, R. Jamison, and C. B. Jordan, "Silicone Brake Fluids: One Year Field Test," MERADCOM Report No. 2132, February 1975.

7. J. H. Conley, R. Jamison, and C. B. Jordan, Silicone Brake Fluids: Two Year Field Test," MERADCOM Report No. 2164, January 1976.

8. M,L-B-46176, Brake Fluid, Silicon, Automotive, All Weather, Operational and Preservative.

TABLE 1
EFFECT OF WATER ON BOILING POINT
BOILING POINT IN °C

INITIAL BOILING POINT	+1% WATER	+2% WATER	+4% WATER	+6% WATER
309	196	163	133	123
270	190	159	134	121
243	193	158	135	123
174	148	139	124	121
161	152	144	131	118

TABLE 2
EFFECT OF WATER ON VISCOSITY

TEMPERATURE IN °C	VISCOSITY IN CENTISTROKES (cSt)			
	CONVENTIONAL FLUID		SILICONE FLUID	
	NEW	HUMIDIFIED*	NEW	HUMIDIFIED*
99	2	2	28	28
25	12	13	90	90
-40	1190	2175	584	590
-54	9540	23460	1200	1220

*HUMIDIFIED ACCORDING TO MVSS 116 (6) FOR 90 HOURS – 80% RELATIVE HUMIDITY

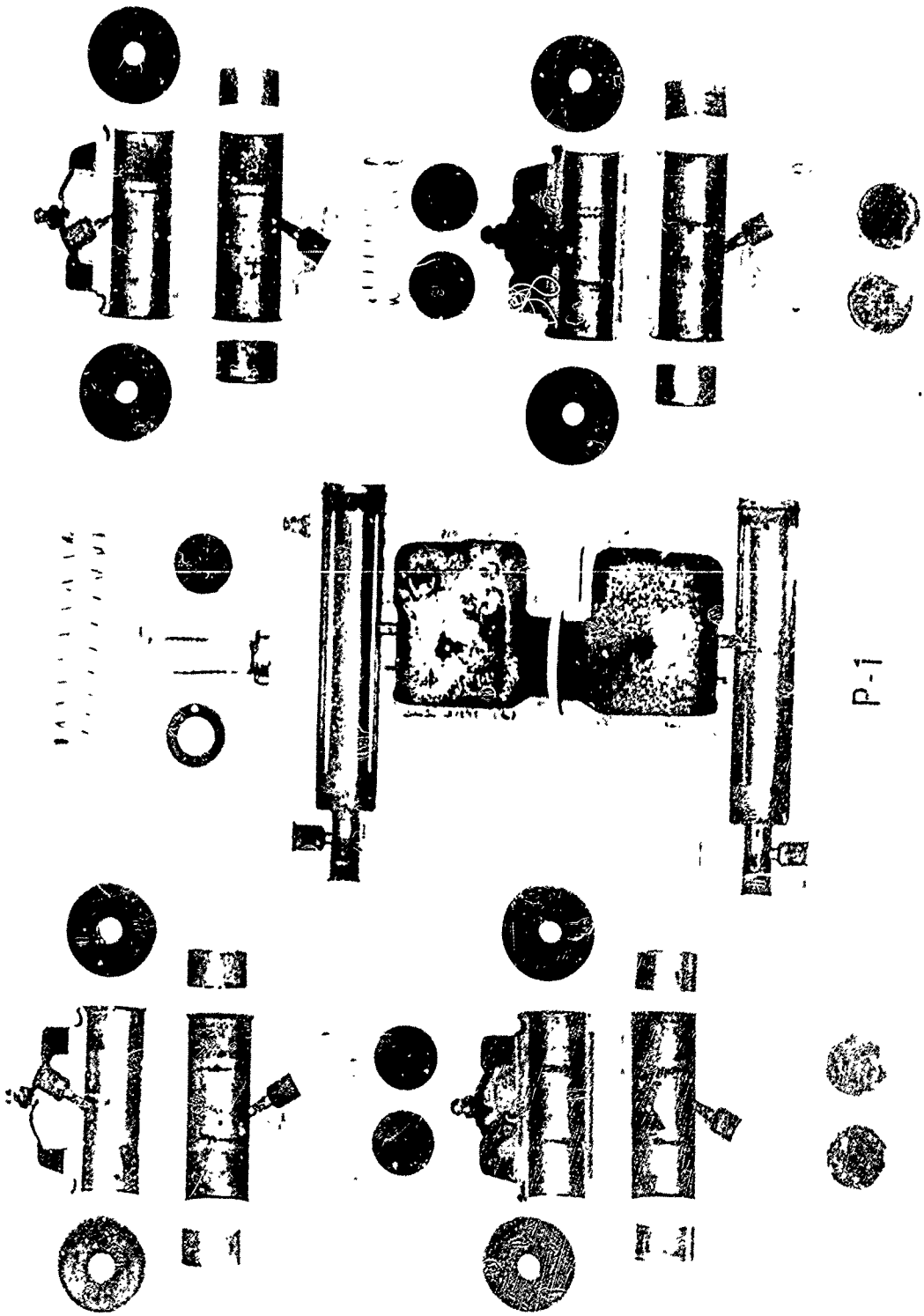


Figure 1 Typical set of cylinders after 2 years' operation at TTC with VV-B-680 fluid

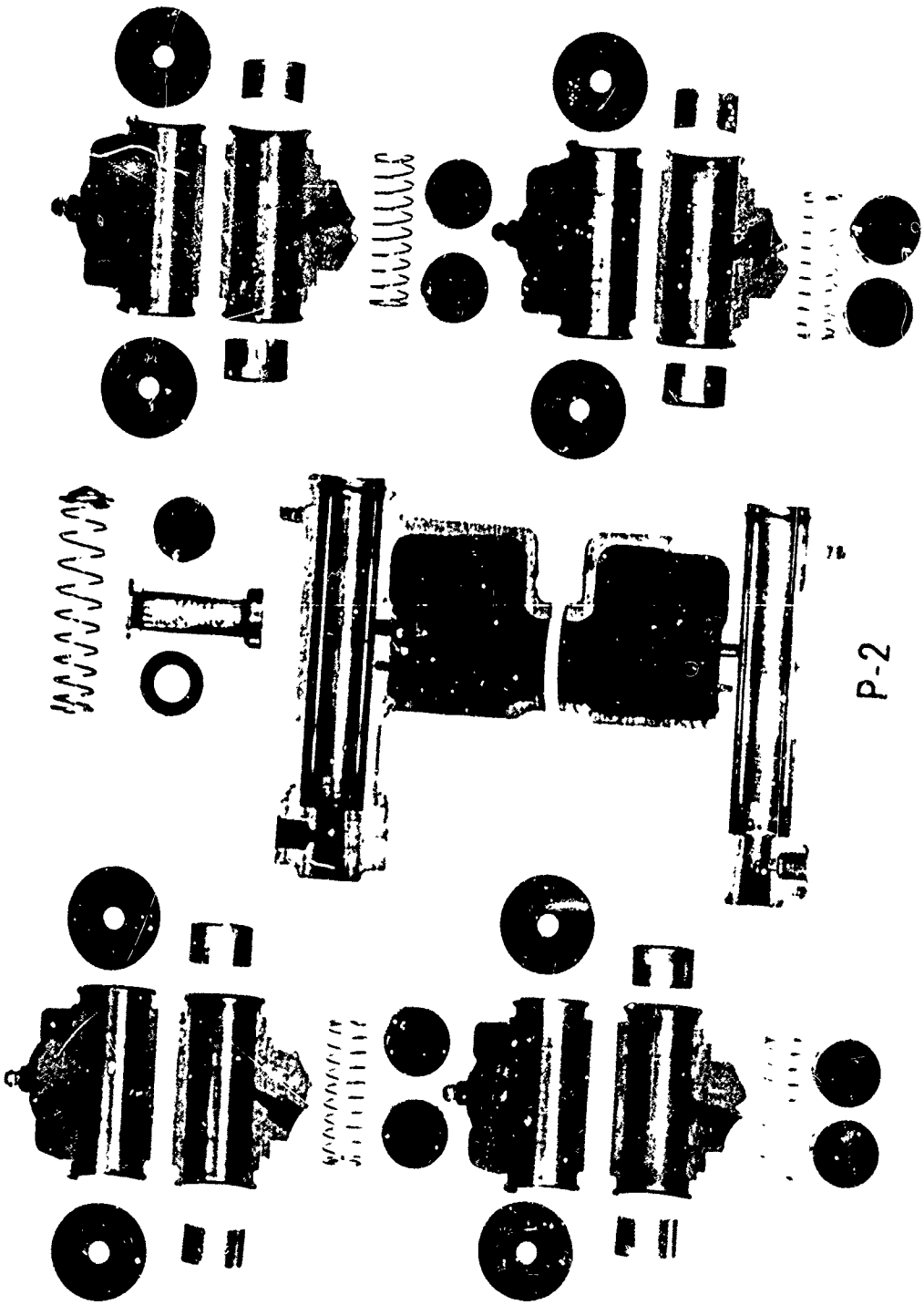


Figure 2 Typical set of cylinders after 2 years' operation at TTC with water-intolerant silicone.

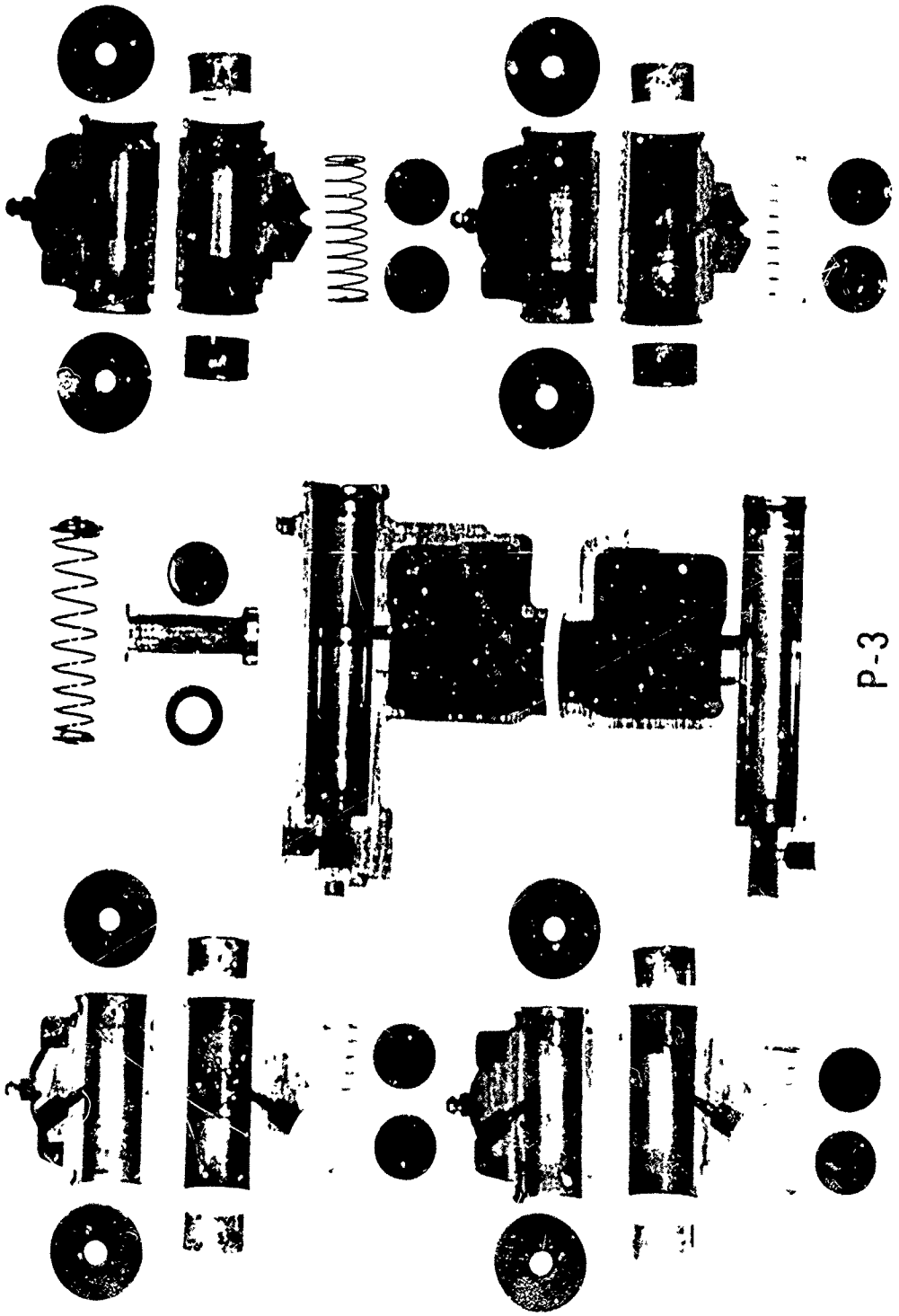


Figure 3 Typical set of cylinders after 2 years' operation at TTC with water-tolerant silicone

PER YOUR REQUEST
FOR INFO

Abstract

Per Your Request for Info

Information requested as a result of student surveys conducted for the Army's Corrosion Control Course are summarized in the areas of (1) type of corrosion, (2) item corrosion, (3) materials, (4) processing and (5) miscellaneous. This info is correlated with the subject content of the 1978 and 1980 Tri-Service Corrosion Conference presentations. Discrepancies are identified and the respective service corrosion control programs should be structured or changed to insure the situation does not become more serious.

Per Your Request for Info

The US Army ARRCOM is responsible for conducting the Prevention of Material Deterioration: Corrosion Control Course. As a part of that course, survey sheets are passed out requesting that the students identify specific corrosion problems or general corrosion areas that they would like covered during the week's presentation. In this way the course is "tailored" to the needs of the individual installation. Data extracted from these survey sheets for the last three years was used as the basis of this study. In a similar fashion, data gathered from the articles and titles of the 1978 and 1980 Tri-Service Corrosion Conference was used as a comparison to see if there was a correlation between the corrosion research and the problems identified for discussion during the corrosion control classes.

The procedure consisted of making a list of all requests for info. These included Army and Air Force requests at Command and depot activities. The course has not been presented to the Navy in general. The only Navy facility that has requested the course recently is Naval Weapons Center at China Lake, CA and their problems would not be typical of the Navy.

Items on the list related to the same problem were combined into specific categories. These categories were summarized under the specific areas of (1) type of corrosion, (2) item corrosion, (3) materials, (4) processing and (5) miscellaneous. The areas and their categories are summarized in Table I for the Army and in Table II for the Air Force. The total number of items in each category were divided by the total items surveyed. The figures shown in Table III represent percentages of the requests for info in specific areas. A similar procedure was used to show the percentage of research efforts presented at the 1978 and 1980 Tri-Service Corrosion Conferences. Again, topics were categorized and identified per the subject areas mentioned previously. The comparitive results are also included in Table III.

Discrepancies were noted in the general areas and also in specific categories. The area discrepancy that is the most obvious is the low number of papers addressing processing. The processing area is really involved with putting corrosion research into practice or, in effect, it amounts to the implementation of what we find out in research efforts. This has been discussed as a problem in the past, but nowhere has it been documented for corrosion research. I guess we suspected as much since this is an all to familar problem with R&D in general.

A deficiency in the processing area is vital since it affects the overall quality (which we seem to pay dearly for) and eventually the reliability which we had hoped to achieve. We can apply the best coatings, materials and corrosion practices on paper but if we never get them applied properly to our equipment, we haven't accomplished what we originally set out to do. (As the Air Force says, "Paper studies make good paper airplanes.")

The most obvious category under processing where problems currently exist involves the pretreatment, priming and topcoating of aluminum and steel. This category represents 35 percent of the Army and Air Force requests for info in the processing area. I guess it was also brought into sharper focus by the recent paint problems experienced on the M198 Howitzer.

The original finish system specified on the trails and other large aluminum components was (1) cleaning, (2) chromic acid anodize, (3) epoxy prime and (4) IR reflective lacquer topcoating. It should be noted that both pre-award surveys reported the contractor did not have the ability to produce the M198. When the contractor got the award, the first thing he did was submit a VECP to eliminate the chromic acid anodizing and apply wash primer. The VECP was accepted on the false premise that residual chromic acid was corrosive. In truth, the contractor did not want to use chromic acid because he didn't want to bother with the chromate waste disposal. After the howitzers were assembled at RIA, they were steam cleaned at 90 psi prior to the application of the final topcoat and decal painting. During steam cleaning, large flakes of the contractor applied paint system were removed and final touch-up and painting required twice the time alloted. Separation of the paint was experienced down to the wash primer in some cases and bare metal in other cases.

The situation indicated poor cleaning prior to the application of the wash primer and improper application of the wash primer. Investigation of the contractor's process revealed that no chromic acid cleaning was being accomplished prior to the application of wash primer and that the wash primer was being applied up to 1.0 mil thick, instead of the required 0.3 mil thickness. DCAS was directed not to accept any more howitzers until the processing was proper. Systems accepted since that time were capable of being steam cleaned for repainting with little or no problems but ten percent of the production contract has already been completed with no assurance the problem won't resurface again. Processing of metal parts for ammunition (M549 RAP round) is another example.

This type of processing problem is typical of most Qualified Products List (QPL) paint specifications. All types of developmental data exists such as humidity tests, salt spray tests, Panama Canal Zone and outdoor exposure tests which indicate the material in the can is satisfactory on panels. When it comes to end items, however, there are no in-process specifications in many cases and, as a result, no in-process inspection. DCAS was only looking at the final paint job and had no reason to reject the

finished item. Laboratory qualification procedures and production painting procedures are two different worlds. The military specification system only has the first step (material qualification) under control in most cases.

To alleviate this problem, service corrosion programs must first acknowledge that there is a problem. Management approaches to solve the problem may include (1) writing application specifications (AF), (2) require QA to write supplementary provisions that insure in-process inspection during cleaning, priming, and painting or (3) knowing the inherent problems, delegate the inspection responsibility to the item manager and not DCAS (AF).

In the area of item corrosion, the corrosion of electronic assemblies represents seventeen percent of the Army requests for info and thirty-five percent of Air Force requests. Reported efforts on this subject represent nine percent of the Tri-Service Corrosion Conference presentations in 1978 and 1980. The basic corrosion prevention concept associated with the construction of electronic black boxes is to seal out the moisture. This concept has not worked in military equipment. Moisture gets in by condensation cycling and the black box literally becomes a humidity cabinet when the water can't get out. Pouring water out of "sealed electronics" is common practice at the depots.

Obviously a drain hole would be more effective in most cases. Also, corrosion prevention of PCB's for use in electronic black boxes has been evaluated in Japan by using modern VCI's for protection. PCB's were exposed for 4,000 hours in humidity cabinets and compared to PCB's protected with VCI subjected to the same environment. PCB's were protected by the VCI for the entire test. Protection of switch gear boxes is currently being evaluated with VCI compounds.

In the area of miscellaneous topics, over fifty percent of the Army requests were for information on lay-away. No efforts were reported during the 1978 and 1980 conference presentations. It would be noted that recent changes in storage conditions have been made based on energy considerations No consideration was given to previous studies that have been published and used for years as the basis for lay-away and storage. No assessment was made to determine the impact of lost assets due to premature replacement of equipment due to corrosion. Lay-away of electronic equipment in industry is accomplished at less than twenty-five percent relative humidity. Army guidance for lay-away of computer controlled industrial plant equipment (IPE) is the same as for conventional IPE, that is, a controlled environment at forty-five percent relative humidity. As a result of little or no data on this subject, equipment worth millions of dollars is being jeopardized and a false sense of readiness results from ignorance.

In conclusion, the subjects of processing (especially painting), electronics corrosion and lay-away exhibit voids that need to be addressed by an effective corrosion program. Data in these areas can help to reduce high maintenance costs and improve our readiness posture significantly.

ARMY

CORROSION TYPES

GENERAL
GALVANIC
CREVICE
SCC/H_2 EMB
UNDERGROUND
BACTERIAL
SALT WATER
HI TEMP
FRETTING
PITTING
VAPOR
CAVITATION

ITEM CORROSION

ELECTRONICS
PIPE
VEHICLES
BATTERY CABLES
WHEEL BEARINGS
WATERCRAFT
REBAR
ROTOR BLADE
HONEYCOMB
GAGE SURFACES
COOLING SYSTEMS
BRAKES
EXHAUSTS
WATER TANKS
CONTAINERS

MATERIALS

STAINLESS STEEL
RUBBER/PLASTICS
GRAPHITE
DRY LUBS
COR-TEN STEEL
WAXES
INHIBITORS
CONFORMAL COATINGS
WASH PRIMER
MOTOR OILS
ADHESIVE/SEALANTS

AMAL-IN-81-4019

ARMY

PROCESSING

CLEAN/TREAT/PAINT

SEALING FAYING SURFACES

PACKAGING

ELECTROPLATING

WASHING AIRCRAFT

ADHESIVE BONDING

SOLDERING PCB'S

SHOT PEENING

CLEANING EXHAUSTS

WASTE DISPOSAL

MISC

NDI

QUALITY ASSURANCE

LAYAWAY

AFWAL-TR-81-4019

AIR FORCE

CORROSION TYPES

GENERAL

SCC/H_2 EMB

GALVANIC

SALT WATER

CREVICE

INTERGRANULAR

HI TEMP

VAPOR

BACTERIAL

ITEM CORROSION

ELECTRONICS

ENGINE

PIPE

FUEL TANK

VEHICLES

HONEYCOMB

DISC BRAKES

BATTERY

FASTENERS

INDUSTRIAL PLANT EQUIPMENT

C-130

HINGE TABS

MATERIALS

CPC'S

PVC/PLASTICS

DRY FILM LUBS

SERMETAL

GRAPHITE

COMPOSITES

D6 AC STEEL

STAINLESS STEEL

HYDRAULIC FLUID

VCI'S

ALODINE

MOLYBDENUM DISULFIDE

AIR FORCE

PROCESSING

PAINTING
METAL PREP/COATING
PHOSPHATING
CADMIUM PLATING
CHROMIUM PLATING
WELDING (HAZ)
UNDERCOATING
CHROMATING
BLACK OXIDE
PACKAGING
WASTE DISPOSAL

MISC

LAYAWAY
NDT
MANAGEMENT
DRAIN HOLES
FATIGUE

% TOTALS

	ARMY*	AIR FORCE**	1978***	1980***
CORROSION TYPES	35	25	25	30
ITEM CORROSION	25	30	15	20
MATERIALS	15	20	30	20
PROCESSING	20	20	10	5
MISC	5	5	15	25

* 280

** 150

*** TRI-SERVICE CORROSION CONFERENCE

Abstract

Ten Commandments of Material Deterioration

The subject of material deterioration is discussed by identifying ten common causes of equipment degradation in the field. The ten causes result in commandments which must be adhered to, to eliminate these problems. A general approach to the areas of materials, design, manufacture and maintenance is identified to point out some of the reoccurring pitfalls associated with fielded items. Methods are proposed for consideration or elimination of these all too common problems.

MATERIEL DETERIORATION

TEN COMMANDMENTS OF MATERIAL DETERIORATION

I. ASSUME WATER WILL GET IN SO MAKE PROVISIONS FOR GETTING IT OUT.

II. LEARN THE BAD POINTS OF A MATERIAL/PROCESS AS WELL AS THE GOOD POINTS.

III. DO NOT ASSUME MAINTENANCE IS THE REMEDY FOR BAD DESIGN.

IV. POSITION PC BOARDS VERTICALLY, NOT HORIZONTALLY.

V. DO NOT COMBINE DISSIMILAR METALS ESPECIALLY WHEN LARGE CATHODE/SMALL ANODE CONDITIONS ARE THE RESULT.

VI. DO NOT EXPOSE STRESSED MATERIALS TO SPECIFIC CORROSIVE ENVIRONMENTS.

VII. PROVIDE PROTECTION OF MATERIALS TO PREVENT GENERAL DETERIORATION.

VIII. USE ALLOYS AND THERMAL TREATMENTS TO PREVENT PITTING AND INTERGRANULAR ATTACK.

IX KEEP MFG/FINISHING PROCESSES UNDER CONTROL TO MAINTAIN MAXIMUM QUALITY.

X. DO NOT ASSUME AN "ENVIRONMENT" - IT WILL ALWAYS BE WORSE.

AFWAL-TR-81-4019

THE TEN COMMANDMENTS OF MATERIAL DETERIORATION

Today's corrosion engineer is basically concerned with all types of material deterioration. In a broad sense, the corrosion engineer is concerned with preserving the designed function of a structure, piece of equipment or other items used in the military or commercial arena. The complexity involved in today's designs and the proliferation of new materials, manufacturing technology and OSHA/EPA requirements, make the corrosion engineer's job even more demanding.

Due to the lack of information in the area of long term performance of today's materials, the corrosion engineer must rely basically on his experience and common sense when addressing potential corrosion or material deterioration problems. These "Ten Commandments of Material Deterioration" will provide a practical rather than theoretical approach to maintaining the design function over the effective useful life of the equipment. These "commandments" apply to items currently being designed and the rework of items already in the field.

I. ASSUME WATER WILL GET INTO YOUR EQUIPMENT, SO MAKE PROVISIONS FOR GETTING IT OUT.

Water gets into used and stored equipment via free water entry, condensation and "desiccant pump." Free water entry occurs during a shower or rainstorm, washing the equipment, coffee or other beverage spillage, run-off of accumulated water or any number of other unexpected situations. Condensation occurs on the surface of materials when the temperature goes through the dew point. "Desiccant pump" occurs when a container with desiccant in it develops a leak. The desiccant absorbs moisture from the container and the outside air until it becomes saturated. Subsequent heating of the desiccant releases water to the inside of the container, which results in the container becoming a humidity cabinet.

One of the most effective means of getting water out is through the use of a drain hole. The guidelines for putting in a drain hole are obvious but are not always adhered to, so they will be reiterated here. (1) Put the hole in the lowest portion of the area to be drained, (2) the drain hole must be large enough for water to run out, (3) the drain hole must be large enough to allow debris to be removed with the water, and (4) the drain hole must be large enough to allow a protective coating to be applied to the walls of the drain hole. In spite of their simplicity, the guidance housing casting for the Hawk missile failed all four and the guidance provided by MIL-STD-721 in the past indicates more attention should be paid to these concepts. Breather systems can be used to eliminate the effects of condensation and "desiccant pump." Also, follow JMPTC guidance and replace desiccant every 18 to 24 months or design accordingly.

Keeping water out eliminates the electrolyte required to support any corrosion cell.

II. LEARN THE BAD POINTS ABOUT A MATERIAL AS WELL AS THE GOOD POINTS - THEY MAY BE MORE IMPORTANT.

Let's say you are looking for an electrical insulation material that has good high and low temperature characteristics, is not affected by weak acids and alkalis, is resistant to oils, alcohol and other hydrocarbons, is capable of being colored, and is low cost. You would probably end up selecting a polyvinyl chloride (PVC) material. However, the decomposition of PVC materials by heat, light, age and atomic radiation is the biggest problem associated with their use. The effects of PVC deterioration include discoloration, embrittlement, stickiness and a general loss of properties. Mild heat, in the range of room temperature to 250°F, causes a release of hydrogen chloride which reacts with moisture to form hydrochloric acid, a highly corrosive material. High heat due to a hot wire short or short circuit causes the formation of up to 75 potentially toxic materials including hydrogen chloride, chlorine monoxide, phosgene, and carbon monoxide. These two deficiencies (corrosivity and toxicity) are never cited in the data sheets involving PVC materials.

The short transverse stress corrosion cracking property of 7075-T6 aluminum is similar to an unknown physical characteristic that is not shown on most data sheets. While the longitudinal strength of 7075-T6 is in the 70,000-80,000 psi range, the strength level to which 7075-T6 can be loaded in the short transverse direction without encountering stress corrosion cracking is limited to a range of 6,000-9,000 psi. Thus, the orientation of the load is very critical when materials exhibit this "duality" in strength.

III. DO NOT ASSUME THAT MAINTENANCE IS THE PROPER REMEDY FOR BAD DESIGN.

Maintenance dollars are spent every day in an attempt to correct design deficiencies. As a result of poor design, maintenance is required in a short period of time. Unsealed faying surfaces or lap joints are an excellent example. When corrosion occurs, alkali is generated at the cathode, paint adhesion is lost and rust becomes evident. This reflects adversely on the maintenance man and soon he is involved in stripping and repainting again. The best example is probably the American automobile and the Army use of alkyd paints which have no alkali resistance.

Another maintenance concept is to replace components that have deteriorated with a component similar to the one that previously failed. As a result, we have become a nation of "parts changers" only to have the same problem surface again. Just as religion should not be thoughtless conformity to tradition, neither should our approach to material deterioration be based on the way we've done it in the past. To sum it up, there is no right way to do the wrong thing.

IV. POSITION PRINTED CIRCUIT BOARDS IN THE VERTICAL PLANE, NOT THE HORIZONTAL.

Printed circuit boards positioned in black boxes in the horizontal position are susceptible to dust, dirt, debris, moisture condensation and spillage accumulations. These accumulations constitute a corrosive atmosphere inside the black box resulting in circuit and component failures. Galvanic corrosion between dissimilar metal contacts, blossoming of soldering and plating residues, absorption of moisture by components which in turn causes a change of their input/output characteristics, short circuiting which occurs between traces of fungus growth are some of the situations encountered on supposedly "sealed" units. Vertical positioning minimizes accumulation of these contaminants and allows better convective cooling of the boards.

Situations to consider with sealed black boxes include (1) locating electrical feed-thru connectors on the side, (2) locating card connectors on the side or back, not the bottom, (3) using similar metals on the connectors and the printed circuit board contacts, (4) making sure box can breathe if not hermetically sealed, and (5) do not use materials that emit corrosive vapors. Thinking of these situations during design and use will go a long way in improving the overall performance of printed circuit boards in black box assemblies.

V. DO NOT COMBINE DISSIMILAR METALS IN AN ASSEMBLY, ESPECIALLY IF LARGE CATHODE/SMALL ANODE CONDITIONS EXIST.

While galvanic (dissimilar metal) corrosion is probably the most familiar type of metallic deterioration, it is also the most neglected from the standpoint of anode/cathode area relationships. Graphite, for example, is cathodic to all materials except platinum and gold. When incorporated into dry film lubricants and used on magnesium, aluminum, steel or stainless steel, graphite becomes the cathode and the other metals become the anode in the presence of an electrolyte. Graphite that is in direct contact with the metal causes severe pitting and can result in stress corrosion cracking in high strength materials. In this case a small cathode/large anode situation exists but the results are devastating. A solution to this problem by the Air Force resulted in substituting molybdenum disulfide for the graphite. However, molybdenum disulfide can also be corrosive forming molybdic and sulfuric acid during decomposition. Additions of antimony oxide and dibasic lead phosphite enhance the lubricity by acting as synergists in the presence of molybdenum disulfide. Thus, superior lubrication and corrosion resistance can be achieved with an INHIBITED molybdenum disulfide material. Copper plated steel results in small anode/large cathode situation. Copper plated steel "bundy-weld" tubing used in many brake systems fail by severe pitting at voids in the copper plating. The pits can completely penetrate the steel resulting in a loss of brake fluid which can cause critical safety problems. The use of copper in contact with or plated on aluminum results in an even more potentially destructive situation. For example, copper flashing on roofs literally destroys aluminum

gutters and down spouts. In the case of large cathode/small anode designs while some people will doubt your sanity, by all means coat the cathode to reduce its effective size, even though it doesn't corrode.

VI. DO NOT EXPOSE HIGHLY STRESSED MATERIALS TO SPECIFIC CORROSIVE ENVIRONMENTS.

Specific corrodents (environments) for specific materials have been identified and reported. Typical examples like ammonia for brass and chlorides for stainless steel are reported continuously in corrosion periodicals. Likewise, hydrogen embrittlement during acid pickling, electrocleaning and electrodeposition or alkaline blackening of high strength steels represents a potential corrosive environment for these materials. It must be pointed out that many other materials are prone to failure in specific environments. Polycarbonate (Lexan) plastics, for example are susceptible to stress cracking in the presence of oxygenated and chlorinated hydrocarbons (degreasing solvents). Many synthetic rubbers under stress are susceptible to cracking in ozone environments. Susceptibility can develop in inherently ozone resistant rubbers when reclaimed rubber or other filler materials are added during compounding. Fuel line hoses are an excellent example of this situation. Various coatings on rubber can cause localized (accelerated) ozone cracking. Paints and tire dressings should be avoided. The topical application of antiozonant materials (per MIL-D-50000) is the one procedure that results in increased performance of rubber items. This was shown at Rock Island Arsenal in the 1956-1958 time frame.

VII. PROVIDE ADEQUATE PROTECTION OF MATERIALS TO PREVENT GENERAL DETERIORATION.

Various materials perform satisfactorily in numerous environments and do not require protective coatings. However, materials like steel and its alloys, aluminum alloys and magnesium must be protected to prevent general deterioration. Inorganic (sacrificial) coatings on steel or organic (paint) coatings on aluminum or magnesium are examples of protection required to prevent material deterioration.

The real problem today is the use of coatings that are hardly adequate. Alkyd paints continue to be used as primers on bridges in lieu of zinc-rich primers. The result is the reported poor condition of many bridges in the U.S., especially in my home state, Iowa. In a response to my suggestion, they complained about the cost of using silicone/alkyd paints compared to the cost of lead-base alkyd paints. Zinc-rich paints have provided in excess of twenty years' protection of structures at Cape Kennedy and are in use on the Golden Gate Bridge in San Francisco. Epoxy primers and urethane topcoats are applied to aircraft, and commercial vans and trucks to provide maximum corrosion resistance and resistance to alkali formed at the cathode during the corrosion process thus maintaining paint continuity at faying surfaces and dissimilar metal assemblies.

VIII. PROVIDE THE NECESSARY ALLOYS AND THERMAL TREATMENTS TO PREVENT PITTING AND INTERGRANULAR ATTACK.

The use of stainless steel in rural environments provides adequate corrosion protection. However, the use of stainless steel is often associated with much more severe environments. An example of this is the use of stainless steel in the chemical process industry. Welded stainless reactor vessels and piping containing nitric and sulfuric acid may be susceptible to intergranular corrosion. Chromium, the main alloying ingredient providing the corrosion resistance, is depleted during welding by reaction with carbon. The area adjacent to the weld is then susceptible to accelerated intergranular attack. Titanium or columbuim can be alloyed to prevent the formation of chromium carbides. Also, low carbon stainless steel and various thermal treatments can be used to eliminate the problem. The use of stainless steel in aggressive environments like sea coastal areas may result in pitting corrosion. Chloride from the salt environment can cause the formation of small localized anodes which can perforate stainless steel tubing. Debris settling on horizontally positioned stainless steel tubing at Cape Kennedy resulted in similar deterioration of stainless steel materials. Zinc-rich paint was applied at the cape to provide cathodic protection. Also, the addition of molybdenum as an alloying agent to conventional stainless steels has been shown to improve their resistance to deterioration by pitting.

IX. KEEP MANUFACTURING/FINISHING PROCESSES UNDER CONTROL TO MAINTAIN MAXIMUM QUALITY.

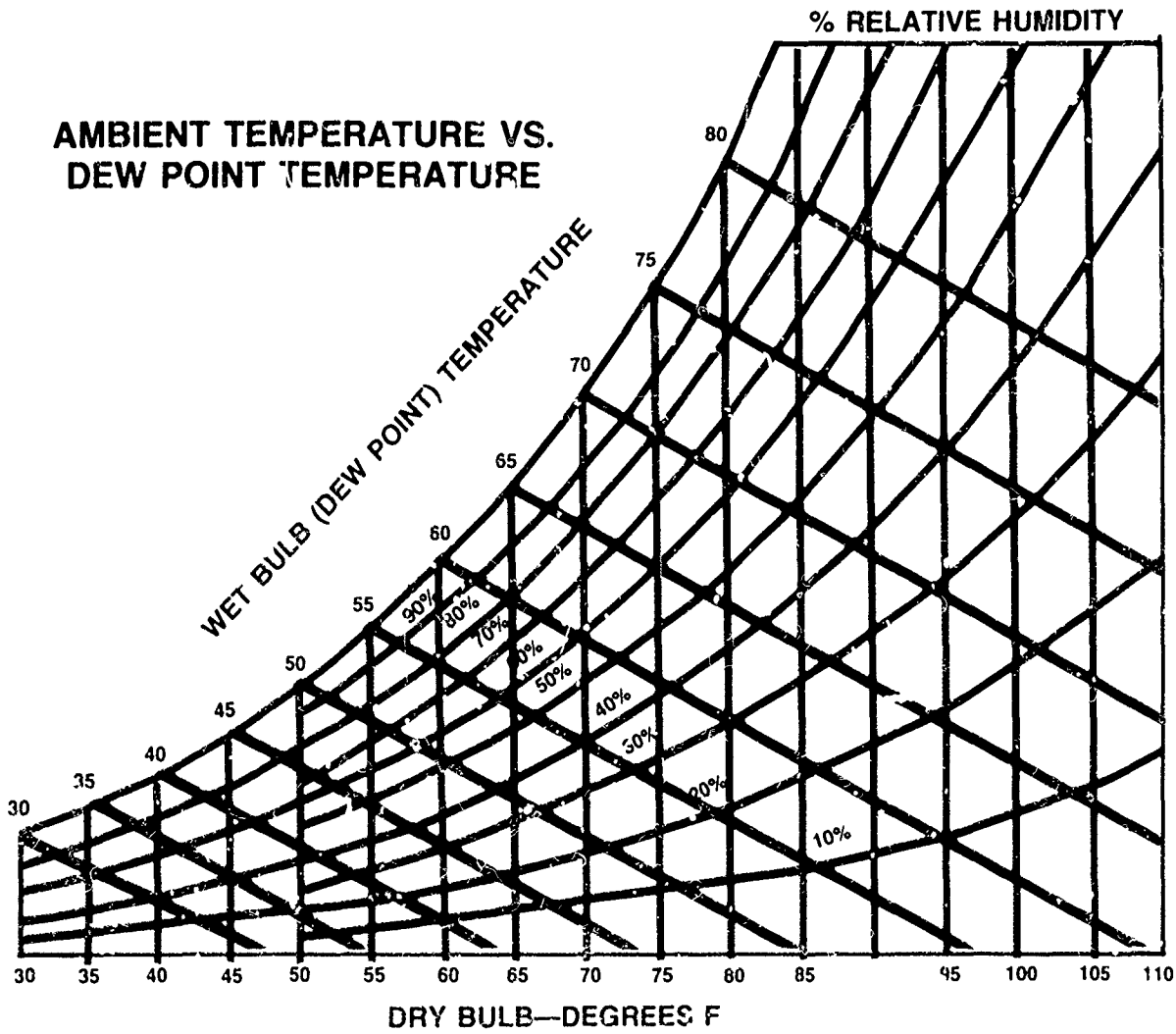
Most manufacturing/finishing processes were initially designed to provide maximum quality. Specifications were then established to define how this quality was to be maintained. It soon became apparent that testing to insure maximum quality was not only time consuming and resulted in production delays, but was also very expensive. As a result, the practice of minimum testing was accepted to alleviate these problems. Today, just passing the minimum is being construed as best available technology. An example of this would be phosphate coating technology. When I first started working for the Army, the average heavy zinc phosphate coating with no supplementary finish would generally pass 20-25 hours in the five percent salt spray cabinet. The finishing process consisted of vapor degreasing, steel grit blasting and one-half hour immersion in the phosphating solution at 198°F to 205°F. Parts were rinsed in cold water and given a chromate treatment. Today, acid and/or alkaline cleaning is used since it is more amenable to automated processing; lower processing temperatures are used due to energy considerations; and subsequent water rinses are warm to hot due to water conservation, disposal problems and production volumes. As a result, the two hour minimum salt spray requirement must often be waived to accept parts. A high percentage of what is received by the depots must be rephosphated before it can be sent to the field. This represents a significant change in twelve years. It appears that implications of the word "quality" means something different today than it did a few years ago.

X. DO NOT ASSUME AN ENVIRONMENT OR USE SITUATION - IT WILL ALWAYS BE WORSE.

In the design of equipment, certain functional requirements must be achieved. Knowing the type of equipment being designed, various operational environments are assumed in which the equipment must perform. When the design is conducted with consideration of the environment, long term reliability can be accomplished.

However, in most cases, testing or operational environments are often far removed from the environments the equipment sees in actual use. The Army performs various operational tests on trucks, missiles and communications equipment in various locations throughout the southwestern deserts. Use of this equipment in places like southeast Asia resulted in less than desirable performance. During the monsoon season, the temperature went through the dew points 23 times in a 24 hour period. None of the equipment saw any "dry" environment, only varying degress of wetness. Thus, the desert environment is hardly indicative of that real world environment. Sometime ago the president of a large automobile corporation was asked what his company was doing about corrosion problems being experienced by his vehicles in the midwest. His response was that it wasn't his company's problem, it was something external to the car, it was the environment and he (the company) couldn't do anything about it. His answer reflected the company's inability to consider the effects of salted streets during the winter months. Shipping equipment in freighters or in railroad cars that were previously used to haul ammonium nitrate is another example.

Problems in any one of these areas should be considered during design and corrected if detected during testing. In this way, the design and the materials used will result in manufactured equipment that will provide reliable performance for a long time. If this is not done, a lot of money will be spent on equipment that has low reliability or is totally incapable of performing its intended function.


AMBIENT TEMPERATURE VS.
DEW POINT TEMPERATURE
% RELATIVE HUMIDITY
WET BULB (DEW POINT) TEMPERATURE
DRY BULB—DEGREES F
30
35
40
45
50
55
60
65
70
75
80
85
95
100
105
110
90%
80%
70%
60%
50%
40%
30%
20%
10%

THE ANATOMY OF AN ADEQUATE DRAIN HOLE

1. DRAIN HOLE MUST BE LOCATED IN THE LOWEST PORTION OF THE AREA TO BE DRAINED.

2. DRAIN HOLE MUST BE LARGE ENOUGH FOR WATER TO RUN OUT.

3. DRAIN HOLE MUST BE LARGE ENOUGH TO ALLOW DEBRIS TO BE REMOVED WITH THE WATER.

4. DRAIN HOLE MUST BE LARGE ENOUGH TO ALLOW A PROTECTIVE COATING TO BE APPLIED TO THE WALLS OF THE DRAIN HOLE.

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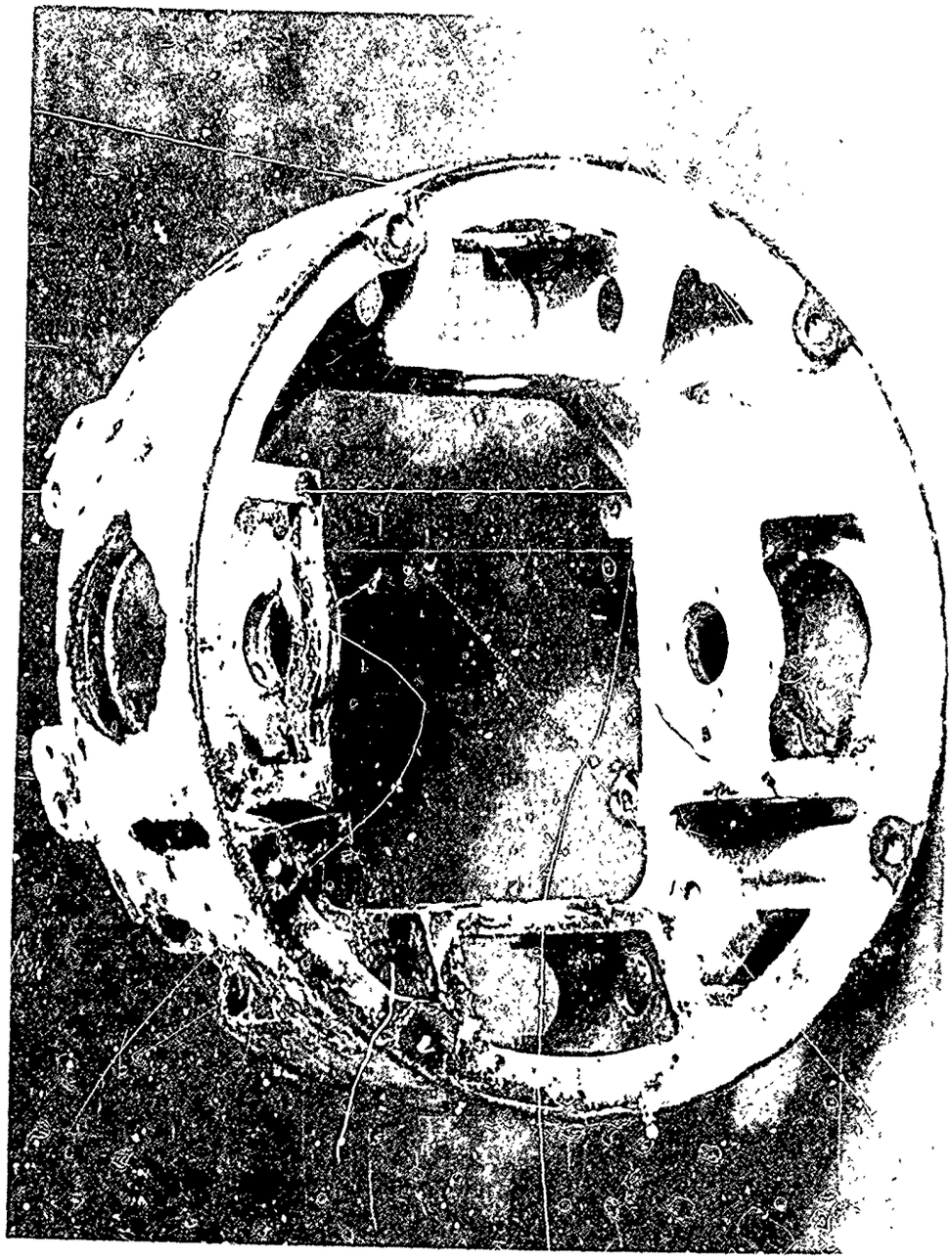
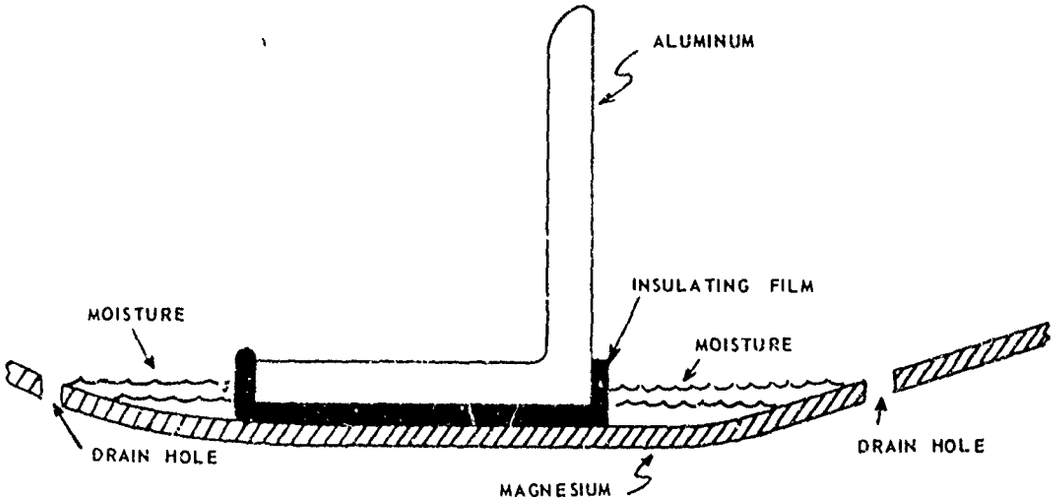


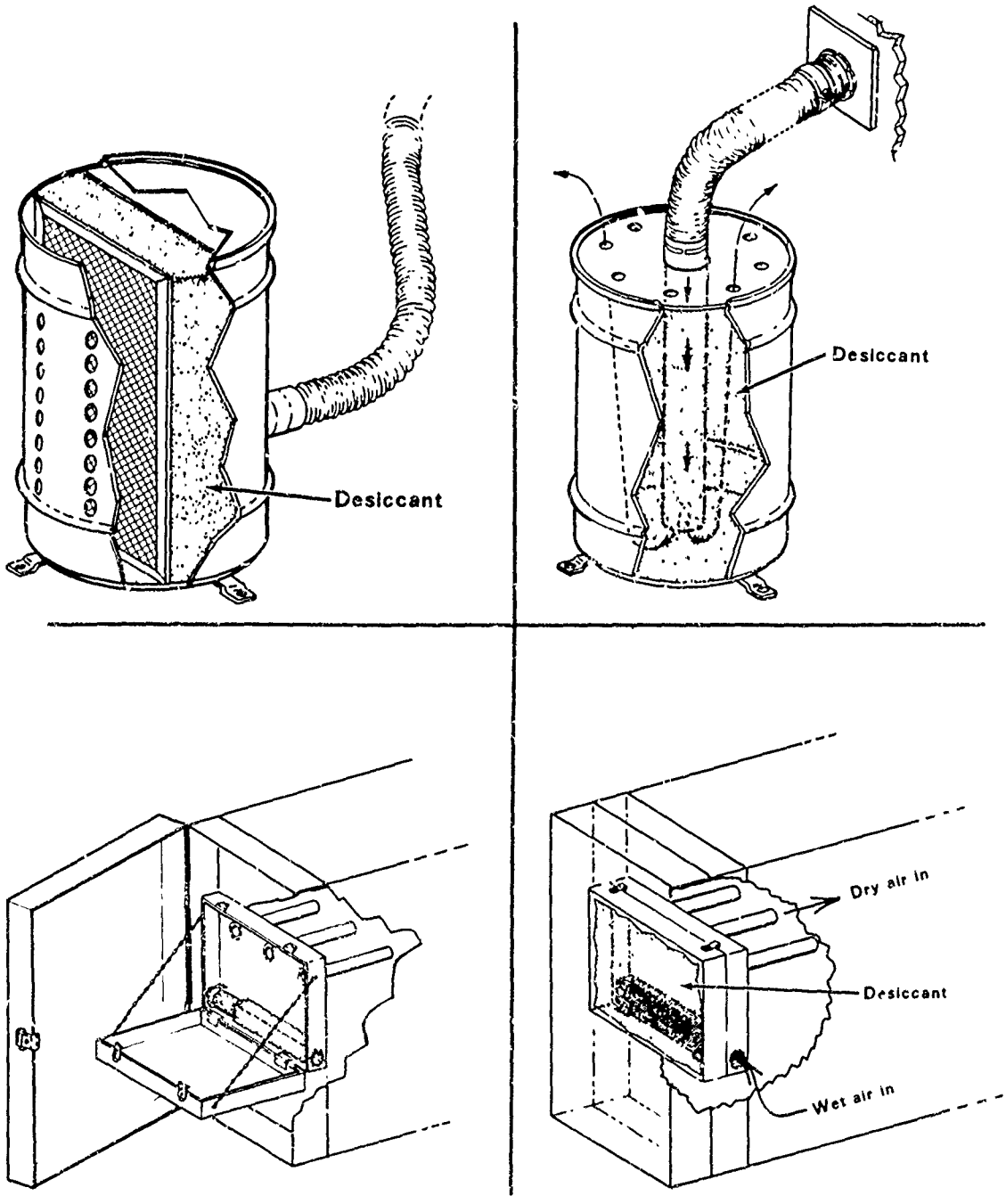
Equipment Miscellaneous, Magnesium Corrosion - Hawk Missile.

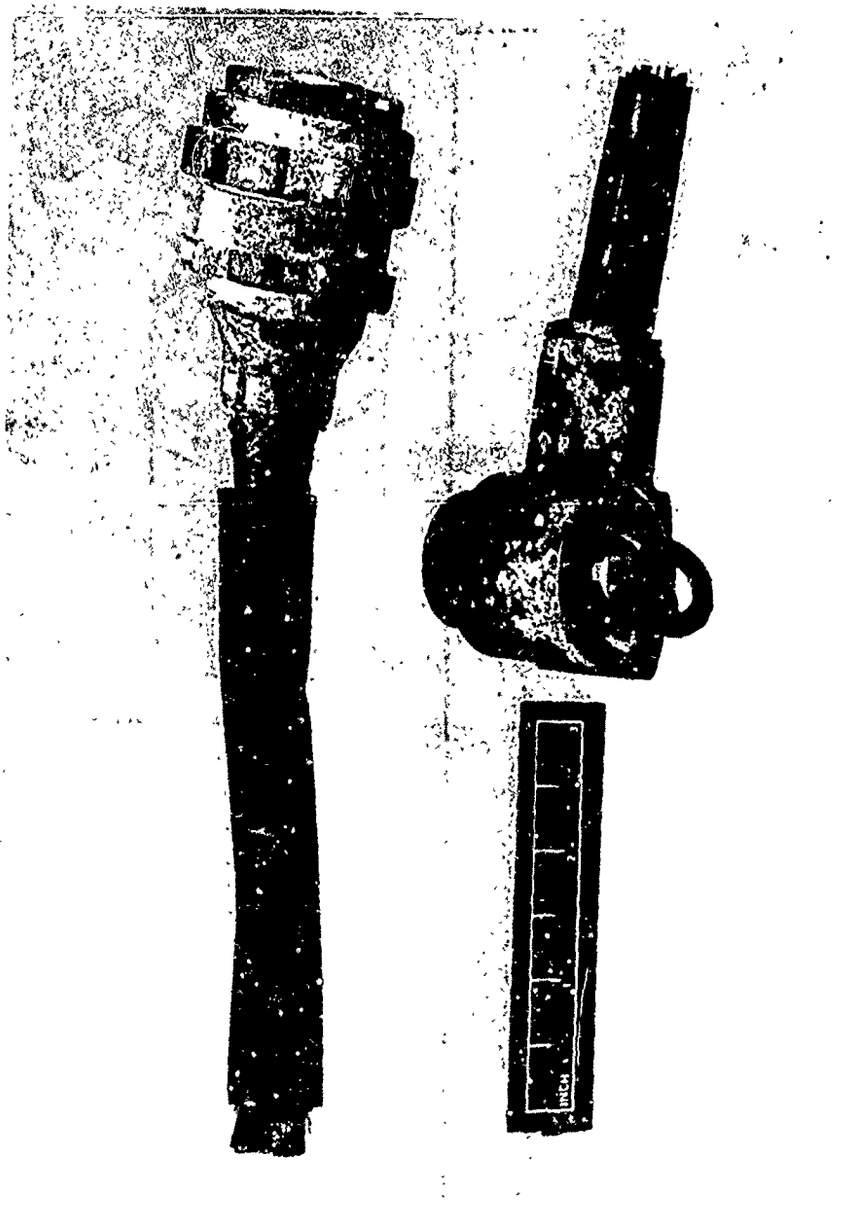


(b) Insulating Film And Drain Hole Used To Prevent Moisture From Bridging Between Magnesium And Aluminum

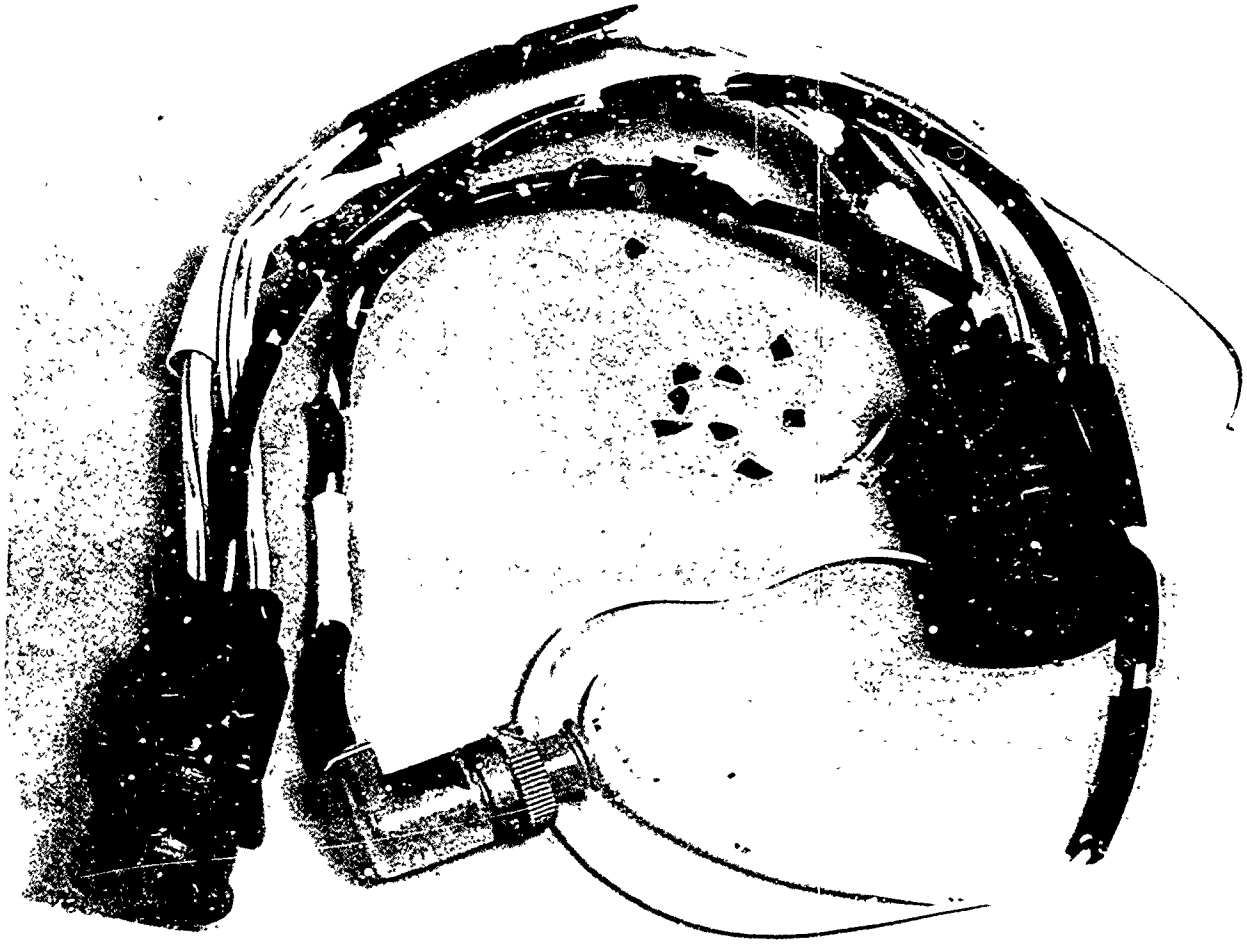
FIGURE 16. Elimination of Moisture Catchment Areas and Use of Drain Holes

BREATHER SYSTEMS



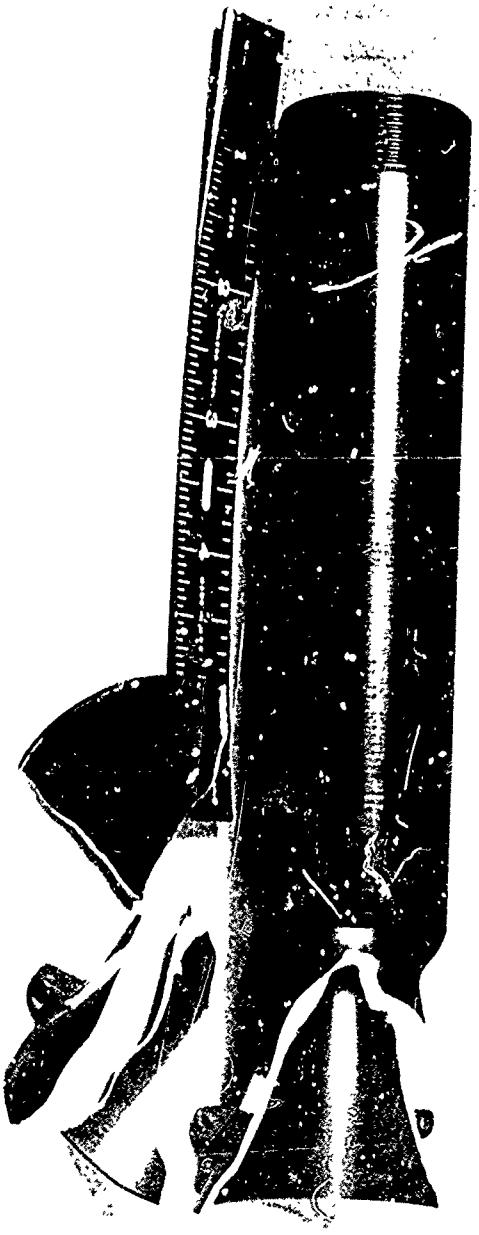


Electrical Connectors from Marine Corp Equipment Showing Effects of Halogen Pitting.



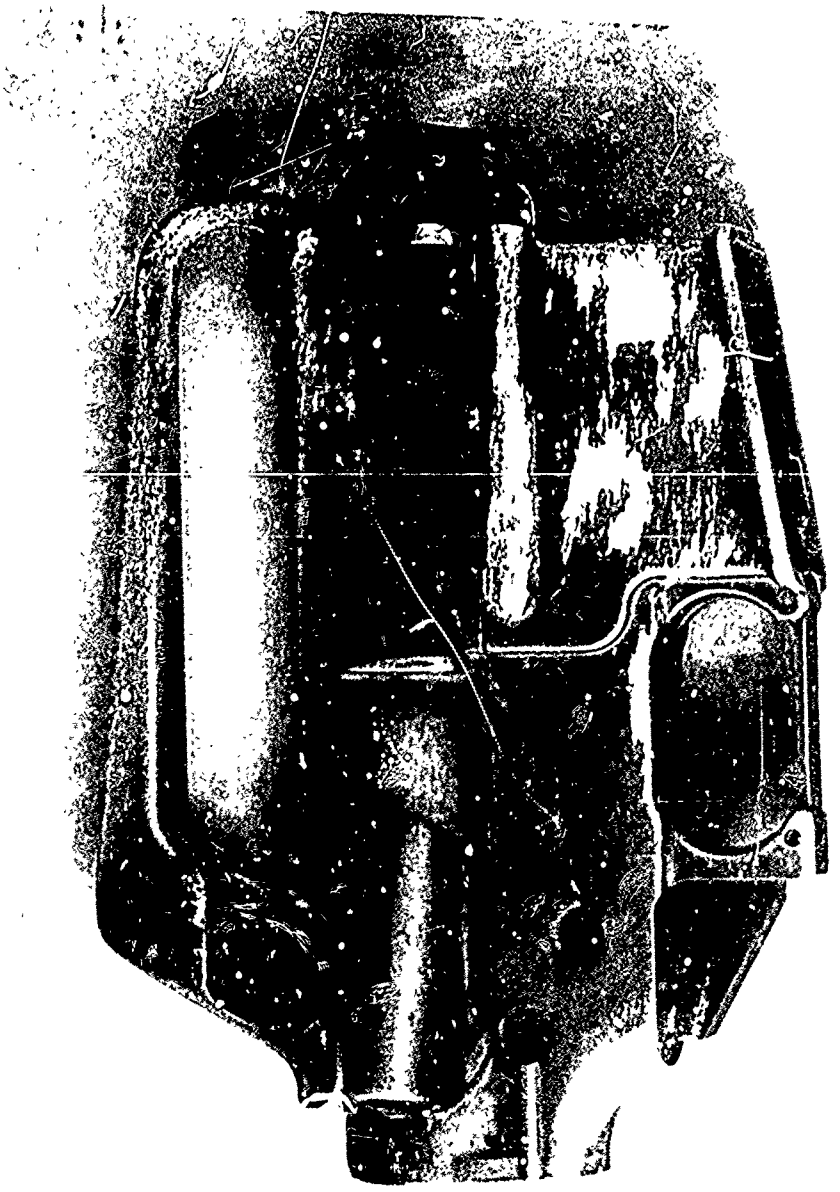
Over All View of an Aircraft Electrical Cables for Weapon Subsystem. Condition of Cable from Spare Parts Storage (Never Used). PVC Inner Insulation Generated Acidic Environment Which Embrittled Outer Urethane Sheathing.

Condition of Electrical Cable from VADS (Vulcan Air Defense System)
Deteriorated Sheathing, Galvanic Corrosion (Green Plaque) and Improper
Wrapping with PVC Tape.



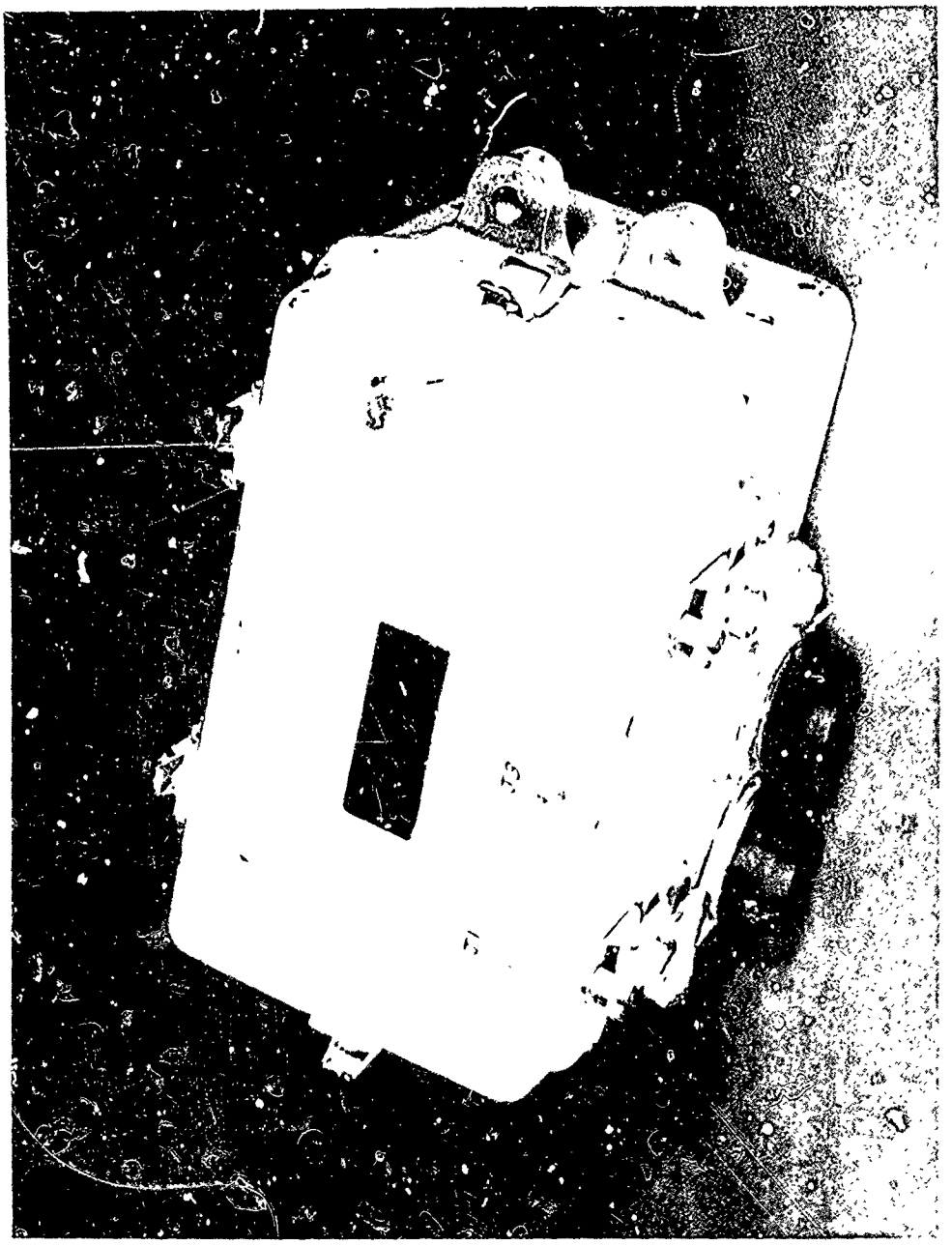
LAW Rocket Motor.

Corrosion.



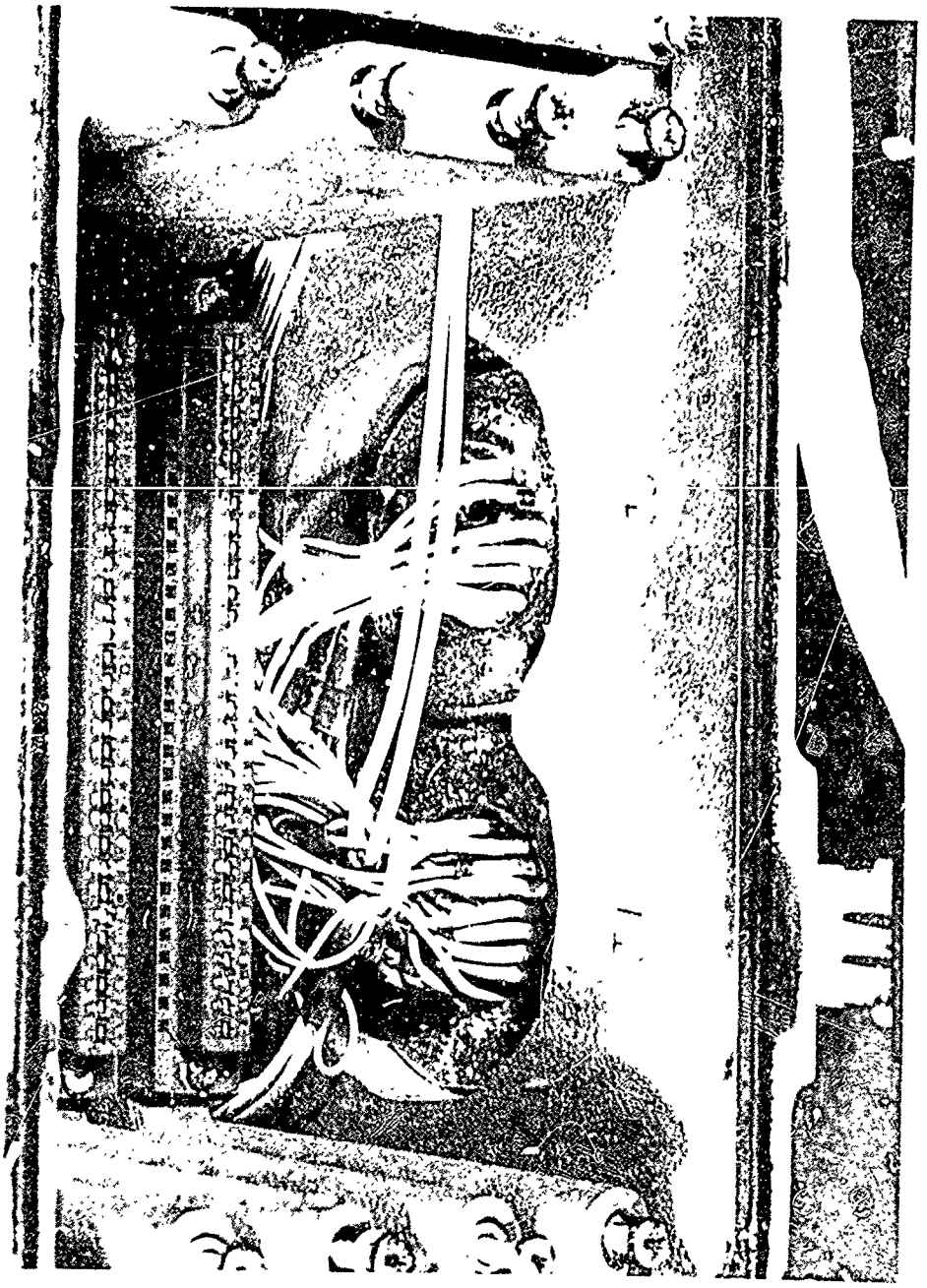
Corrosion - M16 Receiver Parts.

Rust Between Faying Surfaces of Steel Motor Case Assembly (Hawk).

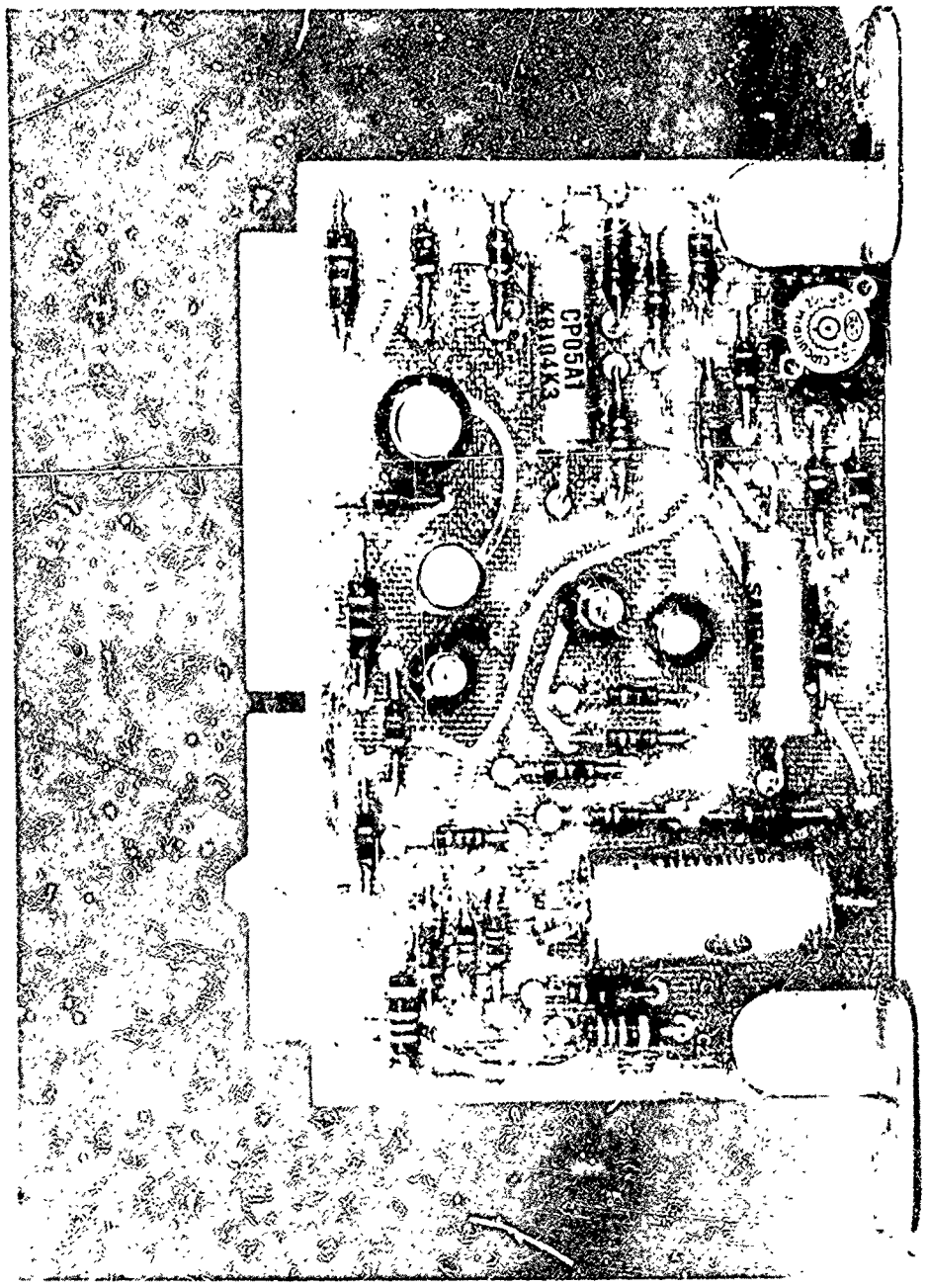


Amplifier Integrator Assy.

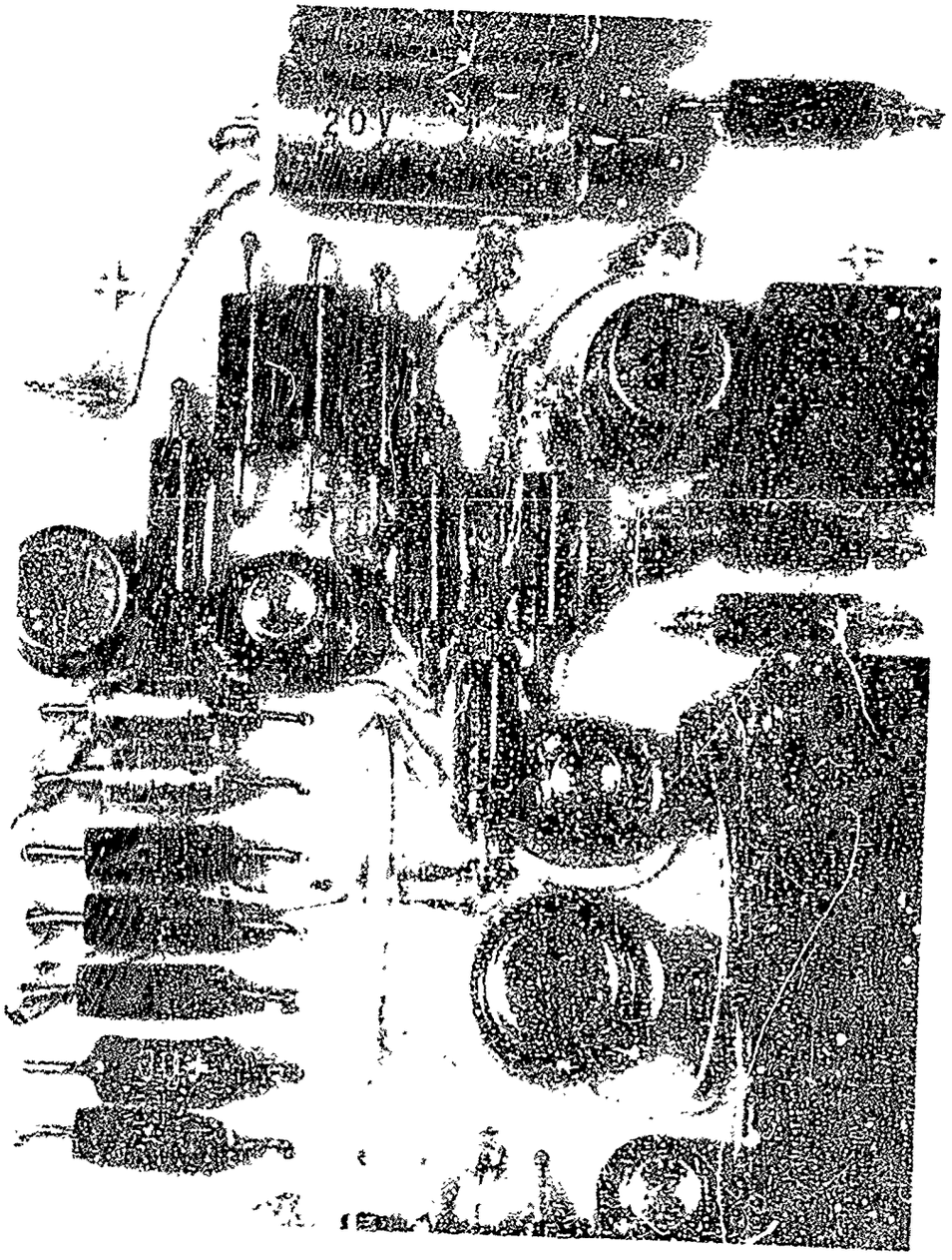
Integrator Amplifier: M551 Sheridan Tank - Note Horizontal Mounting of Circuit Boards



M551 Amplifier Integrator Assy.



Amplifier Integrator Assy.



Corrosion.

Close Up of Ozone Cracked Rubber Seal on M551 Sheridan Integrator Amplifier.

Corrosion.

ANATOMY OF AN ELECTRONIC BLACK BOX

1. LOCATE ELECTRICAL FEED-THRU CONNECTORS ON THE SIDE.
2. LOCATE CARD CONNECTORS ON SIDE OR BACK, NOT ON THE BOTTOM.
3. INSERT PRINTED CIRCUIT BOARDS IN THE VERTICAL POSITION.
4. USE SIMILAR METALS ON CARD CONNECTORS AND PRINTED CIRCUIT BOARD CONTACTS.
5. MAKE SURE BOX CAN BREATHE IF NOT HERMETICALLY SEALED.
6. DO NOT USE MATERIALS THAT MAY EMIT CORROSIVE VAPORS.

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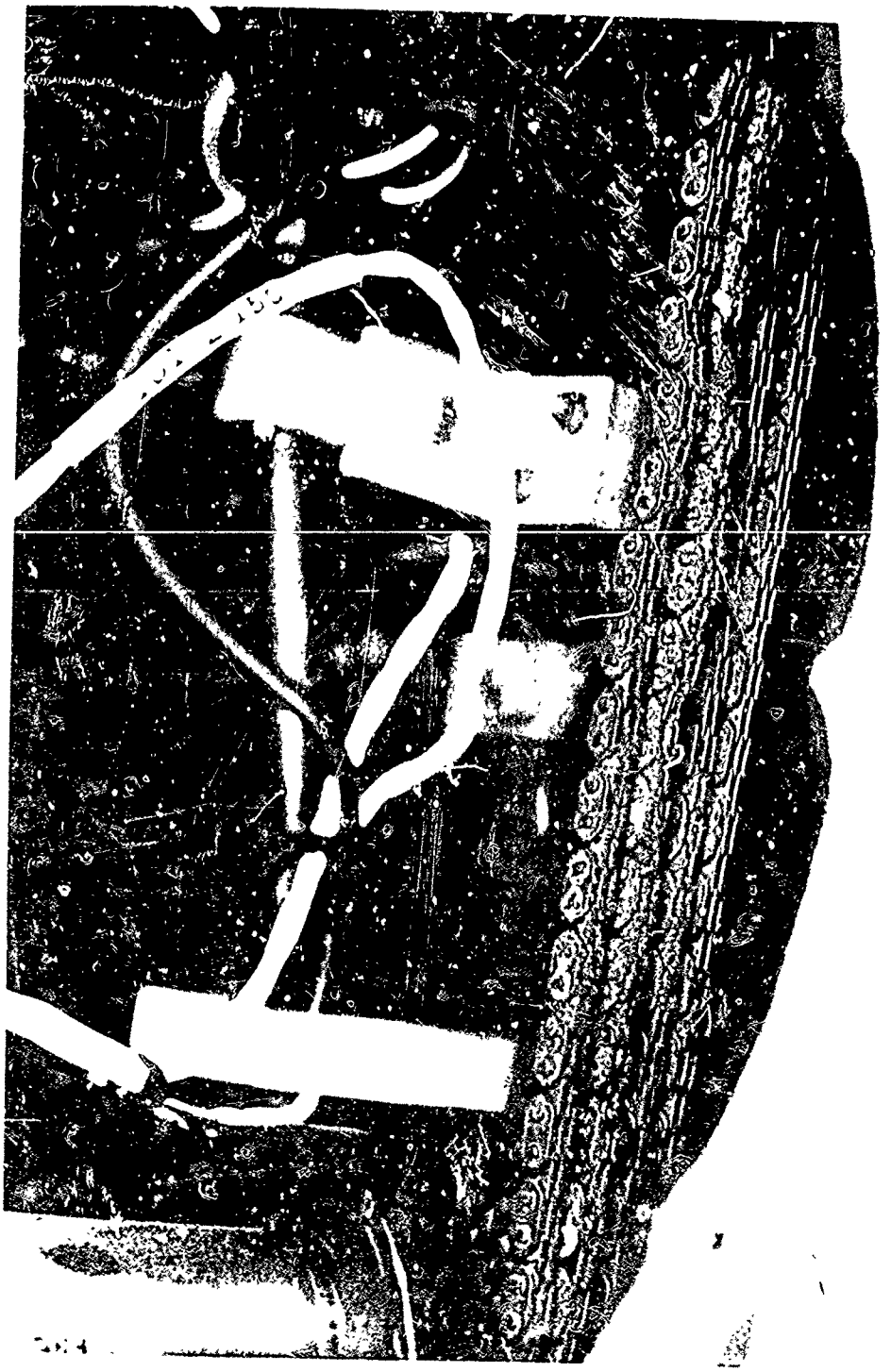
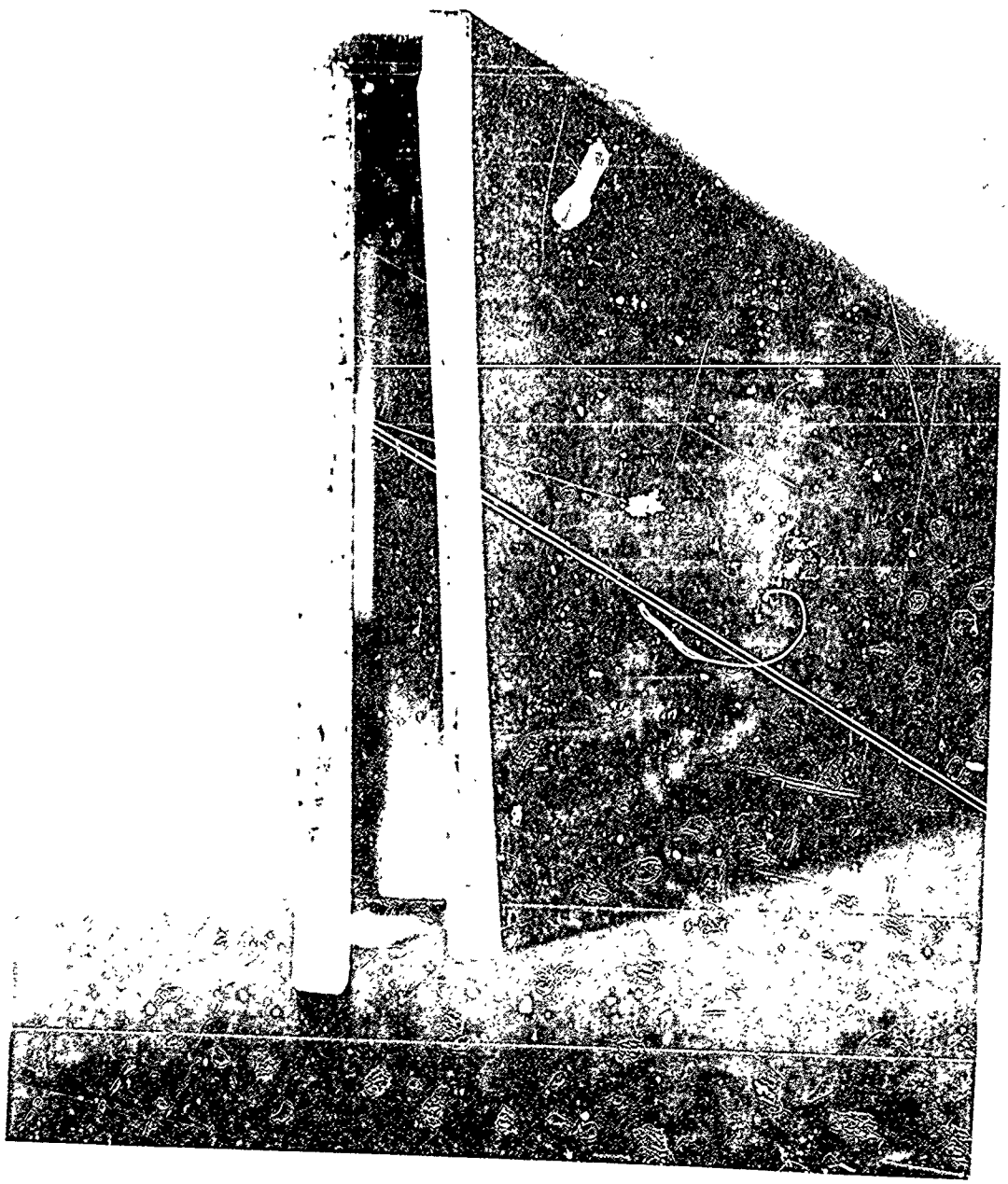
Fig. [illegible] Erosion of Solder [illegible] Coated with Conformal Coatings

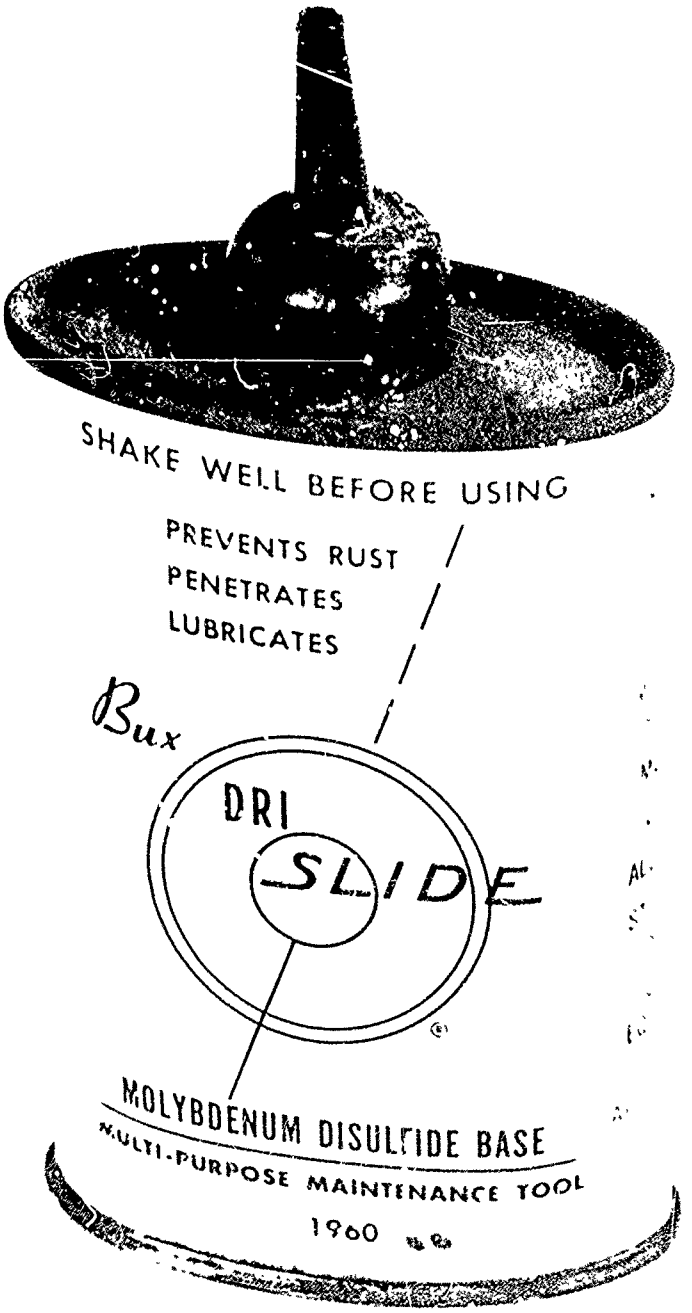


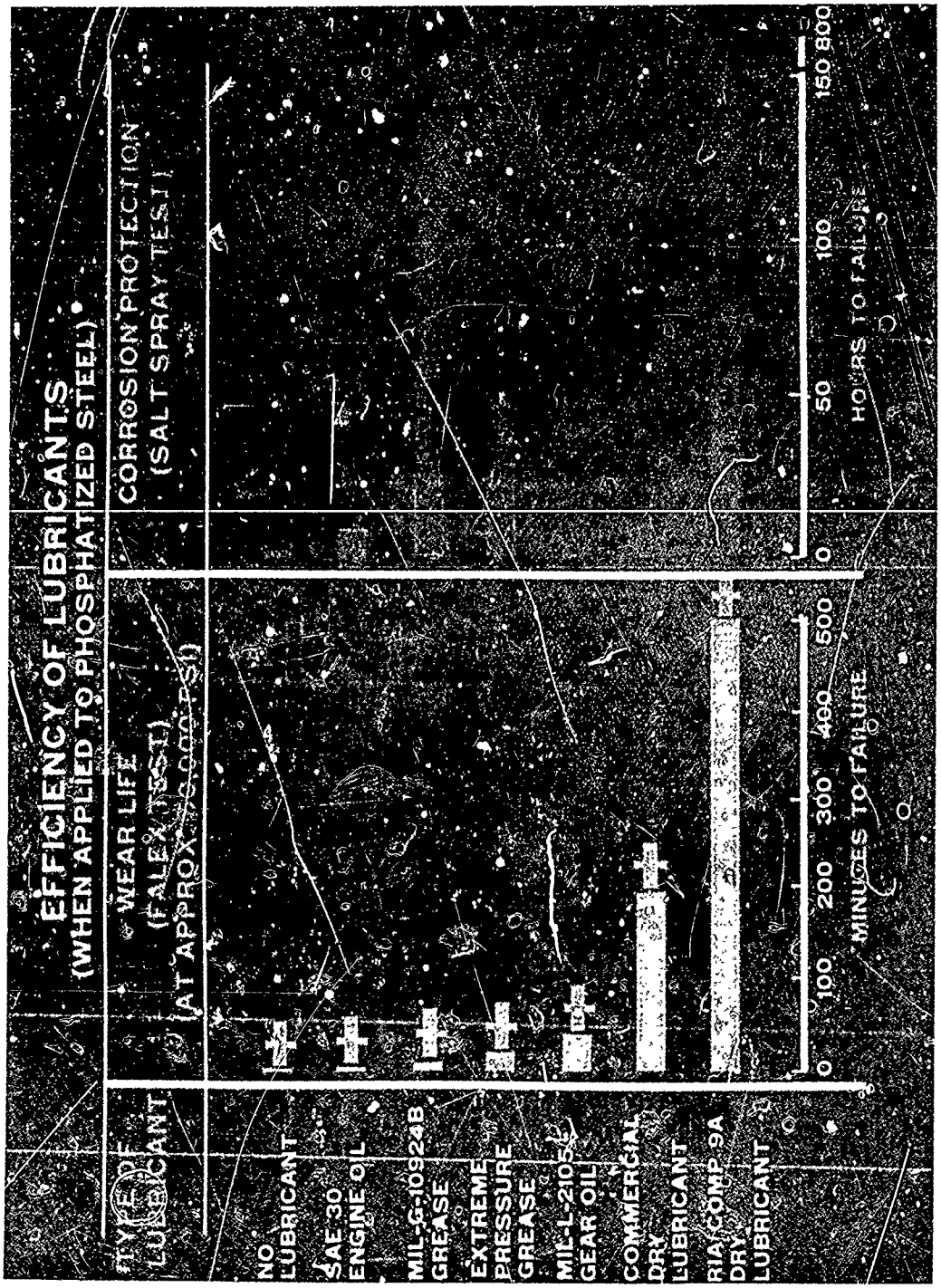
corrosion.

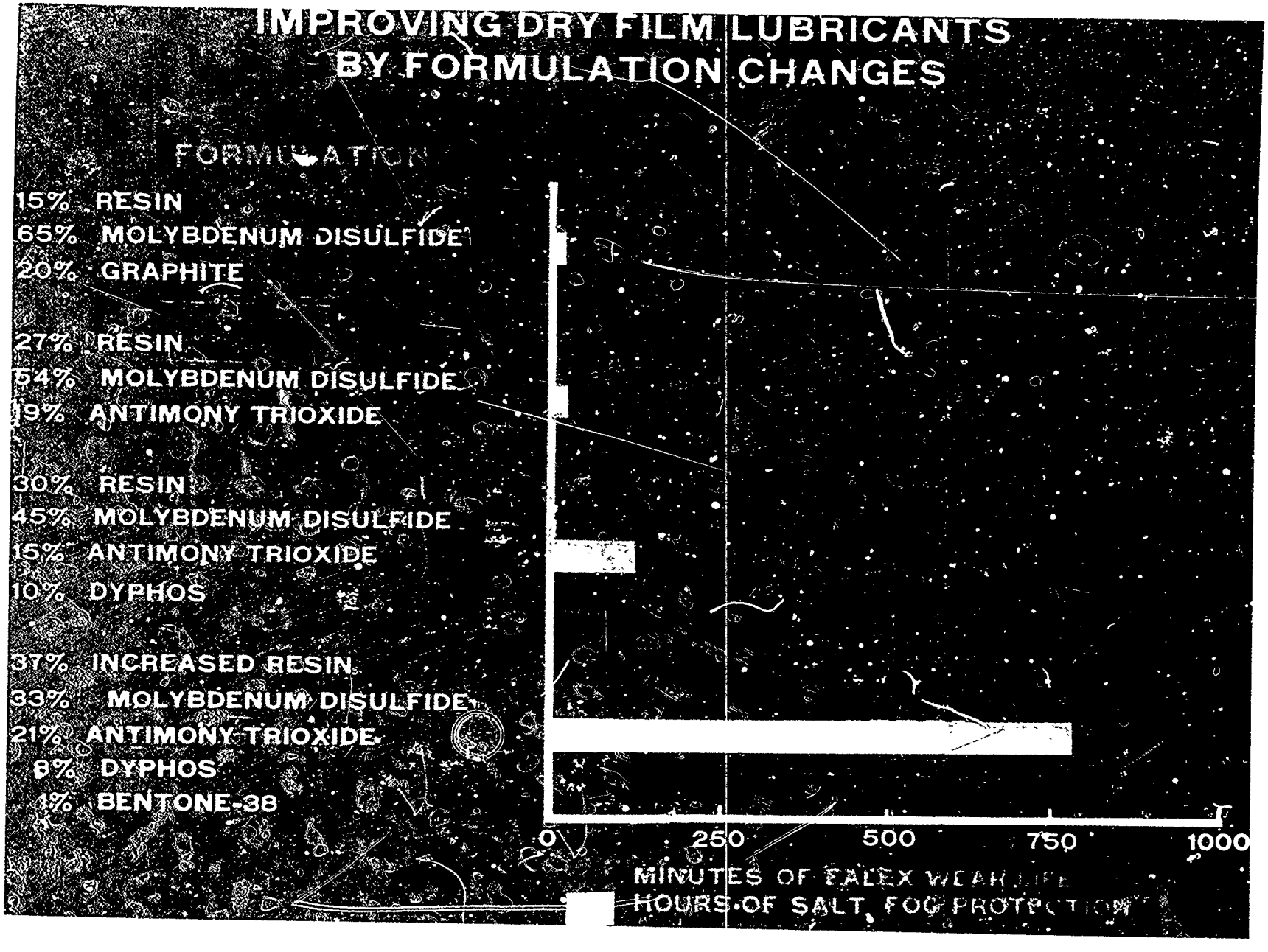


Corrosion.

Quality Assurance Testing; Corrosion Photos:
Closeup of Graphite Dry Film Coated Marman Clamp which Stress-Corrosion Cracked.

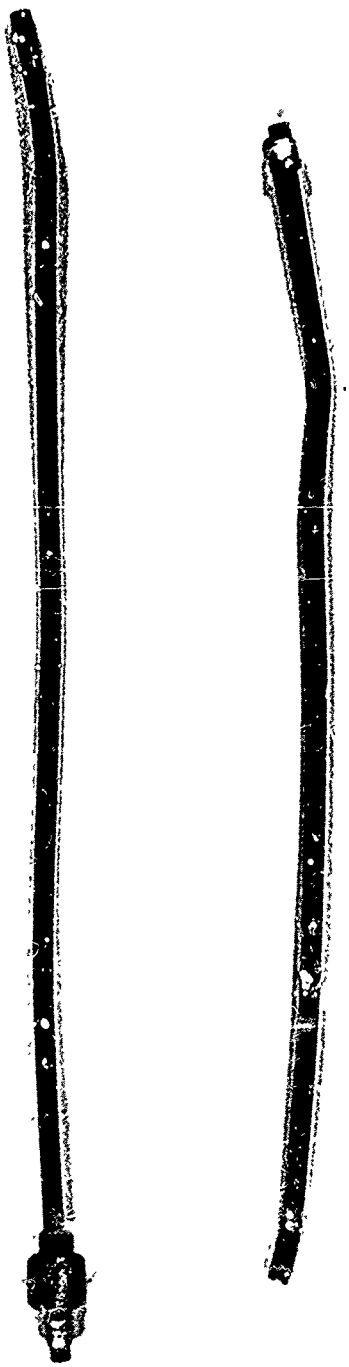

SHAKE WELL BEFORE USING
PREVENTS RUST
PENETRATES
LUBRICATES
Bux
DRI
SLIDE
MOLYBDENUM DISULFIDE BASE
MULTI-PURPOSE MAINTENANCE TOOL
1960


EFFICIENCY OF LUBRICANTS
(WHEN APPLIED TO PHOSPHATIZED STEEL)
TYPE OF LUBRICANT
WEAR LIFE (FALEX TEST) (AT APPROX. 3000 PSI)
CORROSION PROTECTION (SALT SPRAY TEST)
NO LUBRICANT
SAE 30 ENGINE OIL
MIL-G-10924B GREASE
EXTREME PRESSURE GREASE
MIL-L-2105 GEAR OIL
COMMERCIAL DRY LUBRICANT
RIA/COMP 9A DRY LUBRICANT
0
100
200
300
400
500
MINUTES TO FAILURE
0
50
100
150
800
HOURS TO FAILURE

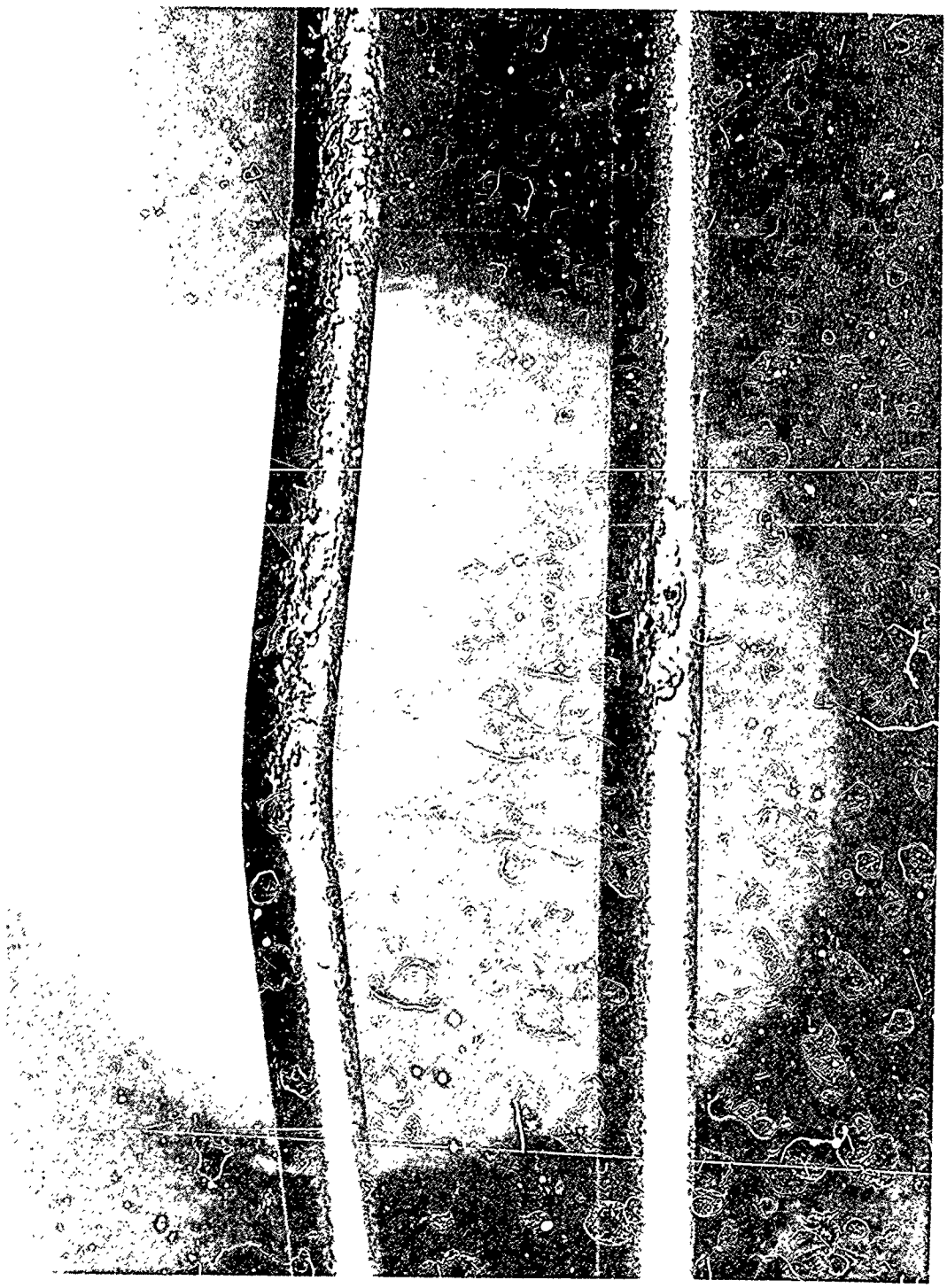

IMPROVING DRY FILM LUBRICANTS
BY FORMULATION CHANGES
FORMULATION
15% RESIN
65% MOLYBDENUM DISULFIDE
20% GRAPHITE
27% RESIN
54% MOLYBDENUM DISULFIDE
19% ANTIMONY TRIOXIDE
30% RESIN
45% MOLYBDENUM DISULFIDE
15% ANTIMONY TRIOXIDE
10% DYPHOS
37% INCREASED RESIN
33% MOLYBDENUM DISULFIDE
21% ANTIMONY TRIOXIDE
8% DYPHOS
1% BENTONE-38
0
250
500
750
1000
MINUTES OF TALEX WEAR LIFE
HOURS OF SALT FOG PROTECTION

NO! NO! NOT WITHOUT . . .

'INHIBITED' DRY LUBE

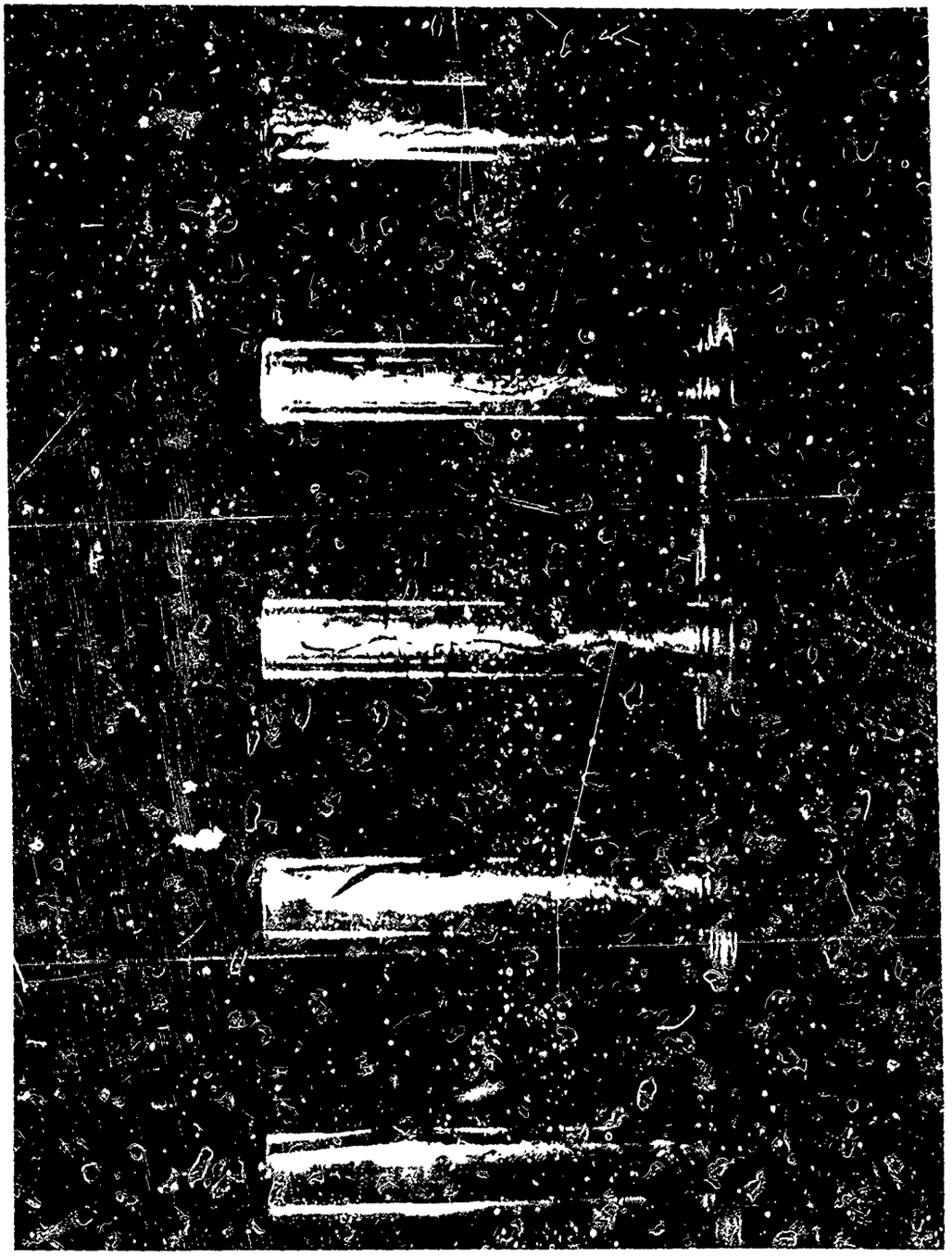


General View of Copper Coated Steel Tubing (Bundy Weld) Used as Fuel Lines in M113 APC.



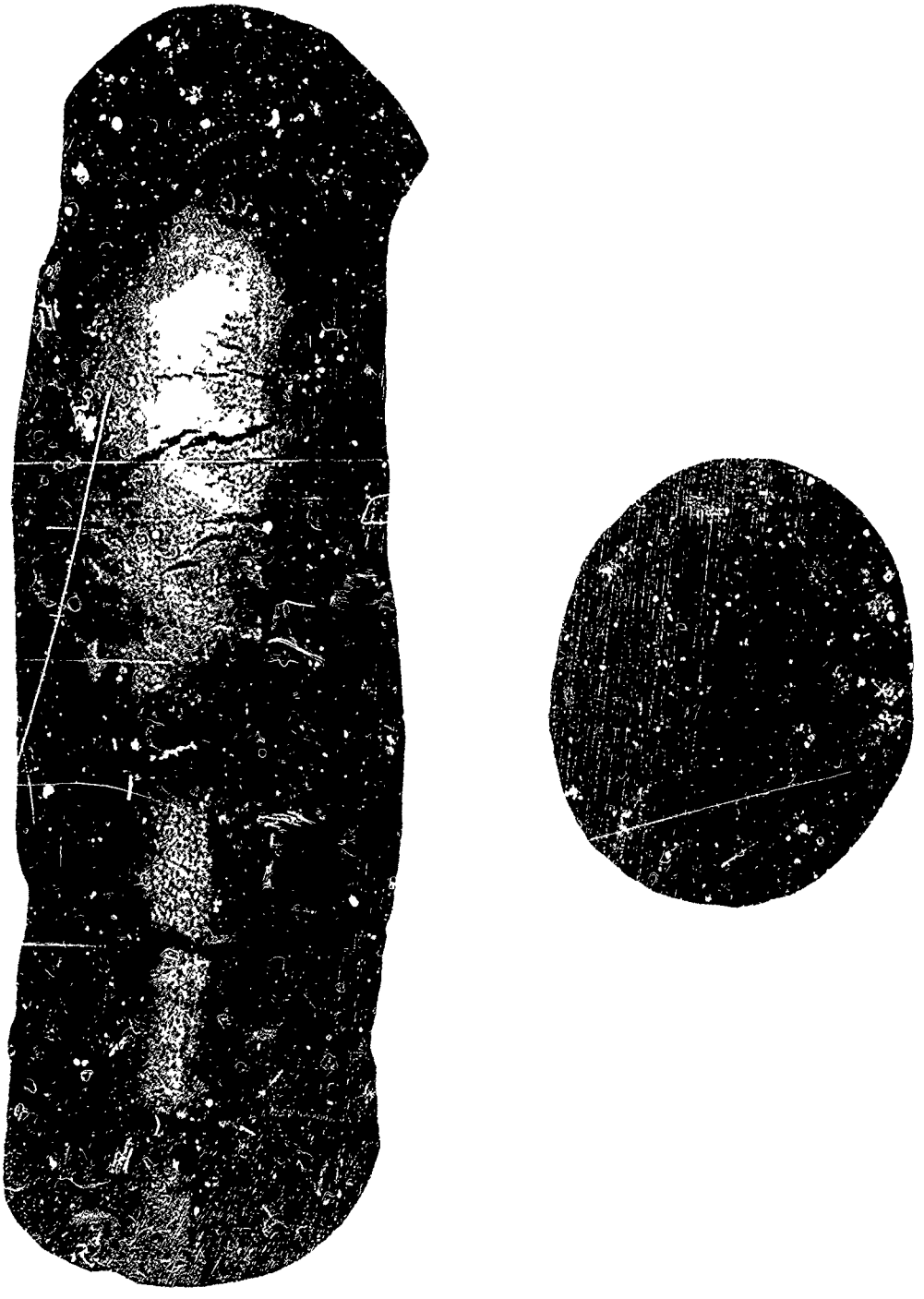
Closeup View of Copper Plated Steel (Bundy-Weld) Fuel Line Tubing from the M43 Tank.

Corrosion.

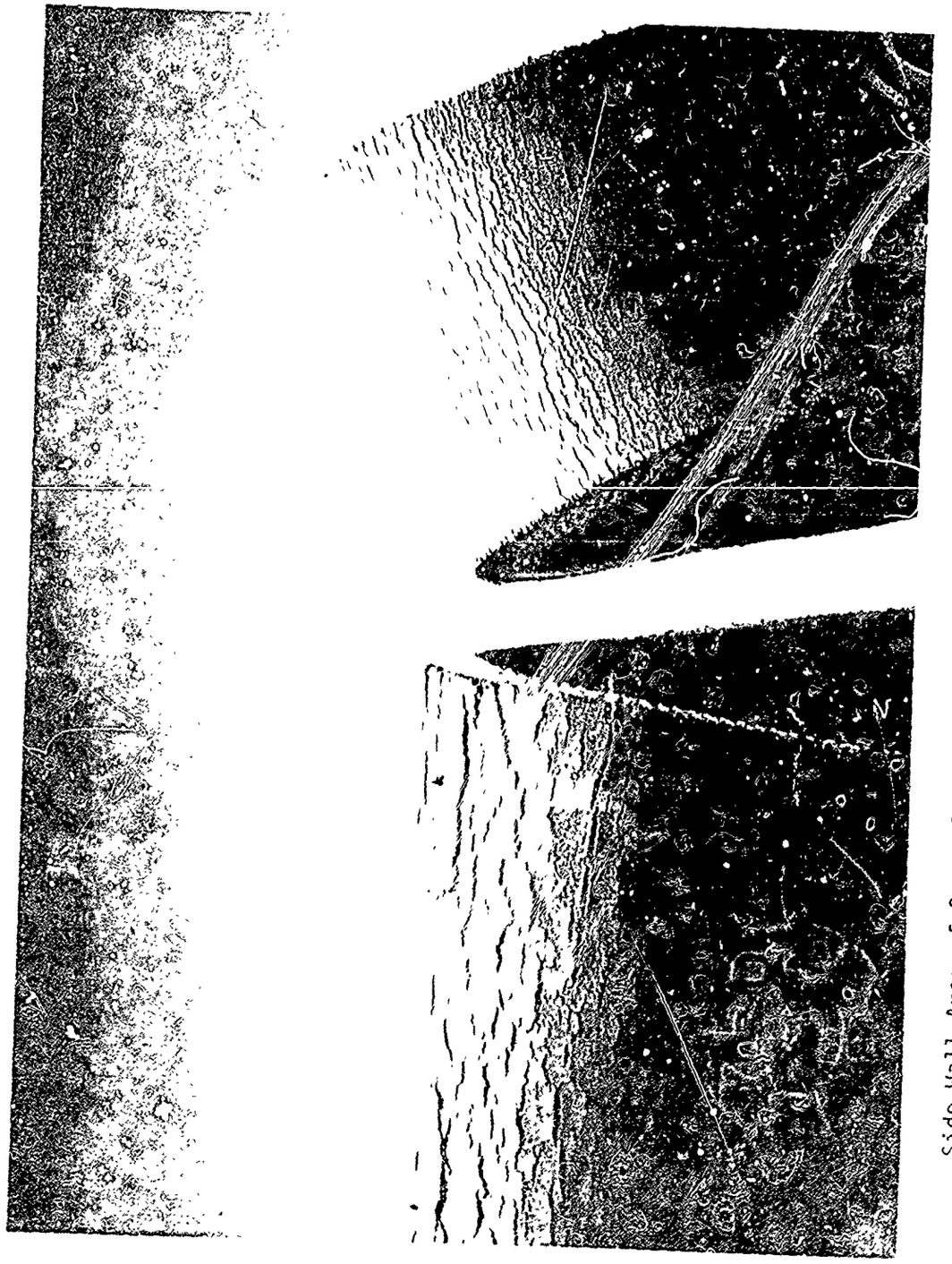


Electrical Insulators - Lexan - Polarized Light - Cracking Produced by Exposure to Fumes from Vapor Degreaser

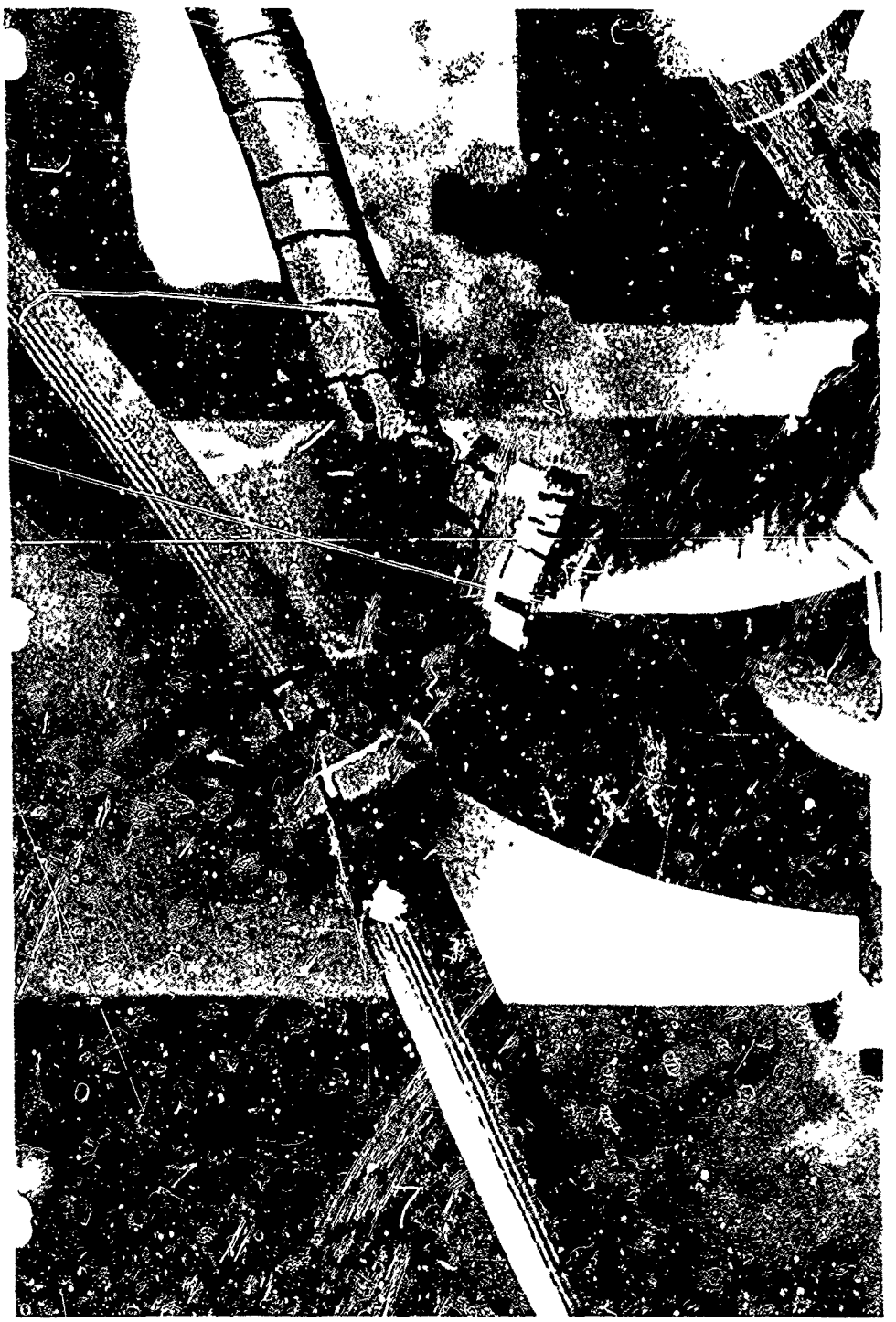
Tire from Ground Support Equipment for Hawk Missile - Less Than One Year Old - Ozone Cracking



GAS LINE, 1½ YEARS SERVICE.



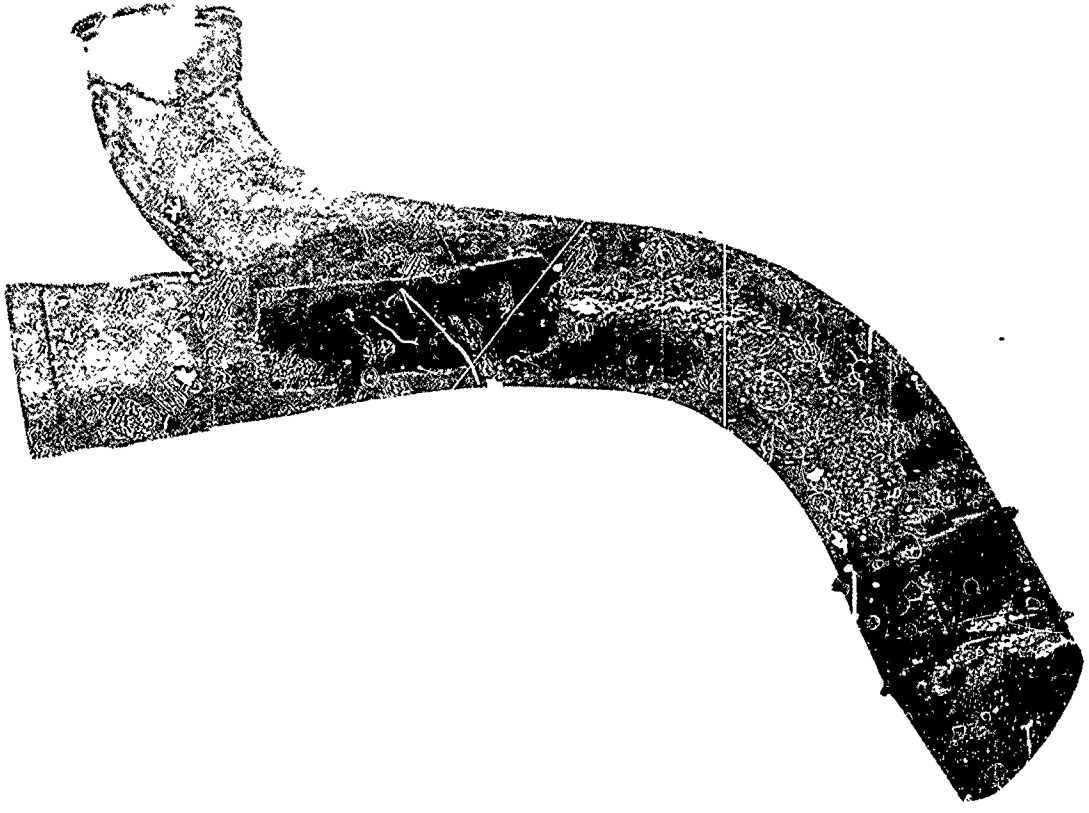
Side Wall Area of Cross-Country Tire Showing the Extent of Ozone Damage after One Year Exposure at Barstow CA.



Ozone Cracking of Cushion Seal

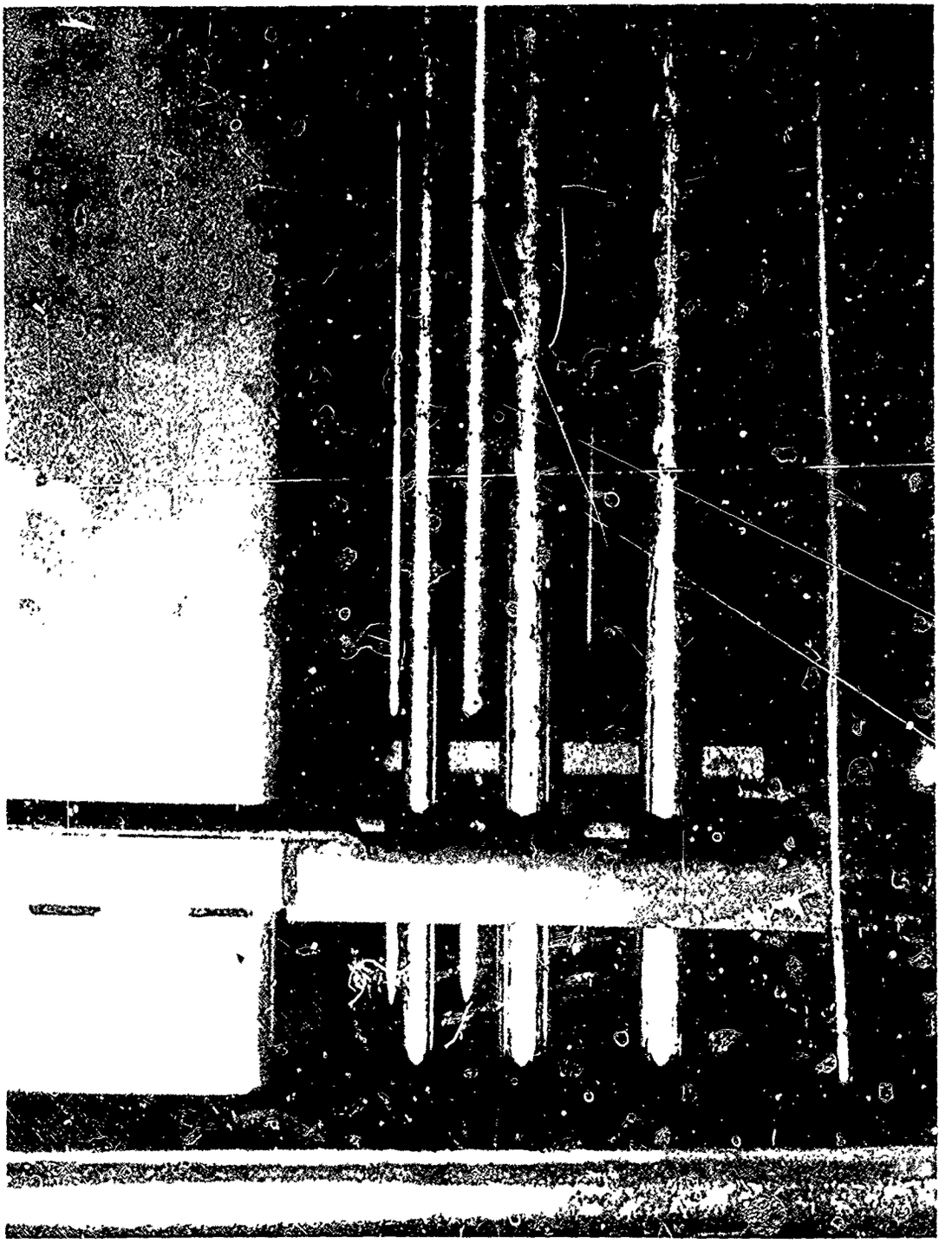
Helicopter - Cargo Area - Hat Section - Water Accumulation - No Drain Holes

B-52 Engine Cowl Skin - Misplaced Drain Hole Caused Crevice Corrosion in Beach Mark Areas

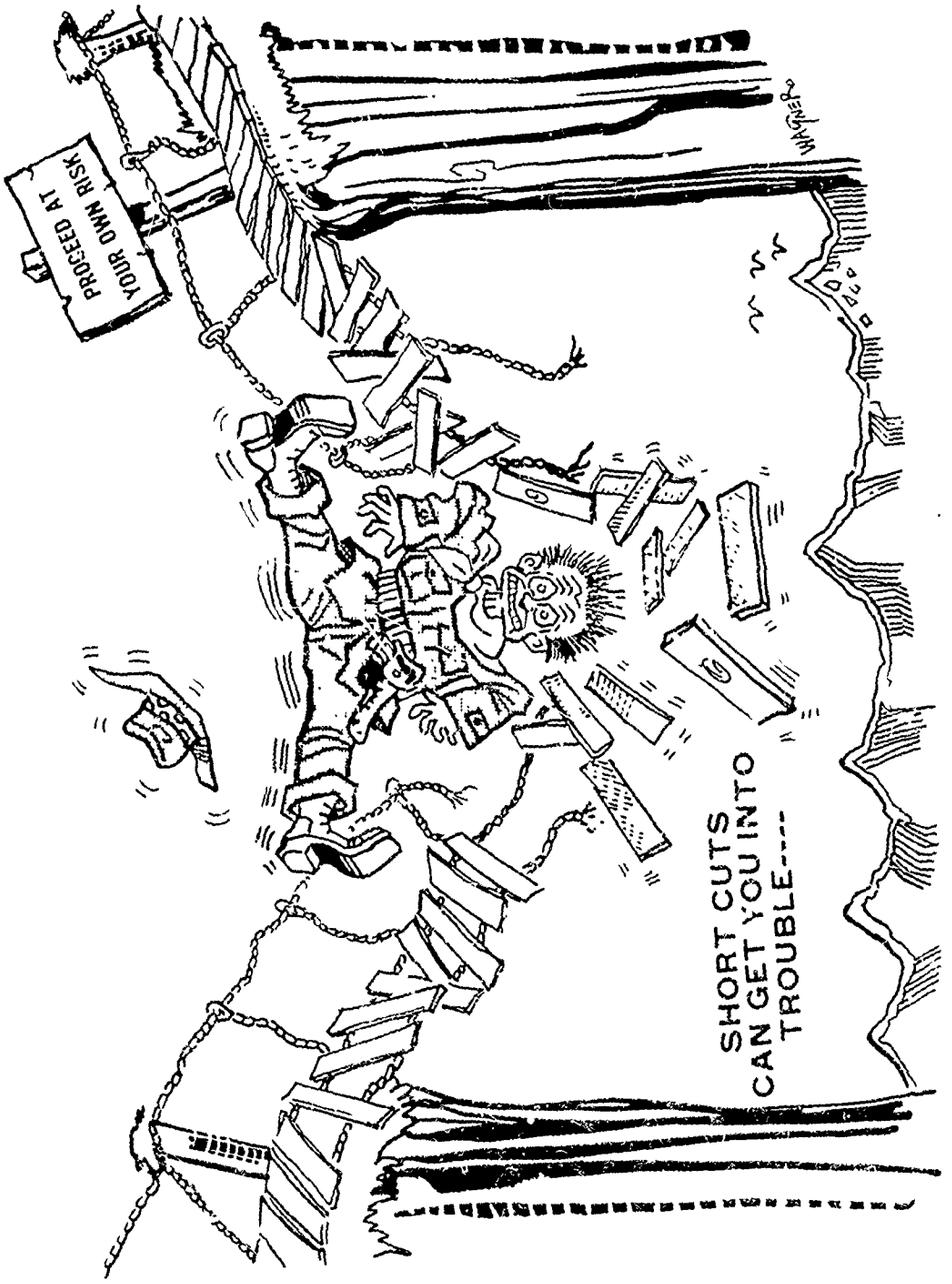


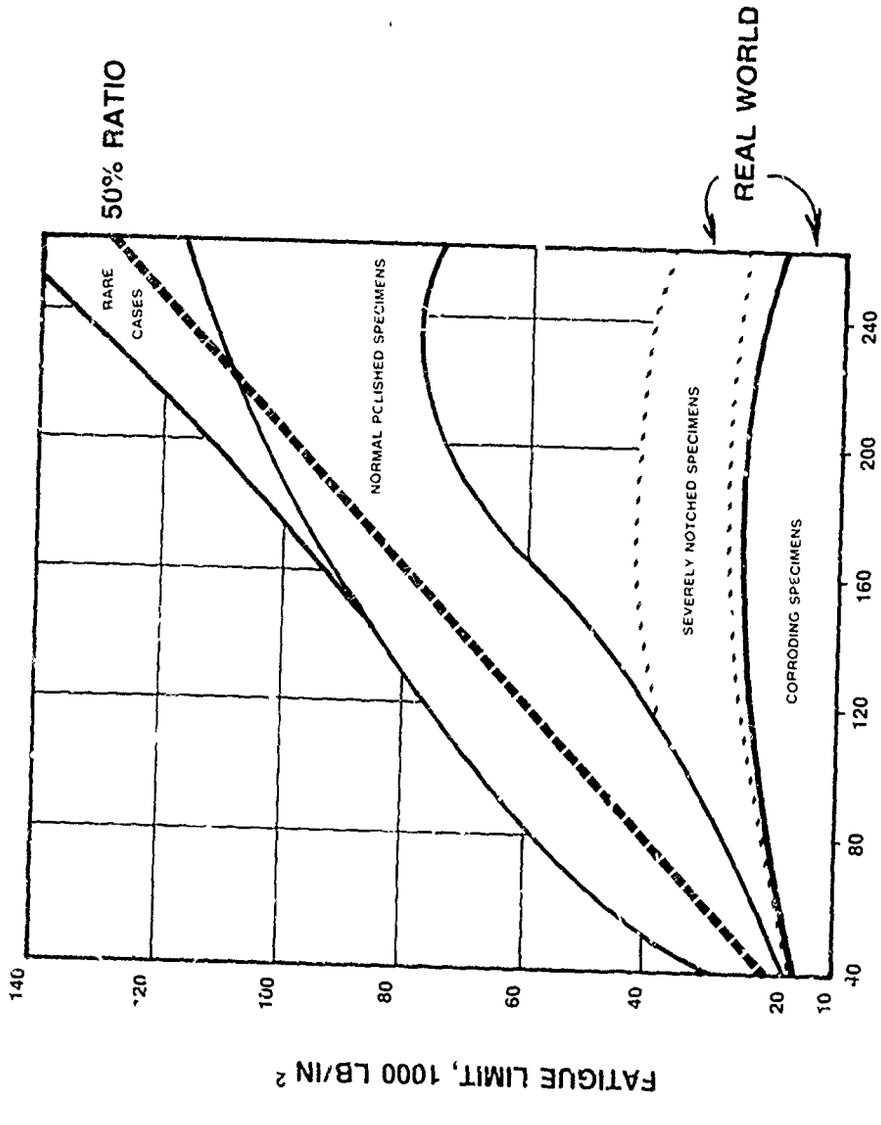
EXHAUST MANIFOLD. S2 NAVAL AIRCRAFT SHOWING FRACTURE CAUSED BY APPLICATION OF DECAL TO STAINLESS. (FAILURE AFTER 3 HOURS SERVICE)

USAWC, R&E Dir., S&T Lab. 11-199-7602/AMC-68

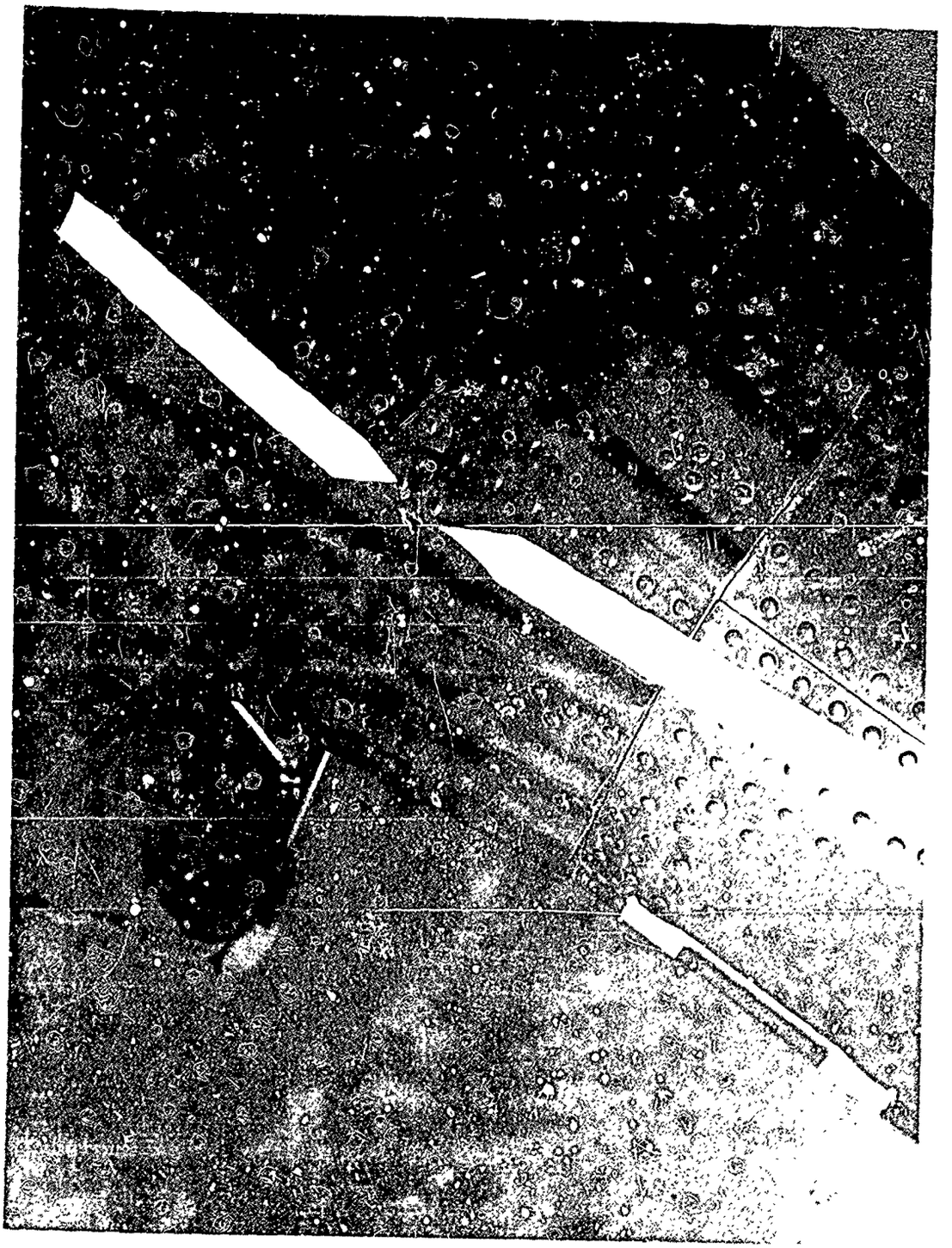


Corrosion.

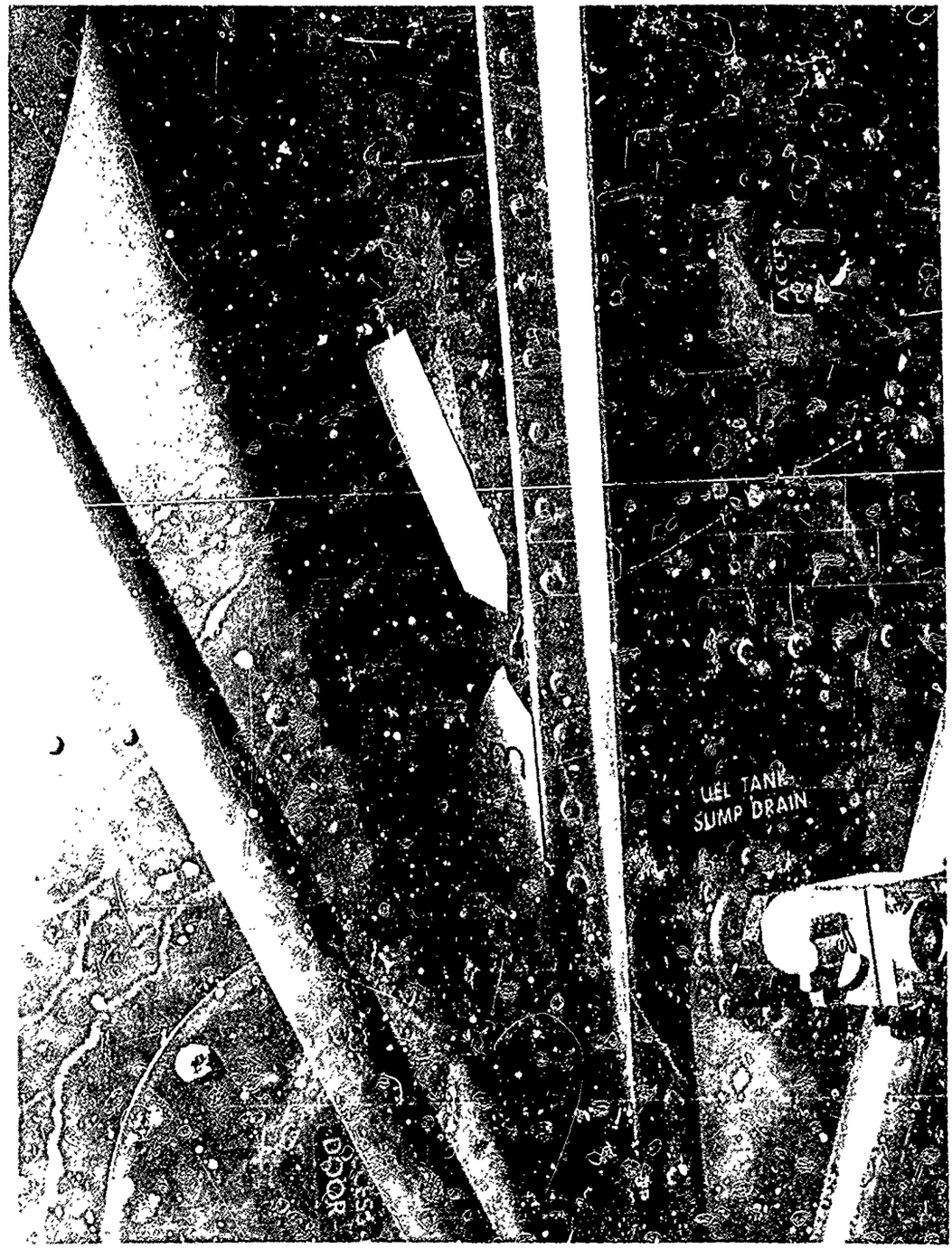

PROCEED AT
YOUR OWN RISK
SHORT CUTS
CAN GET YOU INTO
TROUBLE----



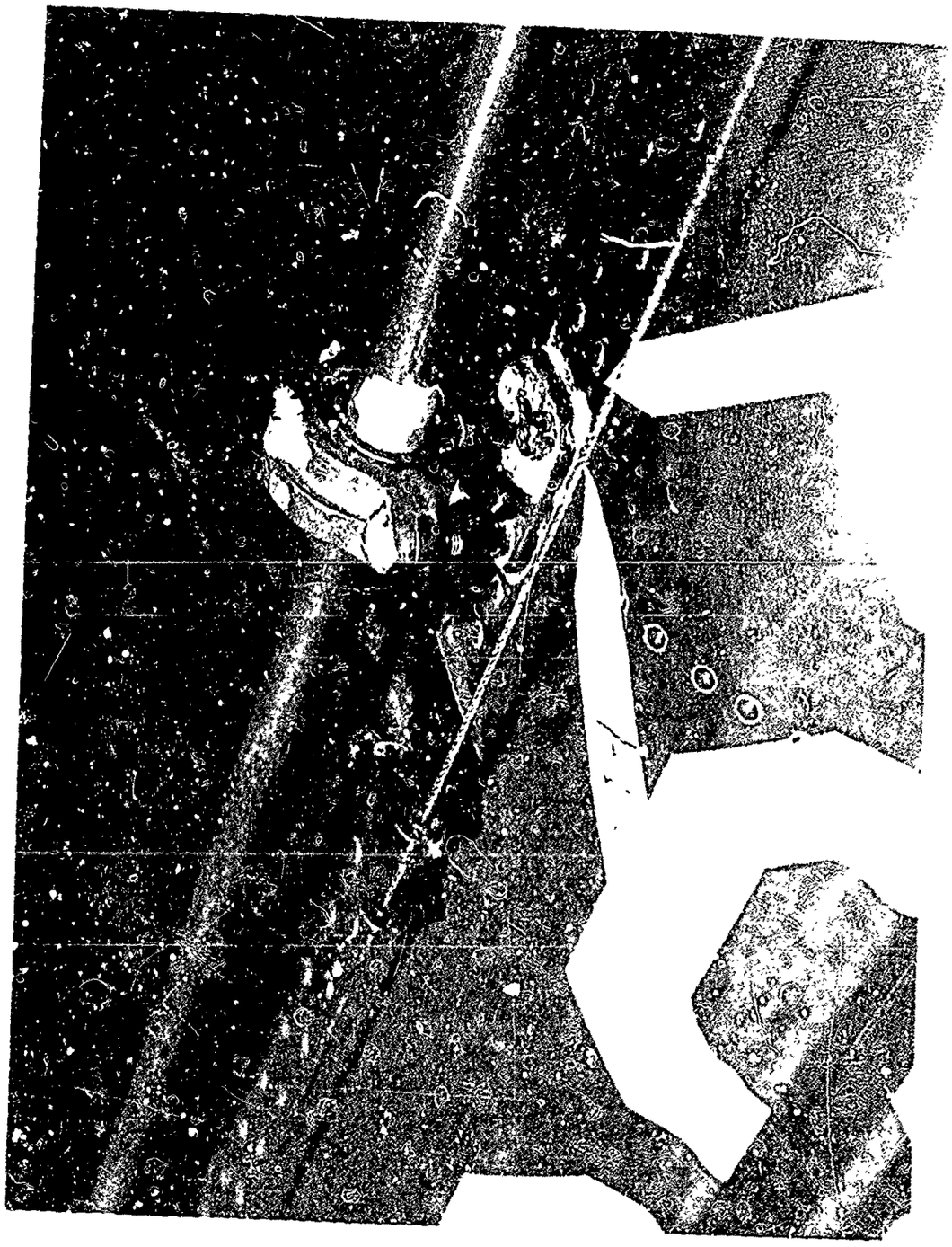
RELATION BETWEEN FATIGUE STRENGTH AND TENSILE STRENGTH FOR STEEL SPECIMENS



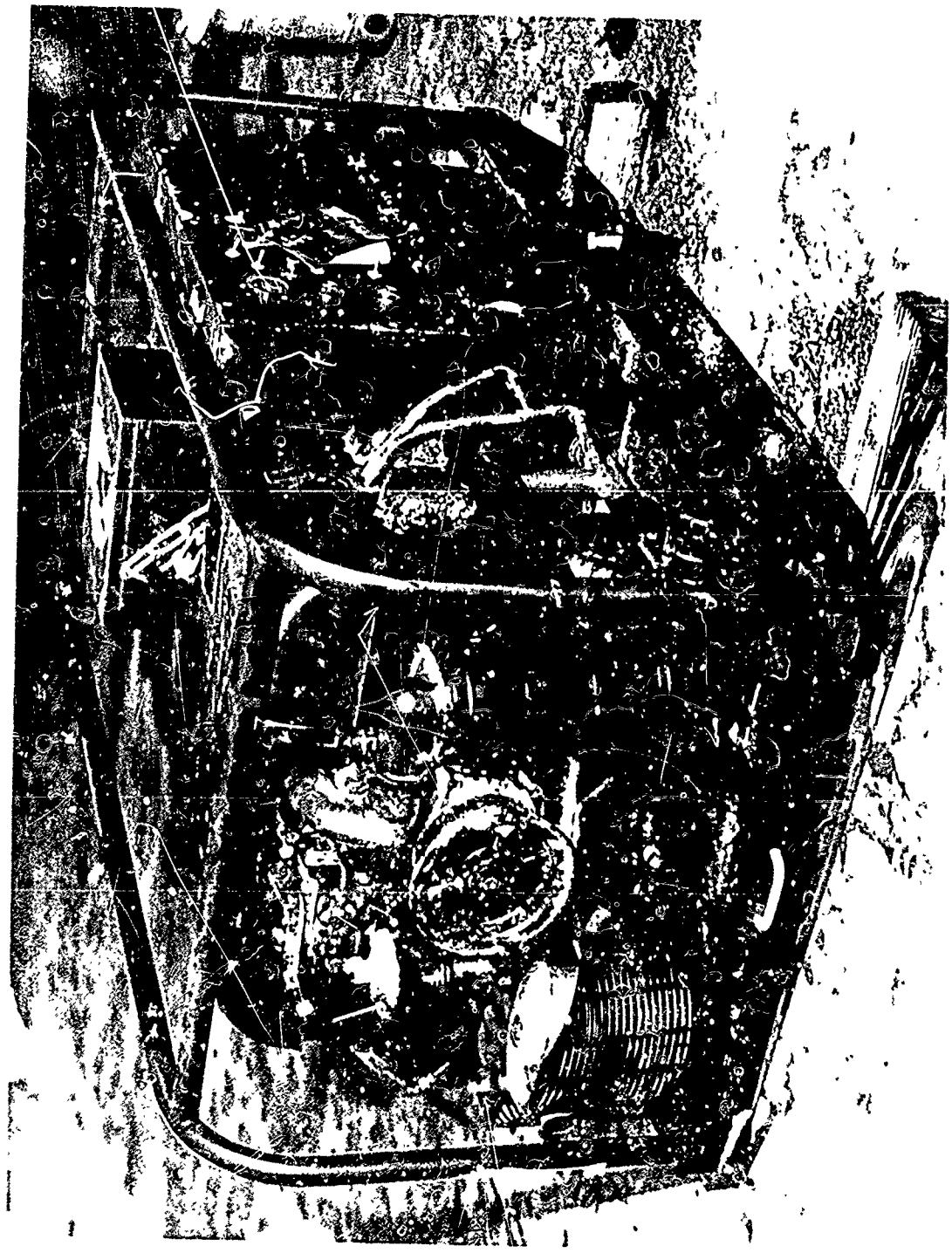
Helicopter - Fuselage - Attack Caused by Ammonium Nitrate Remaining in Ship in Which Helicopter Was Transferred



Helicopter-Ammonium Nitrate Attack on Tail Boom



Helicopter - Control Cable - Ammonium Nitrate Attack



Generator Set - Ammonium Nitrate Attack

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SHIPBOARD EXPOSURE TESTS OF ALUMINUM ALLOYS

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INTRODUCTION

A program is underway to determine quantitatively the corrosivity of the aircraft carrier environment by exposing a variety of materials on a carrier deck. The ultimate objective of the program is to develop an accelerated laboratory test that will more closely simulate that environment than do tests presently in use. The test will then be used to screen materials and protective finishes for naval aircraft.

The environment of a conventionally powered aircraft carrier which uses diesel fuel includes stack gas exhaust products in addition to sea spray. One of these products is sulfur dioxide. Some years ago analyses of moisture condensed on the surfaces of planes parked on the flight deck of four different carriers indicated the presence of sulfate ion and a pH from 2.4 - 4.0. The conventional carrier therefore could be said to have the combined effect of marine and industrial environment. On the other hand a nuclear powered carrier has no stack gases and should provide only a marine environment.

Permission was first obtained to mount a rack on a carrier powered by diesel fuel. It was decided for the first series of tests to use aluminum alloys that were available from a joint ASTM/Aluminum Association interlaboratory testing program. These alloys had been heat treated to provide varying susceptibilities to exfoliation and stress corrosion cracking and had been exposed to a variety of accelerated laboratory tests and natural environments,

both marine and industrial. Therefore, their corrosion behavior had already been well characterized and their use would allow for a comparison of the relative severity of a carrier environment with that of seacoast and industrial environments.

Subsequently the same lots of alloys were exposed on a nuclear powered carrier. Later a rack was placed on a third carrier which was diesel powered.

DESCRIPTION OF TESTS

MATERIALS

Exfoliation Specimens

The aluminum alloys used for the exfoliation tests were supplied by Alcoa, Kaiser and Martin-Marietta and are listed in Table I.

The 2.0 inch plate of 2124 aluminum alloy was machined in three steps to expose the varying thicknesses (T) of T/10, T/4, and T/2. (T/10 means that one tenth of the thickness is removed, T/4 that one quarter is removed, etc.) The 0.5 inch plate of 2124, the 7075 and 2024 extrusions were machined to expose the T/10 and T/2 planes. The 7178 aluminum alloy sheet had only the T/10 plane exposed.

STRESS CORROSION SPECIMENS

Tensile specimens 0.125 inch in diameter, were machined from the short transverse direction of 7075, 2.5 inch thick, aluminum alloy plate supplied by Alcoa. Tempers were as follows:

Temper	Expected Resistance to Stress Corrosion
T651	Low
T7X51	Medium
T7351	High

Properties of the plate used were as follows:[1]

Temper[a]	Electrical Conductivity, % IACS[c]		Test Direction	Tensile Properties: Tensile Strength, ksi	(MPa)	Yield Strength, ksi	(MPa)	Elongation, % in 4D
T651	surface	32 2	longitudinal	81 6	(563)	72 9	(503)	11.0
	T/10	31 5	long transverse	80.9	(558)	70 '	(483)	8.0
	T/2	32.6	short transverse	72.1	(497)	63.3	(436)	4.0
T7X51	surface	37.5	longitudinal	77 8	(536)	65.7	(453)	12 0
	T/10	37 1	long transverse	73 9	(510)	63.3	(436)	10 0
	T/2	38.7	short transverse	70 4	(485)	60 8	(419)	4.0
T7351	surface	41 0	longitudinal	67.0	(462)	55 1	(380)	10 0
	T/10	40 6	long transverse	66 0	(455)	54.5	(376)	10 0
	T/2	41.0	short transverse	59.1	(407)	51.7	(356)	4 0

PREPARATION FOR EXPOSURE TESTS

Exfoliation specimens were prepared as follows:

1. Degreased with solvent
2. Etched in 5% by weight NaOH at 80°C (176°F), 1 to 3 min.
3. Rinsed in water
4. Desmutted in concentrated HNO_3 for 30 sec.
5. Rinsed in deionized water
6. Dried with oil free air

Stress Corrosion Specimens

Specimens, stressing fixtures and method of stressing are illustrated in Figure 3 of ASTM G49.[2]

After stressing in frames that had been sulfuric acid anodized and sealed, the frames were painted with MIL-P-23377 epoxy primer and MIL-C-81773 polyurethane topcoat. The ends were dipped in the paint to protect the threads. Only the gage length was left unpainted. The specimens were then degreased prior to exposure. Triplicate specimens were exposed at each of the following stress levels:

T651 - 25, 15, 8 ksi

T7X51 - 45, 35, 25 ksi

T7351 - 43 ksi

Exposure Racks

For the tests on the first carrier, a steel rack 8 feet by 1 foot, was fabricated, cadmium plated, chromated, and painted with MIL-P-23377 epoxy primer and MIL-C-81773 polyurethane topcoat. The rack was designed so that the specimens would be exposed at an angle of 45° from the vertical. Exfoliation specimens were mounted on the rack with plastic bolts. MIL-S-8802 polysulfide sealant was applied around the bolts to avoid crevice corrosion. The rack was welded onto the radar platform about 7-8 feet above the flight deck. Figure 1 shows the rack in place on the carrier. The radar platform is aft of the ship stacks and so provides an area exposed to both stack gases and sea spray The racks for the other carriers were the same as the first but were installed about 12-14 feet above the flight deck.

Deployment

The first carrier powered by diesel fuel was deployed to the Mediterranean for eight months from June 1978 to March 1979. An inspection trip was made to the carrier after four months. At the end of eight months the ship returned and the specimens were removed at that time.

The nuclear carrier was deployed first to the Mediterranean from July 1979 to December 1979 and then to the Indian Ocean from January 1980 to May 1980. No interim inspection was made so the times to the beginning of exfoliation on the susceptible specimens are not known. The specimens were removed when the ship returned at the end of ten months.

The third carrier was deployed in the Western Pacific and the Indian Ocean from February to October 1980. No interim inspections were made. Specimens were removed at the end of the eight months.

RESULTS AND DISCUSSION

Exfoliation Tests

The results of the exfoliation tests on the three carriers are summarized in Table 2. The same type of attack occurred for the various heat treatments of each alloy. The appearance of low and intermediate resistance samples of 2124 and 7075 from the first two carriers are presented in Figures 2 and 3. These are typical of all the low and intermediate resistance tempers. The appearance of the low resistance 2124 and 7075 from the third carrier is shown in Figure 4. All of the high resistance samples showed only pitting attack.

The most obvious conclusion to be drawn from study of Figures 2 and 3 is that the attack on specimens exposed on the nuclear carrier was more severe than on those exposed on the first conventional carrier. This is attributed to the effect of temperature. The nuclear carrier was in the Indian Ocean for five months where temperatures ranged from 80-95°F.[3] The first conventional carrier was in the Mediterranean for its entire deployment where temperatures were 20-30 degrees lower most of the time. In the Indian Ocean there was little rain to wash off the salt accumulations. With the sun shining on the panels, surface temperatures could be much higher than ambient.

It was unfortunate that no interim inspection on the nuclear carrier was possible. Four month inspection data from the other carrier showed slight corrosion occurring to that point, most taking place in the last four months. Since the nuclear carrier was in the Mediterranean for the first five months also, it is not unreasonable to assume corrosion attack was also slight until the ship moved to the Indian Ocean.

That the temperature effect is more important than the effect of stack gases was verified by the results from the third carrier. This was a conven-

tional carrier with stack gases but was in the Indian Ocean for three months and in the warmer regions of the Western Pacific for the remainder of its cruise. The attack on the low resistance 2124 - 0.5 in. particularly resembled that of the nuclear carrier.

One striking and important conclusion can be made from these tests. The environment of an aircraft carrier, however powered, is considerably more corrosive than seacoast or industrial environments. This is vividly demonstrated in Figure 5 which is based on data from Sprowls et al.[4] It took only eight months on a carrier to develop severe exfoliation corrosion on susceptible alloys whereas at the most severe seacoast location (Point Judith, R.I.) it took twelve months and in the most severe industrial location (Brookfield, Illinois) three years. The other conclusion that can be made is that the effect of climate is more significant than presence or absence of sulfur containing stack gases.

Stress Corrosion Tests

Times to failure are presented in Table 3 and compared with those from Cape Canaveral for the same alloys and tempers. The latter data is taken from a paper which contains the results on the entire interlaboratory testing program on the 2.5 inch, 7075 plate.[1] Times to failure for the T651 and T7X51 tempers on the carrier are analogous to those at Cape Canaveral.

Metallographic examination was made on one broken specimen from each stress level. Findings were as follows:

T651 temper - 25 ksi - no secondary cracks
15 ski - several secondary cracks
8 ksi - many secondary cracks

T7X51 temper - 45, 35, and 25 ksi - few secondary cracks

FUTURE PLANS

The carrier exposure tests have been expanded to include a variety of materials that are used or being considered for use in naval aircraft. These include graphite epoxy composites, metal/metal matrix composites, developmental paint systems and corrosion preventive compounds.

As stated earlier, the ultimate objective of the carrier tests is the development of an accelerated laboratory test that will more closely simulate the carrier environment. The total immersion EXCO test (ASTM G34)[5] gives good correlation with the results of the carrier tests on the aluminum alloys described here. An immersion test is not however considered appropriate for testing composites, paints and corrosion preventives. Tests conducted to date have contributed valuable information on the important variables inherent in the carrier environment. Efforts are underway to devise a laboratory test method that will take more of these variables into account.

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1. "Evaluation of a Proposed Standard Method of Testing for Susceptibility to Stress Corrosion Cracking of High Strength 7XXX Series Aluminum Alloy Products," D. O. Sprowls, et al, Stress Corrosion - New Approaches, STP 610, ASTM, 1976, p. 3.

2. "Standard Recommended Practice for Preparation and Use of Direct Tension SC Test Specimens," ANSI/ASTM G-49, Annual Book of ASTM Standards, Part 10, ASTM 1980.

3. Information obtained from carrier meteorological records.

4. "Exfoliation Corrosion Testing of High Strength Aluminum Alloys in the Atmosphere," D. O. Sprowls, T. J. Summerson and R. I. Lindberg, presented at ASTM Symposium on Atmospheric Corrosion, May 1980, to be published in ASTM STP.

5. "Standard Method of Test for Exfoliation Susceptibility in 2XXX and 7XXX Series Aluminum Alloys," ASTM G-34, Annual Book of ASTM Standards, Part 10, ASTM, 1980

TABLE I

ALUMINUM ALLOYS USED FOR EXFOLIATION TESTS

Alloy/Form	Temper	Thickness mm (in.)	Expected Resistance to Exfoliation	Dimensions mm (in.)
2124 Plate	T851	12.2 (0.5)	High	76 x 152 (3 x 6)
	T351		Intermediate	
	T351 + 0.5 hrs at 375°F		Low *	
	T851	50.8 (2.0)	High	
	T351		Intermediate	
	T351 + 0.5 hrs at 375°F		Low	
7075 Extrusion		12.2 (0.5)	High	76 x 76 (3 x 3)
			Intermediate	
			Low *	
7178 Sheet	T6	2.3 (.091)	Low	76 x 152 (3 x 6)
	T6 + 10 hrs at 325°F		Intermediate	
	T6 + 11 hrs at 325°F		High	

* Only these two materials were exposed on the third carrier.

TABLE 2

EXFOLIATION RATINGS (ASTM G34-79)

	CONVENTIONAL CARRIER		NUCLEAR CARRIER	THIRD CARRIER (CONVENTIONAL)
	4 MOS.	8 MOS.	10 MOS.	8 MOS.
2124 - 12.2 MM (0.5 IN.) PLATE				
LOW RESISTANCE				
T/10	EA	ED	ED	ED
T/2	EA	EC	ED	ED
INTERMEDIATE RESISTANCE				
T/10	EA	EC	ED	
T/2	P	P	EC	
HIGH RESISTANCE				
T/10	P	P	P	
T/2	P	P	P	
2124 - 50.8 MM (2 IN.) PLATE				
LOW RESISTANCE				
T/10	EB	ED	ED	
T/4	EB	ED	ED	
T/2	EA	EC	ED	
INTERMEDIATE RESISTANCE				
T/10	P	P	EB	
T/4	EA	EC	EC	
T/2	EA	EC	ED	
HIGH RESISTANCE				
T/10	P	P	P	
T/4	P	P	P	
T/2	P	P	P	

P - PITTING

EXFOLIATION RATINGS

A	SLIGHT	C	SEVERE
B	MODERATE	D	VERY SEVERE

TABLE 2 (CONT.)

EXFOLIATION RATINGS (ASTM G34-79)

	CONVENTIONAL CARRIER		NUCLEAR CARRIER	THIRD CARRIER (CONVENTIONAL)
	4 MOS.	8 MOS.	10 MOS.	8 MOS.
7075 - 12.2 MM (0.5 IN.) EXTRUSION				
LOW RESISTANCE				
T/10	EB	ED	ED	EC
T/2	EA	EB	EC	EB
INTERMEDIATE RESISTANCE				
T/10	EA	EB	EB	
T/2	P	P	EA	
HIGH RESISTANCE				
T/10	P	P	P	
T/2	P	P	P	
7178 - 2.3 MM (0.091) IN. SHEET				
LOW RESISTANCE				
T/10	EA	ED	ED	
INTERMEDIATE RESISTANCE				
T/10	P	P	PB	
HIGH RESISTANCE				
T/10	P	P	P	

P - PITTING

EXFOLIATION RATINGS

A	SLIGHT	C	SEVERE
B	MODERATE	D	VERY SEVERE

TABLE 3

RESULTS OF STRESS CORROSION TESTS ON 7075 ALUMINUM ALLOY

Temper	Stress Level MPa/ksi	DAYS TO FAILURE			
		Aircraft Carrier *		Seacoast Cape Canaveral	
		Spec. No.		Exposed Nov 71	Exposed May 72
T651	172/25	1	Between 9 and 16	5	1
		2	< 9	5	2
		3	< 9	7	2
				7	2
	103/15	4	< 9	7	5
		5	< 9	5	5
		6	< 9	7	5
				9	5
	55/8	7	Between 9 and 16	12	6
		8	Between 9 and 16	22	27
		9	< 9	18	6
T7X51	310/45	10	Between 26 and 35	26	6
		11	Between 9 and 16	90	6
		12	Between 9 and 16	93	27
	241/35	13	Between 9 and 16	30	5
		14	Between 9 and 16	37	9
		15	Between 9 and 16	37	27
				55	76
	172/25	16	Between 16 and 26	70	76
		17	Between 16 and 26	37	248
		18	Between 16 and 26	545	342
T7351	296/43	19)		< 730	
		20)	- No failure in 8 months	855	
		21)		30	No
				107	Failures (5)
				No Failures (5)	No Failures (5)

* Inspections were made at 9, 16, 26 and 35 day by carrier personnel.

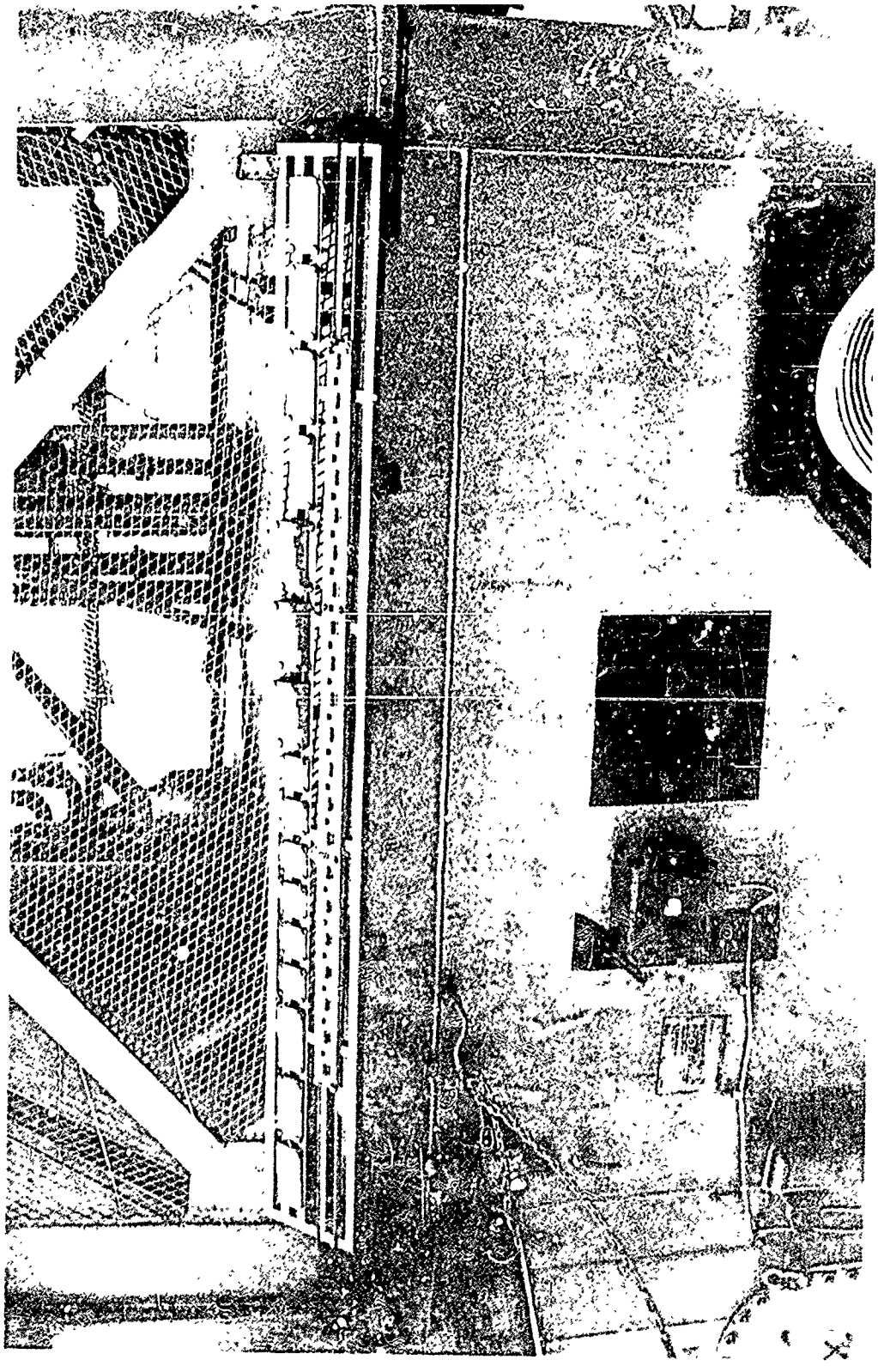
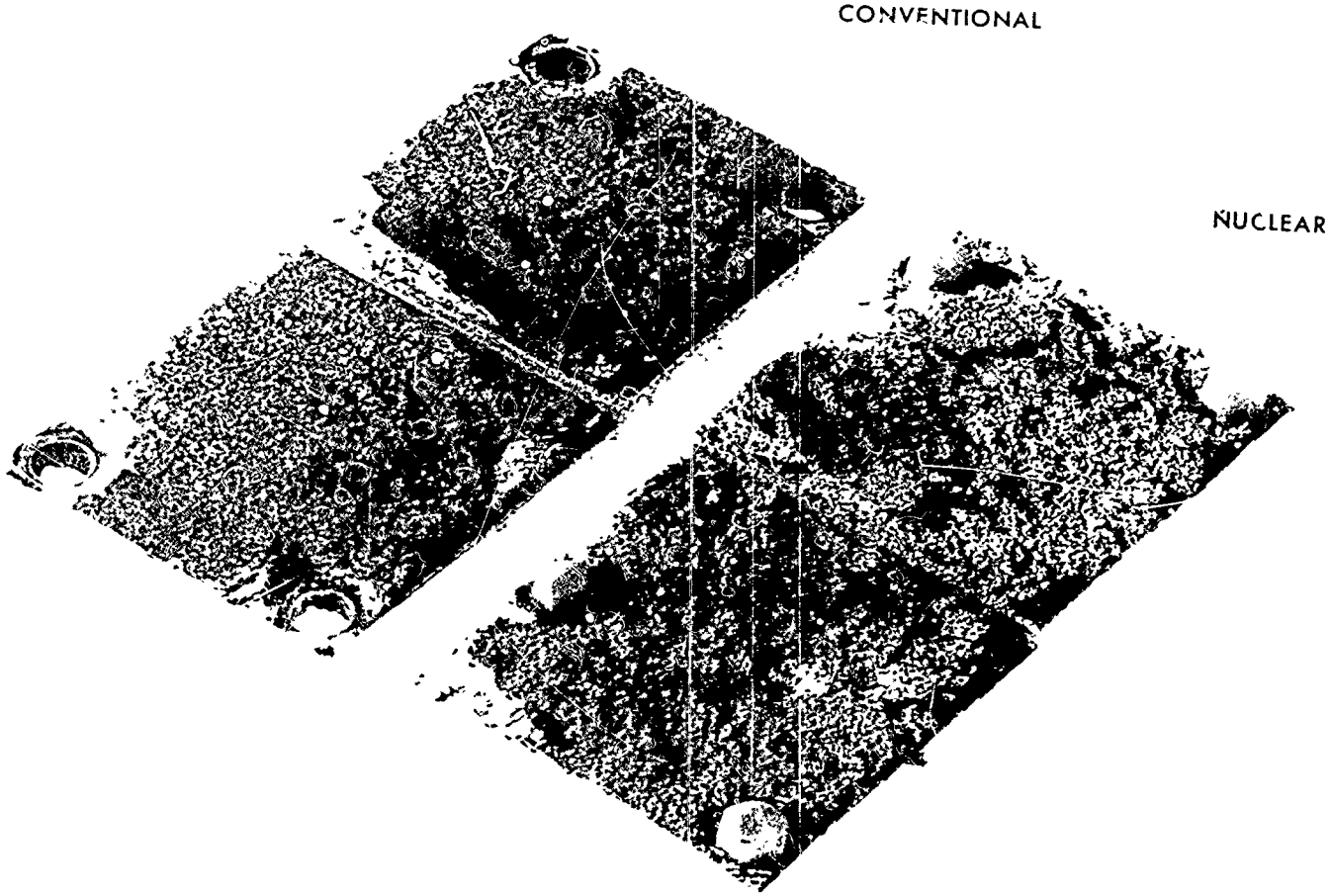


FIGURE 1



2124 - 0.5 INCH PLATE
LOW RESISTANCE

FIGURE 2

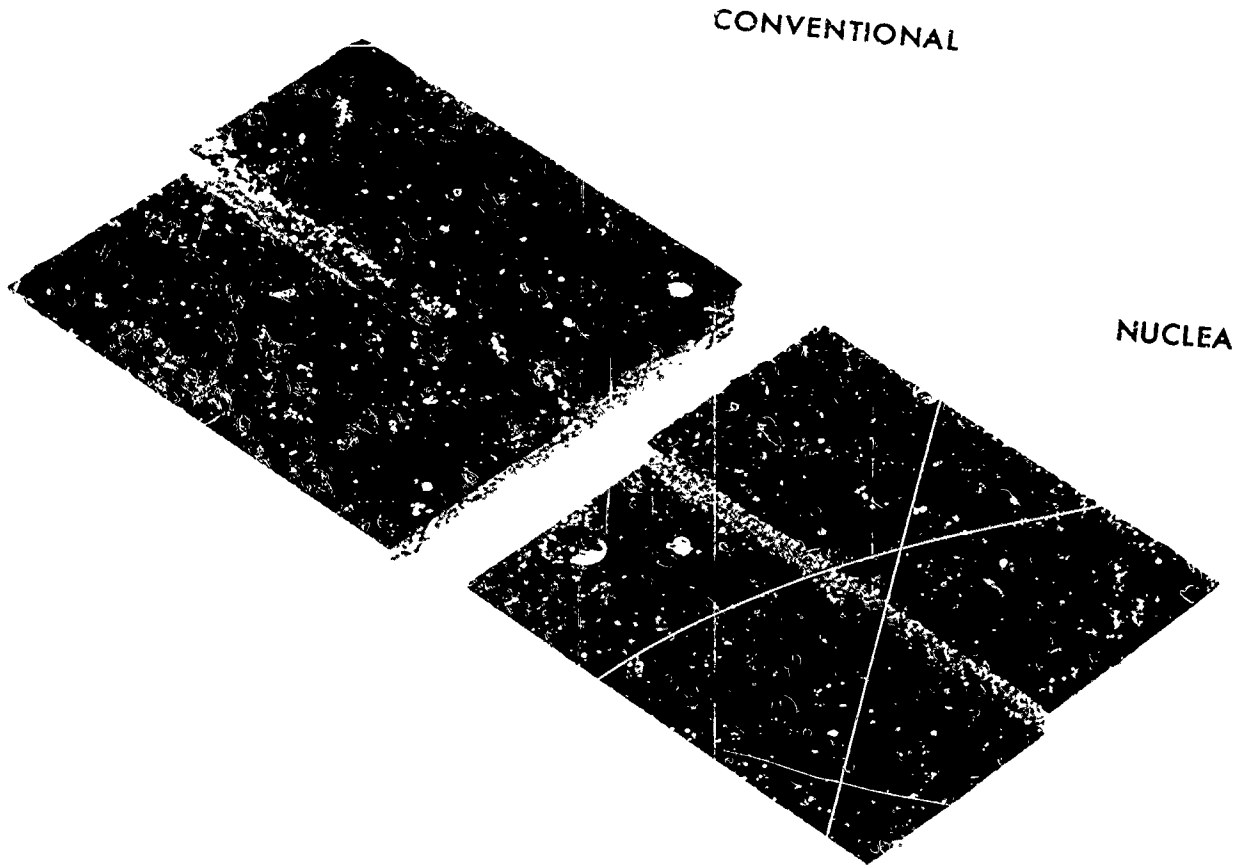


FIGURE 3 7075 - 0.5 INCH EXTRUSION
LOW RESISTANCE

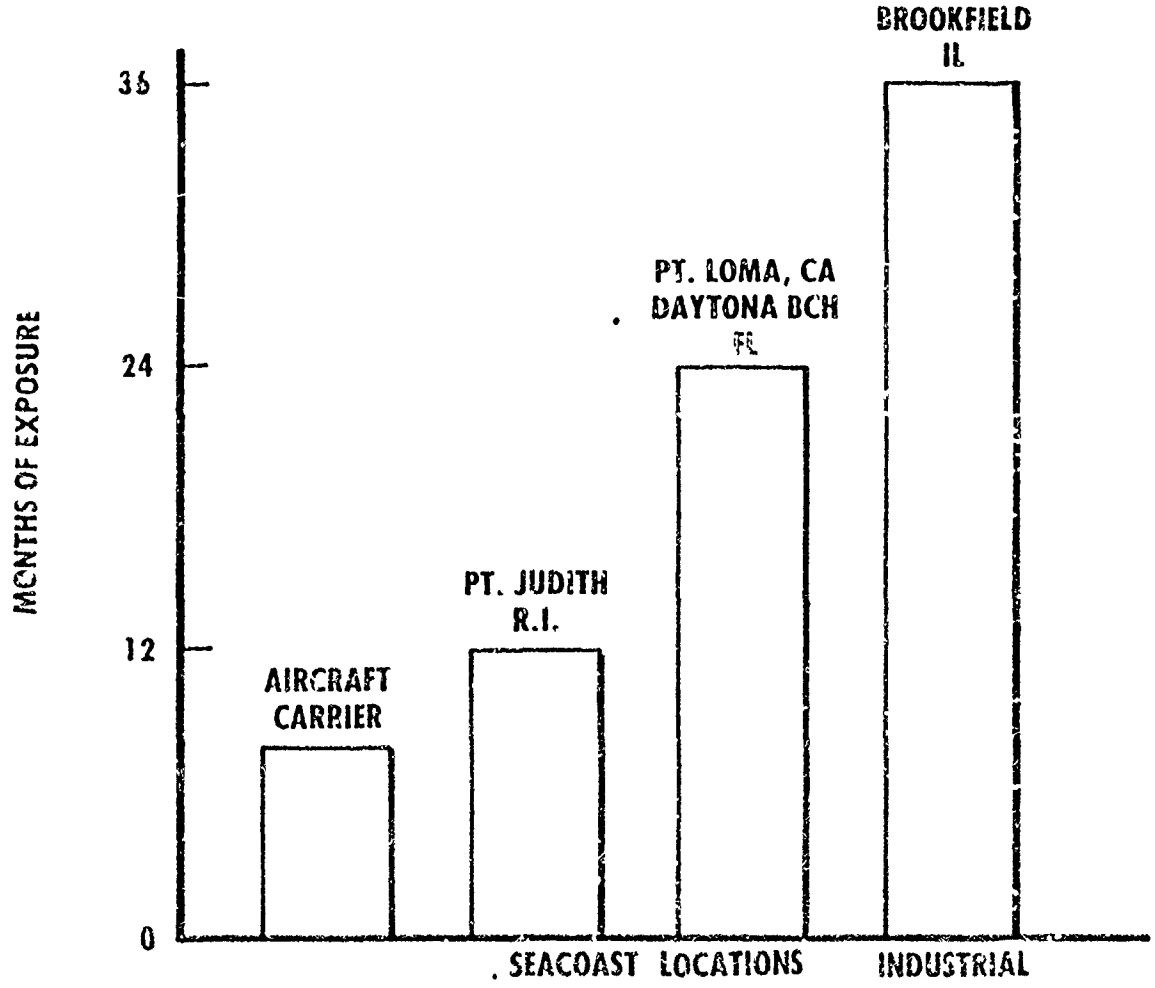
8 MONTHS ON CONVENTIONAL CARRIER

2124 0.5 INCH PLATE
LOW RESISTANCE

7075 EXTRUSION
LOW RESISTANCE

FIGURE 4

COMPARATIVE CORROSIVITY OF ENVIRONMENTS



TIME REQUIRED TO PRODUCE SEVERE EXFOLIATION IN 2124 0.5" PLATE HEAT TREATED TO BE SUSCEPTIBLE TO EXFOLIATION

FIGURE 5

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