THE MECHANISM OF CORROSION OF CADMIUM-SILVER-COPPER BEARING ALLOYS

BY

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I. INTRODUCTION

High-speed, high-compression motors for the automobile industry have brought with them new problems in the design and fabrication of bearings for main and connecting-rod use. One of the newer types of bearing metals, Cadmium-Silver-Copper, while proving quite satisfactory to load demands, was subject to corrosion in certain cases.

Under the direction of Professor J. I. Clower and Dr. F. C. Vilbrandt, research was instigated to determine the mechanism of this corrosion, and to determine the conditions under which corrosion of the Cadmium-Silver-Copper bearing metals in contact with a standard grade and type lubricating oil does occur. It was felt that if the underlying mechanism of this corrosion was ascertained, that methods of preventing corrosion could be more easily investigated.

II. HISTORICAL

Need For New Bearing Metals. Modern high-speed automotive engines have made great progress during the past decade. To illustrate this advancement, Round (17) says:

> "A certain engine which developed 83 horsepower in 1931 would today develop 140 horsepower when specially tuned up for racing. For normal service that same engine now develops 115 horsepower - nearly 40% more power than it was originally designed for. Obviously, the development of 40% more power means more revolutions and more pressure than the unit was originally designed for. Refinements help, but it is easy to see that sometime the last straw will be reached and something will happen."

Other factors which have increased the designers difficulty are the so-called streamlining bringing with it narrow radiators and restricted flow of cooling air, and speeds unheard of a few years ago. These changes in design have led to increased operating temperatures and greater strain on every part of an already strained mechanism.

Mr. Round (17) further states:

> "probably one of the most important and difficult problems the designer has to contend with has been bearings. We have only to read between the advertising lines to see the reason for quick changes to aluminum pistons, harder alloy bearing, and longer water jackets."

The table on page 6 indicates some of the increases in operating characteristics from 1927 to 1937.

Presence of Oxygen. Bierbaum (4) showed that the corrosive action of oil on highly polished Babbitt bearing surfaces was conducive to good lubrication due to the attack being centered on the softer metals thereby increasing the amount of lubricant on the bearing surface. Bierbaum (5) states further with reference to Babbitt bearings:

SOME AVERAGE CHARACTERISTICS OF AUTOMOTIVE I. C. E. (7)			
FACTOR	1927	1937	PER CENT INCREASE
Average B. M. E. P. (lb. per sq. in.)	74.5	93.1	25
R. P. M.	2740	3556	29.8
Brake Horsepower	65.8	115.9	76.3
Piston Speed (ft. per min.)	2150	2547	18.3
Horsepower per cu. in. of displacement	0.233	0.417	79

> "The oxidizing of the oil has the effect of changing a chemically neutral oil to one having a distinct reaction, the acidity depending upon the degree of oxidation. The acidity produces two distinct effects; it changes the oil from an indifferent or non-wetting to a distinctly wetting oil, and the acidity of the oil produces a distinctly corrosive action upon the bearing surfaces. These chemical reactions are exceedingly complex, in some cases the oxidized oil appears to act by catalysis only, requiring air to be mixed with the oil in order to produce a corroding action."

He also notes that the corrosion is not always uniform, in some cases selective, in others general, and that if the destructive action is general and rapid, the bearing will be destroyed.

Other investigators (9) bear out Bierbaum's statement that air must be present for corrosion to occur. It was noted in several cases that no corrosion occurred, and that cadmium base alloys gave exceptionally good service when used in airplane main and connecting-rod bearings. This might be accounted for on the basis that a detached oil sump is used in most airplane engine design which would eliminate chances of air foam being forced with the oil to the bearing.

Retarding Effects Of The Products Of Corrosion. Bertram (3) pointed out the retarding effect of stannous salts on the oxidation of oils. This fact is perhaps an explanation of the extremely slow rate of corrosion experienced with Babbitt bearings, and the absence of similar protective agents on the surface accounting in part for the high rate of corrosion of Cadmium-Silver-Copper bearing metals.

Effects Of Temperature. While there is frequent reference (9) to the relatively small increments of temperature increase necessary for an oil to cease being non-corrosive and be corrosive in its action, no exact figures as to the value of this critical temperature seem to be available.

Break-In-Oils, Fatty Acids, and Oiliness Compounds. The agreement and disagreement concerning the use of break-in oils, fatty acids, and "oiliness" compounds is summed up by Automotive Industries (17) as follows:

> "1. Although failures have occurred with the use of certain break-in oils, that is no indictment of all break-in oils, because satisfactory products are to be found on the market.
>
> 2. Although failures have occurred with certain blended or compounded oils, there can be no blanket indictment of such lubricants, since it is agreed that the right kind of addition compounds are perfectly compatible with the new bearing alloys.
>
> 3. Bearing failures are manifested in severe corrosion, pitting, or complete disintegration due to the action of free fatty acids, particularly acetic and formic acids. Yet it is understood that there are many oiliness compounds available that are perfectly safe to use.
>
> 4. While straight mineral oils appear to be absolutely compatible with the new bearing materials, such oils will develop objectionable acidity in service unless care is taken to select the oils that remain chemically stable and resist oxidation. However, even good mineral oils may develop an increase in acidity due to external effects, if used too long, which may be a warning to those operators who make it a practice to drain the crankcase either infrequently or not at all."

Electrolytic Theory Of Corrosion (15). Any metal when placed in a solution has a definite tendency to go into solution in the form of electrically charged particles, the solution being maintained neutral by the plating out of an equivalent number of charged particles of some other metal. This inherent tendency can be illustrated by the example of iron immersed in water: iron goes into solution and hydrogen is plated out. This hydrogen, in the form of a thin, invisible film gathers on the surface of the iron.

The presence of this film tends to obstruct the progress of the reaction by insulating the metal from the solution. This interference is generally so effective that it either stops corrosion altogether or at least prevents any appreciable damage being done to the metal. In order for corrosion to proceed, the film of hydrogen must be removed in one of two ways - the formation of gaseous hydrogen or the formation of water.

Although the term iron is used in the above discussion, it is used in the generic sense only. The reactions might be written:

(1) Metal (atomic) $+$ H (ions) $=$ Metal (ions) $+$ H (atomic)

(2a) 2H (atomic) $+ \frac{1}{2}O_2$ (atomic) $= H_2O$ or

(2b) 2H (atomic) $= H_2$ (gas)

Obviously, if corrosion is a chain reaction, it can proceed only as rapidly as the slowest reaction of that chain. It has been further pointed out that reaction (2a) or (2b) above is usually the controlling factor in the chain reaction.

Corrosion By Direct Chemical Attack. This type of corrosion needs little discussion. An example of this would be the action of acids on metal to form a salt of that metal.

Factors Influencing Both Electrolytic Corrosion And Corrosion By Direct Chemical Attack.

Factors that are associated mainly with the metal are:

(1) Effective electrode potential of a metal in solution, that is, the position of the metal with respect to hydrogen and other metals with which it is in contact, in the electrochemical series together with the concentration of the ions in solution.

(2) Overvoltage of hydrogen on the metal. Naturally, if there is a considerable tendency for hydrogen to remove itself from the system, the reaction will proceed with great rapidity.

(3) Chemical and Physical homogeneity of the metal. This factor includes differences of structure in the metal tending to set up potential differences on the surface and differences of concentration over the surface.

(4) Inherent ability of the metal to form an insoluble protective film.

Factors which vary mainly with the environment are:

(1) Hydrogen - ion concentration (pH) in the solution.

(2) Influence of oxygen in solution adjacent to the metal.

(3) Specific nature and concentration of other ions in the solution.

(4) Ability of environment to form a protective deposit on the metal.

(5) Temperature. The principal effects of increase of temperature

are:

(a) it increases the rate of chemical reaction;

(b) it decreases the stability of the materials in most cases;

(c) it may change the solubility of some of the products of the reactants;

(d) it decreases viscosity.

(6) Cyclic stress (corrosion fatigue).

(7) Contact between dissimilar metals or other materials as affecting localized corrosion.

(8) Surface condition of the test specimen. A study of surface finishing may have much more to do with irregular corrosion than any variations in chemical composition or other internal factors. A highly polished surface is generally less susceptible to corrosion than a rough surface.

(9) Possible strains in the metal surface. Several investigators have shown that strain and cold working usually cause differences in potential to be set up thereby causing uneven localized corrosion. This uneven corrosion of strained surfaces has also been explained by the breaking of the film on certain areas or to differences in grain distortions.

III. THE INVESTIGATION

MATERIALS

The oils used for this investigation were received direct from the manufacturer in cases of quarts and gallons which had not been opened prior to being received at the Lubrication Laboratory at Virginia Polytechnic Institute

Quaker State, S.A.E. 30, is a non-solvent refined oil of Pennsylvania Crude.

Esso Motor Oil. No. 3, is a solvent refined oil of mixed base crude with "Paraflow" and "Paratone" added.

The new oils conformed to the following specifications:

PROPERTIES OF THE NEW OILS		
ITEM	QUAKER STATE S.A.E. 30	ESSO MOTOR OIL NO. 3
Viscosity Saybolt Universal, sec. 100° F	454	655
130° F	212	292
210° F	63.4	78
Specific Gravity	0.875	0.869
Flash Point	450	445
Fire Point	510	505
Viscosity Index	106	106

<u>The Bearing Metal Samples</u>. The bearing metals were received from the

Federal-Mogul Corporation, Detroit, Michigan, in the form of bars one and one-eighth inches in diameter by seven and one-half inches long. The bars were cut on a milling machine in the shops at Virginia Polytechnic Institute to samples one-tenth inch thick and machined to one and one-sixteenth inches in diameter.

The analysis of the bearing metals is given in the table below:

ANALYSES OF BEARING METALS (2)

TYPE	Cd	Sn	Pb	Ag	Cu	Sb	Ni
CS - 50 (a)	98.75	--	--	0.75	0.50	--	--
CS - 51 (b)	97.45	--	--	2.25	0.30	--	--
B - 10025 S.A.E. No. 10 (c)	--	89	0.25	--	3.7	7.3	--
Leaded Bronze (d)	--	--	39.5	--	68.5	--	2.0
L - 100 Bermox (e)	--	6	83.5	--	0.5	10	--
Cadmium Nickel (f)	98.5	--	--	--	--	--	1.5

(a) Designated as VII in later discussion.

(b) Designated as VIII in later discussion.

(c) Designated as VI in later discussion.

(d) Designated as V in later discussion.

(e) Designated as IX in later discussion.

(f) Designated as X in later discussion.

Structure Of The Bearing Metals.

1. Cadmium base.

(a) CS - 50. This metal consists of cored grains of cadmium-silver solid solution surrounded by a cadmium-copper eutectic. Copper alone will harden and strengthen the cadmium, but it does so at the expense of ductility and toughness. However, if silver be added with the copper, the cored grains of cadmium-silver solid solution effect a combination of strength, hardness and ductility, which is so necessary for good performance under service conditions.

(b) CS - 51. Though very similar in composition and physical characteristics to CS - 50, this metal is a true solid solution and contains no hard constituents which are visible when the metal is polished and etched.

(c) L - 100. Like the tin base Babbitt bearings the metal is shown to be a matrix composed of a eutectic mixture of cadmium and nickel-cadmium (Cd_7Ni) in which are crystals composed of Cd_7Ni.

2. Tin base.

(a) B - 10025. This Babbitt is made up of a matrix composed of a pseudo-eutectic of antimony and tin plus copper with a needle-shaped copper-tin constituent distributed therein.

3. Bronze base.

(a) Leaded Bronze. This bearing metal consists of a copper matrix in which are embedded large particles of lead (any tin present would be in solid solution with the copper). Many bearing specimens of this material show, however, the lead to be segregated in zones toward the center of the sample.

Specific Gravity Of The Bearing Metals. The specific gravity of all the bearing samples was determined in the laboratory. The method of determination and the values for the specific gravity are given in the table below

SPECIFIC GRAVITIES OF BEARING METALS			
$\text{Sp. Gr.} = \dfrac{\text{Wgt. of sample in air}}{\text{Wgt. of sample in air} - \text{Wgt. of sample in water}}$			
1. Leaded Bronze	(V)	$\dfrac{14.1598 - 0.2312}{14.1598 - 12.6965}$ =	9.53
2. Babbitt 10025	(VI)	$\dfrac{10.9140 - 0.2312}{10.9140 - 9.4520}$ =	7.29
3. CS - 50	(VII)	$\dfrac{12.7462 - 0.2312}{12.7462 - 11.2988}$ =	8.66
4. CS - 51	(VIII)	$\dfrac{12.9268 - 0.2312}{12.9268 - 11.4640}$ =	8.66
5. Bermax L - 100	(IX)	$\dfrac{14.6390 - 0.2312}{14.6390 - 13.2300}$ =	10.22
6. Cadmium-Nickel	(X)	$\dfrac{12.8938 - 0.2312}{12.8938 - 11.4214}$ =	8.61

EQUIPMENT

Several types of testing apparatus were used during the investigation; these will be described below and designated by name which will serve to identify them in later discussion.

I. JET-TYPE OIL BATH. The "jet-type oil bath" consisted of a rectangular box constructed of unfinished, welded, sheet steel ten inches long, four inches wide, and four inches deep. A one-eighth inch pipe (nominal) extended the length of the box equidistant from the sides, one and one-half inches below the top edge. This pipe served as a manifold and was connected by means of a tee at the center to the pump. Five one-sixteenth inch holes were drilled one inch apart in the bottom side of the manifold on each branch of the tee. Steel wire hangers were placed on this manifold, between each pair of holes, to hold the sample discs.

Figure 1, page 16, shows the general layout of the oil bath together with the manner in which the bearing specimens were held by the "U" type hangers.

Two lengths of one-eighth inch pipe were run through one side of the box, the top being connected to the tee in the manifold, and the bottom one being welded in place to act as a drain.

The top of the spray box was made from a thin piece of sheet steel bent to the shape of a very shallow V to allow condensed oil vapors to drip back into the bath. A hole was drilled in the center of this cover to receive a thermometer.

The circulating system consisted of a Chevrolet oil pump (vane type)

JET-TYPE OIL BATH

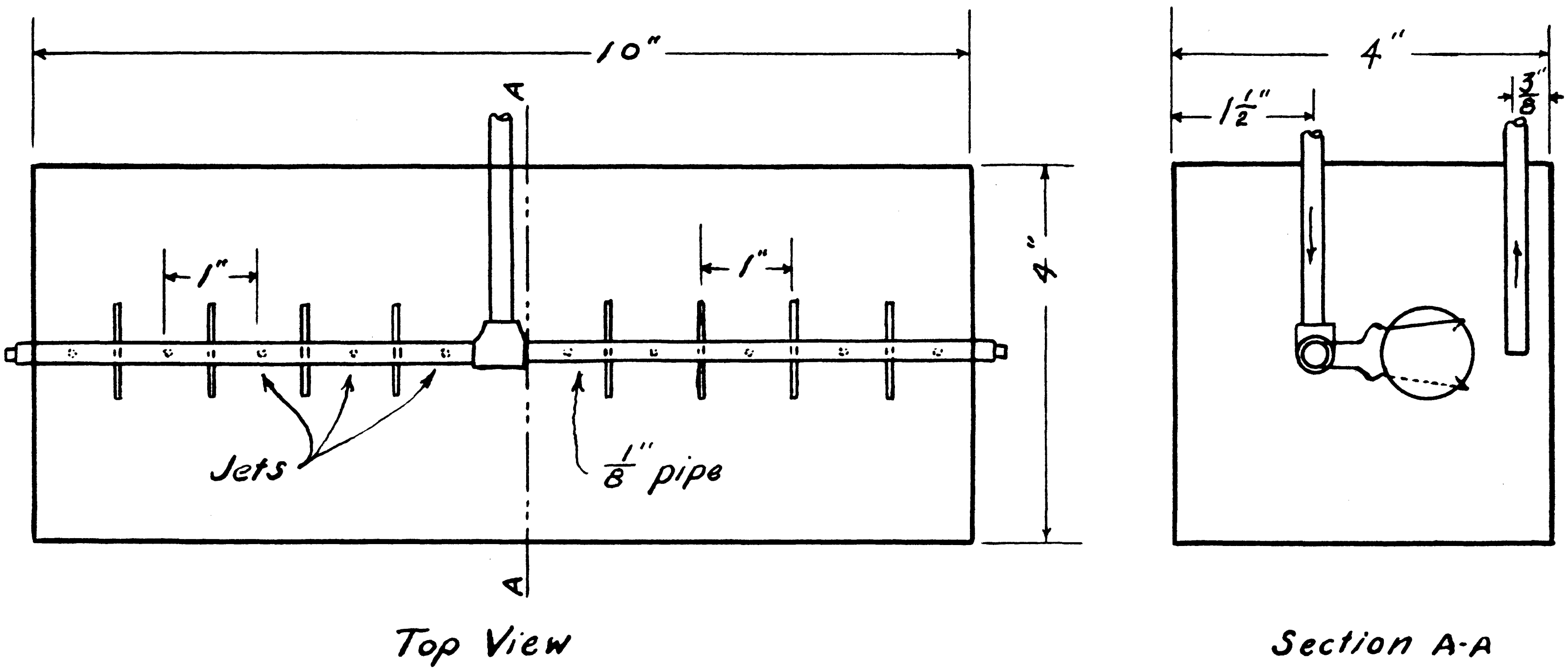


Figure No. 1

fitted with a packing gland. This pump was mounted on wooden supports at approximately the same height as the spray box; and was driven by a one-quarter horsepower electric motor through a flexible coupling at approximately 1725 r.p.m.

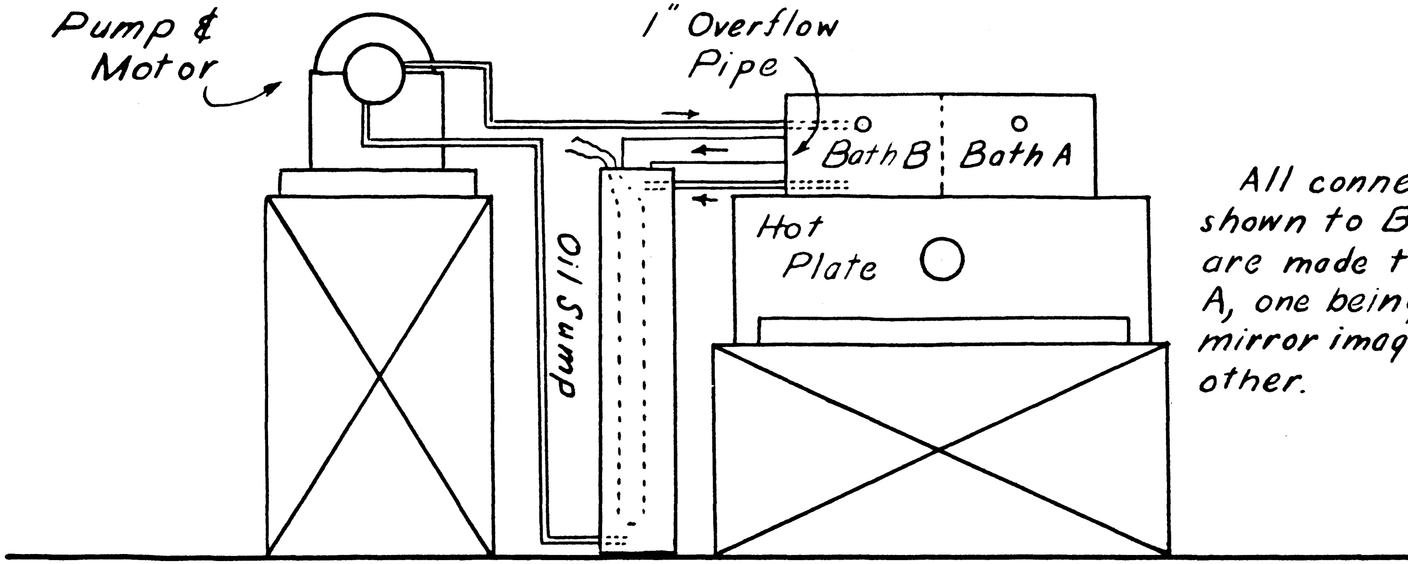
The spray box was placed on top of a Hoskins hot plate of twelve hundred watts capacity connected in series with a variable resistance to facilitate temperature adjustment and control. No insulation was placed on the bath.

This is the same apparatus as was used by Sydnor (16) for corrosion determinations at the Virginia Polytechnic Institute, Lubrication Laboratory, during the year 1935-1936.

II. MODIFIED JET-TYPE OIL BATH. The essential features of the original bath explained above were maintained in the modified apparatus. Certain refinements and enlargements to enable two tests to be run at the same time were added.

A rectangular box of the same material as before, sheet steel, was constructed to the following dimensions; ten inches long, eight inches wide, and four inches deep. A dividing wall ran the length of the box separating it into two equal compartments, ten inches by four inches by four inches. The piping to and from the bath was the same as described above, one side being the mirror image of the other. Figure 2, page 18, illustrates diagrammatically the design of this apparatus. However, in addition to the one one-eighth inch drain pipe (which had previously been connected directly to the suction of the pump), a one inch pipe was welded two inches from the top edge of the long side, providing a gravity overflow to maintain the

SCHEMATIC DIAGRAM of MODIFIED JET-TYPE OIL BATH

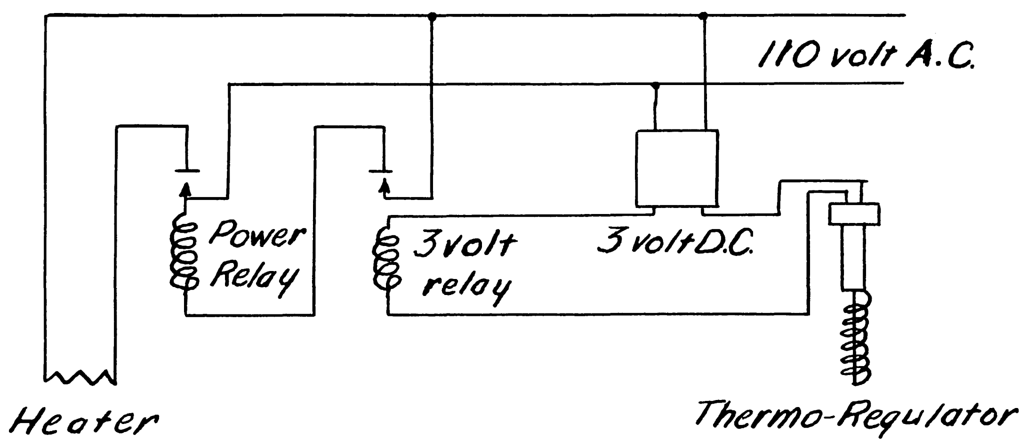


All connections shown to Bath B are made to Bath A, one being the mirror image of the other.

Figure No. 2

proper level in the oil bath. The one-eighth inch pipe drained from the bottom of the bath to prevent stratification of the oil.

Both drain pipes emptied into a three inch pipe sixteen inches in length, set at an angle of thirty-six degrees which was used as an oil sump containing the intermittent electrical heaters. These heaters were three hundred watt capacity copper tube type, and were in series with a power relay which was in turn actuated by a three volt d.c. relay controlled by a De Khotinsky type thermo-regulator according to the circuit given below.



The oil sump was connected at the bottom through a one-eighth inch pipe to the oil pumping mechanism which was described under I. JET-TYPE OIL BATH, page 15.

The type of hanger used with this equipment was modified from the "U" type to what will be designated as the "S" type. This consisted of a piece of three sixty-fourths inch piano wire wound around the manifold and extending below the pipe between the orifices in the form of a hook. The samples were drilled one-eighth inch from the outer edge by a one-sixteenth inch bit to be hung in this manner.

With this set-up the tube heaters operate intermittently in conjunction with the constant heat supplied by the hot plate to give reasonably accurate temperature control (range $\pm$ 2 or 3° F).

III a. GLASS APPARATUS. A one liter beaker was wound externally with a 450 watt chromel heating element and placed in a three liter beaker. The annular space between the beakers was filled with flaked asbestos. The three liter beaker was in turn covered by a one inch layer of 85% magnesia pipe covering. The heating unit was connected in series with the relays and thermo-regulator as was outlined under II. MODIFIED JET-TYPE OIL BATH, page 19. The cadmium plated thermo-regulator was protected from the oil by surrounding it with a glass test tube filled with light mineral oil.

Agitation of the oil was accomplished by rotating the specimen discs on a glass rod of three-sixteenths inches diameter. A hole seven thirty-seconds of an inch in diameter was drilled through the center of each specimen to receive the glass rod. The stirring device was clamped in a pulley block driven by an electrical stirring motor. Spacers of nine thirty-seconds of an inch outside diameter held the samples one inch from the bottom of the beaker and seven-sixteenths inches apart. Figure 3, page 21, shows diagrammatically the assembly of the glass apparatus.

In all tests but one air was injected into the oil bath through a glass tube drawn to approximately one-half millimeter internal diameter. Air was obtained and controlled by allowing water to fill a sealed five gallon carboy which in turn caused the trapped saturated air to be forced through the glass tube into the oil bath.

SCHEMATIC DIAGRAM of GLASS APPARATUS

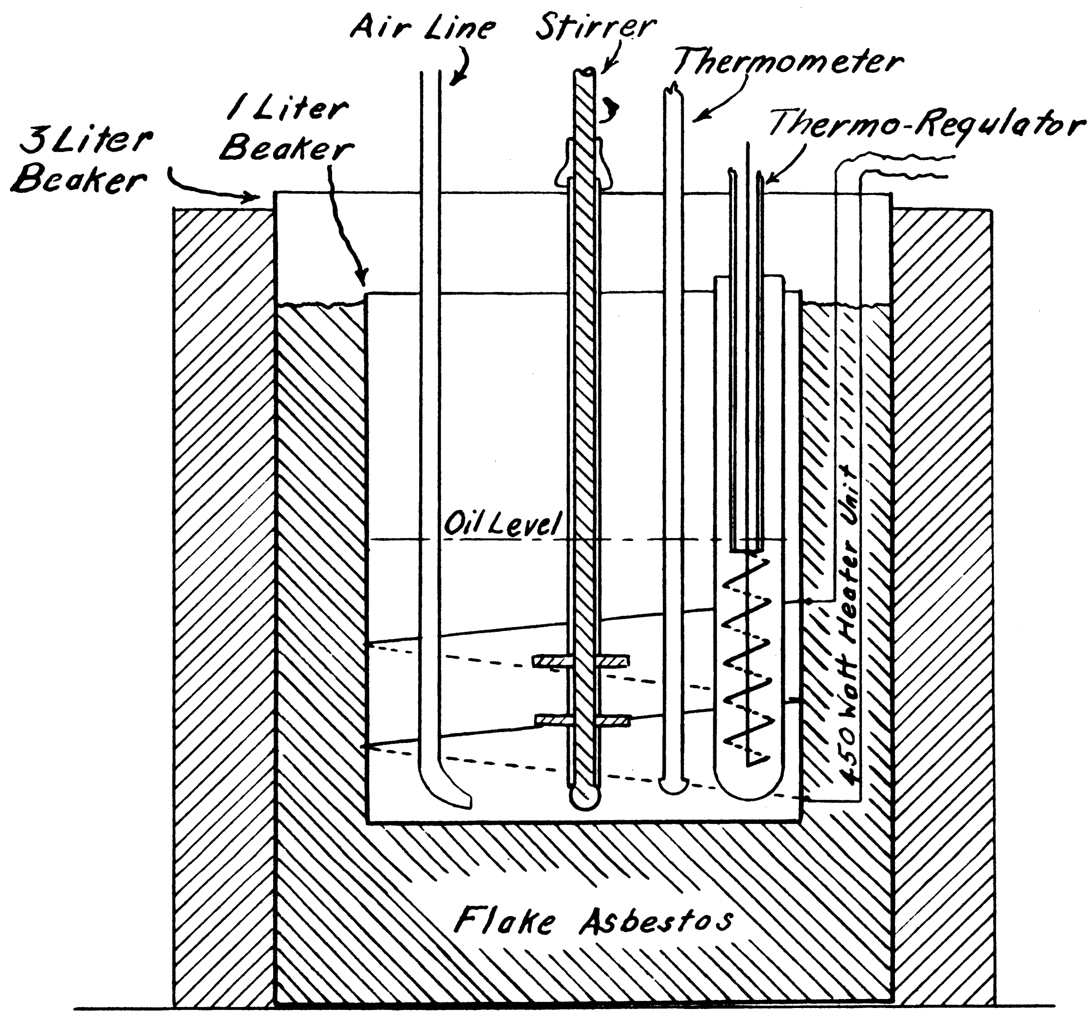


Figure No. 3

III b. MODIFIED GLASS APPARATUS. This apparatus differed from III a. GLASS APPARATUS, page 20, in that a copper plate approximately five by three inches, curved to fit along the inside wall of the beaker, was soldered to a steel spring which acted as a brush and made contact with the stirring rod. The glass stirring rod was replaced by a steel rod machined to the same dimensions. The spacers were also of steel and were held against the bearing specimens by a steel spring placed above the top spacer to assure good contact between the stirrer and the samples.

One test was run using the steel stirring rod without the copper plate attachment. In this case, the bearing metals in contact with the stirrer were dissimilar.

Slight changes were made in II. MODIFIED JET-TYPE OIL BATH, page 17, for several later runs. These changes are fully discussed under PROCEDURE, page 25.

PROCEDURE

The following test procedure was observed in all runs regardless of the equipment.

After the initial treatment, which was varied considerably from run to run, the specimens were washed in gasoline, alcohol, and dried in an electric oven at 220° F to constant weight. The test bath was first thoroughly washed with gasoline, scrubbed with a brush, and finally rinsed in gasoline prior to each test. In the cases where piping was used, gasoline was circulated to clean out any oil deposits. At the termination of a run, specimens were washed in gasoline, wiped with a soft cloth to remove any material adhering to the surface, rinsed in alcohol and dried at 220° F to constant weight.

Corrosion was reported as Average Penetration in Inches Per Year according to the following equation (18):

$$P = \frac{WK}{SAT}$$

where:

P = the average penetration in inches per year

W = the metal removed in grams

K = 0.06102

S = the specific gravity of the metal

A = the area exposed in square inches

T = the duration of the test in years

The method of PROCEDURE is given below on the basis of the type of equipment which was used. This was to facil.itate ease of reading due to the fact that a different method of procedure was used in each specific type of equipment.

A. Equipment I, page 15; Run Nos. 1 through 4.

Bearing specimens were worked on a flat surface to a finish obtainable with 0000 emery paper. Due to the curvature, the edges of the discs were never as highly polished as the faces.

During the test period the orifice holes were cleaned every twelve hours by forcing a wire through them.

B. Equipment II, page 17; Run Nos. 5 through 16.

Run Nos. 5 and 6 did not have oil sump, thermo-regulators, and "S" type hangers attached.

The samples were finished with emery paper as described under A above, for Run Nos. 5 through 12.

In an attempt to control the flow of oil in each bath to more nearly the same rate, Run Nos. 9 through 16 were made with the oil flow controlled by an orifice placed in the suction line of each pump. The adjustment was made using water as the fluid in place of the oil. All rates of flow are expressed in terms of water instead of oil due to the difficulty of measuring oil flow at the temperatures encountered. The velocity of flow observed was approximately 0.67 feet per second through each jet.

In place of the polishing process for finishing, the specimens for Run Nos. 13 through 16 were treated with a 30% solution of nitric acid (sp. gr. 1.190). The samples were placed in the acid until the action became vigorous at which time the surface was assumed to be free from dirt and were then washed in running water for a period of two hours before rinsing in alcohol and drying to constant weight.

C. Equipment III a, page 20; Run Nos. 17 through 20.

It was believed that the nitric acid action induced passivity thereby preventing corrosion. To prevent this specimens for Run No. 17 were treated with a solution of aqua regia made up as follows:

25 parts nitric acid (conc.)

75 parts hydrochloric acid (conc.)

300 parts water

The samples were etched in this solution, cleaned, and dried as usual.

The same specimens were used in Run Nos. 18 through 20 as were used in Run No. 17. Microscopic examination previous to each test showed the surface characteristics unaltered.

D. Equipment III b, page 22; Run Nos. 21 through 23.

The same samples were used in Run Nos. 21 and 22 as were used in Run Nos. 17 through 20.

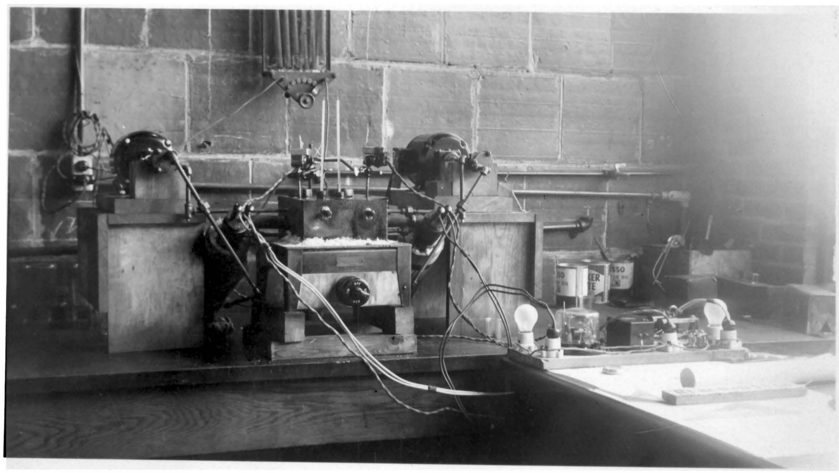
The copper plate was removed from the bath during Run No. 23. One sample of Cadmium-Silver-Copper (bearing VIII) was placed in electrical contact with a copper-lead bearing (V) through the medium of the iron stirring rod. Both samples were treated with aqua regia etch prior to cleaning and drying by the usual method.

E. Equipment II, page 17; Run Nos. 24 through 29.

Equipment II was altered as follows for these runs: Two five sixty-fourths inch holes were drilled one inch apart on each side of the tee in the manifold so as to accomodate two specimens in each bath. The specimens were insulated from each other by glass "S" type hangers. The orifices were kept in the suction line, maintaining the total flow, but increasing the flow from each of the four jets. The velocity of flow from each jet was equal to 1.51 feet per second.

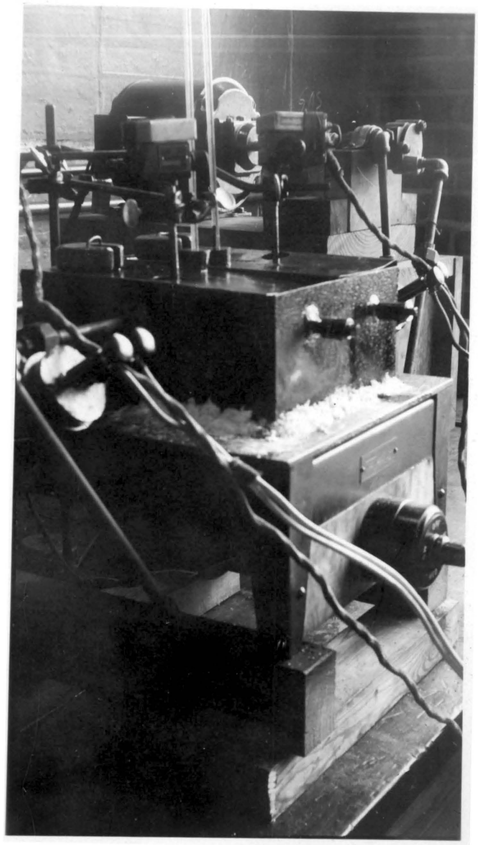
New samples were used in each case, and were treated with the aqua regia etch prior to drying in the usual manner.

PHOTOGRAPHS



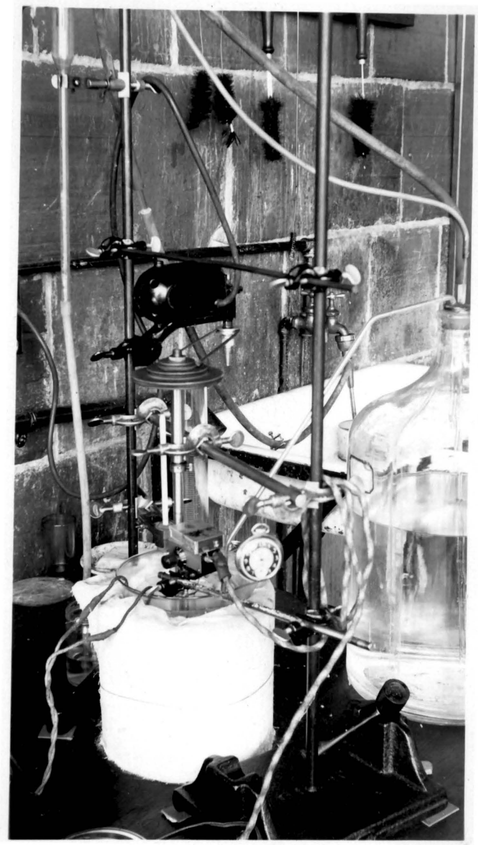
Photograph 1.

Photograph 1 shows the general layout of the Modified Jet-Type Oil Bath described on page 17. The control relays are seen on the small table at the right. Pump, motor, sump, and spray box for the double bath are shown on the large table.



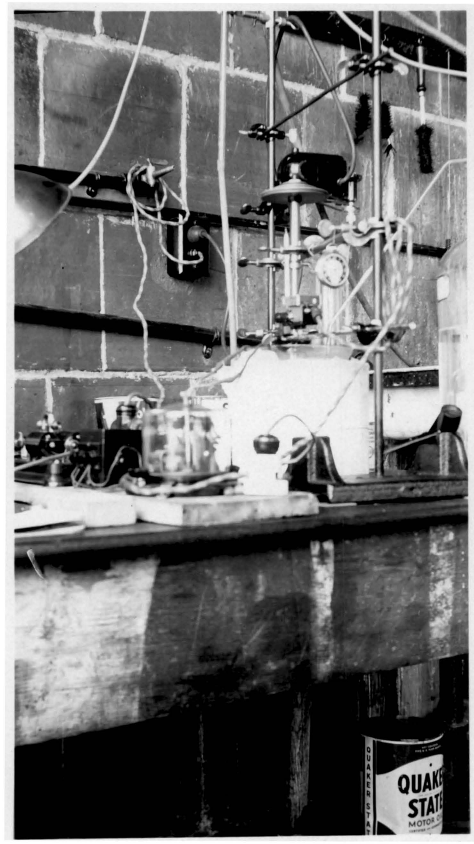
Photograph 2.

The thermometers and thermo-regulators can be readily seen in the close up of the Modified Jet-Type Oil Bath shown in Photograph 2.



Photograph 3.

Photographs 3 and 4 show two views of the Glass Apparatus described on page 20. The glass carboy used for the air supply tank can be seen at the extreme right.



Photograph 4.

IV. DATA AND RESULTS

The Tables which follow represent the data and results obtained with the various pieces of equipment designed and operated in the Lubrication Laboratory of the Mechanical Laboratory, Virginia Polytechnic Institute.

Tables I through XXIV represent the values of the initial weight of the bearing specimens, the weight after a certain interval of testing, and the calculated value of the rate of corrosion expressed in inches of penetration per year. Notes taken in the laboratory relative to each test, the type of oil, the duration of the test, and other data pertinent to the full understanding of any test is also given in each table.

Table I.

RUN NO.1: Corrosion of Bearing Samples Using Jet-Type Oil Bath

OIL: Esso Motor Oil, No. 3

DURATION OF TEST: 43 hours

TEMPERATURE: 310 $\pm$ 15° F

Bearing Metal No.	Weight - Gms. Initial	12.5 hrs.	24.5 hrs.	35.5 hrs.	43 hrs.	Total Loss
V - 1	13.8278	13.8034	13.6949	13.5954	13.5371	0.2907
V - 2	14.6212	14.5903	14.4428	14.3406	14.2805	0.3407
VI - 1	10.4396	10.4393	10.4391	10.4390	10.4389	0.0007
VI - 2	10.1622	10.1617	10.1617	10.1615	10.1617	0.0005
VII - 1	12.1612	11.5976	10.8166	10.1228	9.8078	2.3534
VII - 2	12.2936	11.7243	10.9558	10.2011	9.8540	2.4396
VIII - 1	12.4114	11.9551	11.4581	10.8204	10.5919	1.8195
VIII - 2	13.1594	12.6327	12.0534	11.5301	11.2127	1.9467

Date: Sept. 29, 1936; 8:30 P.M. to Oct. 1, 1936; 3:30P.M.

No temperature control on the apparatus. Jets were noted to clog near the end of run. Hangers were not in contact with the same area of all samples. Bearing metal No. V was covered with a layer of sludge at the end of the run.

Table II.

RATE OF CORROSION: Inches of Penetration Per Year for Run No. 1

Bearing Metal No.	12.5 hrs.	24.5 hrs.	35.5 hrs.	43 hrs.
V - 1	0.0517	0.1438	0.1735	0.179
V - 2	0.0654	0.1924	0.2095	0.2095
VI - 1	----	----	----	----
VI - 2	----	----	----	----
VII - 1	1.132	1.380	1.441	1.372
VII - 2	1.145	1.371	1.486	1.424
VIII - 1	0.918	0.054	1.128	1.061
VIII - 2	1.060	1.131	1.151	1.138

Table III.

RUN NO. 2: Corrosion of Bearing Samples in Jet-Type Oil Bath; With Additive Agent.

OIL: Esso Motor Oil, No. 3

DURATION OF TEST: 38 hours

TEMPERATURE: 310 ± 15° F

ADDITIVE AGENT: Alox AA Compound, 1%

Bearing Metal No.	Weight - Gms. Initial	Final	Loss	Inches of Penetration Per Year
V - 1	13.9682	13.8956	0.0726	0.0506
V - 2	13.7180	13.6242	0.0938	0.0654
VI - 1	10.0332	10.0332	0.0000	----
VI - 2	10.2500	10.2501	0.0001	----
VII - 1	11.7812	9.6121	2.1691	1.436
VII - 2	11.6306	9.5026	2.1280	1.410
VIII -1	11.1258	9.5543	1.5715	1.041
VIII - 2	11.0373	9.4694	1.6679	1.102

Date: Oct. 6, 1936; 5:00 P.M. to Oct. 8, 1936; 7:00 A.M.

No temperature control on the apparatus. Hangers were not in contact with the same area of all samples. The corrosion seemed to start at the edges of the specimens furthest away from the jet.

Table IV.

RUN NO. 3: Corrosion of Bearing Samples in Jet-Type Oil Bath; With Additive Agent

DURATION OF TEST: 38 hours

TEMPERATURE: 310 $\pm$ 15° F

ADDITIVE AGENT: Alox AA Compound, 2%

Bearing Metal No.	Weight - Gms. Initial	Final	Loss	Inches of Penetration Per Year
V - 1	17.6113	17.4777	0.2336	0.1624
V - 2	13.4970	13.3614	0.1356	0.0945
VI - 1	9.9498	9.9492	0.0006	----
VI - 2	9.5567	9.5564	0.0003	----
VII - 1	11.5688	9.7506	1.8182	1.201
VII - 2	11.7036	9.9136	1.7900	1.185
VIII - 1	11.8937	10.5045	1.3892	0.918
VIII - 2	11.0746	10.4730	0.6016	0.399

Date: Oct. 9, 1936; 11:00 P.M. to Oct. 11, 1936; 1:00 P.M.

No temperature control on the apparatus. Hangers were not in contact with the same area of all samples. Bearing No. V pitted so that oil was difficult to remove from the holes; consequently, the final weight may be in error.

Table V.

RUN NO. 4: Corrosion of Bearing Samples in Jet-Type Oil Bath

OIL: Sinclair Pennsylvania, S.A.E. 30

DURATION OF TEST: 38 hours

TEMPERATURE: $310 \pm 15^{\circ}$ F

Bearing Metal No.	Weight - Gms. Initial	Final	Loss	Inches of Penetration Per Year
V - 1	13.4503	13.2367	0.2136	0.1486
V - 2	11.4183	11.1690	0.2493	0.1735
VI - 1	9.5096	9.5096	0.0000	----
VI - 2	9.5888	9.5885	0.0003	----
VII - 1	11.6492	9.7728	1.8764	1.241
VII - 2	11.4257	9.5662	1.8595	1.230
VIII - 1	9.7114	8.5768	1.1346	0.750
VIII - 2	10.3526	9.1116	1.2410	0.821

Date: Oct. 28, 1936; 10:00 A.M. to Oct. 29, 1936; 12:00 Midnight

No temperature control on the apparatus. Hangers were not in contact with the same area of all samples. Bearing No. V pitted badly and was covered with a black sludge at the end of the run.

Table VI.

RUN NO. 5: Corrosion of Bearing Samples in Jet-Type Oil Bath

OIL: Esso Motor Oil, No. 3

DURATION OF TEST: 24 hours

TEMPERATURE: 315° F (See Note Below)

BATH: A

Bearing Metal No.	Weight - Gms.			Inches of Penetration Per Year
	Initial	Final	Loss	
V - 1	13.2216	13.1570	0.0646	0.0713
VI - 1	10.2232	10.2230	0.0002	----
VII - 1	12.0222	10.7910	1.2312	1.291
VII - 2	11.1089	9.9478	1.0611	1.112
VIII - 1	11.8344	10.6423	1.1921	1.250
VIII - 2	11.9198	10.7731	1.1467	1.200
IX - 1	14.3364	14.3368	0.0004	----
X - 1	12.1639	11.4625	0.7014	0.735

Date: Jan. 20, 1937; 4:00 P.M. to Jan. 21, 1937; 4:00 P.M.

Maximum temperature was 332° F, minimum temperature 298° F. Hangers not in contact with same area of all samples.

Table VIII.

RUN NO. 6: Corrosion of Bearing Samples in Jet-Type Oil Bath

OIL: Esso Motor Oil, No. 3

DURATION OF TEST: 24 hours

TEMPERATURE: 310° F (See Note Below)

BATH: B

Bearing Metal No.	Weight - Gms. Initial	Final	Loss	Inches of Penetration Per Year
V - 1	13.2708	13.2196	0.0512	0.0565
VI - 1	10.1503	10.1508	0.0005	----
VII - 1	11.6292	10.3290	1.3002	1.361
VII - 2	11.5732	10.2168	1.3564	1.420
VIII - 1	12.0816	10.6034	1.4782	1.548
VIII -2	12.4023	11.0333	1.3690	1.435
IX - 1	14.1373	14.1373	0.0000	----
X - 1	12.5719	11.4864	1.0855	1.138

Date: Jan. 20, 1937; 4:00 P.M. to Jan. 21, 1937; 4:00 P.M.

No temperature control on the apparatus. Maximum temperature was 329° F, minimum temperature 303° F. Hangers not in contact with same area of all samples.

Table VIII.

RUN NO. 7: Corrosion of Bearing Samples in Modified Jet-Type Oil Bath

OIL: Esso Motor Oil, No. 3

OIL QUANTITY: 1850 c.c.

DURATION OF TEST: 24 hours

TEMPERATURE: 300 $\pm$ 3° F

BATH: A

Bearing Metal No.	Weight - Gms. Initial	Final	Loss	Inches of Penetration Per Year
V - 1	13.1174	13.1038	0.0136	0.0150
VI - 1	9.7392	9.7390	0.0002	----
VII - 1	11.9264	11.9082	0.0176	0.0184
VII - 2	12.3394	12.3218	0.0186	0.0195
VIII - 1	11.6582	11.6481	0.0101	0.0106
VIII - 2	12.1198	12.1034	0.0164	0.0172
IX - 1	15.3592	15.3592	0.0000	----
X - 1	12.1478	12.1456	0.0022	0.0023

Date: Feb. 8, 1937; 9:15 P.M. to Feb. 9, 1937; 9:15 P.M.

Some trouble was encountered with the relay set governing the temperature, but in general the temperature variation was within 3° F. A dropping off of the rate of flow was noted toward the end of the run.

Table IX.

RUN NO. 8: Corrosion of Bearing Samples in Modified Jet-Type Oil Bath

OIL: Esso Motor Oil, No. 3

OIL QUANTITY: 1900 c.c.

DURATION OF TEST: 24 hours

TEMPERATURE: 300 $\pm$ 2° F

BATH: B

Bearing Metal No.	Weight - Gms. Initial	Final	Loss	Inches of Penetration Per Year
V - 1	12.7712	12.7670	0.0042	----
VI - 1	10.2690	10.2688	0.0002	----
VII - 1	12.0702	12.0700	0.0002	----
VII - 2	11.2886	12.2884	0.0002	----
VIII - 1	13.1356	13.1356	0.0000	----
VIII - 2	12.4094	12.4090	0.0004	----
IX - 1	14.2414	14.2410	0.0004	----
X - 1	12.1918	12.1916	0.0002	----

Date: Feb. 8, 1937; 10:00 P. M. to Feb. 9, 1937; 10:00 P. M.

Table X

RUN NO. 11: Corrosion of Bearing Samples In Modified Jet-Type Oil Bath

OIL: Esso Motor Oil, No. 3

OIL QUANTITY: 1800 c.c.

DURATION OF TEST: 24 hours

TEMPERATURE: $325 \pm 3^{\circ}$ F

BATH: A

Bearing Metal No.	Weight - Gms. Initial	Final	Loss	Inches of Penetration Per Year
V - 1	13.5019	13.4734	0.0385	0.0425
VI - 1	10.2669	10.2686	0.0017	----
VII - 1	12.0411	11.8704	0.1707	0.1788
VII - 2	11.8309	11.5589	0.2720	0.2850
VIII - 1	11.3781	11.2325	0.1456	0.1390
VIII - 2	12.3301	12.0937	0.2364	0.2480
IX - 1	15.9778	15.9803	0.0025	----
X - 1	12.3095	12.0377	0.2718	0.2590

Date: Feb. 17, 1937; 3:00 P. M. to Feb. 18, 1937; 3:00 P. M.

Run interrupted for fifteen minutes after three hours to replace impellor vanes of pump. The samples showed uneven corrosion which seemed to be localized along the edges of the sample where polishing could not be effected.

Table XI

RUN NO. 12: Corrosion of Bearing Samples in Modified Jet-Type Oil Bath

OIL: Esso Motor Oil, No. 3

OIL QUANTITY: 1800 c.c.

DURATION OF TEST: 24 hours

TEMPERATURE: 325 ± 3° F

BATH: B

Bearing Metal No.	Weight - Gms. Initial	Final	Loss	Inches of Penetration Per Year
V - 1	12.8528	12.8461	0.0067	0.0074
VI - 1	10.2276	10.2272	0.0004	----
VII - 1	11.9235	11.9237	0.0002	----
VII - 2	12.0248	12.0245	0.0003	----
VIII - 1	11.9187	11.9191	0.0004	----
VIII - 2	12.1670	12.1675	0.0005	----
IX - 1	14.6939	14.6943	0.0004	----
X - 1	12.1863	12.1867	0.0004	----

Date: Feb. 17, 1937; 3:00 P. M. to Feb. 18, 1937; 3:00 P. M.

Table XII

RUN NO. 13: Corrosion of Bearing Samples in Modified Jet-Type Oil Bath

OIL: Quaker State, S. A. E. 30

OIL QUANTITY: 1600 c. c.

DURATION OF TEST: 24 hours

TEMPERATURE: 325 ± 3° F

BATH: A

Bearing Metal No.	Weight - Gms. Initial	Final	Loss	Inches of Penetration Per Year
V - 1	13.8646	13.7097	0.1549	0.1710
VI - 1	10.4579	10.4542	0.0037	0.0053
VII - 1	12.2668	12.2620	0.0048	0.0050
VII - 2	12.0988	12.0823	0.0165	0.0173
VIII - 1	11.6555	11.6535	0.0020	0.0021
VIII - 2	11.5625	11.5551	0.0074	0.0078
IX - 1	15.2052	15.2060	0.0008	----
X - 1	12.3246	12.3020	0.0226	0.0237

Date: Feb. 21, 1937; 6:05 P. M. to Feb. 22, 1937; 6:05 P. M.

Samples had a brown film on the surface after removal from the bath at the end of the test period.

Table XIII

RUN NO. 14: Corrosion of Bearing Samples in Modified Jet-Tpe Oil Bath

OIL: Quaker State, S. A. E. 30

OIL QUANTITY: 1600 c.c.

DURATION OF TEST: 24 hours

TEMPERATURE: 325 $\pm$ 3° F

BATH: B

Bearing Metal No.	Weight - Gms. Initial	Final	Loss	Inches of Penetration Per Year
V - 1	13.7558	13.6697	0.0861	0.0952
VI - 1	10.6124	10.6096	0.0028	0.0018
VII - 1	12.2346	12.2315	0.0031	0.0032
VII - 2	11.8724	11.8698	0.0026	0.0027
VIII - 1	11.5397	11.5392	0.0005	0.0005
VIII - 2	11.7170	11.7168	0.0002	----
IX - 1	15.2191	15.2191	0.0000	----
X - 1	10.6032	10.5992	0.0040	0.0020

Date: Feb. 21, 1937; 6:05 P. M. to Feb. 22, 1937; 6:05 P. M.

Samples had a brown film on the surface after removal from the bath at the end of the test period.

Table XIV

RUN NO. 15: Corrosion of Bearing Samples in Modified Jet-Type Oil Bath

OIL: Quaker State, S. A. E. 30

OIL QUANTITY: 1600 c.c.

DURATION OF TEST: 48 hours

TEMPERATURE: $325 \pm 3^{\circ}$ F

BATH: A

Bearing Metal No.	Weight - Gms. Initial	Final	Loss	Inches of Penetration Per Year
V - 1	13.6459	13.6139	0.0320	0.0177
VI - 1	10.3506	10.3562	0.0054	Error
VII - 1	11.6797	11.6728	0.0069	0.0036
VII - 2	11.4182	11.4164	0.0018	0.0009
VIII - 1	11.1983	11.1913	0.0070	0.0037
VIII - 2	11.1357	11.1296	0.0061	0.0032
IX - 1	15.1264	15.1274	0.0010	-----
X - 1	9.1912	9.1718	0.0194	0.0101

Date: Feb. 23, 1937; 5:00 P.M. to Feb. 25, 1937; 5:00 P.M.

Table XV

RUN NO. 16: Corrosion of Bearing Samples in Modified Jet-Type Oil Bath

OIL: Quaker State, S.A.E. 30

OIL QUANTITY: 1600 c.c.

DURATION OF TEST: 48 hours

TEMPERATURE: 325 ± 3° F

BATH: B

Bearing Metal No.	Weight - Gms. Initial	Final	Loss	Inches of Penetration Per Year
V - 1	13.6409	13.5563	0.0846	0.0111
VI - 1	10.5738	10.5730	0.0008	----
VII - 1	11.6291	11.6277	0.0014	----
VII - 2	11.1636	11.1566	0.0070	0.0057
VIII - 1	11.0826	11.0806	0.0020	----
VIII - 2	11.0124	11.0094	0.0030	0.0016
IX - 1	15.0868	15.0868	0.0000	----
X - 1	11.3047	11.3029	0.0018	----

Date: Feb. 23, 1937; 5:15 P.M. to Feb. 25, 1937; 5:15 P.M.

Table XVI

RUN NO. 17; Corrosion of Bearing Samples in Glass Apparatus

OIL: Esso Motor Oil, No. 3

OIL QUANTITY: 500 c.c.

DURATION OF TEST: 48 hours

TEMPERATURE: 300 $\pm$ 3° F

STIRRER SPEED: 180. r.p.m.

AIR QUANTITY: See note below

Bearing Metal No.	Weight - Gms. Initial	Final	Loss	Inches of Penetration Per Year
VIII - 1	11.6923	11.6891	0.0032	0.0017
VIII - 2	11.7844	11.7818	0.0026	0.0014

Date: April 1, 1937; 5:00 P.M. to April 2, 1937; 5:00 P.M. and
April 3, 1937; 10:00 A.M. to April 4, 1937; 10:00 A.M.

Bearing samples were examined microscopically at the end of twenty-four hours, replaced in the same oil, and run for a second period of twenty-four hours. No air was used during the first twenty-four hours of the run. The air rate during the second twenty-four hour period was 10 c.c. per minute. Samples were not fastened securely on the glass rod, and some wear was noticed on the samples due to slippage of the metal in contact with the glass spacers.

Table XVII

RUN NO. 19: Corrosion of Bearing Samples in Glass Apparatus

OIL: Esso Motor Oil, No. 3

OIL QUANTITY: 500 c.c.

DURATION OF TEST: 36 hours

TEMPERATURE: 350 $\pm$ 4° F

STIRRER SPEED: 194 to 206 r.p.m.

AIR QUANTITY: 15 to 18 c.c. per minute

Bearing Metal No.	Initial	Weight - Gms. 24 hrs.	Final	Loss	Inches of Penetration Per Year
VIII - 1	11.7802	11.7792	11.7792	0.0010	0.0007
VIII - 2	11.6878	11.6876	11.6868	0.0010	0.0007

Date: April 6, 1937; 6:00 P.M. to April 8, 1937; 6:00 A.M.

Samples were out of the oil bath for a period of thirty minutes after twenty-four hours while being weighed. Air supply was interrupted for approximately two hours.

Table XVIII

RUN NO. 20: Corrosion of Bearing Samples in Glass Apparatus

OIL: Esso Motor Oil, No. 3

OIL QUANTITY: 500 c. c.

DURATION OF TEST: 36 hours

TEMPERATURE: 250 $\pm$ 3° F

STIRRER SPEED: 194 to 206 r. p. m.

AIR QUANTITY: 15 to 18 c. c. per minute

Bearing Metal No.	Weight - Gms. Initial	Final	Loss	Inches of Penetration Per Year
VIII - 1	11.7792	11.7782	0.0010	0.0007
VIII - 2	11.6868	11.6863	0.0005	0.0003

Date: April 9, 1937; 12:30 P. M. to April 10, 1937; 12:30 A. M.

During the first twelve hours, trouble was encountered with the temperature control apparatus. Air supply was interrupted for one hour and twenty minutes during the run.

Table XIX

RUN NO. 21: Corrosion of Bearing Samples in Modified Glass Apparatus

OIL: Esso Motor Oil, No. 3

OIL QUANTITY: 500 c. c.

DURATION OF TEST: 36 hours

TEMPERATURE: 300 $\pm$ 5° F

STIRRER SPEED: 196 to 204 r. p. m.

AIR QUANTITY: 15 to 18 c. c. per minute

Bearing Metal No.	Initial	Weight - Gms. Final	Loss	Inches of Penetration Per Year
VIII - 1	11.5541	11.5539	0.0002	----
VIII - 2	11.6513	11.6513	0.0000	----

Date: April 12, 1937; 11:30 P. M. to April 13, 1937; 11:30 A. M.

The poor temperature regulation of the run was due to the lag induced by the stagnant oil film in back of the copper plate. Air supply was interrupted for one hour and forty-five minutes during the run.

Table XX

RUN NO. 22: Corrosion of Bearing Samples in Modified Glass Apparatus

OIL: Esso Motor Oil, No. 3

OIL QUANTITY: 500 c. c.

DURATION OF TEST: 48 hours

TEMPERATURE: 350 $\pm$ 5° F

STIRRER SPEED: 440 to 480 r. p. m.

AIR QUANTITY: 15 to 18 c. c. per minute

Bearing Metal No.	Weight - Gms. Initial	Final	Loss	Inches of Penetration Per Year
VIII - 1	11.5539	11.5538	0.0001	----
VIII - 2	11.6513	11.6513	0.0000	----

Date: April 14, 1937; 2:25 A. M. to April 15, 1937; 2:25 A. M.

The run was interrupted for fifty-five minutes after thirty-eight hours to repair the motor speed reducing mechanism. Air supply was interrupted for two hours and thirty minutes during the run.

Table XXI

RUN NO. 23: Corrosion of Bearing Samples in Contact With a Dissimilar Metal

OIL: Esso Motor Oil, No. 3

OIL QUANTITY: 500 c.c.

DURATION OF TEST: 35.5 hours

TEMPERATURE: 350° F (See note below)

STIRRER SPEED: 470 to 490 r.p.m.

AIR QUANTITY: 15 to 18 c.c. per minute

Bearing Metal No.	Weight - Gms. Initial	Final	Loss	Inches of Penetration Per Year
V - 1	13.7982	13.7858	0.0124	0.0093
VIII - 1	11.5538	11.5534	0.0004	----

Date: April 16, 1937; 2:35 P.M to April 18, 1937; 2:05 A.M.

Some trouble was encountered with the temperature control apparatus. Minimum temperature recorded was 300° F, and the maximum was 400° F. These extremes were at the latter part of the run, and the duration at either of these temperatures was less than thirty minutes. Air supply was interrupted for two hours during the run.

Table XXII

RUN NOS. 24 & 25: Corrosion of Bearing Samples in Modified Jet-Type Oil Bath

OIL: Esso Motor Oil, No. 3

OIL QUANTITY: 1600 c.c.

DURATION OF TEST: 36 hours

TEMPERATURE: No. 24 - 280° F (see note below); No. 25 - 325 ± 3° F

Bearing Metal No.	Initial	Final	Loss	Inches of Penetration Per Year
Run No. 24; Bath A				
VIII - 1	12.1583	9.9717	2.1866	1.530
VIII - 2	12.1947	9.9601	2.2346	1.491
Run No. 25; Bath B				
VIII - 1	12.3218	10.5858	1.7360	1.213
VIII - 2	12.1984	10.3574	1.8410	1.288

Date: April 23, 1937; 11:30 P.M. to April 25, 1937; 11:30 A.M.

Considerable foaming of the oil with leakage occurred during the first twelve hours of the run. 100 c.c. of new oil were added to each bath after ten and one-half hours. 100 c.c. of additional new oil were added after sixteen hours. Run No. 24 maintained at 280° F due to relay failure after the first two hours of the run, after which the temperature varied ± 3° F. Indication in cleaning apparatus that suction line orifice was clogged in Run No. 25 for a considerable time near the end of the run.

Table XXIII

RUN NOS. 26 & 27: Corrosion of Bearing Samples in Modified Jet-Type Oil Bath

OIL: Esso Motor Oil, No. 3

OIL QUANTITY: 1600 c.c.

DURATION OF TEST: 36 hours

TEMPERATURE: $325 \pm 3^{\circ}$ F

Bearing Metal No.	Weight - Gms. Initial	Final	Loss	Inches of Penetration Per Year
Run No. 26; Bath A				
VIII - 1	13.4679	11.7931	1.6748	1.170
VIII - 2	12.1602	10.7113	1.4489	1.012
Run No. 27; Bath B				
VIII - 1	12.9573	11.2034	1.7539	1.227
VIII - 2	12.6739	10.6690	2.0049	1.400

Date: April 27, 1937; 5:30 P.M. to April 29, 1937; 5:30 A.M.

Considerable of the oil with leakage occurred during the first twelve hours of Run No. 27. 150 c.c. of new oil was added to each bath after seventeen hours. Temperature control relay stuck for a short period after sixteen hours on Run No. 26.

Table XXIV

RUN NOS. 28 & 29: Corrosion of Bearing Samples in Modified Jet-Type Oil Bath

OIL: Esso Motor Oil, No. 3

OIL QUANTITY: 1600 c.c.

DURATION OF TEST: 36 hours

TEMPERATURE: $325 \pm 3^{\circ}$ F

Bearing Metal No.	Weight - Gms. Initial	Final	Loss	Inches of Penetration Per Year
Run No. 28; Bath A				
VIII - 1	11.4982	10.7663	0.7319	0.512
VIII - 2	12.3321	10.8919	1.4402	1.008
Run No. 29; Bath B				
VIII - 1	12.3257	10.7099	1.6158	1.129
VIII - 2	12.3437	11.9507	0.3930	0.275

Date: April 29, 1937; 3:15 P.M. to May 1, 1937; 3:15 A.M.

50 c.c. of new oil was added to each bath after seventeen hours. Sample VIII - 1 of Run No. 28 and sample VIII - 2 of Run No. 29 both showed small areas on the surface covered by a thin brown film under which the original etched finish could be seen.

Table XXV

VISCOSITIES OF USED OILS AT 200° F, SAYBOLT UNIVERSAL, SECONDS

Oil	Run No.	Duration of Test	Viscosity	Equipment No.
A	1	43	1546	I
A*	2	38	641	I
A**	3	38	194	I
B	4	38	840	I
A	11	24	85.9	II
A	12	24	84.0	II
C	13	24	103.5	II
C	14	24	88.1	II
C	15	48	101.1	II
C	16	48	101.8	II
A	19	36	83.3	III a
A	21	36	88.5	III a
A	22	48	85.7	III b
A	23	35.5	86.0	III b
A	24	36	102.8	II
A	25	36	115.7	II
A	26	36	91.5	II
A	27	36	117.6	II
A	28	36	83.5	II
A	29	36	83.4	II

Footnotes for Table XXV on page 57.

Table XXV, Viscosity of Used Oils, (cont.)

A - Esso Motor Oil, No. 3

B - Sinclair Pennsylvania, S. A. E. 30

C - Quaker State, S. A. E. 30

A* - Esso Motor Oil, No. 3, plus 1% Alox AA Compound

A** - Esso Motor Oil, No. 3, plus 2% Alox AA Compound

I - Jet-Type Oil Bath

II - Modified Jet-Type Oil Bath

III a - Glass Apparatus

III b - Modified Glass Apparatus

DISCUSSION OF THE TEST DATA

A number of factors and their relative importance to corrosion were not fully appreciated during the first few runs. There are, however, certain facts brought out by these test data that warrant discussion.

Length Of Time For Corrosion To Start. It will be noted from the results of Run No. 1 that corrosion does take place during the first part of the test period. This is contrary to the general opinion that an oil must generate in itself products of decomposition prior to corrosion. A penetration of approximately 0.06, 1.14, and 1.00 inches per year respectively was reported for bearing metals V, VII, and VIII in 12.5 hours. It is safe to say that corrosion at this rate would ruin a bearing in actual operation and make it unfit for service or use.

The Effect Of Oil Stability On The Rate Of Corrosion. Further inspection of Run No. 1 shows that the rate of corrosion expressed in inches of penetration per year increased from the average values of 0.060 to 0.18 for bearing metal V, from 1.14 to 1.46 for bearing metal VII, and from 1.00 to 1.40 for bearing metal VIII in the period from 12.5 hours to 35.5 hours. At the end of 43 hours, the rates had either fallen off considerably or showed no further increase for the bearings mentioned above. This change in the rate of corrosion is believed to be related to two things. First, the initial increase in the rate of corrosion is more than likely due to the removal of the retarding effect caused by the highly polished surface present when the bearing specimens are first placed in the oil bath. Second, the continued heating and agitating of the oil at elevated temperature causes an increase in the viscosity of the oil which would in turn cause a reduction in the rate of flow followed by a decrease in the rate of corrosion. Thus it can be seen that if the decrease in the oil circulation is dependent on the stability of an oil, that this stability is a factor in corrosion.

Length Of Time Required For A Test. The data of Run No. 1 indicates that for this particular oil the maximum rate of corrosion has been reached and passed in 35.5 hours. It is assumed, therefore, that a test period should be approximately 36 to 40 hours in length.

Run Nos. 2, 3, and 4 were made in an effort to ascertain the accuracy which would be necessary for the test data to determine the reduction in corrosion caused by certain commercial inhibiting agents, and the accuracy required to differentiate the amount of corrosion caused by various oils.

Effect Of Alox AA Compound. One per cent of Alox AA Compound was added to Esso Motor Oil, No. 3, in Run No. 2 according to the recommendation of the manufacturer. It will be noted that the corrosion was not decreased appreciably with respect to any bearing metal except V, which did show a slight decrease when compared to the value of penetration calculated for Run No. 1 after 35.5 hours. This result becomes even more significant when it is recalled that each sample during Run No. 1 was twice washed clean of any adhering surface deposits.

With two per cent Alox AA Compound added to the same oil in Run No. 3, a slight reduction in the rate of corrosion is noted when this run is compared to either Run No. 1 or 2. This reduction takes place only with respect to Cadmium-Silver-Copper bearing metals, VII and VIII, while an increase in the rate of corrosion is observed with respect to bearing V.

Effect Of A Different Oil. When the corrosion rate of Run No. 4, using Sinclair Pennsylvania, S. A. E. 30, is compared with the rate determined after 35.5 hours in Run No. 1, a difference in magnitude can be seen in bearing metals VII and VIII, but no satisfactory differentiation can be noted with respect to bearing metal V.

It is readily seen from the first four runs that the accuracy of the tests for corrosion has to be much greater than expected small deviations in the corrosive action of the inhibitors plus oil or the oils themselves. This led the author to believe that a dual system of testing employing two baths, would be advantageous both for checking values obtained and to conserve time. For this reason the double test bath was designed.

Preliminary Test Of The Double Oil Bath. Although the results obtained in each test bath were generally of the same order of magnitude as could be expected, there was little if any agreement in the rate of corrosion when the same type of bearing metal samples were compared between the two baths. The deviations in the rate of corrosion in the same bath between the same type of bearing metals could be attributed to: (1) the uneveness of contact of the "U" type hanger, and (2) the possible differences in the rate of flow from the jets. The deviations in the results between baths were attributed to the variation in temperature between the two test baths. This led to the design of the modified jet-type oil bath.

Test Of The Modified Jet-Type Oil Bath. Immediately upon changing to this apparatus, the rate of corrosion decreased to approximately one one-hundredth of the value which had been normally reported in Run Nos. 1 through 6. After the decrease in corrosion was found in Run Nos. 7 and 8, the author decided that rather than attempt to rate or evaluate the effect of different oils or inhibitors with respect to corrosion, that a study of the mechanism of the corrosion would be advisable, so that a clearer understanding of the factors influencing the study of the corrosion of oil and bearing metals might be had.

In making the change from the jet-type oil bath to the modified jet-type oil bath, a number of new factors were brought in. First, the flow of oil from each jet was decreased due to the fact that restricting orifices had been placed in the suction line of each pump in an attempt to more nearly control the flow of oil to the same amount in each bath. Second, the replacement of the "U" type hangers by the "S" type decreased the contact between the bearings themselves and decreased the contact between the bearings and the steel box. Third, copper heating elements operating intermittently were placed in the oil sumps.

Accordingly, Run Nos. 11, 12, 13, 14, 15, and 16 were made on the modified jet-type oil bath at a constant jet velocity of 0.67 feet per second. Temperature was varied between 300 and 325° F, samples were treated by polishing and by acid etch, and Quaker State, S. A. E. 30 oil was used in Run Nos. 13, 14, 15, and 16 in place of the customary Esso Motor Oil, No. 3. The rate of corrosion of Run Nos. 11 through 16 agreed with the decreased values obtained in Run Nos. 7 and 8; namely, about one one-hundredth of that recorded previously in Run Nos. 1 through 6 for the Cadmium-Silver-Copper bearings VII and VIII, a material decrease in the rate of corrosion of the copper-lead bearing V, and no change in either the Bermax or Babbitt, bearing metals IX and VI respectively.

Three explanations of this phenomena seemed probable: (1) that the corrosion was electrolytic, and that good contact between the bearings themselves or contact between the bearings and the steel bath was essential for corrosion to take place; (2) that the decrease in velocity of the oil stream issuing from the jets caused less air to be mechanically carried beneath the oil surface to the interface of the specimens and the oil; or (and) (3) that the decrease in the velocity of the oil stream issuing from the jets diminished the scrubbing action along the surfaces of the specimens to the point where the products of corrosion were not carried away and thereby inhibited the action of the air on the bearing surface.

Effect Of Air At The Interface And Scrubbing Action Of The Oil Stream. In an attempt to separate the three factors which had apparently influenced the rate of corrosion so markedly, Run Nos. 24 through 29 were made. In order to increase the velocity of oil flow from the jets, the number of jets was diminished while the orifice controlling the total amount of oil being circulated in a bath was left the same. The new velocity of the oil from the jets was calculated as 2.14 feet per second. Electrolytic effects were removed by suspending each sample from a glass "S" type hanger completely insulating it from other samples, and only the Cadmium-Silver-Copper bearing VIII was used to eliminate electrolytic surface effects. Thus any corrosion reported would be due to either the scrubbing action of the oil stream, the air carried below the surface to the oil-bearing interface, or both.

The results of Run Nos. 24 through 29 show a rate of corrosion expressed in inches of penetration per year for bearing metal VIII of the same order of magnitude as was found in Run Nos. 1 through 6, -

approximately 1.2 or 1.3.

In order to further check the fact that corrosion does not take place when air is absent from the interface and when the scrubbing action is small, the glass apparatus was designed. Air was passed into the oil bath at a rate sufficiently great to cause oxidation of the oil, but the air stream was not directed against the face of the bearing specimen. Temperatures of 250, 300, and 350° F were used, and the samples were rotated at a speed of 200 r. p. m. If the oil is assumed to be still, the velocity of the oil past the periphery of the samples at 200 r. p. m. would be 0.93 feet per second. It was assumed that the oil was moving in the same direction as the specimens and that there would be slippage so that the actual velocity would probably be near the velocity (0.67 feet per second) of the oil stream issuing from the jets in Run Nos. 7 through 16.

As was expected, the rate of corrosion determined in Run Nos. 17 through 20 using Cadmium-Silver-Copper bearing metal VIII with Esso Motor Oil, No. 3, expressed in inches of penetration per year was less than one one-thousandth of that obtained in either Run Nos. 24 through 29 or Run Nos. 1 through 6.

The Effect Of Electrolytic Action And Scrubbing Action. In an effort to promote electrolytic action, the copper plate in electrical contact with the bearing metal was inserted for Run Nos. 21 and 22. Run No. 21 was made in the glass bath at a temperature of 300° F, a stirrer speed of 200 r. p. m. Run No. 22 was made at 350° F at a stirrer speed of 460 r. p. m. The stirrer speed of Run No. 21 gives an oil velocity value comparable with Run Nos. 7 through 16, while the opportunity for electrolytic action is increased. There was no corrosion reported. Run No. 22 was made with a stirrer speed which gave a velocity to the oil past the periphery of the specimen of 2.14 feet per second, which is comparable to the value of 1.51 feet per second, the velocity of the issuing oil jets in Run Nos. 24 through 29, when the fact that the oil is in motion is considered. There was no corrosion in Run No. 22, though the scrubbing action was similar to that in Run Nos. 24 through 29.

As a final check on the effect of electrolytic action, bearing metal VIII was rotated in the Esso Motor Oil, No. 3, at 350° F in electrical contact with a leaded-bronze bearing, V. A distance of only eleven thirty-seconds of an inch separated the two specimens. The rate of corrosion determined was zero.

Summary Of Discussion Relative To Conditions For Corrosion To Take Place. Summing up the results obtained for Run Nos. 1 through 29 it is found:

1. That corrosion does take place in the jet-type oil bath at temperatures of 300 and 325° F with an oil velocity from the jets of 1.5 feet per second, when the samples are insulated from each other and the bath.

2. That corrosion does not take place at temperatures of 300 and 325° F in the jet-type oil bath with an oil velocity of 0.67 feet per second, whether conditions are conducive to electrolytic action or not.

3. That corrosion does not take place in the glass apparatus under conditions conducive to electrolytic action at temperatures of

250, 300 or 350° F.

4. That corrosion does occur when sufficient air reaches the bearing-oil interface.

5. That the scrubbing action has no effect on corrosion when air is not present at the bearing-oil interface.

Viscosities Of The Used Oils. It must be remembered that any slight variation of the heating conditions of the test baths will change the value of the viscosity, and hence the values determined at the end of each test can be treated in a general way only.

If the viscosity of the oil at the end of Run Nos. 1 and 4 are compared, and allowance is made for the difference in the duration of the tests, it will be noted that a very large increase in viscosity occurred. This increase can be accounted for in two ways: (1) the formation of a soap from the metal lost due to corrosion, and (2) the thickening of the oils due to oxidation and natural sludging.

Perhaps more significant is the effect on the final viscosity of the addition agent, Alox AA Compound. Esso Motor Oil, No. 3, shows a decrease in viscosity in direct proportion to the amount of additive agent added. That is, this oil had a viscosity of 1546 seconds at 200° F when run for 43 hours; which was decreased to 641 seconds at 200° F when run for 38 hours with the addition of one per cent of Alox AA Compound; and was further reduced to 194 seconds at 200° F when run for 38 hours with the addition of two per cent of the Alox AA Compound.

The viscosity increase of the used oil over the new oil is relatively small when corrosion did not occur to any great extent in Run Nos. 11

through 23. This would lead to the conclusion that the thickening of the oils was due to the formation of soaps rather than to natural sludging due to oil break down.

If the total weight of metal lost due to corrosion is tabulated against the final viscosity, there is a slight tendency for a relationship to be shown. Run Nos. 26 through 28 are compared in this way:

Run No.	Total Weight Lost Due To Corrosion	Viscosity Of The Used Oil In S. U. sec. @ 200° F
26	3.1237	91.5
27	3.7588	117.6
28	2.1271	83.5
29	2.0088	83.4

The viscosity of the new oil at 200° F is approximately 83 seconds. Now if it is assumed that the metal lost due to corrosion is combined with fatty acids present in the oil to form a soap, and that this soap is soluble to a certain extent in the oil at 200° F; it follows that if this concentration of soap is exceeded, the oil will thicken or increase its viscosity as a result. Thus it would seem that Esso Motor Oil, No. 3, is capable of holding in solution approximately two grams of metal combined with a fatty acid after which a further increase in the soap concentration would materially increase the viscosity of the oil.

<u>Suitability Of Test Procedure</u>. The modified jet-type oil bath using only two samples of the same bearing metal in a single test bath seems to

have sufficient accuracy to rate different oils or inhibiting agents with respect to corrosion if certain factors were controlled.

Attention is called to Run Nos. 26 through 29 which in the opinion of the author are the most exact and represent the highest development of test procedure. In Run No. 26 specimen VIII - 2 was in the same position, adjacent to the same jets as specimen VIII - 2 of Run No. 28. Under the same test conditions, the rate of corrosion expressed in inches of penetration per year was determined as 1.012 and 1.008 respectively for the two tests. This represents a deviation from the mean of approximately 0.2%. Comparison of specimen VIII - 1 of Run No. 27 with specimen VIII - 1 of Run No. 29 which were also adjacent to the same jets, shows a rate of corrosion of 1.227 and 1.129 inches of penetration per year. The deviation from the mean in the latter case is approximately 4% and represents only a fair degree of accuracy.

Other testing apparatus, such as the Underwood Machine, designed to determine the rate of corrosion show discrepencies of this same order of magnitude according to private communication received by the author. The extremely low rates of corrosion that are reported in Run Nos. 28 and 29 are believed to be caused by the deposition of an impervious film on the surface of the specimen and should be disregarded entirely as an indication of the corrosive action of an oil.

Great care should be taken in quantitative measurements that all jets are reamed to give exactly the same rate of flow.

V. CONCLUSIONS

The corrosion test data are too meager to permit drawing any definite conclusions. Within the scope of the equipment used, however, the data seem to point to the following conclusions:

1. That corrosion starts immediately the agitated oil and bearing metal are brought in contact.

2. That corrosion is mainly due to the presence of a relatively large quantity of air being present at the oil-bearing interface.

3. That electrolytic action has little, if any, effect on the process of corrosion of the bearing metals in the oil.

4. That the scrubbing action of the oil in contact with the bearing face only partially influences the rate of corrosion. However, it is believed this scrubbing action of the oil is not sufficiently severe to remove any film composed of the products of corrosion.

5. That the degree of corrosion is markedly affected by the surface conditions of the bearing specimens.

6. That the degree of corrosion is greatly influenced by the velocity of oil flow from the jets.

7. That a rather close connection exists between the degree of corrosion and the increase in the viscosity of the oil.

VI. SUMMARY

Tests were made at the Lubrication Laboratory at Virginia Polytechnic Institute to determine the mechanism of corrosion of Cadmium-Silver-Copper bearing metals, and if possible to develop a procedure to quantitatively rate oils and inhibitors with respect to corrosion.

Two pieces of testing apparatus were employed - a jet-type oil bath and a glass apparatus. It was found that corrosion of the cadmium base bearing metals took place in the jet-type oil bath with jet velocities equal to 1.51 feet per second at temperatures of 300 and 325° F with Esso Motor Oil, No. 3. Corrosion did not take place at temperatures of 300 and 325° F in the jet-type oil bath when the jet velocities were decreased to 0.67 feet per second.

Tests on the glass apparatus indicated that the corrosion was not electrolytic, that the presence of air (oxygen) at the oil-bearing interface was necessary for corrosion tomproceed, and that the scrubbing action of the oil past the bearing face only partially influences the rate of corrosion.

The jet-type apparatus is believed to be quantitative in its results if the surface condition of the bearing specimens and the velocity of the issuing oil jets are accurately controlled.

Viscosity of the oil prior to and after the test was measured. No consistant trend of viscosity was noted, but a tendency for the viscosity of the oil to be directly proportional to the total weight of metal lost by corrosion was pointed out.

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