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FAILURE OF HARD CHROMIUM PLATE
ON POWER-PISTON SLEEVE

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Project 2152-3

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ABSTRACT

The cause of flaking of chromium from plated SAE 1112 power-piston sleeves has been found to be galvanic corrosion of the underlying steel, dissolution occurring through the cracks which are invariably present in the chromium.

An accelerated test simulating the type of service failure observed has been developed and used to investigate a number of variations in plating procedure in an attempt to prevent or minimize the flaking. Several types of quench-hardenable stainless steels have also been studied to determine their suitability as sleeve material.

FAILURE OF HARD CHROMIUM PLATE
ON POWER-PISTON SLEEVEINTRODUCTION

Examination of power-piston sleeves, Kelsey-Hayes Drawing C-37664 (Fig. 1), after being in service from six to eight months, revealed localized stripping of the chromium plate. The relation of the sleeve to adjacent parts in the assembly is shown in Drawing E-37700 (Fig. 2). From a service standpoint, the sleeve is exposed to two environments: the major portion, approximately 3 inches in length, is in air or the partial vacuum generated by the engine manifold; the other, about 1-1/2 inches in length, is in brake fluid, which is composed of a mixture of organic liquids, a typical example (Delco 11) being 2-butoxyethanol (butyl cellosolve), diethylene glycol monoethyl ether (methyl carbitol), and 1,2-ethanediol (ethylene glycol), inhibitors, and sodium tetraborate. Immersed in fluid adjacent to the sleeve are the mineral-oil-resistant seal (Drawing 37014), tin-plated steel retainer (Drawing 37015), brake-fluid-resistant primary cup (Drawing 37016), sintered iron spacer (Drawing 37660), sintered bronze bushing (Drawing C-37659), blued steel washer (Drawing 37009), brake-fluid-resistant secondary cup (Drawing 37010), and a tinned steel spacer, spring, and shaft (Drawing B-37662). The entire assembly is held in the cast-iron brake-fluid chamber (Drawing C-37644) by a tinned steel plug (Drawing C-37013). These parts are shown disassembled in Fig. 3. In addition to the seal and cups, direct contact with the sleeve is made by the bushing and the tinned parts of assembly B-37644. The tinned retainer is separated from the sleeve by about 0.02 inch.

The locations of the stripped plate on the sleeves which were investigated corresponded to contact under the seal, the primary cup, the area between these, and also under the secondary cup, the sleeve being in the rest position. Figure 4 shows typical examples.

The failure is considered serious because of the possibility of leak-

age of fluid back into the engine manifold. Leakage may result from the direct removal of the chromium plate, and more seriously, from the excessive wear on the seal and cup caused by the loose flakes and the jagged edges of the plate remaining on the sleeve.

Metallographic examination revealed that the plate is removed by loss of adhesion under sections outlined by the original cracks generated in the plating process, as shown in Fig. 5. Blistering may also be observed because of partial separation from the basis metal. Sections through breaks in the plate show that removal of the basis iron is the cause of loosening (Fig. 6) although the amount of iron lost is not excessive.

The possible causes for the failure which were immediately apparent are:

- (1) Galvanic corrosion produced by current flow resulting from either stray currents or potential differences between the various components, particularly between the sleeve and other parts, or perhaps between the different parts of the sleeve itself.
- (2) Corrodants produced over relatively long periods of time by chemical changes in the fluid, seal, cups, and metal components in the assembly.
- (3) Ball-burnishing of the sleeve bore, which might loosen the brittle plate through plastic deformation of the sleeve.
- (4) The composition of the steel, Type AISI 1112, which has a high sulfur content. This in combination with the hydrogen generated during the plating process and diffused into the steel might form hydrogen sulfide, which might act as a corrodant.

Preliminary tests combined with other arguments concerning these possibilities, which need not be presented here, pointed conclusively to galvanic corrosion as the cause. The basis iron is removed in solution through the cracks in the chromium plate. Subsequent work consisted of seeking alternative designs or materials to reduce the possibility of similar failure.

EXPERIMENTAL PROCEDUREPotential Measurements

Open-circuit potential measurements of the various components paired in contact with brake fluid were made with a Type K, Leeds and Northrup potentiometer. Nonporous samples were washed in a water solution of a detergent (Alconox), rinsed, and dried before testing. The porous bronze bushing and iron spacers were used as received.

Since the method involves a null point determination and no current flows in the circuit consisting of the test parts, fluid, and connecting wires, the sample areas and spacings have no influence on the results. Changes of potential with time resulting from exposure of the fluid to air, and samples to fluid do occur, however, and must be determined by extended observation. Measurements against a standard electrode would be expected to yield results allowing unequivocal conclusions regarding individual potential changes rather than combined couple changes, but these results did not appear to justify the additional effort. In the later work with the stainless steels which were coupled primarily with the porous bronze, the bushing and fluid were exposed to each other and to the air for a long period before potential measurements were made in order to stabilize this electrode and the fluid. To facilitate testing, potentials of as many as ten sleeves were measured in the same fluid, using a multiple switch arrangement, as shown in Fig. 7.

Electrical resistance of the fluid was measured with an a-c Wheatstone bridge, with a conductivity cell as one of the legs of the bridge (Fig. 8). The arrangement of Fig. 9 was used to measure very small direct currents in tests involving the high-resistance brake fluid.

Accelerated Corrosion Test

An accelerated corrosion test was devised to test different types of chromium plate. A plug, seal, and primary cup were assembled to a sleeve with a 1.0% CaCl_2 water solution in the cavity (Fig. 10). This sleeve was made the anode (see Appendix A for nomenclature) and the plug was made the cathode by connecting to a 1.5-volt dry cell. After 1/2 to 12 hours, usually 1 to 4 hours, the plug and cups were removed and the extent of stripping of the chromium plate was observed and judged visually. This test produced the same type of failure as obtained in service. Green ferrous hydroxide resulting from dissolution of basis iron was invariably found in the solution when appreciable stripping was observed. The use of CaCl_2 or the exact amount is

not significant. It was the only electrolyte beside brake fluid which was tried. It is probable that practically any dilute solution of a strong acid or neutral salt which ionizes extensively in water would serve as well.

A ferroxyl test of the chromium plate before and after the accelerated test was made on most sleeves. A piece of thin paper with the same width as the sleeve circumference was wet in the ferroxyl solution (1% NaCl, 1% $K_3Fe(CN)_6$, in water), applied to the sleeve so as to eliminate bubbles, and then allowed to dry. Pits communicating with the basis steel appear as blue areas. The test is not too reproducible, but it permits visual location of small holes in the sleeve plate which might otherwise be missed. A low-power binocular microscope augmented visual inspection. Potential measurements were made on the complete assembly filled with brake fluid with the one modification of boring the bushing hole larger to eliminate an internal electrical short which would otherwise occur.

Metallography

The appearance and thicknesses of chromium plates and the structures of the various high-chromium steels were observed using standard metallographic methods. Mechanical polishing was employed for plated samples and both mechanical and electrolytic polishing were utilized for the alloy steels. The electrolyte was 5 percent by volume of 72% perchloric acid in glacial acetic acid. A Buehler electropolisher was used. An electrolytic etchant consisting of 10 ml HCl + 90 ml of 95% ethanol was employed at 6 volts for 5 to 10 seconds.

Specimen heat treatment was carried out in an automatically controlled electric furnace in an air atmosphere. Low-temperature tempering was accomplished using a recirculating air furnace.

Hardnesses of stainless-steel sleeves were determined with a Rockwell hardness tester on a flat ground on the lateral surface. These measurements, along with the metallographic observations, were made primarily to check the heat treatments and are not included in the report.

All samples investigated are listed in Appendix B.

RESULTS

The results obtained fall into two main categories: (1) proof of the galvanic nature of the failure and (2) investigation of alterations in

sleeve material and production to prevent corrosion. These will be considered in turn.

Proof of the Galvanic Nature of the Failure

Potential Differences. Potential measurements of the various components against each other in the brake fluid exhibited differences of almost 0.5 volt as shown in Table I. In all cases the sleeve was anodic. Potentials of other combinations of parts than those presented were made but are of no importance in the present instance and are therefore not reported. In general, the unreported polarities and potentials correspond to differences derivable from Table I.

TABLE I

ELECTRICAL POTENTIALS IN VOLTS OF CHROMIUM-PLATED SLEEVE
NO. 10 AGAINST VARIOUS COMPONENTS IN BRAKE FLUID¹

	Bearings ²	Spacer ³	Washer ⁴	Retainer ⁵
100% Brake Fluid	0.44	0.40	0.25	0.09
90% Brake Fluid + 10% Water	0.47	0.42	0.18	0.09
99% Water + 1% CaCl ₂	0.46	0.11	0.03	0.12

¹Sleeve anodic in all cases

²Sintered bronze

³Sintered iron

⁴Blued steel

⁵Tin-plated steel

More comprehensive observations revealed variations of potential with time after immersion of the components in the fluid. Figure 11 presents several potential-time curves of sleeves against bushings and a powdered iron retainer. Since the measured potential is the sum of potentials of the separate electrodes in contact with the fluid it cannot be stated unequivocally what the causes of the change are. It appears probable, however, that the generally observed increase is a change of the chromium surface. The initial drop of the one curve involving a bronze powder bushing is attributable to absorption of fluid. As stated in the previous section of this report,

subsequent measurements of sleeves were made in aged fluid against bushings immersed for a long time.

Results of sleeves against tin-plated parts in brake fluid were initially less than 0.10 volt and polarity was erratic. After about 24 hours a value of 0.16 volt, with the sleeve anodic, was reached.

A complete assembly of the cylinder and component parts was arranged for potential measurements as described. Electrical contact was made with the cylinder and sleeve. The results are also plotted in Fig. 11. This arrangement effectively tests the average potential of the components against the sleeve, which approaches a low value because of polarization. Movement of the sleeve with respect to the other parts and stirring of fluid would probably increase the potential difference. Holding another complete assembly (unaltered bushing) filled with fluid for 30 days resulted in a slight amount of corrosion and flaking of the tin-coated parts, with no change in the sleeve.

Fluid Resistance. The electrical resistances of fresh brake fluid alone and of brake fluid with calcium chloride and various amounts of water are listed in Table II. Although the resistance of pure fluid is high, it is capable of carrying a slight current which could cause corrosion at sites where such positive current leaves a metal surface and goes to the fluid. Obviously, the contaminants investigated increase the conductivity markedly and would accentuate any tendency toward corrosion.

TABLE II

RESISTANCE IN OHMS OF BRAKE FLUID WITH ADDITIONS OF WATER AND CALCIUM CHLORIDE*

	0% H ₂ O	1% H ₂ O	10% H ₂ O
0% CaCl ₂	11880) ^{**} 10880)	9220	3910
1% CaCl ₂	2700	2620	1470

*Values are not converted to unit resistances or conductivities. Results on 0.1 normal KCl in the same cell: 35.2 ohms; tap water: 1480 ohms.

**Duplicate determination.

To verify the above analysis it appeared necessary only to increase the magnitude of the current either by increasing voltage or decreasing the electrolyte resistance. To this end variations of the experiment of Fig. 10 were made. These are tabulated in Table III.

TABLE III
EFFECT OF ACCELERATED TESTS ON
STRIPPING OF CHROMIUM PLATE

Sleeve No.	Time of Exposure, hr	Applied Potential, v	Electrolyte	Resulting Current, ma	Results on Cr Plate
6	24	1.5	Brake Fluid	0.00001	None
7	12	20-30	Brake Fluid	1.2-1.8	Pitted slightly; original cracks enlarged.
9	12	1.5	H ₂ O-1% CaCl ₂	0.04*	Stripped where in contact with seal; blistered slightly.

*Initial value; increases to 0.5-1.0 ma on rupture of plate.

Figure 4 is a photograph of the failure of sleeve No. 9 in Table III compared with the service failures. High voltage applied across the brake fluid (sleeve No. 7) tends to dissolve the chromium rather than the basis iron.

Extended time of immersion of sleeves in brake fluid (66 hours) and 1% CaCl₂ solution (12 hours) without an applied potential produced no change in the plate.

On the basis of the above results it may be concluded that the cause of the failure of the chromium plate is galvanic corrosion caused by a potential difference with the sleeve as anode, the brake fluid acting as electrolyte. No special conditions such as subsequent introduction of contaminants, long-time aging of fluid, decomposition of seals, etc., need be considered, although these could accelerate corrosion rates. There are three possible sources of the potential difference:

- (1) that observed between the sleeve and one or more of the various components,
- (2) an active-passive condition of the chromium on the sleeve itself, that part in the fluid being active (anodic) while the surface exposed to air is passive, and
- (3) sustained stray currents in the automobile frame passing through the brake cylinder.

Of these the first is the most probable. More refined work would be necessary to establish the second, and the third is the least likely of the three possibilities.

Proceeding on the conclusion that a complete galvanic cell exists in the cylinder which results in corrosion, the following solutions to the problem present themselves:

- (1) Remove the electrolyte.
- (2) Prevent electrical contact of the corroding part with other parts more noble.
- (3) Change the composition of one or more of the components to decrease the potential or change the polarity of the corroding part.

The service requirements of the fluid prevent any drastic changes in its composition, although removal of sodium tetraborate might increase the electrical resistance and thereby decrease the current flow appreciably. The electrical contact of the sleeve with the cylinder and other parts could not be changed without extensive redesigning because a complete circuit exists through parts outside the cylinder. The only other course is change of components, particularly the sleeve.

Tests of Various Types of Sleeves

The variations investigated, primarily with the accelerated corrosion test, are listed along with results in Table IV, with the exception of the stainless steels which are considered separately. The ratings are qualitative, arrived at by visual inspection, usually with the aid of the ferroxyl test and low-power magnification. Representative samples are shown in Fig. 12; a few potential-time curves are plotted in Fig. 13.

TABLE IV

COMPARATIVE BEHAVIOR OF VARIOUS CHROMIUM
PLATES TO THE ACCELERATED CORROSION TEST

Sleeve	Condition	Rating*, for Given Time of Exposure, hr					
		0.5	1	2	4	6	12
16	0.0002" Cr	-	3	-	-	-	-
17	0.0002" Cr	-	-	4	-	-	-
5	0.0010" Cr, regular production	1	1	2	4	-	-
14	0.0010" Cr, regular production	-	1**	-	-	-	-
15	0.0010" Cr, regular production	-	-	4	-	-	-
8	0.0010" Cr, regular production	-	-	2,4 [†]	-	-	-
9	0.0010" Cr, regular production	-	-	-	-	-	4
E	0.0005" Ni, 0.0010" Cr	-	-	1,2 [†]	2	2	-
A	0.0005" Ni, 0.0005" Cu, 0.0005" Cr	-	-	1,1 [†]	3	-	-
B	0.0005" Ni, 0.0005" Cu, 0.0005" Cr	-	-	1,1 [†]	-	-	-
C	0.0015" Ni, 0.0002" Cr	-	-	2	2	2	-
11	Crackfree Cr	-	-	2	-	4 [†]	-
G	0.0010" Cr, regular production, plastic-impregnated	1	2**	2	-	-	-
H	0.0010" Cr, regular production, plastic-impregnated	-	-	-	4	-	-

*Numerical rating corresponds to the following conditions:

1. no visible effect
2. slight stripping
3. less than one half of circumference under seal or cup stripped
4. most or all of circumference stripped

**1.2 hours.

[†]Duplicate tests on different parts of sleeve.

[‡]5.5 hours.

Table IV reveals the following points:

- (1) The quality measurement is based on the time necessary to produce a given extent of deterioration of the plate.

- (2) Some variation in either the test or the plating or both exists. (Cf. the same exposure times, samples 8, A, B, and E.)
- (3) The thicker the chromium plate, the greater the resistance to stripping.
- (4) The thicker the underplate of copper and nickel, the greater the resistance to stripping.
- (5) Crackfree chromium is not resistant to stripping. (Metallographic examination shows that it is not pore-free.)
- (6) Plastic impregnation does not increase resistance appreciably.

Casual comparison of the appearances of 0.0002-inch and 0.0010-inch chromium plate after testing may lead to the conclusion that the 0.0002-inch plate is superior because of the less noticeable attack on it. The area of plate removed, however, is greater for a given time because of the larger number of cracks and the shorter paths to the basis iron through the cracks. The thicker plate is actually somewhat more resistant to stripping.

The improved behavior afforded by copper and nickel underplating is consistent with published results. It is usually reported that nickel is the more effective of the two. The corrosion resistance is attributed to the decreasing proportion of pores in the undercoat as the thickness increases. This is borne out in these results; increasing time of exposure does not increase the severity of stripping since the number of pores is not increased above those already present during the time of the test.

The above results indicate that of the feasible variations involving chromium plating, nickel underplating shows the most promise of reducing the chromium stripping during service. The corrosion tendency still exists, however, as indicated by the high potential (Fig. 13) and the slight pitting obtained in the accelerated test. Also, difficulty was experienced in grinding the nickel plate prior to chromium plating, because it was stripped from the basis iron.

The use of hardened 440C stainless steel for the model 130B push-rod, which is subjected to essentially the same service conditions as the chromium-plated sleeve with no reported difficulty, pointed to the possibility of using this or a similar material. The hardness required narrowed the choice to the 420 (12 to 14% Cr, 0.15% C minimum) and 440 (14 to 16% Cr, 0.6 to 1.2% C) stainless-steel types, which are quench-hardenable.

Potential-time measurements of the kind previously described were made on samples in various conditions of hardness and surface finish. These

results are presented in Figs. 14 through 20. In all cases the sleeves are anodic to the bronze bushing compact with a potential difference of between 0.1 and 0.5 volts, depending on the sleeve treatment.

In the soft state the potential tends to decrease to a low value, while hardened samples remain high (Fig. 14). Low-temperature tempering does not affect the original high potential exhibited in the hardened state, as seen in Fig. 15. All of the above samples were electropolished to remove at least 0.02 inch from the surface, sufficient to expose metal unaltered by grinding operations subsequent to heat treating. Such mechanical working may materially change the potential values. Rough machining and grinding in the soft state has little effect, as seen in Fig. 16. On the other hand, grinding in the hardened condition produces the greatest observed potential differences (Fig. 17). These curves also show the reproducibility which may be expected on duplicate tests of the same sample conditions. Verification of the increased potential on cold working is also found in Fig. 18. The magnitude is less in this case than that resulting from automatic grinding which is much more severe than hand-abrading with paper.

The surface condition resulting from low-temperature tempering, after hardening and grinding, does not produce high potentials, as may be observed in Figs. 18 and 19. The 400°F temper is better than the 600°F temper, and as seen before, the unaltered metal obtained by electropolishing is more anodic than the as-tempered surface.

No distinctions have been made in the above statements concerning composition variations because the potentials of 440C, 440A, 420, and 420F are very similar when in the same condition of heat treatment and surface finish.

The effect of a passivation treatment (hot nitric acid—sodium dichromate solution) is to make the sleeves slightly more anodic, contrary to the purpose of the treatment, as shown in Fig. 20.

Long-time tests on sleeves in contact with brake fluid with several impressed voltages are listed in Table V. If the effect of voltage and time on pitting were proportional, the tests on Sample V would be expected to show five to ten pits of the same size, or the same number as on Sample O but of smaller size, or some intermediate distribution of these factors. The fact that no trace of pitting is found indicates that at some voltage between 0.5 and 1.5 the corrosion rate drops markedly. Polarization is probably responsible; the observed currents are only about 10 percent of the value calculated from the voltage and resistance.

TABLE V

EFFECT OF TIME AND POTENTIAL ON PITTING
OF STAINLESS-STEEL SLEEVES IN CONTACT WITH BRAKE FLUID*

Sample	Composition	Impressed Voltage	Time, days	Current, ma	Results
V	440C	0.25	7.0	1.2	No effect
V	440C	0.50	7.0	2.5	No effect
O	420F	1.5	15.5	5	63 pits, about 0.006" dia, 0.01" deep

*Sleeves anodic in all cases. Resistance of sleeve-fluid-plug, 22,000 ohms.

This lack of attack at 0.5 volt or less, the possibility of decreasing the maximum potential of the sleeve to considerably less than this value, and the satisfactory behavior of the pushrod of model 130B indicate the suitability of 420 or 420F as a sleeve material. As indicated above, the final operation should be the low-temperature temper. This does not preclude an intermediate temper between quenching and grinding, which may be necessary to minimize cracking during grinding. Some possibility exists that the hardening treatment may be carried out after final grinding, thereby eliminating the latter step after heat treatment.

Two³ further possible solutions should be mentioned. A nitrided sleeve was neutral or slightly cathodic to the various components of the assembly (Fig. 13) and would probably perform satisfactorily in the fluid. Some doubt exists, however, as to the corrosion resistance of that part of the sleeve which is in the chamber communicating with the engine manifold. Only long-time service tests would give the answer and they should be undertaken. Carburizing or carbonitriding would give the necessary abrasion resistance more economically than nitriding and should be investigated.

A chemically deposited, hard nickel-plating method has recently been developed (Kanigen nickel plating) which may give the required hardness and corrosion resistance. Its economic and technical feasibility should be investigated.

RECOMMENDATIONS

1. Stainless steel AISI 420 is recommended as a suitable material for immediate production of power-piston sleeves from the standpoint of desired hardness and corrosion resistance.
2. Tempering of hardened sleeves should be carried out after the final grinding operation in order to obtain maximum resistance to corrosion in brake fluid.
3. Plain carbon steel sleeves surface-hardened by carburizing or cyanitriding should be investigated by means of field service tests to determine their resistance to corrosion in the portion exposed to the manifold side of the power piston. Plain carbon steel exhibits a satisfactory electropotential to the other components of the assembly and would not corrode in the brake fluid.
4. The economic feasibility of chemically deposited hard nickel (Kanigen nickel plating) should be investigated. It has the requisite hardness and probably the necessary corrosion resistance also.

APPENDIX A

Some fundamentals of galvanic corrosion are given here in terms used in the main body of the report.

If electrodes of iron and copper are immersed in solutions of their own ions, as in Fig. A-1, the metals will undergo the following reversible reactions until equilibrium is established.

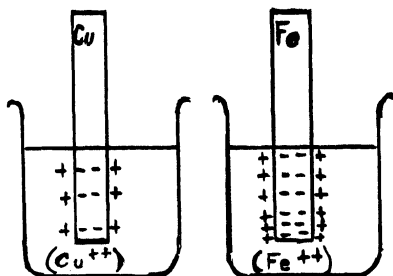
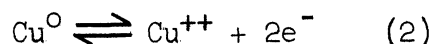
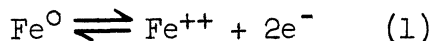


Fig. A-1

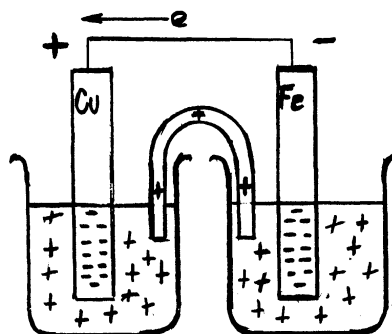


Fig. A-2

The electrons collect on the electrodes and are electrostatically attracted by the positive ions arranged on the electrode surfaces.

If, now, a conducting bridge is inserted and the electrodes are connected by a conductor, as in Fig. A-2, the electrons will tend to flow in the external circuit from the higher (negative) potential to the lower, or, conversely, from the metal having the higher solution pressure to the lower. The equilibria of equations (1) and (2) are then disturbed, being forced in opposite directions: (1) to the right with continual solution of Fe, and (2) to the left with deposition of Cu.

Considering the potentials from standard nomenclature, positive

current flows from the cathode (less negative Cu) through the wire to the anode (more negative Fe), and thence into the solution, in the opposite direction to the electron flow.

The more general case of a single solution with no excess cations to precipitate on the cathode results usually in precipitation of hydrogen. Accumulation of hydrogen on the cathode prevents or minimizes current flow in the circuit (polarization) unless a depolarizer (usually oxygen) is present or the potential is so high that gaseous hydrogen is evolved.

This effect, accumulation of the products of corrosion, usually modifies the course of corrosion to such an extent that a knowledge of the open circuit potentials cannot be relied upon to predict corrosion results. The direction and intensity of potential between a couple in a given medium, however, shows the corrosion tendency. Marked decrease in corrosion rate may be obtained by anodic or cathodic polarization or by increasing the resistance in the circuit. The latter may be accomplished by increasing the electrolyte resistance, a possibility in the present case.

APPENDIX B

LIST OF SAMPLES

Sample
Designation

1. 0.0002" Cr plate, service failure
2. 0.0010" Cr plate, service failure
5. 0.0010" Cr plate, regular production
6. 0.0010" Cr plate, regular production
7. 0.0010" Cr plate, regular production
8. 0.0010" Cr plate, regular production
9. 0.0010" Cr plate, regular production
10. 0.0010" Cr plate, regular production
11. Crackfree Cr plate
13. Nitrided sleeve
14. 0.0010" Cr plate, regular production
15. 0.0010" Cr plate, regular production
16. 0.0002" Cr plate from Moraine Products Division, General Motors Corporation
17. 0.0002" Cr plate from Moraine Products Division, General Motors Corporation
- A. 0.0005" Cu, 0.0005" Ni, 0.0005" Cr, polished
- B. 0.0005" Cu, 0.0005" Ni, 0.0005" Cr, polished and ball-burnished
- C. 0.0015" Ni, 0.0002" Cr, polished and heat-tested
- E. 0.0005" Ni, 0.0010" Cr, polished and ball-burnished
- G. 0.0010" Cr, regular production, plastic-impregnated
- H. 0.0010" Cr, regular production, plastic-impregnated
- I. AISI 440C pushrod from model 130B power brake, hardened
- J. AISI 440C, oil-quenched from 1875°F cold-treated -80°F, tempered at 350°F, finish-ground
- K. AISI 440C, oil-quenched from 1875°F, cold-treated -80°F, tempered at 350°F, finish-ground, passivated
- L. AISI 420, oil-quenched from 1875°F, cold-treated -80°F, tempered at 350°F, finish-ground

- M. AISI 420, oil-quenched from 1875°F, cold-treated -80°F, tempered at 350°F, finish-ground, passivated
- N. AISI 420F, oil-quenched from 1875°F, cold-treated -80°F, tempered at 350°F, finish-ground
- O. AISI 420F, oil-quenched from 1875°F, cold-treated -80°F, tempered at 350°F, finish-ground
- P. AISI 420F, as-received annealed bar stock
- Q. AISI 420F, as-received, rough-machined
- R. AISI 420F, as-received, rough-machined, rough-ground
- S. AISI 420, as-received, rough-machined
- T. AISI 420, as-received, rough-machined, rough-ground
- U. AISI 440C, finish-ground, oil-quenched from 1875°F, cold-treated -80°F, tempered at 350°F
- V. AISI 440C, finish-ground, oil-quenched from 1875°F, cold-treated -80°F, tempered at 350°F
- W. AISI 440A, oil-quenched from 1875°F, cold-treated -80°F, tempered at 350°F, finish-ground

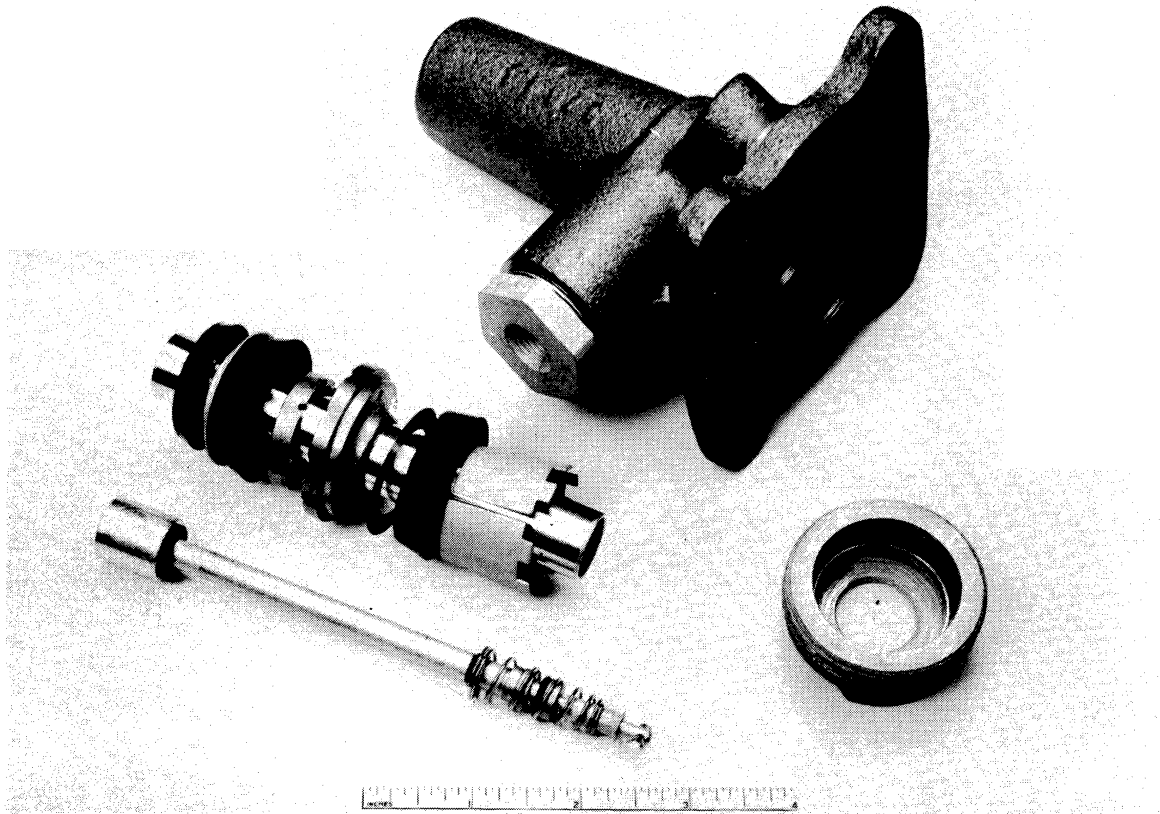


Fig. 3. Component Parts of Master Cylinder.

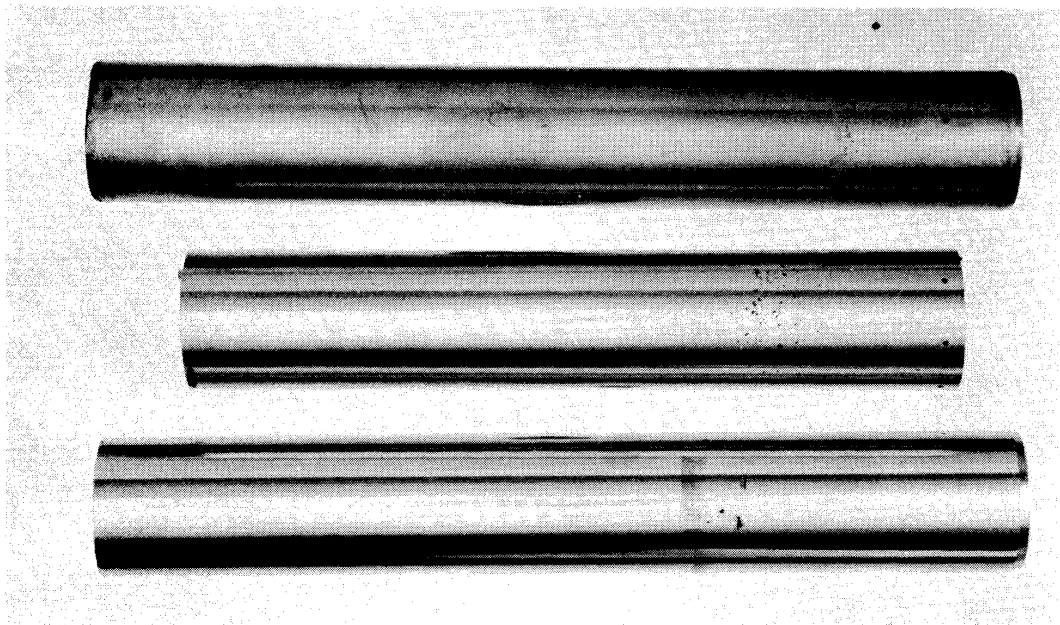


Fig. 4. Top to Bottom: service failure, 0.0002-inch-thick chromium plate, sleeve 1; service failure, 0.0010-inch-thick chromium plate, sleeve 2; accelerated test failure, 1% CaCl₂, 1.5 volts, 12 hours, sleeve 9.



Fig. 5. Removal of Chromium Plate. Area outlined by original cracks in plate, sleeve 2, 100X.

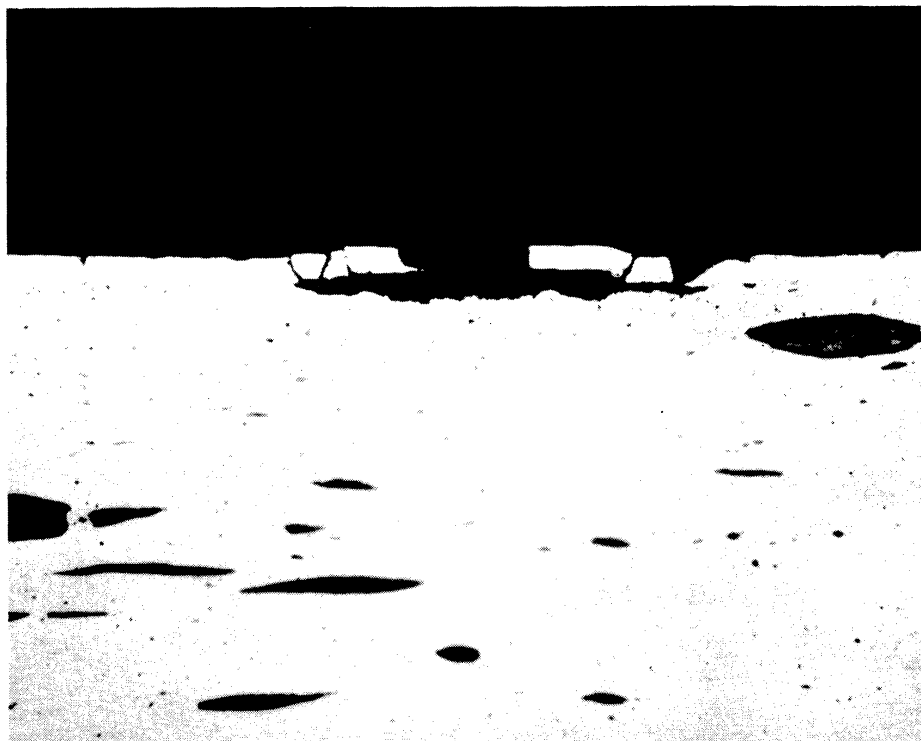


Fig. 6. Section through 0.0010-Inch Chromium Plate. Shows dissolution of basis steel extending from original crack in chromium, sleeve 2, 500X.

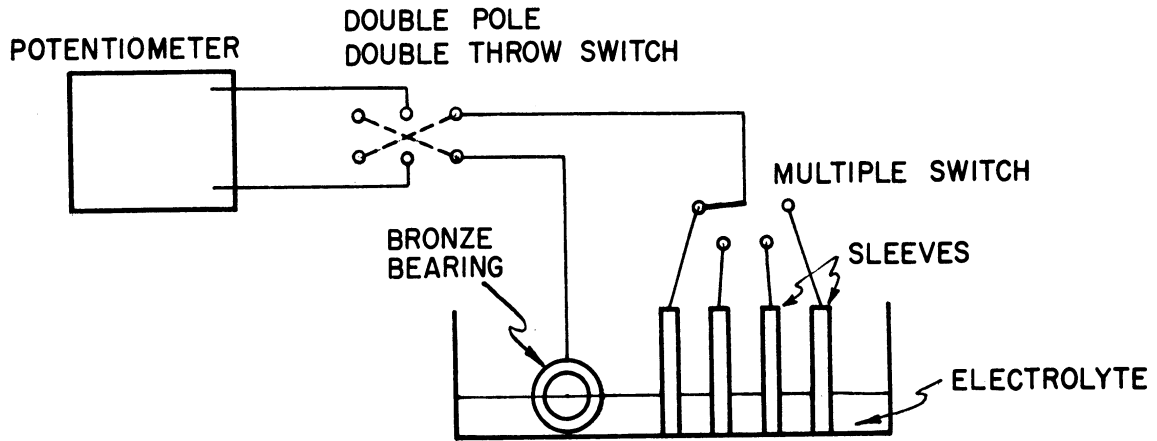


Fig. 7. Wiring Diagram for Measurement of Potential Differences between Components in Various Electrolytes.

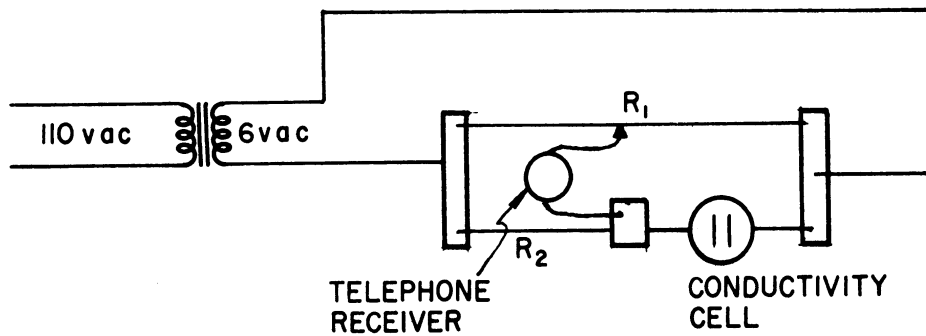


Fig. 8. Wiring Diagram for Measuring Electrical Resistance of Brake Fluid.

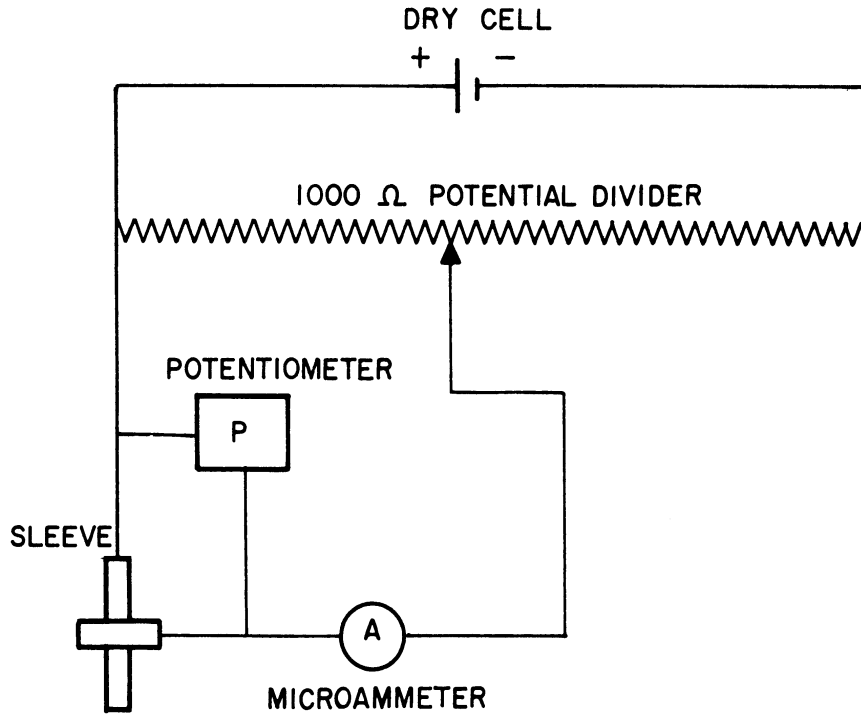


Fig. 9. Wiring Diagram for Measuring Small Currents in Tests Involving High-Resistance Brake Fluid.

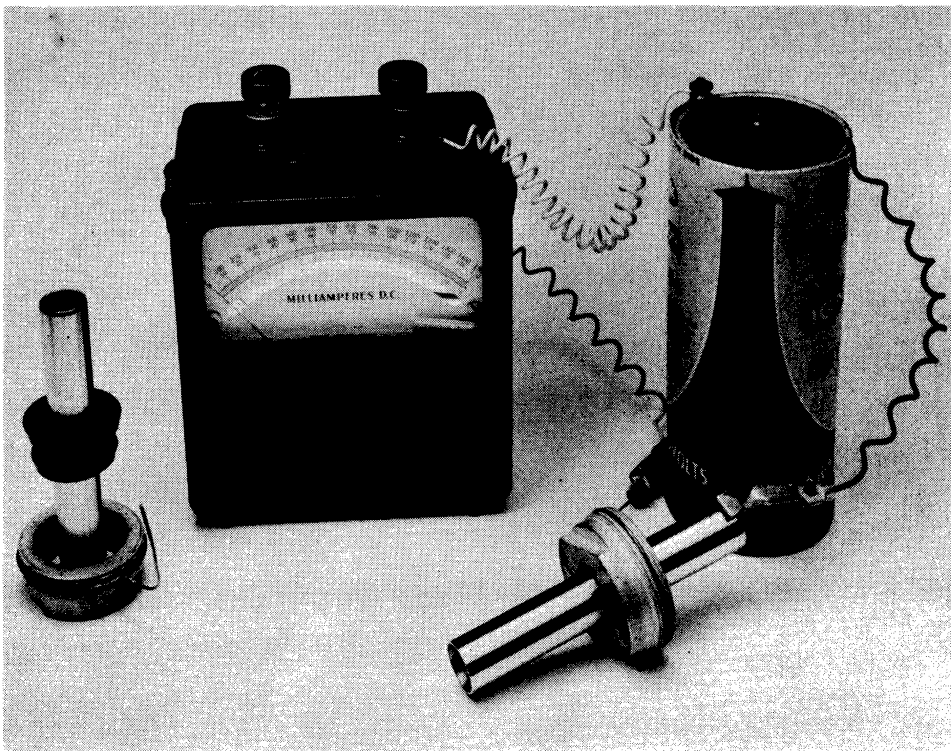


Fig. 10. Left: parts for accelerated test before assembly. Right: arrangement of parts during test; 1% CaCl_2 in water is placed between the seal and cup.

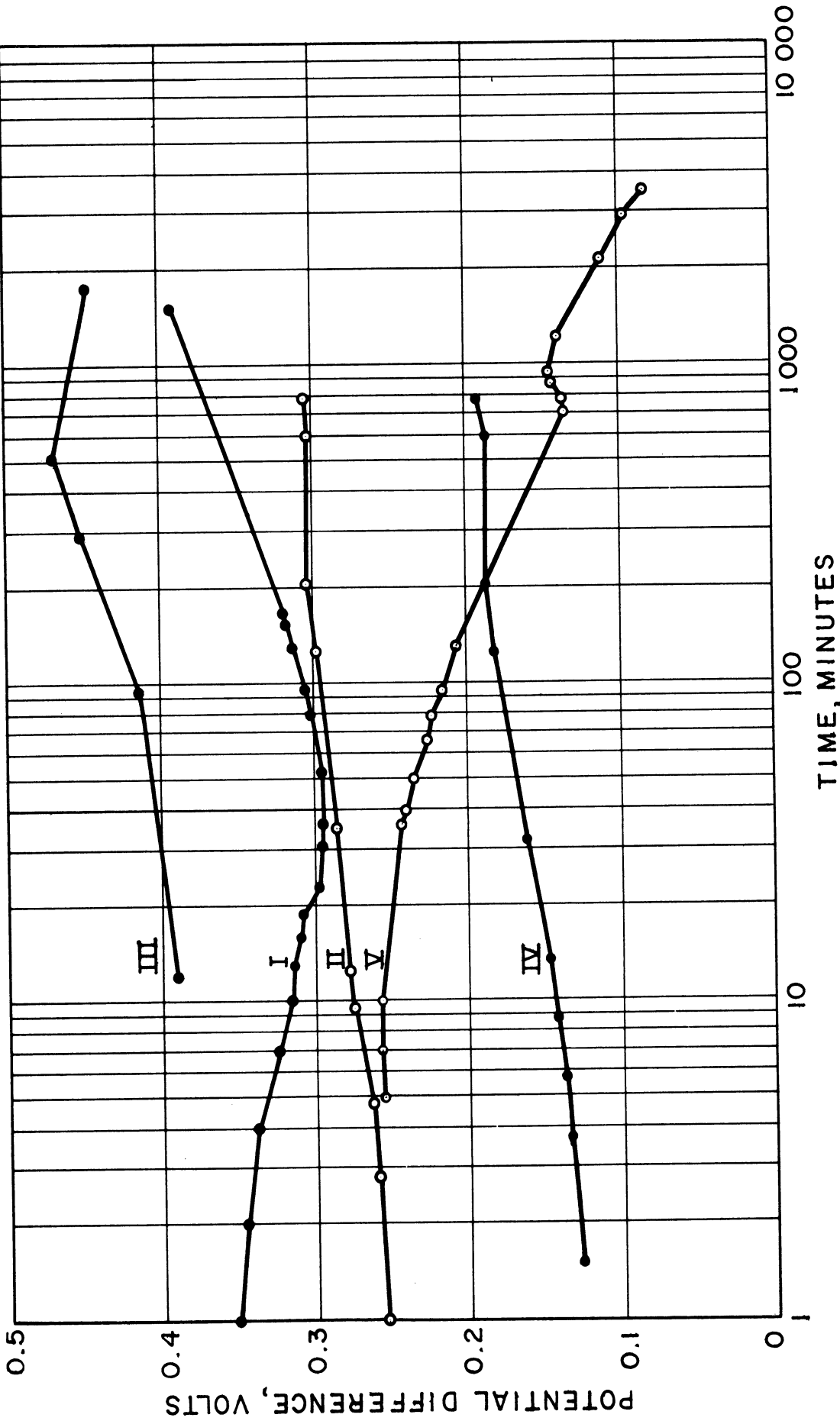


Fig. 11. Potential-Time Curves. Curve I: 0.0010-inch Cr plate vs porous bronze in fresh brake fluid; both samples immersed at 0 time; sleeve 5. Curve II: 0.0010-inch Cr plate vs porous bronze; fluid, bronze-aged; sleeve 6. Curve III: 0.0010-inch Cr plate vs porous bronze; fluid, bronze-aged; sleeve 14. Curve IV: 0.0010-inch Cr plate vs porous iron; fluid, iron-aged; sleeve 6. Curve V: complete assembly; bearing hole enlarged; sleeve 15.

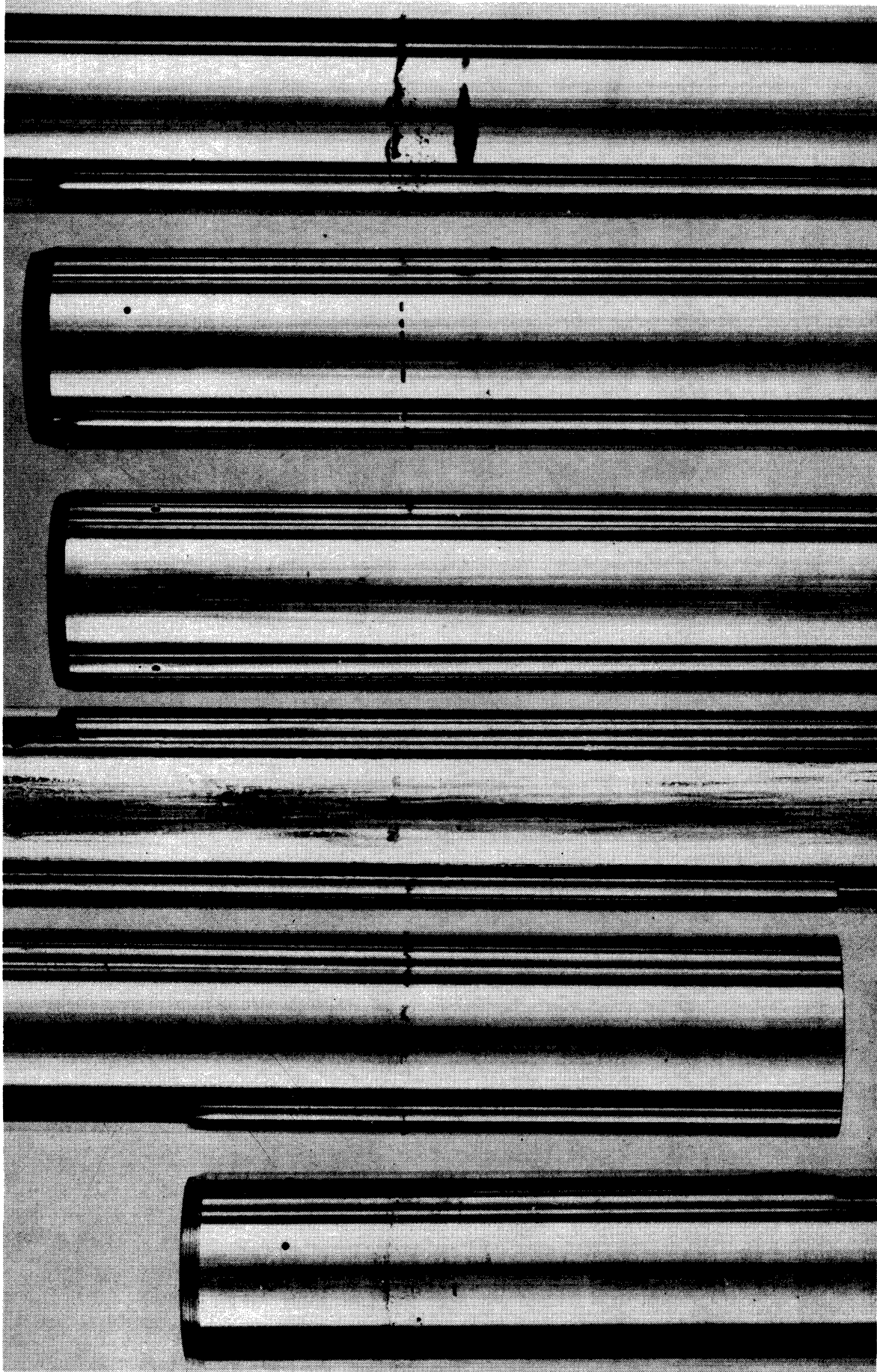


Fig. 12. Examples of Test Failures. Left to right: 0.0002-inch Cr plate, sleeve 17; 0.0010-inch Cr plate, sleeve 15; 0.0005-inch Cu, 0.0005-inch Ni, 0.0005-inch Cr plate, polished, sleeve A; 0.0015-inch Ni, 0.0002-inch Cr plate, polished and ball-burnished, sleeve C; crackfree Cr plate, sleeve 11; 0.0010-inch Cr, plastic-impregnated, sleeve H, 2X.

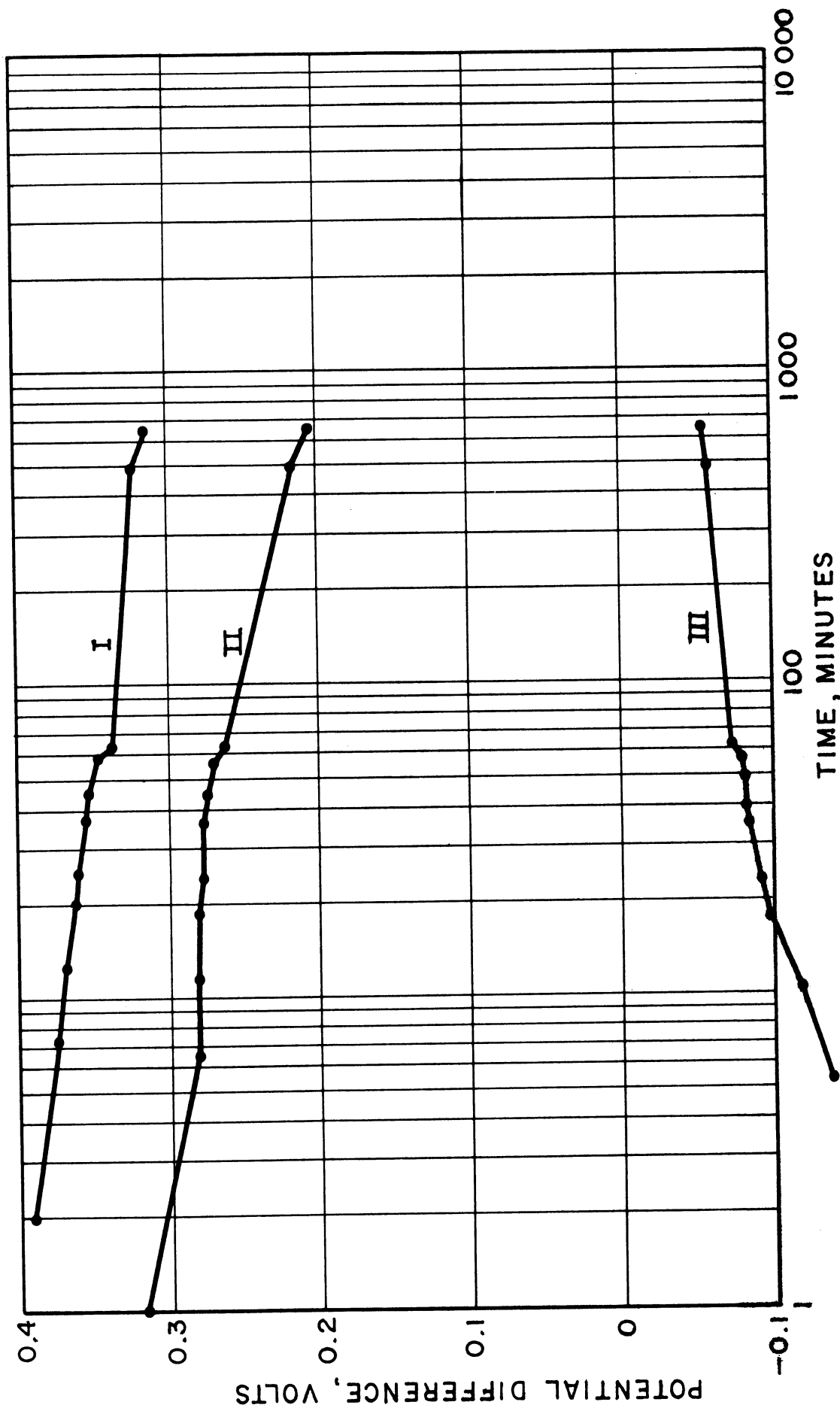


Fig. 13. Potential-Time Curves. Curve I: 0.0015-inch Ni, 0.0002-inch Cr plate vs porous bronze; fluid, bronze-aged; sleeve C. Curve II: crackfree Cr vs porous bronze; fluid, bronze-aged; sleeve 11. Curve III: nitrided sleeve vs porous bronze; fluid, bronze-aged; sleeve 13.

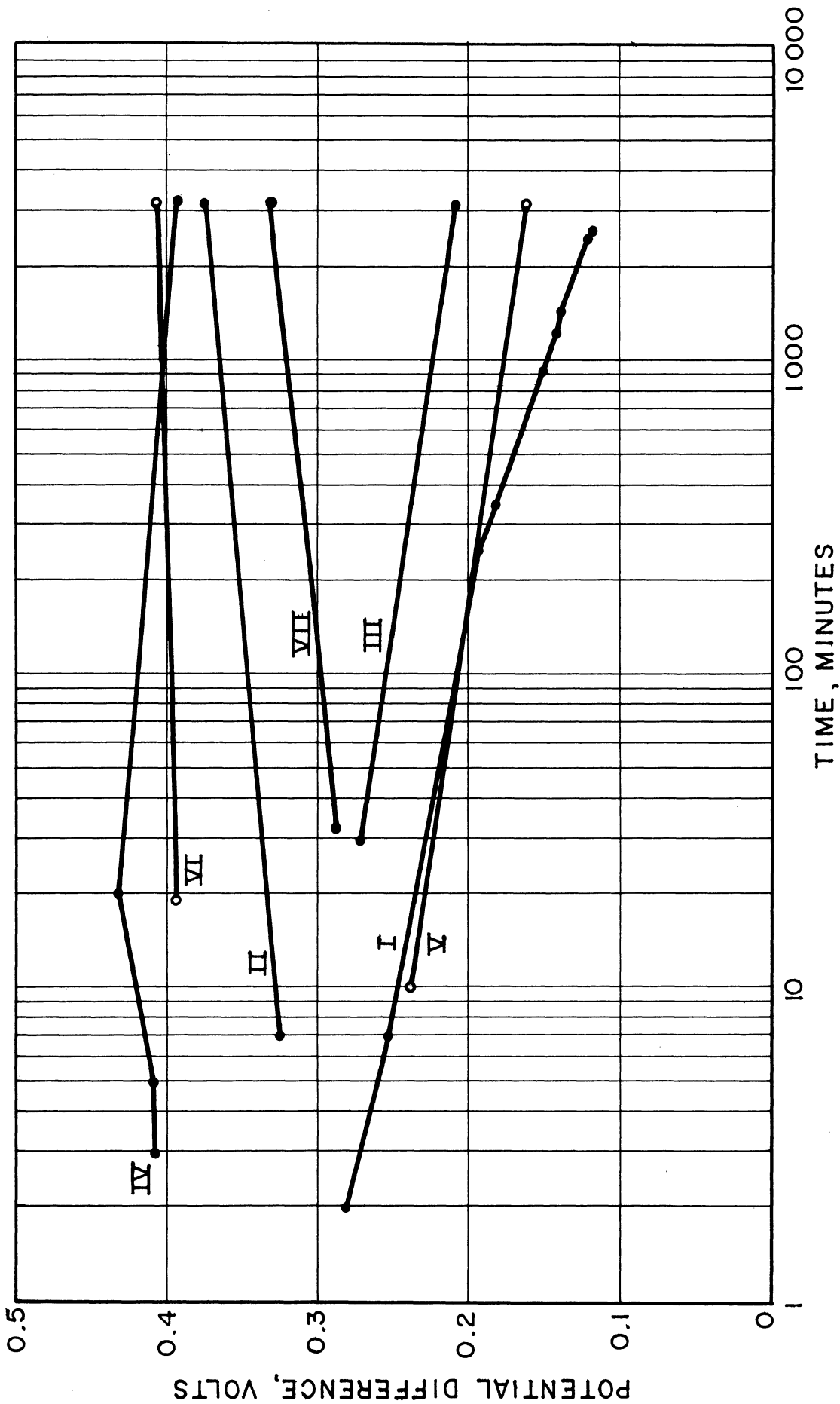


Fig. 14. Potential-Time Curves. Effect of hardness of stainless-steel sleeve vs porous bronze; fluid, bronze-aged in all cases; stainless steel electropolished in all cases to expose unaltered metal. Curve I: AISI 420F, annealed, sleeve P. Curve II: AISI 420F, 1 hour, 1700°F, oil-quenched. Curve III: AISI 420F, 1 hour, 1850°F, oil-quenched. Curve IV: AISI 420F, 1 hour, 1950°F, oil-quenched. Curve V: AISI 420, 1 hour, 1700°F, oil-quenched. Curve VI: AISI 420, 1 hour, 1850°F, oil-quenched. Curve VII: AISI 420, 1 hour, 1950°F, oil-quenched.

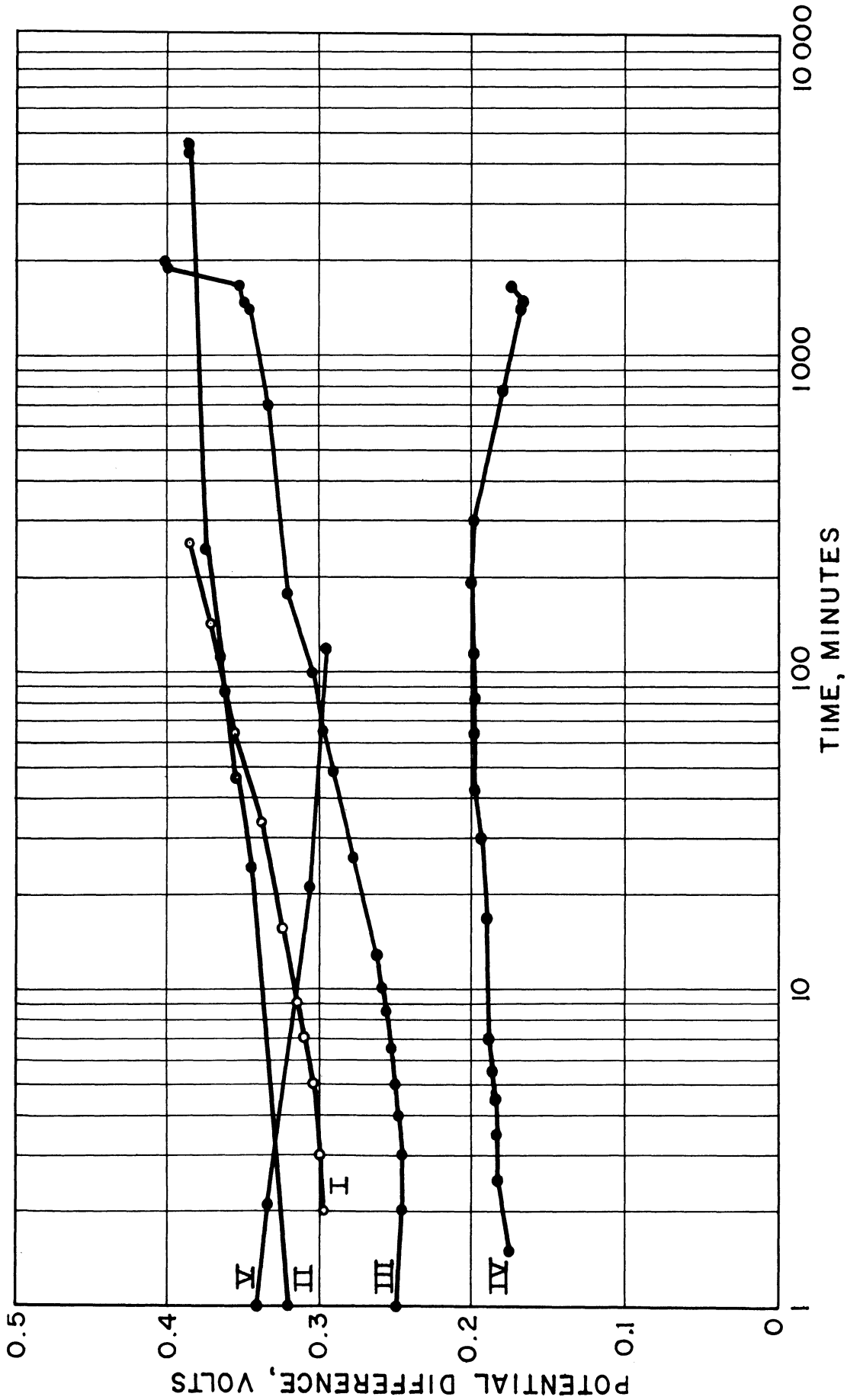


Fig. 15. Potential-Time Curves. Effect of tempering after hardening of stainless steel vs porous bronze; fluid, bronze-aged in all cases; stainless steel electropolished to expose unaltered metal in all cases. Curve I: AISI 420, oil-quenched from 1875°F, cold-treated at -80°F, tempered at 350°F; sleeve L. Curve II: rerun, sleeve L electropolished again after results of Curve I. Curve III: AISI 440C, oil-quenched from 1875°F, cold-treated at -80°F, tempered at 350°F; sleeve K. Curve IV: AISI 440C, oil-quenched from 1900°F, tempering treatment unknown; pushrod from model 130B, sleeve I. Curve V: AISI 440C, oil-quenched from 1875°F, cold-treated at -80°F, tempered at 350°F; sleeve U.

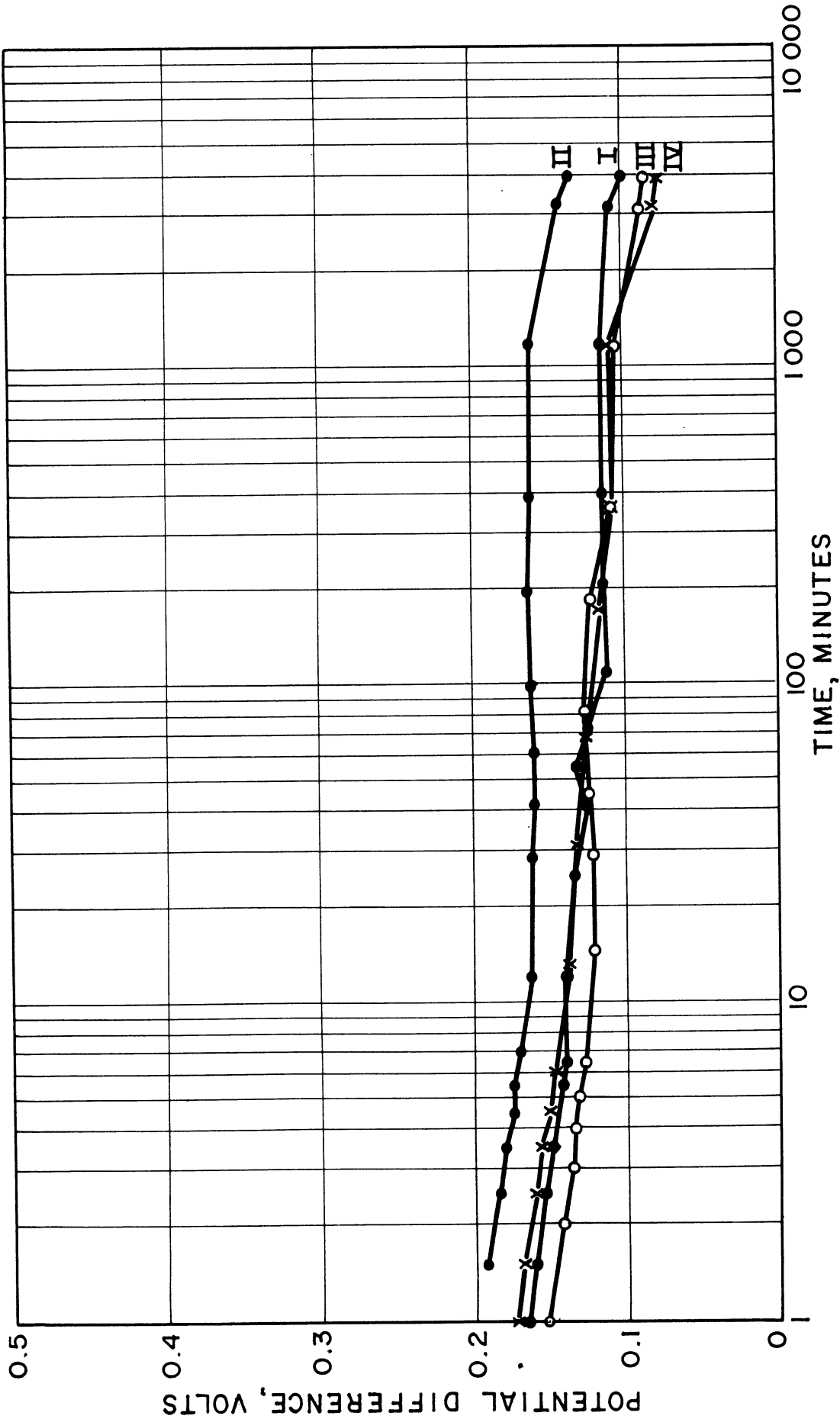


Fig. 16. Potential-Time Curves. Effect of grinding stainless steel in the soft state vs porous bronze; fluid, bronze-aged in all cases. Curve I: AISI 420F, annealed, rough-machined; sleeve Q. Curve II: AISI 420F, annealed, rough-machined, rough-ground; sleeve R. Curve III: AISI 420, annealed, rough-machined, sleeve S. Curve IV: AISI 420, annealed, rough-machined, rough-ground, sleeve T.

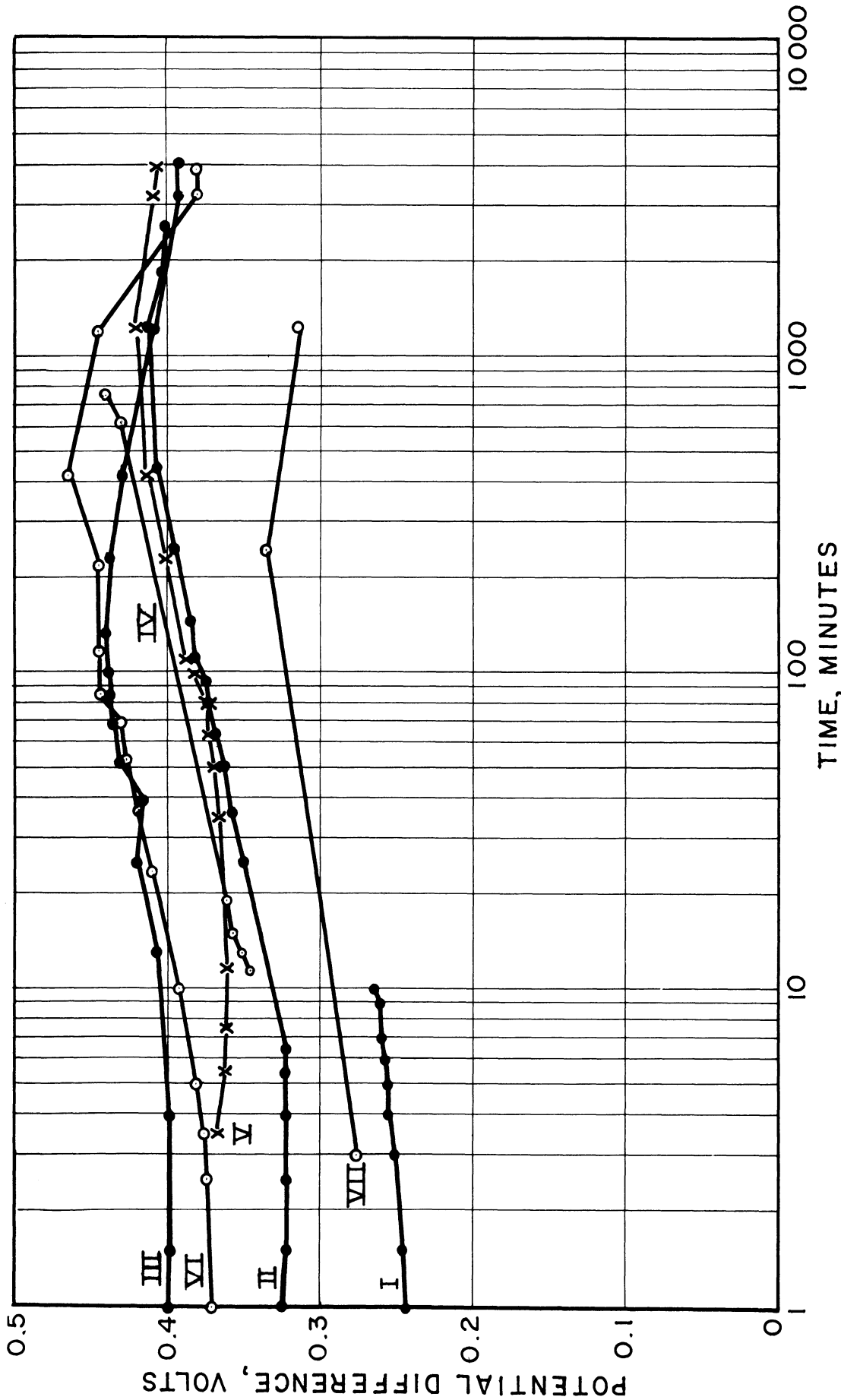


Fig. 17. Potential-Time Curves. Effect of grinding stainless steel in the hard state vs porous bronze fluid, bronze-aged in all cases. Curve I: AISI 440C, oil-quenched from 1875°F, cold-treated at -80°F, tempered at 350°F, finish-ground, sleeve J. Curve II: rerun of sleeve J, 35 days after Curve I. Curve III: AISI 440C, oil-quenched from 1875°F, cold-treated at -80°F, tempered at 350°F, finish-ground, passivated, sleeve K. Curve IV: rerun of sleeve K, 35 days after Curve III. Curve V: AISI 420, oil-quenched from 1875°F, cold-treated at -80°F, tempered at 350°F, finish-ground, sleeve M. Curve VI: AISI 420, oil-quenched from 1875°F, cold-treated at -80°F, tempered at 350°F, finish-ground, sleeve N. Curve VII: AISI 440A, oil-quenched from 1875°F, cold-treated at -80°F, tempered at 350°F, finish-ground, sleeve X.

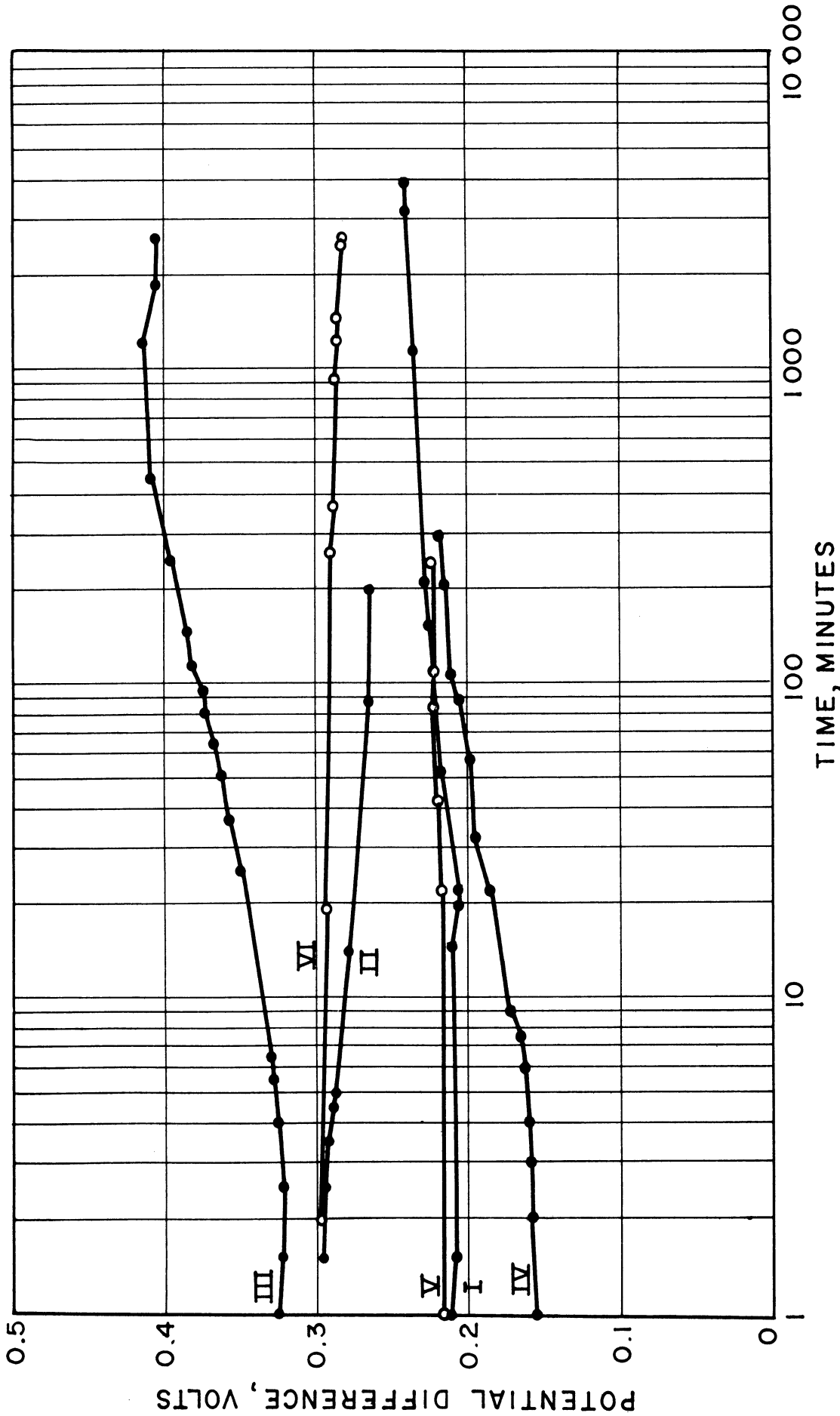


Fig. 18. Potential-Time Curves. Effect of abrading of hardened stainless steel vs porous bronze (Curves I and II); effect of tempering of hardened and ground stainless steel vs porous bronze (Curves III through VI); fluid, bronze-aged. Curve I: AISI 440C, finish-ground, oil-quenched from 1875°F, cold-treated at -80°F, tempered at 350°F, sleeve U. Curve II: sleeve U, abraded with 2/0 emery paper. Curve III: AISI 440C, oil-quenched from 1875°F, cold-treated at -80°F, tempered at 350°F, finish-ground, sleeve J. Curve IV: sleeve J, tempered 1 hour at 400°F after finish-grinding. Curve V: sleeve J, tempered 1 hour at 600°F, after 400°F temper. Curve VI: sleeve J, electropolished after 600°F temper.

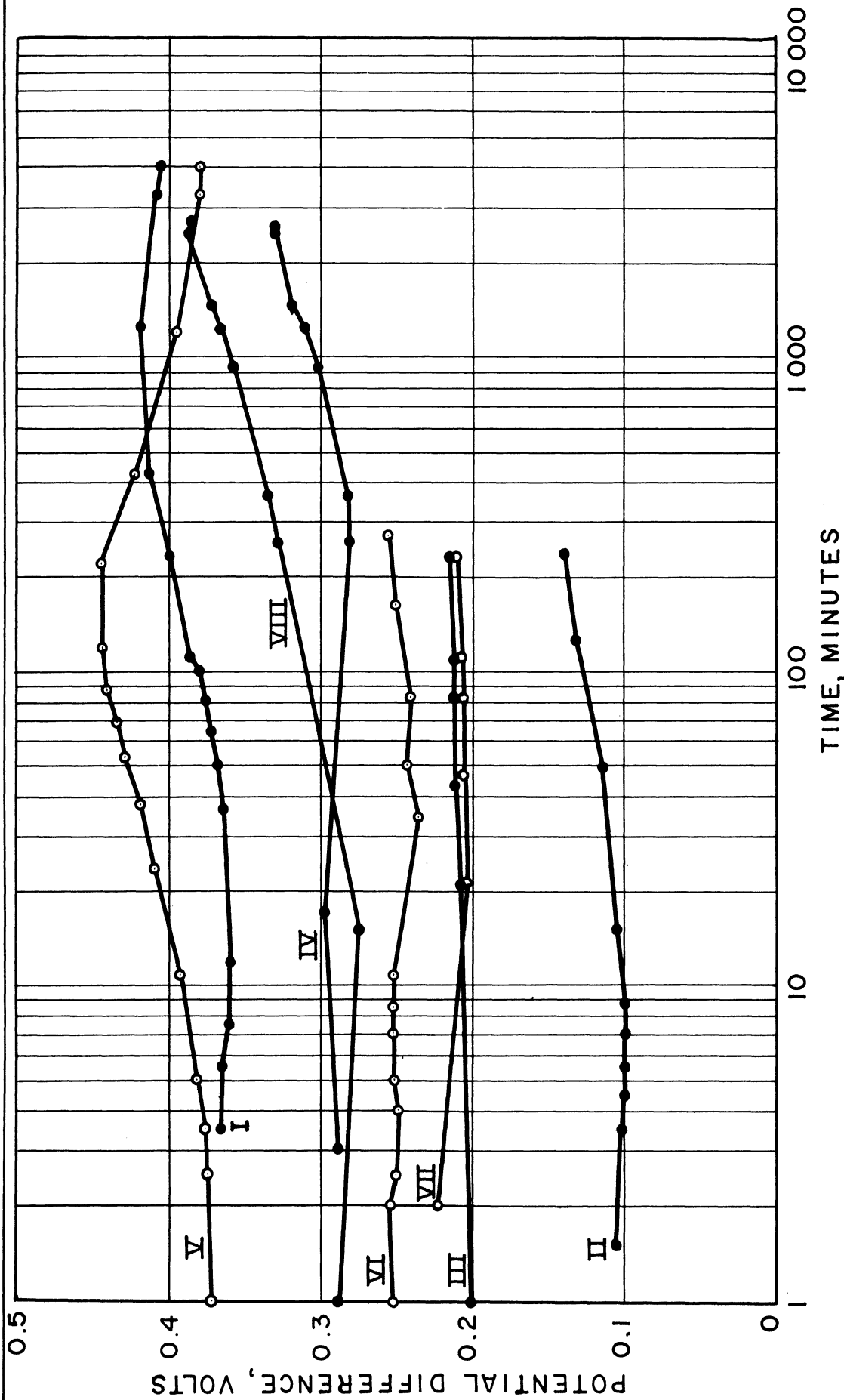


Fig. 19. Potential-Time Curves. Effect of tempering of hardened and ground stainless steel vs porous bronze; fluid, bronze-aged. Curve I: AISI 420, oil-quenched from 1875°F, cold-treated at -80°F, tempered at 350°F, finish-ground, passivated; sleeve M. Curve II: sleeve M, tempered 1 hour at 400°F after finish-grinding. Curve III: sleeve M, tempered 1 hour at 600°F after tempering at 400°F. Curve IV: sleeve M, electropolished after tempering at 600°F. Curve V: AISI 420F, oil-quenched from 1875°F, cold-treated at -80°F, tempered at 350°F, finish-ground, sleeve N. Curve VI: sleeve N, tempered 1 hour at 400°F after finish-grinding. Curve VII: sleeve N, tempered 1 hour at 600°F after 400°F temper. Curve VIII: sleeve N, electropolished after 600°F temper.

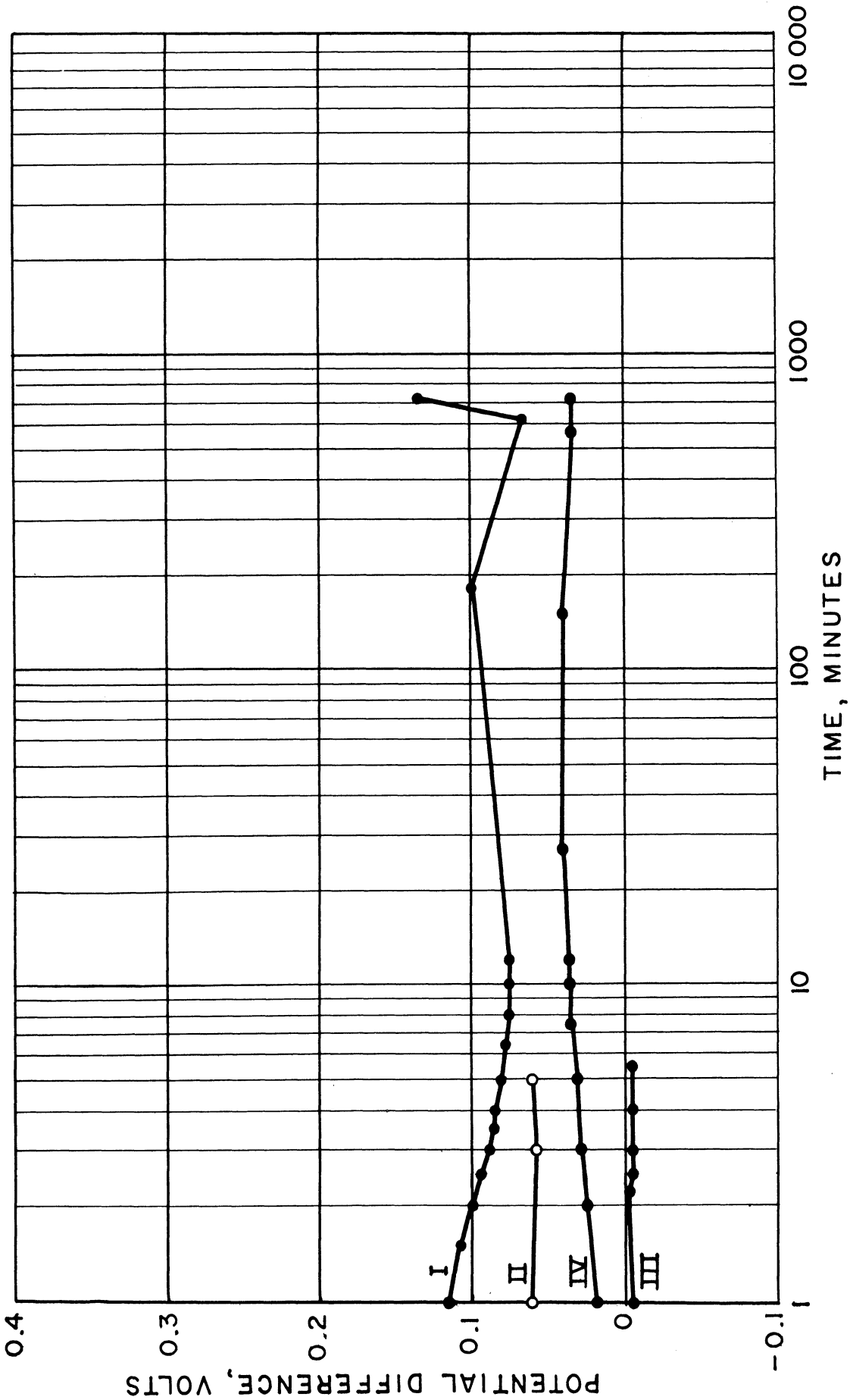


Fig. 20. Potential-Time Curves. Effect of passivation of stainless steel. Curve I: AISI 440C, oil-quenched, cold-treated at -80°F , tempered at 350°F , finish-ground, sleeve J, nonpassivated (cathodic) vs sleeve K, passivated (anodic) in aged brake fluid. Curve II: AISI 420, oil-quenched, cold-treated at -80°F , tempered at 350°F , finish-ground, sleeve L, nonpassivated (cathodic) vs sleeve M, passivated (anodic) in aged fluid. Curve III: sleeves L (anodic) vs M (cathodic) in dilute HNO_3 . Curve IV: sleeves L (cathodic) vs M (anodic) in aged brake fluid after immersion in cold, concentrated HNO_3 .

