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NATIONAL BUREAU OF STANDARDS REPORT

9521

FINAL REPORT ON
CORROSION OF ALUMINUM EMBEDDED IN CONCRETE

by

Joseph W. Pitts

Materials and Composites Section
Building Research Division
Institute for Applied Technology

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Office of the Chief of Engineers, U.S. Army
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I. INTRODUCTION

Aluminum has become a widely-used building material in recent years. Generally, the metal is quite durable, but under certain conditions it corrodes severely. There is a continuing need to know more about the behavior of aluminum in different environments, and particularly its behavior when embedded in concrete.

This project was a feasibility study to determine if laboratory investigations could provide useful information leading to a more intelligent selection and use of aluminum products in concrete construction.

The project was divided into three parts:

(1) A literature survey including a summary and analysis of the literature and an extensive bibliography on this subject.

(2) A case history of a field failure of concrete due to corrosion of embedded aluminum.

(3) Exploratory laboratory experiments.

All three phases of this project were completed between January and March 1967, or earlier; therefore, this report is the final report of the project.

II. RESULTS

(1) The published literature was searched for information pertaining to the behavior of aluminum in contact with concrete or with other alkaline building materials. As a result a sizable bibliography on this subject was compiled. Also, a comprehensive summary and analysis of the literature was written and is attached to this report.

(2) A case history study was made of the aluminum corrosion that occurred in D. C. Stadium and that resulted in extensive cracking of the concrete. This study revealed that one sample of concrete adjacent to a section of severely corroded aluminum conduit contained 1.02% $CaCl_2$ by weight of cement, while another sample of concrete adjacent to uncorroded conduit contained 0.34% $CaCl_2$. The board of consulting engineers who investigated the D. C. Stadium case concluded that the concrete damage occurred as the result of using aluminum conduit embedded in concrete containing $CaCl_2$ and that the problem was accentuated by stray electric currents in the conduit, but they did not specifically state that the primary cause of the corrosion was the galvanic coupling of aluminum to steel. A paper, based partially on this case history study, was published in the January-February 1967 issue of The Military Engineer.

(3) An experiment was designed to accurately determine the effect of distance between aluminum and steel in concrete on the galvanic current that flowed when the two metals were continuously short-circuited. It was found that the magnitude of the current flow in a short-circuited aluminum-steel-concrete galvanic cell did not maintain a proportional

relationship to the distance between the electrodes. Initially, the current was roughly inversely proportional to distance. But the initial high currents which flowed between closely spaced electrodes rapidly diminished until at some later time when these currents became equal to, and eventually less than, the currents flowing between more distantly spaced electrodes. This phenomenon probably was due to polarization of the electrodes.

The initial condition of the natural oxide film on the aluminum was found to have a significant effect on the current flow during the early stages. The film tended to be protective and partially restrict current flow, but soon after embedment in concrete the film changed character, allowing the current to increase to a maximum value before it eventually began to decline. If the aluminum was scraped during casting of the concrete to remove the air-formed protective film, then the initial current was much higher than it would have been otherwise, but the current continued to decrease with time rather than going through an inflection point.

Representative results are shown in Figures 1, 2, and 3.

SUMMARY AND ANALYSIS OF THE LITERATURE ON THE CORROSION OF ALUMINUM EMBEDDED IN CONCRETE

ABSTRACT

Aluminum is considered by several investigators to be compatible with concrete and other alkaline building materials. Although aluminum reacts chemically with alkaline solutions, the resulting corrosion products tend to form a protective film which inhibits further reaction. Under favorable conditions, this self-limiting property of the corrosion reaction results in only superficial corrosion of the aluminum. However, under some conditions of use and in less than favorable environments, the protective film may be attacked, or may even be prevented from forming. In either case the aluminum is susceptible to continuing severe corrosion.

INTRODUCTION

This survey is divided roughly into two parts: the chemical and the electrochemical behavior of aluminum embedded in concrete. Fundamentally, nearly all corrosion is electrochemical (galvanic) in nature, but for the purpose of this discussion, a distinction is made between the corrosion that takes place when the aluminum is isolated from other metals and the very different situation that exists when the aluminum is in contact with a more noble metal. The latter is generally referred to as dissimilar metal corrosion or simply galvanic corrosion. For example, a metal that is essentially inert in a particular environment may corrode severely in that same environment if contacted by a more noble metal. Conversely, a metal that would normally corrode in a particular environment can be protected by coupling it to a less noble metal; a familiar example of the latter situation is the cathodic protection of underground steel pipe by the use of sacrificial anodes of zinc.

THE CHEMICAL BEHAVIOR OF ALUMINUM EMBEDDED IN CONCRETE

"The compatibility of aluminum with concrete, mortars, and plasters" is the title, except for slight variations, of at least three papers on this general subject [3, 5, 9]; also, the word "compatibility" is either used or implied in several additional papers. Furthermore, two papers [1, 4] have the approximate title of "The resistance of aluminum to alkaline building materials." A casual reader of these papers might get the impression that there is little or no problem involved in the use of aluminum in alkaline building materials. But a more careful reading and analysis of the literature reveals that such is not the case, that indeed one must be very cautious in the use of aluminum. Jones and Tarleton [14] indicate that the corrosion of aluminum embedded in plain concrete can crack the concrete under unfavorable circumstances; and it has been shown that the situation can be worse if the concrete contains calcium chloride ($CaCl_2$) and much worse if it contains steel.

Nevertheless, it does seem to be true that under <u>favorable conditions</u> aluminum is quite compatible with alkaline building materials. "Favorable conditions" include (1) the proper selection and use of the aluminum alloy, (2) the minimum corrosiveness of the cementing material, and (3) the maximum dryness of the exposure environment. For example, a most favorable condition of use would be the isolated embedment of commercially pure aluminum in a dry-mix batch of chloride-free concrete exposed in an arid climate. A less favorable condition (although not necessarily doomed to failure) would be the same situation as above except that the aluminum would be coupled to steel. Other variations in the conditions of use and exposure that would progressively render the aluminum more susceptible to corrosion would be (1) a wet-mix batch of concrete, (2) chloride admixtures in the concrete, (3) exposure to continual dampness, and (4) marine exposure.

A number of authors present arguments, opinions, and evidence (both field and laboratory) for the compatibility of aluminum in alkaline building materials. The explanation usually given for compatibility (despite the inherent chemical instability of aluminum in alkaline solutions) is that the aluminum develops a protective film that inhibits the corrosion reaction from proceeding beyond the initial stages. Roebuck and Pritchett [25] expressed the generally accepted theory of the mechanism of corrosion of aluminum in any environment, as follows: "Corrosion of aluminum occurs only when the metal's natural protective oxide film is damaged and when its self-repair is prevented by chemical dissolution of the oxide--lack of oxygen or strong electrochemical cell action. Under such conditions, corrosion occurs at discontinuities and weak or thin points in the air-formed film." In the case of concrete, the consensus of several authorities in this field is that there is an initial reaction between the alkaline cement and the air-formed oxide film on aluminum, but the reaction product tends to stifle further reaction.

Wright, et al [1], as the result of experiments, conclude that, "(1) Aluminum alloys are not seriously corroded by contact with concrete, standard brick-mortar, lime brick-mortar, hard wall plaster and stucco over extended periods. Slight, superficial etching takes place during the period when concretes, mortars, plasters or stucco are setting; unless there is frequent intermittent wetting and drying, no appreciable corrosion takes place. The amount of attack is not sufficiently great to cause deterioration in the properties of the aluminum in other than thin sections. (2) Even under continuously wet conditions, aluminum alloys embedded in concrete are only slightly attacked."

The chemistry of the behavior of aluminum in alkaline environments is briefly summed up by Walton, et al [3], as follows: "Resistance to corrosion of aluminum alloys is attributed to a thin, invisible oxide coating that develops naturally over their surfaces. ..... Alkaline solutions (and acid solutions), however, tend to dissolve the existing oxide coating. These solutions will attack aluminum, but in doing so they develop other types of films. The films that form in sodium hydroxide are highly soluble and high rates of attack ensue. In contrast, the films that form in calcium hydroxide, magnesium hydroxide or ammonium hydroxide have limited solubility and form a highly resistant barrier against further attack. Thus, building products or leaches of such products whose alkalinity is derived from calcium or magnesium hydroxides may cause overall surface attack of bare aluminum, but the process develops protective films that resist further corrosion. Such alkaline materials cause only superficial or mild surface attack, with most of the attack occurring during the initial stages of exposure. During the curing or aging process, free alkali is converted to carbonates that have even less action on aluminum. ..... This self-limiting type of corrosion has been determined by laboratory tests and substantiated by service experience. The measured depth of attack occurring during the setting period of concrete was generally less than one mil; depth of attack after six months or after 27 years was no greater than five mils."

In apparent contradiction to the confidence in the behavior of aluminum expressed by many authors, some of these authors, in the very same articles in which they proclaimed the virtues of aluminum, have indicated a somewhat lack of confidence by recommending protective coatings. For example, Wright, et al [1], stated: "The effectiveness of a single coat of bituminous paint in preventing corrosion of aluminum embedded in various building materials has been well demonstrated by its consistently good performance..... Thus, where aluminum may be in contact with damp concrete or mortar, or with intermittently wet and dry alkaline materials of this type, it is recommended practice to paint the contact surfaces with bituminous paints." Walton, et al [3], noted that the drainage or leaching from fresh concrete, plaster, mortar, etc., may be highly alkaline, and will cause superficial attack and discoloration of unprotected aluminum. They recommended the application of a clear methacrylate resin coating. They also recommended bituminous or asphaltic protective coatings under severely corrosive conditions, such as may arise from unusual "poultice" conditions or galvanic corrosion conditions.

Jenks, et al [4], evaluated three types of protective coatings on three different aluminum alloys embedded in concrete, stucco, and brick mortar. They concluded that bituminous paint offered the best protection, clear lacquer the next best, and zinc chromate offered little or no protection. Surprisingly, they found that after 10 years' exposure under continuously wet conditions there was significant corrosion of aluminum even when coated with bituminous paint.

THE ELECTROCHEMICAL (GALVANIC) BEHAVIOR OF ALUMINUM IN CONCRETE

In 1955, Wright [2], reported a case of failure of concrete containing embedded aluminum conduit. He found that the failure resulted from galvanic corrosion of aluminum in contact with the steel reinforcement in the concrete, which also contained calcium chloride ($CaCl_2$). He concluded that, "....since steel is almost invariably associated with structural concrete work, the conclusion to be drawn from this investigation is that aluminum conduit should not be buried in concrete containing calcium chloride conditions."

Unfortunately, Wright's warning was overlooked, minimized, or ignored by many builders. Even some of the research workers who published papers on this subject after Wright's disclosure failed to realize or acknowledge the potentially disastrous effect of galvanic corrosion of aluminum in concrete. Consequently, a rash of aluminum conduit-concrete failures began to appear in the late 1950's and early 1960's.

Aluminum and steel in concrete constitute the essential components of a galvanic cell; e.g., two dissimilar metal electrodes immersed in an electrolyte. The electrical potential of this system is approximately 1.2

volts; therefore, when the aluminum and steel are connected, a current will flow in the circuit as in any other short-circuited galvanic cell battery. The aluminum is the anode of the cell and, as such, it is the electrode that corrodes. Concrete is a fairly good electrolyte when wet, and since it may remain moist for many weeks or months after casting and since it may subsequently be subjected to external wetting, it may continue to be an electrical conductor indefinitely. Furthermore, the conductivity, and consequently the corrosivity, of concrete is greatly enhanced by the addition of chlorides. It is common practice during cold weather construction to add calcium chloride (up to 2% by weight of cement) to concrete in order to accelerate the set. Chlorides also increase corrosivity by a chemical mechanism: according to Walton, et al [3], chlorides in concrete diffuse to the anode where they break down the protective film on the aluminum. McGeary [8] stated that this chloride ion enrichment at the anode arrests polarization of the aluminum, thus permitting corrosion currents to flow more freely.

It is now generally agreed that aluminum conduit should not be used in concrete that contains $CaCl_2$. The exact reasons though are still a matter of considerable controversy. While most investigators believe that galvanic corrosion can be disastrous in chloride concrete, some investigators still imply that galvanic currents, alone, are not sufficient to cause disruptive corrosion--that failures occur only when the galvanic component is amplified by impressed stray currents.

Some federal agencies now prohibit the use of aluminum conduit in concrete under any circumstances, whatever, for the following reasons: (1) The widespread and increasing use of $CaCl_2$ in concrete makes it very difficult to insure that aluminum will not be used in chloride-containing concrete as long as its use is permitted in chloride-free concrete. In addition to the intentional use of $CaCl_2$ there are several extraneous sources of chlorides, such as beach sands, contaminated aggregates, and brackish water. (2) The aluminum conduit is almost always connected to the reinforcing steel, thus assuring both a galvanic cell and an electrical path for stray currents.

CONCLUSIONS

Inherently, aluminum reacts with a wet alkaline environment such as fresh concrete. The products of the corrosion reaction form a somewhat protective barrier that tends to diminish the rate of the reaction. The practical effect of this is such that in a plain, good-quality concrete that is allowed to dry normally and is not subsequently subjected to continuous or intermittent wetting, the total corrosion of embedded, isolated aluminum is not significant. Thus, it can be said with confidence that under favorable conditions, such as just stated, aluminum is compatible with alkaline building materials. Conversely, under very unfavorable conditions, embedded aluminum can suffer catastrophic corrosion.

The in-between situations are causes for concern and the answer to the question of whether or not aluminum will corrode destructively in a particular application depends on a complex combination of several factors and the degree or intensity of each of them. The fact that there are differences of opinions among competent investigators precludes the establishment of a set of invariant rules to govern the use of aluminum in all situations. There are, however, several general conclusions that most investigators agree on:

1. It is safe to use aluminum in plain, good-quality concrete that will not be subjected to wet conditions.
2. Aluminum should not be used in reinforced concrete containing chlorides.
3. Bituminous coatings on the aluminum are recommended in cases where the aluminum is in contact with steel or where the concrete will be frequently wetted.

BIBLIOGRAPHY

1. "The Resistance of Aluminum to Some Alkaline Building Materials," by T. E. Wright, H. P. Godard, and I. H. Jenks, The Engineering Journal, Vol. 37, October 1954, pp 1250-1256.

2. "An Unusual Case of Corrosion of Aluminum Conduit in Concrete," by T. E. Wright, The Engineering Journal, Vol. 38, No. 10, October 1955, pp 1357-1362.

3. "Compatibility of Aluminum with Alkaline Building Products," by C. J. Walton, F. L. McGeary, and E. T. Englehart, Corrosion, Vol. 13, December 1957, pp 807-816.

4. "The Resistance of Aluminum to Concrete, Stucco and Brick Mortar -- Ten Year Test Results," by I. H. Jenks, T. E. Wright, and H. P. Godard, The Engineering Journal, Vol. 45, January 1962, pp 46-51.

5. "The Compatibility of Some Aluminum Alloys with Wet Building Mortars and Plasters," by L. H. Everett, The Builder, March 30, 1962.

6. "The Building Industry: Some Problems with Corrosion of Non-Ferrous Metals," by L. H. Everett, Corrosion Technology, Vol. 9, No. 3, March 1962, pp 57-59; Vol. 9, No. 4, April 1962, pp 95-98.

7. "Galvanic Corrosion in Concrete Containing Calcium Chloride," by T. E. Wright and I. H. Jenks, Journal of the Structural Division, Proceedings of the American Society of Civil Engineers, Vol. 89, No. ST5, Paper 3669, October 1963, pp 117-132.

8. "Performance of Aluminum in Concrete Containing Chlorides," by Frank L. McGeary, Journal of the American Concrete Institute, Vol. 63, No. 2, February 1966, pp 247-265.

9. "Compatibility of Aluminum with Alkaline Building Materials," by R. E. Brooks, Materials Protection, Vol. 1, No. 4, July 1962, pp 44-48.

10. "Aluminum Embedded in Building Mortars and Plasters-Ten Year Tests," by F. C. Porter, Metallurgia, February 1962, pp 65-71.

11. "Corrosion of Aluminum Conduit in Concrete," by R. E. Brooks, A. H. Roebuck, and Earl Hazan, Electrical Construction and Maintenance, February 1965.

12. "Corrosion of Aluminum Conduit in Concrete," by G. E. Monfore and Borje Ost, Journal of the PCA Research and Development Laboratories, Vol. 7, No. 1, January 1965, pp 10-22.

13. "Corrosion of Embedded Material Other than Reinforcing Steel," by Hubert Woods, STP No. 169-A, ASTM, 1966, pp 230-238.

14. "Effect of Embedding Aluminum and Aluminum Alloys in Building Materials," F. E. Jones and R. D. Tarleton, British DSIR, Building Research Station, National Building Studies, Research Paper 36, 1963, 60 pages.

15. "Spalled Concrete Traced to Conduit," Engineering News-Record, Vol. 172, No. 11, March 12, 1964, pp 28-29.

16. "Corrosion in Buildings," P. J. Sereda, Canadian Building Digest, National Research Council, Canada, CBD 20, August 1961.

17. "Painting Metals in Buildings: 2--Non-Ferrous Metals and Coatings," Digest 71, Building Research Station, England, June 1966.

18. "Corrosion of Metals Under the Influence of Alternating Current," by J. F. Williams, Materials Protection, Vol. 5, No. 2, February 1966, pp 52-53.

19. "Aluminum in Concrete," by R. I. Linberg, Concrete Construction, January 1960, p 9.

20. "Corrosion and Concrete," Concrete Construction, February 1964, p 35.

21. "Galvanic Corrosion of Metals in Cementing Materials," by J. W. Pitts, The Military Engineer, Vol. 59, No. 387, January-February 1967, pp 40-41.

22. "Corrosive Action on Aluminum of Various Cements and Mortars," by L. Tronstad and R. Veimo, Aluminum, December 1939, pp 839-842.

23. "Resistance of Aluminum Alloys to Mortars," E. Fischer and H. Vosskuhler, Aluminum, Vol. 33, No. 9, September 1957, pp 606-612.

24. "New Light on Aluminum Conduit in Concrete," Electrical Contracting and Maintenance, March 1962.

25. "Corrosion Inhibitors for Aluminum," by A. H. Roebuck and T. R. Pritchett, Materials Protection, Vol. 5, No. 7, July 1966, pp 16-19.

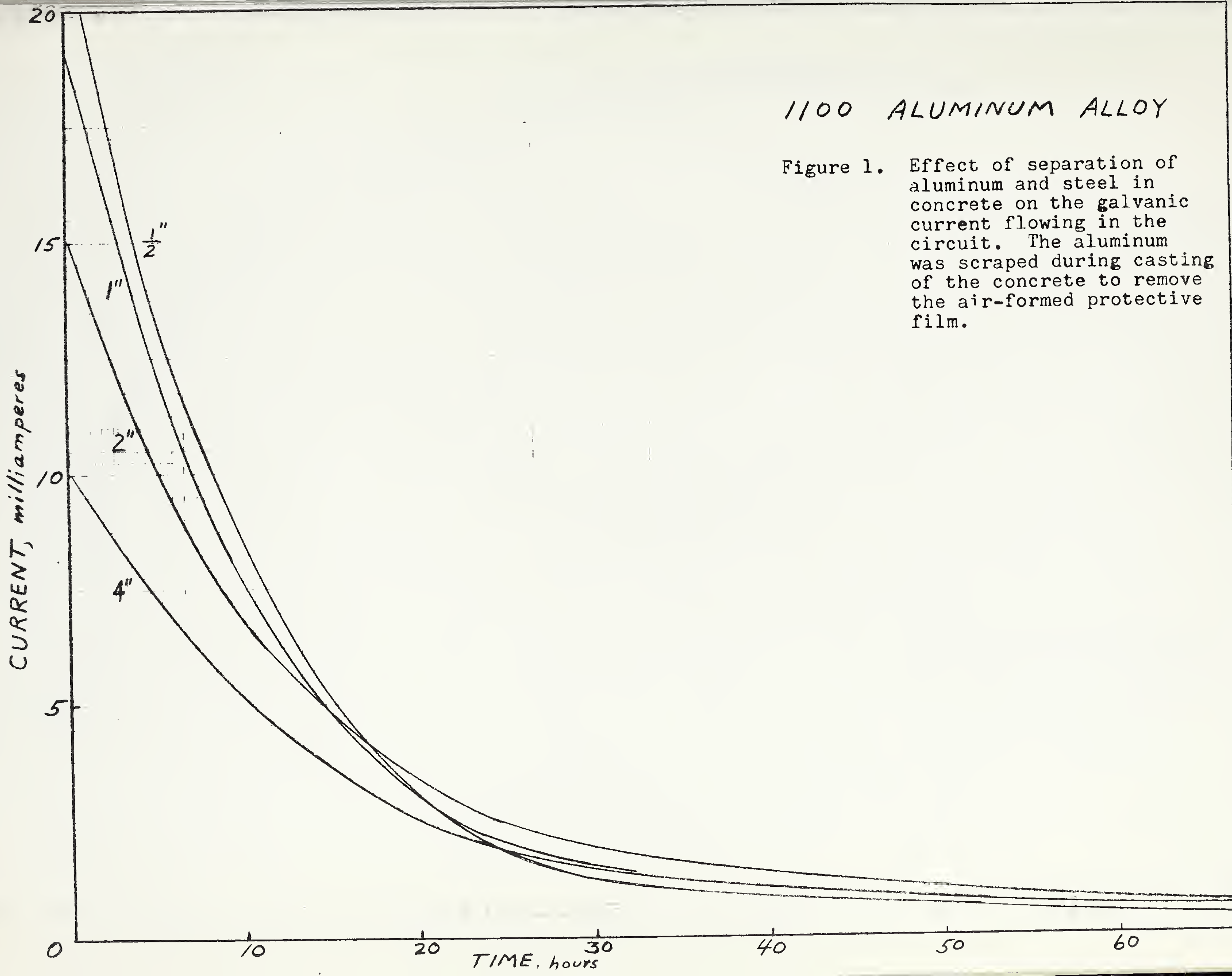

Figure 1. Effect of separation of aluminum and steel in concrete on the galvanic current flowing in the circuit. The aluminum was scraped during casting of the concrete to remove the air-formed protective film.

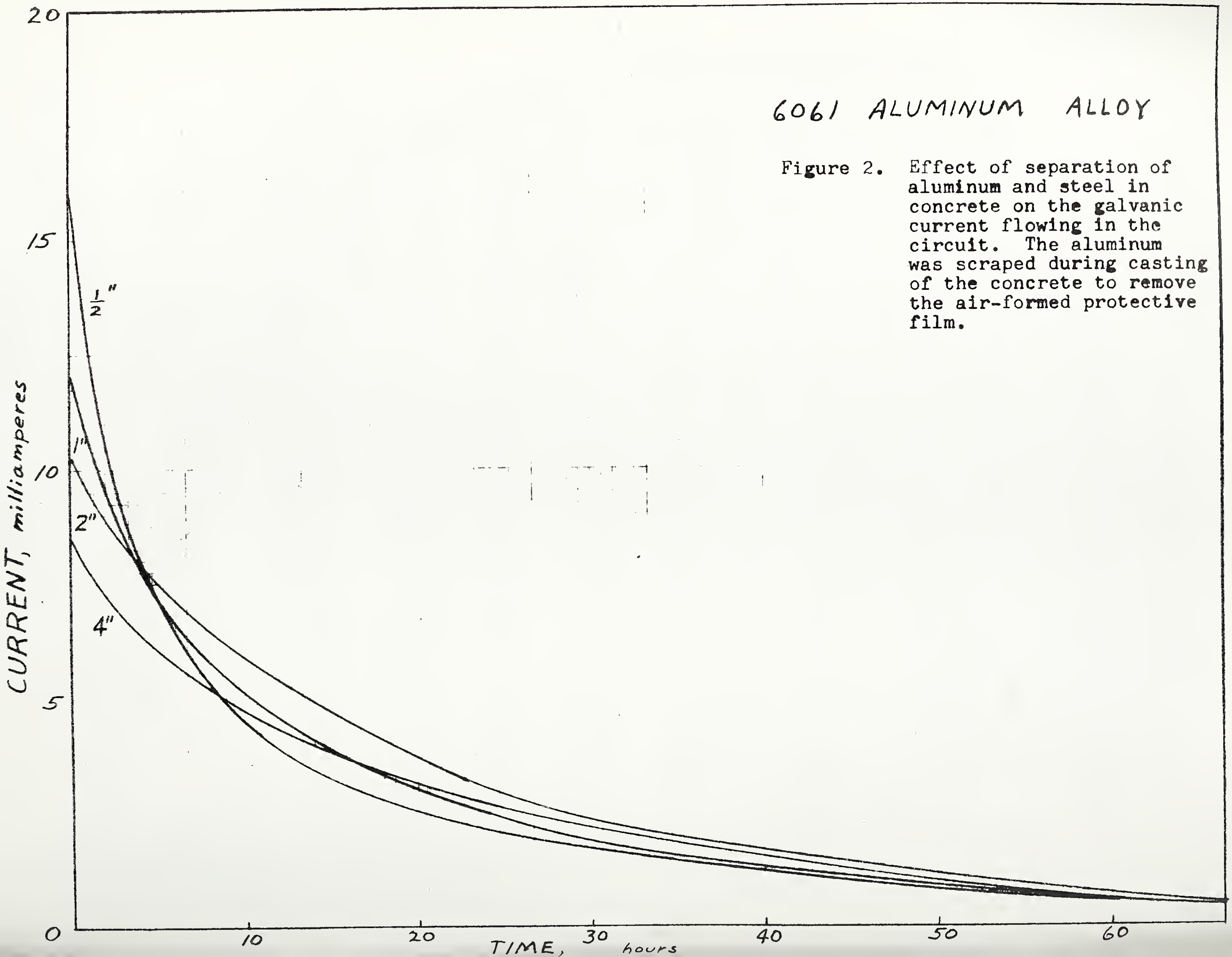

Figure 2. Effect of separation of aluminum and steel in concrete on the galvanic current flowing in the circuit. The aluminum was scraped during casting of the concrete to remove the air-formed protective film.

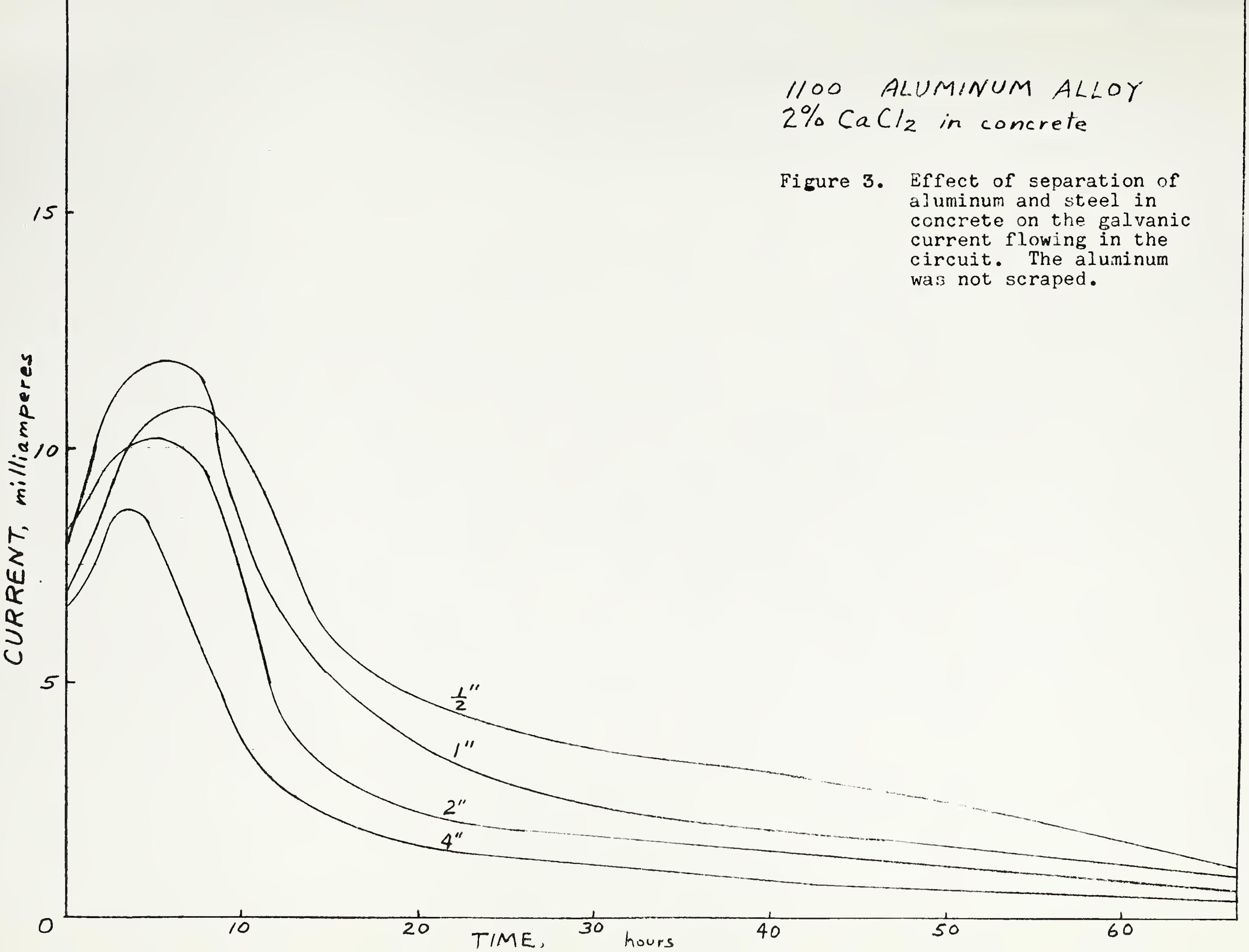

Figure 3. Effect of separation of aluminum and steel in concrete on the galvanic current flowing in the circuit. The aluminum was not scraped.

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