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The Baghdad Battery:
Experimental Verification of a 2,000-Year-Old Device Capable of Driving Visible and Useful Electrochemical Reactions at over 1.4 Volts

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The Baghdad Battery:
Experimental Verification of a 2,000-Year-Old Device Capable of Driving Visible and Useful Electrochemical Reactions at over 1.4 Volts

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ABSTRACT

The "Baghdad Battery" has posed an archaeological enigma for over eighty years. Discovered at the Parthian site of Khujut Rabu (first century CE), this famous artifact's utilitarian yet highly specific design tailors so clearly to the requirements of an electrochemical cell that it is difficult to conceive of another use for it. Although efforts have been made to recreate this battery (König 1938, Keyser 1993, MythBusters 2005), prior experiments have failed to (1) account for all aspects of the artifact's design and (2) make a device that has enough power to be evidently useful for people two thousand years ago. The result of these previous recreations has thus been to cast doubt upon whether the Baghdad Battery was, in fact, a battery at all. The present study's recreation dispels this doubt by accounting for two previously neglected aspects of the artifact's design, namely the use of solder and the function of the ceramic jar, which together form a previously unrecognized second source of voltage for the device: an aqueous tin-air battery. This "outer cell," which is integrally connected in electrical series with the device's already well-understood "inner cell" (comprising copper and iron), enables the Baghdad Battery to generate over 1.4 volts: an electric potential capable of driving a number of useful (and highly noticeable) electrochemical reactions, including electroplating, etching, and the electrolysis of water into hydrogen and oxygen gas. The present study's result therefore provides the strongest evidence to date for people in the Near East having had a working knowledge of electrochemistry nearly two millennia before Alessandro Volta's experiments with the voltaic pile.

Keywords: Baghdad Battery, Parthian Galvanic Cell, tin-air battery, aqueous metal-air battery, ancient electrochemistry

The "Baghdad Battery" has posed an archaeological enigma for over eighty years. First reported in 1939 by Wilhelm König,[1] director of the Baghdad Museum and Antiquities Department, this artifact's utilitarian yet highly specific design is so clearly tailored to the requirements of an electrochemical cell that it is difficult to conceive of any other use for it. Uncovered at the Parthian site of Khujut Rabu (first century CE), the Baghdad Battery is one of several similar artifacts uncovered at sites in Iraq from the same period or later.[2]

Efforts have been made to recreate this battery (König 1938, Keyser 1993, MythBusters 2005). Unfortunately, such experiments have failed to (1) make a device capable of producing visible electrical effects, and (2) account for all aspects of the artifact's design (Figure 1). Although ancient people may have noticed the slight numbing sensation created by extremely weak voltages (as Keyser suggests), it seems likely they would have been more impressed by higher voltage electrochemical effects such as bubbling, the etching/electroplating of a metallic surface, or patination.

The experiment presented here demonstrates that the "Baghdad Battery" was, in fact, two batteries in one, and that it was capable of generating over 1.4 volts, with sufficient power to drive a number of electrochemical reactions, including electroplating, etching, and the electrolysis of water into hydrogen and oxygen gas. Previously published experiments have only recreated the weaker of the device's two batteries (~0.4 volts, referred to here as the "inner cell"), which comprises an iron rod, suspended by an asphalt stopper inside a copper vessel filled with an electrolyte. These studies have neglected to account for the Baghdad Battery's clay jar, which I will demonstrate forms part of the device's second battery cell and real powerhouse—the "outer cell," an aqueous tin-air battery with a potential of over 1.1 volts by itself. As a result, previous reproductions have only produced the feeblest of electrical effects while leaving unanswered fundamental questions about the design of the Khujut

1 Wilhelm König, "Ein galvanisches Element aus der Partherzeit," *Forschungen und Fortschritte* 14.1 (1938): 8–9.

2 See: Paul T. Keyser, "The purpose of the Parthian galvanic cells: A first-century AD electric battery used for analgesia," *Journal of Near Eastern Studies* 52.2 (1993): 81–98 (82, 86–88). For a description of similar artifacts found at Tel Umar see: Leroy Waterman, "Preliminary report upon the excavations at Tel Umar, Iraq," (No Title) 1931 (61–62, Plate 12), and E. Kühnel et al., *Die Ausgrabung der zweiten Ktesiphon-Expedition 1931/32* (Berlin, 1933) (28).

Rabu device. Why was a porous (unglazed) jar chosen to hold the copper vessel? Why was the copper vessel inside it soldered and sealed to be watertight? And why would solder have been used at all[3] in a battery where pure metals are always preferred?

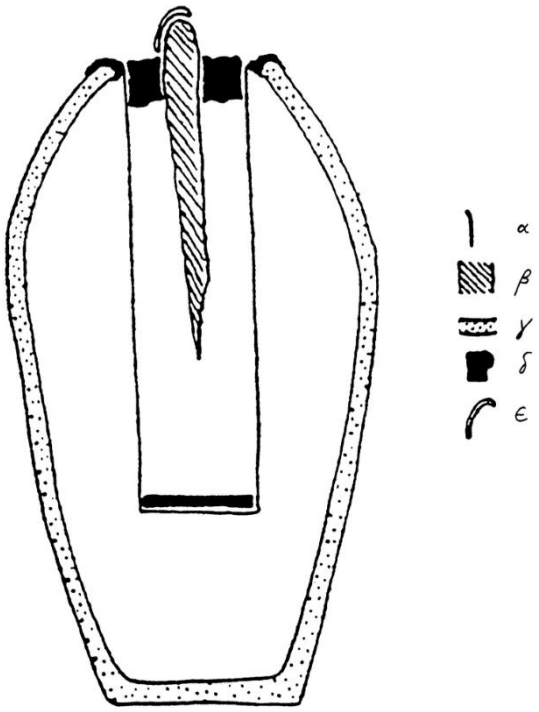

Figure 1. Illustration of the Baghdad Battery's cross-section from Paul Keyser's 1993 study of the artifact (reproduced from König). Note that the central iron rod is electrically insulated from the copper vessel by an asphalt plug and that the copper is likewise insulated from the ceramic jar by more asphalt. Another asphalt seal, at the bottom of the copper vessel, covers the solder joint[4] where the bottom plate has been attached. α=Copper, β=Iron, γ=ceramic, δ=asphalt, ε=? coating.[5]

3 Keyser 81, 97.

4 In experiments, the asphalt alone was a poor adhesive for the bottom plate, although this might have been achievable with different additives to the asphalt (it is unclear from photographs of the artifact whether solder was used at the bottom). Regardless, because the tube itself was soldered, as Keyser notes (81,97), this experiment's result should not be affected by how the bottom plate was attached to it, provided that the seal was watertight.

5 Keyser, 89.

THE BAGHDAD BATTERY'S "OUTER CELL"

Were the Baghdad Battery's only source of voltage the reaction between iron and copper, then placing the copper vessel inside an unglazed ceramic jar would be counterintuitive to its design for several reasons. First, this setup makes the copper cathode terminal unnecessarily difficult to access for practical purposes. Furthermore, if the Baghdad Battery's only electrochemical cell comprises the iron rod and watertight copper vessel, no benefit could be derived by immersing the copper in a liquid isolated from the iron. Finally, because unglazed ceramic is porous, the outside of the jar would become damp and conductive when filled with liquid, draining power from the battery. The fact that the tube of the copper vessel has been soldered (with a mixture of tin and lead) is also inconvenient: when different metals are joined and then immersed in a corrosive liquid, galvanic corrosion quickly occurs, which would drain the battery's voltage and eventually cause the solder joints on the outside of the vessel to fail.

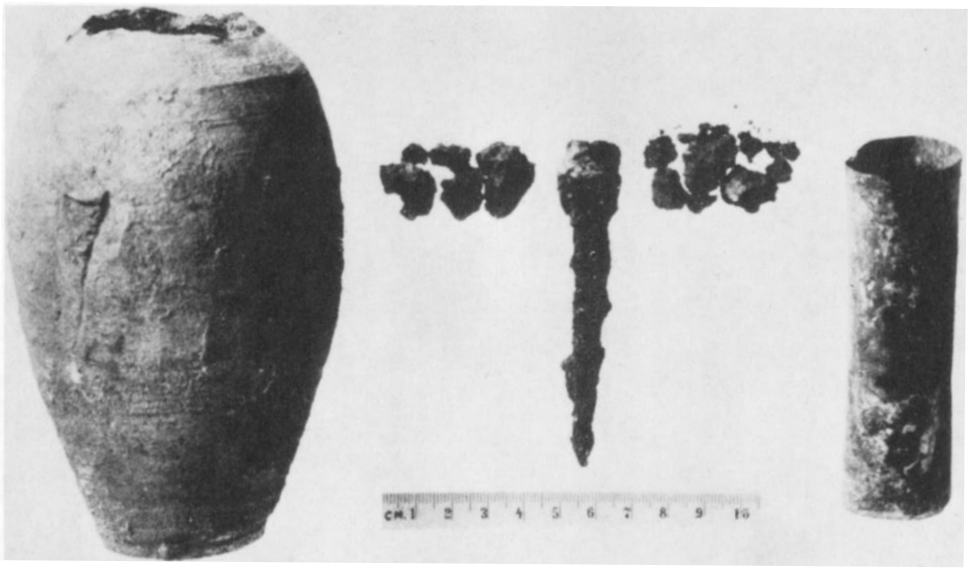

Figure 2. Photograph of the artifact discovered at Khujut Rabu (also taken from Keyser, originally from another study by König).[6] Fragments of asphalt are shown at top, around the iron spike.

6 W. König, *Im Verlorenen Paradies-Neun Jahre Irak* (Munich and Vienna, 1939), 160–161, reproduced in Keyser, 84.

Like the Baghdad Battery, similar artifacts found in Iraq also employed simple unglazed pottery (Figure 3). All of these ceramics assumed the same general amphora shape, which promotes evaporation and the collection of concentrated solutions at the narrow base.[7] These artifacts also all employed some alloy of tin (either solder or bronze), placed within the sealed ceramic. The artifacts discovered at Tel Umar[8] and Ctesiphon[9] contained sealed bronze tubes which lacked any internal iron component at all. This evidence may suggest that the Baghdad Battery employed more than just one galvanic effect—perhaps one that was noticed long before iron was in common use.

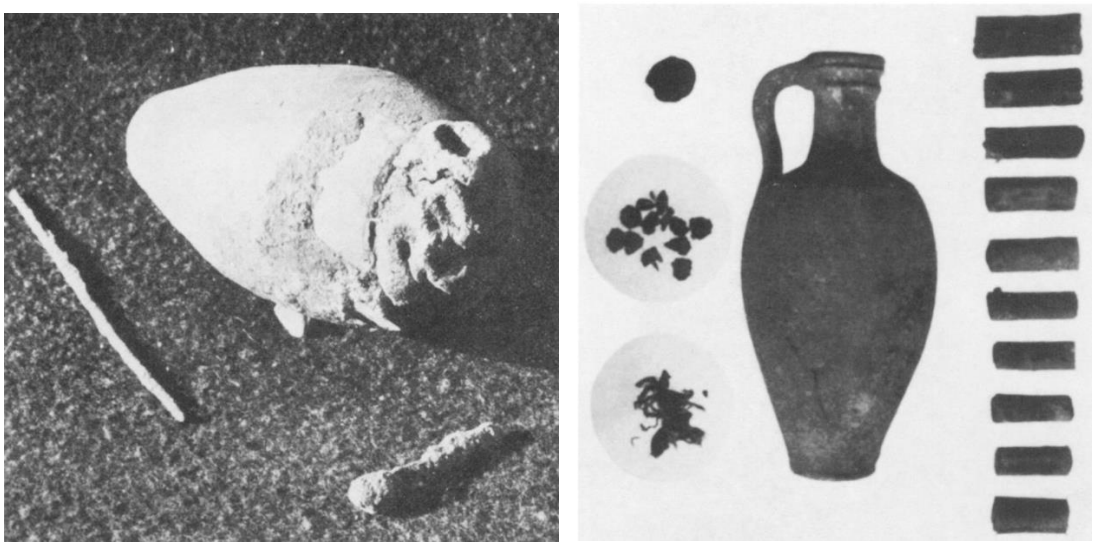

Figure 3. Keyser's presentation of two artifacts evocative of the Baghdad Battery found at Tel Umar (left) and Csestiphon (right). Both of these date to the Sasanian period—several centuries later than the Khujut Rabu device.[10]

When a piece of bronze is dropped into a clay jar of lye (potassium hydroxide) it naturally forms a crude *metal-air battery*, the voltage of which is readily measured against the outside of the ceramic

7 In experiments, the underside of the clay jar consistently yielded higher voltages than the sides. This is likely due to the lye solution being most concentrated at the bottom.

8 Waterman 61–62, Plate 12.

9 Kühnel 28, Keyser 82, 88.

10 Left: Waterman (Plate 12), reproduced in Keyser (86). Right: Kühnel (Plate 45), reproduced in Keiser (88).

(Figure 4). This electric potential accelerates the metal's corrosion in the caustic liquid, prominently etching the surface to reveal the alloy's constituent metals (Figure 5).

Figure 4. Experiment showing the voltage between a piece of bronze and the outside of a clay pot with a small amount of 25% KOH solution at the bottom. (Photograph by author)

Figure 5. After twelve hours in the lye, the tin and copper in the alloy have differentially corroded, creating a distinctive pattern. (Photograph by author)

Although perhaps the most ancient form of electrochemical cell, metal-air batteries are being researched today for their extremely high energy densities.[11] Because these batteries employ oxygen from the ambient air as their cathode (the cell's positive terminal), they only require one type of metal to function: whenever a corrodible metal is immersed in an alkaline electrolyte (such as lye) and separated from the air by a porous material, a voltage is naturally produced against the outside, as seen in Figure 4.

While metal-air batteries typically employ modern materials such as aluminum and zinc as their anode (the negative terminal), the potential advantages of using tin for the anode have, until recently, been unknown.[12] In 2023, a team of Chinese researchers found that aqueous tin-air batteries, employing KOH as the electrolyte, have a very high energy density (their experimental model tested at 420 Wh/kg).[13] By comparison, a standard alkaline AA battery has an energy density of approximately 105 Wh/kg.[14] As shown in Figure 6, the design of the Baghdad Battery's "outer cell" meets the requirements for being an aqueous tin-air battery, and the ideal electrolyte for such a device—lye—would have been a commonplace material in any historical period.

11 See, for example: Yanguang Li and Jun Lu, "Metal–air batteries: Will they be the future electrochemical energy storage device of choice?," *ACS Energy Letters* 2.6 (2017): 1370–1377, and Xin Zhang, et al., "Recent progress in rechargeable alkali metal–air batteries," *Green Energy & Environment* 1.1 (2016): 4–17.

12 Or, as I hypothesize, tin's application for this had once been known and then was forgotten, only to be rediscovered two millennia later.

13 Wanhai Zhou, et al., "High-energy Sn–Ni and Sn–Air aqueous batteries via stannite-ion electrochemistry," *Journal of the American Chemical Society* 145.19 (2023): 10880–10889 (10880).

14 Robert A. Powers, "Batteries for low power electronics," *Proceedings of the IEEE* 83.4 (2002): 687–693 (688).

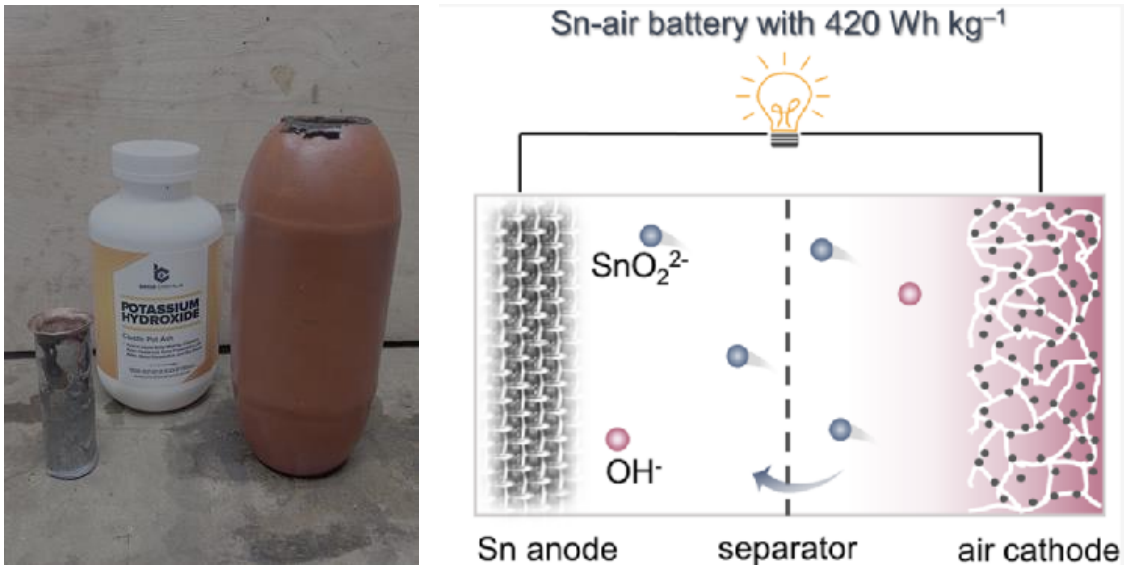

Figure 6. Author's photograph of the present study's recreation of the Baghdad Battery's outer cell (left) compared with Zhou's diagram of how an aqueous tin-air battery works (right).[15] In the present study, tin solder on the outside of the copper vessel serves as the Sn anode, Potassium Hydroxide (KOH) is the electrolyte, and the porous clay jar serves as the separator from the air cathode.

The present study's experimental recreation of the Baghdad Battery's outer cell provided over 1.1 volts without the iron rod inserted (Figure 7). When the same experiment was repeated, but without a metal plate underneath the clay jar, the measured voltage was somewhat lower (0.9 V, Figure 8). This result is perhaps due to greater resistance in the electrical connection (soggy clay) or because the silver plate itself provides an additional galvanic effect. Regardless, both of these results demonstrate that the outer cell is capable of producing significant voltages.

15 Zhou 10880.

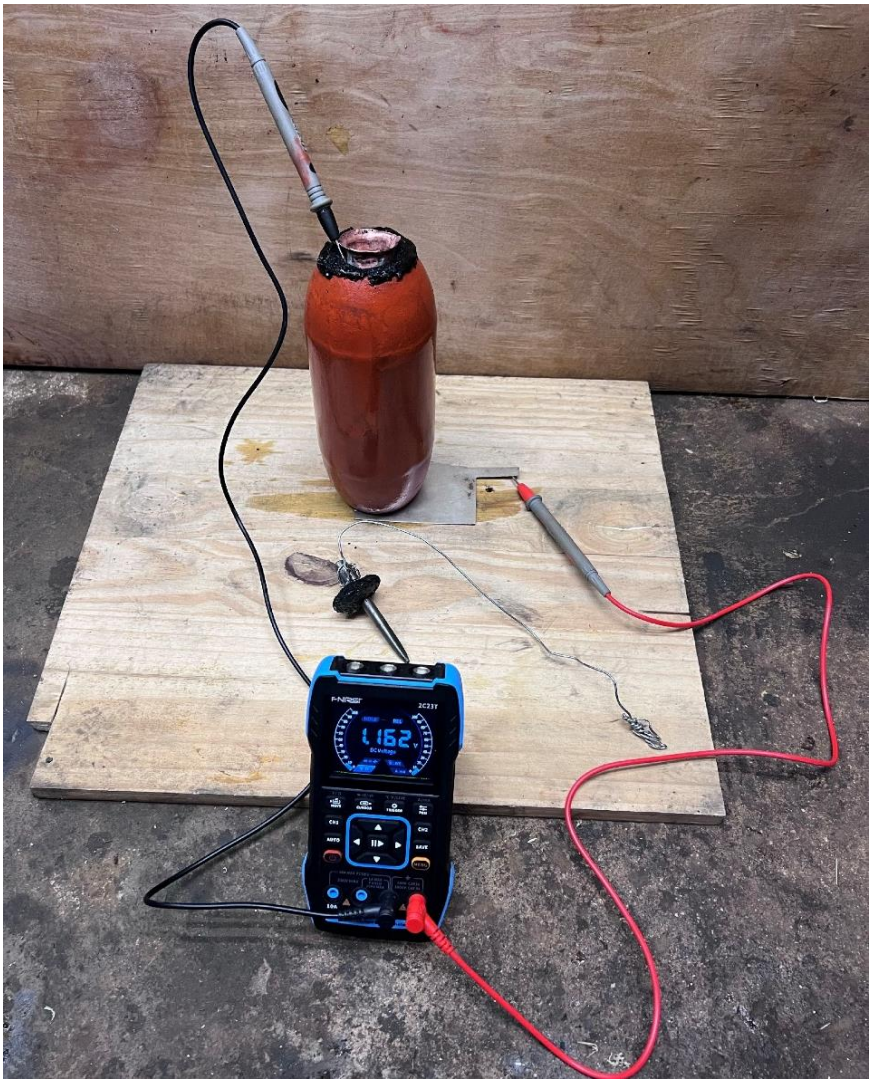

Figure 7. Test showing the functioning of the Baghdad Battery's outer cell. In the photograph, the clay jar has been placed on top of a silver "current collector" plate; the iron rod with asphalt plug and wire are shown in front of it. (Photograph by author)

Figure 8. Test demonstrating that a metal plate is not required underneath the jar for the outer cell to produce a voltage. This finding further supports the hypothesis that oxygen from the ambient air serves as the cathode for this part of the Baghdad Battery. (Photograph by author)

A simple experiment was conducted to determine if solder was the cause of the outer cell's high voltage. First, a pin of pure copper (Figure 9) was tested, being suspended in the clay pot of KOH by a plastic stopper (Figure 10). Intriguingly, the cell still produced a voltage, albeit a significantly lower one (~0.43 V).

The test was tried again, now with a single drop of 60/40 tin-lead solder on the tip of the copper pin (Figure 11). The potential of the outer cell jumped to over 1 volt (Figure 12). The same test conducted

with pure lead vs. pure tin melted onto the copper pin yielded potentials of 0.7 V and 1.04 V respectively, while a rod of iron tested in the KOH produced 0.62 V.

These results show that, while tin secures the greatest advantage for the Baghdad Battery's outer cell, lead would still have given the device a total potential of over 1 volt with the inner cell in place.

Figure 9. A copper pin, wired for testing. (Photograph by author)

Figure 10. When immersed in the clay jar of KOH, the copper pin yielded a potential of over 0.4 volts. (Photograph by author)

Figure 11. The copper pin from the previous test, shown now with a tiny amount of solder melted on the end. (Photograph by author)

Figure 12. With the addition of solder, the outer cell's potential jumped to over 1 volt. (Photograph by author)

THE BAGHDAD BATTERY'S "INNER CELL"

The Baghdad Battery's inner cell, which previous recreations have assumed to have been the device's only source of voltage, functions as a simple primary cell: an electric potential is produced between two dissimilar metals if they are kept from contacting each other while being immersed together in an electrolyte. As shown in Figures 1 and 13, an asphalt plug allows the inner cell's iron rod to sit in the electrolyte without touching the sides of the copper vessel. When filled with an electrolyte such as lemon juice or salt water, a modest voltage can be measured between the copper and iron (Figure 14). Significantly for how the two cells of the Baghdad Battery function together, the copper vessel serves as the inner cell's *cathode* (+); because tin solder on the outside of the copper tube serves as the outer cell's anode (-), the two cells end up being wired in electrical series (+ - + -). This results in the device's total output being the sum of both cells' potentials when measured between the iron rod and the outside of the clay jar (Figure 15). In other words, the inner cell functions as a "booster," which serves to raise the Baghdad Battery's total voltage to a level capable of producing visible electrochemical reactions (Figures 16–18). After heavy use, the solder on the outside of the copper vessel showed signs of extreme corrosion, further evincing tin's role in the functioning of the outer cell (Figure 19).

Figure 13. Components of the Baghdad Battery's "inner cell." The copper vessel (left) is made from a rolled and soldered sheet of copper with a round plate of copper soldered on to form a bottom; a seal of bitumen (example fragments are shown in front of the white dish) was then melted on top of this, preventing liquid inside the tube from contacting the solder joint. Another bitumen plug was then shaped around the iron rod (right), which allows it to hang inside the copper vessel without touching the sides, which would cause a short circuit. Experiments with salt water and lemon juice electrolytes (represented by the white dish) inside the copper vessel have yielded potentials of ~0.26 V and ~0.35 V respectively. (Photograph by author)

Figure 14. With lemon juice inside the experimental copper vessel, ~0.35 volts were measured between the iron anode (-) and copper cathode (+). Note that when testing the inner cell, the positive lead (red wire) of the voltmeter has now been attached to the copper vessel; when testing the outer cell (Figures 7 & 8), the copper vessel was tested with the negative terminal (black lead) because it comprises the anode of the outer cell. (Photograph by author)

Figure 15. When fully assembled, the device delivers over 1.4 volts. A solder wire has been wrapped around the battery's negative "terminal" (the head of the iron rod) to allow for an electrical connection. (Photograph by author)

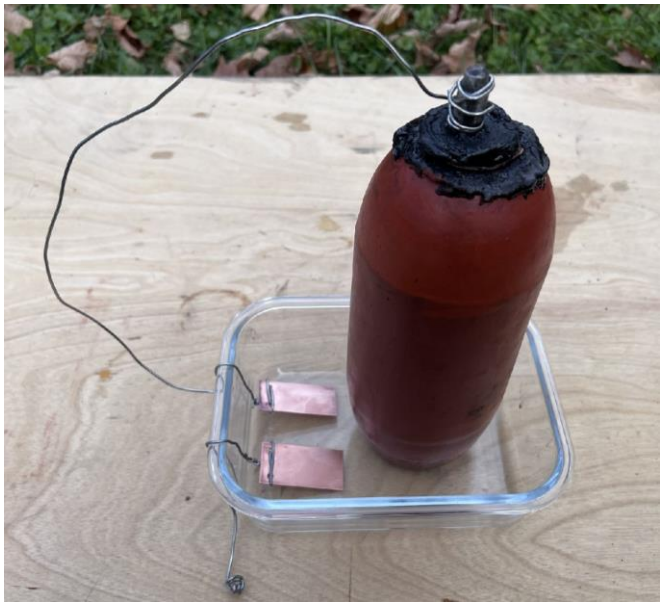

Figure 16. Experiment to determine if the Baghdad Battery would have been capable of achieving noticeable electrochemical effects. A plate of copper was wired to the iron rod and then immersed in a salt water bath with the clay jar, thereby forming a circuit. A control plate was placed next the electrified one to determine if there would be any difference. (Photograph by author)

Figure 17. Almost immediately, bubbles began to form on the surface of the electrified plate while the control plate was unaffected. (Photograph by author)

Figure 18. After sitting overnight in the salt water bath, the immersed surface of the electrified plate (shown on the left) had been etched. The control plate (at right) was unaffected below the waterline. (Photograph by author)

Figure 19. When removed from the KOH solution, the solder on the copper vessel showed signs of heavy oxidation. This photograph shows how the caustic solution has rapidly attacked the solder joint between the copper tube and bottom plate. This evidence further supports the hypothesis that the Baghdad Battery's outer cell functions as an aqueous tin-air battery. (Photograph by author)

CONCLUSION/SUMMARY

The Baghdad Battery functions as two batteries connected in electrical series. The device's "inner cell," comprising an iron rod inside a copper vessel filled with electrolyte, has been understood since Wilhelm König first announced the artifact's discovery in 1939. Unfortunately, his recreation and later experiments fail to account for major aspects of the artifact's design.

The experiment described in this paper demonstrates that the Baghdad Battery's "outer cell," comprising tin solder on the copper vessel and lye (KOH) solution in the unglazed clay jar, functions as a powerful aqueous tin-air battery. Tests on the recreation (Figure 20) have shown that the Khujut Rabu device would have been quite capable of producing a number of remarkable electrochemical effects using only the simplest of materials. This result provides the strongest evidence to date for König's original hypothesis that people in the Near East had a working knowledge of electrochemistry nearly two millennia before Alessandro Volta's experiments with the voltaic pile.

Figure 20. Assembled recreation of the Baghdad Battery used in the present study. (Photograph by author)

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