

The colored matting patterns of Hesy-Ra as technical instructions for CO₂ production

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The colored matting patterns of Hesy-Ra as technical instructions for CO₂ production

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Abstract

An engineering reconstruction of Old Kingdom graphic heritage is performed, identifying Hesy-Ra—the proto-chemist of Djoser—and his tent-cloth patterns as operational manuals for chemical reagent sequence loading. By applying four specialized visual analytical methods, planar compositions are decoded as process-initiating mimic ideograms. Closed-circuit reactors are reconstructed, exposing a standardized ancient infrastructure designed for automated CO₂ generation and subsequent irrigation fluid carbonation

Introduction

The hypothesis that ancient Egyptians used carbonated water on an industrial scale inherently implies the presence of equally extensive indirect evidence, whether domestic, iconographic, or subsequently religious. It is possible that information regarding carbonation was concealed from other nations. However, in an ancient society, the most plausible mechanism for such concealment was likely religious-mythological coding, while the actual phenomenon remained visible, understood only by the initiated.

The core of this hypothesis is the assumption that ancient Egyptians possessed technology for a chemical reaction utilizing three elements—natron, a reagent, and water—which, within an enclosed space, could carbonate water. This process was applied to irrigation water and could also generate low pressure to facilitate the construction of megalithic structures. Over time, the carbonation process may have been refined based on the objective. For instance, natron could be purified to sodium carbonate (Na_2CO_3), and acetic acid could be concentrated or substituted with hydrochloric or sulfuric acid. However, due to the lack of access to molecular analysis of artifacts under laboratory conditions, this study focuses on the visual and morphological examination of the graphical and technological traces left by the ancient Egyptians from this chemical reaction.

The hypothesis targets a generalized model of chemical and technological components capable of generating carbon dioxide for a period of one week to one month without operator intervention. Concurrently, CO_2 released from the reactors could carbonate irrigation water over a similar one-month duration, after which the cartridge was replaced, while reaction residues were retained inside the reactor.

Probably the most prominent iconographic evidence detailing this chemical technology was left in mastaba S2405, which belonged to the royal official Hesy-Ra. [1]. This official held numerous titles, but he is linked to the proposed hypothesis regarding CO_2 application through his title, 'Scribe of the Desert Regions'. Hesy-Ra directed this system and effectively headed the department managing desert expeditions and Egypt's mineral resource extraction[2].

Presumably, the polychrome 'palace facade' or 'carpet' patterns discovered in his mastaba (Fig. 1a) were not merely aesthetic elements; they functioned as visual technological passports for literate workers, indicating a strict chronological and spatial stratification of chemical components (natron, gypsum, alum, mineral salts) within batch reactors. These structures served as repositories for chemical cartridges awaiting seasonal precipitation to initiate large-scale carbonation. Hesy-Ra was not the first; similar stylized ideograms were found in Saqqara, tomb 3121. [3] (Even earlier, a cone mosaic pattern appeared on columns from a temple in the Eanna district of Uruk, ca. 3400–3100 BCE (Pergamon Museum, Berlin; photo by L.D. Graham, 2015, reproduced from unreviewed preprint Graham, 2019, Academia.edu/38900455, p. 15). The entire carbonation technology might have been adopted simultaneously from there. This is indirectly evidenced by the sudden, mass appearance of high-legged beds in First Dynasty Egypt,

whereas people had slept on the floor for centuries; notably, CO₂ is heavier than air and is lethal. [4] .

The proposed hypothesis is verified through a cross-comparative analysis of three independent archaeological sites from different eras and scales of technological planning, benchmarks against the reference as-built graphics of the architect Hesy-Ra (Third Dynasty).

1. At the micro-technological level, the internal architecture and friezes of individual batch reactors (sarcophagi) from the late Middle Kingdom are examined, exemplified by the sarcophagus of the steward Khnumhotep (Twelfth Dynasty), revealing reduction and schematization of the original Hesy-Ra codes.
2. At the macro-technological level, the non-textual polychrome decorative register surrounding the royal sarcophagus in the Pyramid of Unas (Fifth Dynasty) is analyzed, interpreted as a multi-column assembly of reaction modules.
3. At the mega-technological (industrial) level, the spatial logistics of open areas and passive separation units within the architectural complex of the Heb-Sed court in the Step Pyramid of Djoser complex (Third Dynasty) are investigated.

This interdisciplinary approach establishes the continuity and universality of a unified state regulation governing the batch distribution and phase separation of chemical ingredients over more than a millennium.

Methods

1. Graphical and Descriptive Re-engineering

Planar compositions from Dynasties I–III are analyzed as orthogonal engineering projections and functional process mimic diagrams. Applying descriptive geometry, we perform a reverse 3D spatial reorientation of technical elements, mapping laterally displaced icons back onto the upper horizontal plane of the apparatus. This allows for the structural unification of multi-aspect views and the vector verification of dynamic fluid flows through deviation analysis of graphical anomalies.

2. Hydrodynamic and Pneumatic Modeling

Multiphase fluid dynamics within closed circuits are evaluated via visual-morphological phase-state differentiation of solid and liquid markers. Spatial-level analysis is used to reconstruct the apparatus hydraulic cycle, including hydrostatic level boundaries and color-coded binary piping control. The method incorporates pneumatic re-engineering of interconnected vessels to model self-actuating flow control driven by negative gas-pressure feedback.

3. Chrono-Morphological Material Verification

A material science assessment is performed using end-to-end evolutionary mapping of technological signs and architectural profiles across Dynasties I–XIII to confirm structural standardization. The corrosion resistance of the apparatus hulls (timber versus monumental stone) is evaluated to determine operational partial pressures and chemical agent specifications. Bulk accumulations and textile components are modeled as granular packing beds and semi-permeable filtration membranes.

4. Landscape-Climatic Hazard Modeling

Environmental and industrial safety risks within the macro-spatial boundaries of the Djoser plant site are assessed based on heavy gas dynamics at ambient winter temperatures. The model simulates the formation of surface-level gas pools due to carbon dioxide density $p = 1.53$, validating seasonal evacuation protocols and historical shifts in domestic ergonomics. The positioning of specific fauna is analyzed under an anthro-environmental framework as a functional biological early-warning system.

Appendix A. Final Comprehensive Research Methodology Classifier (M-Codes) is located at the end of the article.

Results.

Structure of elements from the Tomb of Hesi-ra.

Quibell's (1913) ideograms are reflected in the Tomb of Hesi-Ra, Third Dynasty. [1] (Fig. 1a). Presumably, the so-called 'Palace Façade' provides information not only on the content of chemical and technological elements intended for the CO₂ production reaction, but also replicates their spatial arrangement within the chemical reactors. Mudbrick recesses and niches offer a clear indication of ingredient packing. Analyzing and comparing their representations across other locations reveals that these ideograms are classified into two categories: Technical/Chemical (hereafter designated as T/C No., indicating the category and element number)(Fig. 1b)(M-01).

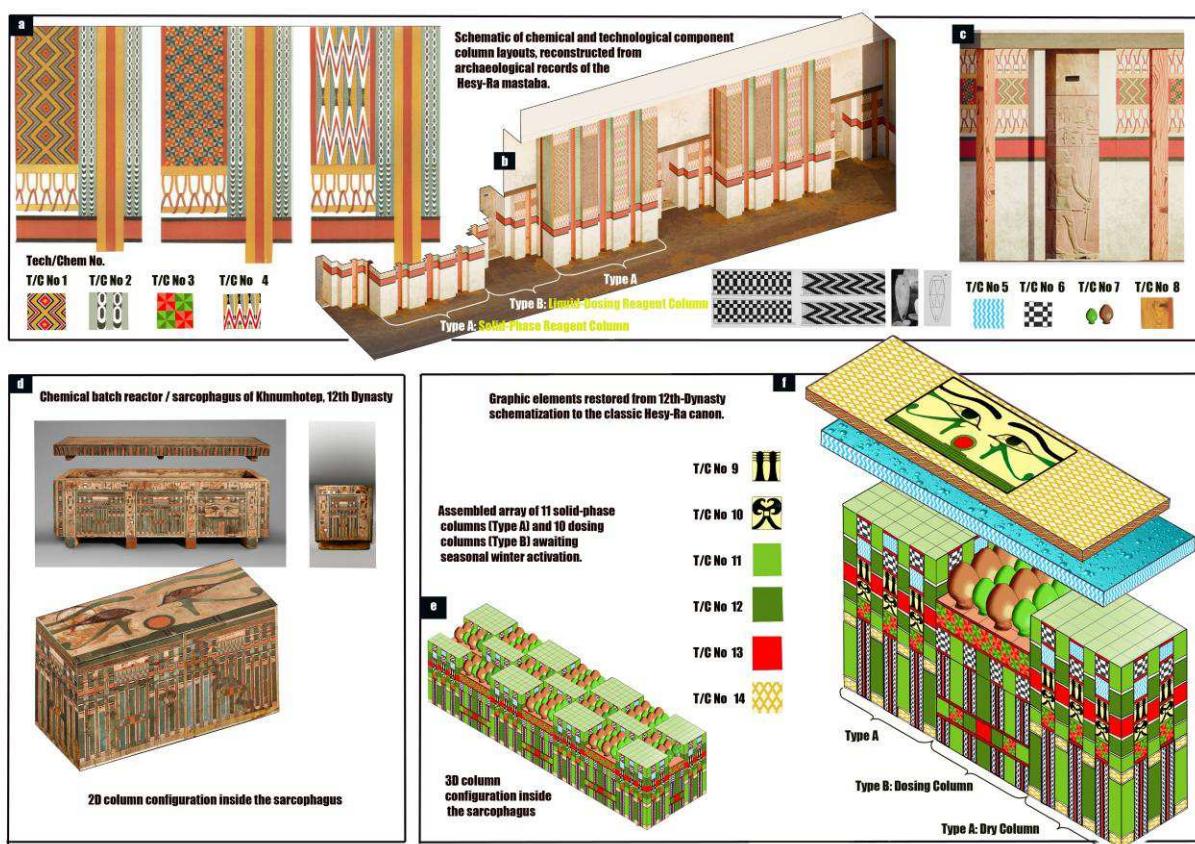


Fig. 1 Comparative analysis of ideograms from the tomb of Hesi-Ra with those from Twelfth Dynasty wooden batch reactors (sarcophagi). Figure a , b, c: Digital architectural reconstruction and 3D sectional view of the corridor in the Mastaba of Hesi-Ra (Saqqara, 3rd Dynasty). Image by Alexander Pruess, based on the archaeological data by J.E. Quibell

(1913). Image d: Wooden outer coffin of Kheni, showing the elaborate "palace facade" decoration and false door motifs, Asyut, Egypt (Middle Kingdom, Dynasty 12, ca. 1981–1802 B.C.). Image of The Metropolitan Museum of Art, New York (Accession Number: 11.150.15a, b). Figures e, f: cluster columns Type A, Type B, I. Popovichev 2026.

Currently, assigning a specific category to the ideograms is not possible; hence, a dual definition is applied to the elements. Cassette columns composed of these elements are also divided into two types. Type A (Solid-Phase Reagent Column) consists of stacked dry T/C elements: T/C No. 1 along the edges, and T/C No. 3 and T/C No. 4 in the center. Type B columns (Liquid-Dosing Reagent Column) incorporate liquid ingredients : T/C No. 7. (M-02)

The reactors must be initiated at the onset of the rainy season. To activate the reactor (sarcophagus), water must be poured above the level of the stacked ingredients: T/C No. 5, and the T/C No. 7 drippers (Fig. 1f) must be opened. The reactors must feature a tightly sealed lid, T/C No. 14 (Fig. 1f) (M-03). The application of the word 'columns' to Hesy-Ra's rectangular niches and pilasters derived from the Mesopotamian prototype, where these objects comprised circular columns. (Reference to Uruk above, p.3)

A Type B column is invariably positioned between two Type A columns. The ancient Egyptians meticulously highlighted this zone with depictions of wooden partitions (insulators), designated as T/C No. 8 (Fig. 1c). The Type B zone is flanked on both sides by T/C No. 1 elements (Fig. 1c). Type A columns occasionally feature a so-called 'false door to the underworld', presumably indicating the most active zone of the gas-evolving chemical reaction.(M-04).

Decoding of Technical/Chemical Elements

Because water carbonation technology was presumably identical regardless of reactor scale, subsequent analysis examines the features of T/C elements across various locations. For clarity, elements are evaluated not sequentially, but by increasing

analytical complexity (from simple to complex).

T/C No. 2 (T/C No. 6)

Based on ideogram T/C No. 2, this feature presumably served to vent CO₂ to the reactor surface (Fig. 1a). The ideogram closely resembles a pictogram of rising gas bubbles (M-05). Two hypotheses describe this configuration within an actual reactor: an empty vertical channel formed around solid ingredients, or a vertical wooden multichannel fluid-gas manifold. The former is less probable; as reacting chemical components degrade, they could obstruct reagent access to the lower substrate and block free CO₂ venting. Consequently, the vertical wooden multichannel fluid-gas manifold was likely utilized.

Hesyr-Ra's technological matting patterns include an explanatory ideogram, T/C No. 6 (Fig. 1b–c), which illustrates an end-view alternative of the pipeline structure. Utilizing a 2D format, the ancient artisan attempted to convey its three-dimensional volume (a modern 3D reconstruction is shown adjacently; Fig. 2a). The applied blue coloration indicates that only water descended through the pipeline, while gas escaped countercurrently (M-06).

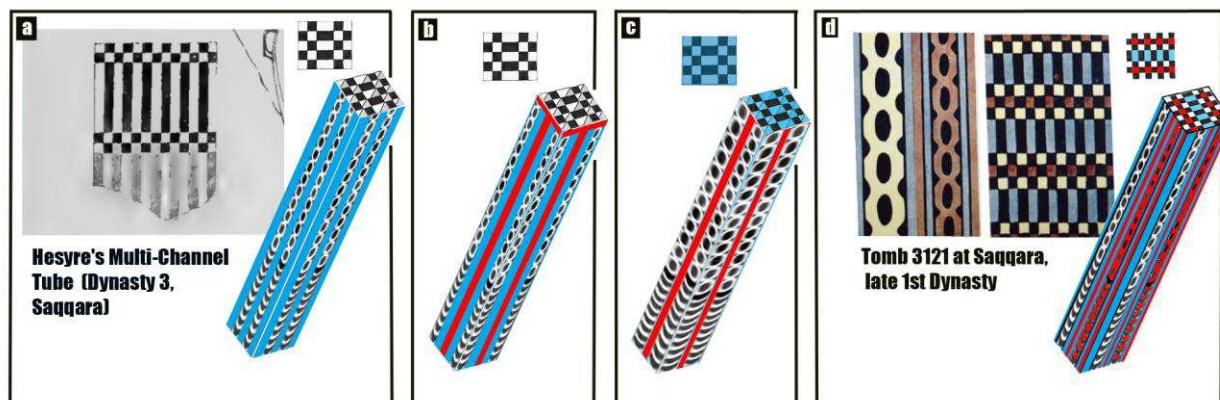


Fig. 2 a: Fragmentary wall decoration from the corridor of the Mastaba of Hesyr (Saqqara, Dynasty 3), illustrating early geometric and structural architectural patterns. Adapted from Quibell (1913, Pl. XV, Fig. 11). a, b, c, d: Universal vertical wooden multichannel fluid-gas manifolds. Figure by I. Popovichev, 2026. d: Reconstructed painted wall decoration patterns from Tomb 3121 at Saqqara (late Dynasty 1). Adapted from Emery (1949, Pl. 50).

T/C No. 7

"In small local reactors, two types of ceramic dosing vessels are invariably depicted. One half of the vessels differs from the other either by a smaller size or by color. From these, two types of liquids presumably flowed, which the ancient Egyptians represented with red and black wavy lines. These liquids passed through the vertical wooden multichannel fluid-gas manifold and were also designated with the marking (M-07). In the reactor of the official Khnumhotep (Twelfth Dynasty), water and a red liquid flowed through the vertical wooden multichannel fluid-gas manifold. This marking is reflected on the side of the vertical wooden multichannel fluid-gas manifold T/C No. 2 by blue and red bands (Fig. 2b) (M-08).

A red band is also visible on the side of the multichannel fluid-gas manifold of Pharaoh Unas's sarcophagus; however, water passage is indicated in blue only on the end-view portion of the drawing, where the checkerboard pattern is colored blue and black—T/C No. 6 (Fig. 2c) (M-09). The most informative component is the multichannel fluid-gas manifold from Tomb 3121 at Saqqara, late Dynasty I [3]. In this case, not only were the checkerboard ends marked in blue and red, but the sides of the multichannel manifold also demonstrated which fluids passed through it. The CO₂, ascending through the vertical wooden multichannel fluid-gas manifold, countercurrent to the red reagent, is likewise colored red (Fig. 2d) (M-10).

On one of the Serapeum sarcophagi [4] the artisan engraved the actual construction of the vertical wooden multichannel fluid-gas manifold, assembled from planks and divided into four channels, two of which conveyed liquid while the other two transferred gas (Fig. 3). The remaining sarcophagus ideograms indicate the spatial sequence of ingredients.

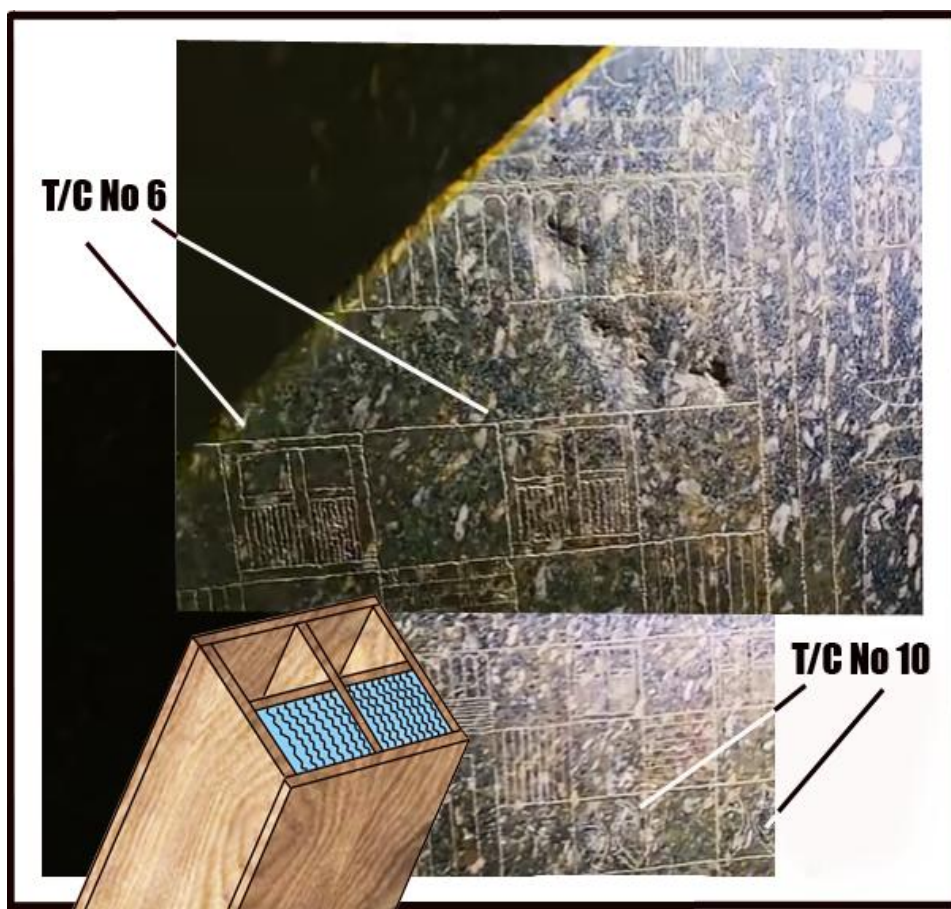


Fig. 3 Ideograms on the Serapeum sarcophagus—T/C No. 6.
(<https://www.youtube.com/shorts/we1V4qqG4BY>) Figure by I. Popovichev, 2026.

Consequently, T/C No. 2 and T/C No. 6 evidently represent different projections of the identical component (the wooden multichannel fluid-gas manifold); nevertheless, for clarity, the dual marking is retained (M-11). Furthermore, the lateral ideograms T/C No. 5, T/C No. 6, T/C No. 9, and T/C No. 10 (Fig. 1f) should be positioned on the top surface of the corresponding 3D model. The ancient Egyptians depicted these ideograms laterally due to their unfamiliarity with axonometric projection (M-12). Specifically, the layout of the multichannel manifold (T/C No. 6) on the upper face can be observed on the sarcophagus reactor from Tomb 3121 [3] (link:

Graham, L. D., 2019, available at Academia.edu/38900455, p. 11, Fig. 3).

T/C № 10

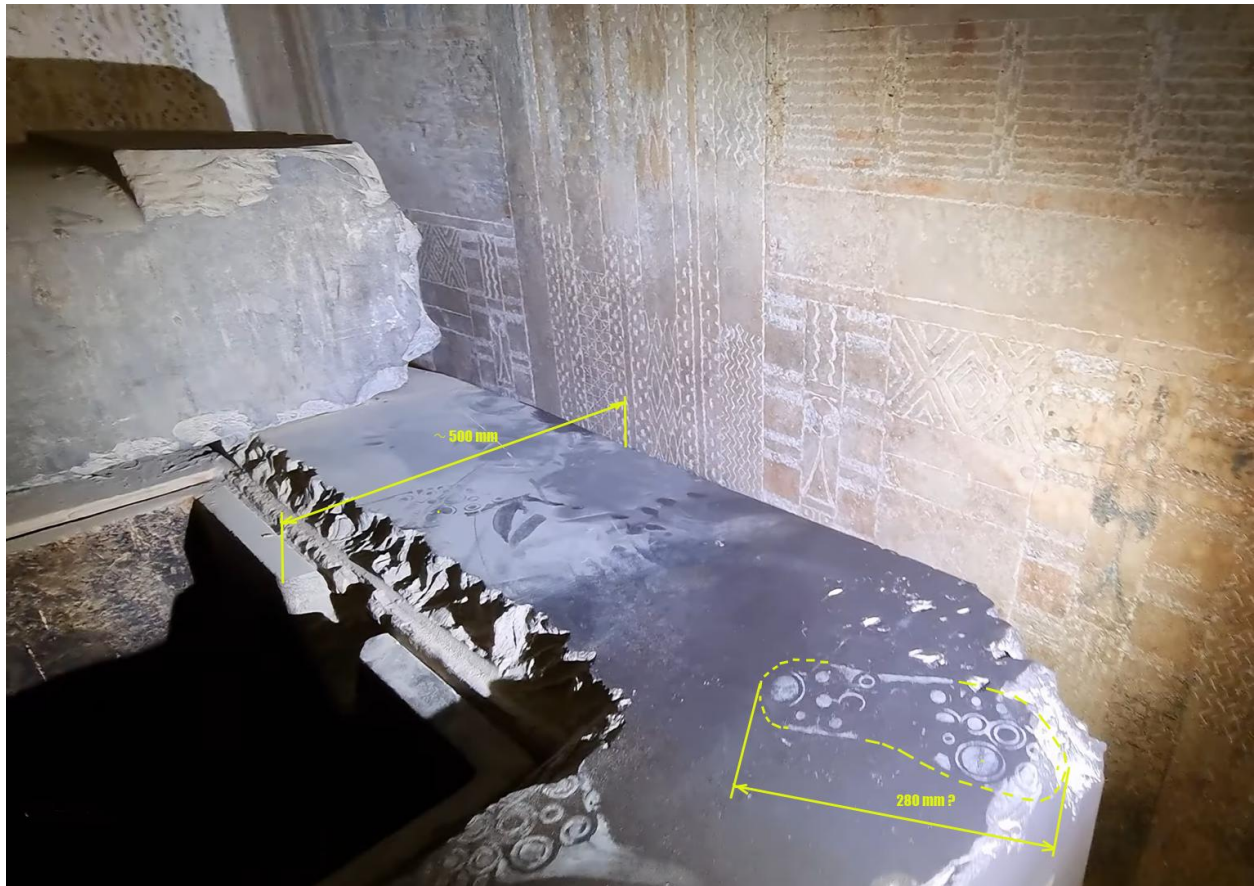
The second most critical issue in ancient Egyptian CO_2 generation technology was controlling process kinetics: the high purity of the initial reagents triggered an avalanche-like acceleration of the reaction, whereas technological requirements demanded stable gas evolution over winter weeks or months. This likely explains the regular occurrence of the crossed papyrus flowers ideogram within the graphic schemes of Egyptian reactors. The biochemical properties of papyrus sap and its fibers—specifically their ability to form an adhesive reinforced matrix with subsequent controlled dissolution in an aqueous medium—render it an optimal diffusion inhibitor. Papyrus plant fibers, along with gelatin, were presumably introduced into the sodium carbonate mixture as a sustaining agent to retard the dissolution and chemical interaction of active components [5] (Fig. 4)(M-13). Alternatively, the entire column-based chemical assembly of the reactor might have been enclosed in a woven papyrus lining.



Fig. 4 Bundles of papyrus flowers, T/C № 10. Close-up of the carved papyrus flower pairs from an anonymous 4th-Dynasty limestone sarcophagus from Giza. Egyptian Museum, Cairo (JE 54934 / CG 6170). Photo by L. D. Graham, after Hassan (1932) and Kemp (2006).

Hypothetically, the chemical reaction for CO_2 evolution was utilized by the ancient Egyptians across various locations for nearly a millennium and a half, presumably from the First to the Thirteenth Dynasty and beyond. This continuity is evidenced by the

virtually unchanged arrangement of the ideograms, as well as the graphic representations of vessels containing liquid reagents, where one is invariably 1.5 times larger than the other (see below). The timber material of the Twelfth to Thirteenth Dynasty sarcophagi suggests that either sulfuric and hydrochloric acids were excluded from the chemical process, or the inner walls were treated with plant resins. [6]. However, the thickness of the stone walls in Unas's sarcophagus-reactor strongly indicates the involvement of a highly potent reagent. (Fig.5)(M-14).



5 Fig. 5 Medium-sized, locked reactor of Unas. Wall thickness ≈ 500 mm, internal volume ≈ 0.833 m³ [7]image of Unas's sarcophagus via SPIRIT in STONE YouTube channel, URL: <https://youtu.be/Qw579CPkSU8?t=321>

To evaluate the theoretical limits of sustained carbon dioxide generation within the 0.833

m³ [7] Unas sarcophagus, a mineral-driven proton augmentation model was simulated. The complete stoichiometric derivations, mass balance sheets, and fluid parameters for this theoretical setup are detailed in Supplementary Note 1. (Fig.6 c)

By approximating the volume of the ingredients, their position within Unas's reactor can be estimated by comparing the ideograms with analogues in Hesy-Ra's mastaba (Fig. 6a, b).

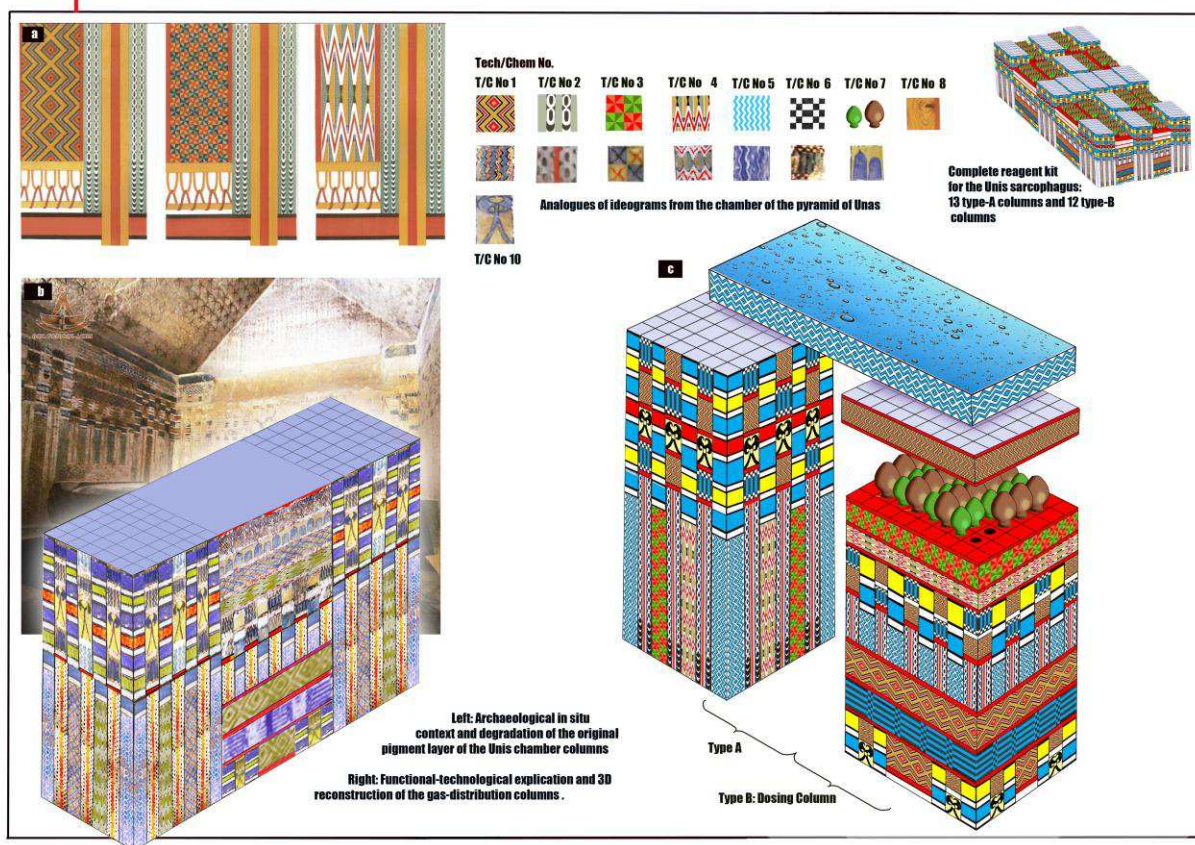


Fig. 6 Comparative analysis of ideograms from Hesy-Ra's tomb and Pharaoh Unas's chamber. Figure a : Digital architectural reconstruction and 3D sectional view of the corridor in the Mastaba of Hesyre (Saqqara, 3rd Dynasty). Image by Alexander Pruß, based on the archaeological data by J.E. Quibell (1913). Figure b: Pharaoh Unas's chamber, reproduced with permission of ISIDA Project (isida-project.org). Figure c: I. Popovichev, 2026, Type A and Type B cassette columns of technical/chemical elements.

During the analysis of the palace-facade hanging mats, a structural feature was noted. A horizontal red boundary stripe runs along the perimeter of the Hesyre tomb corridor, which features 11 Type-A and Type-B columns (Fig. 1b). The vertical wooden multichannel fluid-gas manifolds (T/C No. 2) extend through this stripe down to the floor level (Fig. 7(A)). A similar horizontal boundary plane is observed in other reactor designs from Dynasties I to XIII (indicated by white arrows, Fig. 7a–j)

In the absence of any designation for the lower cavity, it can be assumed that it contained either a foundation for large-scale reactors or a compartment for the composite holder of the wooden multichannel fluid-gas manifold (the sarcophagus variant). Alternatively, this was a hollow compartment for pure sodium carbonate, which occupies approximately 20% of the total ingredient volume and may be reinforced with papyrus (M-15).

Such a foundation is logical, as Hesy-Ra's drawings indicate that these vertical wooden multichannel fluid-gas manifolds supported wooden crossbeams for woven graphic mats featuring ideograms (Fig. 7(B)). The woven reed mats themselves, tensioned with ropes between the columns, formed a basket for the chemical ingredients. They functioned as plant-woven filters allowing gas and aqueous solutions to flow freely through them (Fig. 7(C)) (M-16).

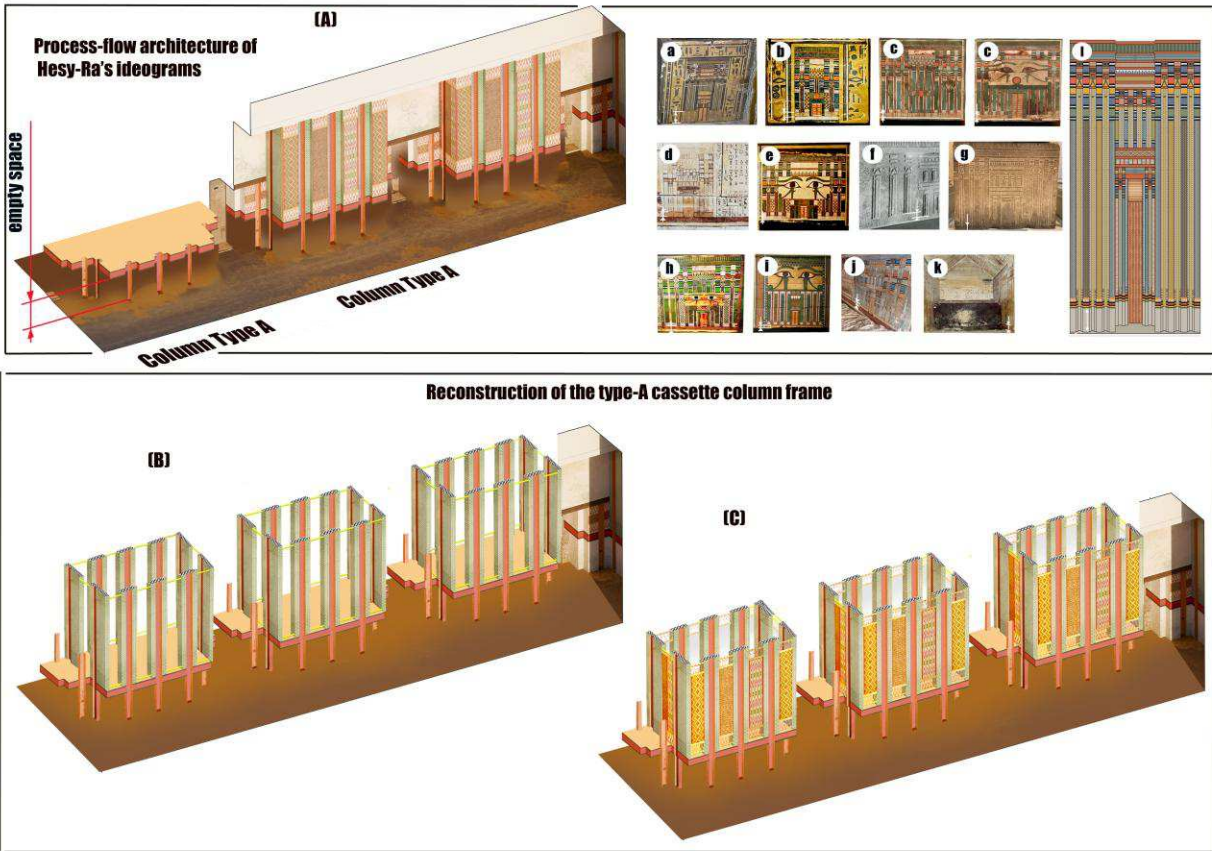


Fig. 7 (A) : Digital architectural reconstruction and 3D sectional view of the corridor in the Mastaba of Hesyre (Saqqara, 3rd Dynasty). Image by Alexander Pruß, based on the archaeological data by J.E. Quibell (1913).

(A) a: Inner wooden coffin of Idi from Asyut, Egypt (Dynasty 12). Photo: Jochem Kahl / The Asyut Project.

(A) b: Outer wooden coffin of Mentuhotep from Thebes, Egypt (Dynasty 12). Adapted from the State Museum of Egyptian Art, Munich (SMÄK).

(A) c: Outer wooden coffin of Khnumhotep from Meir, Egypt (Dynasty 12). Adapted from The Metropolitan Museum of Art, New York (Accession Number: 12.182.1c).

(A) d: Detailed view of the painted wooden coffin of Deshri from Beni Hasan, Egypt (Dynasty 11–12). Adapted from the Egyptian Museum, Cairo (CG 28026).

(A) e: Outer wooden coffin of Mentuhotep from Thebes, Egypt (Dynasty 12). Adapted from the State Museum of Egyptian Art, Munich (SMÄK).

(A) f: Red granite sarcophagus of Khufuankh from Giza, Egypt (Dynasty 5). Adapted from the Egyptian Museum, Cairo (JE 18220 / CG 1790).

(A) g: Limestone sarcophagus with palace-facade decoration from Giza, Egypt (Dynasty 4–6). Adapted from the Egyptian Museum, Cairo.

(A) h: Outer wooden coffin of Ameny from Meir, Egypt (Dynasty 12). Adapted from The Metropolitan Museum of Art, New York (Accession Number: 11.150.39a, b).

(A) i: Outer wooden coffin of Khnumnakht from Meir, Egypt (Dynasty 12). Adapted from The Metropolitan Museum of Art, New York (Accession Number: 15.2.2a, b).

(A) j: Inside the burial chamber of the royal physician Tetinebef from Saqqara, Egypt (Dynasty 6). Courtesy of the Ministry of Tourism and Antiquities.

(A) k: Palace-facade decoration on the burial chamber walls of the Pyramid of Unas at Saqqara, Egypt (Dynasty 5). Screenshot from the documentary video by *Ancient Egypt Alive*.

(A) l: Reconstruction of the palace-facade decoration from the Mastaba of Ptahhotep at Saqqara, Egypt (Dynasty 5). Vector drawing by Alexander Pruß.

(B), (C) Reconstruction of the Type-A cassette column

The fact that both the matting patterns and the rope fastenings of the technical elements (mattings) were graphically replicated on the reactor surfaces for a millennium and a half indicates that this was a technological design rather than a mere illustration. Specifically, the continuously permuting positions of ideograms T/C Nos. 1–7 on the Type B column suggest that they essentially functioned as icons, indicating the presence of a technological attribute rather than its exact spatial location within the structure.

Ideogram T/C No. 10 is present across all reactors. However, ideogram T/C No. 9 (the dual Djed pillar sign) is documented only on a select group of sarcophagi (Fig. 7b, c, e); its omission on the others suggests that this component was considered an inherent structural specification. Ideograms T/C Nos. 11–12 varied in color, but their spatial position invariably remained unchanged. For T/C No. 14, only the grid pattern was altered (M-17).

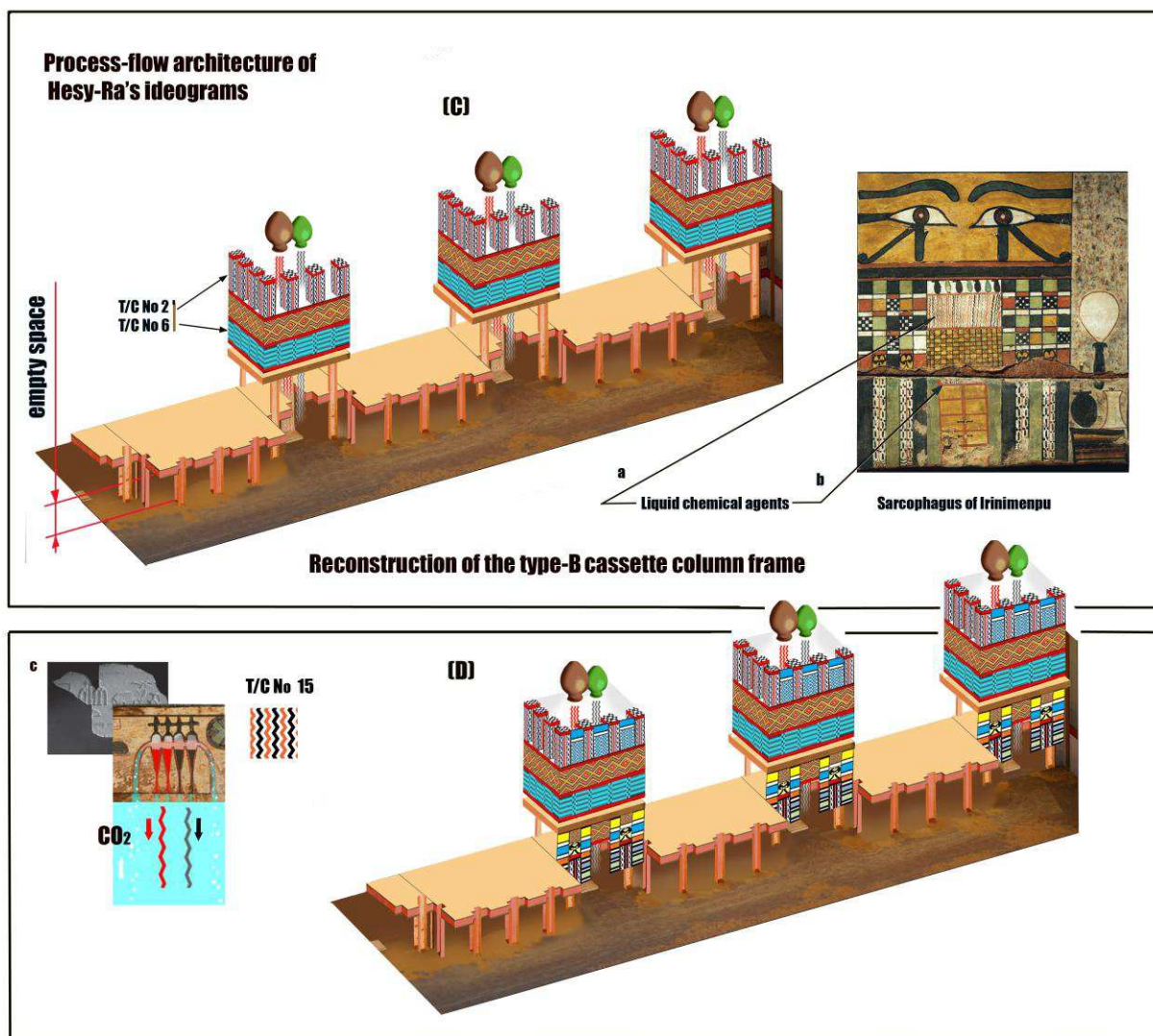


Fig. 8 (C): Process-flow architecture of cassette column frames and ideograms (top and left) compared with archaeological records. (C) a-b: sarcophagus Irimenetiypi with the image of flowing liquid. c: Drip dispenser (photo by M. Frouz); relief fragment from a rock-cut tomb at Saqqara, dated to the 6th Dynasty (Sixth/Fifth Dynasty transition, Old Kingdom). panel c is reproduced after: Bárta, M., 2011, Oxbow Books, pp. 9–21, available at Academia.edu/6211200). Schematic diagram of the drip dispenser operation, I. Popovichev, 2026. (D): Reconstruction of Type-B columns with liquid reagent.

T/C No. 15

However, rare cases occur where the ancient artisan departed from canon and produced an actual drawing 'from life'. For instance, across most ideograms (Fig. 7a–j), the red and black fluid streams flowing from the jars (T/C No. 15) are constrained by the artwork boundaries and positioned wherever convenient for the artist. Conversely, the decoration on the sarcophagus of Irimenetiypi (Fig. 8a) depicts a genuine motion vector of the chemical fluid. It flows from the jars and passes behind the 'false door' [8], entering the primary zone of the chemical reaction (the Type B column) (Fig. 8b). The reagents pass completely through the T/C No. 3 element (M-18). Most likely, the fluid did not flow continuously from these jars; rather, they functioned as drip dosers, as the reaction was required to extend over weeks or even months.

Within the Type B columns, the components designated as T/C No. 2 also vent CO₂ to the reactor surface (Fig. 8(C)). However, in the middle section of the column, these elements are rotated 90 degrees omnidirectionally to distribute reagents into adjacent columns (Type A). Chemical reagents are also concentrated within the lower, hollow portion of the Type B column, although the exact filling level above the floor remains unclear (Fig. 8(D))

Images of interconnected vessels, consisting of two, three, or four containers with hollow lateral channels (hieroglyph *hnt*, Gardiner sign W17) [9], are frequently recorded on sarcophagi alongside the Type A and Type B column ideograms. From an engineering perspective, this configuration could be interpreted as a drip doser within a CO₂-evolving reactor (Fig. 8c). Gas ascending from below entered the channels, displacing the reagents through small bottom orifices. Concurrently, if the bubble ascent ceased, the release of the acidic reagent was blocked, functioning as an autonomous static-type doser (M-19)

T/C No. 4

Probably, unlike the sarcophagi, where technical/chemical elements were compactly located inside the reactor and were essentially a disposable chemical cartridge, the Djoser pyramid complex was rather an entire factory located inside a regulated water basin (544.9 m x 277.6 m x 10 m) [10]. This Complex was a continuation of the CO₂ generator line, such as mastabas 3500, 3505, 3506, and 3507, located directly above the Nile branch for a shorter gas path to the water. Traditionally in winter, after the reaction was initiated, this site became completely toxic (or destructive)

to the entire environment. Consequently, the complex's technological cycle was divided into two seasonal phases: summer-autumn atmospheric CO₂ absorption for soda accumulation and winter controlled gas generation under high pressure (M-20).

Chemical elements were likely not only stored in closed depositories but also processed within the same territory. The Djoser complex functioned as a seasonal supply center for raw materials and water resources as a unified Industrial Carbonator. On the west bank of the Nile [11, p. 35] in Ancient Egypt, hundreds or thousands of large and small sarcophagi-reactors existed; thus, producing reagents in a single hub—the Djoser factory—was more efficient.

Pictogram T/C No. 4 strongly resembles stones fastened together (forming rhombuses) washed by a reagent, depicted in red. See the depiction of the Hesy-Ra pictogram from the wall of the Unas chamber (Fig. 9a). Notably, in depictions of ancient sanctuaries (and we consider the Djoser pyramid complex to be precisely such an ancient sanctuary), a wall with a Palace Façade is almost always observed, above which rises a mound of rhomboidal stones (Fig. 9b). Item 1: Ivory plaque, 1st Dynasty, Petrie excavations; Items 2–6: Cylinder seal impressions, 1st Dynasty. Depictions of Upper Egyptian sanctuaries; Emery excavations, Hor-Aha [12, p. 28]

Today, virtually all rooms within the Djoser Complex are filled with miscellaneous blocks arranged in a rhomboidal configuration. For instance, consider the stone mound of the South Tomb Superstructure (Fig. 9c). We observe a lower masonry made of one material, above which larger masonry is laid in radial rows. Rhomboidal gaps are left within the masonry. Exactly the same technology is visible on the stone mound of the South Tomb Superstructure (Fig. 9d). For better understanding, the drawing has been color-corrected (Fig. 9e). A similar stone mound is located behind the Chapels and near the Colonnade entrance, as well as inside the granary. Everything was filled with some material on an industrial scale. It should probably be assumed that T/C No. 4 (natural natron) was previously stored there.(M-21).

Natural Egyptian natron from lakes (Wadi El Natrun) is a mixture of three main components: sodium carbonate (Na₂CO₃), required for the reactor; common salt (Cl), serving as ballast; and sodium sulfate (Na₂SO₄, thenardite), an unnecessary impurity for the reactor. [13, 14].

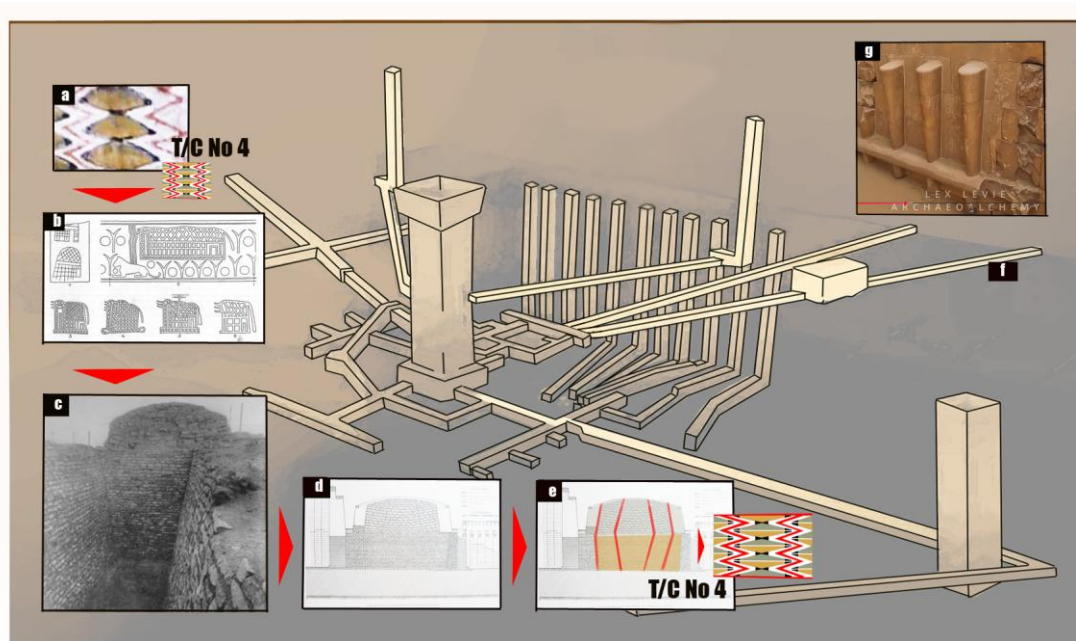
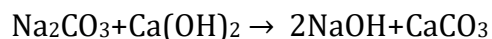


Fig. 9 Visual comparison of the T/C No. 4 ideogram with the rhomboidal features in the depictions of "royal tents" and the geometric masonry layout of the mound within the Djoser pyramid Complex. a: Screenshot from the video by *Ancient Sites Girl* (available at: <https://youtu.be/RyqEcj1ugL0?t=429>). b: Cylinder seal impressions, 1st Dynasty [12 p.28] c,d,e: Superstructure embankments within the false chambers of the Djoser complex. Adapted from Hamilton K., *Djoser's Step Pyramid Complex (Part 2)*, 2020, pp. 14, 41. f: Cut out plan of the Stepped Pyramid complex, with the 11 shafts indicated, Saqqara, Egypt. Image by Franck Monnier (Bakha), used under CC BY-SA 1.0. g: Simulation of bollards on the Heb-Sed chapels. Screenshot from the video by *ARCHAEOALCHEMY* (available at: <https://youtu.be/mRpYr5JytpY?t=1057>). f: An underground channel running from the Djoser pyramid reactor toward the Nile (Image: F. Monnier/Bakha, CC BY-SA 1.0).

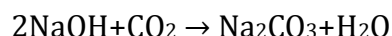
The fluid capable of extracting soda from this mixture is a weak aqueous solution of sodium hydroxide (caustic soda, NaOH) or milk of lime ($\text{Ca}(\text{OH})_2$). This required calcining ordinary

limestone (CaCO_3) over a fire. [15]. This required calcining ordinary limestone (CaCO_3) over a fire.

A kiln was necessary for calcination; perhaps the South Court was designed precisely for a high-temperature kiln, while the B-shaped structures served as foundations for huge bellows to achieve elevated temperatures. The resulting quicklime (CaO) was slaked in water to produce milk of lime. Subsequently, a portion of crude natron was added, initiating a classical causticization reaction:



The resulting active alkaline NaOH fluid was passed through natron (T/C No. 4). NaOH acted as a chemical extractor on crude natron. Next, atmospheric carbonation (gas charging from air) followed. A thin layer of alkaline NaOH solution spread across the vast courtyard area, where atmospheric gas binding occurred:



The liquid alkali converts back into water-dissolved sodium carbonate. The subsequent step involves nocturnal cryo-precipitation (thermal shutter). The soda solution remains until the cold Egyptian winter night drops to $+9^\circ\text{C}$. During the day, while the solution was exposed to sunlight and absorbed air, its solubility was maximal. At night, as the temperature plummeted, the solubility limit of sodium carbonate dropped fourfold. Consequently, all the sodium carbonate newly generated from the air across the courtyard area precipitously precipitated onto the stone slabs as white powder crystals.

T/C No. 15

Another reaction ingredient was concentrated acetic acid, which could be produced via solar evaporation and fractionation (fractional evaporation) powered by the Egyptian sun. A physicochemical explanation justifies the exact requirement of 40,000 vessels. Pouring dilute vinegar into a wide, open trough causes water and acetic acid to evaporate simultaneously (Fig. 10a) but at different rates. At solar air temperatures of $+35$ – 40°C , water vaporizes slightly faster than heavy acetic acid. Once the solution volume decreased, for instance, by one-third, the acid concentration marginally increased (e.g., from 5% to 6%). Operators did not leave this enriched portion to evaporate further in the open trough, which would cause rapid acid loss. Instead, it was immediately decanted and hermetically sealed into a narrow clay jar beneath the pyramid, serving as a first-level cassette accumulator. Portions from these first-level jars were subsequently combined, mixed in strictly calibrated proportions, and re-exposed to short, controlled solar radiation.

The solution could be brought to a limiting fractional concentration of 10–12%. The industrial quantity of sequentially arranged jars discovered within the Complex likely indicated transportation on rafts (Fig. 10b).

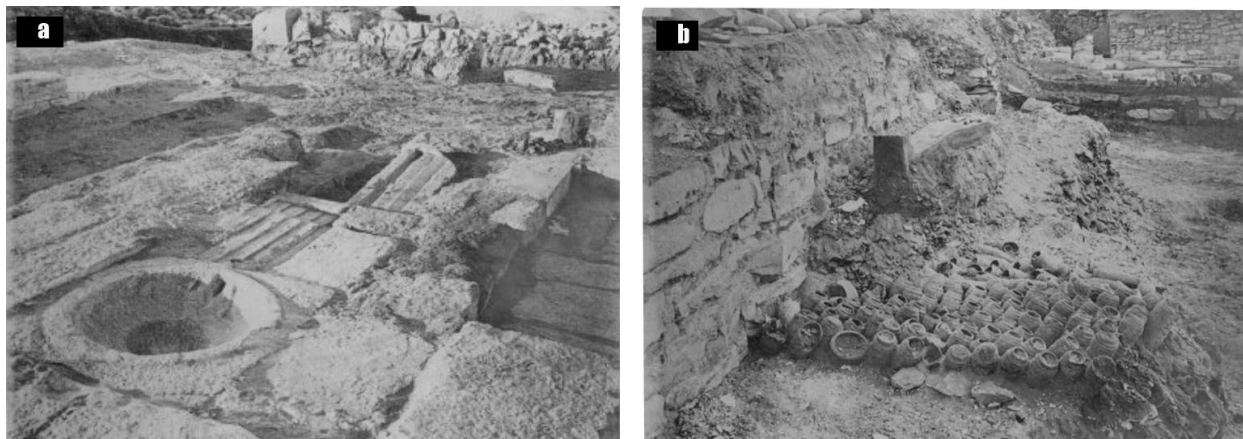


Fig. 10 Structural and artifactual elements of the Djoser Step Pyramid complex at Saqqara (3rd Dynasty) during early excavations: a — remains of a limestone feature with drainage channels in the southern section of the complex; b — a dense deposit of ritual vessels discovered inside the subterranean galleries. (*Adapted from the research guide: Hamilton, K., 2024, available at Academia.edu/120335277*)

Discussion.

1. The utilization of alum and 12% vinegar during the Old Kingdom contradicts A Lucas [15], who noted that vinegar was 4–6% and alum was used only since Pliny's time [15, p. 292]. However, the Hesy-Ra ideograms (matting patterns) indicate that two liquid reagents were utilized in the carbonation reaction from the 1st to the 12th Dynasties, with vessel depictions remaining virtually unchanged for a millennium. Hypothetically, the Egyptians possessed 12% vinegar and knew how to utilize alum since early dynastic times (Fig. 11a–i); otherwise, the reactors could not have generated CO₂ on

the requisite industrial scale.

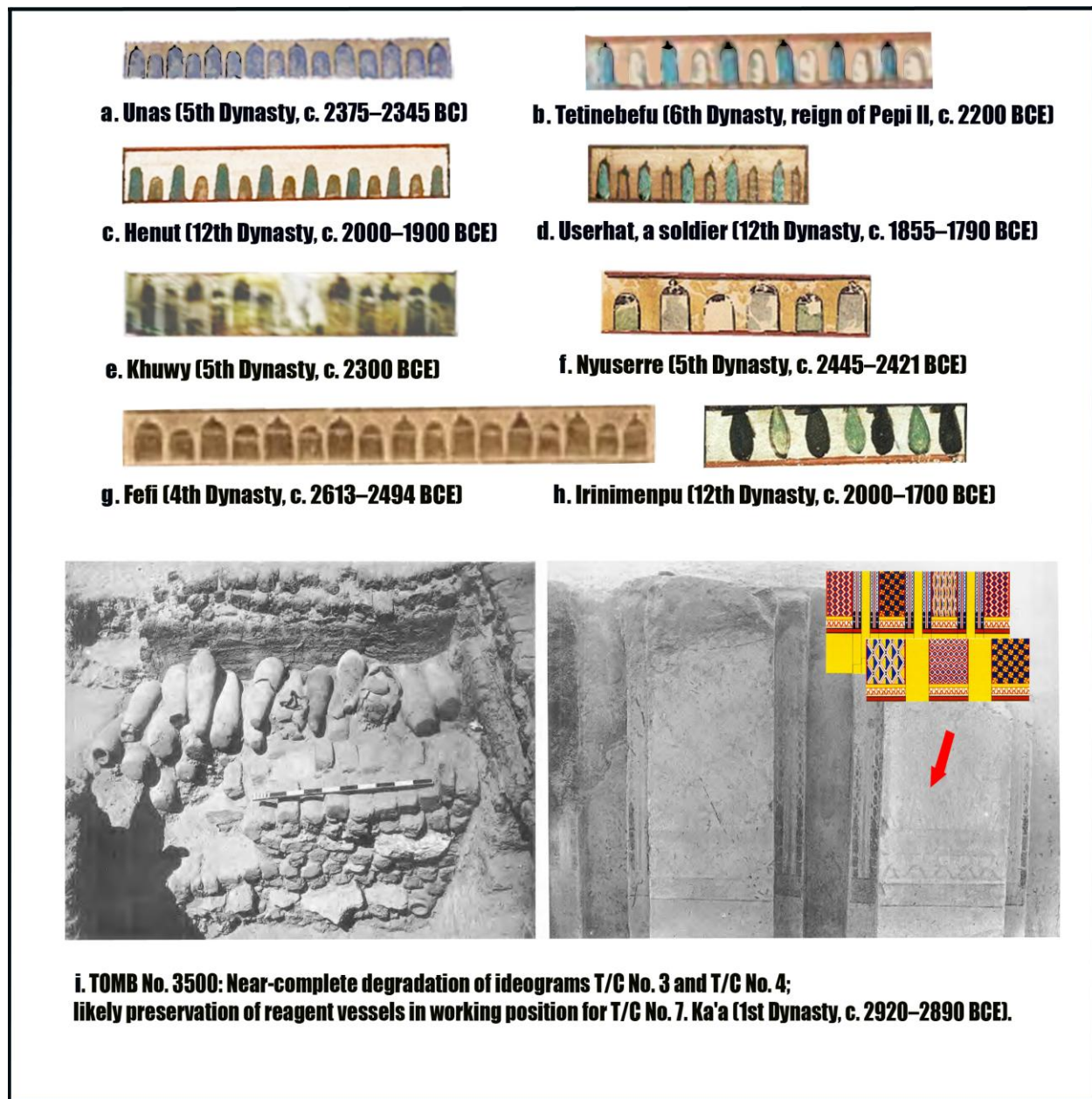


Fig. 11 For nearly a millennium, reactors (sarcophagi, tombs) featured panels mimicking reed mats, reagent vessel ideograms, or actual vessels. [17].

a. Unas (5th Dynasty c. 2613–2494 BC)

<https://www.youtube.com/watch?v=RYqEcj1ugL0&t=519s>

b. Tetinebefu (6th Dynasty, reign of Pepi II, c. 2200 BCE)

<https://eng.obozrevatel.com/section-news/news-a-magnificent-tomb-of-the-pharaohs->

doctor-was-discovered-in-egypt-photo-08-01-2025.html

c. Henut (late 11th – early 12th Dynasty, c. 2000–1900 BCE)

<https://www.bavarikon.de/object/bav:SMA-OBJ-00000BAV80011861?cq=&p=1&lang=de>

d. Userhat, a soldier (12th Dynasty, c. 1855–1790 BCE)

<https://garstangmuseum.wordpress.com/2014/09/02/the-texts-of-the-coffin-of-userhat-e-512/>

e. Khuwy (5th Dynasty, c. 2300 BCE) <https://edition.cnn.com/travel/article/egypt-paintings-color-scli-intl>

f. Nyuserre (5th Dynasty, c. 2445–2421 BCE) <https://digi.ub.uni-heidelberg.de/diglit/borchardt1907bd1>

g. Fefi (4th Dynasty, c. 2613–2494 BCE)

https://www.academia.edu/38900455/A_comparison_of_the_polychrome_geometric_patterns_painted_on_Egyptian_palace_fa%C3%A7ades_false_doors_with_potential_counterparts_in_Mesopotamia

h. Irinimenpu (12th Dynasty, c. 2000–1700 BCE)

<https://www.meisterdrucke.uk/fine-art-prints/Egyptian-12th-Dynasty/1450630/Panel-Detail-with-Apotropaic-Eyes-Surmounting-Closed-Door,-Symbolizing-Transition-to-Underworld,-from-Sarcophagus-of-Irinimenpu.html>

i. TOMB No. 3500: Near-complete degradation of ideograms T/C No. 3 and T/C No. 4; likely preservation of reagent vessels in working position for T/C No. 7. Ka'a (1st Dynasty, c. 2920–2890 BCE).

<https://ia903107.us.archive.org/4/items/EXCMEM47/47%20Walter%20B.%20Emery%20->

[%20Excavations%20at%20Saqqara%20Great%20tombs%20of%20the%20first%20dynasty%20III%20%281958%29%20LR.pdf](https://ia903107.us.archive.org/4/items/EXCMEM47/47%20Walter%20B.%20Emery%20-%20Excavations%20at%20Saqqara%20Great%20tombs%20of%20the%20first%20dynasty%20III%20%281958%29%20LR.pdf)

2. Ricke argued that the Heb-Sed court (in front of the chapels) was the location of timber-frame buildings with woven reed mats [12]. Alternatively, according to Verner, they occupied the sites of the chapels themselves before being replaced by stone dummies with false doors. However, the Djoser factory was constructed as a basin with a regulated water level. This is evidenced by the 10-meter water-retaining walls, mooring fenders, imitation bitts (palisade) in the courtyards of the western chapels, semicircular entrance panels, and mooring fenders on the corners of the eastern chapels (Fig. 9g). Furthermore, the lower

steps of the staircases in front of the western chapels are rounded; this is done to prevent injury, as the corners are hidden by water [18, pp. 11, 13, 16, 17, 24, 30, 31, 32, 41]. The dummy structures within the Djoser complex hint at a cargo cult, likely dating to the New Kingdom, when the obsolete rudiments of the aquatic technological infrastructure were meticulously reproduced on a restored, dehydrated site a millennium later.

A hypothesis explaining this meticulousness naturally suggests itself. During 2778–2263 BC, when regular winter rains occurred in Egypt, the Djoser factory supplied fellahin fields with carbonated irrigation water, increasing crop yields. In the winter season, CO₂ entering the Nile Delta inevitably killed tons of fish and waterfowl. Consequently, an annual, free distribution of meat resources began in temples, keeping the population well-fed. However, when the rainy period abruptly ended, the technology became obsolete, though prosperity remained in the collective memory. Therefore, in subsequent centuries, the old ruins of the factory-basin were likely restored with a religious rather than technological focus. Only this explains the perfectionism in reconstructing minor architectural forms and even filling new buildings with technical debris—local limestone rubble [18, p. 11]. Nonetheless, this proved to be a "good" restoration, meticulously reconstructing the visual layout. The factory-basin of the Djoser complex thus transformed into a terrestrial religious complex, an imitation that survives in ruins today.

Therefore, it is highly probable that during the reign of Djoser, the timber-frame structures made of mats (with pillars of types A and B) were located outside the territory of Djoser's Step Pyramid Complex. These lightweight timber-frame structures with woven reed mats, which functioned as freestanding display panels, could have been erected within the forecourts of the entrance gateway or affixed directly to the exterior Temenos walls to orient trade dispatchers and exchange agents arriving via the Nile from all over Egypt. These elements served as a visual operational protocol for the application and dosage of the supplied chemical agents.

The presence of a vast number of "dummy" buildings can only be explained by understanding their former, non-religious function. First, they could have functioned as a counterweight over the underground reactors. For instance, the Dummy Magazine / Dummy Store-room [18, p. 65] might have served as a weight over the shafts where water could be carbonated under high pressure by Djoser's predecessors using the Gisir el-Mudir dam [19]. Indeed, the building's contour strictly aligns with the contour of the underground shafts. Second, some could have been containers for refining natron, which was subsequently utilized in the reactor shaft beneath the Djoser pyramid. Carbonating water within the chapels themselves is impossible due to the inability to generate pressure there. Conversely, within the Central Underground Shaft, pressure could be generated to carbonate water, discharging it into the Nile via a channel (Fig. 9f).

3. T/C No. 9 (Djed)

Figures 7b, c, and e depict sarcophagi with icons featuring a double image of the Djed pillar. According to the ideograms, pillars of chemical/technological elements were located inside the wooden sarcophagi. Within all buildings of the Djoser Complex, vast mounds (pillars) of chemical elements must have also been stacked. The South Tomb Superstructure depicts numerous Djed pillars, resembling a storehouse (Fig. 12a). Therefore, the Djed pillar itself is likely a pillar of chemical elements, with CO_2 as its reaction product (Hypothesis). Even the ropes wrapped around the sarcophagus-reactor to maintain pressure are reflected in the Djed symbol (Fig. 12b) (M-22) . Although, to maintain pressure, an Anubis figure additionally lay on top.



Fig. 12 a: Hypothetically, Temple T could have functioned as the primary assembly shop of the Djoser factory, where ready-made sets of Type-A and Type-B cassette columns were assembled for the pyramid reactor and external customers. Architectural details of Temple T within the Djoser complex. Adapted from Hamilton K., Djoser's Step Pyramid Complex (Part 3), 2024, pp. 32–37. b : Polychrome Djed column from the tomb of Nefertari (QV66, column 1, north side). Image of Amigos del antiguo Egipto (available at: https://amigosdelantiguoegipto.com/?page_id=22057). c: Schematic representation of the *Shen-ring* motif located below the Udjat-eyes. Drawing by the author, adapted from the outer coffin of Khnumhotep (The Metropolitan Museum of Art, New York, Acc. No. 12.182.131a, b). d: Purification ritual depicting a stream of *ankh* hieroglyphs. Adapted from the Cornice Block from Philae (The Metropolitan Museum of Art, New York, Acc. No. 12.182.2), <https://www.metmuseum.org/art/collection/search/547283>. e: False door to the realm of the dead. Detail from the limestone sarcophagus of Queen Kawit (Egyptian Museum, Cairo, JE 47397), <https://curiosidadesartehistoria.wordpress.com/2024/02/09/amntenofre-palace-facade-with-the-central-doors/>

4. The initial evidence of mass CO₂ utilization by ancient Egyptians is identified at the onset of the First Dynasty. This is indirectly linked to the emergence of the first high-legged beds among the nobility and wooden headrests among poor fellahin [20]. Since CO₂ gas is 1.53 times heavier than air, it flows along the ground and accumulates in depressions. Being invisible and odorless to humans, it required detection methods. Such methods could involve keeping insects and reptiles nearby. The snake appearing on royal crowns was not accidental but a necessity to timely perceive the approaching dangerous gas (Hypothesis).

Meanwhile, ordinary fellahin could carry common scorpions in a Pocket-sized box . Probably, the historical emergence of the Scorpion King's name carries practical significance, and anyone handling snakes required a snake catcher's stick. This likely gave rise to the was-scepter as a symbol of power.(Hypothesis)(M-23).

The surface of the wooden reactor features the *Shen* ring sign. Based on its location, this represents a CO₂ gas bubble—a product of the chemical reaction. In mythology, this sign denotes the atmosphere of the Realm of the Dead (Hypothesis). (Fig. 12 c)(M-24)

6. The Ankh sign (the symbol of life ♀) — further signifies carbonated water (Hypothesis). (Fig. 12 d)

7. The false door, which religiously signifies the gateway to the Realm of the Dead,

actually denotes a space where a chemical reaction occurs under pressure, generating CO₂ (Hypothesis) (Fig. 12 e) (M-25)

8. The mass agricultural application of CO₂ technology initially led to increased crop yields, subsequently to the emergence of the first dynastic states in Southern Egypt, and eventually to unification into a single state with Northern Egypt (Hypothesis; directions for future research).

Supplementary Note 1: Stoichiometric Modeling and Material Balances of the Non-Organic Gas Generation Unit (The Unas Core)

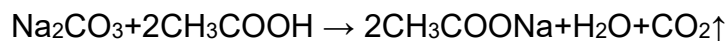
Section S1.1. Methodological framework, chemical pathways, and volumetric gas yield calculations for the 0.833 m³ reactor. [7]

To evaluate the operational limits and gas-production efficiency of the internal volume of the Unas sarcophagus (strictly constrained to a total inner volume of 0.833 m³ [7], or 833 liters), a multi-component stoichiometric model was developed. This model bypasses the thermodynamic limitations of open-air organic acid concentration by utilizing mineral-driven proton augmentation (hydrolysis), which is historically consistent with Old Kingdom resource capabilities. [15]

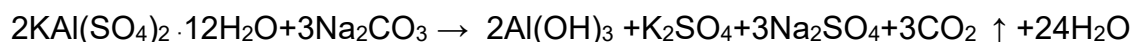
The reaction matrix is composed of three interconnected phases: a liquid vehicle consisting of 412 liters of 12% aqueous acetic acid (CH₃COOH, estimated solution density $\rho = 1.015$ kg/L), a primary mineral proton booster consisting of 494 kg of potassium alum (KAl(SO₄)₂ · 12H₂O), and a condensed alkaline core consisting of 210 kg of anhydrous sodium carbonate (Na₂CO₃) encapsulated within a high-density papyrus composite matrix.

The chemical decomposition of the carbonate core occurs via two parallel, competing stoichiometric pathways:

Pathway 1 (Carboxylic Neutralization):



Pathway 2 (Acidic Sulfate Hydrolysis):



Stoichiometric Balance and Mass Allocation

1. Total Available Carbonate Substrate: The 210 kg mass of Na_2CO_3 (molar mass: 105.99 g/mol) yields a total substance amount of exactly 1981.32 moles of carbonate ions.
2. Acidic Capacity of the Liquid Vehicle: The 412 liters of 12% solution contain 50,18 kg of pure, unassociated CH_3COOH (molar mass: 60.05 g/mol), equivalent to 835.66 moles of monobasic acid. According to Pathway 1, this volume completely neutralizes 417.83 moles of the sodium carbonate substrate, generating 417.83 moles of CO_2 gas.
3. Acidic Capacity of the Mineral Booster: The remaining unreacted carbonate substrate equals 1563.49 moles. The 494 kg charge of dodecahydrate potassium alum (molar mass: 474.39 g/mol) provides 1041.34 moles of aluminum ions. Operating under a 2:3 stoichiometric ratio (Pathway 2), the alum possesses a maximum neutralization capacity of 1562.01 moles of carbonate.

The combined proton-donating capacity of the system (835,66 mol from CH_3COOH and 3124.02 mol equivalent from alum hydrolysis) reaches a total of 3959.68 moles of H^+ , which is perfectly balanced against the 1981.32 moles of Na_2CO_3 requiring 3962.64 moles of H^+ for absolute decomposition. The system operates at a near-perfect stoichiometric equilibrium, leaving a negligible unreacted carbonate residue of approximately 0.16 kg at the base of the

Volumetric Gas Yield and Spatial Dynamics

The total accumulation of gaseous carbon dioxide CO_2 generated by both pathways equals 1979.84 moles.

Under Standard Temperature and Pressure (STP, 0 °C, 101.3 kPa), the molar volume of 22.414 L/mol dictates a net gas generation of 44.38 m³.

Under localized environmental conditions of the Saqqara plateau (assumed average operational temperature of +35 °C / 308.15 K), application of the ideal gas law yields an expanded gas volume of 50.06 m³.

Volumetric displacement analysis shows that the 500 liters of the liquid vehicle, combined with the structural volume of the fully dissolved 600 kg of alum and 255 kg of carbonate (accounting for ion contraction and chemical dissolution factors), results in a total fluid pulp volume of approximately 780–800 liters. This volume fits precisely within the 833-liter physical boundary of the Unas reactor, leaving a critical 4–6% headspace. This headspace prevents slurry overflow during the continuous, layer-by-layer erosion of the compressed papyrus blocks.

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Table

Appendix A. Final Comprehensive Research Methodology Classifier (M-Codes)

Section 1. Graphical and Descriptive Re-engineering of Process Mimic Diagrams)

M-Code: M-01, M-11, M-12, M-13, M-17, M-18, M-24, M-25.

Section 2. Hydrodynamic and Pneumatic Modeling of Multiphase Media)

M-Code: M-02, M-03, M-05, M-06, M-07, M-09, M-10, M-19.

Section 3. Chrono-Morphological Verification of Materials and Structural Parameters

M-Code: M-08, M-14, M-15, M-16, M-21, M-22.

Section 4. Landscape-Climatic Analysis and Anthro-Environmental Hazard Modeling

M-Code: M-04, M-20, M-23

Method Code	Expanded Methodology Title and Cross- Reference	Full Technical Definition and Application
M-01	Spatial-Layout Re-engineering / Spatial-Configuration Modeling	It translates the planar graphic schematics of the "palace facades" from the Hesy-Ra tomb (Third Dynasty) into three-dimensional models. The method correlates the shape, pitch, and depth of limestone or brick niches with the physical distribution, layered stacking, and movement trajectory of chemical ingredients within the active zone of the reactor.
M-02	Visual-Morphological Phase-State Mapping	It identifies the aggregation states of reagents based on sign geometry. Dense block stacking of segments encodes the solid-phase of dry stacks (Type A: T/C No. 1, No. 3, No. 4). Rounded, teardrop-shaped, or elongated markers encode the liquid-phase (liquid-dosing) and liquid fluid injection nodes (Type B: T/C No. 7).
M-03	Functional-Graphic Modeling of Hydraulic Cycles	It verifies reactor startup protocols using elevation marks and control valve symbols. Marker T/C No. 5 determines the hydrostatic flooding "liquid cap" level, marker T/C No. 7 fixes the dynamic droplet activator supply, and the upper component T/C No. 14 defines the pressurized autoclave's rigid clamping lid.
M-04	Topological Method for Spatial Phase Separation	It analyzes the spatial periodicity and barriers of multi-section cassette pillars (alternating Type A – Type B – Type A columns). The method qualifies the wooden partition markers T/C No. 8 and side support markers T/C No. 1 as physical phase boundary insulators, and the false door geometry as relief nozzle-diffusers for directional discharge of the evolved CO ₂ gas.
M-05	Morphological Analysis of Multiphase Flow Dynamics	It correlates the shape, fractional composition, and vertical orientation of signs with the physics of gas buoyancy in a liquid medium. Symmetrical vertical

		chains of cells (T/C No. 2) are interpreted as movement vectors of the dispersed gas phase (carbon dioxide bubbles) driven by the Archimedes force along exhaust gas vents.
M-06	Functional-Geometric Flow Clearance Analysis	It models the risks of packed bed choking and permeability loss during solid-phase degradation, logically justifying the necessity of a rigid wooden multichannel fluid-gas manifold. The end-face image (T/C No. 6) is examined as a cross-section of a tube bundle operating as a film countercurrent absorber (water down, gas up).
M-07	Functional-Colorimetric Analysis of Binary Fluid Streams	It verifies multi-component hydrodynamic systems based on vessel scale and color. The volume variance between the vessels (1.5:1) demonstrates stoichiometric control of proportions, while the polar stream separation (red and black wavy lines) is classified as pipeline color-coding to prevent premature fluid mixing.
M-08	Stratigraphic and Chronological Industrial Code Evolution	It investigates the end-to-end continuity of graphic signs from the Old to the Middle Kingdom (Khnumhotep reactor, Twelfth Dynasty). The application of longitudinal blue and red stripes onto the body of the wooden multichannel fluid-gas manifold (T/C No. 2) is verified as a dual-channel coaxial pipeline marking, demonstrating the stability of Egyptian technological standards across centuries.
M-09	End-Face Chromatic Analysis of Matrix Structures	It deciphers the cellular end-face distributors (T/C No. 6) from the Unas sarcophagus (Fifth Dynasty). The checkerboard alternation of blue and black segments in orthogonal projection is classified as a segmented injector matrix grid, where water supply channels (blue) alternated with partitions (black) as a nozzle body array.
M-10	End-to-End Colorimetric Verification of Countercurrent Flows	It analyzes the full spatial unfolding (end-face and side) of the wooden multichannel fluid-gas manifold from tomb S3121 in Saqqara (late First Dynasty). Coloring the countercurrent stream of the rising CO ₂ gas red (the color of the precursor acid) is classified as visualization of mass transfer, where the gas physically entrains fine reagent droplets.
M-11	Method of Orthogonal Projectional Component Unification	It utilizes the laws of descriptive geometry to demonstrate the structural identity of signs. The method establishes that T/C No. 2 (longitudinal side view of the multichannel manifold) and T/C No. 6

		(transverse end-face plan view of the multichannel manifold) represent multi-angle projections of the same physical node (combined manifold).
M-12	Method of Axonometric Unfolding and Spatial Reorientation	It compensates for the planar nature of the ancient Egyptian drafting canon. The method demonstrates that, due to the lack of axonometry, elements physically located on the upper horizontal level of the reactor (T/C No. 5, No. 6, No. 9, No. 10) were forced into the lateral vertical register on the drawing, and performs their reverse 3D reorientation onto the upper face.
M-13	Biochemical and Kinetic Re-engineering of Visual Markers	This method elevates the botanical symbol of crossed papyrus flowers to the status of a process technological marker. It justifies using adhesive polymeric papyrus sap and stalks as a framework element in the reactor, which supports and stabilizes the reaction for weeks and months.
M-14	Cross-Dynastic Chrono-Morphological Verification	It evaluates the corrosion resistance and barocentric parameters of casings from the First to the Thirteenth Dynasties. The utilization of wood demonstrates the absence of mineral acids and the application of organic vinegar, whereas the transition to thick-walled megaliths (the granite-basalt Unas sarcophagus) confirms increasing partial pressure and a transition to acid concentrate.
M-15	Structural-Topological Zoning and Phase Delimitation	It verifies the schematics' end-to-end linear indicator—the horizontal red boundary stripe (First to Thirteenth Dynasties)—as the structural project zero (datum line). The method qualifies the underlying void beneath it as a foundation bedplate supporting the vertical wooden multichannel fluid-gas manifold (T/C No. 2) or as a bottom sump for loading 20% of the soda volume.
M-16	Functional-Structural and Filtration Re-engineering of Soft Enclosures	In this concept, the pillars and textile ornaments of Hesi-Ra are interpreted as a spatial frame and porous semi-permeable membranes (filter layers). The woven mats created a flexible filter basket: they retained dry natron while allowing a flow of liquid vinegar and a continuous release of CO ₂ bubbles
M-17	Functional-Semiotic Mapping and Variational Analysis	It qualifies movable signs T/C No. 1–7 on Type B columns as industrial interface mimic diagram icons. Parameters are separated into basic invariants (T/C No. 10 and the default embedded power bitt—double Djed pillar T/C No. 9) and variable channels (T/C No. 11–12) changing color but not essence.

M-18	Method of Deviation Re-engineering and Vector Flow Verification	It uses single deviations ("scribe errors") within regular graphic canons as a source of dynamic data. A draftsman's error inside the Irimenetpi sarcophagus recorded a live vector of fluid droplets falling from jars through the T/C No. 3 choke directly behind the "false door" (into the active mixing zone), revealing a live technology.
M-19	Functional-Pneumatic Re-engineering and Closed-Circuit Modeling	It translates blocks of paired vessels with side arms (<i>henket</i>) into the class of gas-liquid displacement dispensers with negative feedback (a pneumatic feedback loop). The rising gas forced vinegar droplets through bottom nozzles; when the reaction intensity decreased, the system automatically terminated the supply without a single moving part.
M-20	Macro-Spatial and Climatic Re-engineering of Industrial Sites	The model simulates the landscape and environmental risks of the Djoser megacomplex (544.9 x 277.6 x 10 m). The method links the intense winter gas generation cycle at temperatures ranging from +7 to +9 °C with passive industrial safety: an avalanche-like release of CO ₂ gas from 28-meter shafts required the complete evacuation of people and the creation of a seasonal exclusion zone
M-21	Method of Functional-Morphological Bulk Massif Re-engineering	According to this interpretation, the regular rhomboidal mounds of T/C No. 4 within the Djoser complex, located behind the chapels and inside the granaries (<i>Scheinspeicher</i>), represent porous granular chemical materials. These mounds were constructed as industrial bunkers for the storage and reaction processing of natural natron.
M-22	Method of Functional-Typological Unification and Semantic Coding	It demonstrates the engineering identity between a small cassette-sarcophagus and a monumental Saqqara megalith based on the structural similarity principle. The method unifies the hieroglyph and the architectural Djed pillar as the technical name for a heavy-duty multichannel reaction core column generating gases under pressure.
M-23	Method of Anthropo-Environmental Re-engineering and Behavioral Modeling	It explains the emergence of early dynastic household standards (high beds, headrests) as passive protection from CO ₂ condensing on the ground. The method allows the identification of snakes (<i>urai</i> on crowns in the inhalation zone) and scorpions inside small cases as portable biosensors (early warning systems) for the first gas safety inspectors.

M-24	Iconographic analysis and spatial-semantic deconstruction of signs +Engineering-mnemonic re-engineering	Comprehensive iconographic analysis and spatial-semantic deconstruction of signs combined with engineering-mnemonic re-engineering of planar graphic markers on closed-circuit vessels. Traditional conceptualization of the symbol as the "air of the underworld" is functionally inverted to decode the physical accumulation and boundary location of the generated gas phase. Applied to Fig. 12 c to identify the Shen-ring ideogram as a process mimic marker representing a forming gas bubble (CO ₂) at the upper fluid-gas interface directly prior to pressure-driven discharge.
M-25	Architectural-iconographic re-engineering and spatial-functional stratification	Architectural-iconographic re-engineering and spatial-functional stratification of recessed monumental profiles. Sacral portals to the underworld are deconstructed as physical front-panel sealing assemblies, and the lethal "underworld environment" is mapped as a toxic, stagnant carbon dioxide gas zone. Applied to Early Dynastic and Old Kingdom structures to model the multi-recessed profile as a labyrinthine pressure-lock system that guarantees gas-tight containment and compensates for operational internal pressure.

Have you used or generated research data in this study?

Yes. I used or generated research data in this study.

Ethics declarations

Competing interests

The author declares no competing interests.

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