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Groat, N. (2025) Reappraising the Gandhāra still: implications for understanding early distillation technology through experimentation and experimental reconstruction. Archaeological and Anthropological Sciences, 17 (9). 194. ISSN: 1866-9557

https://doi.org/10.1007/s12520-025-02301-8

Archaeological and Anthropological Sciences (2025) 17:194
https://doi.org/10.1007/s12520-025-02301-8

RESEARCH

Reappraising the Gandhāra still: implications for understanding early distillation technology through experimentation and experimental reconstruction

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Received: 21 February 2025 / Accepted: 30 July 2025

Abstract
The use of experimentation within studies of early distillation technology has largely taken a methodological approach which aims to demonstrate how suggested technical evolutions and apparatus configurations operate. This paper examines the viability of the 'Gandhāra still' reconstruction for distillation within a unified campaign of comparative and exploratory experimentation, acting as a framework for critical evaluation. First generated from interpretations on the function of predominately 2nd c. BCE– 4th c. CE ceramic vessels found across South-Central Asia, the Gandhāra still has been a central component in the conceptualisation of an "ancient Indian distillation hypothesis" that has received considerable attention in the historiography of science. This uptake in interest has led to researchers from a variety of disciplinary backgrounds to reinforce the still's existence and distilling capacity, including through the use of experimentation. In response, this paper details a new campaign of experimental trials which identified functional reasons as to why the apparatus does not operate. Crucially, trials demonstrated how the interpreted set of apparatus components together cannot sufficiently condense produced distilling vapour due to their morphology. In tandem, the campaign revealed practical issues associated with internal reflux actions and pressurisation in the still that had not been identified previously. Further analysing such a pervasive dialogue on technical innovation invites wider re-evaluations of distillation technology chartings and introduces a nuanced suite of considerations in discussing the inception of early distillation.

Keywords Technology · Experimental archaeology · Distillation · Ceramic analysis · Pottery function · Morphology

Introduction

Distillation - a mode of selective separation of mixed miscible liquid components through evaporation and condensation - marks a significant change in human understandings of material composition and transformation. Applications of distillation methods are utilised in many contexts, including water purification, alcoholic spirits production, oil refinement, and perfume manufacture (see Forbes 1970). In charting its global development, the "Gandhāra still" has been positioned as a point of origin for distillation and an early distilling apparatus configuration, with roots in parts of modern Pakistan, Afghanistan, and northern India (South-Central Asia) (e.g., Allchin 1979b; Husain 1993; Mahdihassan 1972; Needham et al. 1980 pp. 85–87, Park 2021 pp. 27–29; 40–42) (Fig. 1). First conceptualised by Marshall (1951) from 2nd c. BCE excavated vessels from Pakistan in Sirkap, Taxila that he reassembled as a distillation apparatus, the reconstruction comprises a 'condenser' (later 'receiver', 'receiver-condenser', or 'distiller') connected by a tube to a 'still head' fitted over the top of a *handī* (cooking vessel acting as a still body), and stood on a tripod over a fire, heating it from a single point at the *handī* base (1951, p. 420) (Fig. 2a). Later iterations by Mahdihassan (1972), Allchin (1979a, b), and Husain (1980, 1993) extrapolated on the operation of the still, generating several reconstructions (Fig. 2b). Hence, dialogues on the development of technical innovations in the Indian subcontinent have centralised the Gandhāra still as a constituent of an "ancient Indian

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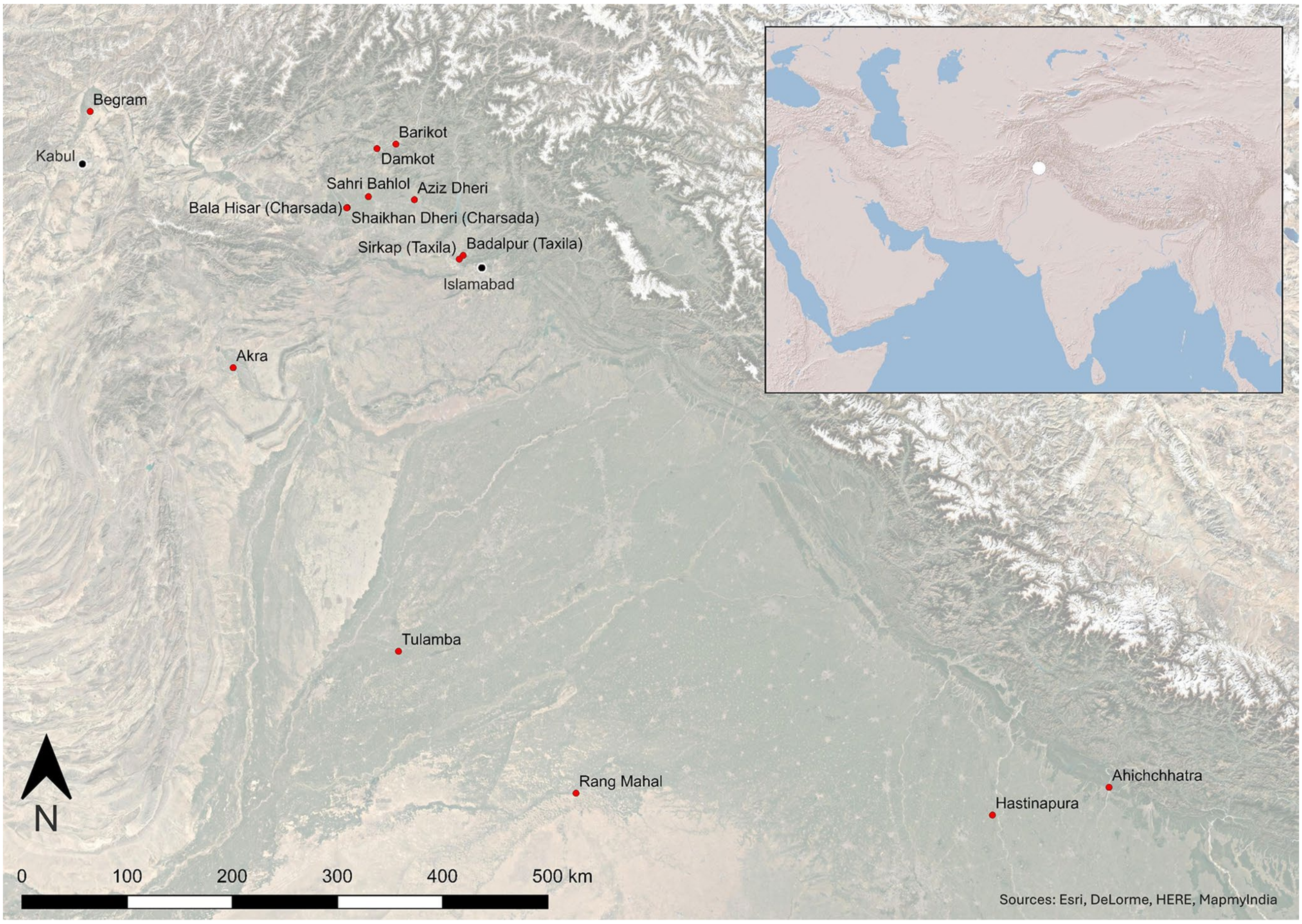


Fig. 1 Approximate reported extent of the "Gandhāra still" and sites with reported finds of apparatus components (map by the author, basemap data by Esri; Copyright © ESRI (UK) Limited 2025)

distillation tradition", seen to have emerged from a nexus of East Asian and Western European cultural influences (Needham et al. 1980 pp. 85–87). Ethnographic evidence and experimentation have been introduced to support the still's viability and provide seemingly conclusive examples of the apparatus in action - a demonstration of how the still operated and empirical dataset to illustrate its functional capacity, thus mitigating for issues in archaeological representation (e.g.Mahdihassan 1972; Allchin 1979a, b; Butler and Needham 1980). Subsequent attempts to identify component parts across the region sought to justify the still's prolificness (e.g., Allchin 1979b), introducing explanations of how the distillation tradition became embedded in long-term sociocultural changes, including religion, language, and hybridisation of alcohol practices (e.g., Brancaccio and Liu 2009; Park 2021). In consequence, stadial, evolutionary, and diffusionist ideas on distillation change have embellished the notion that branches of distillation technology followed a logical developmental growth pattern.

Previous studies, therefore, often set out to methodologically prove, rather than critique, the Gandhāra still reconstruction based on its original conceptualisation in the 1950s - a commitment exemplified by the still's extensive citing in secondary literature that has entrenched "ancient Indian distillation" as a reality without comprehensive critical oversight (see McHugh 2020 for analysis). In contrast, recent detailed criticisms have systematically challenged the still's material foundation, contesting its plausibility (e.g., McHugh 2014; 2020; Groat 2024; 2025). Evaluations demonstrated how the reconstruction had derived from typological assumptions, broad vessel characterisations, and modern optimised models of distillation that had been projected onto a series of incongruent archaeological remains. Such a body of analysis confidently showed why the selected original materials used in the reconstruction together were unlikely to be a still. Hence, discussions on component morphologies, material properties, and suggested heating and cooling methods (which implicate distillation ability) are needed to unify archaeological and functional critiques. Instead, relying on its expected functional capacity has helped perpetuate the Gandhāra still as a plausible interpretation, going

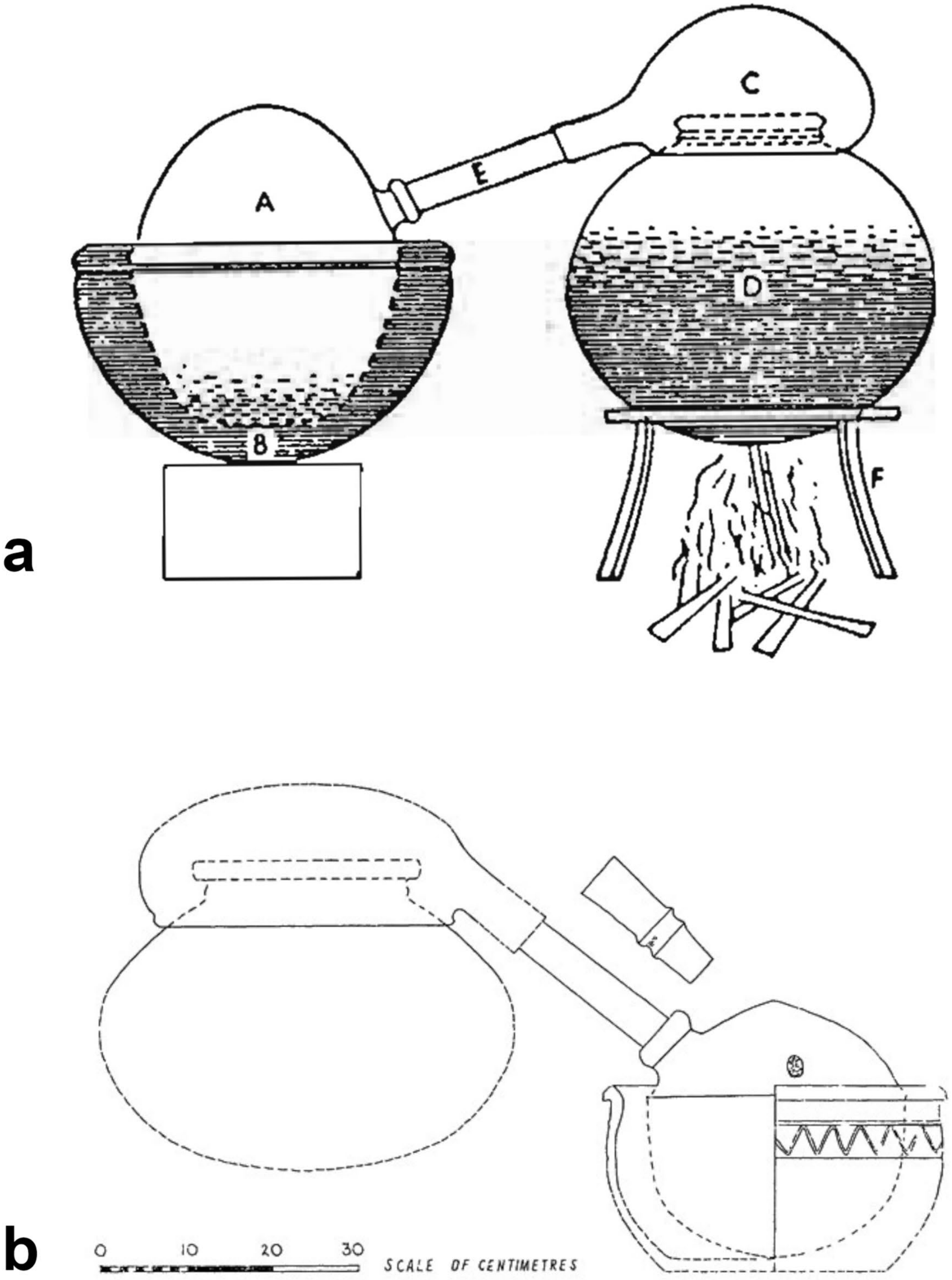


Fig. 2 Reconstructions of the Gandhāra still: (**a**) Marshall's original "water condensing unit" from Sirkap, Taxila (1951, pl. 125); (**b**) Allchin's reconstruction from Shaikhān Dherī, Charsada (1979b, p. 60). Drawings used under a UK Copyright Exception

beyond being a theory or suggestion, and positioning it as an established technological innovation.

In response, this paper details a campaign of experimentation that acts as a critical framework for addressing the functionality of the Gandhāra still and plausibility of the configuration morphology as an early apparatus form comprising the “ancient Indian branch” of distillation technology. Based on the reconstruction created by Marshall (1951), and following suggestions for its use, operation, and distilling capacity by later authors, the experiments ascertain the limits of such an interpretation, rather than attempt to explain how the configuration could function with alternative suitable amendments. Such an approach compliments the body of existing critical evaluation identifying how select archaeological finds from the region had been optimistically reconstructed as a complete still, despite inherent issues with the material. Instead, through offering a more robust assessment alongside archaeological critiques, a rounded approach to reconstruction is utilised that unifies comparative replication and exploratory practical engagement to identify issues within specific functional parameters associated with distillation operation. This refined version of experimental reconstruction generates essential insights central to understanding processes involved in early distillation technology and helps further a holistic criticism of its history.

Background

Decades of chemical research have led to an acute interest in the origins of distillation from a modern understanding of chemical processes, emphasising questions of apparatus efficiency and efficacy (e.g., Egloff and Lowry 1930; Kockmann 2014). Within a still configuration, distillation is realised through the selective boiling of a mixture (the *distilland*) and condensation of its vapours (creating *distillates*). Exploiting the relative volatility of components and temperatures at which different substances will turn to vapour allows the separation of liquids from non-volatile solids and multiple liquids with different boiling points, such as in alcohol distillation, where ethanol boils at a much lower temperature (78.23 ± 0.09 °C) than water (e.g., Gwei-Djen et al. 1972). Temperature differences between the distilland and area in which it condenses must be great enough for vapour to move from a hotter to a cooler, and higher to lower pressure, environment (Stichlmair et al. 2021). Failure to do so results in a reflux action in which vapour condenses in the incorrect area of the still and returns to the distilling vessel. Hence, when the rate of the vaporisation and condensation processes are the same, a point of equilibrium is maintained, dependent on the temperature and the quantity of the liquid and vapour (Stichlmair et al. 2021). Integral to the rate of distillation, consistent heat sources, condensing methods, and still material properties influence rates of heating and cooling within distillation apparatuses. Likewise, boiling temperatures of distilland mixtures and the use of direct or indirect methods of apparatus heating directly affects rates of pressure build-up. This influences the degree of mechanical and thermal stress upon the apparatus and its constituent parts (e.g., ethanol-water mixtures versus only water). Distillation processes are, therefore, highly sensitive and require achieving precise physical conditions during operation, whereby apparatus functionality (and success) is dependent on each apparatus component’s shape and volume, its points of articulation, and how they join.

Despite the sensitivity of distillation, such functional concerns are rarely discussed in accounts and interpretations of the Gandhāra still. Detailed histories and critiques of the reconstruction are set out elsewhere (McHugh 2020; Groat 2025); in summary, Marshall’s first ‘reassembling’ of disparate pottery components at Sirkap into a reconstructed still proposed it was a distillation system used for condensing water, offering a short explanation of how his select vessels collectively worked as an apparatus (1951, p. 420). Derived from a suggested function of his ‘water condenser’ typological class, his reconstruction was presented as a model drawing based on archaeological illustrations of vessels, projecting modern representations of distillation configurations onto his selected artefacts (see McHugh 2020; Groat 2025 for analysis). This was done, however, irrespective of the geometry, proportions, and dimensions of individual components, or whether their thermal properties were suitable for his proposed use. Subsequent versions of the Gandhāra still reconstructed by Allchin based on materials from Shaikhān Dherī (1979a; 1979b) sought to expand the apparatus’ visibility, presenting a typological evolution of the ‘receiver-condenser’ (renaming Marshall’s ‘water condenser’). However, many of Allchin’s characterised components were significantly different, morphologically and geometrically, from Marshall’s (notably still heads, condensing tubes, and receiver-condensers), generalising the suggested function of other vessels to fit within a hypothetical configuration (see Groat 2025). In addition, information on the material properties of these components, which would directly implicate apparatus performance, is limited. Pottery fabrics of vessels noted in the Taxila reconstruction by Marshall vary greatly and cannot be corroborated with his reconstruction drawing. Hussain’s more thorough pottery studies from Shaikhān Dherī (1980; 1990; 1992) provided some impressions on physical properties, describing receiver-condensers as made from “rough pinkish-buff sandy micaceous clay” to help promote cooling (Husain 1980, p. 140). This manufacturing choice was also noted by Allchin adding that coarse sand applied to the vessels before firing would increase porosity and therefore cooling ability (1979a p. 769). Complete understandings of porosity and thermal insulation characteristics of individual apparatus components, however, cannot be determined from such descriptions.

Aside from the archaeological vessels themselves, little attention has been given throughout the history of the Gandhāra still on other operational factors that affect distillation functionality. Marshall offered few details on how his apparatus would be sealed, heated, and cooled (beyond sitting the vessel in a basin of water). Based on archaeological evidence from their respective sites, direct methods of heating were proposed by both Marshall - using a tripod and open fire (1951, p. 420) - and Allchin - a fire-lit hearth (1979a p. 774). However, these suggestions were limited to brief explanations and did not address the impact such heating methods would have on the functionality of the complete system. Equally pivotal, sealant materials for joining components in the configuration were not elaborated on. Instead, ethnographic accounts were used to fill gaps in the archaeological evidence. In later additions to the reconstruction, Allchin suggested the use of clay as a sealant and use of wet cloths to promote cooling along the tube and still head (1979b p.56). These ideas originated from the assumption that distillation was practiced in South Asia for thousands of years, based on the belief that "primitive people" were distilling with an apparatus bearing some resemblance to the reconstructed configuration that stemmed from an ethnographic study published in 1943 (Allchin 1979a, pp. 783–784). While potentially similar in function and shape, Allchin's connection between the still's supposed archaeological representation and ethnographic account was conjectural. As an application of ethnographic data through logicisms and middle-range theories to contrast 'modern' practices (see Gosselain 2016 for analysis), this connection did not demonstrate clear morphological links between Allchin's selected archaeological and contemporary examples to justify a continued tradition of use from a supposed 'ancient' still.

However, from technical backgrounds and contemporary understandings, the Gandhāra still has been considered legitimate through experimentation to support the validity of the reconstruction. As part of Joseph Needham's *"Science and Civilization in China"* series, the Gandhāra still was included as a distillation tradition with ancient 'Chinese', 'Hellenistic', and 'Mongolian' antecedents (see Needham et al. 1980). Here, a specific form of "retort with cooled receiver deriving from the Gandhāran tradition" was presented within his evolutionary tree of distillation (Needham et al. 1980, Fig. 1454i). Emphasising morphological changes in stills as observed in archaeological and textual depictions, Needham, along with Anthony Butler, undertook a series of experiments demonstrating the capacity of several proposed early stills (Butler and Needham 1980). Using glass working models of apparatus 'basic forms', acetic acid-water (10% wt/wt, 50 ml) and ethanol-water (46% wt/wt ethanol, 50 ml) mixtures were distilled (Butler and Needham 1980, pp. 71–72), concluding in statements on the efficiency and condensing ability of the "simple still". Scaled-down glass components, a series of taps and controlled water flows, and fixed-setting electric mantel underpinned a version of experimental reconstruction to confirm the hypothesis, but derived from optimal models in a controlled laboratory setting, and eschewing variability. Accordingly, Butler and Needham's study applied experimentation to ultimately confirm the "ancient Indian hypothesis" and demonstrate its place in the development of distillation. Such an approach, despite fitting neatly within the protocols of the laboratory, does not mirror the material and practical basis of the interpretation. This is especially true when evaluating archaeological remains of chemical technologies and accounting for their paucity of final products.

Refined campaigns of experimentation, building on insights from previous trials, are, therefore, necessary to establish the validity of the Gandhāra still, including considerations of heat sources, cooling methods, influence of ceramic vessel properties, and the functionality of a complete configuration. The potentially limitless number of variables that affect distillation operation, and increases due to the heterogeneous nature of craft practices, means direct replication of an apparatus from a historical standpoint is somewhat unworkable. Instead, framing experimentation as an evaluative framework that gradually reveals a series of functional parameters surrounding the Gandhāra still enables issues with the reconstruction to be identified. This utilises and unifies insights generated from controlled conditions (i.e. laboratory) and more 'authentic' settings where the apparatus might be used, generated from historical information. Thus, the evaluative process would not replicate a specific form of distillation (e.g., alcohol) but rather detail a series of practical, technical, and material concerns surrounding the Gandhāra apparatus reconstruction.

Methodological approach

The experimental reconstruction was divided into two sets to identify areas of weakness within the Gandhāra still interpretation (see Table 1). Several techniques and practical concerns were explored using a reconstructed ceramic Gandhāra still and different heating, cooling, and condensing methods to better approximate the original conditions of the apparatus in both controlled and 'historically appropriate' settings. Alcohol distillation is another suggested use for the reconstructed apparatus (e.g., Allchin 1979a; Hussain 1993), though water was used as the tested distilland following Marshall's original proposed function of the

Table 1 Summary of experimental sets

Set	Heat source; location	Run / trial no.	Heat source mean (°C)	Cooling / condensing strategy	Run time (mins)	Start / end water distilland (ml)	Collected distillate (ml)
Comparative (lab-based)	Hotplate; base	2000 ml (Run 1)	261.5	Regulated condensing tube cooling; all components sealed	240	2000 / 563	0
		4000 ml (Run 2)	234.1		240	4000 / 2477	9
		6000 ml (Run 3)	274.1		240	6000 / 4490	3
Exploratory (outside)	Rock hearth fire; base/lower-body	1	510.4	Condensing tube cooling; all components sealed	120	4000 / 2750	0
	Clay hearth fire; base/lower-body	2	561.4	Condensing tube/basin cooling; all components sealed	60	4000 / 2850	146
		3	509.2	Condensing tube/basin cooling; still body, head, and tube sealed, receiver not sealed	60	4000 / 2910	0
		4	365.7		120	4000 / 2010	0
	Rock hearth fire; base/lower-body	5	320.1		60	4000 / 2950	3
		6	502.9		180	4000 / 1010	16

characteristic 'water condenser' (1951, p. 420) and due to its historical relevance in early distillation practices (see Forbes 1970). Lower-boiling distillands (such as water-ethanol mixtures) would affect apparatus operation and potentially success. However, using water in this context allowed for practical considerations on use to emerge (e.g., the implications of a fire-lit hearth on heat retention properties) while putting the apparatus through different levels of thermal and mechanical stress during a single run and wider temperature range (up to 100 °C). These conditions would also be experienced in lower-boiling distillations to an extent (i.e., achieving 78.23 ± 0.09 °C for ethanol) and so are contextually relevant, but accounts for the potential of successful evaporation-condensation or full distillation to occur before water reaches boiling. Equally, due to the flammability and combustibility of ethanol, using water created a more controlled testing environment, considering the unpredictability of a reconstructed apparatus for ethanol distillation. Practical observations could then be directly related to specific items of evidence or suggested components of the configuration that had been introduced into the reconstructed iterations of the Gandhāra still.

By varying distilland volumes, heating and cooling methods, and run times, specific issues with the apparatus were identified. Temperatures of components were continually measured through both sets to provide insights on heat exchange, retention, and rates of heating and cooling within the configuration. As multiple repetitions of each individual experiment were not done, the campaign would not conclusively prove apparatus functionality. Instead, it would recognise a suite of issues with the reconstruction and directly address specific variables affecting distillation ability, alleviating issues with data reliability. Variable conditions then contextualises the evaluation of the reconstruction within questions of actualisation, or the reality of using the apparatus, and accepting certain conditions of control in experimentation. Together, the total number of runs provided a comprehensive dataset to inform a detailed critique of the functional properties of the apparatus and establish certain key features required to distil.

Experiments took place at the University of Sheffield Department of Archaeology's Material Science Laboratory (April 2019–July 2019 for apparatus creation, September 2019–September 2020 for comparative trials) and at Beauchief Abbey, Sheffield (May 2021–May 2022 for exploratory trials). First, a comparative set of water distillation trials was undertaken based on Marshall's (1951) reconstruction in a controlled laboratory environment. Using differing water volumes and fixed run times, functional parameters were identified connected to heating and condensing methods. A second exploratory set was conducted outdoors using a hearth, more closely resembling the original setting of the Gandhāra apparatus and taking into consideration identified weaknesses and adopting suggestions on distilling practice. Run times were adjusted to refine the distillation method and more securely identify influencing factors. This was deemed suitable to adequately determine heating and heat retention properties of the apparatus, allowing different factors to be explored beyond testing one variable per trial.

Creating the apparatus

Apparatus components were made as 1:1 scale replicas where possible, based on Husain's pottery studies from Shaikhān Dherī (1980, 1990, 1992), using terracotta 20% sanded red clay (Potclays GVR20) and sand temper (B&Q calcite-free sharp sand, grain size ~ 0.2–0.63 mm) (see Table 2). Dimensions of the replicas were chosen to ensure a flush fit and increase the chances of successful distillation. This was done despite the variable geometries and lack of standardisation in the archaeological materials from Sirkap, and Shaikhān Dherī, where some components in the original

Table 2 Reconstructed vessel properties

Vessel	Mass of clay used (kg) (approx.)	Dimensions (cm)	Volume (ml) (approx., as spherical bowl)	Drying time	Firing duration and temperature
Still body	7	19 cm wide (at rim), 31.4 cm (at shoulder), 30 cm deep, 1.6 cm wall thickness	Maximum capacity to rim of 13,200 ml	7 days	1. Increase 100 °C every hour until reaching 600 °C 2. Increase 200 °C every hour until reaching 1050 °C 3. One hour stabilisation period 4. Natural cooling period
Still head (body) (1)	4	21 cm wide, 10 cm deep, 0.6 cm wall thickness	2256 ml		
Still head (body) (2)	5	25 cm wide, 13 cm deep, 1.5 cm wall thickness	4342 ml		
Still head (body) (3)	5	25 cm wide, 16 cm deep, 1.5 cm wall thickness	6072 ml		
Still head (spout) (1)	0.5	5 cm wide, 14 cm length (cut down to 7 cm), 1.3 cm wall thickness	Min. internal surface area approx. 149 cm^2		
Still head (spout) (2)	0.5	5 cm wide, 14 cm length (cut down to 7 cm), 1.3 cm wall thickness	Min. internal surface area approx. 149 cm^2		
Still head (spout) (3)	0.5	5 cm wide, 14 cm length (cut down to 7 cm), 1.3 cm wall thickness	Min. internal surface area approx. 149 cm^2		
Still head (spout) (4)	0.5	5 cm wide, 14 cm length (cut down to 7 cm), 1.3 cm wall thickness	Min. internal surface area approx. 149 cm^2		
Still head (spout) (5)	0.5	5 cm wide, 14 cm length (cut down to 7 cm), 1.3 cm wall thickness	Min. internal surface area approx. 149 cm^2		
Still head (spout) (6)	0.5	5 cm wide, 14 cm length (cut down to 7 cm), 1.3 cm wall thickness	Min. internal surface area approx. 149 cm^2		
Condensing tube	0.5	4.8–3.5 cm wide, 15 cm length, 1.2 cm wall thickness	Min. internal surface area approx. 184 cm^2		
Receiver (1)	5	Failed thrown vessel	Unknown		
Scaled receiver (2)	5	17.5 cm wide, 22 cm deep, 1.1 cm wall thickness	8222 ml		
Basin	Unknown (repurposed vessel)	32 cm wide, 27 cm deep, 1.5 cm wall thickness	21,164 ml	Unknown (repurposed vessel)	Unknown (repurposed vessel)

reconstructions were unlikely have a full articulating and flush fit (i.e. between suggested condensing tubes and still heads). Approximate vessel volumes and surface areas were calculated assuming consistent shapes:

1. Still body: made in two parts with the same capacity as those in the original reconstructed apparatuses. A large water pot similar to suggested *handi* vessels was created in two sections with a level base ensuring a stable and flush alignment with a heat source.
2. Receiver-condenser: modelled on later examples from Shaikhān Dherī as the most complete typology in comparison to earlier forms (see Allchin 1979a; Husain 1993). Originally made to scale in two sections following archaeological methods, though reduced to 1:2 scale due to structural issues. The receiver spout was made separately and attached after.
3. Still head: Multiple attempts were required to achieve the correct shape, due to its drastic wall and rim incline. The final form was thrown with a less severe inward curvature at the rim (approximately 20°). Because of the delicate fabric of the still head, a flat exterior base was produced on the final form. This, theoretically, would not affect distillation operation as the interior of the vessel was concave, allowing distillate to run down the interior sides.
4. Condensing tube: hand built as a ‘standardised’ ceramic tube as archaeological examples vary in morphology (see Groat 2025). The inconsistent morphology of the still head and receiver spouts would require individually unique condensing tubes, hence creating a tube to fit two differing spouts perfectly was challenging. The replica was made without external flanges and features exhibited on the examples so that the ceramic tube could be adapted depending on the needs of the experiment.
5. Basin: recycled experimental vessel to hold the receiver.

Comparative distillation experiments

Three trials using 2000, 4000, and 6000 ml distilland volumes evaluated the reconstructed apparatus’ distillation performance (Fig. 3). Each volume was expected to produce sufficient distillate for measurement, but also significantly fill the receiver-condensers following the calculated capacity of archaeological examples (see Allchin 1979a p. 772). Using a range of volumes enabled different functional parameters affected by still capacity to be explored, including a lower partial load (2000 ml) that allowed for

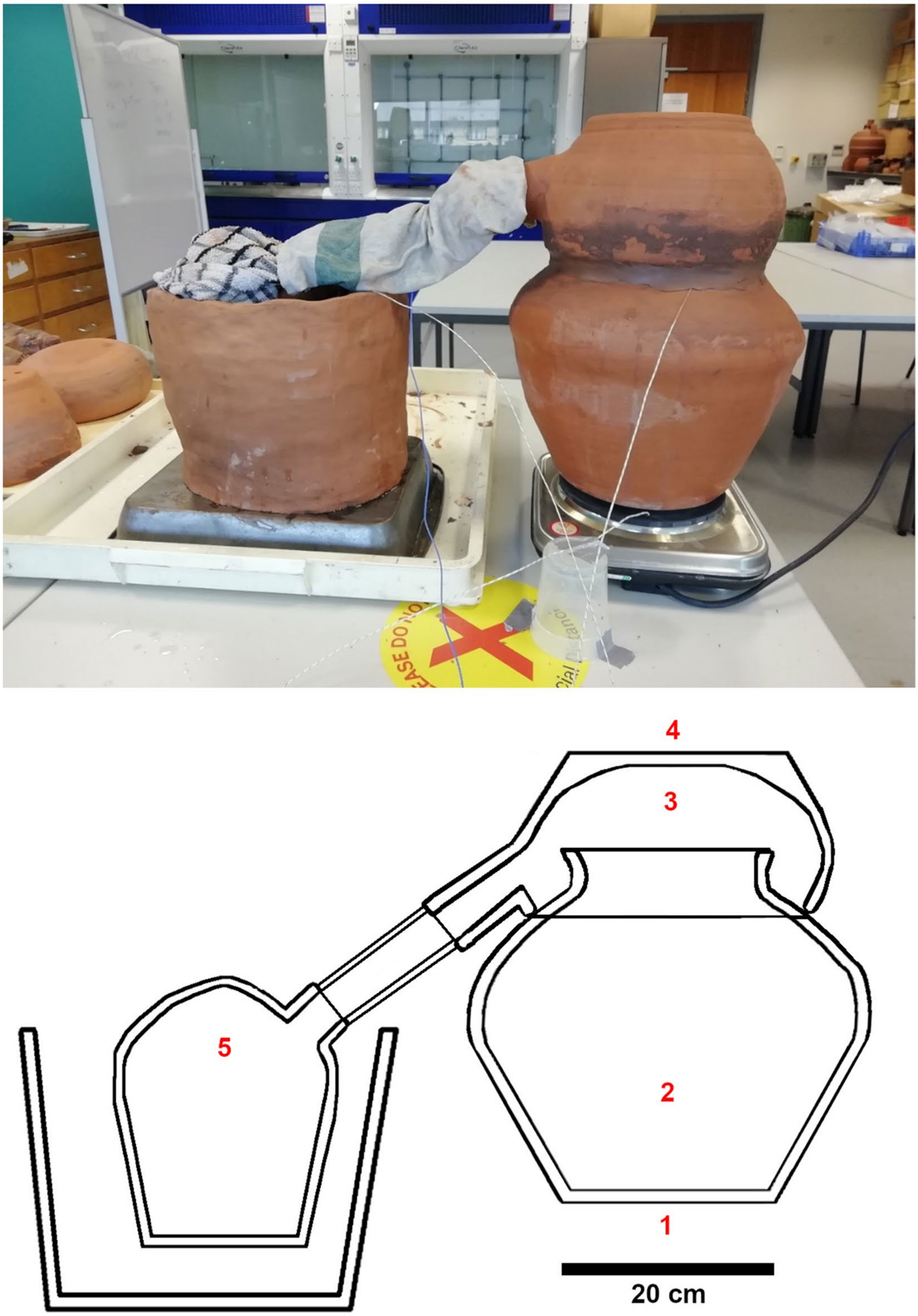


Fig. 3 Apparatus in use during the comparative experiments (4000 and 6000 ml runs) and technical drawing of apparatus with thermocouple locations: (1) heat source, (2) distilland, (3) condensing area, (4) condenser (2000 ml run), (5) receiver (4000 and 6000 ml runs). Photograph and drawing by the author

a more rapid response of the apparatus. Before operation, the apparatus was soaked in water for 20 min to saturate the fabric and help contain liquids. The still body was filled with the relevant distilland volume and the cavity between the body and the still head was sealed with clay. Each run lasted for four hours with a one-hour cooldown, allowing for familiarisation with the configuration, troubleshooting, and to develop impressions on heating and cooling abilities. Temperatures of the condenser, condensing chamber environment (condensing area), heat source, and distilland were measured using Thermosense TW-KF3-1000 K-type fiberglass insulated welded-tip thermocouples (temperature range 0–400 °C ± 0.75% T) connected to a HH-520 thermocouple data logger taking readings at 2 s intervals. Apparatus heating was maintained by a Lloytron E831SS hotplate (max. 250 °C under load), starting from its 'off' position and set to its maximum power (1500 W), to simulate the single point of direct heating exhibited in the original reconstructions (see Fig. 2). Seals showing breakage were repaired during the runs. Temperature recording continued through cooldown to analyse heat retention. Distillate and remaining distilland were measured after each run.

Two still cooling methods ('condenser') were used based on Allchin's reconstruction (1979a, pp. 773; 784). The 2000 ml run tested the distillation ability of the apparatus using still head cooling through changing a cold soaked cloth every 15 min on top of the still head and the water bath was manually topped up with water until reaching capacity. For the 4000 and 6000 ml runs, damp cloths were wrapped around the still head spout and tube, and placed on top of the receiver. With the receiver sitting in a basin of cold water, this configuration mirrored Marshall (1951) and Allchin's (1979a; Allchin 1979b) interpretations. Condenser temperatures were measured in the 2000 ml run directly on top of the still head and in the receiver in the 4000 and 6000 ml runs. Measuring the temperature of the condensing area inside the still in all runs provided a provisional level of comparability and repetition within each individual run. Instrumentation errors were noted as probes were not isolated and hotplate temperatures exceeded their tolerance, causing thermocouples to cease reading in the 4000 ml run, earlier than in the 2000 and 6000 ml runs. Temperature data was analysed using SPSS Statistics 26 (see Table 3); anomalous data points caused by instrumentation errors were excluded for statistical analysis.

Temperature data revealed performance issues, where distilland volume was directly influencing heating rates within the apparatus (Fig. 4). In the 2000 ml run, upon the distilland reaching 53.8 °C and the still head condensing area rising to 25.6 °C, damages to seals at articulation points between components were visible at 45 min and significant breakages were noted from 195 min. Condensed vapour was escaping through breaks in seals, suggesting that distillate was gathering in the channel created between the still body and still head, caused by inducing a reflux action at the top of the still rather than creating an adequately cool, lower pressure environment in the spout and tube. The trend repeated during the 4000 ml and 6000 ml runs with cooling directed onto the condensing tube and receiver. Though noted later than in the 2000 ml run, distillate was seen to be escaping at 135 min (4000 ml run) and 165 min (6000 ml run). Seals were repaired early on into each run, indicating that articulations were experiencing high amounts of stress irrespective of the condensing method used.

Changes between cooling cloths during the 2000 ml run were visible in condensing area temperatures (reaching a maximum of 50.8 °C at 01:59:26), promoting a lower mean (32.5 °C) compared to the 4000 (52.4 °C) and 6000 ml (40.8 °C) runs. Condenser temperatures stayed consistent, though the large discrepancy noted in the condensing area

Table 3 Measured temperatures of individual components within the Gandhāra configuration during comparative experiments

Run	Distilland starting volume	Measured component	*n*	Minimum temp. (°C)	Maximum temp. (°C)	Mean temp. (°C)	SD	Affected data points (assuming complete run)
1	2000 ml	Heat source	9001	20.8	434.8	261.5	93.4	None
		Distilland	9001	18.1	68.8	57.0	13.8	None
		Condensing area	7263	17.3	38.4	32.5	6.5	04:02:06 − 04:03:52/end (53)
		Condenser	9001	18.8	50.8	39.9	10.0	None
2	4000 ml	Heat source	8633	20.5	390.7	234.1	101.9	None
		Distilland	8633	18.9	65.8	51.6	14.3	None
		Condensing area	8633	18.9	65.9	52.4	13.4	None
		Condenser	8633	18.8	21.4	19.1	0.4	None
3	6000 ml	Heat source	8825	19.6	414.5	274.1	93.6	03:42:14 − 03:43:52 (47) 04:18:48–04:23:00 (127)
		Distilland	8998	17.1	68.7	52.3	14.1	04:18:48; 04:20:30; 04:17:58 (3)
		Condensing area	9001	17.6	53.3	40.8	10.0	None
		Condenser	8999	16.1	19.7	17.4	0.4	04:18:50; 04:20:30 (2)

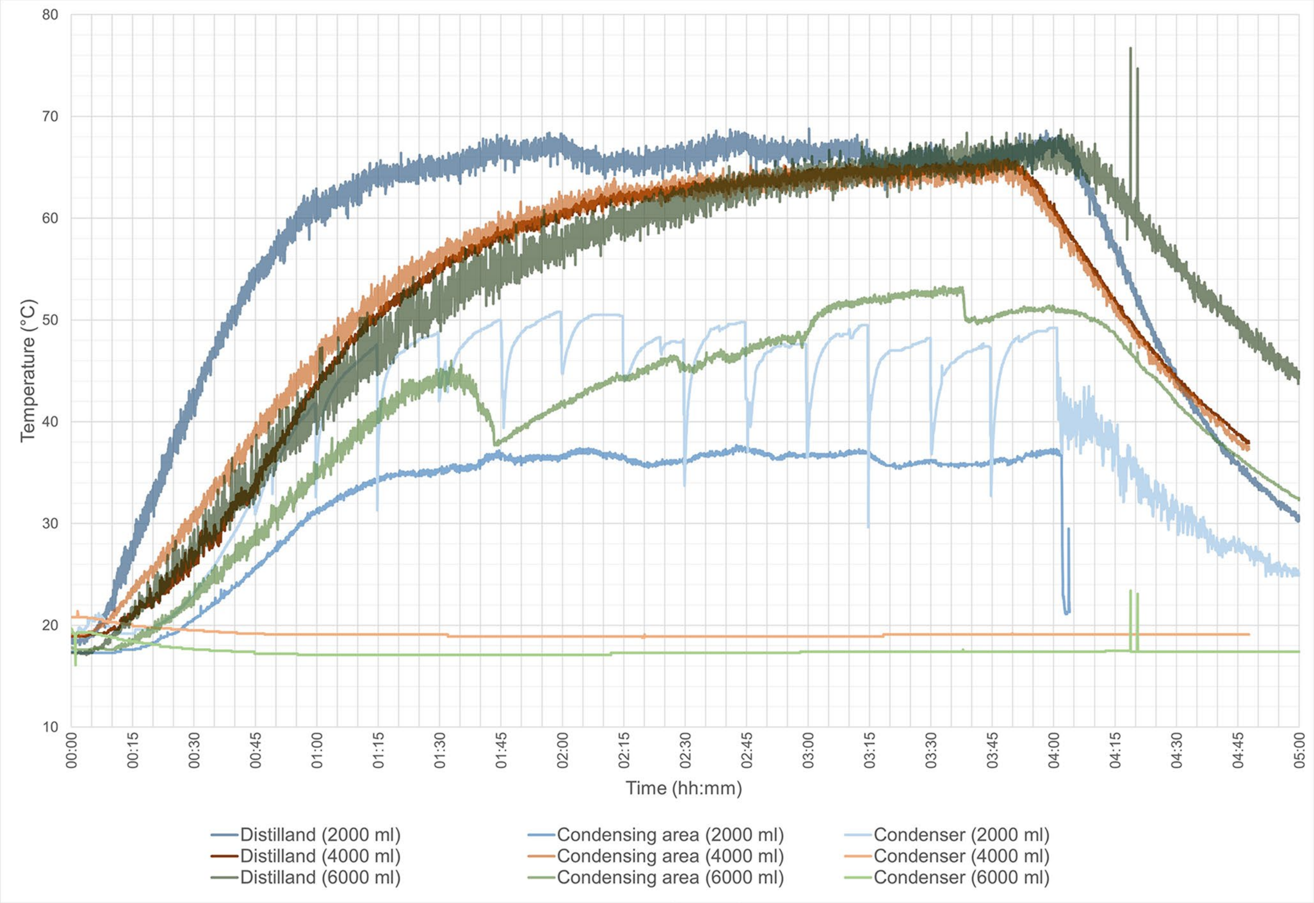


Fig. 4 Temperature readings from comparative distillation trials (distilland in still body, condensing area, and condenser, noting that the condensing methods are different for the 2000 ml run). Volumes in brackets correspond to starting water distilland volume

mean temperatures in the 4000 and 6000 ml runs is unclear and cannot be attributed to a single cause. Moreover, the sudden drop in condensing area temperature in the 6000 ml run from 43.8 °C around 01:35:02 (lowest in this period of 38.7 °C at 01:47:06 and a slight decrease in temperature recorded at 02:00:18) during the 2000 ml run could not be connected to a single intervention or cooling method.

Exploratory experiments

Using 4000 ml of water distilland and placing the still body within an enclosed hearth, six exploratory trials were carried out to establish how the apparatus could afford full distillations. Trials explored optimal vapour equilibrium, distillation conditions, distillate production, and additional practical considerations (Table 4). Trial 1 focused only on cooling at the still head (i.e. only atmospheric distillation with cold wet cloths), whereas Trials 2–6 introduced the full apparatus to combine atmospheric and water-cooled cooling methods as suggested in the reconstructions (changing cold wet cloths and using a water bath around the receiver). Cloths were routinely changed, and the water bath was refilled with cold water when warm. 4000 ml of water was decanted into the still body, immediately sealed with clay, and placed into the hearth. Once the hearth was lit and maintaining an internal temperature of at least 400–500 °C, recording began, marking the start of each distillation run (Fig. 5). Temperature of the heat source, distilland, and atmospheric temperatures in the still head (condensing area) and receiver were recorded using CCPI sheathed K-type 3 mm alloy 600 mineral insulated thermocouples (temperature range of 0–1250 °C approx. ± 0.4%), coupled to a HH-520 thermocouple data logger (Table 5). Wind speed and atmospheric temperatures were monitored using reported Met Office data as these could influence heating rates (Table 4). Fuel was added continually, followed by a burn-down period to observe apparatus heat retention and temperature control.

Trial 1: Condensing vapour in a specific component

Trial 1 aimed to see if water vapour could be drawn through the still and condensed in the still head spout, validating the apparatus' fundamental condensing ability. Cold wet

Table 4 Properties of exploratory experimental distillation trials

Trial	Hearth	Duration of distillation (mins)	Duration of burn down (mins)	Cooling / condensing strategy	Wind speed min. - max. (mph)	Ambient temperature min. - max. (°C)	Produced distillate (ml)	Remaining distilland (approx. ml)	Notes
1	Rock	120	30	Cold cloths (changed); all components sealed	7–9	9–11	0	2750	Partial apparatus (without condensing tube and receiver), slow distillation
2	Clay	60	60	Cold cloths (changed) and basin replenished; all components sealed	4–7	7–12	146	2850	Success, small yield of distillate, seal burst, and pressure drop noted
3	Clay	60	60	Cold cloths (changed) and basin replenished; still body, head, and tube sealed, receiver not sealed	5–7	15–17	0	2910	Failed distillation
4	Clay	120	60	Cold cloths (changed) and basin replenished; still body, head, and tube sealed, receiver not sealed	4–8	21–28	0	2010	Failed distillation
5	Rock	60	60	Cold cloths (changed) and basin replenished; still body, head, and tube sealed, receiver not sealed	7–9	10–15	3	2950	Very small yield of distillate
6	Rock	180	60	Cold cloths (changed) and basin replenished plastic tube; still body, head, and tube sealed, receiver not sealed	7–9	10–15	16	1010	Very small yield of distillate

cloths were wrapped over the still head spout and replaced irregularly once they had warmed. Seals were repaired when needed. Distillate began to visibly collect at the spout from 48 min into the run. Figure 6 shows that heating was consistent and maintained boiling temperatures, though with reduced condensing effectiveness when overheated. Although distillate production was slow, condensation was primarily occurring within the apparatus. Distillate production almost slowed to a halt when cloths were either too warm or no cloths were on the spout during changeovers, though did not appear to directly affect temperature change within the still.

Trial 2: 60-minute run with full apparatus

Trial 2 attempted distillation using the complete reconstructed apparatus, repeating the previous cooling and repair regime (see Trial 1: Condensing vapour in a specific component). The trial proved successful, though yielded a low volume of distillate. Temperatures of distilland and still head condensing area reached boiling point quickly; however, at 00:36:45, excessive pressure caused the clay seam between the still body and head to burst, dislodging the still head, reflected in the sudden spike in receiver temperature readings (Fig. 7). This indicated that the apparatus maintained sufficient pressurisation for distillation but was not fully condensing vapour due to an inadequate condensing surface area. After repairs, component temperatures stabilised during the burndown period.

Trial 3: Repeat 60-minute run

Trial 3 repeated the protocol from Trial 2, intended to demonstrate the apparatus could consistently distil, and left the join between the receiver and condensing tube unsealed to avoid pressure buildup (see Trial 2: 60-minute run with full apparatus). The trial, however, yielded no distillate. Temperatures of the distilland and condensing area dropped at 00:38:30, which was not reflected in the receiver or heat source temperatures, demonstrating the apparatus was not fully pressurised (Fig. 8). Condensed vapour appeared to accumulate and penetrate through the join between the still body and head, indicating reflux. Hence, vapour was only condensing at the top of the still and not in the spout and condensing tube.

Trial 4: 120-minute run

Trial 4 repeated the protocol in Trials 2 and 3, though extended the run to 120 min to diagnose and repair faults. Distillation again yielded no distillate; distilland and still head condensing area temperatures were not consistent (Fig. 9), where it took the distilland longer to reach boiling point. Anecdotally, the temperature, heating rate,

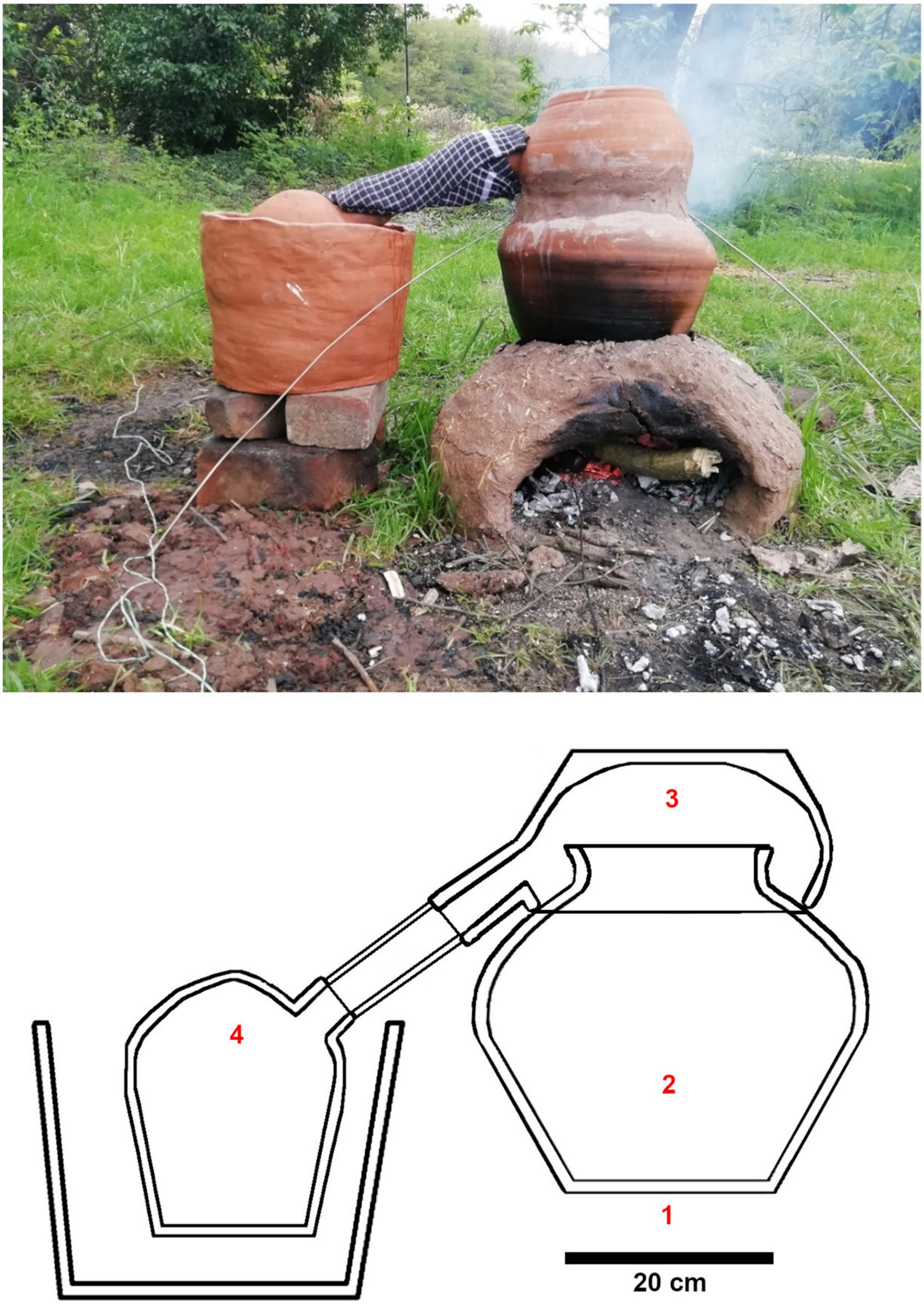


Fig. 5 Apparatus in use during the exploratory experiments with clay hearth (Trials 2, 3, 4) and technical drawing of apparatus with thermocouple locations: (1) heat source, (2) distilland, (3) condensing area, (4) receiver Photograph and drawing by the author

Table 5 Measured temperatures of individual components within the Gandhāra configuration during exploratory experiments

Trial	Measured component	*n*	Minimum temp. (°C)	Maximum temp. (°C)	Mean temp. (°C)	SD
1	Heat source	605	127.6	816.2	507.9	147.3
	Distilland	605	39.8	99.1	83.7	16.6
	Condensing area	605	26.7	77.4	61.5	15.4
2	Heat source	479	246.2	825.9	561.4	145.6
	Distilland	479	16.7	100.4	88.8	19.7
	Condensing area	479	17.8	100.5	77.3	22.7
	Receiver	479	11.1	94.6	24.8	25.0
3	Heat source	491	271.8	804.1	504.5	133.0
	Distilland	491	26.7	100.0	78.3	17.5
	Condensing area	491	23.1	83.7	59.4	15.4
	Receiver	491	15.7	19.2	17.7	0.5
4	Heat source	721	58.1	770.4	365.8	193.2
	Distilland	721	27.7	100.3	80.8	18.5
	Condensing area	721	28.6	91.7	67.5	16.9
	Receiver	721	20.1	22.7	21.5	0.9
5	Heat source	481	16.8	728.8	320.1	264.3
	Distilland	481	52.5	100.2	82.1	15.4
	Condensing area	481	34.9	92.1	63.3	16.8
	Receiver	481	9.9	10.7	10.3	0.3
6	Heat source	961	20.5	809.0	502.9	217.5
	Distilland	961	22.4	100.7	77.7	23.4
	Condensing area	961	16.1	91.9	62.2	20.4
	Receiver	961	9.7	15.0	11.6	1.5

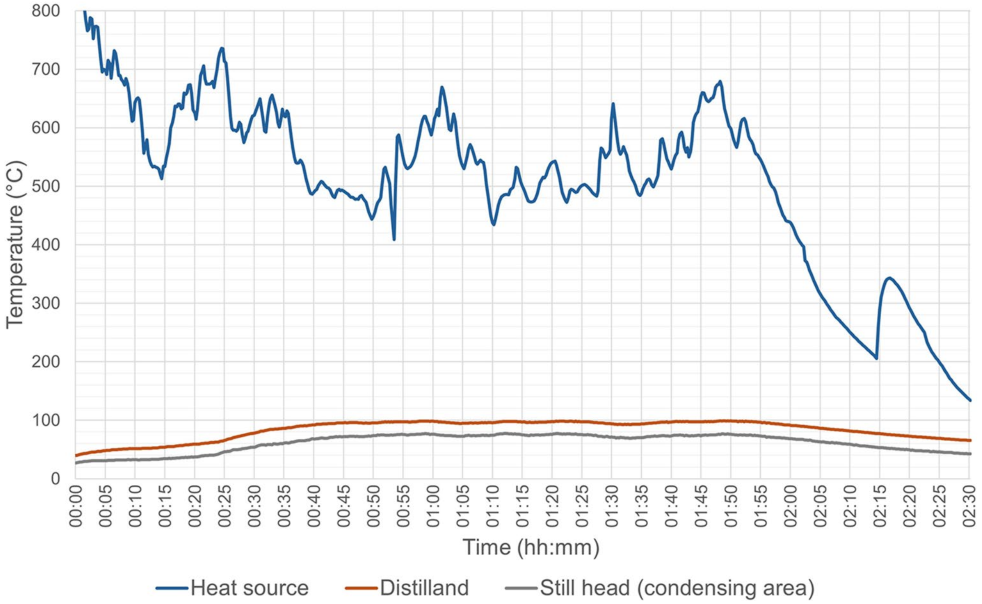


Fig. 6 Temperature readings derived from Trial 1 (all components)

and surface area of the hearth during Trial 2 (see Trial 2: 60-minute run with full apparatus) were considered to be greater than those in Trial 4. While fuel consumption was not measured, temperature readings of the heat source in Trial 2 and Trial 4 were significantly different, with the heat source in Trial 2 as consistently hotter. Distillate soaked through the seams between the still head and body, noted once 100 °C had been reached. This indicates the apparatus was too hot internally and the differentiation between the still body and condensing area was not great enough to promote distillation.

Trial 5: 60-minute run maintaining specific temperatures

Using a rock hearth, Trial 5 aimed to ascertain the ease of maintaining the distilland and still head at 80–90 °C to prevent reflux and enhance temperature differentiation through

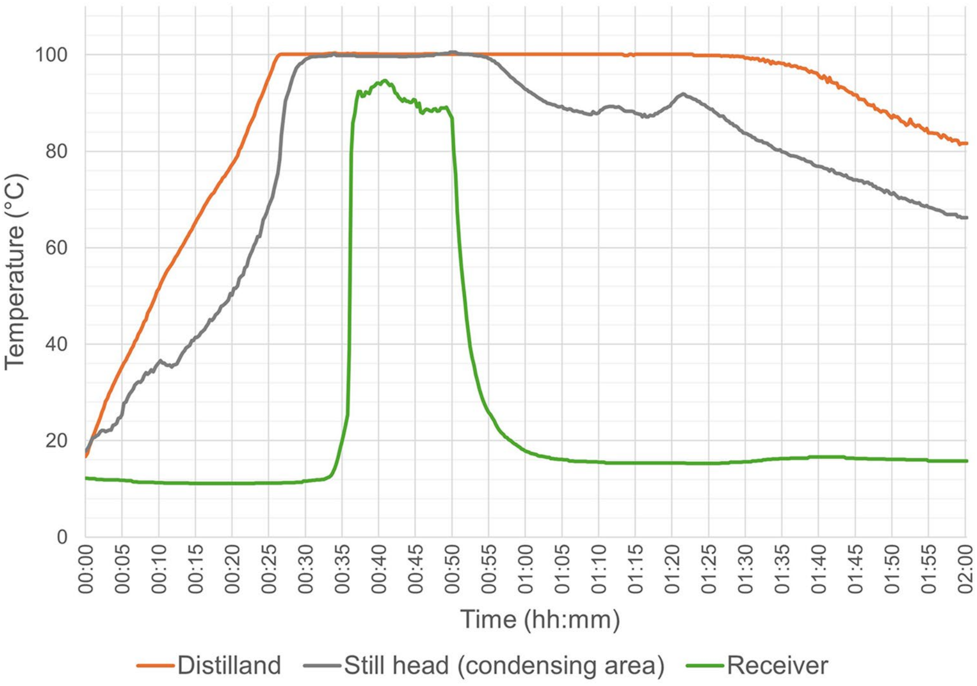


Fig. 7 Temperature readings derived from Trial 2 (without heat source)

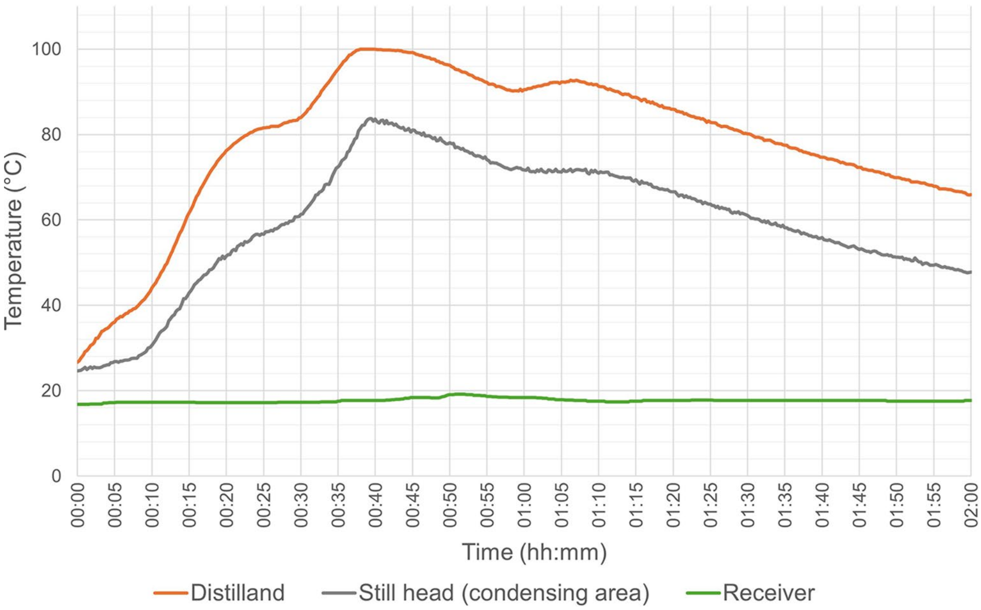


Fig. 8 Temperature readings derived from Trial 3 (without heat source)

cooling and monitoring the heat source; previous trials showed that distilland and still head temperatures dropped quickly when the hearth was not tended. Trial 5, however, yielded no distillate. The hearth retained heat, rendering consistent temperature control difficult (Fig. 10). Attempts to adjust heating by letting the hearth burndown were ineffective due to the ceramic apparatus' heat retention properties, whereby components were not reaching temperatures necessary for distillation or maintaining a sufficiently cool environment throughout (Fig. 11).

Trial 6: 180-minute run with clear condensing tube

A clear plastic condensing tube was used to observe one area of condensation during the distillation process and identify any potential issues influencing distillation operation. An attempt was made to keep the hearth at a consistently lower temperature to slow the rate of vapour production and pressure build-up within the system and steadily produce vapour at a manageable rate. This was not reflected in the apparatus components (Fig. 12). A small volume of distillate was produced; vapour was successfully condensing close to the

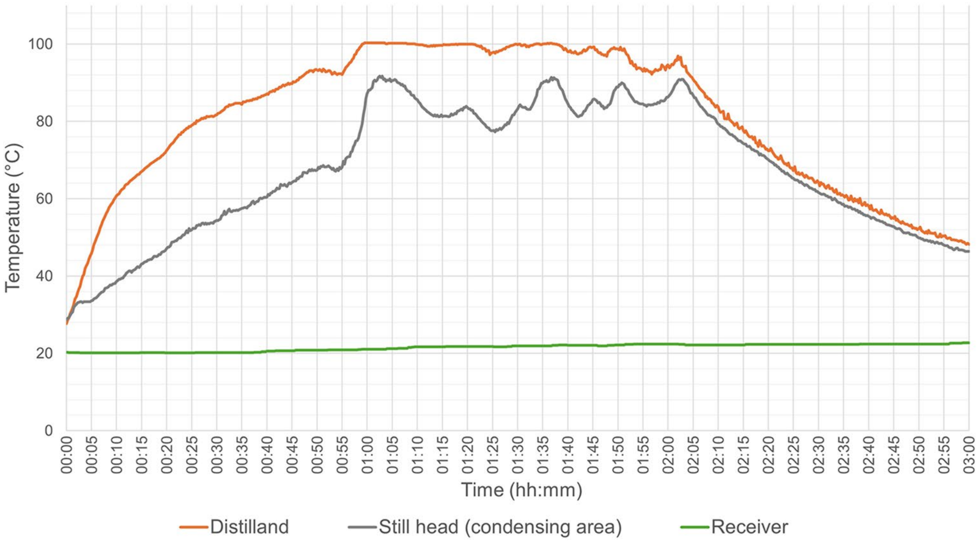


Fig. 9 Temperature readings derived from Trial 4 (without heat source)

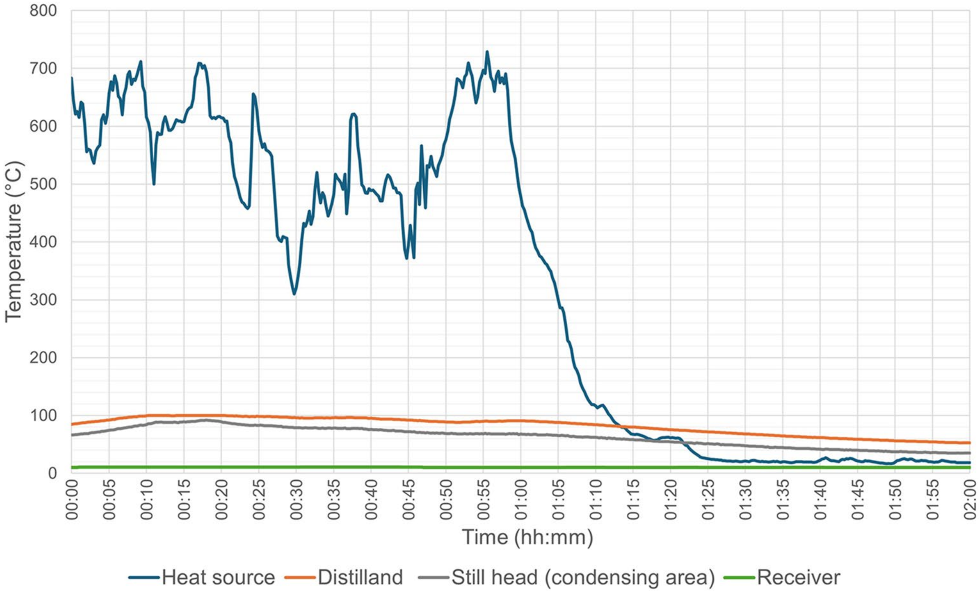


Fig. 10 Temperature readings from Trial 5 (all components)

spout of the still head and running through along the plastic tube, suggesting the head was sufficiently cool.

Discussion

The experimental campaign developed a practical basis for evaluating the Gandhāra still reconstruction, though couched in a specific set of conditions for how it was used, i.e. atmospheric and partial water-cooled distillation of water with flexible sealing materials (clay). Following suggested modifications from previous research on heating methods, sealant materials, and condensing techniques, experiments demonstrated how the apparatus routinely failed to accommodate conducive distillation conditions. Crucially, an inability to fully condense produced vapour within the apparatus impeded distillation, caused by internal reflux processes, vapour build-up, and insufficient areas for condensation. Such issues are rooted in the fundamental morphology of the selected components that formulate the reconstruction, and the points of articulation between them: factors not demonstrated or discussed in the original reconstructions. Generalisations on the appropriateness of selected vessels as apparatus components, therefore, require greater scrutiny, and have significant implications for the success of distillation processes. While interventions could be introduced to make the reconstruction 'work' (and the experimental campaign did not cover all practical or technical eventualities), this range of identified issues supports critiques of the original archaeological materials used to assemble the Gandhāra still.

Fig. 11 Temperature readings from Trial 5 (without heat source)

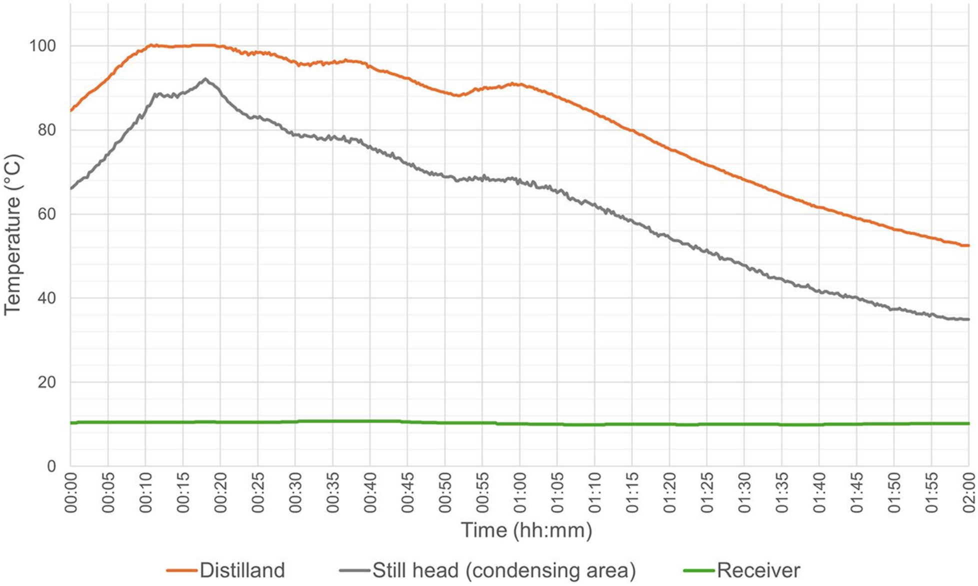
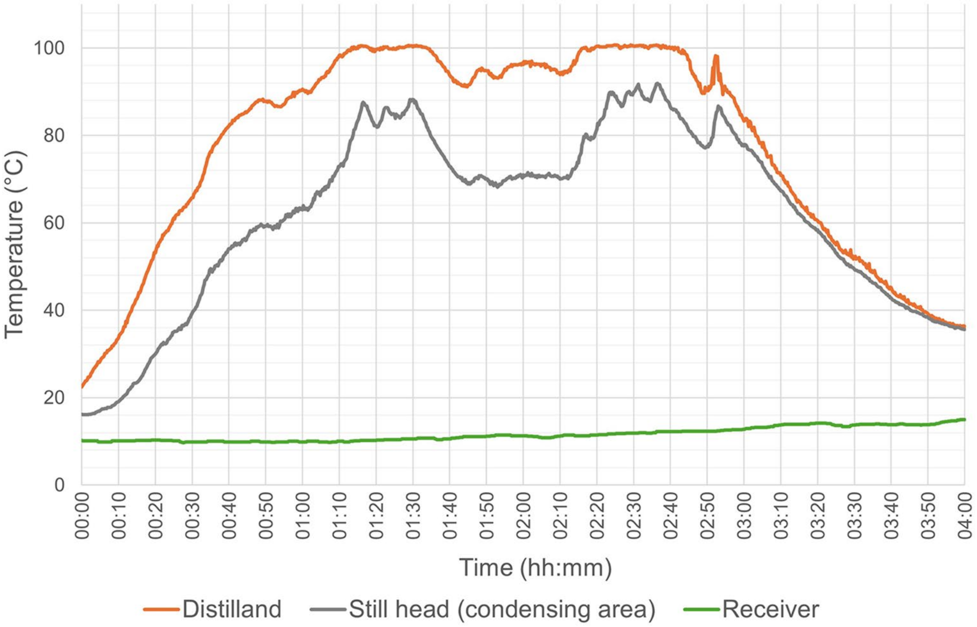


Fig. 12 Temperature readings derived from Trial 6 (without heat source)



The campaign demonstrated that ceramic vessels suggested as apparatus components were morphologically unsuitable for cooling the volume of produced vapour in the correct parts of the still. Throughout runs, a cyclical reflux process within the still head area was occurring, exacerbated by a channel formed between the still head and body that gathered distillate, causing the apparatus to leak (Fig. 13). Produced vapour, instead of being channelled and condensed through the tube, was running down the interior of the head and collecting where the head and body joined. This suggests that vapour was not being condensed fast enough across all trials, contributing to the reflux action occurring, and indicating the apparatus lacked a sufficiently large interior cooling surface. Further, the insufficient height difference between the top of the still head interior and base of the still body (needed to create a large enough condensing environment and increase the temperature difference between the distilland and condensing area) contributed to a significant temperature imbalance. Together, the internal surface area of the condensing tube, still head spout, and receiver was not large enough and continuous to consistently condense produced vapour. This suggests that the principal points of cooling and the maximum condensing area in the original reconstructions are too small and inadequate.

While unsuccessful, trials concurrently illustrated why the selection of archaeological materials for the reconstruction had overlooked the impact of their morphology and dimensions upon distillation ability. Despite the replica tube

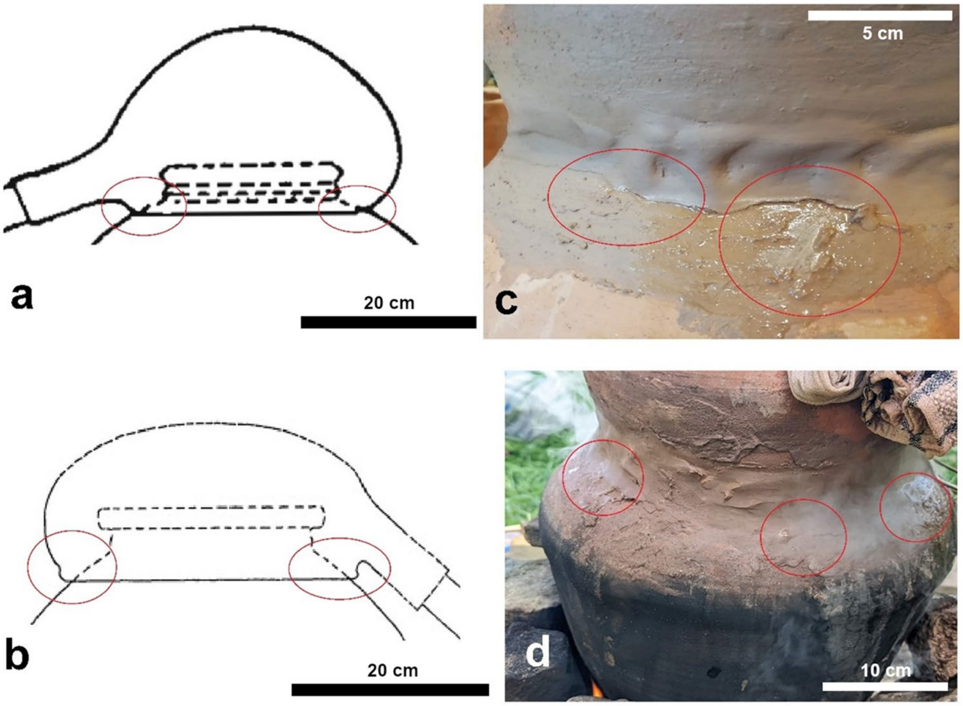


Fig. 13 Formed channel (red circles) between still head and body in the original Taxila (**a**) (after Marshall 1951, p. 420) and Shaikhān Dherī (**b**) (after Allchin 1979b, p. 773) reconstructions (see original publications for scales), and leaking distillate from the channel during the comparative experimental trials (**c**) and Trial 6 of the exploratory experiments (**d**). Drawings used under a UK Copyright Exception; photographs by the author, scales are approximate

not being a faithful reproduction, its shape, size, and surface area mirrored representative aspects of archaeological examples, particularly as no typologically or volume-consistent tubes and still heads exist (see Groat 2025). Hence, the accepted idea that such vessels were specialised components is unlikely. This observation supports McHugh's opinion on the remarkability of the still head and why the form is not overly unusual (2020, p. 45), underscoring the need for such a component to be tailored to others in a complete apparatus. This is an issue in all iterations of the Gandhāra configuration as still head and tube morphology are not fully considered, but significantly affect distilling ability. Porous unglazed and unslipped ceramic interiors, such as those exhibited in the Gandhāra apparatus components, were also likely inhibiting the movement of vapour and liquids within the still. Accordingly, the arrangement of individually selected archaeological vessels to formulate the Gandhāra apparatus is unsuitable, despite showing some resemblance to model distillation configurations.

Additionally, poor flushness and seals between components caused a significant loss in collected distillate and inability to maintain a conducive distilling environment. The constant need to repair seals was an omnipresent concern throughout all trials, suggesting that clay was not strong enough to sustain a fully pressurised environment in the correct part of the still (i.e., the condensing area). While this was noted in the comparative experiments, including how a different material may have been more suitable as a sealant, clay seals did still promote a pressurised environment and adequate distillation conditions in Trial 2. However, in both experimental sets, joins between the still head spout and condensing tube may have inhibited condensing vapour flow, demonstrating that the ability of the apparatus is not exclusively contingent on how components fit and join. Highlighting practical issues with the original reassembly of the apparatus, this concern is rooted in the selection of ceramic vessels that would not change if a different sealant material was used. Further experimentation with sealants would be a useful conduit to explore how distillation practices were refined; less porous materials with greater elasticity and malleability (such as tars and resins) could withstand higher pressures and potentially sustain stronger seals.

Experiments demonstrated how altering modes of heating subsequently affected rates of heat exchange in the configuration, requiring appropriate and adequate methods of cooling. Comparative experiments identified that generalisations on heating methods within interpretations could not be made (see Comparative distillation experiments); the suggestion of a tripod as a single point of heating (Marshall 1951, p. 420) placed the still body too far away from a heat source to maintain consistent heat transfer. In the exploratory experiments, this was further exemplified by using a purpose-built hearth to provide a more consistent and powerful heat source, adequately heating the distilland. This afforded a level control over heating rates despite varying wind speeds within each trial (Table 4), though subsequently affected the temperatures of other components in the configuration (e.g., Trial 5). However, despite mean heat source temperatures being lower in the comparative experiments (see Table 1), high volumes of distillate were ‘boiled off’ instead of condensing in both experimental sets, suggesting the apparatus was becoming too hot too quickly and water distillands were not consistently reaching a high enough temperature to be fully distilled. Heating the distillate at a much slower rate would theoretically prevent this, though as demonstrated in exploratory experiments Trial 2 (vapour producing too fast) and Trial 5 (vapour producing too slow), maintaining a level of control was implicated by many interacting factors beyond basic interventions. As the combination of individual vessel morphologies struggled to facilitate distillation, how the apparatus is made, and its fabric properties, directly influence heating and cooling abilities that have a far greater impact on distillation ability than only the still’s morphology. These combined insights reiterate why variability in distillation system heating must be fully considered when discussing early distillation practices.

The campaign also noted how pressurisation must be reconsidered within early distillation configurations, as internal cooling surfaces require a sufficient large area to both condense vapour and dissipate pressure build-up. To an extent, the correct pressurised environment and cooling points were achieved within the Gandhāra configuration; Trial 2 was successful at one stage in its run (see Trial 2: 60-minute run with full apparatus), though the still failed to reach a point of efficiency for continuous distillation. Suitable pressurised environments to produce vapour, and maintain a sufficiently cool atmosphere to condense it, were not attained constantly at different points in the still. Water condensation appeared to be hindered by inert gases produced during the evaporation stage (i.e., closed pockets of air) that became trapped in the upper parts of the still, leading to the still breaking in Trial 2. Air needs to escape to allow for condensation to occur, though modifications and points of sealing in the reconstructions to do this are not accounted for. Further, despite producing a volume of distillate in Trials 2, 5, and 6, a sufficiently large temperature discrepancy between the heating distilland and cooling method was not being consistently achieved, even during the coolest external ambient temperatures recorded in Trials 1 and 2 (see Table 4). This, notably, would greatly impact the still’s ability to distil alcohol considering its lower boiling point than water. Differing atmospheric pressures caused by temperature imbalances and uneven rate of heat transfer, therefore, prevented the system from reaching a point of equilibrium and optimal vapour condensation. Certain issues with pressurisation could potentially be rectified; modifying the still by unsealing and altering the end of the tube to create a vent near the top of the still head would release built-up pressure, hypothetically preventing an explosion, and let out other non-condensable gases (e.g. in Trial 2). This would, in theory, promote more consistent vapour flow and yield higher volumes of distillate. Fixed channels to divert produced distillate as suggested in other early apparatus examples (see Needham et al. 1980 Fig. 1454) would also, presumably, mitigate for excessive leaks noted throughout both experimental sets. Modifications such as these, however, are neither represented in the original archaeological materials nor accounted for in previous reconstructions.

Failures during the experimental trials could be seen as a consequence of the experimenters having insufficient experience with a particular form of distillation apparatus, and equally, testing with lower-boiling distillands (such as ethanol-water mixtures) would potentially lead to a higher rate of success. Approaching experimentation from refined knowledge of how the still operates would undoubtedly introduce a robust series of ideas on what can be modified to make the reconstruction ‘work’. Yet distancing experimental research from rigid hypothesis-testing structures was effective for simultaneously exploring multiple variables and influencing factors, and increasing the angles of critique, but also developing an idea on how distillation could be enabled within the limits of the apparatus. The lack of multiple repetitions of individual trials may be seen to undermine the confidence of generated insights, though multiple runs allowed for a substantial understanding of functionality and associated issues to be developed. In particular, this highlighted the distinct lack of detailed information in the original reconstruction by Marshall (1951) and its later iterations (beyond suggesting that the vessels together are a distillation system), which does not account for inherent issues with the archaeological components’ geometry and dimensional proportions. As revealed through the sequential experimental trials, and in conjunction with comprehensive analysis of the archaeological materials, this further demonstrates the unlikelihood that the Gandhāra still existed and that these components together were a still. Indeed, Marshall conceded in his first recording of a ‘water-condenser’ that the “precise use of these vessels is not certain” (1951, p. 420). New interpretations of the ‘receiver-condenser’, therefore, need to be developed away from established assumptions surrounding distillation. With a focus on seeing such ceramics as a distillation apparatus, opportunities to meaningfully reassess the position of such unique vessels within a dynamic interconnected region, and the communities that made and used them, may be missed.

Conclusion

The experimental studies demonstrated why the Gandhāra still does not function as assumed, determined by investigating a series of parameters that influenced its operational ability, and identifying how condensing conditions were not being consistently met in the configuration. Together with robust material synthesis, this process emphasises how archaeological evidence, when reconstructed as new technological introductions, needs to be approached through an adequate framework of critical evaluation. The focus on presenting distillation as a specialised activity in South-Central Asia illustrates this concern, exemplifying how experimental reconstruction is underutilised as an analytical tool for illuminating functional dynamics, technical details, and practical implications of early apparatus configurations. By establishing fundamental morphological issues with the apparatus, and demonstrating how this affected distillation, the sequence of tested variables and trialled apparatus acts as a substantial body of results by which to further existing critiques. How experimental methodologies are utilised as tools within the analysis of technological innovation is, therefore, a key consideration. Positioning experimentation and reconstruction in the campaign as an evaluative framework gradually introduced different functional parameters and assessed the impact of these upon individual practical concerns tied to distillation operation. This approach moved away from previous experimental work that aimed to prove the applicability of configurations, avoiding a line of reasoning that accepted the Gandhāra still reconstruction at face value.

However, insights from experimentation should not be seen to suggest that forms of early distillation categorically did not exist. Rather, the experimental campaign revealed valuable considerations surrounding the technicalities of early distillation practices, while simultaneously identifying why the archaeological 'reality' of one interpreted branch of distillation development requires wider re-examination. Sealants, vessel geometry, material properties, and technical decisions certainly require greater attention, and exploring them would generate vital questions for understanding early distillation technology. Seeing the control of such elements as central to the practice of distillation, and its conceptualisation as a craft activity, builds an understanding of the practical issues surrounding the creation of the apparatus itself. Direct practice and engagement central to socially-mediated elements of skill learning, matter exploration, and material knowledge invites reappraisals of how early stages of distillation technology have been reconstructed. Unpacking this discourse asks us to reflect on how such narratives are generated and endure, though equally fosters positive reconsiderations of the contexts within which early iterations of transformative material practices emerged.

Acknowledgements The author is grateful to Caroline Jackson for reviewing earlier iterations of this paper, and to Jane Rempel for helping shape the project. Thanks also go to Sue Sherratt, Robert Falconer, Ann Brysbaert, and Peter Day for their input. Replica versions of the distillation apparatus were made by Gareth Perry. Thanks also to colleagues instrumental in supporting the experimental campaign: Nicholas Clarke, Matthew Lester, Christos Giamakis, Yvette Marks, and Angelos Hadjikoumis. The author also thanks the anonymous reviewers for their helpful comments and suggestions that improved the quality of the manuscript.

Author contributions The author completed all data collection and analysis, and wrote the manuscript.

Funding This work was supported by the Arts & Humanities Research Council [grant number AH/L503848/1] through the White Rose College of the Arts & Humanities, and Ancient India and Iran Trust Research Bursary Scheme.

Data availability The datasets generated by the research are available in the White Rose eTheses Online repository: https://etheses.whiterose.ac.uk/id/eprint/34286/.

Declarations

Competing interests The authors declare no competing interests.

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