**Studies in Knowledge and Innovation**
Vol. 2 No. 4A (2026)

# Conditional Pressure Retention in a Historical Table of Lunar Thermal Conductivity

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Published: April 30, 2026 | Article 838

## Abstract

Pressure corrections for lunar thermal properties require more context than a single multiplier. We audited 28 rows in an official historical compilation and identified seven matched conductivity pairs at 100,000 and 0.01 Pa. They represent five sample–study series and three sample identifiers. Equal-series geometric retention was 0.526, compared with 0.558 under equal identifier weighting. A source condition whose original value remains unresolved changed retention to 0.563 when omitted. This exceeded the 0.518–0.533 range obtained under a stated printed-rounding assumption. Three additional pairs with interval-valued pressure labels were reported separately. The calculations describe compiled laboratory-derived parameters; they establish neither a universal vacuum factor nor lunar surface conductivity. Source support and averaging unit matter beyond the precision of the displayed numbers.

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Pressure corrections for lunar thermal properties require more context than a single multiplier. We audited 28 rows in an official historical compilation and identified seven matched conductivity pairs at 100,000 and 0.01 Pa. They represent five sample-study series and three sample identifiers. Equal-series geometric retention was 0.526, compared with 0.558 under equal identifier weighting. A source condition whose original value remains unresolved changed retention to 0.563 when omitted. This exceeded the 0.518-0.533 range obtained under a stated printed-rounding assumption. Three additional pairs with interval-valued pressure labels were reported separately. The calculations describe compiled laboratory-derived parameters; they establish neither a universal vacuum factor nor lunar surface conductivity. Source support and averaging unit matter beyond the precision of the displayed numbers.


## A conductivity number carries its conditions

A thermal-property table invites reuse. A sample identifier, temperature and conductivity value can be transferred into a later calculation with little effort, while a pressure label or original-source note is left behind. That omission is consequential for porous material. The quantity being reused is not solely a property of its chemical constituents: the conditions under which heat crosses the material and its pore space also matter. A numerical comparison is therefore meaningful only after the observation and its conditions have been reconstructed.

Robertson's U.S. Geological Survey report compiles thermal properties for engineering and scientific use, including lunar solid rocks, breccias and fines (Robertson, 1988). Table 8 offers a small, unusually explicit opportunity to compare reported conductivities at different pore-gas pressures. It supplies both sample information and condition labels, but its compressed layout includes inherited entries, an interval-valued pressure endpoint and a change of conductivity units on the following page. Reading the values without their layout would define a different dataset.

The original laboratory literature already establishes that pressure can affect lunar-rock thermal transport. Fujii and Osako measured diffusivity of three lunar rocks under atmospheric and vacuum conditions across temperature (Fujii and Osako, 1973). We do not seek to rediscover that qualitative effect. Our question concerns the finite numerical evidence in the later compilation: **how does reported low-/high-pressure conductivity retention vary across matched conditions, and how dependent is its summary on the unit being averaged and the support of an unresolved source entry?**

The measurand must be distinguished from its displayed numerical value. Metrological vocabulary treats the specification of the quantity and relevant conditions as part of measurement description (JCGM, 2012). Here the outcome is a ratio of two compiled conductivities with a common reported temperature, material and study. The ratio is not a pressure-response coefficient, and its denominator is not an independently established lunar truth. We use the term retention for the fraction of the high-pressure compiled value remaining at the lower reported pressure.

Two propositions organize this audit. P1 states that retention is conditional: matching the nominal pressure endpoints does not make different materials, temperatures or source series exchangeable. P2 states that the precision of printed values cannot by itself characterize uncertainty about source support or the averaging unit. Both propositions are assessed descriptively within the recovered table. There is no

population null hypothesis, estimated sampling variance or claim that the records represent independent experiments.

## Physical context without a universal correction

Studies of consolidated porous media distinguish heat transport through the solid framework from contributions associated with the pore contents (Woodside and Messmer, 1961). Removing gas can therefore change an effective conductivity while leaving the specimen identifier unchanged. That physical motivation does not determine the size of every change in a historical table. Pore geometry, matrix properties, temperature and the range of pressure covered remain relevant.

An additional distinction separates thermal diffusivity from conductivity. Horai and Fujii explicitly write conductivity as diffusivity multiplied by density and specific heat, and calculate it from smoothed quantities in their review of returned lunar material (Horai and Fujii, 1972). Consequently, a conductivity number in the compilation need not be a raw instrument reading of conductivity. Our observations are reported laboratory-derived parameters. We neither reconstruct the full original reduction chain nor treat estimates derived from common quantities as new independent measurements.

Broader treatments of rock and mineral conductivity discuss its dependence on material composition and physical conditions (Clauser and Huenges, 1995). Experimental work on pressure and saturating fluid in compact rock also makes clear that the surrounding fluid is part of a transport problem (Walsh and Decker, 1966). These sources motivate retaining conditions. They do not supply a fitted correction for the lunar entries analyzed here. In particular, we do not infer a porosity law from the small number of sample identifiers.

## Recovering seven exact-pressure pairs

We downloaded the official 1988 USGS report on 16 November 2026. The PDF contains 110 pages and 1,997,759 bytes; its SHA256 and retrieval URL accompany the data. The report's printed page 63 is PDF page 67. We rendered that page and the continuation, transcribed every row of the solid-rock and breccia table, and retained the printed decimal strings. The 28-row audit includes 26 lunar entries and two terrestrial comparator entries, with inclusion roles recorded individually.

The table gives sample identifier, original study, rock type, bulk density, solidity, temperature, pressure and conductivity. Its page-63 conductivity unit is $10^{-3}$ cal $cm^{-1}$ $s^{-1}$ $K^{-1}$. The fines on the continuation use $10^{-6}$ instead and are outside this cohort. We calculate dimensionless within-unit ratios, so a common positive unit conversion cancels exactly. This does not authorize mixing different unit scales. Measurement-scale principles constrain which numerical operations preserve meaning (Stevens, 1946), and the SI description distinguishes a quantity from its numerical expression in a chosen unit (BIPM, 2019).

Seven pairs have explicitly matching $10^{5}$ and $10^{-2}$ Pa endpoints and matching reported temperature, density, solidity, material and study. Here exact denotes scalar printed endpoint labels, not the precision of laboratory pressure control or identity of apparatus. They comprise three sample identifiers-10049, 10069 and 14311-in five sample-study series across two studies. One series contributes three temperatures; each other series contributes one. The full ten-pair collection adds a fourth identifier and third study, but those additional pressure labels belong to another stratum. These counts cannot be interchanged with seven or ten independent experiments.

The column audit removed a particularly misleading interpretation. For samples 10057,20 and 10046,65, a printed numeral 4 lies in the temperature column: it means 4 K. The pressure cell on that row is blank. A

table parse that shifts the numeral into the pressure column would invent a matched 4 Pa condition and a large apparent pressure contrast. We retain all four associated rows as unpaired temperature conditions. Two further lunar rows have only a single pressure value; the two terrestrial rows remain explicit comparators rather than lunar observations.

Missing conditions are not reconstructed merely to increase the number of comparisons. Missing-data reasoning distinguishes an absent value from an observed outcome (Little and Rubin, 2019). We leave the two cryogenic pressure cells blank and attach no retention result to excluded rows. The standard output keeps their source positions and status, making exclusion review possible without deleting inconvenient evidence.

## Ratios, weights and the meaning of a range

For a matched condition j in series s, retention is r = k_low/k_high, and the corresponding log-retention is ln(r). Our primary summary first averages log-retentions equally within a series, then equally across the five series, and exponentiates. Each single-condition series therefore receives one fifth of the total weight. Each of the three temperatures in the longer series receives one fifteenth. Geometric averaging is suited to a specified collection of multiplicative ratios; work on summarizing comparative results explains why the averaging rule must be explicit (Fleming and Wallace, 1986).

The weights do not express inverse measurement variance or random-sample inclusion probabilities. They give each named sample-study series the same influence. Weighting decisions need to follow the target of the summary (Solon et al., 2015). We also report an arithmetic mean under the same series weights and a geometric description that first averages series within sample identifiers and then gives the three identifiers equal weight. The latter is a different finite target, not a statistical repair for dependence.

No regression relates retention to its numerator, denominator or the table's solidity field. Ratios can create misleading associations when their mathematical structure is ignored (Kronmal, 1993). Likewise, ratio interval estimation requires more than the presence of two printed numbers; Fieller's work concerns a sampling framework that these compiled entries do not provide (Fieller, 1954). We therefore calculate no standard error or confidence interval for retention.

Instead, two deterministic sensitivities are specified. First, we remove each complete primary series and summarize the four remaining series with equal weights. Second, we omit one condition whose original source support remains unresolved, recomputing its series from its other two temperatures while keeping all five series equally weighted. These procedures reveal changes in this collection's composition and source support. They supply no confidence coverage for an unknown material or another laboratory.

A separate calculation addresses displayed precision. Suppose each printed conductivity lies within half a unit of its last printed decimal place, as if rounded to nearest. Positive ratio bounds are then (low - half-unit)/(high + half-unit) and (low + half-unit)/(high - half-unit). We propagate those extremes through the fixed weighted log-summary. This is a deterministic sensitivity under an explicit rounding assumption. The uncertainty guide requires the inputs and model behind an uncertainty statement to be specified (JCGM, 2008); our interval is not a full measurement-uncertainty budget or an error bar supplied by the original investigators. Figure 1 separates condition matching from the subsequent finite summary, linking P1 and P2 to the corresponding operations.

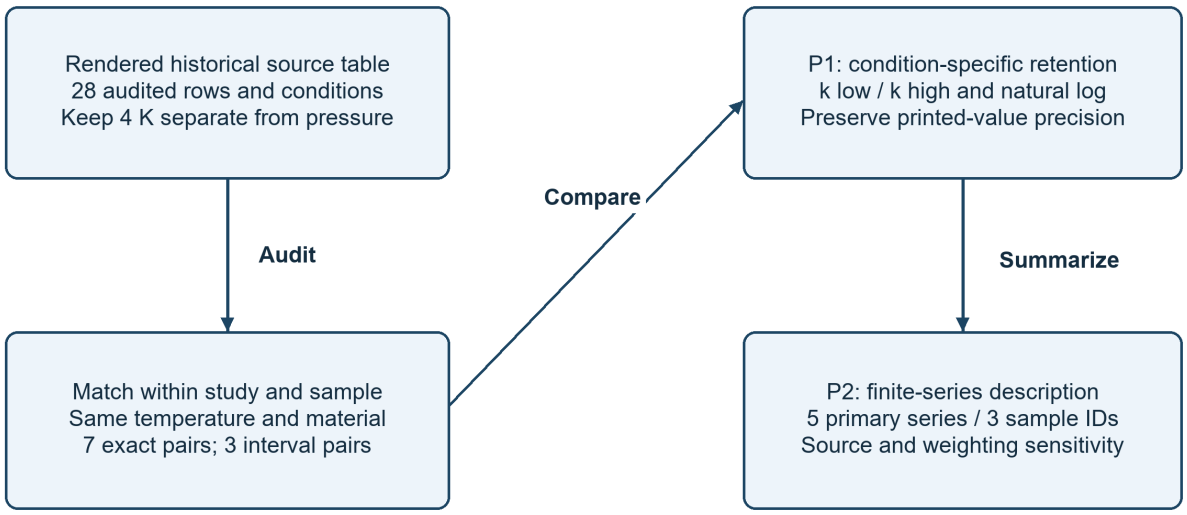



*Figure 1. Source conditions define admissible pairs before retention is calculated. P1 concerns the condition-specific values; P2 concerns finite-series weighting, printed precision and source support. Three interval-pressure pairs remain outside the exact-pressure summary. Arrows show analytic operations, not a causal model of all lunar materials.*

## Retention differs across the reported conditions

The seven exact-pressure ratios range from 0.222 to 0.752. Equal weighting of the five series gives mean log-retention -0.643 and geometric retention 0.526. The complement, 0.474, describes the fractional reduction in this particular multiplicative summary. It does not mean that every lunar rock loses 47.4% of its conductivity. Table 1 displays every pair and its source rather than allowing the aggregate to replace them.

*Table 1. All seven primary conditions at $10^{5}$ versus $10^{-2}$ Pa. Conductivity columns retain the source's $10^{-3}$ cal $cm^{-1}$ $s^{-1}$ $K^{-1}$ values. HF72 denotes Horai and Fujii; FO73 denotes Fujii and Osako. The 500 K low value is the legible but original-source-unresolved USGS entry. Rounding ranges use only the stated half-last-digit assumption. Scope: five series, three identifiers, two studies; no independent-experiment or confidence-interval interpretation.*

| Sample ID | Source | T (K) | k high | k low | Retention r | ln r | Rounding sensitivity |
|---|---|---|---|---|---|---|---|
| 10049 | HF72 | 300 | 3.51 | 2.4 | 0.684 | -0.380 | 0.669-0.699 |
| 10069 | HF72 | 300 | 3.27 | 1.6 | 0.489 | -0.715 | 0.473-0.505 |
| 10049 | FO73 | 100 | 2.34 | 1.28 | 0.547 | -0.603 | 0.544-0.550 |
| 10049 | FO73 | 300 | 3.49 | 2.41 | 0.691 | -0.370 | 0.688-0.693 |
| 10049 | FO73 | 500 | 3.38 | .75 | 0.222 | -1.506 | 0.220-0.224 |
| 10069 | FO73 | 300 | 3.26 | 1.19 | 0.365 | -1.008 | 0.363-0.367 |
| 14311 | FO73 | 300 | 3.15 | 2.37 | 0.752 | -0.285 | 0.750-0.755 |

The series-weighted arithmetic retention is 0.555. Giving the three sample identifiers equal weight instead produces geometric retention 0.558. Thus a reader can recover different legitimate descriptive numbers from the same seven pairs by asking a different averaging question. The table does not identify a

privileged population weighting. P1 is supported at the level claimed: nominally shared pressure endpoints do not yield one invariant reported retention value.

Source disagreement is visible even at the same nominal temperature. At 300 K, the two source entries for sample 10049 give retention 0.684 and 0.691. For sample 10069, they give 0.489 and 0.365. We do not call these estimates of laboratory repeatability, because the physical specimens and full reduction histories are not established as independent and interchangeable. Agreement analysis distinguishes correspondence of measurements from simple association (Bland and Altman, 1986); concordance likewise requires attention to differences in value (Lin, 1989).

The three secondary conditions concern sample 12002,85. The original study by Horai and Winkler measured diffusivity with a modified Ångström method under varied temperature and gas pressure (Horai and Winkler, 1975). The USGS table labels its high-pressure values $10^4$ Pa and its lower-pressure values with an interval, $10^{-1}$-$10^{-4}$ Pa. We retain those labels as printed. Table 2 shows retentions of 0.534, 0.817 and 0.780 at 85, 315 and 450 K, respectively. They are not exact-endpoint repetitions of the primary comparison.

*Table 2. Separate interval-pressure stratum, source HW75. High pressure is printed as $10^4$ Pa; the lower endpoint is a printed $10^{-1}$-$10^{-4}$ Pa interval, not a chosen scalar. Conductivity units match Table 1. One sample-study series with three conditions is shown; these values do not enter the primary five-series summary.*

| Sample ID | T (K) | k high | k low | Retention r | ln r |
|---|---|---|---|---|---|
| 12002,85 | 85 | 0.88 | .47 | 0.534 | -0.627 |
| 12002,85 | 315 | 1.86 | 1.52 | 0.817 | -0.202 |
| 12002,85 | 450 | 2.18 | 1.70 | 0.780 | -0.249 |

## Source support changes the temperature interpretation

For sample 10049 in FO73, the compilation's retentions are 0.547, 0.691 and 0.222 at 100, 300 and 500 K. The final point uses a low-pressure conductivity printed clearly as .75. The publisher abstract for the original paper describes a general decrease in the atmospheric-vacuum diffusivity difference with temperature. That statement and this compiled trajectory leave an unresolved source question. They are not sufficient grounds to change .75 to an imagined alternative or to announce a physical nonmonotonic law.

We obtained complete scans of the 1972 and 1975 works and inspected their relevant methods. The original 1973 full scan was unavailable from the examined archive, although its publisher abstract and bibliographic record were available. Accordingly, the primary calculation remains explicitly as compiled, with the 500 K condition flagged. Removing that condition raises the five-series geometric retention from 0.526 to 0.563. All five series remain represented; only the disputed condition's contribution changes. Table 3 places this omission alongside the alternative averaging definitions.

*Table 3. Alternative finite summaries and the prespecified source-support omission. The primary seven-pair geometric retention has a delete-one-series range of 0.481-0.576 and a rounding-assumption range of 0.518-0.533. Neither range is a confidence interval. The omission is a source sensitivity, not a corrected estimate of the underlying 500 K conductivity.*

| Finite description | Retention | Scope and weighting |
|---|---|---|
| Equal five-series geometric retention | 0.526 | 7 conditions; 5 series; 3 sample IDs |
| Equal five-series arithmetic retention | 0.555 | Same 7 conditions and series weights |
| Equal three-ID geometric retention | 0.558 | Series averaged within IDs, then IDs equally |
| Omit unresolved 500 K condition | 0.563 | 6 conditions; same 5 series equally |

The rounding-assumption range is 0.518-0.533, narrower than the change associated with omitting the unresolved condition. This comparison illustrates P2: additional decimal arithmetic does not settle an uncertain source interpretation. Source uncertainty, model approximation and numerical perturbation address different questions (Smith, 2013). Measurement-error analysis similarly shows why uncertainty in constructed quantities cannot generally be reduced to the precision with which their final values are stored (Carroll et al., 2006).

Data quality also includes whether information is adequate for its intended reuse (Wang and Strong, 1996). Our table audit resolves an identifiable column-placement problem, but it does not certify every historical numerical entry. A potential transcription issue in the compilation remains distinct from a calibration uncertainty in the original apparatus. Treating both as one small rounding interval would conceal rather than quantify the unresolved evidence.

## What the finite comparison cannot transfer

The table does not support estimating a pressure-dose curve or separating porosity, temperature and matrix composition statistically. The physical distinctions are nevertheless well motivated. Effective-medium models represent rock conductivity using properties of solid and fluid phases, pore fraction and geometry (Zimmerman, 1989). Bounds for porous materials also distinguish internally porous solids from granular structures (Carson et al., 2005). We fit neither model; the small set of compiled pairs cannot validate its assumptions or supply its missing parameters.

Returned solid-rock and breccia entries also cannot directly stand for the regolith fines surrounding an instrument. Modern lunar regolith models at low temperature combine physical assumptions with measurements and fits to particulate materials (Woods-Robinson et al., 2019). Diviner-based work infers spatial thermophysical properties using orbital radiometry and modeling (Hayne et al., 2017). These are different evidence pathways and physical supports. Our ratios do not calibrate those models or validate the thermal state of a lunar surface location.

No probabilistic sampling mechanism connects these few historical series to all lunar materials. Sampling theory distinguishes an explicitly selected finite collection from a population supported by a probability design (Neyman, 1934). The repeated identifiers and temperature conditions are especially important here: increasing the row count does not create independent material replications. Case-based research can still clarify a bounded phenomenon without pretending that the cases constitute such a sample (Flyvbjerg, 2006). Our contribution is the recoverable conditioning and quantitative sensitivity of this table.

## Reusing material parameters in lunar scenarios

Lunar-R1 names energy among the domains of its lunar scenarios (Xiao et al., 2026). That domain supplies a limited reason to care about the conditions attached to material inputs. A thermal parameter entering an energy-related calculation should retain its temperature, pressure regime and derivation. Lunar-R1 does not provide a dedicated thermal-conductivity test in the material examined here. We execute no language model, reconstruct none of its questions, and infer no effect on its reasoning procedure or performance.

For the acquired compilation, a reusable numerical statement should therefore identify the paired condition and averaging unit alongside retention. A value near 0.526 is a five-series description, not a universal vacuum multiplier. The separate interval-pressure cases and the unresolved 500 K condition remain part of the result. Their explicit treatment allows later users to decide whether this source supplies the condition needed by their own calculation.

The analysis plan was fixed after reading the source values and original-method evidence, before programmed ratio calculation; it is not prospective registration. The retained 28-row audit preserves exclusions, raw decimal strings and source locations. Derived fields appear once per pair, on the lower-pressure anchor row, so a user cannot accidentally double the total weight by counting both input rows. Independent high-precision arithmetic checks the ratios and all reported summaries. Recovering the connection from original evidence to a calculation is a central requirement of reproducible computational work (Peng, 2011).

Source files, identities, access conditions, transformation rules and output checksums are retained to support reuse, consistent with FAIR principles (Wilkinson et al., 2016). Accountable human source verification and final approval remain pending. The finite evidence supports condition-specific descriptions and exposes the consequences of source support and weighting; it does not warrant a single context-free correction for lunar thermal conductivity.

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