

# Thermal Conductivity Performance and Insulation Benefits of Hybrid Drilling and Production Strings for Geothermal Wells

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## ABSTRACT

This paper presents an ASTM-based thermal conductivity testing program for bare titanium Grade 5 and coated pipe materials intended for high-temperature or super-hot rock geothermal drilling and production. Measurements between 120°C and 500°C using two standardized methods provide a consistent dataset of apparent thermal conductivity and thermal resistance under controlled laboratory conditions.

The results show that thermal barrier coatings can significantly reduce heat transfer through the drill pipe wall compared with bare titanium and coated titanium and steel, with one advanced coating achieving particularly low conductivity over its qualified temperature range. By comparing the two test methods, the study clarifies when each is best applied using D5470-17R24 as the primary standard for coated systems and E1225-25 as a complementary method for uniformed materials (i.e. bare metals) and high-temperatures.

The resulting dataset and benchmarking protocol are intended for direct integration into wellbore thermal models and hybrid drill string and production casing / tubing design workflows, enabling more accurate prediction of internal fluid temperatures and supporting strategic placement of titanium, coated titanium, and coated steel sections along the drill string in superhot geothermal wells. This dataset and protocol can effectively support casing and production design processes.

## 1. INTRODUCTION

High-temperature geothermal drilling and production represents a growing opportunity for sustainable energy production, with wells targeting formations exceeding 400°C now under development. These extreme conditions present significant thermal challenges for conventional drill pipe materials, which degrade at relatively low geothermal temperatures and corrode rapidly in aggressive geothermal fluids.

Accurate characterization of thermal properties in material systems such as titanium, coated titanium and coated steel is essential for designing safe and reliable drill strings and production casing / tubing designs in these environments. The primary objective of this work is to generate a comprehensive, ASTM-based dataset of apparent thermal conductivity and thermal resistance for bare titanium Grade 5, coated titanium, and coated steel across 120-500°C range (ASTM D5470, 2024; ASTM E1225, 2025). These measurements will serve as reference data for material benchmarking and to support future integration with wellbore thermal models.

A secondary objective is to evaluate two complementary ASTM standards D5470-17R24 and E1225-25 and establish clear guidance on when each method is most appropriate for characterizing interfacial thermal resistance and multi-layer response in heterogeneous and coated pipe materials (ASTM D5470, 2024; ASTM E1225, 2025). Recent technology gap assessments for superhot geothermal drilling and production have identified drill string designs with coated steel, vacuum insulated pipe, and titanium sections in strategic high-temperature and high-stress zones as a promising approach to manage extreme downhole temperatures while balancing cost and mechanical performance (Pearce, et al., 2025). Such designs require reliable, standardized thermal conductivity data as foundational inputs to physics-based insulation models and material selection tools. The present study directly supports these efforts by supplying ASTM D5470-17R24 and E1225-25 measurements and a reproducible framework that can be integrated into transient wellbore thermal simulators and techno-economic analyses.

**Structure of this paper:** Section 2 establishes material and thermal requirements for high-temperature and SHR geothermal drilling and production. Section 3 provides background on wellbore heat transfer and the hybrid drill string and production casing / tubing concepts. Section 4 describes the experimental methods, including detailed methodology comparison. Sections 5 and 6 present D5470-17R24 and E1225-25 results. Section 7 summarizes thermal performance across all materials and uncertainty analysis. Section 8 addresses downhole thermal validation. Sections 9 and 10 discuss methodological and design implications, limitations, and future work.

## 2. MATERIAL REQUIREMENTS AND THERMAL CHALLENGES FOR SUPER HOT ROCK (SHR) GEOTHERMAL PIPE

### 2.1 Material Degradation in Conventional Pipe

In SHR temperature geothermal environments, conventional drill pipe or casing materials face severe degradation. Steel grades, such as S135, begin to lose mechanical strength above 250°C, leading to accelerated corrosion and fatigue failure in wells with temperatures exceeding 400°C. Geothermal fluids often contain aggressive species of hydrogen sulfide (H<sub>2</sub>S), carbon dioxide (CO<sub>2</sub>), and chloride ions that further accelerate corrosion. Cyclic stresses from deviated well geometry and extended-reach applications exacerbate fatigue-related failures in conventional materials. This is then compounded by the thermal stresses associated with a geothermal well. Geothermal production casing / tubing designs experience similar loads and stresses from production operations.

### 2.2 Titanium Pipe

Titanium pipe offers significant advantages in these environments. Laboratory testing demonstrates that titanium has stable mechanical properties at temperatures exceeding 400°C and exhibits fatigue life approximately 10 times greater than conventional steel, based upon rotary fatigue studies. (ALTISS Technologies, et al., 1996).

Titanium provides superior corrosion resistance, particularly in CO<sub>2</sub> or H<sub>2</sub>S-bearing fluids and aggressive drilling environments (Jackson, et al., 2025; ALTISS Technologies, et al., 2025). Galvanic corrosion couples are addressed for drilling applications, contributing to long-term reliability in multi-material drill string or casing / tubing configurations. This level of corrosion resistance may be critical for future applications involving supercritical CO<sub>2</sub> drilling fluids or for production systems operating in corrosive or supercritical reservoir conditions.

### 2.3 Thermal Insulation Through Coatings

Beyond mechanical and corrosion resistance, the thermal properties of pipe materials and coating systems merit investigation. Strategic application of thermal barrier coatings can reduce the rate of radial heat transfer from the formation to the circulating fluid, thereby potentially maintaining lower internal fluid temperatures during drilling operations. This protection is important for:

- Preventing downhole tool failures
- Extending the operational life of temperature-sensitive downhole tools (e.g., measurement-while-drilling devices)
- Improving drilling efficiency
- Enabling economic operation in formations exceeding 400°C

The specific thermal performance of candidate coatings and substrate materials across the operating temperature range has not been comprehensively characterized using standardized methods. Quantitative data on the apparent thermal conductivity of bare and coated pipe materials across the 120-500°C range are limited in published literature. This work addresses that gap by providing ASTM-standard measurements that can be incorporated into wellbore thermal models and used as reference data for evaluating coating systems and material combinations for advanced drill string design.

## 3. BACKGROUND AND DESIGN BASIS

### 3.1 Thermal Transport in Wellbores

Regional geothermal regimes are commonly described in terms of a geothermal gradient, where formation temperatures increase with depth in a manner controlled by heat flow and rock thermal conductivity (Smith Nash et al., 2022). This temperature gradient is the primary driver for all heat exchange phenomena in a wellbore, both in oil and gas extraction and in geothermal energy production.

In a drilling wellbore, energy is exchanged between (Abdelhafiz et al., 2021; Chandrasekhar et al., 2023):

- The flowing fluid stream and the conduit boundary (forced convection)
- The wellbore and the casing strings and annular contents (conduction through coating layers)
- The formation and the wellbore boundary (semi-infinite domain diffusion)

**Radial heat flow pathway:** Heat flows into the pipe's interior fluid through a series of layers: Formation → Cement → Casing → Annulus Fluid → Exterior Coating → Pipe Metal → Interior Coating → Interior Fluid. The cement and casing layers are absent when the drill pipe is in the open hole section. Understanding and accurately modeling this radial heat-transfer path is critical for predicting fluid temperature profiles, designing thermal insulation systems, and protecting sensitive downhole equipment (Chandrasekhar et al., 2023).

The thermal transmission properties of pipe wall components, specifically the interior coating, pipe metal, and exterior coating layers, are central to wellbore thermal design. Conventional approaches often use a single average thermal conductivity for the entire pipe wall. However, a higher-fidelity approach quantifies the individual thermal resistance of each layer, allowing more accurate prediction of overall thermal performance. Modern geothermal well designs demonstrate the importance of detailed thermophysical characterization of all wellbore components.

### 3.2 Hybrid String Concept - Drilling or Production

The hybrid drill string and production casing / tubing design approach places bare and coated materials in strategic zones throughout the wellbore to balance cost, mechanical performance, and thermal characteristics. The optimal design of hybrid strings combining different material and coating combinations must account for:

- Non-linear dynamic characteristics at material transitions
- Stress concentration effects at the material transitions
- Thermal boundary layer effects
- Overall mechanical and thermal performance across the entire wellbore profile

Recent modeling studies have evaluated the impact of various bare and coated material configurations on bottom-hole circulation temperature and tool life using measured or estimated thermal conductivities (Vetsak et al., 2024). The standardized ASTM apparent thermal conductivity dataset and benchmarking protocol developed in this work provides a pathway to ground such assessments with measured material properties, enabling more accurate predictions of downhole thermal performance and refined material selection guidance for superhot geothermal systems.

## 4. EXPERIMENTAL METHODS

All ASTM testing was conducted by an ISO/IEC 17025-accredited third-party independent test facility, with results taken directly from the official test reports. The program comprised of six test studies, each performed in accordance with relevant ASTM standards using the same calibrated instruments and procedures.

### 4.1 Test Materials and Coatings

The testing program utilized bare titanium Grade 5 and carbon steel substrates with various coating systems. Test specimens represented commercially available pipe materials and advanced thermal-barrier coating systems. Specific material compositions and coating formulations are proprietary and governed by non-disclosure agreements; therefore, only bare titanium and coating designations (Coating A, Coating B, Coating C, Coating D, and Coating E) are disclosed in this report.

Specimens were prepared from pipe samples nominally ranging from 104mm to 140mm in length and approximately 21 mm to 22mm in width and thickness, with thermocouple holes drilled into end surfaces to enable precise temperature measurement during testing. Specimens were tested as received without additional conditioning.

### 4.2 ASTM D5470-17R24: Guarded Hot-Plate Method

ASTM D5470-17R24 specifies a method for measuring thermal impedance and calculating apparent thermal conductivity of thermally conductive electrical insulating materials, from liquid compounds, heterogeneous and layered systems, and hard uniform materials (ASTM D5470, 2024). The method uses a guarded-through-thickness apparatus in which specimens are compressed between hot and cold plates under controlled pressure. It directly yields the total thermal impedance of the specimen plus all interfaces, reported as an apparent thermal conductivity representing the effective property of the entire layer stack under specific test conditions (pressure, surface finish, and interface material) (ASTM D5470, 2024).

Apparent thermal conductivity is calculated from measured heat flow using Fourier's First Law:

$$\lambda = \frac{Q \cdot L}{A \cdot \Delta T}$$

where  $\lambda$  is thermal conductivity (W/(m·K)),  $Q$  is heat flow in the metered section (W),  $A$  is cross-sectional area (m<sup>2</sup>),  $L$  is specimen's length (m), and  $\Delta T$  is temperature difference across the specimen (°C) (ASTM D5470, 2024).

**Test procedure:** Specimens were prepared to D5470-17R24 specifications and loaded into the guarded apparatus with controlled thickness and contact pressure. Temperature points tested ranged from 120°C to 500°C. Meter bars, matched in thermal resistance to specimens and instrumented with thermocouples, were used for heat-flux measurements. Copper adaptor plates (6.3 mm thick) served as heat spreaders; thermocouples were inserted into predrilled holes, wrapped along isotherms, and secured with tape. A small amount of thermal grease was applied to each thermocouple tip to improve thermal contact. A suitable thermal interface material was applied at all interfaces, and a constant compressive force of 0.69 MPa was maintained to minimize contact resistance. The stack was enclosed in fiberglass insulation (with thermal conductivity of 0.038 W/(m·K)), surrounded by an IR-reflective, low-emissivity aluminum shield, an actively heated guard, and a final radiation shield to minimize lateral heat loss. The apparatus was ramped to target temperature and held until steady state was achieved. All specimens were tested in the thickness direction, with the coating on side 2 facing down.

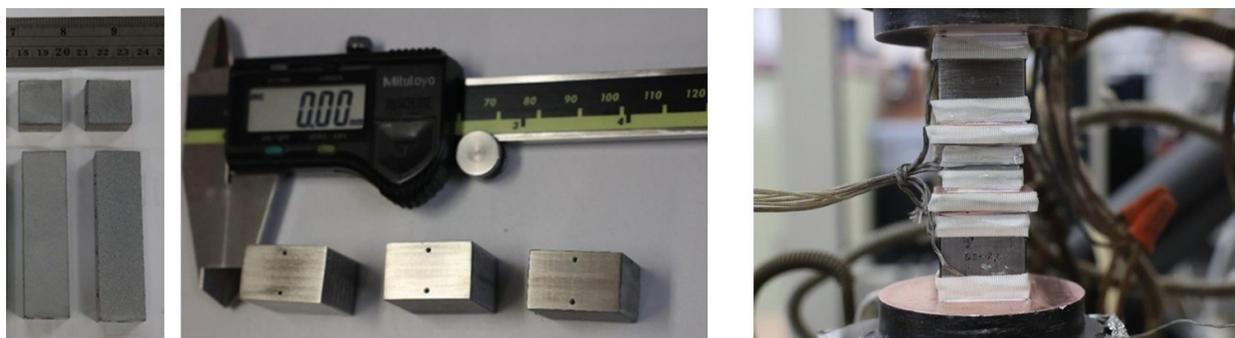


Figure 1: D5470-17R24 Test Samples & Fixture Without Shields

### 4.3 ASTM E1225-25: GUARDED-COMPARATIVE-LONGITUDINAL HEAT-FLOW METHOD

ASTM E1225-25 is intended for uniform, opaque solids and uses a guarded-comparative-longitudinal heat-flow technique with meter bars matched in thermal resistance to the specimen (ASTM E1225, 2025). This method infers specimen conductivity indirectly from meter-bar temperature gradients and applies corrections to account for contact resistance (ASTM E1225, 2025). A suitable thermal interface material was applied at all interfaces, and a constant compressive force of 0.39 MPa was maintained to minimize contact resistance. Apparatus performance was verified using Pyroceram 9606 and NIST SRM 1462 austenitic stainless steel reference materials, compared against published thermophysical property data (TPRC) and NIST certificate data to confirm measurement accuracy. Testing precision was  $\pm 0.1^\circ\text{C}$ , with absolute temperature error less than  $\pm 0.5^\circ\text{C}$ .

### 4.4 MEASUREMENT UNCERTAINTY QUANTIFICATION

Measurement uncertainty was quantified using the root-sum-square (RSS) method. The combined standard uncertainty  $u_c$  was calculated as:

$$u_c = \left[ \left( \frac{\partial \lambda}{\partial x_1} u_1 \right)^2 + \left( \frac{\partial \lambda}{\partial x_2} u_2 \right)^2 + \dots + \left( \frac{\partial \lambda}{\partial x_n} u_n \right)^2 \right]^{1/2}$$

where  $x_i$  is the measurement input ( $i = 1 \dots n$ ),  $u_i$  is the estimated uncertainty in each measurement input,  $x_i$ , and  $\partial \lambda / \partial x_i$  is the weighted contribution of each input,  $x_i$ .

Table 1: Estimated Uncertainty

Quantity	Symbol	Estimated Uncertainty	Unit
Thermal Conductivity	$\lambda$	5% of reading	W/(m·K)
Cross-Sectional Area	A	1%	m <sup>2</sup>
Specimen Length	L	0.127 x 10 <sup>-3</sup> (D5470) 0.254 x 10 <sup>-3</sup> (E1225)	m
Temperature Difference	T	0.25	°C

### 4.5 Methodological Comparison: D5470-17R24 vs. E1225-25

A key contribution of this work is systematic comparison of ASTM D5470-17R24 and ASTM E1225-25, establishing when each method is best applied for thermal property characterization of pipe and coating materials in geothermal applications.

Table 2: Comparison D5470-17R24 vs. E1225-25

Aspect	D5470-17R24	E1225-25
Intended Material Type	Heterogeneous, coatings, layered systems	Uniform, opaque solids
Configuration	Guarded- through-thickness	Guarded-comparative-longitudinal

Interfacial Resistance	Directly measured; included in reported apparent conductivity	Inferred indirectly; corrected for contact resistance
Contact Pressure	0.69 MPa	0.39 MPa
Specimen Geometry	Flexible; accommodates thin coatings and irregular shapes	Requires long, bar-shaped specimens (~50 mm); close dimensional matching
Observed Measurement Uncertainty	Lower: 1.8-8.2 %	Higher: 6.4-12.9 %
Best Application	Bare metal or coated tubulars to 500 °C	Uniform materials (bare titanium, bare steel) as complementary method

The D5470-17R24 and E1225-25 measurements in this program were performed successfully at temperatures up to 500 °C, with no apparent limitations imposed by the test apparatus. Calibration checks conducted both before and after testing confirmed that the equipment operated within acceptable performance bounds.

**Application guidance:** For coated and coating pipe materials, D5470-17R24 is best suited for characterization over the temperature range 120-500°C because of its applicability to heterogeneous systems, lower measurement uncertainty, direct quantification of interfacial thermal resistance, and practical specimen geometry requirements. For uniform bare materials such as titanium and carbon steel, E1225-25 provides a complementary method over the same range, using a different heat-flow geometry and instrumentation, offering cross-validation of high-temperature data up to 500°C.

The two methods should be viewed as complementary; D5470-17R24 as the primary standard for coated and coating systems and for establishing reference properties of bare substrates, and E1225-25 as a complementary method for uniform materials to enable full validation of wellbore thermal models (ASTM D5470, 2024; ASTM E1225, 2025).

## 5. ASTM D5470-17R24 RESULTS

Bare titanium specimens were tested to establish a baseline for thermal conductivity and thermal resistance. The coated configurations were evaluated as integrated systems of metal substrate plus coating. The metal substrates consisted of either Grade 5 titanium or a carbon steel representative of standard tubulars. The results presented below therefore reflect the combined thermal response of each substrate-and-coating system, rather than the coating alone. Temperature-dependent apparent thermal conductivity data are presented in accompanying tables and figures.

**Bare titanium baseline:** Titanium Grade 5 exhibited thermal conductivity increasing from 7.27 W/(m·K) at 120°C to 10.06 W/(m·K) at 500°C, establishing a consistent reference baseline for uncoated titanium drill pipe performance across the geothermal temperature range.

**Coating A performance:** Coating A demonstrated a reduced apparent thermal conductivity of 3.69-3.95 W/(m·K) over the 120-232°C range, representing an approximate 49-53% reduction relative to bare titanium. This substantial thermal barrier improvement indicates suitability for wellbore sections operating below 232°C. Testing above this temperature was not conducted per the supplier's recommendation.

**Coating B performance:** Coating B exhibited an apparent thermal conductivity of 6.98-7.92 W/(m·K) over the 120-500°C range, corresponding to an approximate 4-21% improvement compared to bare titanium. These improvements suggest suitability for high-temperature applications (>300°C), where coating adhesion, durability, and minimal added thickness are prioritized. No coating degradation was observed up to 500°C.

**Coating C performance:** Coating C showed an apparent thermal conductivity of 6.64-8.52 W/(m·K), corresponding to a 9-15% improvement compared to bare titanium. Like Coating B, this performance profile favors applications above 300°C or where mechanical durability and thin-film integrity are critical. No degradation was observed up to 500°C.

**Coating D performance:** Coating D exhibited exceptional thermal barrier properties, with an apparent thermal conductivity of 0.31-0.48 W/(m·K) across the 120-287°C range. This represents nearly an order-of-magnitude reduction (~96%) relative to bare titanium and other tested coatings. Testing beyond 287°C was not performed per the supplier's guidance.

**Coating E performance:** Coating E displayed apparent thermal conductivity of 4.07-4.34 W/(m·K) across the 90°C -232°C temperature range, corresponding to an approximate 40-52% improvement compared to bare titanium. This significant improvement makes it suitable for moderate-temperature wellbore sections (<232°C). Testing above 232°C was not performed as recommended by the supplier.

Tables 3 & 4: ASTM D5470-17R24 Test Studies 1 and 3 Results

ASTM D5470 Results (120-232°C)				
Material ID	Nominal Specimen Temperature (°C)	Apparent Thermal Conductivity (W/(m·K))	Thermal Resistance (m <sup>2</sup> -K/W)	Estimated Uncertainty (%)
Titanium Bare	120	7.27	0.001842	7.2
	180	7.89	0.001697	7.7
	232	8.42	0.001591	8.2
Coating A	120	3.69	0.003742	5.5
	180	3.86	0.003571	5.6
	232	3.95	0.003497	5.7
Coating B	120	6.98	0.001933	6.9
	180	7.52	0.001793	7.4
	232	7.94	0.001698	7.8
Coating C	120	6.64	0.002016	6.7
	180	7.15	0.001873	7.2
	232	7.57	0.001769	7.5

ASTM D5470 Results (300-500°C)				
Material ID	Nominal Specimen Temperature (°C)	Apparent Thermal Conductivity (W/(m·K))	Thermal Resistance (m <sup>2</sup> -K/W)	Estimated Uncertainty (%)
Titanium Bare	300	9.19	0.001456	5.2
	370	9.61	0.001393	5.2
	425	10.05	0.001332	5.3
	500	10.06	0.001331	5.6
Coating B	300	8.39	0.001608	5.3
	370	8.67	0.001556	5.4
	425	8.68	0.001553	5.5
	500	7.92	0.001703	5.9
Coating C	300	8.12	0.001649	5.2
	370	8.57	0.001563	5.2
	425	8.73	0.001534	5.2
	500	8.52	0.001572	5.3

Tables 4 & 5: ASTM D5470-17R24 Test Studies 5 and 6 Results

ASTM D5470 Results (120-287°C)				
Material ID	Nominal Specimen Temperature (°C)	Apparent Thermal Conductivity (W/(m·K))	Thermal Resistance (m <sup>2</sup> -K/W)	Estimated Uncertainty (%)
Coating D	120	0.31	0.0836	1.8
	180	0.37	0.0693	1.5
	232	0.42	0.0616	4.3
	287	0.48	0.0517	3.4

ASTM D5470 Results (90-232°C)				
Material ID	Nominal Specimen Temperature (°C)	Apparent Thermal Conductivity (W/(m·K))	Thermal Resistance (m <sup>2</sup> -K/W)	Estimated Uncertainty (%)
Coating E	90	4.34	0.00232	4.6
	107	4.39	0.00229	4.6
	120	4.37	0.00231	4.6
	150	4.37	0.00231	4.6
	180	4.27	0.00236	4.6
	210	4.17	0.00241	4.6
	232	4.07	0.00248	4.7

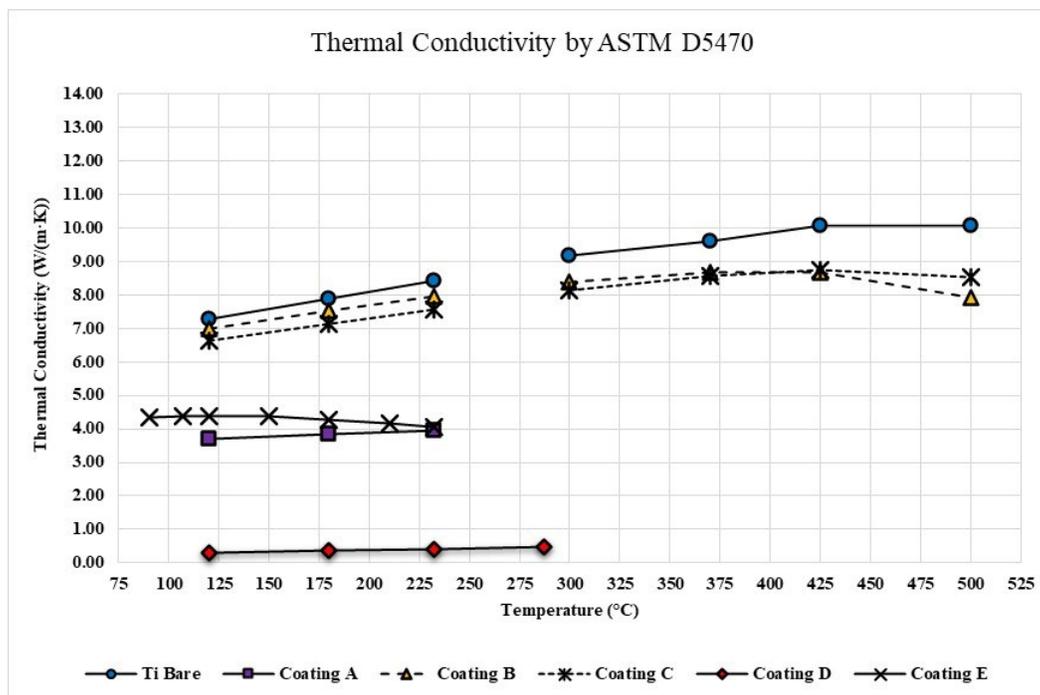


Figure 2: ASTM D5470-17R24 Thermal Conductivity Data

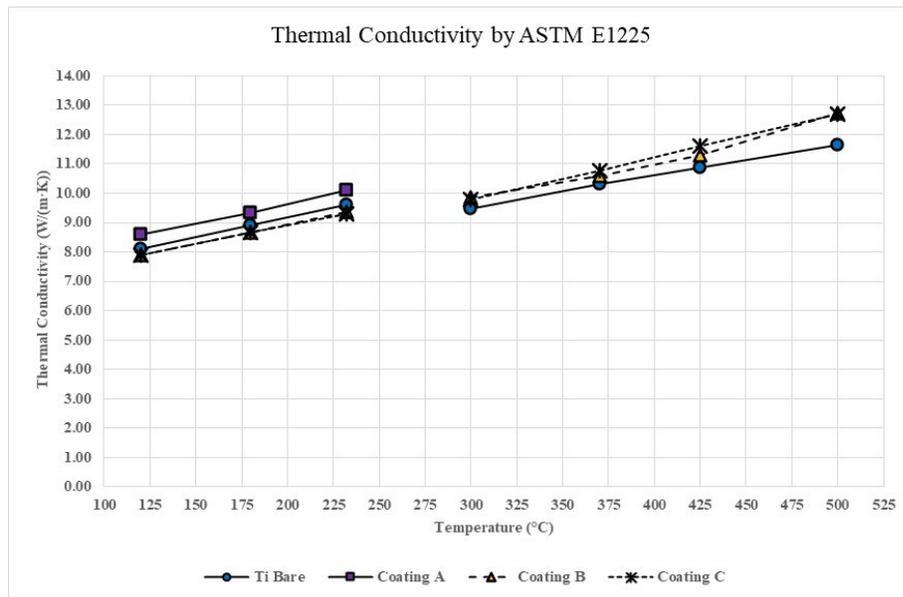
**6. ASTM E1225-25 RESULTS**

In parallel with D5470-17R24 testing, E1225-25 was also performed up to 500°C using appropriate meter-bar materials and high-temperature insulation systems, providing an independent and complementary high-temperature dataset. These measurements extended the temperature coverage and enabled cross-validation of the two methods.

**Tables 7 & 8: ASTM E1225-25 Test Study 2 and 4 Results**

ASTM E1225 Results (120-232°C)				
Material ID	Nominal Specimen Temperature (°C)	Apparent Thermal Conductivity (W/(m·K))	Thermal Resistance (m <sup>2</sup> ·K/W)	Estimated Uncertainty (%)
Titanium Bare	120	8.12	NA	10.6
	180	8.93	NA	11.8
	232	9.61	NA	12.9
Coating A	120	8.61	NA	11.7
	180	9.34	NA	12.8
	232	10.1	NA	13.9
Coating B	120	7.88	NA	10.1
	180	8.68	NA	11.2
	232	9.37	NA	12.2
Coating C	120	7.89	NA	9.9
	180	8.66	NA	11.0
	232	9.29	NA	11.8

ASTM E1225 Results (300-500°C)				
Material ID	Nominal Specimen Temperature (°C)	Apparent Thermal Conductivity (W/(m·K))	Thermal Resistance (m <sup>2</sup> ·K/W)	Estimated Uncertainty (%)
Titanium Bare	300	9.49	NA	6.4
	370	10.31	NA	6.6
	425	10.86	NA	6.7
	500	11.64	NA	7.1
	300	9.87	NA	6.6
Coating B	370	10.58	NA	6.8
	425	11.31	NA	7.0
	500	12.72	NA	8.0
	300	9.79	NA	6.4
	370	10.77	NA	6.5
Coating C	425	11.6	NA	6.6
	500	12.68	NA	7.0



**Figure 3: ASTM E1225-25 Thermal Conductivity Data**

**7. PERFORMANCE COMPARISON AND UNCERTAINTY ANALYSIS**

**7.1 Comparative Thermal Performance Across All Materials**

At 232°C, bare titanium exhibited an apparent thermal conductivity of 8.42 W/(m·K), while coated variants showed widely different values ranked from lowest to highest W/(m·K):

1. Coating D: 0.42 W/(m·K)
2. Coating A: 3.95 W/(m·K)
3. Coating E: 4.07 W/(m·K)
4. Coating C: 7.57 W/(m·K)
5. Coating B: 7.94 W/(m·K)

Direct comparison among coated specimens must account for differences in substrate material, coating thickness, specimen composition, and surface finish, as each factor influences apparent conductivity measurements.

Table 8 shows the comparison and improvement of the coating sample relative to bare titanium. Coatings B and C exhibited increasing improvement at high temperatures which may be indicative of their unique material characteristics.

**Table 9: Percentage Improvement from Bare Titanium**

Percentage Improvement from Bare Titanium					
Temperature °C	Coating A	Coating B	Coating C	Coating D	Coating E
120	49%	4%	9%	96%	40%
180	51%	5%	9%	95%	46%
232	53%	6%	10%	95%	52%
300		9%	12%		
370		10%	11%		
425		14%	13%		
500		21%	15%		

Thermal resistance, a more relevant parameter for radial heat-transfer analysis in wellbore applications, showed that all coated variants possessed higher thermal resistance (lower apparent conductivity) than bare titanium across the tested temperature range.

## 7.2 Measurements - Uncertainty and Validation

D5470-17R24 measurements exhibited uncertainties ranging from 1.8 to 8.5 %, reflecting the direct nature of thermal impedance measurement and minimal need for corrective adjustments. E1225-25 uncertainties ranged from 6.4 to 13.9 %, primarily due to the indirect determination of heat flux and additional corrections required for lateral heat shunting and meter-bar calibration. The lower uncertainty associated with D5470-17R24 makes it well suited for establishing high-accuracy reference data on coated and coating materials, while E1225-25 provides adequate accuracy for extending measurements into higher temperature ranges for uniform materials.

All measurements were performed in accordance with ASTM standards, with systematic uncertainty quantification throughout. Apparatus accuracy was verified using reference materials, including Pyroceram 9606 and NIST SRM 1462 austenitic stainless steel. These validations confirmed the reliability and accuracy of both testing setups across the investigated temperature ranges.

## 8. DISCUSSION

### 8.1 Downhole Thermal Validation and Implications

The measured apparent thermal conductivity and thermal resistance values provide critical inputs for physics-based wellbore thermal models (Abdelhafiz et al., 2021; Chandrasekhar et al., 2023). Direct use of measured apparent conductivity and thermal resistance in transient, coupled thermal-hydraulic simulators enable more accurate prediction of downhole temperature profiles than approaches that assume a single effective pipe-wall conductivity. This improved fidelity is essential for:

- Predicting internal fluid temperature profiles under realistic circulation and shut-in schedules
- Assessing downhole tools for survivability and operational life
- Optimizing material placement and zoning in hybrid drill string and production casing / tubing designs

### 8.2 Summary of Key Thermal Performance Trends

The experimental program produced a comprehensive ASTM-based baseline of apparent thermal conductivity and thermal resistance for bare titanium Grade 5 and coated metal substrates across 120-500°C temperature range, enabling direct comparison of coating systems under consistent conditions. These results confirm that both coating system and substrate selection strongly modulate thermal transport, and that high-performance coatings can significantly lower radial heat transfer in critical wellbore sections.

Bare titanium thermal conductivity ranging from 7.27 W/(m·K) at 120°C to 10.06 W/(m·K) at 500°C establishes a reliable reference for uncoated titanium pipe. Coating A reduces apparent thermal conductivity by approximately 50 % relative to bare titanium at 120°C, with this reduction maintained across the 120-232°C measurement range, representing substantial thermal barrier enhancement suitable for wellbore sections up to 232°C. Coatings B and C applied to bare titanium reduced apparent thermal conductivity by 4-21% depending on temperature and formulation, with moderate thermal barrier performance. However, these coatings were the only coatings tested that could perform at 300-500°C. Coating D exhibited exceptional thermal barrier properties with apparent thermal conductivity ranging from 0.307 to 0.483 W/(m·K) across 120-287°C. Coating E had similar performance as Coating A. It reduced the apparent thermal conductivity by approximately 40-50% relative to bare titanium at 120-232°C, representing substantial thermal barrier enhancement suitable for wellbore sections up to 232°C.

### 8.3 Methodological Contributions and Framework

For coated and coating specimens, ASTM D5470-17R24 demonstrated clear advantages as the primary characterization method. Its guarded-through-thickness configuration directly measures total thermal impedance of heterogeneous, multilayer stacks under representative contact pressure (0.69 MPa), capturing interfacial resistances and yielding an apparent thermal conductivity that can be applied directly in radial heat-transfer models. Uncertainties for D5470-17R24 ranged from 1.8-8.5%, reflecting direct heat-flux measurement and limited corrective terms. In contrast, ASTM E1225-25, optimized for uniform solids, relies on indirect heat-flux determination and additional corrections for lateral shunting and meter-bar calibration, resulting in higher uncertainties of 6.4-13.9%.

Consistency between D5470 and E1225 on bare titanium in the 120-232°C overlap range, within combined uncertainties, confirms the robustness of the dataset and the complementary roles of the two methods.

This work establishes a comparative framework clarifying when D5470-17R24 and E1225-25 are each most appropriate. D5470-17R24 is best suited for coated and coating specimens because of its explicit design for heterogeneous systems, superior measurement uncertainty, and direct quantification of interfacial thermal resistance up to 425-500°C. E1225-25 provides complementary high-temperature capability up to 500°C or higher for uniform materials and serves as an independent validation check in overlap temperature ranges.

#### **8.4 Design Implications for Hybrid Drilling and Production Strings**

The resulting dataset is well aligned with the needs of geothermal wellbore thermal analysis, where layer-by-layer thermal resistance strongly influences circulating fluid temperature and tool survivability. In the context of hybrid drill string and production casing / tubing designs, the data provides a quantitative basis for zoning high-thermal-barrier coatings such as Coatings A, D, and E in intervals below 232-287°C, while deploying materials with different thermal and mechanical characteristics in hotter or higher-stress sections. This zoning approach balances insulation, structural performance, and cost. This is applicable for operations expecting temperatures below 300°C. For operations over 300°C, titanium is applicable and coatings B and C may add additional smaller benefits.

The standardized D5470-17R24 based protocol, including defined contact pressure, temperature envelope, interface conditions, and reporting format, establishes a reproducible benchmark for evaluating future coating formulations and alternative substrates on a common basis. The wide range in thermal conductivities, from 0.307 W/(m·K) for Coating D to 8.42 W/(m·K) for bare titanium at 232°C, demonstrates that strategic pairing of coatings and substrates can substantially tailor thermal performance along the drill string.

#### **8.5 Limitations and Validation Requirements**

Despite this progress, several limitations must be recognized when extrapolating laboratory measurements to field conditions. The tests were conducted under controlled, steady-state conditions with silicone-based thermal grease and fixed contact pressure under vacuum conditions, which may differ from dynamic downhole environments characterized by vibration, cyclic loading, fluid chemistry, and evolving contact conditions. Long-term aging, thermal cycling, and exposure to drilling-fluid additives were not addressed in the present program and may affect coating integrity, interfacial resistance, and overall thermal performance.

Accordingly, field-scale validation of model predictions using measured thermal properties through pilot deployments or dedicated test wells will be essential to fully quantify performance and refine design margins for superhot geothermal applications.

### **9. CONCLUSIONS**

This study presents a unified ASTM 5470-17 standard thermal conductivity dataset for bare titanium Grade 5 and metal substrates with commercial and advanced coating systems (Coatings A, B, C, D and E) over 120-500 °C temperature range, with explicit uncertainty quantification and validation against NIST-traceable reference materials. Titanium Grade 5 exhibited thermal conductivity increasing from 7.27 W/(m·K) at 120°C to 10.06 W/(m·K) at 500°C, providing a robust baseline for uncoated drill pipe in high-temperature geothermal wells. Coating A and E reduced apparent thermal conductivity by roughly 40-50% relative to bare titanium over 120-232°C. Coatings B and C achieved moderate 4-11% reductions depending on temperature and formulation. Coating D delivered the lowest apparent thermal conductivity of all materials tested (0.307-0.483 W/(m·K) over 120-287°C temperature range), demonstrating exceptional thermal barrier performance.

#### **9.1 Methodological Framework**

The work establishes a clear framework for selecting ASTM D5470-17R24 and ASTM E1225-25 for geothermal pipe and coating characterization. D5470-17R24, with uncertainties of 1.8-8.5%, is identified as the primary standard for coated and coating materials due to its suitability for heterogeneous systems, direct quantification of interfacial resistance, and practical specimen geometries. E1225-25, with uncertainties of 6.4-13.9%, serves as a complementary method for uniform bare materials and as an independent cross-check in the overlapping temperature ranges. Agreement between the two methods on bare titanium within combined uncertainties validates their joint use for building consistent, high-temperature datasets extending to 500°C.

#### **9.2 Applications and Implications:**

The measured apparent thermal conductivity and thermal resistance values provide critical inputs for physics-based wellbore thermal models, enabling more accurate prediction of internal fluid temperatures and improved assessment of downhole tool life in superhot geothermal environments. The significant variation in thermal properties across coating systems demonstrates that strategic coating selection and substrate material choice can substantially modulate thermal performance across the drill string. These standardized measurements directly support the design of hybrid drill strings and production casing / tubing designs in which high-performance coatings are deployed in the hottest zones and alternative material/coating combinations are used elsewhere to optimize thermal, mechanical, and economic performance.

#### **9.3 Future Work Priorities:**

Material selection for hybrid drill strings or casing / tubing systems extends far beyond the results of a single ASTM thermal conductivity test. Numerous factors such as mechanical loading, environmental exposure, and long-term durability must be considered. To quantify

thermal and mechanical stability over extended periods, a comprehensive coating durability assessment under simulated downhole conditions, including elevated temperature and pressure, cyclic bending and fatigue loads, and exposure to aggressive fluids is needed.

1. **Alternative substrate and coating systems:** Characterize thermal properties of candidate alternative pipe materials and next-generation coating formulations using the standardized D5470 protocol.
2. **Field validation program:** Integrate measured thermal conductivity values into validated thermal simulators, run predictions for representative geothermal wellbores, and compare predicted temperature profiles with actual measurements from field wells.
3. **Mechanical-thermal-economic optimization:** Develop coupled thermal-mechanical-economic models that optimize hybrid drill string designs for specific wellbore scenarios by integrating measured thermal properties, mechanical requirements, and cost constraints.
4. **Tubular screening testing methodology:** In parallel with this ASTM testing, ALTISS Technologies is developing an alternative screening method for thermal conductivity evaluation. This approach employs scaled or full-size tubular specimens with either bare or coated surfaces. The detailed ASTM data presented in this work serves as a baseline to guide refinement and correlation of these screening tests.
5. **Coating durability, fatigue assessment:** Upon validation of the screening methodology, available in-house equipment will be used to conduct bending and harmonic fatigue tests. These tests will assess the coated tube's mechanical integrity using full- or reduced-scale specimens. Post-fatigue and post-bending thermal conductivity measurements will be performed using the established screening procedure to capture any degradation in thermal performance.
6. **Super critical autoclave:** A collaborative corrosion testing initiative at approximately 500°C is being launched in partnership with an international research laboratory. This program will employ ALTISS Technologies' proven autoclave technology to evaluate drilling and production assemblies within a three-meter vessel exposed to extreme thermal, pressure, chemical, and supercritical conditions (Podnos, et al. 2018). The assemblies will be tested under combined tension, burst, and collapse loads representative of downhole SHR environments. Results from this work will guide the final design and commissioning of a large-bore (3 m) autoclave system capable of circulating fluids through bare and coated tube specimens under realistic downhole and supercritical conditions, delivering critical insights for future field-scale applications.

Ultimately, the D5470-17R24 and the E1225-25 based benchmarking protocols and associated apparent-conductivity datasets offer a reproducible framework for ongoing development and comparison of advanced materials and coating systems, supporting the technical and economic viability of superhot geothermal drilling and production to 500°C and beyond.

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