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Industry Recommended Practice

Radial Thermal Conductivity Performance Evaluation of Vacuum Insulated Tubing

January 2020
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NOTICE

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This IRP has been compiled by knowledgeable and experienced industry professionals and is intended to provide the User with a set of best practices and guidelines on the subject of Radial Thermal Conductivity Performance Evaluation for Vacuum Insulated Tubing (VIT).

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FOREWORD

The authors wish to acknowledge the funding provided by Canada's Oil Sands Innovation Alliance Inc. ("COSIA") members for the development of this Industry Recommended Practice. The authors also wish to acknowledge the input provided by members of the associated working group and the project team at C-FER Technologies (1999) Inc. ("C-FER") to guide and execute the scope of this project.

Furthermore, the authors would like to recognize the contributions and feedback provided by Vacuum Insulated Tubing suppliers including Western Alliance Tubulars LTD., ANDMIR Group Canada, Exceed (Canada) Oilfield Equipment Inc., Continental Steel Corporation, and Shengli Oilfield Freet Petroleum Equipment Co., LTD.

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1. INTRODUCTION

Use of Vacuum Insulated Tubing (VIT) offers the potential to reduce heat loss in thermal enhanced oil recovery (EOR) operations, thereby improving operational efficiency and reducing greenhouse gas (GHG) emissions. In addition, by minimizing the heat transfer to intermediate or production casing strings, VIT may reduce thermally-induced loads and improve well integrity. However, successful use of VIT largely depends on the thermal conductivity of the VIT system, which can vary significantly between joints (Zatka 2016).

The purpose of this Industry Recommended Practice (IRP) is to provide a practical and cost-effective test procedure for determining the apparent radial thermal conductivity (λ, often referred to as a "k-factor" or "k-value") of a VIT joint. While the focus is on VIT applications related to thermal EOR, this IRP may be useful when evaluating other VIT-related field applications, including permafrost conditions, deep-water completions and geothermal operations.

This IRP aims to balance the objectives of providing practical assessment procedures to facilitate participation from the greatest number of VIT suppliers, while providing sufficiently accurate and detailed information to allow Users to make informed decisions. To this end, this IRP builds on relevant literature, existing Supplier procedures, field trial experience, and recent full-scale experimental validation testing in addressing the most significant sources of measurement error and establishing the foundational requirements for determining and reporting the apparent radial thermal conductivity of a VIT joint.

This IRP is intended to be updated and refined as new research is conducted and new technologies are developed.

2. SCOPE

This IRP provides requirements and procedures for experimentally determining the apparent radial thermal conductivity of a VIT joint, consisting of two metallic tubulars with a vacuum-filled annulus, for thermal EOR applications. The impacts of threaded end connections and couplings on the apparent radial thermal conductivity are not considered.

The method for determining the apparent radial thermal conductivity is based on measurement of electrical power input with internal and external temperature measurement at steady-state conditions. It is acknowledged that other methods exist to measure the apparent radial thermal conductivity, such as transient state temperature measurements following a getter activation (bake-out) process (Lombard 2012); however, such methods are beyond the scope of this IRP.

3. REFERENCES

The following referenced documents provided formative information for the development of this IRP and may provide relevant supplemental information regarding the requirements and procedures described herein.

ASTM International. 2017. Standard test method for steady-state heat transfer properties of pipe insulation. West Conshohocken (PA): ASTM International. Designation: C335/ C335 – 17.

Azzola JH, Patillo PD, Richey JF, Segreto SJ. 2004. The heat transfer characteristics of vacuum insulated tubing. Proceedings of the SPE Annual Technical Conference and Exhibition; 2004 Sept 26-29; Houston, TX. Richardson (TX): Society of Petroleum Engineers. SPE 90151.

Lombard MS. 2012. What every engineer should know about vacuum insulated tubing. Proceedings of the SPE Western Regional Meeting; 2012 Mar 21-23; Bakersfield, CA. Richardson (TX): Society of Petroleum Engineers. SPE 153837.

National Energy Administration. 2013. China petroleum and natural gas industry standard – pre-stressed insulated tubing. SY/T5324-2013.

Zatka M. 2016. Application of vacuum-insulated tubing VIT in thermal oil sand projects. Proceedings of the SPE Heavy Oil Conference and Exhibition; 2016 Dec 6-8; Kuwait City, Kuwait. Richardson (TX): Society of Petroleum Engineers. SPE 184155.

4. TERMS AND DEFINITIONS

4.1 Terms and Definitions

Apparent Radial Thermal Conductivity
A measure of a VIT joint's ability to transfer heat in the radial direction, to the extent that the radial heat transfer through a VIT joint can be considered analogous to Fourier's law of heat conduction.

Evaluator
The party that evaluates the thermal performance properties of a VIT product in accordance with this IRP. The Evaluator may also be the Supplier.

Internal Heater
The internal heating device, or portion of which, that provides a uniform heat distribution along the heated length.

K-factor (or k-value)
A term indicating a measure of a material's ability to transfer heat, and often used to refer to the Apparent Radial Thermal Conductivity of a VIT joint.

Supplier
Any party that manufactures, distributes or otherwise supplies VIT products that may be evaluated in accordance with this IRP. The Supplier may also be the Evaluator.

Getter
A material which absorbs or chemically converts specific gas molecules into solids to help maintain a pressure vacuum.

Specified Target Temperature
A temperature at which the Apparent Radial Thermal Conductivity is to be measured and reported, based on the average inner surface temperature.

Specimen
The VIT joint being evaluated in accordance with this IRP.

Test Report
A document containing relevant VIT geometry and thermal performance information, as outlined in this IRP.

User
Any party that uses the evaluated VIT joint and/or results in a field application.

4.2 Symbols

λ apparent Radial Thermal Conductivity

L_e length of a Specimen outboard end section that represents non-uniform VIT cross-section geometry and associated Apparent Radial Thermal Conductivity

L_r length of the Specimen that is considered representative of a constant VIT cross-section geometry and associated Apparent Radial Thermal Conductivity

L_h length of the Specimen which is uniformly heated, corresponding to the length of the Internal Heater

D_i average measured inner diameter of the Specimen within the representative length

D_o average measured outer diameter of the Specimen within the representative length

T_i average inner surface temperature

T_o average outer surface temperature

Q_s average electrical power input to the internal heater at steady-state conditions

5. THERMAL CONDUCTIVITY EVALUATION

5.1 General Information

The thermal conductivity evaluation process consists of five main components, which are summarized by the flowchart in Figure 1.

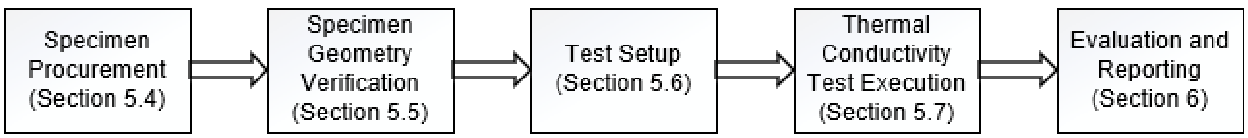

Figure 1 Evaluation Program Flowchart

5.2 Assessment Philosophy

Existing literature provides recommendations to most accurately determine thermal conductivity. For example, ASTM Standard C335/C335M-17 *Standard Test Method for Steady-State Heat Transfer Properties of Pipe Insulation* provides details for either actively controlling (through independently controlled heaters) or quantifying (through calibration or calculation) the heat loss at the outboard ends (i.e. end effects). While efforts have been made to address the largest sources of measurement error, many of these detailed procedures are not included in this IRP, which aims to emphasize procedural simplicity and practicality. Wherever possible, Suppliers are encouraged to follow more stringent procedures – provided that those procedures can be demonstrated to provide results that exceed the minimum requirements provided within this document.

To facilitate evaluation and comparison of thermal performance properties, it is important that the internal and external surface temperatures are accurately measured and reported for each thermal conductivity test. In general, where deviations from the recommended procedures defined in this IRP exist, the onus is on the Evaluator to demonstrate that the procedure followed exceeds the minimum requirements identified by this IRP.

5.3 Test Facility Safety

The test program shall be set up and conducted in compliance with local laws and regulations, and in accordance with established Health, Safety and Environmental practices for the parties involved in the evaluation program.

The Evaluator's facility shall have a documented emergency response procedure in place for uncontrolled events including fire and electrical hazards.

5.4 Specimen Procurement

The thermal conductivity test is to be performed on a full-length VIT Specimen following completion of the manufacturing and Getter activation processes.

Specimens shall be uniform in diameter and thickness in accordance with established manufacturing procedures, which shall be identified by the VIT Supplier in the Test Report.

5.5 Specimen Geometry Verification

Each of the outboard end sections (L_e), representative section (L_r) and heated (L_h) lengths identified in Figure 2, as well as the overall total Specimen length, shall be measured and documented in the Test Report for the Specimen subjected to thermal conductivity testing.

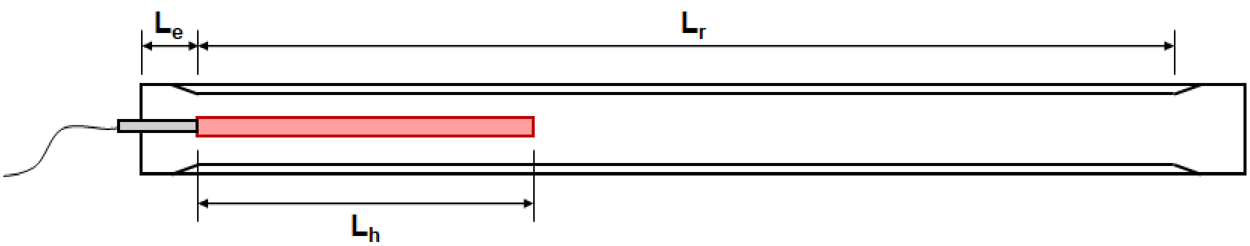

Figure 2 Test Setup Schematic

A cross-section of the heated length is provided in Figure 3, where circumferential position references are defined as viewed from the left-end of the Specimen shown in Figure 2.

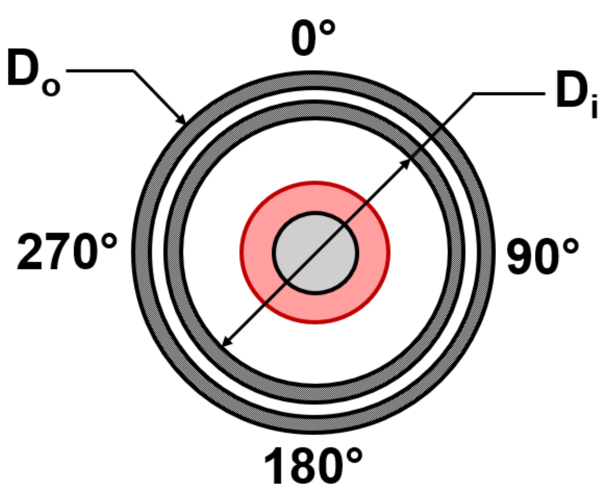

Figure 3 Circumferential Position Schematic

The Specimen shall also be measured to identify the inner diameter (D_i) and outer diameter (D_o) within the representative section for calculation of the Apparent Radial Thermal Conductivity. The measured diameters and location(s) of measurement shall be documented on a Specimen Geometry Data Sheet, as described in Section 6.5.

5.6 Test Setup

The thermal conductivity test shall take place in a controlled environment with the test setup conforming to the following conditions:

1. The ambient air temperature is between 10°C and 40°C.
2. The area immediately surrounding the test setup consists of relatively still air which is free from sources of forced convection (e.g. fans, vents, windows or doors) or any other conditions that would significantly affect heat transfer from the Specimen.
3. There are no objects or obstructions adjacent to the Specimen that would significantly affect heat transfer from the Specimen. Testing multiple Specimens in parallel, where Specimens are adjacent to each other in the horizontal plane (i.e. 90° and/or 270° circumferential locations), is permissible.
4. The Internal Heater shall be placed within the representative length of the Specimen (L_r), where a relatively constant VIT cross-section geometry and associated Apparent Radial Thermal Conductivity is expected, such that the heated section of the Internal Heater does not extend into either of the outboard end sections (L_e) where insulation will be placed.
5. The Internal Heater shall be oriented within the Specimen to maintain a minimum radial clearance of 1 cm between the heated surface and the inner surface of the Specimen at the 180° circumferential location (i.e. at the bottom), and a maximum clearance representing centralization within the Specimen (i.e. equal clearance in all circumferential directions). Any deviation from centralization within the range above is expected to result in a higher Apparent Radial Thermal Conductivity.
6. Outboard end sections (L_e) shall be insulated with non-flammable, high-temperature insulation (e.g. mineral wool) at the outer and inner surfaces, including the annulus between the Internal Heater and the inner surface, to minimize heat losses from the test setup.

In the event that the above conditions are not achieved during thermal conductivity testing, any deviations shall be explicitly documented in the Test Report.

5.6.1 Temperature Measurement

Temperatures shall be measured using thermocouples with a specified accuracy of ±3°C at room temperature (i.e. ±1% of absolute temperature) or better. For reference, standard and Special Limits of Error (SLE) thermocouple wires are typically ±2.2°C (±0.75%) and ±1.1°C (0.4%), respectively. If a different temperature measurement device is used, measurement accuracy that meets the above requirements shall be demonstrated by the Evaluator and documented in the Test Report.

Thermocouples shall be attached to the inner and outer surfaces of the Specimen in a manner that provides representative local temperature measurement. Welding individual thermocouple wires onto the Specimen surface is the preferred attachment method, and it is recommended that the thermal mass of the thermocouple wire and any attachment device be as small as practical to reduce heat loss from the thermocouple junction. If thermocouples are attached with adhesive, magnetic, mechanical or another method, best efforts shall be applied to ensure accurate surface temperature measurements.

The external thermocouple shall be placed on the top of the Specimen's outer surface (i.e. at the 0° circumferential position) and at the approximate center of the heated length (L_h) to minimize end effects. For example, if a 2 m long heating element is used, the thermocouple shall be placed 1 m from one end of the heated length. If multiple thermocouples are used, locations shall be centered around the approximate center of L_h, and the average external temperature shall be calculated using a representative average of the external thermocouple measurements.

The internal thermocouple shall be placed at the top of the Specimen's inner surface (i.e. at the 0° circumferential location) as close to the center of L_h as practical. Due to physical constraints with accessing the inner surface, it is permissible to attach the internal thermocouple at a minimum of 0.3 m (12 in) from the edge of L_h. Should physical constraints prevent placement of an internal thermocouple at least 0.3 m from the edge of L_h, measurement of a lower internal surface temperature (due to end effects) is expected to result in a higher estimate of the Apparent Radial Thermal Conductivity.

Thermocouple location, type and attachment method shall be documented in the Test Report.

5.6.2 Test Equipment

The Internal Heater shall provide a minimum heated length (L_h) of 2 m and a maximum heated length equal to the representative length (L_r) of the Specimen. The Internal Heater must be capable of generating sufficient heat to achieve and maintain the Specified Target Temperature(s).

An appropriate feedback control system shall be used to ensure temperature and/or power setpoints are safely achieved and maintained during execution of the thermal conductivity test. In addition, the Data Acquisition System (DAS) and instruments utilized to measure the electrical power input must be capable of collecting data at a sufficiently high frequency to minimize sampling rate error.

For example, sampling errors were estimated during a laboratory test using a burst switching mode (i.e. on/off control) interval of 10 seconds, a target temperature of 100°C, and a heated length (L_h) roughly equivalent to the representative length (L_r). Relative to a data acquisition rate of 64 Hz, sampling errors at 16 Hz and 4 Hz were approximately 0.6% and 2.0%, respectively. The corresponding power measurement data over one control interval is shown in Figure 4.

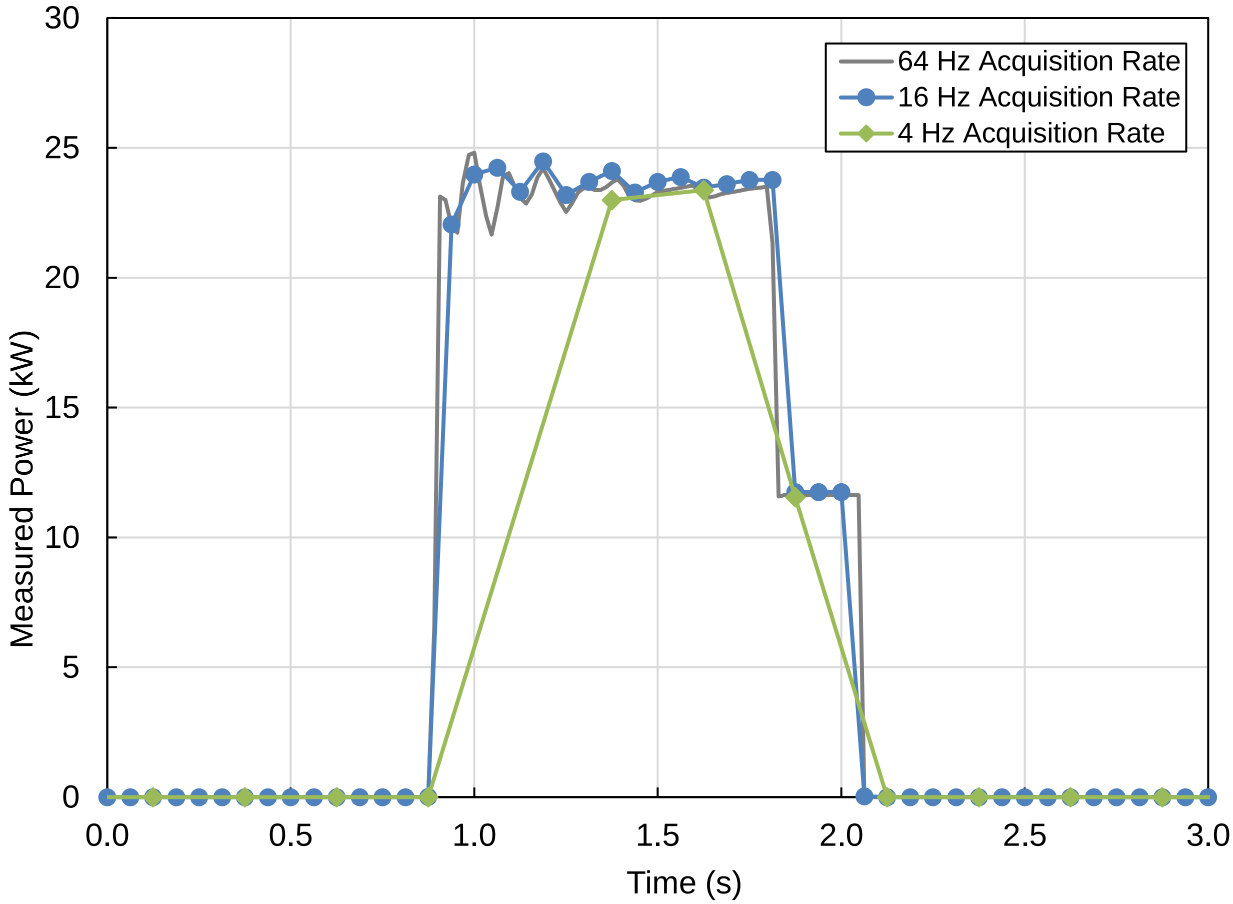

Figure 4 Power Measurement Data at various Data Acquisition Rates

It is noted that the sampling error is expected to increase for a given acquisition rate as the control interval duration and/or the average power input (Q_s) decreases (e.g. at a lower target temperature).

It is the responsibility of the Evaluator to demonstrate a combined power measurement and sampling error less than 5% in the Test Report.

5.6.3 Calibration Requirements

Instruments shall be selected for a high degree of accuracy (typically less than 1% of full-scale reading) over an appropriate measurement range. Each instrument shall be calibrated over the selected measurement range according to the manufacturer's recommendations, and calibration intervals shall not exceed one year.

A computer-based DAS is recommended. Each DAS component shall be calibrated according to the manufacturer's recommendations, and calibration intervals shall not exceed one year.

Standards used for calibration must be traceable according to the Evaluator's National Metrology Institute (NMI).

5.7 Thermal Conductivity Test Execution

The thermal conductivity test shall be conducted as follows:

1. Ensure the test setup meets the requirements specified in Section 5.6.
2. Heat the Specimen to achieve an inner surface temperature within ±10°C or ±3.0% of the Specified Target Temperature, whichever is less.
3. Perform a minimum 10-minute hold during which the following conditions are met:
   - The inner and outer surface temperatures vary by less than ±5°C or ±2.0% of the temperatures measured at the start of the hold, whichever is less;
   - The temperature and/or power control set points are held constant for the duration of the hold;
   - The ambient air temperature varies by less than ±5°C or ±1.5% of the Specified Target Temperature, whichever is less; and
   - The test setup requirements specified in Section 5.6, including ambient conditions, are maintained.
4. Record the following test parameters at the start and end of the hold, and determine the average of each test parameter over the duration of the hold:
   - Inner surface temperature (T_i);
   - Outer surface temperature (T_o);
   - Electrical power input (Q_s); and
   - Ambient air temperature.

Thermal steady-state conditions (as described in Step 3) shall be maintained during recording of the test data described in Step 4. Should any of the conditions deviate from thermal steady-state at any point during the hold, Steps 3 and 4 of the above procedure shall be repeated. It is also noted that the minimum 10-minute hold period may be extended at the Evaluator’s discretion to achieve more accurate test results. If multiple Specimens are tested simultaneously, the above requirements apply to each individual Specimen.

6. EVALUATION AND REPORTING

6.1 Apparent Radial Thermal Conductivity

The Apparent Radial Thermal Conductivity per unit length shall be calculated according to Equation [6.1]:

$$\lambda = \frac{Q_s ln(D_o/D_i)}{2\pi L_h(T_o - T_i)} \quad [6.1]$$

with the above values representing the average test parameters for the duration of the hold at steady-state conditions, as per the procedure described in Section 5.7.

6.2 Diameters Used for Calculation

For the purpose of discussion and clarification, two additional diameters are introduced: the outer diameter of the inner tube, $D_{o,i}$, and the inner diameter of the outer tube, $D_{i,o}$, as shown in Figure 5.

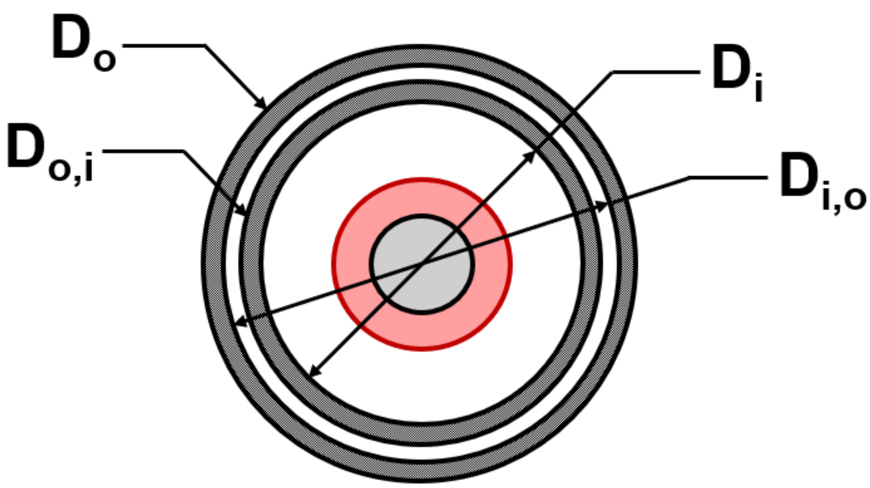

Figure 5 Specimen Diameter Schematic

Although the use of the $D_{o,i}$ and $D_{i,o}$ has been suggested in some references to isolate the thermal insulation performance of the vacuum annulus (which offers several advantages including easier comparison with ideal performance levels (Azzola et al. 2004)), using D_o and D_i offers advantages in line with this IRP's emphasis on practicality. As Specimens may consist of a vacuum annulus, Getter material, a radiation barrier and/or other insulating materials in addition to the tubing pipe body, the simplest approach to evaluating the thermal performance of the Specimen is to consider the system as a whole, represented by D_o and D_i. In addition, the Apparent Thermal Conductivity Factor is highly sensitive to the diameters used in the calculation, and the easier physical measurement of D_o and D_i should provide for more accurate evaluation and comparison between

VIT systems. Accordingly, this IRP defines Apparent Radial Thermal Conductivity relative to the measured outer and inner diameters of the Specimen (i.e. D_o and D_i).

For comparison, should the Apparent Radial Thermal Conductivity of the vacuum annulus (λ_v) be provided relative to $D_{o,i}$ and $D_{i,o}$, it can be converted to the Apparent Radial Thermal Conductivity relative to D_o and D_i as defined in this IRP (λ) using Equation [6.2]:

$$\lambda = \lambda_v \left| \frac{ln(D_o/D_i)}{ln(D_{o,i}/D_{i,o})} \right| \quad [6.2]$$

6.3 Assessment Criteria

The intent of this IRP is to facilitate comparison of radial thermal conductivity performance between different VIT Specimens. As such, no specific assessment criteria is provided, and the extent to which the test results are representative of a VIT design or production lot is beyond the scope of this IRP.

6.4 Test Report

A Test Report shall be prepared for each thermal conductivity test performed and provided upon the User's request. The Test Report shall include the following information for each Specimen:

1. Specimen details:

    - Specimen manufacturer and facility;
    - Specimen identification number (e.g. serial number);
    - Material grade and weight;
    - Nominal geometry;
    - Measured Specimen geometry (per Section 6.5);
    - Applicable Mill Test Reports (MTRs);
    - Welding and weldment inspection procedures;
    - Specimen pre-stress details;
    - Surface treatments (e.g. sandblasting, chemical cleaning, coating, etc.), if applicable; and
    - Bake-out and/or Getter activation details.

2. Thermal conductivity test details:

    - Date of testing;

- Date of report preparation;
- Test facility and location;
- Thermocouple attachment method and locations;
- Specified Target Temperature;
- Ambient air temperature during hold periods.
- Average inner surface temperature during hold period (T_i);
- Average outer surface temperature during hold period (T_o);
- Average electrical power input during hold period (Q_s);
- Apparent Radial Thermal Conductivity factor (λ);
- Plots of temperatures and power input versus time, where practical;
- Name, signature and company affiliation of individuals who performed the test; and
- Statement of conformance with or deviations from the IRP.

6.5 Specimen Geometry Data Sheet

A Specimen Geometry Data Sheet shall be prepared for each joint of VIT subjected to the thermal conductivity test and provided upon the User's request. The Specimen Geometry Data Sheet shall include the following information:

- Dates of measurement;
- Overall Specimen length;
- Outboard end section lengths (L_e);
- Representative length (L_r);
- Average measured inner diameter (D_i);
- Average measured outer diameter (D_o);
- Diameter measurement locations;
- Maximum inner and outer tube ovality measurements and locations;
- General observations (e.g. surface conditions, welds, coatings, etc.); and
- Name, signature and company affiliation of individuals who performed the measurements.