National Fenestration Rating Council Incorporated

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Procedure for Determining Thermophysical Properties of Materials For Use in NFRC-Approved Software Programs

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FOREWORD

The NFRC rating procedures rely on NFRC approved computer simulation programs for calculating total fenestration thermal performance indices. Manufacturers and suppliers of materials used in the design and construction of fenestration products have relied upon a variety of standards for determining the thermophysical properties of specific materials, including ASTM, ISO, ASHRAE and other proprietary methods. This standardized procedure provides a uniform method for determining the thermophysical properties, long wave surface emissivity and solar surface absorptivity of framing and other opaque materials used in the construction and manufacture of fenestration products.

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1. INTRODUCTION

The National Fenestration Rating Council has developed a uniform national rating system for energy performance characteristics of fenestration products.

The rating system is reinforced by a product certification program where ratings are determined by NFRC accredited laboratories, and then reviewed and authorized by NFRC licensed independent certification and inspection agencies (IA's) as conforming to NFRC requirements.

This procedure has been developed to provide uniform and credible tables (libraries) of thermophysical properties of materials used in the construction and manufacture of fenestration products in approved software tool(s). The following thermophysical properties, currently considered, are: thermal conductivity, long-wave surface emissivity and solar surface absorptivity, hereafter referred to as thermophysical properties.

In this procedure, a table of generic materials and their associated thermophysical properties is provided, as well as a process of introducing custom materials or new, manufacturer specific materials. This procedure should improve the credibility of the values used in simulating thermal performance indices of fenestration systems.

This procedure may involve hazardous materials, operations and equipment. This procedure does not purport to address all of the safety problems associated with its use. It is the responsibility of the user of this procedure to establish appropriate health and safety practices and to determine the applicability of any regulatory limitations prior to use.

The values stated in metric (SI) units shall be regarded as the standard. The inch-pound (IP) units shown in parenthesis shall be for reference only.

2. PURPOSE AND SCOPE

2.1 Purpose

The purpose of this procedure shall be to provide a uniform method for determining the thermophysical properties of glazing (thermal conductivity only), framing, and other opaque materials used in the construction and manufacture of fenestration products. These thermophysical properties shall be used in NFRC approved software tools for the simulation of thermal performance indices of fenestration products.

2.2 Scope

2.2.1. Materials Covered By This Document

- All frame materials, either single component or composite,
- All glazing materials, thermal conductivity only,
- All sealants and adhesives,
- Weather-stripping materials,
- Thermal barrier materials,
- Cladding materials,
- Spacer materials,
- Desiccant materials.

2.2.2. Materials and/or Properties Not Covered By This Document

- Thermal conductivity of finishes,
- Glass coatings,
- Solar-optical properties of glazing and other transparent materials. (See NFRC 300 and solar-optical database).

3. TERMINOLOGY

See NFRC Glossary and Terminology of all definitions.

4. REPRESENTATIVE THERMOPHYSICAL PROPERTIES

All materials used in the design and fabrication of a fenestration product shall have either generic thermophysical properties assigned from the list in Appendices A or B, or a manufacturer shall supply thermophysical properties determined by an approved test procedure(s) (see Section 5) and shall be listed in Appendix C.

4.1 Generic Thermophysical Properties

Those materials determined by NFRC to be generic in nature shall be identified and listed in Appendix A (Basic Set of Generic Materials), or Appendix B (Extended Set of Generic Materials). NFRC may add or remove materials as needed.

All simulators shall use Appendix A, unless the simulator's client requests the use of Appendix B or the material is not represented in Appendix A.

The NFRC Thermophysical Properties Subcommittee shall review the list of generic materials and update the thermophysical properties, as necessary. Each update shall be announced and promptly posted on the NFRC website for easy retrieval by NFRC-accredited simulation laboratories, NFRC-certified simulators, NFRC IAs, and other interested parties. The update shall have its version number clearly identified and NFRC shall post the date when this new material library becomes effective. Upon the effective date of the new material property file as posted by NFRC, old versions of the material library are deemed obsolete.

If the material data are not in the generic material library, and an interested party believes that the material in question is generic, the interested party may request in writing that NFRC include said material in Appendix A or Appendix B. Such requests shall be handled as outlined in NFRC 103 Sections 2.4 through 2.6. If the interested party disagrees with a published Generic Thermophysical Property, the interested party may request, in writing, testing of representative samples to determine a corrected thermophysical property. In such a case, a minimum of three different samples of the same generic material, preferably supplied by three different manufacturers, shall be tested. The verification of the tested data shall be done according to NFRC 103. If the difference between any individual sample value and the average value of all samples is more than 10% or 0.003 W/(m•K) [0.02 Btu•in./(hr•ft^2•°F)], whichever is greater, of the average value, the materials shall not be considered to be the same, and the reasons for outlier(s) shall be determined. The average of the measured thermophysical properties shall be compared to the currently used generic thermophysical property. If the difference is less than 10%, or 0.003 W/(m•K) [0.02 Btu•in./(hr•ft^2•°F)], whichever is greater, the current thermophysical property shall be considered valid. If the average of the three individual thermophysical property values is more than 10%, or 0.003 W/(m•K) [0.02 Btu•in./(hr•ft^2•°F)], whichever is greater, different from the current generic thermophysical property, this new thermophysical property shall be peer-reviewed, and upon acceptance, shall become the new thermophysical property of that generic material and be included in the updated material database.

4.2 Manufacturer Specific Thermophysical Properties

If the material is not considered generic and is not part of generic material library, its thermophysical properties shall be determined in accordance with Section 5. The manufacturer is responsible for providing typical samples for testing.

Two methods for determining thermophysical properties shall be allowed under this procedure:

1) Manufacturer may use its own equipment or hire a non-NFRC approved laboratory to determine thermophysical properties in accordance with Section 5;

2) Manufacturer may submit test samples to an NFRC accredited laboratory or a laboratory that is third-party accredited by an NFRC approved accreditation agency for the specific test method to be used from Section 5.

Emissivity and solar absorptance of materials is not required to be determined if manufacturer accepts default values of 0.9 for emissivity and NFRC default values for solar absorptance.

4.2.1 Manufacturer Supplied Test Data

Under this option, the manufacturer shall be permitted to perform its own testing, or to hire a non-NFRC approved laboratory, and to submit test data to the NFRC Thermophysical Properties Subcommittee for verification. The testing shall be done according to the procedure(s) outlined in Section 5. In addition, the manufacturer shall submit the three original test samples to NFRC so that verification can be done according to NFRC 103.

5. REPRESENTATIVE THERMOPHYSICAL PROPERTIES

Thermophysical properties shall be determined according to appropriate ASTM standards, as indicated in Sections 5.1, 5.2, and 5.3. A minimum of three samples shall be measured and the mean value reported. Refer to the NFRC website (http://www.nfrc.org/) for a list of the NFRC accredited labs that can provide further guidance and perform the required testing outlined in this section.

5.1 Thermal Conductivity

For the determination of thermal conductivity, the test shall be done according to ASTM C177, C518, C1114, E1225, E1530 or E1952, as applicable for the specific material. The test equipment shall be calibrated at least once each year as per the recommendations in the appropriate ASTM document(s).

Note: The specimen conductance should be less than 16 $W/m^2 \cdot K$ (thermal resistance greater than 0.0625 $m^2 \cdot K/W$) if the test is done using C177. C518 may be used for a specimen with thermal conductance less than 10 $W/m^2 \cdot K$ (thermal resistance greater than 0.10 $m^2 \cdot K/W$). For either of these tests, the temperature difference across the specimen shall not be less than 10 K. C1114 is applicable to a low conductance specimen only and the specimen shall be thermally homogeneous. Apparatus of the type covered by C1114 apply to the study of thermal properties of specimens containing moisture because of the use of small temperature differences and the low thermal capacity of the heat source. E1530 is similar in concept to C518 and is especially useful for materials in sheet and similar forms having a thermal resistance in the range from 20 x10-4 to 400x10-4 m^2•K/W over the approximate temperature range from 150 to 600 K. Reduced accuracy will be achieved for thicker specimens and for thermal conductivities up to 10 W/m•K. E1225 uses a steady state technique for the determination of thermal conductivity of homogeneous, opaque solids with effective conductivities in the approximate range of 0.2 to 200 W/m•K over the approximate temperature range between 90 and 1300 K. E1952 covers the determination of thermal conductivity of homogeneous, non-porous solid materials in the range of 0.10 to 1.0 W/m•K by modulated temperature differential scanning calorimeter. This information is summarized in Table 1. NFRC Accredited labs may be relied on for the determination of the most appropriate test. Refer to the NFRC website (http://www.nfrc.org/) for a list of the NFRC accredited labs.

Table 1. Summary of thermal conductivity standards and their applicability

ASTM Standard	**Conductivity Range** (W/m•K)	**Conductance Range** (W/m^2•K)	**Min ΔT (K)**	**Remarks**
C177		< 16	10	Thermally homogeneous
C518		< 10	10	Thermally homogeneous
C1114			None	Thermally homogeneous, for specimens with moisture
E1225	0.2-200		90-1300	Thermally homogeneous, Opaque
E1530		25-500	150-600	Thermally homogeneous
E1952	0.1-1.0		None	Thermally homogeneous

5.1.1 Mean temperatures

The test shall be conducted at a mean temperature of 2±1ºC (35±2ºF) unless otherwise specified by the applicable ASTM test method.

5.1.2 Specimen thickness

The thickness of the specimen shall be chosen based on the standard procedure selected. With ASTM E1530, the thickness of specimen is required to be less than 12 mm. ASTM C177 and C1114 recommend that maximum specimen thickness depends on several parameters, including the size of the apparatus, thermal resistance of the specimen and the accuracy desired. For more specific quantitative information on thickness limitation see Refs (1), (2), (3) and (4).

5.1.3 Non-homogenous specimens

Non-homogeneities normal to the heat flux direction, such as layered structures, can be evaluated using ASTM C177. However, for testing specimens with non-homogeneities in the heat flux direction, such as an insulation system with thermal bridges, see test method ASTM C1363 for guidance. To use ASTM E1225 for composites or heterogeneous systems consisting of slabs of plates bonded together, the specimen shall be more than 20 units wide and 20 units thick, respectively, where a unit is the thickness of the thickest slab or plate.

5.2 Emissivity

For the determination of long wave surface emissivity, the test shall be done according to ASTM E1933 or ASTM C1371. ASTM E1933 requires the specimen to be at a temperature at least 10 K warmer or cooler than the ambient temperature while ASTM C1371 provides a comparative means of quantifying the emittance of opaque, highly thermally conductive materials near room temperature. The long wave range is considered from 2.5 μm to 40 μm.

5.2.1 Cleanness of the surface

ASTM C1371 recommends that the procedure used should ensure minimum alteration of the specimen surface. For example, if the emittance of a dust-covered specimen is desired, the dust shall not be removed. However, if the surface is intended to be clean and free of any residue, it shall be visually inspected for signs of contamination prior to the measurement and, if necessary, cleaned with the appropriate solution and dried.

5.2.2 Finishes

For painted or finished specimens, the paint or finish shall be fully cured and in good contact with the substrate (i.e., no bubbles, peeling, or scratches). For further instructions see ASTM D3359.

5.3 Solar Absorptivity

For the determination of surface solar absorptivity, the test shall be done according to ASTM E903.

5.3.1 Finishes

The painted or finished surfaces shall be treated as in the case of emissivity measurement. See Section 5.2.2.

5.3.2 Specularity

This test method has been found practical for materials having both specular and diffuse optical properties.

5.3.3 Cleanness of the surface

Surfaces that are measured shall be clean and free of any residue.

5.4 Laboratory Accreditation

Refer to the NFRC Laboratory Accreditation Program (LAP) document for laboratory accreditation procedures and information.

6. REFERENCES

6.1 Standards

NFRC LAP: Laboratory Accreditation Program

NFRC PCP: Product Certification Program

NFRC 100-2004: Procedure for Determining Fenestration Product U-Factors.

NFRC 200-2004: Procedure for Determining Fenestration Product Solar Heat Gain Coefficient and Visible Transmittance at Normal Incidence.

NFRC 300-2004: Test Method for Determining the Solar Optical Properties of Glazing Materials and Systems.

NFRC 400-2004: Procedure for Determining Fenestration Product Air Leakage

NFRC 500-2004: Procedure for Determining Fenestration Product Condensation Resistance Values

ASTM C177-04: Standard Test Method for Steady-State Heat Flux Measurements and Thermal Transmission Properties by Means of the Guarded-Hot-Plate Apparatus

ASTM C518-04: Standard Test Method for Steady-State Thermal Transmission Properties by Means of the Heat Flow Meter Apparatus

ASTM C1114-00: Standard Test Method for Steady-State Thermal Transmission Properties by Means of the Thin-Heater Apparatus

ASTM C1363-97: Standard Test Method for the Thermal Performance of Building Assemblies by Means of a Hot Box Apparatus

ASTM C1371-04a: Standard Test Method for Determination of Emittance of Materials Near Room Temperature Using Portable Emissometers

ASTM D3359-02: Standard Test Methods for Measuring Adhesion by Tape Test

ASTM E903-96: Standard Test Method for Solar Absorptance, Reflectance, and Transmittance of Materials Using Integrating Spheres

ASTM E1225-04: Standard Test Method for Thermal Conductivity of Solids by Means of the Guarded-Comparative-Longitudinal Heat Flow Technique

ASTM E1530-04: Standard Test Method for Evaluating the Resistance to Thermal Transmission of Materials by the Guarded Heat Flow Meter Technique

ASTM E1933-99a (2005)e1: Standard Test Methods for Measuring and Compensating for Emissivity Using Infrared Imaging Radiometers

ASTM E1952-01: Standard Test Method for Thermal Conductivity and Thermal Diffusivity by Modulated Temperature Differential Scanning Calorimetry

IEEE / ASTM SI10-02: American National Standard for Use of the International System of Units (SI): The Modern Metric System

6.2 Other Documents

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5. ASHRAE Fundamentals Handbook (SI), 2001

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7. D.F. Miner and J.B. Seastone, Handbook of Engineering Materials, 1955

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16. Bankvall, C.G., “Mechanisms of Heat Transfer in Permeable Insulation and Their Investigation in a Special Guarded Hot Plate”, Heat Transmission Measurements in Thermal Insulations, ASTM STP 544, Edited by R.P. Tye, 1974, pp 34-48.

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22. IS. Emissivity Values for Common Materials. Infrared Services Co.; 2000.

23. Exergen. Tech Note 69. Exergen Co. 2002.

APPENDIX A BASIC SET OF GENERIC THERMOPHYSICAL PROPERTY VALUES OF MATERIALS

Table A.1: Thermophysical Properties of Solids

Name	Density ρ	Conductivity k			Source	Emissivity ε	Absorptivity[1] α
	kg/m^3	W/m•K	Btu/hr•ft•F	$Btu•in/hr•ft^2•°F$	-	-	-
Rubbers							
Butadiene	980	0.250	0.144	1.733	1	0.9	0.50/0.30
Butyl rubber (isobutene, solid/hot melt)		0.240	0.139	1.664	1,6,11	0.9	0.50/0.30
Expanded rubber (rigid)	72	0.032	0.018	0.222	2	0.9	0.50/0.30
Ethylene propylene diene monomer (EPDM)	1150	0.250	0.144	1.733	1	0.9	0.50/0.30
Foam Rubber	60-80	0.060	0.035	0.416	1	0.9	0.50/0.30
Neoprene (polychloroprene)	1,240	0.230	0.133	1.595	1	0.9	0.50/0.30
Polyisobutylene (PIB)	930	0.200	0.116	1.387	1	0.9	0.50/0.30
Polysulphide	1,700	0.400	0.231	2.773	1	0.9	0.50/0.30
Polymers							
PVB		0.221	0.128	1.536	21	0.9	0.50/0.30
Polyamide (nylon)		0.250	0.144	1.733	1,6,11	0.9	0.50/0.30
Polycarbonate	1,200	0.200	0.116	1.387	1	0.9	0.50/0.30
Polyethylene/polythene HD (high density)	980	0.500	0.289	3.467	1	0.9	0.50/0.30
Polyethylene/polythene LD (low density)	920	0.330	0.191	2.288	1,6	0.9	0.50/0.30
Polypropylene	910	0.22	0.127	1.525	1	0.9	0.50/0.30

[1]Solar absorptance of all materials is defaulted to 0.50 for commercial products and to 0.30 for residential products without actual measurements

Name	Density ρ	Conductivity k			Source	Emissivity ε	Absorptivity[1] α
	kg/m^3	W/m•K	Btu/hr•ft•F	$Btu•in/hr•ft^2•°F$	-	-	-
Polymers - Continued							
Polystyrene	1,050	0.160	0.092	1.109	1	0.9	0.50/0.30
Polytetrafluoroethylene(PTFE)	2,200	0.250	0.144	1.733	1	0.9	0.50/0.30
Polyurethane	1,200	0.250	0.144	1.733	1	0.9	0.50/0.30
Polyurethane foam	70	0.050	0.029	0.347	1	0.9	0.50/0.30
Polyvinylchloride (PVC) flexible, with 40% softener	1,200	0.140	0.081	0.971	1	0.9	0.50/0.30
PVC/Vinyl (rigid)	1,390	0.170	0.098	1.179	6,11	0.9	0.50/0.30
Silicone		0.350	0.202	2.427	1	0.9	0.50/0.30
Silicone foam		0.170	0.098	1.179	6,11	0.9	0.50/0.30
Silicone, filled		0.500	0.289	3.467	1	0.9	0.50/0.30
Urethane-thermal break		0.121	0.070	0.839	13	0.9	0.50/0.30
Urethane/polyurethane		0.210	0.121	1.456	1	0.9	0.50/0.30
Composites							
Fiberglass		0.300	0.173	2.080	6,11	0.9	0.50/0.30
Polyamide 6.6 with 25% glass fiber		0.300	0.173	2.080	1	0.9	0.50/0.30
Timbers							
Coniferous woods (Softwoods)		0.140	0.081	0.971	6,11	0.9	0.50/0.30
Deciduous woods (Hardwoods)		0.160	0.092	1.109	6,8,11	0.9	0.50/0.30
Wood based panels							
Hardboard (medium density)	800	0.110	0.064	0.763	11	0.9	0.50/0.30
Particleboard, Plywood (low density)	300	0.100	0.058	0.693	1	0.9	0.50/0.30
Particleboard, Plywood (medium density)	700	0.170	0.098	1.179	1	0.9	0.50/0.30
Particleboard, Plywood (high density)	1,000	0.240	0.139	1.664	1	0.9	0.50/0.30

Name	Density ρ	Conductivity *k*			Source	Emissivity ε	Absorptivity[1] α
	kg/m³	W/m•K	Btu/hr•ft•F	Btu•in/hr•ft²•°F	-	-	-
Metals							
Aluminum (oxidized, mill finish)		237.000	136.936	1643.235	8	0.2	0.50/0.30
Aluminum alloys (oxidized, mill finish)	2,800	160.000	92.446	1109.357	1,6,11	0.2	0.50/0.30
Aluminum (anodized)		237.000	136.936	1643.235	8	0.8	0.50/0.30
Aluminum alloys (anodized)	2,800	160.000	92.446	1109.357	1,6,11	0.8	0.50/0.30
Steel (oxidized)	7,800	50.000	28.890	346.674	1	0.8	0.50/0.30
Steel (rolled, ground)	7,800	50.000	28.890	346.674	1	0.6	0.50/0.30
Steel Stainless (oxidized)	7,900	17.000	9.822	117.869	1	0.8	0.50/0.30
Steel Stainless (buffed)	7,900	17.000	9.822	117.869	1	0.2	0.50/0.30
Steel- galvanized sheet (0.14%C)		62.000	35.823	429.876	11	0.2	0.50/0.30
Glazing Materials							
Glass (Plate or Float)		1.000	0.578	6.933	1,6,11	0.84	N/A
Glass mosaic	2,000	1.200	0.693	8.320	1	0.84	N/A
Glass-Flint (lead), Pyrex	4,280	1.400	0.809	9.707	5	0.84	N/A
Glass-Quartz		1.400	0.809	9.707	1	0.90	N/A
Plexiglass (PMMA) / Lucite		0.200	0.116	1.387	11	0.90	N/A
Insulating Materials							
Cellulosic fiber, Cotton fiber	56	0.042	0.023	0.277	11	0.9	0.50/0.30
Expanded perlite, organic bonded	16	0.052	0.030	0.361	2	0.9	0.50/0.30
Polystyrene-expanded	15	0.038	0.022	0.263	11,1	0.9	0.50/0.30
Extruded polystyrene (XPS) with CFC and HCFC	25-65	0.029	0.017	0.201	11, 1	0.9	0.50/0.30
Extruded polystyrene (XPS) with CO2	30-50	0.034	0.020	0.236	1	0.9	0.50/0.30
Felt	330	0.050	0.029	0.347	5	0.9	0.50/0.30

Name	Density ρ	Conductivity *k*			Source	Emissivity ε	Absorptivity[1] α
	kg/m³	W/m•K	Btu/hr•ft•F	Btu•in/hr•ft²•°F	-	-	-
Insulating Materials - Continued							
Glass fiber (semi-rigid) Sheathing		0.034	0.020	0.236	11	0.9	0.50/0.30
Glass fiber (spray applied)		0.039	0.023	0.270	11	0.9	0.50/0.30
Glass fiber (rigid) Roof insulation		0.047	0.027	0.326	11	0.9	0.50/0.30
Glass wool	52	0.038	0.022	0.263	5	0.9	0.50/0.30
Insulation Fiberboard (Ceiling Tile, Lay-in Panel)		0.061	0.035	0.423	11	0.9	0.50/0.30
Insulation Fiberboard (Roof Board)		0.055	0.032	0.381	11	0.9	0.50/0.30
Insulation Fiberboard		0.050	0.029	0.347	11	0.9	0.50/0.30
Mineral fiber-low density (rock, slag, glass)		0.042	0.024	0.291	11	0.9	0.50/0.30
Mineral fiber-loose fill (rock, slag, glass)		0.050	0.029	0.347	11	0.9	0.50/0.30
Perlite		0.053	0.031	0.367	11	0.9	0.50/0.30
Polyester fibre	15	0.040	0.023	0.279	1	0.9	0.50/0.30
Polyisocyanurate/polyurethane-Unfaced Board		0.020	0.012	0.139	11	0.9	0.50/0.30
Polyisocyanurate/Polyurethane-Faced Sheathing		0.024	0.014	0.166	11	0.9	0.50/0.30
Polyurethane Foam Insulation (Spray Applied)		0.024	0.014	0.166	11	0.9	0.50/0.30
Ureaformaldehyde foam	11--26	0.040	0.023	0.277	2	0.9	0.50/0.30
Vermiculite	179	0.077	0.044	0.534	10	0.9	0.50/0.30
Miscellaneous							
Foam glass		0.040	0.023	0.277	1,12	0.9	0.50/0.30
Mohair		0.140	0.081	0.971	6,11	0.9	0.50/0.30
Silica gel (desiccant) – bulk	720	0.130	0.075	0.901	1	0.9	0.50/0.30
Silica gel (desiccant) – loose fill		0.030	0.017	0.208	6,11	0.9	0.50/0.30
Silicone Foam		0.170	0.098	1.179	11	0.9	0.50/0.30

Name	Density ρ	Conductivity k			Source	Emissivity ε	Absorptivity[1] α
	kg/m^3	W/m•K	Btu/hr•ft•F	$Btu•in/hr•ft^2•°F$	-	-	-
Miscellaneous - Continued							
Foam weather stripping		0.030	0.017	0.208	6,11	0.9	0.50/0.30
Paints		N/A	N/A	N/A	-	0.9	0.50/0.30

Table A.2: Thermophysical Properties of Gases

	Conductivity $k = a + bT+cT^2$ [W/m•K]			Dynamic Viscosity $\mu = a + bT+cT^2$ [kg/m•s]		
Gas	**Coefficient a** [W/m•K]	**Coefficient b** $[W/m•K^2]$	**Coefficient b** $[W/m•K^3]$	**Coefficient a** [kg/m•s]	**Coefficient b** [kg/m•s•K]	**Coefficient c** $kg/m•s•K^2$
Air*	$2.873x10^{-3}$	$7.760x10^{-5}$	0	$3.723x10^{-6}$	$4.94x10^{-8}$	0
Argon	$2.285x10^{-3}$	$5.149x10^{-5}$	0	$3.379x10^{-6}$	$6.451x10^{-8}$	0
Krypton	$9.443x10^{-4}$	$2.826x10^{-5}$	0	$2.213x10^{-6}$	$7.777x10^{-8}$	0
Xenon	$4.538x10^{-4}$	$1.723x10^{-5}$	0	$1.069x10^{-6}$	$7.414x10^{-8}$	0
CO_2	$-5.8181x10^{-3}$	$7.4714x10^{-5}$	0	$8.5571x10^{-7}$	$4.7143x10^{-8}$	0

*Note: Nitrogen shall be treated as air.

	Specific Heat $Cp = a + bT + cT^2$ [J/kg•K] -				**Molecular Masses**
Gas	**Coefficient a** [W/m•K]	**Coefficient b** $[W/m•K^2]$	**Coefficient c** $[W/m•K^3]$		Mass [kg/kmol]
Air*	$1.00274x10^{3}$	$1.2324x10^{-2}$	0		28.97

	Specific Heat $Cp = a + bT + cT^2$ [J/kg•K] -				**Molecular Masses**
Gas	**Coefficient a** [W/m•K]	**Coefficient b** [W/m•K^2]	**Coefficient c** [W/m•K^3]		Mass [kg/kmol]
Argon	5.21929×10^2	0	0		39.948
Krypton	2.48091×10^2	0	0		83.80
Xenon	1.58340×10^2	0	0		131.30
CO_2	5.76903×10^2	9.18088×10^{-1}	0		44.01

*Note: Nitrogen shall be treated as air.

APPENDIX B EXTENDED SET OF GENERIC THERMOPHYSICAL PROPERTY VALUES OF MATERIALS

Table B.1: Thermophysical Properties of Solids

Name	Density ρ	Conductivity k			Source	Emissivity ε	Absorptivity[1] α
	kg/m³	W/m•K	Btu/hr•ft•F	Btu•in/hr•ft²•°F	-	-	-
Rubbers							
Neoprene(polychloroprene)	146	0.036	0.021	0.246	10	0.9	0.50/0.30
Neoprene(polychloroprene)	1290	0.237	0.137	1.643	10	0.9	0.50/0.30
							0.50/0.30
Polymers							
Polyurethane foam	24-40	0.026	0.015	0.180		0.9	0.50/0.30
ABS	1,020-1,210	0.190			Web	0.9	0.50/0.30
							0.50/0.30
Timbers							
California Redwood	392-448	0.118	0.068	0.818	2	0.9	0.50/0.30
Cedars (western, red)	247-502	0.130	0.075	0.901	2	0.9	0.50/0.30
Cedars (western red)	401	0.104	0.060	0.719	7	0.9	0.50/0.30
Cypress		0.097	0.056	0.673	8	0.9	0.50/0.30
Cypress (southern)	465	0.120	0.069	0.829	7	0.9	0.50/0.30
Cypress (southern)	502-514	0.132	0.076	0.915	2	0.9	0.50/0.30
Elm (soft)	521	0.131	0.076	0.909	7	0.9	0.50/0.30
Fir		0.140	0.081	0.971	6,11	0.9	0.50/0.30
Fir (white)	401	0.094	0.054	0.649	7	0.9	0.50/0.30
Fir (white)	430	0.120	0.069	0.832	5	0.9	0.50/0.30
Douglas Fir	529	0.111	0.064	0.769	7	0.9	0.50/0.30

Name	Density ρ	Conductivity *k*			Source	Emissivity ε	Absorptivity[1] α
	kg/m^3	W/m•K	Btu/hr•ft•F	$Btu•in/hr•ft^2•°F$	-	-	-
Timbers - Continued							
Hemlock (eastern)	457	0.115	0.067	0.799	7	0.9	0.50/0.30
Hemlock	502	0.130	0.075	0.901	2	0.9	0.50/0.30
Larch (western)	625	0.143	0.082	0.988	7	0.9	0.50/0.30
Mahogany	550	0.130	0.075	0.901	5	0.9	0.50/0.30
Maple	625	0.150	0.087	1.038	7	0.9	0.50/0.30
Maple	634	0.157	0.099	1.186	2	0.9	0.50/0.30
Maple	704	0.171	0.099	1.186	2	0.9	0.50/0.30
Maple (sugar)	720	0.187	0.108	1.297	5	0.9	0.50/0.30
Oak	659	0.106	0.092	1.109	2	0.9	0.50/0.30
Oak (red)	721	0.173	0.1	1.198	7	0.9	0.50/0.30
Oak (white)	745-750	0.176	0.102	1.218	5,7	0.9	0.50/0.30
Oak	749	0.180	0.104	1.248	2	0.9	0.50/0.30
Pine (sugar)	409	0.099	0.057	0.689	7	0.9	0.50/0.30
Pine	392	0.107	0.062	0.742	2	0.9	0.50/0.30
Pine (white)	430	0.110	0.064	0.763	5	0.9	0.50/0.30
Pine (Norway)	441	0.120	0.069	0.829	7	0.9	0.50/0.30
Pine (northern white)	481	0.121	0.070	0.839	7	0.9	0.50/0.30
Pine (ponderosa)	489	0.122	0.071	0.849	7	0.9	0.50/0.30
Pine (Radiata)	504	0.128	0.074	0.887	10	0.9	0.50/0.30
Pine	502	0.130	0.075	0.901	2	0.9	0.50/0.30
Pine (longleaf)	609	0.138	0.080	0.958	7	0.9	0.50/0.30
Pine (shortleaf)	545	0.141	0.082	0.978	7	0.9	0.50/0.30
Pine (southern, yellow)	570	0.144	0.083	0.998	2	0.9	0.50/0.30
Pine (southern, yellow)	659	0.161	0.093	1.116	2	0.9	0.50/0.30
Red Alder	440	0.114	0.066	0.791	10	0.9	0.50/0.30
Spruce	392	0.107	0.062	0.742	2	0.9	0.50/0.30
Spruce	420	0.110	0.064	0.763	5	0.9	0.50/0.30

Name	Density ρ	Conductivity *k*			Source	Emissivity ε	Absorptivity[1] α
	kg/m³	**W/m•K**	**Btu/hr•ft•F**	**Btu•in/hr•ft²•°F**	**-**	**-**	**-**
Spruce	502	0.130	0.075	0.901	2	0.9	0.50/0.30
Spruce, Sitka	425	0.098	0.057	0.679	7	0.9	0.50/0.30
Wood based panels							
Particleboard, Plywood	500	0.130	0.075	0.901	1	0.9	0.50/0.30
Particleboard, Plywood	600	0.140	0.081	0.971	1	0.9	0.50/0.30
Insulating Materials							
Cellulose	48	0.039	0.023	0.273	10	0.9	0.50/0.30
Cellulose	54	0.057	0.033	0.395	5	0.9	0.50/0.30
Cellulosic fiber	96	0.049	0.028	0.340	1	0.9	0.50/0.30
Polystyrene expanded (EPS)	50-60	0.031	0.018	0.218	1	0.9	0.50/0.30
Polystyrene expanded (EPS)	35-45	0.032	0.019	0.223	1	0.9	0.50/0.30
Polystyrene expanded (EPS)	30	0.033	0.019	0.227	1	0.9	0.50/0.30
Polystyrene expanded (EPS)	25	0.034	0.020	0.236	1	0.9	0.50/0.30
Polystyrene expanded (EPS)	20	0.035	0.020	0.243	1	0.9	0.50/0.30
Polystyrene expanded (EPS)	10	0.043	0.025	0.300	1	0.9	0.50/0.30
Polystyrene expanded, molded beads	16	0.037	0.021	0.257	1	0.9	0.50/0.30
Polystyrene expanded, molded beads	24	0.035	0.020	0.243	1	0.9	0.50/0.30
Polystyrene expanded, molded beads	32	0.033	0.019	0.229	1	0.9	0.50/0.30
Extruded polystyrene(XPS) CO2	30-50	0.034	0.020	0.236	1	0.9	0.50/0.30
Mineral fiber with resin binder		0.042	0.024	0.291	2	0.9	0.50/0.30
Polyester fiber	25	0.035	0.020	0.243	1	0.9	0.50/0.30
Polyester fiber	35	0.033	0.019	0.230	1	0.9	0.50/0.30
Polyester fiber	45	0.032	0.019	0.225	1	0.9	0.50/0.30
Silica Aerogel	73	0.024	0.014	0.166	10	0.9	0.50/0.30
Polyurethane foam, HCFC blown		0.021	0.012	0.146	11	0.9	0.50/0.30

Name	Density ρ	Conductivity *k*			Source	Emissivity ε	Absorptivity[1] α
	kg/m³	W/m•K	Btu/hr•ft•F	Btu•in/hr•ft²•°F	-	-	-
							0.50/0.30
Masonry Materials							
Concrete – medium density	1,800	1.15	0.66	7.97		0.90	0.50/0.30
Concrete – high density	2,400	2.00	1.16	13.87		0.90	0.50/0.30
Concrete – reinforced (2% steel)	2,400	2.50	1.44	17.33		0.90	0.50/0.30
Brick, Fired clay – high density	2,400	1.47	0.85	10.19		0.90	0.50/0.30
Brick, Fired clay – medium density	1,600	0.74	0.43	5.13		0.90	0.50/0.30
Brick, Fired clay – low density	1,120	0.45	0.26	3.12		0.90	0.50/0.30
Gypsum plasterboard	900	0.25	0.14	1.73		0.90	0.50/0.30
							0.50/0.30
Metals							
Bronze (polished)	8,700	65	37.56	450	1,9	0.05	0.50/0.30
Bronze (other)	8,700	65	37.56	450	1,9	0.20	0.50/0.30
Brass (polished)	8,400	120	69.34	832	1,9	0.05	0.50/0.30
Brass (other)	8,400	120	69.34	832	1,9	0.20	0.50/0.30
Copper (polished)	8,900	380	219.56	2634	1,9	0.03	0.50/0.30
Copper (other)	8,900	380	219.56	2634	1,9	0.80	0.50/0.30
Gold - 99.999% (polished)	19,290	310	179.12	2149	9	0.03	0.50/0.30
Gold - 99.999% (other)	19,290	310	179.12	2149	9	0.50	0.50/0.30
Iron, cast (polished)	7,500	50	28.89	346	1,9	0.20	0.50/0.30
Iron, cast (other)	7,500	50	28.89	346	1,9	0.80	0.50/0.30
Lead (polished)	11,300	35	20.22	242	1,9	0.08	0.50/0.30
Lead (other)	11,300	35	20.22	242	1,9	0.30	0.50/0.30
Nickel - 99+% (polished)	8,800	93	53.74	644	9	0.05	0.50/0.30
Nickel - 99+% (other)	8,800	93	53.74	644	9	0.40	0.50/0.30
Platinum (polished)	21,400	60	34.67	416	9	0.05	0.50/0.30
Platinum (other)	21,400	60	34.67	416	9	0.20	0.50/0.30
Silver - 99.98+% (polished)	10,500	3,600	2,080	24,960	9	0.03	0.50/0.30

Name	Density ρ	Conductivity *k*			Source	Emissivity ε	Absorptivity[1] α
	kg/m³	W/m•K	Btu/hr•ft•F	Btu•in/hr•ft²•°F	-	-	-
Metals - Continued							
Zinc (polished)	7,200	110	63.6	762	1,9	0.05	0.50/0.30
Zinc (other)	7,200	110	63.6	762	1,9	0.30	0.50/0.30

Table B.2: Approved Documented Generic Materials Sources:

1. prEn 12524: *Building material and products-Hygrothermal properties-Tabulated design values* , November 1999 (and B.R. Anderson, et al., Final Report of the Thermal Values Group, March 1999)
2. *ASHRAE Fundamentals Handbook (SI)*, 2005
3. D.F. Miner and J.B. Seastone, *Handbook of Engineering Materials,* 1955
4. F.P. Incropera and D.P. Dewitt, *Fundamental of Heat and Mass Transfer(Third edition)*, 1990
5. Kuzman Raznjevic, *Handbook of Thermodynamic Tables and Charts*, McGraw-Hill Book Company
6. *NIST Heat Transmission Properties of Insulation and Building Materials Database*
7. Harper, C.A. *Modern Plastics Handbook.* McGraw-Hill. P. C51.
8. Frank M. White, *Heat and Mass Transfer*, Addison-Wesley, 1991
9. IS. *Emissivity Values for Common Materials*. Infrared Services Co.; 2000.
10. *Wood as an engineering material*. General Technical Report 113. Madison, WI: U.S. Department of Agriculture, Forest Service, Forest Products Laboratory - March, 1999

APPENDIX C MANUFACTURER SPECIFIC THERMOPHYSICAL PROPERTY VALUES OF MATERIALS

Table C.1: Thermophysical Properties of Solid Materials

Name	Density ρ	Conductivity *k*			Emissivity ε[2]	Absorptivity[1] α
	kg/m³	W/m•K	Btu/hr•ft•F	Btu•in/hr•ft²•°F	-	-
Mikron XTD composite		0.106	0.061	0.736	0.9	0.50/0.30
Edgetech- Silicone foam spacer	968	0.159	0.092	1.10	0.9	0.50/0.30
Edgetech-EPDM foam spacer	876	0.162	0.094	1.12	0.9	0.50/0.30
Ensinger, Inc.- Insulbar Material	1,292	0.251	0.145	1.74	0.9	0.50/0.30
TrueSeal Technologies - Butyl 761-71X		0.231	0.133	1.603	0.9	0.50/0.30
Trinity Glass International - Wood Flour Resin	45.80	0.081	0.047	0.559	0.9	0.50/0.30
Major Industries - Translucent Thermal Insulation 24	4.31	0.098	0.057	0.680	0.9	0.50/0.30
Major Industries - Translucent Thermal Insulation 15	6.94	0.079	0.046	0.549	0.9	0.50/0.30
ICT, Inc. - Cellulosic Thermoplastic Composite	1,057	0.244	0.141	1.693	0.71	0.50/0.30
Major Industries - Ultimate Series FRP	1,236	0.143	0.083	0.993	0.9	0.50/0.30
Royal Moldings- cellular PVC	635	0.066	0.038	0.456	-	-
Kalwall Insulation A	4.54	0.115	0.066	0.794	-	-
Kalwall Insulation B	4.06	0.093	0.054	0.648	-	-
Kalwall Insulation C	12.82	0.047	0.027	0.327	-	-
Kalwall Insulation D	38.98	0.032	0.019	0.222	-	-

[2] Emissivity for non-metallic materials is defaulted to 0.90 without actual measurements