DEVELOPMENT AND EXPERIMENTAL VERIFICATION OF A COMPUTER PROGRAM FOR PREDICTING TEMPERATURE DISTRIBUTION AND HEAT TRANSFER THROUGH COATED AND UNCOATED, SINGLE OR MULTI-GLAZED WINDOW SYSTEMS

Gary M. Korb
Ronald D. Dayton
Duncan Sommerville
Midwest Research Institute

*** Export controls have been removed ***

This document is subject to special export controls and each transmittal to foreign governments or foreign nationals may be made only with prior approval of the Air Force Flight Dynamics Laboratory (FDX), Wright-Patterson Air Force Base, Ohio 45433.

Approved for Public Release
This research was performed to develop and experimentally verify a computer program for predicting the temperatures of and heat transfer through windows of advanced Air Force aerospace vehicles. In addition to supplying data for validation of the computer program, the heat transfer test results provide experimental data on realistic window components. The work was performed from June 1966 to February 1969 by Gary M. Korb, Ronald D. Dayton, and Duncan Somerville of Midwest Research Institute, 428 Volker Boulevard, Kansas City, Missouri 64110. The work was sponsored by the Air Force Flight Dynamics Laboratory, Air Force Systems Command, Wright-Patterson Air Force Base, under Contract No. AF 33(613)-5184, Project No. 1568, "Structural Design Concepts," Task No. 15602, "Window System Concepts."

Lt. Joseph S. Harmer and Lt. David B. Reuber, USAF, of the Air Force Flight Dynamics Laboratory, were project engineers for the periods of June 1966 - March 1967 and March 1967 - February 1969, respectively.

Acknowledgement is hereby given to the following individuals for their counsel and assistance: Dr. Frank Kreith, Consultant and Professor of Mechanical Engineering, University of Colorado; Mr. Robert Gardon, Consultant, Farmington, Michigan; Mrs. Leilah G. Fay of the ASNC Open Shop Computer Facility, Wright-Patterson Air Force Base; and Dr. Florence Metz, Mr. Harold Pinch, Mr. Eugene Moeller, Mr. Michael Noland, and Mr. Herman Fasel of Midwest Research Institute.

Publication of this report does not constitute Air Force approval of the report's findings or conclusions. It is published only for the exchange and stimulation of ideas.

This report was submitted by the authors in February 1969.

This technical report has been reviewed and is approved.

KEITH L. COLLIER
Chief, Applied Mechanics Branch
Structures Division
Air Force Flight Dynamics Laboratory
The severe thermal environment of future hypervelocity aerospace vehicles will place rigorous demands on direct vision window systems. At the high temperatures encountered, heat will be transferred within window materials by both conduction and radiation. This report describes the development and experimental verification of a computer program for predicting the temperature distribution and heat transfer through coated and uncoated, single or multiple glaze window systems. The heat balance equations in the computer program account for emission, attenuation, and absorption of radiant energy within the glaze. Reflection and transmission of glaze surfaces having multilayer, thin-film coatings are computed. Window temperatures and heat flux can be predicted for transient conditions of individual and/or combined convective and radiative heating. The computer program was experimentally verified with heat transfer tests in which specimens of various glaze materials and thicknesses were used. Typical aerospace reflection and antireflection coatings were employed on one and/or both surfaces of the test specimens. The work was performed in three phases. In the first phase the research was applicable to single uncoated glazes. In the second phase the scope was expanded to include coated single glazes, and in the third phase coated and uncoated multiple glazes were investigated. Good agreement between the analytical and experimental results was obtained. The computer program is written in FORTRAN IV language and for the IBM 7094 digital computer. A program user's manual is available as a separate publication.

(This document is subject to special export controls and each transmittal to foreign governments or foreign nationals may be made only with prior approval of the Air Force Flight Dynamics Laboratory (AFED), Wright-Patterson Air Force Base, Ohio 45433.)
Approved for Public Release
<table>
<thead>
<tr>
<th>SECTION</th>
<th>PAGE</th>
</tr>
</thead>
<tbody>
<tr>
<td>I. INTRODUCTION</td>
<td>1</td>
</tr>
<tr>
<td>II. COMPUTER PROGRAM</td>
<td>3</td>
</tr>
<tr>
<td>A. DESCRIPTION AND CAPABILITIES</td>
<td>3</td>
</tr>
<tr>
<td>B. ANALYTICAL MODEL</td>
<td>4</td>
</tr>
<tr>
<td>C. RADIATION WITHIN THE GLAZE</td>
<td>6</td>
</tr>
<tr>
<td>D. HEAT BALANCE EQUATIONS</td>
<td>6</td>
</tr>
<tr>
<td>E. BOUNDARY CONDITIONS</td>
<td>7</td>
</tr>
<tr>
<td>F. GLAZE THERMOHYDRAULIC AND OPTICAL PROPERTIES</td>
<td>9</td>
</tr>
<tr>
<td>G. FLIGHT CONDITIONS AND RADIATIVE HEATING</td>
<td>11</td>
</tr>
<tr>
<td>H. NUMERICAL SOLUTION</td>
<td>12</td>
</tr>
<tr>
<td>III. EXPERIMENTAL PROGRAM</td>
<td>15</td>
</tr>
<tr>
<td>A. TEST APPARATUS</td>
<td>13</td>
</tr>
<tr>
<td>B. WINDOW TEST SPECIMEN</td>
<td>25</td>
</tr>
<tr>
<td>C. THIN-FILM COATINGS</td>
<td>25</td>
</tr>
<tr>
<td>D. COATING TEMPERATURE LIMITS</td>
<td>25</td>
</tr>
<tr>
<td>E. TEMPERATURE SENSORS</td>
<td>29</td>
</tr>
<tr>
<td>F. SUPERPOSITION TESTS</td>
<td>32</td>
</tr>
<tr>
<td>G. HEAT TRANSFER TESTS</td>
<td>32</td>
</tr>
<tr>
<td>H. COATING AND GLAZE DAMAGE</td>
<td>35</td>
</tr>
<tr>
<td>IV. ANALYTICAL AND EXPERIMENTAL RESULTS</td>
<td>36</td>
</tr>
<tr>
<td>A. COMPUTER PROGRAM VERIFICATION</td>
<td>38</td>
</tr>
<tr>
<td>B. ADDITIONAL EXPERIMENTAL RESULTS</td>
<td>53</td>
</tr>
<tr>
<td>C. ADDITIONAL ANALYTICAL RESULTS</td>
<td>58</td>
</tr>
<tr>
<td>V. CONCLUSIONS</td>
<td>67</td>
</tr>
<tr>
<td>APPENDIX A - EQUATIONS FOR COMPUTING RADIATION WITHIN WINDOW GLAZES</td>
<td>69</td>
</tr>
<tr>
<td>APPENDIX B - EQUATIONS USED TO COMPUTE TRANSMITTANCE AND REFLECTANCE OF COATED AND UNCOATED GLAZE SURFACES</td>
<td>99</td>
</tr>
<tr>
<td>APPENDIX C - THERMOHYDRAULIC AND OPTICAL PROPERTIES OF GLAZE MATERIALS</td>
<td>111</td>
</tr>
<tr>
<td>APPENDIX D - CORRELATIONS USED TO PREDICT IN-FLIGHT HEATING</td>
<td>119</td>
</tr>
<tr>
<td>CONTENTS (CONTINUED)</td>
<td>PAGE</td>
</tr>
<tr>
<td>------------------------------------------</td>
<td>------</td>
</tr>
<tr>
<td>APPENDIX E - SUPERPOSITION TESTS</td>
<td>127</td>
</tr>
<tr>
<td>APPENDIX F - EXPERIMENTAL RESULTS</td>
<td>137</td>
</tr>
<tr>
<td>REFERENCES</td>
<td>166</td>
</tr>
<tr>
<td>FIGURE</td>
<td>TITLE</td>
</tr>
<tr>
<td>--------</td>
<td>-----------------------------------------------------------</td>
</tr>
<tr>
<td>1</td>
<td>WINDOW PANNE CROSS SECTION</td>
</tr>
<tr>
<td>2</td>
<td>PRIMARY AND MULTIPLE REFLECTED RADIANT ENERGY</td>
</tr>
<tr>
<td>3</td>
<td>ABSORPTION COEFFICIENT FOR PYCOR (96% FUSED SILICA)</td>
</tr>
<tr>
<td>4</td>
<td>RADIATIVE AND CONVECTIVE TRANSPARENT BOUNDARY APPARATUS</td>
</tr>
<tr>
<td>5</td>
<td>MODIFIED VERSION OF TBA NO. 2 FOR VACUUM TESTING</td>
</tr>
<tr>
<td>6</td>
<td>HIGH TEMPERATURE RADIANT HEATER</td>
</tr>
<tr>
<td>7</td>
<td>SCHEMATIC OF WINDOW AND HEATER CONFIGURATION</td>
</tr>
<tr>
<td>8</td>
<td>CONFIGURATION FACTORS FOR TWO PARALLEL RISERS</td>
</tr>
<tr>
<td>9</td>
<td>RADIATION IN VACUUM WITH h = 9/16 IN.</td>
</tr>
<tr>
<td>10</td>
<td>CONVECTIVE TRANSPARENT BOUNDARY APPARATUS</td>
</tr>
<tr>
<td>11</td>
<td>TEST SPECIMEN SUPPORT</td>
</tr>
<tr>
<td>12</td>
<td>SCHEMATIC OF APPARATUS COMPONENTS, INSTRUMENTS, AND</td>
</tr>
<tr>
<td></td>
<td>CONTROLS</td>
</tr>
<tr>
<td>13</td>
<td>WINDOW TEST SPECIMEN</td>
</tr>
<tr>
<td>14</td>
<td>CALIBRATION FIXTURE - OPEN</td>
</tr>
<tr>
<td>15</td>
<td>CALIBRATION FIXTURE - CLOSED</td>
</tr>
<tr>
<td>16</td>
<td>PARALLEL OUTER-INNER GLAZINGS OF THE MULTIPLE GLAZE TESTS</td>
</tr>
<tr>
<td>17</td>
<td>1/4-IN. FUSED SILICA WINDOW HEATED BY RADIATION, STEADY-</td>
</tr>
<tr>
<td></td>
<td>STATE CONDITIONS</td>
</tr>
<tr>
<td>18</td>
<td>1/4-IN. FUSED SILICA WINDOW HEATED BY CONVECTION, STEADY-</td>
</tr>
<tr>
<td></td>
<td>STATE CONDITIONS</td>
</tr>
<tr>
<td>19</td>
<td>EFFECTIVE ENERGIVITY OF 1/4-IN. FUSED SILICA PLATE</td>
</tr>
<tr>
<td>FIGURE</td>
<td>TITLE</td>
</tr>
<tr>
<td>--------</td>
<td>----------------------------------------------------------------------</td>
</tr>
<tr>
<td>20</td>
<td>MEASURED AND COMPUTED TRANSIENT TEMPERATURES</td>
</tr>
<tr>
<td>21</td>
<td>MEASURED AND COMPUTED TRANSIENT TEMPERATURES AND HEAT FLUX</td>
</tr>
<tr>
<td>22</td>
<td>1/4-IN. FUSED SILICA, 1/8-IN. YCOCR DOUBLE WINDOW HEATED BY RADIATION IN AIR, STEADY-STATE CONDITIONS</td>
</tr>
<tr>
<td>23</td>
<td>1/4-IN. FUSED SILICA, 1/8-IN. YCOCR DOUBLE PANEL WINDOW HEATED BY CONVECTION IN AIR, STEADY-STATE CONDITIONS</td>
</tr>
<tr>
<td>24</td>
<td>1/4-IN. FUSED SILICA, 1/8-IN. YCOCR DOUBLE PANEL WINDOW HEATED BY RADIATION AND CONVECTION IN AIR, STEADY-STATE CONDITIONS</td>
</tr>
<tr>
<td>25</td>
<td>1/4-IN. FUSED SILICA, 1/8-IN. YCOCR DOUBLE PANEL WINDOW HEATED BY RADIATION IN A VACUUM, STEADY-STATE CONDITIONS</td>
</tr>
<tr>
<td>26</td>
<td>COMPUTED TEMPERATURE DISTRIBUTION IN 1/4-IN. FUSED SILICA, OPAQUE AND SEMITRANSPARENT ANALYSIS</td>
</tr>
<tr>
<td>27</td>
<td>COMPUTED TEMPERATURE DISTRIBUTION IN 1/4-IN. FUSED SILICA, HEATED BY RADIATION AND CONVECTION</td>
</tr>
<tr>
<td>28</td>
<td>COMPARISON OF TEMPERATURES AND CABIN HEAT FLUX OF WINDOW SYSTEM HEATED BY RADIATION IN AIR AND IN A VACUUM</td>
</tr>
<tr>
<td>29</td>
<td>THERMAL PERFORMANCE OF A DOUBLE PANEL WINDOW DURING A HYPERSO nic SKI P-GLIDE RE-ENTRY</td>
</tr>
<tr>
<td>30</td>
<td>PORTION OF HYPERSO nic SKI P-GLIDE RE-ENTRY TRAJECTORY</td>
</tr>
<tr>
<td>31</td>
<td>THERMAL PERFORMANCE OF A DOUBLE PANEL WINDOW DURING A MACH 3 SUPERSO nic FLIGHT</td>
</tr>
<tr>
<td>32</td>
<td>MACH 3 SUPERSO nic TRANSPORT FLIGHT PATH</td>
</tr>
<tr>
<td>33</td>
<td>THERMAL PERFORMANCE OF A DOUBLE PANEL WINDOW IN 200 NM CIRCULAR ORBIT</td>
</tr>
</tbody>
</table>

viii

Approved for Public Release
<table>
<thead>
<tr>
<th>FIGURE</th>
<th>TITLE</th>
<th>PAGE</th>
</tr>
</thead>
<tbody>
<tr>
<td>34</td>
<td>SEDIMENTATION POINT HEAT TRANSFER RATE</td>
<td>65</td>
</tr>
<tr>
<td>35</td>
<td>THERMAL PERFORMANCE OF A DOUBLE PANE WINDOW ASSUMING WINDOW HEATING TO BE 0.02 TIMES $q_{at}$ OF FIGURE 53</td>
<td>66</td>
</tr>
<tr>
<td>A-1</td>
<td>MULTIPLE-GLAZE WINDOW SYSTEM</td>
<td>82</td>
</tr>
<tr>
<td>B-1</td>
<td>SELECTED BOUNDARY CONDITIONS</td>
<td>129</td>
</tr>
<tr>
<td>B-2</td>
<td>BOUNDARY CONDITIONS THAT CAN BE ELIMINATED BY APPLICATION OF SUPERPOSITION PRINCIPLE</td>
<td>129</td>
</tr>
<tr>
<td>E-3</td>
<td>SUPERPOSITION TEST IN VACUUM WITH $h = \frac{9}{16}$ IN.</td>
<td>131</td>
</tr>
<tr>
<td>E-4</td>
<td>SUPERPOSITION TEST IN VACUUM WITH $h = 8.0$ IN.</td>
<td>132</td>
</tr>
<tr>
<td>E-5</td>
<td>SCHEMATIC OF HEAT FLOW BETWEEN TWO PARALLEL PLATES FOR RAYLEIGH NUMBER $\ll 1700$</td>
<td>133</td>
</tr>
<tr>
<td>E-6</td>
<td>SUPERPOSITION TESTS</td>
<td>134</td>
</tr>
<tr>
<td>E-7</td>
<td>PHASE III TEST SETUP</td>
<td>136</td>
</tr>
<tr>
<td>TABLE</td>
<td>TITLE</td>
<td>PAGE</td>
</tr>
<tr>
<td>-------</td>
<td>-------</td>
<td>------</td>
</tr>
<tr>
<td>I</td>
<td>VARIATION OF GLAZE TEMPERATURES AND HEAT FLUX WITH THICKNESS FOR FUSED SILICA HEATED BY RADIATION AND CONVECTION</td>
<td>45</td>
</tr>
<tr>
<td>II</td>
<td>VARIATION OF GLAZE TEMPERATURES AND HEAT FLUX WITH TYPICAL GLAZE MATERIALS FOR 1/4-IN. WINDOW HEATED BY RADIATION AND CONVECTION</td>
<td>45</td>
</tr>
<tr>
<td>III</td>
<td>EFFECT OF TYPICAL WINDOW COATINGS ON TEMPERATURES AND HEAT FLUX OF 1/4-IN. FUSED SILICA SPECIMEN HEATED BY RADIATION AND CONVECTION</td>
<td>45</td>
</tr>
<tr>
<td>IV</td>
<td>TEMPERATURES AND HEAT FLUXES FOR VARIOUS GLAZE CONFIGURATIONS AND A CONSTANT RADIATIVE INPUT</td>
<td>51</td>
</tr>
<tr>
<td>V</td>
<td>TEMPERATURES AND HEAT FLUXES FOR VARIOUS GLAZE CONFIGURATIONS AND A CONSTANT CONVECTIVE INPUT</td>
<td>51</td>
</tr>
<tr>
<td>VI</td>
<td>TEMPERATURES AND HEAT FLUXES FOR VARIOUS COATING CONFIGURATIONS ON A 1/4-IN. FUSED SILICA AND 1/8 IN. VYCOR WINDOW SYSTEM IN AN AIR ENVIRONMENT</td>
<td>52</td>
</tr>
<tr>
<td>VII</td>
<td>TEMPERATURES AND HEAT FLUXES FOR VARIOUS COATING CONFIGURATIONS ON A 1/4-IN. FUSED SILICA AND 1/8-IN. VYCOR WINDOW SYSTEM IN A VACUUM ENVIRONMENT</td>
<td>52</td>
</tr>
<tr>
<td>VIII</td>
<td>EFFECT OF NUMBER OF GLAZES IN A WINDOW SYSTEM ON TEMPERATURES AND HEAT FLUX</td>
<td>58</td>
</tr>
<tr>
<td>B-I</td>
<td>TRANSMITTANCE OF UV-IR COATING ON VYCOR GLAZE</td>
<td>106</td>
</tr>
<tr>
<td>B-II</td>
<td>TRANSMITTANCE OF UV-IR COATING ON FUSED SILICA GLAZE</td>
<td>106</td>
</tr>
<tr>
<td>B-III</td>
<td>TRANSMITTANCE OF UV-IR COATING ON ALUMINOSILICATE GLAZE</td>
<td>107</td>
</tr>
<tr>
<td>B-IV</td>
<td>TRANSMITTANCE OF MICA COATING ON VYCOR GLAZE</td>
<td>107</td>
</tr>
<tr>
<td>B-V</td>
<td>TRANSMITTANCE OF MICA COATING ON FUSED SILICA GLAZE</td>
<td>107</td>
</tr>
<tr>
<td>B-VI</td>
<td>TRANSMITTANCE OF MICA COATING ON ALUMINOSILICATE GLAZE</td>
<td>108</td>
</tr>
</tbody>
</table>
### TABLES (CONCLUDED)

<table>
<thead>
<tr>
<th>TABLE</th>
<th>TITLE</th>
<th>PAGE</th>
</tr>
</thead>
<tbody>
<tr>
<td>B-VII</td>
<td>TRANSMITTANCE OF GOLD COATING ON VYCOR GLAZE</td>
<td>108</td>
</tr>
<tr>
<td>B-VIII</td>
<td>TRANSMITTANCE OF GOLD COATING ON FUSED SILICA GLAZE</td>
<td>108</td>
</tr>
<tr>
<td>C-I</td>
<td>MATERIAL = FUSED SILICA</td>
<td>113</td>
</tr>
<tr>
<td>C-II</td>
<td>MATERIAL = VYCOR (96 PERCENT SILICA)</td>
<td>114</td>
</tr>
<tr>
<td>C-III</td>
<td>MATERIAL = ALUMINOSILICATE</td>
<td>115</td>
</tr>
<tr>
<td>C-IV</td>
<td>MATERIAL = BOROSILICATE</td>
<td>116</td>
</tr>
<tr>
<td>C-V</td>
<td>MATERIAL = SODA LIME</td>
<td>117</td>
</tr>
<tr>
<td>D-I</td>
<td>COEFFICIENT FOR THE LEAST-SQUARES FIT, LOW TEMPERATURE: $1000 \leq T \leq 5000^\circ K$</td>
<td>122</td>
</tr>
<tr>
<td>D-II</td>
<td>COEFFICIENTS FOR THE LEAST-SQUARES FIT, HIGH TEMPERATURE: $5000 \leq T \leq 18000^\circ K$</td>
<td>125</td>
</tr>
</tbody>
</table>
Contrails

Approved for Public Release
SECTION I

INTRODUCTION

Previously, pilot visibility has been treated as a relatively minor problem in the design of aircraft. The aircraft designer simply modified his design to provide the pilot with the most advantageous view of the outside surroundings from within the confines of the cockpit using ordinary, highly transparent window materials. However, the severe thermal environment of future hypersonic (Mach 5+) and hypervelocity (Mach 10+) aerospace vehicles will place much more rigorous demands on direct vision window systems than were ever contemplated in our current window designs. Steady-state temperatures approaching 2000°F will be experienced, not for a few brief minutes, but for prolonged periods of time during hypersonic cruise and lifting re-entry flight.

If direct vision systems continue to play a major role in mission performance, design engineers must undertake new design approaches rather than continue the preferred method of modification and improvement of an existing, proven design. The limited amount of operational experience of high-temperature windows has underscored the severity of this problem. The designer of advanced high-temperature window systems will require realistic approaches to aid him in evaluating thermal shock, thermal gradients, and heat soak conditions of transparent materials. Toward this end, Midwest Research Institute under contract to the Air Force has completed the development of a computer program to predict the heat flux and temperature distributions through high-temperature transparent materials, both coated and uncoated. The glasses, the coatings, and the test conditions have been selected to simulate the requirements and the thermal environment of hypersonic flight. This approach yields empirical data on realistic window components in addition to supplying input data for validation of the computer program.

The work was performed in three phases. In the first phase, the research was applicable to single uncoated glasses. In the second phase, the scope was expanded to include coated single glasses, and in the third phase, coated and uncoated multiple glasses were investigated.

During Phase I, 27 single glass experimental tests were conducted involving three window glass materials, three glass thicknesses, and three

* The term glass as used in this discussion refers to window materials such as fused silica, plastic, etc.
modes of heat transfer. The three specimen materials tested were fused silica, aluminosilicate, and 96% fused silica having thicknesses of 1/8, 1/4, and 5/8 in. Each of the nine specimens was subjected to convective, radiative, and combined radiative and convective heating. Modifications of the single glaze computer program (Ref. 1) were completed, resulting in a good correlation between the computer and experimental glaze temperatures and heat flux.

Eighty-five single glaze tests were conducted in Phase II of the research program. These tests were similar to those conducted in Phase I with the exception of the test specimen. The glass specimens were of the same materials and thicknesses as those of Phase I, but employed thin-film coatings on one or both surfaces. A subroutine was added to the computer program which calculated the transmittance and reflectance of glass surfaces having thin-film, multiple-layer coatings. In addition, a routine was included in the program so that the coating transmission and reflectance can be read as input data, rather than being computed, if these data are available. The temperatures of and heat fluxes through coated single glases were computed and compared with those measured experimentally. A good correlation was obtained between the computed and measured values.

During Phase III, 112 double glaze experimental heat transfer tests were conducted in both air and vacuum environments using coated and uncoated glaes of various materials and thicknesses. The computer program was modified and expanded to include the thermal analysis of coated and uncoated, multi-glaze window systems. Computed temperatures of, and heat flux through, double glaze window configurations were in good agreement with the Phase III experimental results.

A discussion of the theory, heat balance equations, and the capabilities of the computer program is presented in Section II of this report. Section III describes the equipment, glaze test specimens, and instrumentation employed in the experimental effort. A comparison and discussion of the experimental and analytical results are presented in Section IV and the conclusions are given in Section V.

Approved for Public Release
SECTION II
COMPUTER PROGRAM

A major objective of the effort described in this report was to generate a method of predicting temperature distributions and heat fluxes through coated and uncoated single and multiple-glaze aerospace windows subjected to individual and combined convective and radiative heating. This objective was accomplished by modifying and expanding a computer program previously developed (Ref. 1) for single-glaze windows.

A. Description and Capabilities

The computer program is designed for the thermal analysis of window systems containing as many as five window panes of different materials and thicknesses with thin-film coatings on any or all of the glaze surfaces. The spaces between the window panes can contain a moving gas, a stationary gas, or a vacuum. Transient window temperatures and heat flux to the cabin can be computed for time-dependent radiative and/or convective heating conditions. The computer program contains subroutines for computing the heat flux to the window using accepted aerodynamic heating correlations. As an alternative option, heat transfer rates to the window can be included in the input data. Reflection and transmission of the glaze surfaces may be computed for coated and uncoated window panes or be input if these data are available. The basic assumptions made in the analysis are:

1. The heat transfer is one-dimensional and normal to the glaze.

2. The window panes are composed of plane parallel, optically smooth, homogeneous, and isotropic glaze material.

3. The materials are considered to be nondissipative.

4. Any external radiant source is considered perfectly diffuse and initially unpolarized.

5. Radiation emitted within the glaze is considered to be perfectly diffuse and initially unpolarized.

6. Attenuation of radiation within the glaze material is described by the Bouguer-Lambert law.

7. Radiative emission within the glaze is described by Gardon's derived volumetric emissive power.

Approved for Public Release
B. Analytical Model

Assuming one-dimensional heat transfer to be the case, an analytical model was established by treating each window pane as being composed of 11 finite slices or elements (Figure 1).

![Figure 1 - Window Pane Cross Section](image)

Unlike opaque bodies, absorption by dielectric materials takes place in depth, and unlike perfectly transparent materials, semitransparent materials partially absorb impinging radiation. Thus, the energy absorbed by each element within the window is that received by both conduction and radiation since the glass is considered transparent or semitransparent to radiation emitted within given spectral bands. Each slice receives radiant energy from each of the remaining ten elements as well as from external radiant sources. Radiation from an external source is partially reflected and partially refracted at the glass surface. A portion of the refracted energy is absorbed as it traverses the window and is then partially reflected back into the glass at the second surface. This internally reflected radiation is treated as multiple reflected beams which are partially reflected each time they reach the surfaces and are partially absorbed each time they traverse the window. Radiation energy emitted from each elemental slice is also absorbed and multiply reflected within the glass. Thus, each element absorbs energy emitted directly from the external and internal sources as well as from the multiple reflections of the radiation from these sources (Figure 2).
Figure 2 - Primary and Multiple Reflected Radiant Energy
C. Radiation Within the Glaze

The theory employed in the analysis is that developed by Gordon (Refs. 2 and 3) and used by Liss, M. E. and English (Ref. 4) in the initial development phase of the subject computer program. This theory has as its basis the well-known Bouguer-Lambert law and a volumetric emissive power derived by Gordon (Ref. 4) to compute the radiant energy absorbed and emitted, respectively, by the elements within the glaze. The Bouguer-Lambert law,

\[ I_x = I_0 e^{-\gamma_x x \sec \alpha} \]

relates the attenuation and absorption of radiation to an absorption coefficient, \( \gamma \), and to the distance, \( x \sec \alpha \), traveled by the radiation. Volumetric emissive power,

\[ J_\lambda = \frac{\gamma_\lambda a^2 w_{E\lambda}}{\pi} \]

relates the radiant intensity emitted per unit volume to the glaze absorption coefficient, the glaze index of refraction, \( n \), and the hemispherical emissive power of a blackbody radiator, \( w_{E\lambda} \).

The radiant energy that is absorbed by a given element is based on the reduction in intensity of the radiation as the beams pass through the element.

D. Heat Balance Equations

The general heat balance equation for each element is written in its finite difference form as:

\[ \rho c \frac{\partial T_\lambda}{\partial t} = \sum_{\lambda} \left[ Q_{A\lambda}(t) + Q_{R\lambda}(t) \right] + \kappa \left[ \frac{\delta^2 T_\lambda}{\delta x^2} + \frac{V_{i+1}}{\delta x^2} \right] \]

Net heat transfer to and from the glaze element by conduction is defined by the last term in the equation. The term \( Q_{A\lambda}(t) \) represents the radiant energy absorbed by the element at position \( x \). Sources of this radiation consist of the other elements and surface coatings within the window system and the shock heated air flowing over the window's outer surface. Energy
emitted by the element at position \( x \) is represented by the term \( Q_{N_1}(1) \). Since the absorption and emission of radiation by the elements are spectrally dependent, these values are computed for and summed over finite wavelength bands within the spectral region for which the glaze is considered to be semitransparent. The spectrally dependent glaze properties are considered constant within a given finite wavelength band. The percent of energy emitted within a given finite wavelength band by the external source, the surface coatings, and the glaze elements is based on a table of Planck's blackbody radiation functions. The equations for the radiant energy absorbed and emitted in the glaze, i.e., for \( Q_{R_1}(1) \) and \( Q_{R_2}(1) \) are developed and presented in Appendix A.

E. Boundary Conditions

In addition to conduction and radiation within the glaze material, the heat balance equations for the surface elements include terms which account for heat transfer to and from the window by convection and by radiation at wavelengths to which the glaze is considered opaque. For Element 1, the energy balance equation is written as:

\[
\frac{\partial \theta_1}{\partial t} + \frac{\partial}{\partial x} \left[ \alpha \sum_k \left( Q_{R_1}(1) - Q_{R_2}(1) \right) + \frac{h}{\alpha} \left[ T_1 - T_2 \right] \right]
+ \left[ (1 - \rho_1)^P_L + (1 - \rho_2)^P_R \right] e \sigma T_1^4 - \left[ (1 - \rho_1)^P_L + (1 - \rho_2)^P_L \right] e \sigma T_4^4
+ h \left[ T_1 - T_{sh} \right] + q_{sh}
\]

In this equation the convective heating or cooling can be input as a heat flux, \( q_{sh} \), or can be defined using a heat transfer coefficient, \( h \), times the difference between the air temperature, \( T_{sh} \), and the element temperature, \( T_1 \). Radiation of wavelengths to which the glaze is considered to be opaque is absorbed and emitted at the surface, and is computed by the terms containing \( T_1^4 \) and \( T_4^4 \), respectively. Temperature, \( T_{sh} \), is that of the shocked heated air if the glaze under consideration is the outermost pane in the window system. For the remaining window panes, \( T_{sh} \) is taken as the temperature of the lower surface of the preceding glaze. The symbols \( T_1 \) and \( T_2 \) represent the percent of energy emitted at wavelengths from zero to the left cutoff point and from zero to the right cutoff point, respectively, of the spectral region in which the glaze is considered to be transparent or semitransparent. For example, fused silica is considered to be transparent.
and/or semitransparent over the wavelength region from \( \lambda = 0.4 \ \mu \) to \( \lambda = 4.8 \ \mu \). Thus, the left and right cutoff points for fused silica are at 0.4 and 4.8 \( \mu \), respectively. Symbols \( P_L \) and \( P_R \) are the mean reflectivities of the glaze to radiation in the spectral regions to the left and to the right of the transparent region's cutoff points.

For Element 11 the heat balance equation is written as:

\[
\frac{\partial q_{11}}{\partial t} = \Delta v \sum_{\lambda} \left[ \sigma A_{\lambda} (11) + \omega_{\lambda} (11) \right] + \frac{h}{\Delta v} \left[ T_{10} - T_{11} \right]
\]

\[
- \left[ (1-P_L)P_L \right] \frac{\partial T_{11}}{\partial t} + \left[ (1-P_R)P_R \right] \frac{\partial T_{11}}{\partial t} + \left[ (1-P_L)(1-P_R) \right] \kappa \sigma T_{11}^4
\]

\[
- h_{\text{c}} [T_{11} - T_{\text{c}}]
\]

The temperature, \( T_{\text{c}} \), represents the aircraft or spacecraft cabin temperature if the glaze under consideration is the innermost pane in the window system. For the remaining window panes, \( T_{\text{c}} \) is taken as the temperature of the upper surface of the succeeding glaze.

When predicting the temperatures for uncoated glasses, the reflectivities of the surfaces are computed with Fresnel's equations (see Appendix B, p. 101). The transmittance of the glass surface is computed as \( 1 - \rho \).

In many instances the windows of aerospace vehicles employ thin-film coatings designed to provide certain desirable optical features. For example, various coatings have been developed to reflect ultraviolet radiation, to reflect infrared radiation, and to reduce glaze surface reflection in the visual region of the spectrum. For coated glasses, the computer program incorporates a subroutine to compute the reflectance and transmittance of glaze surfaces having single or multiple-layer, dielectric and/or metallic thin-film coatings. The technique employed in the computation is that developed by Renshaw (Ref. 3) in which the reflectance is determined as the final step in a recursion process which calculates the admittance of each layer of the thin-film coating beginning with the innermost layer and ending with the incident media (see Appendix B). The absorptance of the coating is evaluated as \( 1 - \rho - \tau \).
A read-in subroutine is also included in the computer program so that the transmission and reflection of a given thin-film coating can be included in the input data rather than be computed by the thin-film subroutine if these data are available. When the transmission and reflection data for coated surfaces are input, the absorptance of the coating is computed as \( l = \tau + \rho \).

F. Glass Thermophysical and Optical Properties

The glass properties employed in the analysis, which are considered to be temperature-dependent, are: the glass index of refraction, thermal conductivity, heat capacitance (density times specific heat) and absorption coefficient. Properties for which the spectral dependence is taken into account include the glass absorption coefficient and the reflectance, transmittance, and absorptance of the coated glass surfaces.

The values of index of refraction, thermal conductivity, and heat capacitance were obtained from Ref. 6 for the glass materials used in the calculations. Spectral values of absorption coefficient were determined by Finch (Appendix A of Ref. 7) based on transmittance of glaze specimens of known thicknesses and taking into account the reflectance of the specimen surfaces. Typical values of absorption coefficient are presented in Figure 5. The dashed line represents the average value of the absorption coefficient used in each of the five finite wavelength bands employed in the numerical integration over the spectral region in which the glass is considered to be transparent or semitransparent.

The reflectance of uncoated window surfaces is computed from Fresnel's equation as a function of beam incident angle and glass index of refraction. For coated glass surfaces the reflectance and transmittance are computed using Ferming's analysis as a function of incident angle and the wavelength of the incident beam. Data required for this calculation include the thickness, extinction coefficient, and index of refraction of each layer in the multiple layer coating. Average values of these properties are input for each of the five finite wavelength bands considered in the numerical integration over wavelength.

When the reflectance and transmittance of a coated surface are included in the input data, values must be input as an array versus incident angle for each of the five wavelength bands considered in the analysis.

The thermophysical and optical properties of five typical glass materials are given in Appendix C. These properties are stored as block data in the computer program. Thus, calculation of the temperatures and the heat flux through window systems constructed from these five materials can be accomplished without inputting glass property data.
Figure 3 - Absorption Coefficient for Vycor (98% Fused Silica)
G. Flight Convective and Radiative Heating

Various methods of computing the heat input to the window are used by the program, depending on the mission under consideration, i.e., hypersonic flight, re-entry, supersonic flight, or orbital flight.

For hypersonic flight and re-entry, the convective input to the window is expressed as a percentage of the stagnation point heat transfer rate. The stagnation point convective heating is computed using the correlation of Kemp and Ridell (Ref. 8). The percentage or ratio of convective heat transfer rate at the window to that at the stagnation point is generally determined by heat flux data obtained during wind tunnel tests using a model of the actual vehicle being designed. Radiative heating of the window during hypersonic flight and re-entry is from the hot air in the shock layer. Emissivities of the shock heated air are determined by curve fits of the data of Kivel and Bailey (Ref. 9) which present the emissivity of heated air as a function of its temperature and density. The temperature and density of the air behind the shock wave is determined from the free stream conditions and normal shock relationships.

For supersonic flight, the convective input is computed from a flat plate heating correlation (Ref. 10) based on free stream conditions. No radiative input is considered for the supersonic case because the gaseous radiation is negligible. Since the emissivity of air is relatively low, gaseous radiation does not become significant until extreme air temperatures are reached such as those in the shock layer of hypersonic flight and re-entry.

For orbit and above an input critical altitude in the hypersonic and supersonic flight cases, the convective heating is computed from a free molecular heat transfer correlation (Ref. 8). The radiative heating from the sun is approximated by using a solar temperature of 6000°K and an appropriate form factor. Since the solar radiation is collimated and the computer program analysis assumes the external radiation to be perfectly diffuse, solar heating of the window is only approximated.

The input data required for using the flight heating subroutines are dependent on the type of flight being considered. These data include flight time, altitude, free stream conditions (velocity, temperature, pressure, density, viscosity, and Mach number), and shock layer conditions (temperature, pressure, and density). Appendix D contains a discussion and outline of the equations and correlations used by the program to compute inflight heating of aerospace windows.
A convective heating rate versus time can also be included in the input data. This allows the convective heat flux computed by any desirable method to be used in the program. A constant radiative heating rate can be described by input data if so desired by inputting a heat source temperature and emittance, and an appropriate configuration factor. This option was used when computing glaze temperatures for comparison to those measured in the experimental heat transfer tests.

H. **Numerical Solution**

The heat balance equations for each glaze element in the window system can be written in either the explicit or implicit form, i.e., the heat transfer between elements and to the surrounding environment can be related to the element temperatures at time \( t \) or time \( t + \Delta t \). In order not to violate the second law of thermodynamics, an explicit or forward difference equation is subject to a stability criterion which limits the time step used in the numerical solution (Refs. 11 and 12). No stability criteria are required for the implicit or backward difference equation. The heat balance equations employed in the computer solution are of mixed form and written as follows:

\[
p_c \frac{T_i - T_i}{\Delta t} = \sum_{x} \left[ Q_{A_x}(t) - Q_{B_x}(t) \right] + h \frac{T_i - T_i - E_x(t + \Delta t)}{\Delta t}
\]

where the primed temperatures refer to values at time \( t + \Delta t \). Conductive heat transfer between the elements, described by the last term in the above equation, is based on the element temperatures at time \( t + \Delta t \). The radiant energy absorbed, \( Q_{A_x}(t) \), and that emitted, \( Q_{B_x}(t) \), by an element at location \( x \) are computed from the glaze element temperatures at the beginning of the time step.

Since the finite difference equations used in the numerical solution are approximations of integral-differential equations, both the implicit and explicit forms are subject to truncation error. To minimize truncation error and ensure computational stability, a technique developed by Las (Ref. 1) is employed in the program. Glaze temperatures at time \( t + \Delta t \) are computed using a given time step, \( \Delta t \). Next, the glaze temperatures at time, \( t + 2\Delta t \), are computed using two \( \Delta t/2 \) time steps. This temperature field is compared to that computed using a single time step, \( \Delta t \), and if the comparison agrees within a prescribed accuracy the computed temperatures are accepted. If the temperature fields do not agree, the given time step is halved and the procedure is repeated until agreement is obtained.

Approved for Public Release
The experimental effort included heat transfer testing of coated and uncoated glasses subjected to radiative, convective, and combined radiative and convective heating. The test apparatus (Figures 4 and 5) was designed such that the test specimen(s) have a transparent boundary allowing the tests to be carried out under conditions similar to those encountered in flight of aerospace vehicles. This approach yields empirical data on realistic window components in addition to supplying input data on which to validate the computer program.

A. Test Apparatus

The test apparatus, Transparent-Boundary Apparatus (TBA) No. 1 (used for radiation and radiation plus convection testing), TBA No. 2 (used for convection only testing), and a modified version of TBA No. 2 (used for vacuum testing), were designed after that used for the work done under Contract No. AF 33(657)-9158 (Ref. 7), with the major differences being in the method of measuring heat flux through the window glass system and in the manner of attaching potential and current leads to the gold temperature sensors on the glass specimen. These differences will be described later in this report.

1. Heat sources: The sources of heat for the test apparatus were high velocity convective burners and/or an electric element, radiant heater.

a. Radiant heater: The radiant heater (Figure 6) has a spiral resistance element 3/8 in. wide and 1/16 in. thick with a resistance of approximately 0.1 ohm; maximum voltage was 20 v. It was made of Hastelloy X alloy, which has an adherent oxide coating at temperatures exceeding 2000°F and has sufficient strength at these temperatures to maintain its shape without sagging. To assure no distortion of the long spiral element, Hastelloy X rods (5/32 in. diameter) were butt welded to the flat spiral strip to provide support. These rods and the terminal rods passed through a refractory insulating block, 2-1/2 in. thick, and were held on the back of the block by clips. Thus the refractory block supported the heater element and thermally insulated the rear side of it. Two chromel-alumel thermocouples were employed for measuring the heater temperature.

The heat flow through aerospace windows in actual flight and in simulated flights on the subject computer program is essentially one-dimensional. Therefore, in the experimental program it was important that the impinging radiation be uniformly distributed over the window surface.

Approved for Public Release
Figure 4 - Radiative and Convective Transparent Boundary Apparatus
Figure 5 - Modified Version of THA No. 2 for Vacuum Testing
This can be accomplished with a disk-shaped heater provided that its surface temperature, $T_H$, is uniform and the relative size and the spacing of the heater and window are carefully analyzed.

The temperature distribution of the heater was determined with an iron model 560 optical pyrometer. At $T_H = 1150^\circ F$, the absolute temperature varied by $\pm 5\%$ and at $T_H = 1950^\circ F$, the absolute temperature varied by $\pm 3\%$. These differences result in maximum variations of emissive power of approximately $4$ and $5\%$, respectively.

If the heat is emitted uniformly it will impinge the window uniformly provided either of the following conditions exist:

1. The heater is designed and positioned in such a way that every element on the window surface "sees" nothing but the heater; or

2. The heater is positioned such that it is "seen" equally well by each element of the window surface.

The first criterion is satisfied if $\tau_H/\tau_W \rightarrow \infty$ or $h \rightarrow 0$; the second requires that $h \rightarrow \infty$. The variables $\tau_H$, $\tau_W$, and $h$ are illustrated in Figure 7. These ideal conditions are not practical in the laboratory; therefore, reasonable compromises based on further analysis were made.

The local heat flux impinging the window surface is characterized by

$$
\eta = c F_A \cdot \frac{\tau_W}{\tau_H}
$$

where $F_A$ is the local configuration factor which allows for the average angle through which the heater is "seen." The shape factor frequently reported and used for two parallel, finite disks is an average value and does not account for local variations. Since it is these variations that must be maintained in the experimental program, the apparatus design was not based solely on the average configuration factor.

By employing shape factor algebra—that is, by subdividing the disks into rings, a study was made by Finch (Ref. 7) to determine the relationship between the local configuration factor and the variables $h$ and $\tau_W$ for $R_H = 3$. The results are plotted in Figure 6. For comparison, the average values of $F_A$ were obtained from configuration charts developed by Hamilton and Morgan (Ref. 13) and are plotted as dashed lines for $h = 2.0$ in. and $h = 4.0$ in.
Figure 8 - Configuration Factors for Two Parallel Disks
The configuration factor curves indicate that the percent deviation of the local value of \( F_A \) from the average is greatest when the heater is positioned about 3 in. from the window. At \( h = 2.0 \) and \( h = 4.0 \) the variation from average is approximately \( \pm 15 \% \) and \( \pm 10 \% \), respectively. As expected, \( F_A \) approaches a constant as \( h \to 0 \) or when \( h \gg 1.0 \). At \( h = 0.562 \) in., \( F_A \) deviates from the average by less than 2%; at \( h = 3.0 \) in., the variation is approximately 4%. Primarily as a result of this analysis, the following heater positions were selected for the experimental program:

\[ h = 9/16 \text{ in. and } h = 3 \text{ in.} \]

For the case where radiation was the primary source of heat transfer to the window, the heater was positioned 9/16 in. above the glass, and for the case where radiation and convection were simultaneously used, the heater was placed 3 in. above the window.

To determine the emittance of the radiant heater the heat flux from the heater was measured in a vacuum environment with the heater positioned 9/16 in. above the calorimeter mounted in the heat sink of the test apparatus (Figure 8). Using these data and a configuration factor from Figure 8, a value of 0.85 was computed for the heater emittance from the expression:

\[ \varepsilon = \frac{q}{\sigma \left(T_H^4 - T_A^4\right)} \]

Temperatures of 2200°F were reached by the radiant heater resulting in a heat flux of 75,000 Btu/hr-ft² at the incident surface of the test specimen. At this temperature approximately 85% of the energy is emitted at wavelengths for which the glass is considered to be transparent or semi-transparent to radiation.

b. Convective burners: The convective source consisted of three burners mounted so that they could each be adjusted in three directions (Figure 10). These are 81⁄2-3 Belas superheat burners with a rectangular blast opening 2-1/2 in. long by 1/8 in. wide and a flared tongue. The burners were supplied with natural gas and compressed air. Combustion occurs inside the burner and the products of combustion are forced out the blast opening at a high velocity. Various combinations of burner positions were experimentally evaluated to determine the optimum arrangement with respect to uniform heating. These tests were run on a 1/32 in. stainless steel plate.
Figure 9 - Radiation in Vacuum With h = 9/16 In.
Figure 11: Convective Transport Boundary Apparatus
Contrails

steel disk (in the glass specimen position); the temperature distribution was determined by thermocouples welded to the backside at 12 different positions. Thermocouples positioned in front of the burners were used to indicate exhaust temperatures. The gas flow rate for each burner was adjusted manually to obtain equal indications of exhaust temperatures. The hot transparent gases were at a static temperature of approximately 3000°F and supplied convective heating rates to 20,000 Btu/hr-ft². This heating rate is typical of that experienced by hypersonic aircraft, for example, flying at Mach 9 at 65,000 ft. or Mach 10 at 120,000 ft.

2. Specimen mounts: Foamed, fused-silica disks were employed to support the test specimens and associated instrumentation circuitry. Contact between the circuitry and the specimen's temperature sensors was made through small leaves of gold foil welded to the ends of the wires in the disk. Spring rods were employed to insure electrical continuity between the upper glass temperature sensors and the instrumentation circuitry. These rods applied pressure to small ceramic slugs which held the gold foil against the temperature sensors at the edge of the specimen (Figure 11). In a similar manner, steel leaf springs mounted in the heat sink insured continuity between the circuitry and the lower glass temperature sensors. This unique and simplified approach provided electrical contact without mechanically bonding the circuitry to the test specimen, as was done for the work done under Contract No. AF 33(657)-8538 (Ref. 7), and allowed specimen changes in the test apparatus to be easily accomplished. For the multiglass (two glasses) apparatus, an extra set of foamed, fused-silica disks was needed to support the outer specimen and to provide instrumentation circuitry for the connection between the temperature sensors of the outer specimens and the temperature sensors of the inner specimen. Contact between the circuitry of the extra disks and temperature sensors was achieved by using the pressure applied by the spring rods as explained above and by placing stainless steel wool under each leaf of gold foil so that when pressure was applied through the rods, the stainless steel, in effect, acted as a spring and insured good electrical contact between the gold foil connectors and the temperature sensors.

3. Heat sink: The heat sink for the apparatus is a water-cooled copper plate. The surface of the heat sink was coated with a black paint having an emissivity of approximately 0.88. Two commercial heat flux gauges were purchased from Hy-Gal Engineering (parts Nos. 1-1287-A-29, 140 and 1-1104-C-15-252) and were installed in the heat sink to measure the net heat flux passing through and from the test specimen. Two heat flux gauges were used so that if one failed or underwent a change in calibration, a backup would be available. A copper-constantan thermocouple along with a thermal switch which activated a buzzer were mounted in the heat sink to prevent overheating of the heat flux gauges.

Approved for Public Release
4. Instrumentation and controls: The instrumentation and controls used with the test apparatus are shown schematically in Figure 12. Signals from the temperature sensors, heat flux gauges, radiant heater thermocouples, burner thermocouples, and heat sink thermocouple were measured with a DRS Model No. 5600, millivolt potentiometer.

The controlling system for the radiant heater consisted of a manually operated DC power supply driving a saturable core reactor. The power supply used was a Trygon Model NESO-2.5A constant voltage source. This system maintained the radiant heater temperature to within ± 0.06.

B. Window Test Specimens

The test specimens included combinations of three glass materials and three thicknesses. The 4-in. diameter specimens (Figure 13) were fabricated from fused silica, 95% fused silica (Vycor), and aluminosilicate. For each material, glass thicknesses of 1/8 in., 1/4 in., and 3/8 in. were used.

C. Thin-Film Coatings

Four thin-film coatings were employed on the test specimens for the purpose of reducing heat transmission through the glass in the infrared region of the spectrum and to increase the transmission in the visual range of the spectrum. These coatings included: (1) a high efficiency anti-reflection coating, (2) an ultraviolet-near infrared reflecting coating, (3) a multi-layer coating containing layers of gold and dielectric materials, and (4) a single layer gold film. The first three of these coatings were developed and applied to the specimens by the Optical Coating Laboratory, Inc. (OCLI), while the single layer gold film was developed and applied to test specimens by Midwest Research Institute.

D. Coating Temperature Limits

Temperature limits for these coatings were determined when it was revealed that the design temperatures of the coatings were below the temperature specified in the contract to which the specimens were to be heated. The coating supplier (OCLI) suggested that these coatings might function as specified above the design temperatures; however, the supplier did not know at what temperature the coating transmission would be adversely affected. It was decided to determine the limiting temperature for each coating and conduct the coated-specimen heat transfer tests within this temperature limit to preclude deterioration of the coatings.

Approved for Public Release
Figure 12 - Schematic of Apparatus Components, Instruments, and Controls
To this end, Pyeec microscope slides with the specified thin-film coatings were used to determine the temperature at which the design transmission of the coatings is adversely affected. This was accomplished by heating the slides to successively higher and higher temperatures and measuring the transmission after each heating cycle.

Two slides with the high efficiency antireflection (HRA) coating were heated for 24 hr. at each 100° interval through 1200°F without apparent damage. Transmission data were taken with some slight transmission changes noted after each heating. During the 1300°F heating the HRA coating was damaged to the extent that deterioration of the coating could be detected visually.

To evaluate the effect of changes in coating transmission on the radiant energy transfer through the coating and into the glaze, the emissive power as well as the change in transmission must be considered at each wavelength. Thus, the change in energy, W, transferred through the coating and into the glaze can be obtained by evaluating the integral

\[ W = \int_{\lambda_1}^{\lambda_2} (\Delta T)(E) \, d\lambda \]

where the change in transmission, \( \Delta T \), and the emissive power, \( E \), are functions of wavelength, \( \lambda \). The limits of integration define the wavelength range for which the test specimens (glazes) are considered to be semitransparent to radiant energy. Evaluation of the above integral indicates that the change in transmission of the coating after being heated to 1200°F will result in a change of less than 1% in the radiant energy transferred through the coating. Thus, the upper temperature limit of 1200°F was set for the HRA-coated specimens during the Phase II heat transfer tests.

Two slides coated with the ultraviolet-infrared (UV-IR) coating were heated for 24 hr. at each 200° interval to 1200°F. Transmission data were taken after each heating through 1200°F. The 1200°F heating resulted in severe damage (creasing) of the UV-IR coatings. Changes in the transmission of the coating after being heated to 1000°F will result in a change of approximately 3% in the energy transferred through the coating and into the glaze. Since 3% is within the accuracy of experimental measurement of heating rates, the decision was made to heat the UV-IR coated glazes to 1000°F during the Phase II heat transfer tests.
The transmission of the gold coatings applied by MRF exhibited significant changes after each heating even at relatively low temperature (600°F). It was noted that if the gold coatings were cured at 1000°F for 24 hr., subsequent heatings to 1000°F did not additionally affect the transmission.

The initial cure, however, significantly increased the transmission of the gold coating, reducing its reflectiveness and increased its effectiveness as an infrared (heat) reflector. The cure was necessary, since without it, changes in the gold coating transmission would occur at some undetermined rate during the heat transfer tests. Without the correct transmission data, the computer program could not be expected to predict the glass temperatures for these tests. Since the transmission of the gold coatings was already significantly increased by the 1000°F cure, it was decided not to exceed this temperature on the gold coated specimens during the heat transfer tests.

E. Temperature Sensors

The sensors developed (Ref. 14) for measuring the surface temperatures of the specimens were a gold resistance thermometer. Gold was adopted because the metal has a high thermal coefficient of resistivity. The gold grids were vacuum deposited on each side of the specimen as shown in Figure 13. The inner legs of the four grids are connected electrically in a series and act as current conductors. The outer legs of each grid are used as potential taps to measure the voltage drop across the active ("U" shape section) portion of the temperature sensor.

Calibration of the temperature sensors was accomplished by determining their resistance while at various temperature levels in a Hoskins Type ME/50 electric furnace. The specimens were mounted in a special fixture (Figures 14 and 15) constructed of stainless steel and fused silica. External leaf springs of Hastelloy-X applied pressure on small ceramic sticks passing through the case of the fixture. These ceramic sticks, like those employed in the test apparatus, held the instrumentation circuitry of the calibration fixture against the temperature sensors of the test specimens. The specimen temperature was measured with two chromel-alumel thermocouples inserted into the fixture. The reference junction for the thermocouples was maintained at 50°F by means of an ice bath.

The power source for the sensor circuit was a Trygon Model HE20-1.5 constant voltage DC power supply. Instrumentation circuitry similar to that used in the test apparatus was employed in the calibration fixture. The temperature sensors were connected in series. The current was determined by measuring the voltage drop across a precision 10-ohm resistor connected in series with the temperature sensors and a 10 K-ohm resistor. The sensor voltage junctions were connected to a multiple channel switch which, in turn, was connected to a LEM Model 5555 millivolt potentiometer. The output from the two thermocouples was also connected to the switch.

29
After installation in the calibration fixture, the glaze specimen was placed in the furnace and calibration measurements were then made at approximately 300°F intervals from room temperature to the maximum temperature the specimen would undergo during testing. The system was allowed to stabilize at each temperature level before making measurements of the voltage drop across each of the four temperature sensors, the voltage drop across the precision resistor, and the emf output of the thermocouples. At each temperature, as determined by the thermocouples, the resistance of each sensor was then computed from

\[ R = \frac{V}{V_0} \text{ (ohms)} \]

where \( V \) is the voltage drop across the sensor, \( V_0 \), is the voltage drop across the precision resistor and \( R_0 = 10 \) ohms is the resistance of the precision resistor. The value of \( R \) versus temperature was then plotted for each sensor. These calibration plots were used to determine the glaze temperature during the heat transfer tests.

F. Superposition Tests

The planned experimental tests used to verify the computer program were based in part on the so-called superposition technique. The primary advantage of this “additive” approach was that it required experimental tests to be run for only two sets of boundary conditions, all-air and all-vacuum, eliminating the need for other possible test combinations. Superposition tests were conducted to demonstrate the validity of all-vacuum and all-air tests as required in the contract for the work discussed in this report. The results of these superposition tests are presented in Appendix B.

G. Heat Transfer Tests

The tests were performed in three phases. In Phase I, the research was applicable to single uncoated glazes. In Phase II, the scope was expanded to include coated single glazes, and in Phase III, coated and uncoated multiple glazes were investigated.

During Phase I, 27 single-glass experimental tests were conducted involving three window glaze materials, three glaze thicknesses, and three modes of heat transfer. The three specimen materials tested were fused silica, aluminosilicate, and 96% fused silica having thicknesses of 1/8, 1/4, and 3/8 in. Each of the nine specimens were subjected to convective, radiative, and combined radiative and convective testing.

Approved for Public Release
Eighty-five single glaze tests were conducted in Phase II of the research program. These tests were similar to those conducted in Phase I with the exception of the test specimens. The glaze specimens were of the same materials and thicknesses as those of Phase I, but had thin-film coatings on one or both surfaces. Specimen material and thickness combinations employed in the Phase II tests included:

1. Fused silica, 1/4 in. thick;
2. Fused silica, 3/8 in. thick;
3. Vycor, 1/4 in. thick;
4. Vycor, 1/8 in. thick; and
5. Aluminosilicate, 1/4 in. thick.

Seven each of the specimen types listed above were coated as follows:

1. Gold film, upper surface
   No coating, lower surface
2. No coating, upper surface
   Gold coating, lower surface
3. Gold film, both surfaces
4. High efficiency anti-reflection (HEA), upper surface
   No coating, lower surface
5. HEA, both surfaces
6. Gold film, upper surface
   HEA, lower surface
7. No coating, upper surface
   Ultraviolet-infrared (UV-IR) reflecting coating, lower surface

Modes of specimen heating included radiation, convection, and combined radiation and convection.

During Phase III, 112 double glaze experimental heat transfer tests were conducted in both air and vacuum environments using coated and uncoated glazes of various materials and thicknesses. The combinations of specimen materials, thicknesses, and coatings and the environment and modes of heating are outlined below. Figure 18 is a schematic representing the double glaze window configuration.
HEAT SOURCE

Figure 16 - Parallel Outer-Inner Glazings of the Multiple Glaze Tests

Specimen material and thickness combinations used in the Phase III tests included:

1. 1/4 in. Fused Silica - Outer
   1/8 in. Vycor - Inner

2. 3/8 in. Fused Silica - Outer
   1/8 in. Vycor - Inner

3. 1/4 in. Fused Silica - Outer
   3/8 in. Fused Silica - Inner

4. 1/4 in. Aluminosilicate - Outer
   1/4 in. Aluminosilicate - Inner

5. 1/4 in. Fused Silica - Outer
   1/4 in. Aluminosilicate - Inner

6. 3/8 in. Aluminosilicate - Outer
   1/4 in. Aluminosilicate - Inner
Contrails

7. 1/4 in. Aluminosilicate - Outer
    3/8 in. Aluminosilicate - Inner
8. 3/8 in. Fused Silica - Outer
    1/4 in. Aluminosilicate - Inner
9. 1/4 in. Fused Silica - Outer
    3/8 in. Aluminosilicate - Inner

Heat transfer tests were conducted on each of the above double glass window configurations having no surface coatings. Experimental tests were also conducted using each double glass configuration 1 through 5 with the following surface coating combinations:

1. No Coating - Surface A
   UV-IR Coating - Surface B
   No Coating - Surface C
   No Coating - Surface D

2. No Coating - Surface A
   UV-IR Coating - Surface B
   HPA Coating - Surface C
   HPA Coating - Surface D

3. HPA Coating - Surface A
   HPA Coating - Surface B
   HPA Coating - Surface C
   HPA Coating - Surface D

4. No Coating - Surface A
   UV-IR Coating - Surface B
   Gold Coating - Surface C
   HPA Coating - Surface D

Both the coated and uncoated double glass configurations, 1 through 5, were used in tests conducted in air and vacuum environments. The uncoated window configurations 6 through 8, were used only in tests conducted in air. Window heating was accomplished by radiation, convection, and combined radiation and convection in the air tests and by radiation in the vacuum tests.

M. Coating and Glaze Damage

After all Phase III experimental heat transfer tests were completed, several brief tests were conducted in the presence of the Air Force Project Engineer to demonstrate the temperature-time effect on the different coatings
and glaze materials used in this work. These different tests are enumerated and explained below.

In the first test a 3/8 in. thick, fused silica glaze (uncoated) was subjected to a temperature of approximately 1400°F by means of convective heat. With the glaze at this temperature, there was no visual change in the transmission characteristics of the glaze. The glaze did not appear to glow and neither was there any other visual physical change at this temperature. As a measure of fused silica’s ability to withstand thermal shock and stress, the convective input to the glaze was cut-off sharply at the 1400°F level and the glaze allowed to cool. The glaze, when subjected to this thermal shock, suffered no apparent damage. Although no Vycor (96% fused silica) glasses were tested in this manner, it is anticipated that had they been, the results would have been identical since the physical properties of the two materials are very similar.

The second test involved a 3/8 in. thick, uncoated, aluminosilicate glaze which was heated by convection to approximately 1500°F. At this temperature, the glaze broke into several pieces. The elapsed time from initial heating to point of failure was approximately 10 min. The probable cause of the breakage was an excessive increase in heating rate which set up a large temperature gradient through the specimen and resulted in severe thermal shock and stresses. Before failure, the transparency of the glaze did not seem to be affected in any way. These results bear out those obtained during the experimental heat transfer tests in which several aluminosilicate glasses broke for no apparent reason other than an increase in heating rate.

Test No. 3 involved a 1/4 in. fused silica glaze which was coated on one surface with a high efficiency anti-reflection (HEA) coating and on the other surface with a multi-layer gold (MLG) coating. For this test, the glaze was heated by convection to approximately 1400°F with the HEA coated surface being the surface to which the heat was applied. After about 2 hr. at 1400°F, the HEA coating started blinding. A short time later, the coating started blistering at what seemed to be a hot spot on the surface. The rest of the coating changed from the violet to a deep red color. These results agree with those reported earlier in this report in which an HEA coating was damaged to the extent that deterioration of the coating could be detected visually when heated to 1200°F. With this damage, it was obvious that the coating was no longer fulfilling the purpose for which it was intended.

Test No. 4 was conducted using the same coated glaze used for Test No. 3. In this test, the gold coated surface was used as the incident surface; and like the previous test, the glaze was heated by convection to approximately 1400°F. With the glaze and coating at this temperature, there
was no apparent damage to the coating or any visual change in its transmission characteristics.

No test was conducted using the ultraviolet-infrared (UV-IR) coating; but based on results obtained by heating UV-IR coated slides and by examining UV-IR coated glasses after repeated use during the experimental heat transfer tests, it is apparent that subjecting the coating to repeated use and to temperatures of 100°F and above results in severe damage (crasing) of the coating so that it is no longer performing as intended.
SECTION IV

ANALYTICAL AND EXPERIMENTAL RESULTS

A. Computer Program Verification

Since a major objective of the experimental heat transfer tests was to verify the validity of the computer program, measured values of window surface temperatures and heat flux to the cabin were compared to those computed. The "heat flux to the cabin" as used in this discussion refers to the flux from the cold side of the window. This includes the heat transfer from the cold surface by convection and radiation, and the radiation through and from the interior of the glaze.

Comparisons of computed and measured glaze surface temperatures and heat flux to the cabin for a single-pane window are presented graphically in Figures 17, 18, 20 and 21, and in Tables I, II and III. All single-pane window tests were conducted in an air environment. Figure 17 presents a comparison of the analytical and experimental results for a 1/4-in. fused silica window heated by radiation. In the experimental tests employing the radiant heater, the heater was placed 1/16 in. above the glaze. In this position, heater temperatures from 1000\textdegree\ to 6200\textdegree\ resulted in incident radiant flux ranging from 6,700 to 72,000 Btu/hr-ft\textsuperscript{2}.

Figure 18 compares measured and computed values of glaze temperatures and the heat flux to the cabin for a 1/4-in. fused silica window that is convectively heated. Different levels of convective heating in the experimental tests were obtained by adjusting the burners to various positions on burner mounts (Figure 10). The convective input to the glaze at steady-state conditions for each burner position was determined by performing a heat balance calculation on the glaze as follows:

\[ Q_{\text{in}} = \varepsilon(\epsilon) \sigma (T_{\text{room}}^4 - T_{\text{h}}^4) + \varepsilon(\epsilon) \sigma (T_{\text{h}}^4 - T_{\text{c}}^4) + \frac{\dot{m} \times c}{d} (T_{\text{h}} - T_{\text{c}}) \]

The effective emissivity, \( \varepsilon(\epsilon) \), was determined using the emissivity, \( \varepsilon_{\lambda} \), of glass plates presented by Gordon (Figure 8 of Ref. 4) as a function of the absorption coefficient times the plate thickness. Since the absorption coefficient and in turn \( \varepsilon(\epsilon) \) are wavelength-dependent, the total effective emissivity of the glass plate was determined for a given temperature from the expression

\[ \varepsilon(\epsilon) = \sum_{\lambda} \varepsilon_{\lambda} \Delta\lambda \]

38
Figure 10 - 1/4-In. Fused Silica Window Heated by Convection, Steady-State Conditions
in which $\varepsilon_{\lambda}$ and $\Delta \varepsilon_{\lambda}$ are evaluated for each finite wavelength band considered in the summation. Values of total effective emissivity vs. temperature computed for a 1/4-in. fused silica plate are plotted in Figure 19. Using these values in the above heat balance equation, the convective heating rates at the glaze surface were determined for each test point. As seen in Figure 19, the experimental convective heating rates ranged from 6,800 to 20,000 Btu/hr·ft².

![Figure 19 - Effective Emissivity of 1/4 In. Fused Silica Plate](image)

In order to evaluate the capability of the subject computer program to accurately compute transient temperatures, computed values were compared to the glaze cooling and heating experimental test data of Refs. 7 and 15. The glaze cool-down data of Ref. 7 (obtained from a specimen allowed to cool from 900°F to room temperature) are compared to the computed glaze cool-down temperature in Figure 20. Figure 21 compares calculated glaze temperatures and the heat flux to the cabin to the experimental values presented in Figure 3 of Ref. 15. These transient heating data were obtained by instantaneously positioning the specimen under a radiant heat source. The predicted heat flux to the cabin is greater than that measured due to non-one-dimensional radiant flux incident on the glaze and to an instrumentation problem in the test radiometer as explained in Ref. 15.

41
Figure 20 - Measured and Computed Transient Temperatures
Figure 21 - Measured and Computed Transient Temperatures and Heat Flux
A comparison of computed and measured glaze steady-state temperatures and heat flux is presented in Table I for fused silica test specimens of various thicknesses subjected to radiative and convective heating. As suspected, when the glaze thickness is increased, the hot side temperature is higher, the cold side temperature is lower, and there is a decrease in the heat flux to the cabin.

Table II presents a comparison of analytical and experimental results for 1/4-in. test specimens under thermal equilibrium conditions for the same radiative and convective heating rates. The difference in temperatures of these glaze materials is attributed to their different spectral absorption coefficients.

Computed and measured heat fluxes are compared in Table III for 1/4-in. fused silica specimens having various thin-film coatings on one and/or both surfaces. The coatings, which were deposited on the test specimens by Optical Coating Laboratory, Inc., included an ultraviolet-short infrared reflecting coating (UV-IR), a high-efficiency antireflection coating (HRA) and a gold coating for infrared reflectance. Temperatures of the glazes coated with only UV-IR and HRA coatings were close to the temperatures of the uncoated specimen. These two coatings were designed for their optical characteristics at or near the visual region of the spectrum; and their transmission is relatively high for the longer wavelengths at which the major portion of radiant energy is emitted in the cases of Table III. The temperatures and heat flux of the gold coated specimen, however, were significantly lower than those of the uncoated specimen. This is due to the very high reflectance of the gold coating at the longer wavelengths.

The gold coatings referred to in Table III are the multiple layer coatings of OCLI containing layers of gold and dielectric materials. Temperatures of the glazes with the single layer gold coating applied at NRI were not significantly different than temperatures of the uncoated specimens. This was due to a microscopic migration of the gold when heated, resulting in a coating transmission close to that of the uncoated glaze. Since the single layer gold coatings did not operate as an efficient infrared reflector, only the gold-dielectric coating applied by OCLI was employed in the Phase III heat transfer tests.

Comparisons of computed and measured glaze surface temperatures and heat flux to the cabin for double-pane windows are presented graphically in Figures 22 through 25 and in Tables IV through VII. All of these computed and measured data are for steady-state heat transfer conditions.
### Table I

**VARIATION OF GLASS TEMPERATURE AND COMPOUNDING**: 
**FOR FUSED SILICA SUCCESSED IN VARIOUS COMPOUNDING**

<table>
<thead>
<tr>
<th>Window Thickness (in)</th>
<th>Heat Source</th>
<th>Hot Side Temperature (°F)</th>
<th>Cold Side Temperature (°F)</th>
<th>Flux to Cold Side (mils/hr-ft²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1/4</td>
<td>1449</td>
<td>1465</td>
<td>1433</td>
<td>1600</td>
</tr>
<tr>
<td>1/4</td>
<td>1501</td>
<td>1506</td>
<td>1576</td>
<td>1588</td>
</tr>
<tr>
<td>1/4</td>
<td>1512</td>
<td>1513</td>
<td>1517</td>
<td>1589</td>
</tr>
<tr>
<td>1/4</td>
<td>1447</td>
<td>1450</td>
<td>1333</td>
<td>1594</td>
</tr>
<tr>
<td>1/4</td>
<td>1410</td>
<td>1390</td>
<td>1332</td>
<td>1580</td>
</tr>
<tr>
<td>1/4</td>
<td>1410</td>
<td>1390</td>
<td>1332</td>
<td>1580</td>
</tr>
</tbody>
</table>

### Table II

**VARIATION OF GLASS TEMPERATURE AND COMPOUNDING**: 
**FOR A-P & B-P WINDOW SHEETS OF FUSED SILICA* COMPOUNDING**

<table>
<thead>
<tr>
<th>Window Material</th>
<th>Heat Source</th>
<th>Hot Side Temperature (°F)</th>
<th>Cold Side Temperature (°F)</th>
<th>Flux to Cold Side (mils/hr-ft²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ried Silica</td>
<td>1170</td>
<td>1187</td>
<td>1030</td>
<td>7,000</td>
</tr>
<tr>
<td>Alumina oxide</td>
<td>1170</td>
<td>1187</td>
<td>1030</td>
<td>7,000</td>
</tr>
<tr>
<td>Fused Silica</td>
<td>1170</td>
<td>1187</td>
<td>1030</td>
<td>7,000</td>
</tr>
<tr>
<td>Alumina oxide</td>
<td>1170</td>
<td>1187</td>
<td>1030</td>
<td>7,000</td>
</tr>
</tbody>
</table>

### Table III

**EFFECT OF TYPE OF WINDOW MATERIAL ON TEMPERATURES**: 
**AND COMPOUNDING**: 
**FOR A-P & B-P WINDOW SHEETS OF FUSED SILICA* COMPOUNDING**

<table>
<thead>
<tr>
<th>Material</th>
<th>Heat Source</th>
<th>Hot Side Temperature (°F)</th>
<th>Cold Side Temperature (°F)</th>
<th>Flux to Cold Side (mils/hr-ft²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ried Silica</td>
<td>1170</td>
<td>1187</td>
<td>1030</td>
<td>7,000</td>
</tr>
<tr>
<td>Alumina oxide</td>
<td>1170</td>
<td>1187</td>
<td>1030</td>
<td>7,000</td>
</tr>
<tr>
<td>Fused Silica</td>
<td>1170</td>
<td>1187</td>
<td>1030</td>
<td>7,000</td>
</tr>
<tr>
<td>Alumina oxide</td>
<td>1170</td>
<td>1187</td>
<td>1030</td>
<td>7,000</td>
</tr>
</tbody>
</table>

*Approved for Public Release
As was done in comparing the analytical and experimental results of the single-pane windows, double-pane window temperatures and heat flux to the cabin were computed and compared to selected experimental data to evaluate the various capabilities of the computer program. The capabilities verified were to compute the temperatures of and heat flux through multiple glaze windows for:

1. A wide range of radiative, convective, and combined radiative and convective heating conditions in air and vacuum environments;

2. Various combinations of glaze materials and thicknesses; and

3. Various combinations of reflective and antireflective coatings on the window glasses.

Figures 22, 23, and 24 present comparisons of analytical and experimental results for a selected double glaze window heated over a wide temperature range by radiation, convection, and combined convection and radiation in an air environment. The glazes employed in the window for which this comparison was made consisted of uncoated 3/4-in. fused silica for the outer pane and uncoated 1/8-in. Y-604 for the inner pane. For the radiant heating tests, the heater was position 9/16 in. above the upper glaze. The distance between the glaze specimens was 3/16 in. and the inner specimen was 3/16 in. above the apparatus cold plate. Figure 25 presents a comparison of the computed and measured glaze temperatures and heat flux to the cabin for this window system when heated radiantly in a vacuum environment.

Tables IV and V present a comparison of computed and measured temperatures and cabin heat flux for the various combinations of glaze materials and thicknesses employed in the double-pane window configurations heated by radiation and by convection in an air environment. A comparison of the analytical and experimental results is given in Table VI for the various coating combinations employed on a double-pane window system heated in air by radiation and by convection. The computed and measured values compared in Table VII are for the coated double glaze combinations heated by radiation in a vacuum environment.

Based on the good agreement obtained in the comparison of the analytical and experimental results presented in Figures 27 through 28 and Tables I through VII, it is concluded that the developed computer program accurately computes the temperature distribution and heat flux through coated and uncoated, single- and multiple-pane window systems.
Figure 22 - 1/4-In. Fused Silica, 1/8-In. Vycor Double Window Heated by Radiation in Air, Steady-State Conditions
Figure 24 - 1/4-In. Fused Silica, 1/6-In. Mycor Double Pane Window Heated by Radiation and Convection in Air, Steady-State Conditions
Figure 25 - 1/4-In. Fused Silica, 1/8-In. Vycor Double Pane Window Heated by Radiation in a Vacuum, Steady-State Conditions.
<table>
<thead>
<tr>
<th>Glass Configuration</th>
<th>Dust Input (G/sq m)</th>
<th>Dust Output (G/sq m)</th>
<th>Dust Input (G/sq m)</th>
<th>Dust Output (G/sq m)</th>
<th>Dust Input (G/sq m)</th>
<th>Dust Output (G/sq m)</th>
<th>Dust Input (G/sq m)</th>
<th>Dust Output (G/sq m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1/4 in. Gf. Filter</td>
<td>0.1,000</td>
<td>0.1,000</td>
<td>0.1,000</td>
<td>0.1,000</td>
<td>0.1,000</td>
<td>0.1,000</td>
<td>0.1,000</td>
<td>0.1,000</td>
</tr>
<tr>
<td>1/8 in. Gf. Filter</td>
<td>0.1,000</td>
<td>0.1,000</td>
<td>0.1,000</td>
<td>0.1,000</td>
<td>0.1,000</td>
<td>0.1,000</td>
<td>0.1,000</td>
<td>0.1,000</td>
</tr>
<tr>
<td>1/4 in. Alum. Filter</td>
<td>0.1,000</td>
<td>0.1,000</td>
<td>0.1,000</td>
<td>0.1,000</td>
<td>0.1,000</td>
<td>0.1,000</td>
<td>0.1,000</td>
<td>0.1,000</td>
</tr>
<tr>
<td>1/8 in. Alum. Filter</td>
<td>0.1,000</td>
<td>0.1,000</td>
<td>0.1,000</td>
<td>0.1,000</td>
<td>0.1,000</td>
<td>0.1,000</td>
<td>0.1,000</td>
<td>0.1,000</td>
</tr>
<tr>
<td>1/4 in. Alum. Filter</td>
<td>0.1,000</td>
<td>0.1,000</td>
<td>0.1,000</td>
<td>0.1,000</td>
<td>0.1,000</td>
<td>0.1,000</td>
<td>0.1,000</td>
<td>0.1,000</td>
</tr>
<tr>
<td>1/8 in. Alum. Filter</td>
<td>0.1,000</td>
<td>0.1,000</td>
<td>0.1,000</td>
<td>0.1,000</td>
<td>0.1,000</td>
<td>0.1,000</td>
<td>0.1,000</td>
<td>0.1,000</td>
</tr>
<tr>
<td>1/4 in. Gf. Filter</td>
<td>0.1,000</td>
<td>0.1,000</td>
<td>0.1,000</td>
<td>0.1,000</td>
<td>0.1,000</td>
<td>0.1,000</td>
<td>0.1,000</td>
<td>0.1,000</td>
</tr>
<tr>
<td>1/8 in. Gf. Filter</td>
<td>0.1,000</td>
<td>0.1,000</td>
<td>0.1,000</td>
<td>0.1,000</td>
<td>0.1,000</td>
<td>0.1,000</td>
<td>0.1,000</td>
<td>0.1,000</td>
</tr>
<tr>
<td>1/4 in. Alum. Filter</td>
<td>0.1,000</td>
<td>0.1,000</td>
<td>0.1,000</td>
<td>0.1,000</td>
<td>0.1,000</td>
<td>0.1,000</td>
<td>0.1,000</td>
<td>0.1,000</td>
</tr>
<tr>
<td>1/8 in. Alum. Filter</td>
<td>0.1,000</td>
<td>0.1,000</td>
<td>0.1,000</td>
<td>0.1,000</td>
<td>0.1,000</td>
<td>0.1,000</td>
<td>0.1,000</td>
<td>0.1,000</td>
</tr>
</tbody>
</table>

- q = Radiation incident on outer surface of outer plate; radiation temperature, Td = DMTM.

TABLE IV

<table>
<thead>
<tr>
<th>Glass Configuration</th>
<th>Dust Input (G/sq m)</th>
<th>Dust Output (G/sq m)</th>
<th>Dust Input (G/sq m)</th>
<th>Dust Output (G/sq m)</th>
<th>Dust Input (G/sq m)</th>
<th>Dust Output (G/sq m)</th>
<th>Dust Input (G/sq m)</th>
<th>Dust Output (G/sq m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1/4 in. Gf. Filter</td>
<td>0.1,000</td>
<td>0.1,000</td>
<td>0.1,000</td>
<td>0.1,000</td>
<td>0.1,000</td>
<td>0.1,000</td>
<td>0.1,000</td>
<td>0.1,000</td>
</tr>
<tr>
<td>1/8 in. Gf. Filter</td>
<td>0.1,000</td>
<td>0.1,000</td>
<td>0.1,000</td>
<td>0.1,000</td>
<td>0.1,000</td>
<td>0.1,000</td>
<td>0.1,000</td>
<td>0.1,000</td>
</tr>
<tr>
<td>1/4 in. Alum. Filter</td>
<td>0.1,000</td>
<td>0.1,000</td>
<td>0.1,000</td>
<td>0.1,000</td>
<td>0.1,000</td>
<td>0.1,000</td>
<td>0.1,000</td>
<td>0.1,000</td>
</tr>
<tr>
<td>1/8 in. Alum. Filter</td>
<td>0.1,000</td>
<td>0.1,000</td>
<td>0.1,000</td>
<td>0.1,000</td>
<td>0.1,000</td>
<td>0.1,000</td>
<td>0.1,000</td>
<td>0.1,000</td>
</tr>
<tr>
<td>1/4 in. Alum. Filter</td>
<td>0.1,000</td>
<td>0.1,000</td>
<td>0.1,000</td>
<td>0.1,000</td>
<td>0.1,000</td>
<td>0.1,000</td>
<td>0.1,000</td>
<td>0.1,000</td>
</tr>
<tr>
<td>1/8 in. Alum. Filter</td>
<td>0.1,000</td>
<td>0.1,000</td>
<td>0.1,000</td>
<td>0.1,000</td>
<td>0.1,000</td>
<td>0.1,000</td>
<td>0.1,000</td>
<td>0.1,000</td>
</tr>
<tr>
<td>1/4 in. Gf. Filter</td>
<td>0.1,000</td>
<td>0.1,000</td>
<td>0.1,000</td>
<td>0.1,000</td>
<td>0.1,000</td>
<td>0.1,000</td>
<td>0.1,000</td>
<td>0.1,000</td>
</tr>
<tr>
<td>1/8 in. Gf. Filter</td>
<td>0.1,000</td>
<td>0.1,000</td>
<td>0.1,000</td>
<td>0.1,000</td>
<td>0.1,000</td>
<td>0.1,000</td>
<td>0.1,000</td>
<td>0.1,000</td>
</tr>
<tr>
<td>1/4 in. Alum. Filter</td>
<td>0.1,000</td>
<td>0.1,000</td>
<td>0.1,000</td>
<td>0.1,000</td>
<td>0.1,000</td>
<td>0.1,000</td>
<td>0.1,000</td>
<td>0.1,000</td>
</tr>
<tr>
<td>1/8 in. Alum. Filter</td>
<td>0.1,000</td>
<td>0.1,000</td>
<td>0.1,000</td>
<td>0.1,000</td>
<td>0.1,000</td>
<td>0.1,000</td>
<td>0.1,000</td>
<td>0.1,000</td>
</tr>
</tbody>
</table>

- q = Convective heat loss to outer surface of outer plate.

51

Approved for Public Release
### Table VI

**Contrails: Bemergments and Exit Points for Various Coupled Configurations as a 1/4-in. Field Length**

<table>
<thead>
<tr>
<th>Config</th>
<th>1/4-in. Length</th>
<th>1/2-in. Length</th>
<th>3/4-in. Length</th>
<th>1-in. Length</th>
<th>1 1/4-in. Length</th>
<th>1 1/2-in. Length</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Bemergments (ms)</td>
<td>Exit Points (ms)</td>
<td>Bemergments (ms)</td>
<td>Exit Points (ms)</td>
<td>Bemergments (ms)</td>
<td>Exit Points (ms)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1/4-in.</td>
<td>1.285</td>
<td>0.965</td>
<td>2.215</td>
<td>1.405</td>
<td>3.345</td>
<td>2.245</td>
</tr>
<tr>
<td></td>
<td>1.285</td>
<td>0.965</td>
<td>2.215</td>
<td>1.405</td>
<td>3.345</td>
<td>2.245</td>
</tr>
<tr>
<td>1/2-in.</td>
<td>1.285</td>
<td>0.965</td>
<td>2.215</td>
<td>1.405</td>
<td>3.345</td>
<td>2.245</td>
</tr>
<tr>
<td>3/4-in.</td>
<td>1.285</td>
<td>0.965</td>
<td>2.215</td>
<td>1.405</td>
<td>3.345</td>
<td>2.245</td>
</tr>
<tr>
<td>1-in.</td>
<td>1.285</td>
<td>0.965</td>
<td>2.215</td>
<td>1.405</td>
<td>3.345</td>
<td>2.245</td>
</tr>
<tr>
<td>1 1/4-in.</td>
<td>1.285</td>
<td>0.965</td>
<td>2.215</td>
<td>1.405</td>
<td>3.345</td>
<td>2.245</td>
</tr>
<tr>
<td>1 1/2-in.</td>
<td>1.285</td>
<td>0.965</td>
<td>2.215</td>
<td>1.405</td>
<td>3.345</td>
<td>2.245</td>
</tr>
</tbody>
</table>

**Note:** The table continues with similar data for other configurations.

### Table VII

**Contrails: Bemergments and Exit Points for Various Coupled Configurations as a 1 1/4-in. Field Length**

The table for Table VII is not provided in the image. It should follow the same format as Table VI.
E. *Additional Experimental Results*

In addition to supplying data for validation of the computer program, a second objective of the experimental testing was to provide empirical data on realistic window glaze components. Toward this end a large number of heat transfer tests were conducted, and data from 50 representative tests are presented in Appendix F of this report.

C. *Additional Analytical Results*

Calculations, in addition to those made for the validation of the analysis, were accomplished for the comparison of interesting analytical results and to check out the in-flight radiative and convective heating subroutines. A comparison of window temperatures and heat flux to the cabin was made for:

1. An opaque analysis as opposed to the semitransparent analysis;
2. A window heated by radiation and by convection;
3. A window heated in air and in a vacuum; and
4. An increasing number of panes in a window system.

The in-flight cases included the calculation of window temperatures and cabin heat flux for:

1. A hypersonic re-entry;
2. A supersonic trajectory;
3. A convective heating rate versus time specified by input data; and
4. A circular orbit.

Figure 26 is a plot of the computed temperature distributions within a 1/4-in. fused silica window subjected to radiative heating assuming the glaze to be semitransparent in one case and to be opaque in a second case. The semitransparent analysis resulted in lower computed glaze temperatures and a higher heat flux to the cabin since radiant energy from the heater was not totally absorbed as it passed through the window. In the opaque analysis it was assumed that radiation is absorbed at the surface. A similar effect is seen when comparing the temperature distribution in a glaze heated by convection and by radiation (Figure 27). The convective heat is applied to the surface, whereas the radiative heat is partially absorbed.
Figure 26 - Computed Temperature Distribution in 1/4-In. Fused Silica, Opaque Opaque and Semitransparent Analysis
Figure 27 - Computed Temperature Distribution in 1/4-In. Fused Silica, Heated by Radiation and by Convection
and partially transmitted by the window. The temperature gradient computed in the semitransparent analysis is less than that in the opaque case. This is due to the internal radiation between the glass elements, which is accounted for in the semitransparent analysis.

Figure 28 compares glaze temperatures and heat flux to the cabin for the 1/4-in. fused silica, 1/8-in. Vycor window heated by radiation in air and in a vacuum. The cabin heat flux is higher in the air environment since the heat flux to the calorimeter in the apparatus cold plate includes conduction through the air as well as radiation from the glasses. Since the heat flux from the window to the cold plate was greater for the air environment, the steady-state glaze temperatures were lower than those measured in the vacuum tests. At elevated temperatures radiation becomes the predominant mode of heat transfer resulting in smaller differences between the air and vacuum cases.

The effects of increased number of glazes on the temperatures of and heat transfer through a window system heated by radiation are presented in Table VIII. These values were calculated with the subject computer program for windows varying from one to five uncoated 1/8-in. Vycor glazes. As expected, an increase in the number of glazes increases the resistance to heat transfer, resulting in a higher outermost surface temperature and lower innermost surface temperature of the window system, and a lower heat flux through the window to the cabin.

As stated above, window temperatures and heat fluxes were predicted for various types of missions in order to check out the subroutines employed in computing the flight heating conditions. Figure 28 is a plot of the thermal performance of a double-pane window during a hypersonic skip-glide re-entry. The flight path employed in this calculation is that presented in Figure 30 which is for a re-entry vehicle with a wing load of $W/S = 22$ psf and an initial velocity of 25,000 ft/sec at 400,000 ft. (Figure 4 of Ref. 1). The window configuration for this case consisted of a 1/4-in. fused silica outer pane and a 1/8-in. Vycor inner pane.

Window temperatures and cabin heat flux predicted for a portion of a supersonic transport flight are presented in Figure 31. The flight path is described in Figure 32 and is typical of a New York to Paris flight plan. In this case the window configuration analyzed contained two coated panes. The outer pane was a 1/4-in. fused silica glass with an ultraviolet-infrared (UV-IR) reflecting coating on its emergent side. A 1/8-in. Vycor glass with a gold infrared reflecting coating on its incident surface and a high efficiency antireflection (HRA) coating on its emergent side was employed as the inner window pane.

Approved for Public Release
Figure 28 - Comparison of Temperatures and Cabin Heat Flux of Window System
Heated by Radiation in Air and in a Vacuum
### TABLE VIII

**EFFECT OF NUMBER OF GLAZES IN A WINDOW SYSTEM**

**ON TEMPERATURES AND HEAT FLUX**

<table>
<thead>
<tr>
<th>Number of Glazes in Window System</th>
<th>Heat Input (Btu/hr-ft²)</th>
<th>Hot Side Temperature (°F)</th>
<th>Cold Side Temperature (°F)</th>
<th>Flux to Cabin (Btu/hr-ft²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>( Q_H = 89,000 )</td>
<td>1608</td>
<td>1520</td>
<td>61,000</td>
</tr>
<tr>
<td>2</td>
<td>1886</td>
<td>1596</td>
<td>1496</td>
<td>59,500</td>
</tr>
<tr>
<td>3</td>
<td>2009</td>
<td>1583</td>
<td>1483</td>
<td>43,300</td>
</tr>
<tr>
<td>4</td>
<td>2082</td>
<td>1573</td>
<td>1473</td>
<td>35,200</td>
</tr>
<tr>
<td>6</td>
<td>2149</td>
<td>1563</td>
<td>1463</td>
<td>34,600</td>
</tr>
</tbody>
</table>

Reliant heater temperature, \( T_H = 5200^\circ°F \).
Figure 29 - Thermal Performance of a Double Pane Window During a Hypersonic Skip-Glide Re-entry
Figure 30 - Portion of Hypersonic Skip-Glide Re-Entry Trajectory
Figure 31 - Thermal Performance of a Double Pane Window During a Mach 3 Supersonic Flight
Figure 32 - Mach 3 Supersonic Transport Flight Path
Figure 33 presents the thermal analysis of a window of a spacecraft in a 200-nautical-mile circular orbit. The window configuration used in the orbital flight was identical to the one described above for the supersonic transport case. Techniques utilized by the computer program subroutines to compute radiative and convective heating to the windows for the hypersonic, supersonic, and orbital flights described above are discussed in Appendix D.

In addition to the cases in which the radiative and aerodynamic heating were computed by the program, the thermal response was predicted for a window subjected to a time-dependent convective heating rate as defined by input data. The input convective heat transfer rate at the window location was assumed to be 0.02 times the stagnation point heat rate plotted in Figure 34. Figure 35 presents the window temperatures and the heat flux to the cabin for a portion of flight for which the thermal environment is defined in Figure 34. A window configuration consisting of a 1/4-in. fused silica outer glaze and a 1/8-in. Vycor inner glaze was used in this case.
Figure 23 - Thermal Performance of a Double Pane Window in 200 MI Circular Orbit
Figure 34 - Stagnation Point Heat Transfer Rate (Ref. 16)
Figure 36 - Thermal Performance of a Double Pane Window Assuming Window Heating to be 0.02 Times $q_{01}$ of Figure 35
SECTION V

CONCLUSIONS

A computer program was developed for predicting the temperatures distribution and heat transfer through aerospace window systems subjected to the thermal environments of hypersonic cruise, re-entry, supersonic and orbital flight. The program analysis has been experimentally validated for single and double pane windows having coated and uncoated surfaces. The subject computer program will be a valuable tool in the design of aerospace window systems when material temperature limits, thermal gradients, and cabin heating must be considered.

In addition to the experimental tests used to validate the computer program analysis, heat tests were conducted to provide empirical data on realistic window glare components. These data can be used by the designer as a preliminary guide in selecting combinations of coated and uncoated glaces for window systems when thermal considerations are required.

A constant value of surface emittance is used by the program when computing the absorption and emission of radiation in the spectral region to which the glasses are considered opaque. When computing the temperatures of glasses coated with dielectric films (HEA and UV-IR coatings) a surface emittance equal to that of the uncoated glaze was used, resulting in good agreement with the measured temperatures. Comparison of measured and computed temperatures for the gold-coated specimens indicated that the emittance of the gold-coated surfaces is temperature-dependent. For example, to obtain good agreement between measured and computed steady-state temperatures (810°F) for the gold-coated glass specimens of Table III, a value of 0.8 was used for the surface emittance. For the gold-coated specimen of Table VII (T = 550°F), an emittance value of 0.4 was required. To satisfactorily compute transient temperatures of gold-coated windows, the temperature-dependent emittance (and possibly reflectance and transmittance) of the coatings should be determined; and the program logic should be changed to use the temperature-dependent emittance, reflectance, and transmittance of thin-film coatings.

Computer time is relatively long for the subject program, especially for multiple glaze calculations, since each element in each glaze absorbs radiant energy from each element in each glaze. An example of the computation time is that required for the calculation of temperatures for the double glaze window configurations presented in Figures 31 and 35. The computation times for these two runs were 35 min. and 95 min., respectively. Simplification of the analysis could result in a decrease in computation time. For example, if polarization effects were neglected, the complexity of the auxiliary functions of the heat balance equations would be reduced.

Approved for Public Release
As discussed in Section II, Subsection H of this report, truncation errors are minimized by comparing the temperature field computed for a time-step of $\Delta t$ to that computed using two $\Delta t/2$ time-steps. If the temperature fields do not agree, the input time-step is halved and the procedure is repeated until agreement is obtained. Even if agreement is obtained, the program is required to compute the temperature field at least three times for each time-step accepted. Computation time could be significantly reduced if a procedure were employed which required the temperature field to be computed only once each time-step. This could be accomplished by allowing the computer program to define an acceptable, upcoming time-step using some stability and/or accuracy criteria possibly based on the transient heating conditions. The present procedure employed by the program could be retained and used by option.
APPENDIX A

EQUATIONS FOR COMPUTING RADIATION WITHIN WINDOW GLAZES
## TABLE OF CONTENTS

<table>
<thead>
<tr>
<th>Section</th>
<th>Page No.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nomenclature</td>
<td>71</td>
</tr>
<tr>
<td>Introduction</td>
<td>75</td>
</tr>
<tr>
<td>Thermal Analysis</td>
<td>75</td>
</tr>
<tr>
<td>Previously Developed Analytical Relationships</td>
<td>76</td>
</tr>
<tr>
<td>Absorption of Radiation Entering a Glaze</td>
<td>76</td>
</tr>
<tr>
<td>Absorption of Radiation Emitted within Glaze</td>
<td>78</td>
</tr>
<tr>
<td>Transmission of Radiation at Glaze Surface</td>
<td>80</td>
</tr>
<tr>
<td>Multiple-Glaze Analysis</td>
<td>81</td>
</tr>
<tr>
<td>Radiation Absorbed by a Finite Glaze Element</td>
<td>87</td>
</tr>
<tr>
<td>Glaze Elements as Radiation Sources</td>
<td>87</td>
</tr>
<tr>
<td>Glaze Coatings as Radiation Sources</td>
<td>89</td>
</tr>
<tr>
<td>Radiation Source External to Window</td>
<td>91</td>
</tr>
<tr>
<td>Radiation Emitted by a Finite Glaze Element</td>
<td>92</td>
</tr>
<tr>
<td>Heat Flux to the Cabin</td>
<td>94</td>
</tr>
<tr>
<td>Radiation from Glaze Elements to the Cabin</td>
<td>95</td>
</tr>
<tr>
<td>Radiation from Glaze Coatings to the Cabin</td>
<td>96</td>
</tr>
<tr>
<td>Radiation from an External Source to the Cabin</td>
<td>96</td>
</tr>
</tbody>
</table>
### NOMENCLATURE

<table>
<thead>
<tr>
<th>Symbols</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>a</td>
<td>surface absorptance</td>
</tr>
<tr>
<td>G</td>
<td>number of media in window system</td>
</tr>
<tr>
<td>h</td>
<td>convection coefficient (Watt/cm²·°C) (Btu/sec·ft²·°R)</td>
</tr>
<tr>
<td>l</td>
<td>number of absorbing element</td>
</tr>
<tr>
<td>I</td>
<td>intensity (Watt/cm²·ster-μ) (Btu/sec·ft²·ster-μ)</td>
</tr>
<tr>
<td>j</td>
<td>number of emitting element</td>
</tr>
<tr>
<td>$j_\lambda$</td>
<td>volume emissive power (Watt/cm³·ster-μ) (Btu/sec·ft³·ster-μ)</td>
</tr>
<tr>
<td>k</td>
<td>thermal conductivity (Watt/cm °C) (Btu/sec·ft°R)</td>
</tr>
<tr>
<td>T</td>
<td>thickness of glaze (cm.) (ft.)</td>
</tr>
<tr>
<td>M</td>
<td>medium number of glaze containing emitting element</td>
</tr>
<tr>
<td>n</td>
<td>index of refraction</td>
</tr>
<tr>
<td>N</td>
<td>medium number of glaze containing absorbing element</td>
</tr>
<tr>
<td>$\hat{P}$</td>
<td>function defined in text</td>
</tr>
<tr>
<td>q</td>
<td>rate of heat flux (Watt/cm²) (Btu/sec·ft²)</td>
</tr>
<tr>
<td>Q</td>
<td>rate of energy per unit volume (Watt/cm³) (Btu/sec·ft³)</td>
</tr>
<tr>
<td>s</td>
<td>set equal to 1 for internal glaze elements and to ½ for edge elements</td>
</tr>
<tr>
<td>Symbol</td>
<td>Description</td>
</tr>
<tr>
<td>--------</td>
<td>-------------------------------------------------</td>
</tr>
<tr>
<td>t</td>
<td>time</td>
</tr>
<tr>
<td>T</td>
<td>absolute temperature</td>
</tr>
<tr>
<td>W</td>
<td>radiant flux</td>
</tr>
<tr>
<td>x</td>
<td>distance of the absorbing element, i, from the</td>
</tr>
<tr>
<td></td>
<td>glaze upper surface</td>
</tr>
<tr>
<td>y</td>
<td>distance of the emitting element, j, from the</td>
</tr>
<tr>
<td></td>
<td>glaze upper surface</td>
</tr>
<tr>
<td>z</td>
<td>total number of thin-film coatings in window</td>
</tr>
<tr>
<td></td>
<td>system</td>
</tr>
<tr>
<td>α</td>
<td>angle between the direction of the beam and the</td>
</tr>
<tr>
<td></td>
<td>normal to the glaze slab</td>
</tr>
<tr>
<td>γ</td>
<td>glaze absorption coefficient</td>
</tr>
<tr>
<td>ε</td>
<td>emittance</td>
</tr>
<tr>
<td>λ</td>
<td>wavelength</td>
</tr>
<tr>
<td>v</td>
<td>function defined in text</td>
</tr>
<tr>
<td>ρ</td>
<td>surface reflectance</td>
</tr>
<tr>
<td>σ</td>
<td>Stefan-Boltzmann constant</td>
</tr>
<tr>
<td>γ</td>
<td>surface transmittance</td>
</tr>
<tr>
<td>Ψ</td>
<td>function defined in text</td>
</tr>
<tr>
<td>Symbols</td>
<td>Units</td>
</tr>
<tr>
<td>---------</td>
<td>-------</td>
</tr>
<tr>
<td>$\chi$</td>
<td>Function defined in text</td>
</tr>
<tr>
<td>$\rho_v$</td>
<td>Volumetric specific heat (Watt sec/cm² °C) (Btu/ft² °F)</td>
</tr>
</tbody>
</table>

**Subscripts**

- $\lambda$ - denotes wavelength dependence
- $A$ - denotes radiation absorbed by glaze finite element
- $B$ - denotes radiation emitted by glaze finite element
- $i$ - denotes absorbing glaze finite element
- $j$ - denotes emitting glaze finite element
- $o$ - denotes initial conditions
- $x$ - denotes location at distance $x$ from the glaze upper surface
- $N$ - denotes medium number of glaze containing the absorbing element, $i$
- $M$ - denotes medium number of glaze containing emitting element, $j$
- $T$ - denotes top or upper glaze surface
- $B$ - denotes bottom or lower glaze surface
- $n$ - denotes parallel component of polarized beam
Subscripts

l - denotes perpendicular component of polarized beam

† - denotes beam striking upper surface of a glaze

↓ - denotes beam striking lower surface of a glaze

c - denotes critical angle or cabin temperature

R - denotes radiation absorbed by a given glaze finite element from the remaining elements within the window system

F - denotes radiation absorbed by a given finite element from the emitting thin-film coatings in the window system

H - denotes radiation absorbed by a given finite element from an external radiant source

f - denotes emitting glaze thin-film coating

h - denotes external heat source

s - surface

G - denotes innermost glaze of the window system
INTRODUCTION

As discussed in Section II of this report, heat is transferred within semitransparent materials by the combined mechanism of conduction and radiation. Thus to predict the thermal response of heated windows, the analysis must account for the emission, absorption, attenuation, and reflection of radiant energy as well as the conduction heat transfer within the glasses. This Appendix presents and discusses the equations employed by the subject computer program in describing the radiation heat transfer within the glaze materials of a multiple glaze window system.

THERMAL ANALYSIS

The analytical model used in the analysis was established by assuming each window glass to be composed of eleven finite slices or elements (Figure 1). The thermal response of each element of the window glasses is defined by the heat balance equation:

$$\rho c \frac{dT}{dt} = \sum_k [q_{A_k}(t) + q_{B_k}(t)] + k \frac{dT}{dx}$$

where the radiation absorbed and emitted by the element at position x within the glaze is represented by $q_{A_k}(t)$ and $q_{B_k}(t)$, respectively. As a result of the spectral dependence of the glaze properties that govern internal radiation, $q_{A_k}$ and $q_{B_k}$ are computed for and summed over a finite number of wavelength bands within the spectral region for which the glazes are considered to be transparent and/or semitransparent. Term $q_{A_k}(t)$ is further complicated in that it represents the absorption of radiant energy emitted from each element and surface coating of each glaze in the window system as well as that from the surroundings. Partial reflection at the glaze surfaces results in multiple reflections of radiation beams between and within the glazes of the window system (Figure 2 and 5-1).
PREVIOUSLY DEVELOPED ANALYTICAL RELATIONSHIPS

The theory employed in the thermal analysis is that developed by Gardon (References 3, 4, and 5) and as used by Lis, Barile, and Engblom (Reference 1) in developing a computer program for predicting temperatures of a single glaze window. Using the theory and analytical terms developed in References 1 through 5, the above single glaze program analysis was extensively modified and expanded to include the thermal analysis of multiple glaze windows. This theory has as its basis the Bouger-Lambert law and a volumetric emissive power derived by Gardon. The analytical terms developed by Gardon and Lis referred to in this discussion are:

1. The percent of radiant intensity of a beam entering a glaze that is absorbed by a given element within the glaze, when considering both the primary beams and its multiple reflections;

2. The percent of radiant intensity of a beam emitted by one element of a given glaze that is absorbed by another element within the same glaze, when considering both the primary beam and its multiple reflections; and

3. The percent of radiant intensity of a beam traveling within a glaze that is transmitted by a surface of the glaze, when considering both the primary beam and its multiple reflections.

Absorption of Radiation Entering a Glaze

A beam of radiation striking a glaze surface is partially reflected and partially transmitted. As the beam enters the glaze, its angle of travel is altered according to Snell's law:

\[
\eta_2 \sin \alpha_2 = \eta_1 \sin \alpha_1
\]

which relates the angle of refraction, \( \alpha_2 \), to the angle of incidence, \( \alpha_1 \), the glaze index of refraction, \( \eta_2 \), and the index of refraction, \( \eta_1 \), of the incident medium. As the beam travels through the glaze, its intensity attenuation is described by the Bouger-Lambert law:

\[
I_x = I_0 e^{-\gamma x} \sec \alpha
\]
which relates the attenuation of radiation intensity to an absorption coefficient, \( \gamma \), and to the distance, \( x \) sec \( \alpha \), traveled by the beam. The amount of the radiant intensity absorbed by an element at location \( x \) is equated to the attenuation of the beam as it passes through the element:

\[
\Delta I_x = I_x - I_0 e^{-\gamma \Delta x \sec \alpha} = I_x (1 - e^{-\gamma \Delta x \sec \alpha})
\]

When the beam reaches the second glaze surface it is partially transmitted through the surface and partially reflected back into the glaze. This internally reflected radiation is treated as multiple reflections of energy which is partially reflected each time it reaches the surfaces and is partially absorbed each time it traverses the glaze. Thus, an elemental slice in the glaze absorbs energy from the multiple reflections of a beam as well as directly from a beam entering the glaze. The percent of radiant intensity absorbed from this beam and its multiple reflections is defined by the analytical expression:

\[
X_{2G} = \left( \frac{1-e^{-\gamma x \Delta x \sec \alpha}}{\Delta x} \right)
\times \left[ \frac{\frac{\rho_{BL}}{\tau_{TL}} e^{-\gamma x \Delta x \sec \alpha}}{1 + \frac{\tau_{HL}}{\tau_{TL}}} \right]
\times \left( \frac{p_{TL} e^{-\gamma x \Delta x \sec \alpha} + e^{+\gamma x \Delta x \sec \alpha}}{\tau_{TL}} \right)
\times \left( \frac{p_{HL} e^{-\gamma x \Delta x \sec \alpha} + e^{+\gamma x \Delta x \sec \alpha}}{1 - \rho_{BL}} \right)
\]

This expression is for beams entering the upper surface of the glaze. The value for \( \rho \) is \( \frac{1}{2} \) and the coating absorption is \( 1 - \rho \) when the glaze finite element under consideration is a surface element, i.e., elements I and II. For glaze elements 2 through 10, \( s \) is 1 and \( a \) is set to zero. When beams are entering the lower surface of the glaze, the percent of intensity absorbed by a given element at location \( x \) is defined by:


Approved for Public Release
\[ \chi_{xy} = \left( \frac{1-e^{-\gamma \Delta x \sec \alpha}}{s \Delta x} \right) \times \left( e^{-\gamma (L-x) \sec \alpha} + \frac{e^{-2\gamma L \sec \alpha}}{1 + \frac{T_{BL}}{\tau_{BL}}} \left[ \frac{P_{0}}{1 - e^{-2\gamma L \sec \alpha}} \right] \right) \]

In the development of these expressions it was assumed that the radiation is polarized parallel and perpendicularly to the plane of incidence. Both the parallel and perpendicular components are accounted for in the above analytical terms.

Absorption of Radiation Emitted Within a Glass

The percent of radiant intensity of the beams emitted by one element of a given glass, that is absorbed by another element within the same glass is defined as:

\[ \bar{P} = \left( \frac{1-e^{-\gamma \Delta x \sec \alpha}}{s \Delta x} \right) \times \left[ e^{-\gamma |x-y| \sec \alpha} + \left( P_{xy} e^{-\gamma (2L-x) \sec \alpha} + P_{yx} e^{-\gamma (2L-y) \sec \alpha} \right) \times e^{-\gamma (L-x) \sec \alpha} + \left( P_{xy} e^{-\gamma (L-y) \sec \alpha} + P_{yx} e^{-\gamma (L-x) \sec \alpha} \right) \times e^{-\gamma (L-y) \sec \alpha} \right] \]

where
\[
\begin{align*}
P_1 &= \frac{1}{2} \left[ \frac{P_{pl}}{1 - \rho_{pl}^2 \rho_{pl} e^{-2\gamma L \sec \alpha}} + \frac{P_{pl}}{1 - \rho_{pl}^2 \rho_{pl} e^{-2\gamma L \sec \alpha}} \right] \\
P_2 &= \frac{1}{2} \left[ \frac{P_{pl}}{1 - \rho_{pl}^2 \rho_{pl} e^{-2\gamma L \sec \alpha}} + \frac{P_{pl}}{1 - \rho_{pl}^2 \rho_{pl} e^{-2\gamma L \sec \alpha}} \right] \\
& \text{and} \\
P_{2c} &= \frac{1}{2} \left[ \frac{P_{pl} P_{pl}}{1 - \rho_{pl}^2 \rho_{pl} e^{-2\gamma L \sec \alpha}} + \frac{P_{pl} P_{pl}}{1 - \rho_{pl}^2 \rho_{pl} e^{-2\gamma L \sec \alpha}} \right]
\end{align*}
\]

The percent of radiant intensity, of a beam emitted by a thin-film coating, that is absorbed by a given element within the same glaze is computed as:

\[
\hat{P}_1 = \left( \frac{L \exp(-\gamma L \sec \alpha)}{s \Delta x \sec \alpha} \right) \\
\times \left[ \exp(-\gamma L \sec \alpha) + (P_{pl} \exp(-\gamma L \sec \alpha)) + \frac{P_{pl}}{1 - \rho_{pl}^2 \rho_{pl} e^{-2\gamma L \sec \alpha}} \right]
\]

when the emitting coating is on the upper surface of the glaze. If the coating is on the lower surface the percent of intensity absorbed by the given element is:

\[
\hat{P}_2 = \left( \frac{L \exp(-\gamma L \sec \alpha)}{s \Delta x \sec \alpha} \right) \\
\times \left[ \exp(-\gamma L \sec \alpha) + (P_{pl} \exp(-\gamma L \sec \alpha)) + \frac{P_{pl}}{1 - \rho_{pl}^2 \rho_{pl} e^{-2\gamma L \sec \alpha}} \right]
\]
Transmission of Radiation at Glass Surface

The percent of radiant intensity of a beam and its multiple reflections that is transmitted by a given glass surface is described by the following terms depending on the direction of travel of the primary beam and the particular surface being considered. For example, the percent of the radiant intensity, of a beam striking the upper glass surface, that is transmitted at the bottom glass surface is expressed as:

\[
\psi_B = \frac{1}{2} \left[ \frac{\tau_{BL} \rho_{BL} e^{-\gamma L \sec \alpha}}{1 - \rho_{BL} \rho_{BH} e^{-2\gamma L \sec \alpha}} + \frac{\tau_{BH} \rho_{BH} e^{-\gamma L \sec \alpha}}{1 - \rho_{BH} \rho_{BL} e^{-2\gamma L \sec \alpha}} \right]
\]

For beams striking the lower surface, the percent transmitted at the bottom surface is defined by the relationship:

\[
\psi_B = \frac{1}{2} \left[ \frac{\tau_{BL}}{1 - \rho_{BL} \rho_{BH} e^{-2\gamma L \sec \alpha}} + \frac{\tau_{BH}}{1 - \rho_{BH} \rho_{BL} e^{-2\gamma L \sec \alpha}} \right]
\]

The percent of intensity transmitted at the top glass surface of a beam striking the upper surface and of a beam striking the lower surface is expressed as:

\[
\psi_T = \frac{1}{2} \left[ \frac{\tau_{TL} \rho_{TL} e^{-\gamma L \sec \alpha}}{1 - \rho_{TL} \rho_{BL} e^{-2\gamma L \sec \alpha}} + \frac{\tau_{BL}}{1 - \rho_{BL} \rho_{TL} e^{-2\gamma L \sec \alpha}} \right]
\]

and

\[
\psi_L = \frac{1}{2} \left[ \frac{\tau_{TL} \rho_{TL} e^{-\gamma L \sec \alpha}}{1 - \rho_{TL} \rho_{BH} e^{-2\gamma L \sec \alpha}} + \frac{\tau_{BH}}{1 - \rho_{BH} \rho_{TL} e^{-2\gamma L \sec \alpha}} \right]
\]
MULTIPLE GLAZE ANALYSIS

In order to demonstrate how the above analytical relationships for $x, \nu, P, I_1$, and $I_2$ are utilized in the analysis, the following example is employed. For this example, the window system depicted in Figure A-1 is considered. The energy absorbed by an element in the third glaze will be determined considering the source of radiation to be an element in the first glaze.

Radiation beams of an intensity $I_0$ are emitted at an angle $\alpha_1$ by the element in glaze 1 of Figure A-1. The intensity of the beam striking the upper surface of glaze 1 is:

$$I_1 = I_0 e^{-\gamma y \sec \alpha_1}$$

and the intensity of this beam and its multiple reflections that are transmitted through the bottom of medium 1 is $I_1^0 + B_1$. Intensity, $I_0$, of a beam striking the lower surface of medium 1 is:

$$I_2 = I_0 e^{-\gamma(L-y) \sec \alpha}$$

and the intensity of this beam and its multiple reflections that are transmitted through the bottom of medium 1 is $I_0^0 + B_2$. As the beams enter medium 2, their angle of travel is altered according to Snell's law:

$$n_1 \sin \alpha_1 = n_2 \sin \alpha_2$$

which relates the angle of refraction, $\alpha_2$, to the angle of incidence, $\alpha_1$, and to the indices of refraction, $n_1$ and $n_2$. Intensity, $I_3$, of the radiation entering medium 2 is then defined as:

$$I_3 = \left[ I_1^0 + B_1 \right] \frac{n_2^2 \cos \alpha_2}{n_1^2 \cos \alpha_1}$$
If medium 2 is semitransparent, the beams of intensity, $I_4$, are attenuated in travel and reach the lower surface of medium 2 with an intensity of

$$I_4 = I_3 e^{-\gamma_2 L_2 \sec \alpha_2}$$

The portion of $I_4$ that is transmitted into medium 3 (the second glaze) is expressed as:

$$I_5 = \left(\frac{I_4 N_4 L_3}{n_3^2 \cos \alpha_3} \right) \frac{\cos \alpha_3}{n_2^2 \cos \alpha_2}$$

Continuing with the transmission of intensity at the media interfaces and the attenuation of intensity between the interfaces, the following relationships are established:

$$I_6 = I_5 e^{-\gamma_3 L_3 \sec \alpha_3}$$

$$I_7 = \left(\frac{I_6 N_4 L_3}{n_3^2 \cos \alpha_3} \right) \frac{\cos \alpha_3}{n_4^2 \cos \alpha_4}$$

$$I_8 = I_7 e^{-\gamma_4 L_4 \sec \alpha_4}$$

$$I_9 = \left(\frac{I_8 N_4 L_3}{n_3^2 \cos \alpha_3} \right) \frac{\cos \alpha_3}{n_5^2 \cos \alpha_5}$$

The energy absorbed by the element in glaze 3 (medium 5) from the beam of intensity, $I_9$, entering the glaze's upper surface is expressed as $I_9 N_5 L_3$. In addition, the energy which passes through glaze 3 and is reflected back from the upper surface of glaze 4 is also considered. This energy may be significant if the lower surface of glaze 3 exhibits a high transmittance and the upper surface of glaze 4 is highly reflective to infrared radiation. Following the beam through medium 5,
\[ I_{10} = I_0 e^{-\gamma_6 L_6 \sec \alpha_6} \]

\[ I_{11} = (I_{10}^* L_{13}) \frac{n_2^2 \cos \alpha_2}{n_0^2 \cos \alpha_0} \]

\[ I_{12} = I_{11} e^{-\gamma_6 L_6 \sec \alpha_6} \]

\[ I_{13} = (I_{12}^* L_{11}) \frac{n_2^2 \cos \alpha_2}{n_0^2 \cos \alpha_0} \]

The energy absorbed by the element in glaze 3 from the beam entering the glaze's lower surface is expressed as \( I_{13} \delta_{35} \). Adding this to the energy absorbed from the beams entering the upper surface of glaze 5 gives:

\[ \Delta I_{12} = I_{13} \delta_{35} + I_{13} \delta_{35} \]

This, then, represents the increment of the beam intensity emitted by the element in glaze 1 that is absorbed by the element in glaze 5. Using the above relationships to define \( I_2 \) through \( I_{13} \), the equation for \( \Delta I \) in terms of \( I_0 \) is derived as follows:

\[ I_3 = I_0 (e^{-\gamma_1 (I_1 - V_1) \sec \alpha_1 \gamma_4 P_3} + e^{-\gamma_1 V_1 \sec \alpha_1 \gamma_4 P_3}) \frac{n_0^2 \cos \alpha_0}{n_1^2 \cos \alpha_1} \]

\[ I_2 = I_3 e^{-\gamma_2 L_2 \sec \alpha_2 \gamma_4 P_2} \frac{n_2^2 \cos \alpha_2}{n_0^2 \cos \alpha_0} \]

\[ I_1 = I_2 e^{-\gamma_1 L_2 \sec \alpha_1 \gamma_4 P_1} \frac{n_1^2 \cos \alpha_1}{n_0^2 \cos \alpha_0} \]

\[ I_0 = I_4 e^{-\gamma_1 L_3 \sec \alpha_3 \gamma_4 P_4} \frac{n_2^2 \cos \alpha_3}{n_0^2 \cos \alpha_0} \]

\[ \times e^{-\gamma_4 L_2 \sec \alpha_4} \gamma_4 P_2 \frac{n_2^2 \cos \alpha_4}{n_0^2 \cos \alpha_0} \gamma_4 P_4 \frac{n_2^2 \cos \alpha_4}{n_0^2 \cos \alpha_0} \]

Approved for Public Release
\[ I_9 = I_0 \left( e^{-\gamma_1(L_1-Y_1) \sec \alpha_1 \nu_{4} \nu_{1} \nu_{2}} + e^{-\gamma_1 Y_1 \sec \alpha_1 \nu_{4} \nu_{1} \nu_{2}} \right) \frac{\alpha_5^2 \cos \alpha_5}{\alpha_1^2 \cos \alpha_1} \times \prod_{k=2}^{4} \left( e^{-\gamma_k L_k \sec \alpha_k \nu_{4} \nu_{1} \nu_{2} \nu_{3}} \right) \]

\[ I_{13} = I_0 \left( e^{-\gamma_5 L_5 \sec \alpha_5 \nu_{4} \nu_{1} \nu_{2} \nu_{3}} \right) \frac{\alpha_5^2 \cos \alpha_5}{\alpha_1^2 \cos \alpha_1} \]

\[ = I_0 \left( e^{-\gamma_1(L_1-Y_1) \sec \alpha_1 \nu_{4} \nu_{1} \nu_{2}} + e^{-\gamma_1 Y_1 \sec \alpha_1 \nu_{4} \nu_{1} \nu_{2}} \right) \frac{\alpha_5^2 \cos \alpha_5}{\alpha_1^2 \cos \alpha_1} \times \prod_{k=2}^{4} \left( e^{-\gamma_k L_k \sec \alpha_k \nu_{4} \nu_{1} \nu_{2} \nu_{3}} \right) \frac{\alpha_5^2 \cos \alpha_5}{\alpha_1^2 \cos \alpha_1} \]

Substituting the above expressions for \( I_9 \) and \( I_{13} \) into the equation for \( \Delta I \) and factoring out common terms gives

\[ \Delta I_{13} = I_0 \left( e^{-\gamma_1(L_1-Y_1) \sec \alpha_1 \nu_{4} \nu_{1} \nu_{2}} + e^{-\gamma_1 Y_1 \sec \alpha_1 \nu_{4} \nu_{1} \nu_{2}} \right) \frac{\alpha_5^2 \cos \alpha_5}{\alpha_1^2 \cos \alpha_1} \times \prod_{k=2}^{4} \left( e^{-\gamma_k L_k \sec \alpha_k \nu_{4} \nu_{1} \nu_{2} \nu_{3}} \right) \]

or

\[ \Delta I_{13} = I_0 \phi \]

where the symbol, \( \phi \), represents the expression in the brackets, \{ \}.
Since the radiation from the emitting element is considered perfectly diffuse, the total radiant energy gained by the absorbing element is obtained by integrating the contribution of the incoming beams over a hemispherical surface above the absorbing element.

\[ Q_R = \int_0^{2\pi} \int_0^{\pi} I_0 \sin \alpha_5 \ d\alpha_5 \ d\phi \]

\[ = 2\pi \int_0^{\pi} I_0 \xi \sin \theta_5 \ d\theta_5 \]

Also, since the absorption coefficients of the media are wavelength dependent, \( \Delta I_\lambda \) is computed for and summed over finite wavelength bands within the spectral region for which the glasses are considered to be semi-transparent.

\[ Q_R = 2\pi \sum_\lambda \int_0^{\alpha_{CS}} I_0 \xi \sin \alpha_5 \ d\alpha_5 \]

The integration limit, \( \alpha_{CS} \), represents the critical angle beyond which no energy is refracted into glass S.

This critical angle is computed as:

\[ \alpha_{CS} = \sin^{-1} \left( \frac{R_{\lambda}}{N_{\lambda}} \right) \]

Using the approach described in this example, relationships were developed defining the radiant energy absorbed by a given finite element when considering the radiation from a source external to the window system, from each of the remaining elements in the window system, and from any emitting glass coatings in the window system. These relationships are presented in the following sections.
RADIATION ABSORBED BY A FINITE GLAZE ELEMENT

The total radiant energy, within a given spectral band to which the window is considered semitransparent, that is absorbed by a given element is represented as $Q_{AB}(1)$ in the element's heat balance equation. Sources of radiant energy include each element in each glaze, the thin-film coatings on the surfaces of the glazes, and an external radiating medium or heater. Considering these sources, the energy absorbed by a given element, $i$, is computed as:

$$Q_{AB}(1) = Q_{R}(1) + Q_{F}(1) + Q_{E}(1)$$

The equations for $Q_{R}(1)$, $Q_{F}(1)$, and $Q_{E}(1)$ are presented in the following subsections.

Glaze Elements as Radiation Sources

The radiant intensity emitted by a glaze element is defined by Garden's volumetric emissive power as:

$$I_\lambda = \frac{\lambda n^2 W_{DA}}{n}$$

which relates the intensity emitted per unit volume to the glaze absorption coefficient, the glass index of refraction, and the hemispherical emissive power of a blackbody radiator, $W_{DA}$. Hemispherical emissive power is computed as:

$$W_{DA} = P_{\lambda} \sigma T_{\lambda}^4$$

where $T_{\lambda}$ is the temperature of the emitting element and $P_{\lambda}$ is the percent of energy emitted within a finite wavelength band.

The energy absorbed by an element as emitted from the other elements in the window system is computed from the equation

87

Approved for Public Release
\[ Q_{Ei}(1) = \frac{11(0+1)/2}{2(0+1)\sum_{j=1}^{11} \frac{\pi}{m_{ij}} \frac{1}{\tau_{ij}} \tau_{jk} \Delta y} \]

or

\[ Q_{Ei}(1) = 2 \frac{11 \times 0}{\sum_{j=1}^{11} \frac{\pi}{m_{ij}} \frac{1}{\tau_{ij}} \tau_{jk} \Delta y} \]

where \( i \) refers to the absorbing element, \( j \) refers to the emitting elements, and \( m \) is the number of media in the window system. The auxiliary function \( \beta_{ij} \) defined the percent of energy emitted by the beam of an emitting element, \( j \), that is absorbed by the absorbing element, \( i \). This auxiliary function is computed from one of three equations depending on the relative positions of elements \( i \) and \( j \).

1. When the emitting element is in a glass which is located above the glass containing the absorbing element,

\[ \beta_{ij} = \int_0^\infty \left( e^{-\gamma(L-y) \sec \alpha} \sec \alpha \tau_{ij} \right) dy \]

\[ \times \int_{\frac{1}{2}}^{\frac{1}{2}+1} \left( \frac{\pi}{2} \sec \alpha \int_0^{\alpha B} \left( e^{-\gamma L \sec \alpha} \sec \alpha \tau_{ij} \right) \right) \frac{\tau_{ij}}{\pi} \cos \alpha \sin \alpha \] \[ \Delta \tau_{ij} \]

where the subscript, \( N \), refers to the medium containing the emitting element, \( j \), and the subscript, \( B \), refers to the medium containing the absorbing element, \( i \). The window glasses are represented by media \( 1, 5, 5, \) etc. (Figure A-1) with \( 11 \) elements in each glass. Thus, the number, \( m \), of the absorbing element ranges from:

\[ i = 1 \ \text{to} \ i = 11(0+1)/2 \]

Approved for Public Release
Similarly the number, \( J \), of the emitting element ranges from:

\[
J = 1 \text{ to } J = \frac{11(2 \pi - 1)}{2}
\]

2. When the glaze containing the emitting element is below the glaze containing the absorbing element, i.e., when \( N > M \)

\[
\phi_{\lambda d} = \int_0^{\sigma_c} \left( e^{-\lambda y \sec \alpha} \nu_{tL}^2 + e^{-\lambda y (L-y) \sec \alpha} \nu_{tL}^2 + \sum_{k=M+1}^{N} \left( e^{-\lambda y \sec \alpha} \nu_{tB}^2 \right) \right) \frac{\sin \alpha}{\cos \alpha} \sin \alpha \, d\alpha
\]

3. When the emitting and absorbing elements are within the same glaze, i.e., when \( M = N \)

\[
\phi_{\lambda d} = \int_0^{\sigma_c} \left( \left( e^{-\lambda y (L-y) \sec \alpha} \nu_{tB}^2 \right) + \left( e^{-\lambda y \sec \alpha} \nu_{tB}^2 \right) \right) \frac{\sin \alpha}{\cos \alpha} \sin \alpha \, d\alpha + \int_{\sigma_c}^{\gamma} \frac{\sin \alpha}{\cos \alpha} \sin \alpha \, d\alpha
\]

**Glaze Coatings as Radiation Sources**

The intensity of radiation beams from an emitting glaze thin-film coating is computed as:

89
$I_{\lambda} = \varepsilon_f \frac{W_{\lambda}}{n} \cos \alpha$

where

$W_{\lambda} = \int \sigma_\lambda dT$

The energy absorbed by an element as emitted from the thin-film coatings in the window system is computed as:

$Q_{\lambda f}(t) = \sum_{f=1}^{n} 2\pi \left( \frac{W_{\lambda}}{n} \right) P_{\lambda f}$

where $i$ refers to the absorbing element, $f$ refers to the emitting thin-film coatings, and $n$ is the number of emitting coatings in the window system. The equation employed in computing the auxiliary function, $P_{\lambda f}$, depends on the relative location of element $i$ and coating $f$:

1. When $M < N$ and the coating is on the lower surface of glaze $M$,

$P_{\lambda f} = \int_{0}^{\sigma_f} \left( \varepsilon_f \prod_{k=1}^{N-1} \left( e^{-\gamma L \sec \alpha_{v_{1B}}^{(k)}} \right) \left( x_{1M} + e^{-\gamma L \sec \alpha_{v_{1B}}^{(k)}} \right) \right. \times \left( e^{-\gamma L \sec \alpha_{v_{1B}}^{(k)}} \right) \left. x_{1M} \right) e^{2\pi \cos \alpha_{\lambda} \sin \alpha_{\lambda}} d\alpha_{\lambda}$

If the coating is on the upper surface of glaze $M$, the above integrand is multiplied by:

$(e^{-\gamma L \sec \alpha_{v_{1B}}^{(M)}})
2. When \( N > N \) and the coating is on the upper surface of glaze \( M \),

\[
\beta_{\text{Mf}} = \int_0^{\pi/2} \left\{ \varepsilon_\text{f} \prod_{k=N+1}^{M-1} \left[ (\varepsilon - \varepsilon \gamma L \sec \sigma \gamma \delta_{\text{Mf}}) \frac{x_\text{Mf}}{x_\text{MN} - (\varepsilon - \varepsilon \gamma L \sec \sigma \gamma \delta_{\text{Mf}}) x_\text{MN} + (\varepsilon - \varepsilon \gamma L \sec \sigma \gamma \delta_{\text{Mf}}) x_\text{MN}} \right] \cos \sigma_\text{N} \sin \sigma_\text{N} \right\} \, d\sigma_\text{N}
\]

If the coating is on the lower surface of glaze \( N \), the above integrand is multiplied by:

\[
(\varepsilon - \varepsilon \gamma L \sec \sigma \gamma \delta_{\text{Mf}})
\]

3. When \( M = N \) and the coating is on the upper surface of the glass,

\[
\beta_{\text{Mf}} = \int_0^{\pi/2} \left\{ \varepsilon_\text{f} \left[ (\varepsilon - \varepsilon \gamma L \sec \sigma \gamma \delta_{\text{Mf}}) \frac{x_\text{Mf}}{x_\text{MN}} \sin \sigma_\text{N} \right] \right\} \, d\sigma_\text{N}
\]

If the coating is on the lower surface of the glaze,

\[
\beta_{\text{Mf}} = \int_0^{\pi/2} \left\{ \varepsilon_\text{f} \left[ (\varepsilon - \varepsilon \gamma L \sec \sigma \gamma \delta_{\text{Mf}}) \frac{x_\text{Mf}}{x_\text{MN}} \sin \sigma_\text{N} \right] \right\} \, d\sigma_\text{N}
\]

**Radiation Source External to Window**

The intensity of radiation beams from an emitting source outside the window system is computed as:

\[
I_\text{M} = \varepsilon_\text{N} \frac{W}{A} \cos \sigma
\]
where

\[ W_{BA} = \frac{F_{\lambda}}{\pi} \sigma T^4 \]

Energy emitted by the external source that is absorbed by a given finite element in the window system is computed as:

\[ Q_H(1) = 2\pi \left( \frac{W_{BA}}{\pi} \right) \hat{\delta}_{1,1h} \]

where \( i \) refers to the absorbing element and \( h \) refers to the external source. The auxiliary function, \( \hat{\delta}_{1,1h} \) is calculated as follows:

\[ \hat{\delta}_{1,1h} = \int_0^{2\pi} \left\{ \varepsilon_h \tau_{th} \prod_{k=1}^{P-1} \left( e^{-\gamma L \sec \alpha} \nu_{1B} \right)_k \left[ \cos \alpha_h + (e^{-\gamma L \sec \alpha} \nu_{1B})_h \right] \times \left( e^{-\gamma L \sec \alpha} \nu_{1T} \right) \right\} \cos \alpha_h \sin \sigma_h \, d\sigma_h \]

**RADIATION EMITTED BY A FINITE GLAZE ELEMENT**

As indicated by the heat balance equations, the thermal response of a finite glaze element, \( i \), is partially dependent on the radiation, \( Q_H(1) \), emitted by the element. Radiation intensity emitted per unit volume is defined by a volumetric emissive power derived by Gordon as:

\[ J_{\lambda} = \frac{\nu \sigma T^4}{\pi} \]

which relates the intensity, \( J \), to the glaze absorption coefficient, \( \nu \), the glaze index of refraction, \( n \), and the hemispherical emissive power, \( W_{BA} \), of a blackbody radiator. The hemispherical emissive power is computed as:

\[ W_{BA} = \frac{F_{\lambda}}{\pi} \sigma T^4 \]
\[ W_{EM} = \frac{P_\lambda \sigma T^4_\lambda}{T_\lambda^4} \]

where \( P_\lambda \) is the percent of energy emitted within a finite wavelength band of the spectral region in which the glass is considered to be semi-transparent.

When considering radiation emitted from the elements, \( J_j \), in computing \( Q_{EM}(1) \), it was assumed that the radiation was emitted from the midpoint (nodal point) of the elements. Thus, some of the energy is attenuated (or absorbed) as it travels from the midpoint to the edge of the emitting element. As a result of this attenuation, the intensity of radiation leaving the edge of the element was defined as:

\[ I = I_0 e^{-\gamma_\lambda \Delta x/2 \sec \alpha} \]

In order not to violate the second law of thermodynamics, the same consideration is given to the intensity leaving an element when computing \( Q_{EM}(1) \).

The intensity leaving element, \( I \), is defined as:

\[ I_\lambda = J_\lambda e^{-\gamma_\lambda \Delta x/2 \sec \alpha} \]

where \( J_\lambda \) is the volumetric emissive power lumped at the elements nodal point. To obtain the heat radiated from the element, the intensity, \( I_\lambda \), is integrated over the surrounding spherical area as follows:

\[ Q_{EM}(1) = \frac{2}{3} \int_0^{\pi/2} \int_0^{\pi/2} J_\lambda e^{-\gamma_\lambda \Delta x/2 \sec \alpha} \, d\alpha \, d\theta \]

Substituting the analytical definition for volumetric emissive power, \( J_\lambda \), into the above integrand and performing the integration over \( \theta \) gives:

\[ Q_{EM}(1) = 4\pi \lambda^2 \int_0^{\pi/2} e^{-\gamma_\lambda \Delta x/2 \sec \alpha} \, d\alpha \]

95

Approved for Public Release
HEAT FLUX TO THE CABIN

The heat flux to the cabin is a result of radiation from and through the window glasses and of convection from the innermost window surface. This cabin flux is expressed analytically as:

\[ q_c = h(T_a - T_C) + [(1 - P_L)P_L + (1 - P_R)(1 - P_R)] \sigma T_a^4 - \sigma T_C^4 + \sum_\lambda q_\lambda(c) \]

Convection heat transfer from the window is computed from the term in which the difference between the window’s lower surface temperature, \( T_a \), and the cabin temperature, \( T_C \), is multiplied by the heat transfer coefficient, \( h \). The heat transfer coefficient is assumed to be that resulting from free convection.

The net heat transfer from the window surface to the cabin by radiation, to which the glasses are considered to be opaque, is computed by the terms:

\[ [(1 - P_L)P_L + (1 - P_R)(1 - P_R)] \sigma T_a^4 - \sigma T_C^4 \]

The symbols \( P_L \) and \( P_R \) represent the percent of energy emitted at wavelengths from zero to the left cutoff point and from zero to the right cutoff point, respectively, of the spectral region in which the glass is considered to be semitransparent. For example, fused silica is considered to be semitransparent over the wavelength region from \( \lambda = 0.4 \mu \) to \( \lambda = 4.0 \mu \). Thus, the left and right cutoff points for fused silica are at 0.4 and 4.0 \( \mu \), respectively. Symbols \( \rho_L \) and \( \rho_R \) are the mean hemispherical reflectivities of the glass to radiation in the spectral regions to the left and to the right of the semitransparent region.

Radiative flux through the window is represented by the term, \( q_\lambda(c) \). This flux is computed for and summed over finite wavelength bands of the spectral region in which the glass is considered to be semitransparent. Contribution of radiative flux to the cabin that is represented by \( q_\lambda(c) \) includes:

94

Approved for Public Release
1. Radiation from each finite element in each window glass;
2. Radiation from coatings on the glass surfaces; and
3. Radiation from an external medium or heater.

Considering the above sources of radiation, the flux through the window is expressed as:

\[ q_\lambda(c) = q_{R\lambda}(c) + q_{X\lambda}(c) + q_{B\lambda}(c) \]

The terms on the right side of the equal sign are analytically defined in the following subsections.

**Radiation from Glaze Elements to the Cabin**

The radiative flux emitted by the finite elements, \( j \), of the window glasses that travel through the window and into the cabin is computed as:

\[ q_{R\lambda}(c) = \sum_{j=1}^{\text{all}} \omega_{jk} \sigma_{Bj} \delta_{\lambda j} \Phi_j \text{d}y \]

where

\[ \omega_{Bj} = \frac{R_j r_j^4}{\lambda_j} \]

The auxiliary function, \( \Phi_{\lambda j} \), is computed from the equation:

\[ \Phi_{\lambda j} = \int_0^{\alpha_0} \left( e^{-\gamma (L-y) \sec \alpha \gamma_1} + e^{-\gamma W \sin \alpha \gamma_1} \right) \times \prod_{k=1}^{\alpha_0} \left( e^{-\gamma L \sec \alpha \gamma_1} \right) \frac{n_0 \cos \alpha_0}{n_0 \cos \alpha_0 \sin \alpha_0} \text{d}y \]

Approved for Public Release
where $N$ refers to the medium number of the glaze containing the emitting element, and $G$ refers to the medium number of the innermost glaze.

**Radiation from Glass Coatings to the Cabin**

Cabin heating, resulting from the radiation emitted by the glaze coatings, is computed from the equation:

$$q_{FL}(c) = \sum_{r=1}^{2} \varepsilon_{\text{R}_{r}^{2} \text{R}_{r}^{2}}$$

where

$$\varepsilon_{\text{R}_{r}^{2} \text{R}_{r}^{2}} = \varepsilon_{r} \sigma_{T}^{2}$$

If the emitting coating is on the lower surface of a glaze, the auxiliary function, $\theta_{R_{r}}$, is defined as:

$$\theta_{R_{r}} = \int_{0}^{\pi} \int_{0}^{\alpha} \left[ \varepsilon_{r} \sigma_{T} \varepsilon_{r} \sigma_{T} \cos \theta \sin \theta \right] d\alpha$$

where $r$ refers to the emitting coating and $N$ refers to the medium number of the glaze containing the coating. If the coating is on the upper surface of medium $N$, the integrand in the above equation is multiplied by:

$$(e^{-\gamma L \sec \alpha} \varepsilon_{r} \sigma_{T}^{2})$$

**Radiation from an External Source to the Cabin**

The radiation flux emitted by an external source that travels through the glaze and into the cabin is computed from the equation:

96

Approved for Public Release
\[ q_{11}(c) = \mathcal{N}_{11} \hat{q}_{1c} \]

where

\[ \mathcal{W}_{111} = P \mathcal{E}_{11} \]

The auxiliary function, \( \hat{q}_{1c} \), is defined as:

\[
\hat{q}_{1c} = \int_{0}^{\theta_{cr}} \tau_{TL} \left( \prod_{k=1}^{G} \left( e^{-\gamma L \sec \alpha} \nu_{ibk} \right) \cos \sigma_{c} \sin \sigma_{c} \right) \, \mathrm{d} \psi_{c}
\]

where \( \tau_{TL} \) is the transmittance at the upper surface of the outermost glaze.
APPENDIX B

EQUATIONS USED TO COMPUTE TRANSMITTANCE AND REFLECTANCE
OF COATED AND UNCOATED GLAZE SURFACES
Symbols

\( \gamma \) - Index of refraction for film layer
\( n \) - Real part of the refractive index
\( \imath \) - Complex or imaginary part of refractive index
\( k \) - Extinction coefficient of the film layer
\( Y \) - Admittance (ratio of electric and magnetic field intensities)
\( \phi \) - Function defined by Eq. (3)
\( \lambda \) - Vacuum wavelength
\( \delta \) - True geometric film thickness
\( R \) - Reflectance
\( \alpha \) - Real part of admittance \( Y \)
\( \beta \) - Imaginary part of admittance \( Y \)
\( T \) - Transmittance
\( \Psi \) - Function defined by Eq. (6a)
\( \theta_0 \) - Angle of incidence in incidence medium
\( \varphi \) - Angle of refraction in successive layers defined by Eq. (8)

Subscripts

\( j \) - Refers to film layer under consideration
\( o \) - Refers to medium of incidence \((j=\infty)\)
\( p \) - Refers to the innermost film layer \((j=p)\)
\( p+1 \) - Refers to medium of emergence
\( \parallel \) - Parallel component of polarized radiation
\( \perp \) - Perpendicular component of polarized radiation
INTRODUCTION

The heat balance equation for the internal as well as the edge finite elements of each glass contains auxiliary functions (see Appendix A) which include values of surface reflectance, transmittance, and absorptance. These surface optical properties can be calculated by the subject computer program for both coated and uncoated glass surfaces. If transmittance and reflectance data are available they can be included in the input data rather than be computed by the program.

COMPUTED UNCOATED GLAZE SURFACE OPTICAL PROPERTIES

When predicting temperatures of uncoated glasses, the reflectivity of the surfaces is computed from Fresnel’s equations as follows (Ref. 2):

\[ \rho_\perp = \frac{n \cos \alpha - \sqrt{1-n^2 \sin^2 \alpha}}{n \cos \alpha + \sqrt{1-n^2 \sin^2 \alpha}} \]

for radiation polarized perpendicularly to the plane of incidence, and

\[ \rho_\parallel = \frac{\frac{1}{n} \cos \alpha - \sqrt{1-n^2 \sin^2 \alpha}}{\frac{1}{n} \cos \alpha + \sqrt{1-n^2 \sin^2 \alpha}} \]

The values of transmittance for uncoated glasses are computed as:

\[ T_\perp = 1 - \rho_\perp \]

and

\[ T_\parallel = 1 - \rho_\parallel \]

For unpolarized radiation, i.e., for radiation beams prior to the first reflection, the effective transmittance is given by:

101

Approved for Public Release
\[ \tau = \frac{1}{2} (\tau_1 - \tau_2) \]

**COMPUTED COATED GLAZE SURFACE OPTICAL PROPERTIES**

In many instances the windows of aerospace vehicles employ thin-film coatings designed to provide certain desirable optical features. For example, various coatings have been developed to reflect ultraviolet radiation, to reflect infrared radiation, and to reduce glaze surface reflection in the visual region of the spectrum. For coated glazes, the computer program incorporates a subroutine to compute the reflectance and transmittance of glaze surfaces having single or multiple layer, dielectric and/or metallic thin-film coatings. The technique employed in the computation is that developed by Berling (Ref. 6) in which the reflectance is determined as the final step in a recursion process which calculates the admittance of each layer of the thin-film coating beginning with the innermost layer and ending with the incident media. The computation procedure and equations are presented below.

The index of refraction for each film layer is denoted as

\[ \tilde{n}_j = n_j - i k_j \]  \hspace{1cm} (1)

which is complex when the film under consideration is absorptive. For nonabsorptive films the refractive index is equal to \( n_j \).

The reflectance is obtained by the successive solution of the equation which calculates film admittance, \( Y_j \):

\[ Y_{j-1} = a_{j-1} + 2b_{j-1} = \frac{Y_j \cos \psi_j + i \eta_j \sin \psi_j}{\cos \psi_j + i \sin \psi_j / \eta_j} \]  \hspace{1cm} (2)

where

\[ \psi_j = (2\pi/\lambda) \eta_j d_j . \]  \hspace{1cm} (3)
Equation (2) is solved successively for each thin-film layer of the coating beginning with the innermost film until \( X_0 \) is evaluated. The calculations are started by using a value of admittance for the innermost film layer computed from the formula

\[ Y_p = \frac{1}{n_i} = \frac{n_{p+1}}{n_{p+1} - i k_{p+1}}. \tag{4} \]

The real and imaginary parts \( (a_0 \) and \( b_0 \) \) of the admittance \( X_0 \) are then evaluated and used in the calculation of the reflectance, \( \rho \), as follows:

\[ \rho = \left| 1 - \left\{ a_0^2 \frac{b_0}{b_0 + i a_0} \right\} \right|^2. \tag{5} \]

The transmittance is calculated from the formula

\[ \tau = (1-\rho) \prod_{j=1}^{p} \psi_j \tag{6} \]

where

\[ \psi_j = \frac{1}{\sqrt{\left( a_{j-1} \cos \phi_j + i b_{j-1} \sin \phi_j \right)^2}}. \tag{6a} \]

For a nonabsorbing coating, i.e., \( \eta_j = \eta_j \), the function \( \psi \) is unity and \( \tau = 1-\rho \).

The above equations are for radiant energy of normal incidence. For oblique incidence, the same equations are applicable if effective values of \( \eta_j \) and \( \phi_j \) are used. Upon reflection, radiation becomes polarized and is considered as having parallel polarized and perpendicular polarized components. For perpendicular polarization, the effective refractive index for any angle of incidence is given by

\[ \eta_{jL} = \eta_j \cos \phi_j. \tag{7} \]
where

$$\cos \theta_j = \left[ \frac{(\alpha_j^2 + \beta_j^2)^{1/2} + \alpha_j}{2} \right]^{1/2} - \left[ \frac{(\alpha_j^2 + \beta_j^2)^{1/2} - \alpha_j}{2} \right]^{1/2}$$

and

$$\alpha_j = 1 + n_0 \sin \theta_0 \left( \frac{n_j^2 + k_j^2}{n_j^2} \right)^2 (n_j^2 - n_j^2)$$

$$\beta_j = -2 n_j k_j \left[ n_0 \sin \theta_0 \left( \frac{n_j^2 + k_j^2}{n_j^2} \right)^2 \right].$$

For parallel polarisation the effective index is given by

$$n_{j\parallel} = \frac{n_j}{\cos \theta_j}. \quad (9)$$

The effective thickness function is the same for both states of polarisation and is given by

$$\delta_{\parallel} = \delta_j \cos \theta_j. \quad (10)$$

The absorptance of the coating is evaluated as $1 - \rho - \tau$.

**INPUT GLAZE SURFACE OPTICAL PROPERTIES**

A read-in subroutine was also included in the computer program so that the transmittance and reflectance of a given thin-film coating can be included in the input data rather than be computed by the thin-film subroutine if these data are available. When the transmittance and reflectance data for coated surfaces are input, the absorptance of the coating is computed as $1 - \rho - \tau$.

The data are input in an array or table which gives the average values of transmittance and reflectance versus incident angle for each of the
finite wavelength bands within the spectral region in which the glaze is considered to be semitransparent. Tables B-I through B-X present transmittance data used in predicting the temperatures of the coated glaze specimens employed in the experimental heat transfer tests. Coatings used in the experimental tests included:

1. An ultraviolet-infrared (UV-IR) reflecting coating;

2. A high efficiency antireflection (HEA) coating; and

3. A gold coating for infrared reflection.

These coatings were deposited on the glaze test specimens by Optical Coating Laboratory, Inc. (OCLI). The transmittance of the glaze surfaces with UV-IR and with HEA coatings was obtained from data supplied by OCLI. These data were the spectral transmission of UV-IR and HEA coated microscope slides recorded for incident angles of 0, 20, 40 and 60 degrees. Zero transmission was assumed for the limiting incident angle, 90 degrees. The average coated surface transmittance, for each of the finite wavelength bands considered in the semitransparent analysis, was determined as follows:

\[ \tau_m = \tau_c \cdot \tau_g ^ {\gamma L \sec \alpha} \]

or

\[ \tau_c = \frac{\tau_m}{\tau_g ^ {\gamma L \sec \alpha}} \]

where

- \( \tau_m \) = transmission of coated microscope slide
- \( \tau_g \) = transmittance of uncoated surface
- \( \tau_c \) = transmittance of the coated surface
- \( \gamma \) = glaze absorption coefficient
- \( L \) = microscope thickness
- \( \alpha \) = angle of refraction

105

Approved for Public Release
Average values of the above variables were used for each wavelength band considered. Transmittance versus incident angle for the gold coating was based on transmittance at zero angle of incidence and the shape of the HEA and UV-IR "transmittance versus incident angle" curves. It was assumed that the absorptance of these thin-film coatings was negligible. Thus, the reflectance was evaluated at $1-t$. Since inputting surface transmittance and reflectance rather than computing these values, polarization effects are neglected. Transmittance and reflectance of the HEA, UV-IR, and gold multiple-layer, thin-film coatings were not computed with the subroutine discussed in the above section because the film data required for these calculations were considered by OCLI to be proprietary.

### TABLE B-I
TRANSMITTANCE OF UV-IR COATING ON YCOR GLAZE

<table>
<thead>
<tr>
<th>Wavelength Band</th>
<th>Incident Angle</th>
<th>0°</th>
<th>20°</th>
<th>40°</th>
<th>60°</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td></td>
<td>0.86</td>
<td>0.86</td>
<td>0.86</td>
<td>0.78</td>
</tr>
<tr>
<td>2</td>
<td></td>
<td>0.90</td>
<td>0.90</td>
<td>0.80</td>
<td>0.61</td>
</tr>
<tr>
<td>3</td>
<td></td>
<td>0.78</td>
<td>0.76</td>
<td>0.76</td>
<td>0.67</td>
</tr>
<tr>
<td>4</td>
<td></td>
<td>0.75</td>
<td>0.75</td>
<td>0.75</td>
<td>0.61</td>
</tr>
<tr>
<td>5</td>
<td></td>
<td>0.84</td>
<td>0.84</td>
<td>0.84</td>
<td>0.77</td>
</tr>
</tbody>
</table>

### TABLE B-II
TRANSMITTANCE OF UV-IR COATING ON FUSED SILICA GLAZE

<table>
<thead>
<tr>
<th>Wavelength Band</th>
<th>Incident Angle</th>
<th>0°</th>
<th>20°</th>
<th>40°</th>
<th>60°</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td></td>
<td>0.68</td>
<td>0.56</td>
<td>0.55</td>
<td>0.47</td>
</tr>
<tr>
<td>2</td>
<td></td>
<td>0.66</td>
<td>0.63</td>
<td>0.58</td>
<td>0.77</td>
</tr>
<tr>
<td>3</td>
<td></td>
<td>0.72</td>
<td>0.72</td>
<td>0.72</td>
<td>0.665</td>
</tr>
<tr>
<td>4</td>
<td></td>
<td>0.74</td>
<td>0.74</td>
<td>0.78</td>
<td>0.71</td>
</tr>
<tr>
<td>5</td>
<td></td>
<td>0.84</td>
<td>0.85</td>
<td>0.88</td>
<td>0.78</td>
</tr>
</tbody>
</table>
### TABLE B-III
TRANSMITTANCE OF UN-IR COATING ON ALUMINO-SILICATE GLAZE

<table>
<thead>
<tr>
<th>Wavelength</th>
<th>0°</th>
<th>20°</th>
<th>40°</th>
<th>60°</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.48</td>
<td>0.45</td>
<td>0.56</td>
<td>0.46</td>
</tr>
<tr>
<td>2</td>
<td>0.66</td>
<td>0.89</td>
<td>0.90</td>
<td>0.75</td>
</tr>
<tr>
<td>3</td>
<td>0.71</td>
<td>0.74</td>
<td>0.73</td>
<td>0.65</td>
</tr>
<tr>
<td>4</td>
<td>0.74</td>
<td>0.71</td>
<td>0.77</td>
<td>0.66</td>
</tr>
<tr>
<td>5</td>
<td>0.85</td>
<td>0.85</td>
<td>0.87</td>
<td>0.76</td>
</tr>
</tbody>
</table>

### TABLE B-IV
TRANSMITTANCE OF HRA COATING ON VICTOR GLAZE

<table>
<thead>
<tr>
<th>Wavelength</th>
<th>0°</th>
<th>20°</th>
<th>40°</th>
<th>60°</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.84</td>
<td>0.84</td>
<td>0.86</td>
<td>0.86</td>
</tr>
<tr>
<td>2</td>
<td>0.85</td>
<td>0.86</td>
<td>0.88</td>
<td>0.80</td>
</tr>
<tr>
<td>3</td>
<td>0.85</td>
<td>0.85</td>
<td>0.88</td>
<td>0.88</td>
</tr>
<tr>
<td>4</td>
<td>0.86</td>
<td>0.85</td>
<td>0.89</td>
<td>0.88</td>
</tr>
<tr>
<td>5</td>
<td>0.86</td>
<td>0.86</td>
<td>0.89</td>
<td>0.89</td>
</tr>
</tbody>
</table>

### TABLE B-V
TRANSMITTANCE OF HRA COATING ON FUSED SILICA GLAZE

<table>
<thead>
<tr>
<th>Wavelength</th>
<th>0°</th>
<th>20°</th>
<th>40°</th>
<th>60°</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.67</td>
<td>0.86</td>
<td>0.87</td>
<td>0.865</td>
</tr>
<tr>
<td>2</td>
<td>0.85</td>
<td>0.86</td>
<td>0.86</td>
<td>0.865</td>
</tr>
<tr>
<td>3</td>
<td>0.85</td>
<td>0.85</td>
<td>0.89</td>
<td>0.865</td>
</tr>
<tr>
<td>4</td>
<td>0.85</td>
<td>0.84</td>
<td>0.90</td>
<td>0.87</td>
</tr>
<tr>
<td>5</td>
<td>0.88</td>
<td>0.87</td>
<td>0.89</td>
<td>0.86</td>
</tr>
</tbody>
</table>
### TABLE B-VI
TRANSMITTANCE OF PILL COATING ON ALUMINOSILICATE GLASS

<table>
<thead>
<tr>
<th>Wavelength</th>
<th>Incident Angle</th>
<th>0°</th>
<th>20°</th>
<th>40°</th>
<th>60°</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td></td>
<td>0.65</td>
<td>0.56</td>
<td>0.375</td>
<td>0.27</td>
</tr>
<tr>
<td>2</td>
<td></td>
<td>0.65</td>
<td>0.55</td>
<td>0.37</td>
<td>0.27</td>
</tr>
<tr>
<td>3</td>
<td></td>
<td>0.64</td>
<td>0.54</td>
<td>0.36</td>
<td>0.26</td>
</tr>
<tr>
<td>4</td>
<td></td>
<td>0.65</td>
<td>0.55</td>
<td>0.35</td>
<td>0.25</td>
</tr>
<tr>
<td>5</td>
<td></td>
<td>0.65</td>
<td>0.55</td>
<td>0.35</td>
<td>0.25</td>
</tr>
</tbody>
</table>

### TABLE B-VII
TRANSMITTANCE OF GOLD COATING ON TUXOR GLASS

<table>
<thead>
<tr>
<th>Wavelength</th>
<th>Incident Angle</th>
<th>0°</th>
<th>20°</th>
<th>40°</th>
<th>60°</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td></td>
<td>0.25</td>
<td>0.25</td>
<td>0.25</td>
<td>0.25</td>
</tr>
<tr>
<td>2</td>
<td></td>
<td>0.075</td>
<td>0.075</td>
<td>0.075</td>
<td>0.075</td>
</tr>
<tr>
<td>3</td>
<td></td>
<td>0.065</td>
<td>0.065</td>
<td>0.065</td>
<td>0.065</td>
</tr>
<tr>
<td>4</td>
<td></td>
<td>0.065</td>
<td>0.065</td>
<td>0.065</td>
<td>0.065</td>
</tr>
<tr>
<td>5</td>
<td></td>
<td>0.045</td>
<td>0.045</td>
<td>0.045</td>
<td>0.045</td>
</tr>
</tbody>
</table>

### TABLE B-VIII
TRANSMITTANCE OF GOLD COATING ON FUSED SILICA GLASS

<table>
<thead>
<tr>
<th>Wavelength</th>
<th>Incident Angle</th>
<th>0°</th>
<th>20°</th>
<th>40°</th>
<th>60°</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td></td>
<td>0.30</td>
<td>0.30</td>
<td>0.30</td>
<td>0.30</td>
</tr>
<tr>
<td>2</td>
<td></td>
<td>0.075</td>
<td>0.075</td>
<td>0.075</td>
<td>0.075</td>
</tr>
<tr>
<td>3</td>
<td></td>
<td>0.065</td>
<td>0.065</td>
<td>0.065</td>
<td>0.065</td>
</tr>
<tr>
<td>4</td>
<td></td>
<td>0.065</td>
<td>0.065</td>
<td>0.065</td>
<td>0.065</td>
</tr>
<tr>
<td>5</td>
<td></td>
<td>0.045</td>
<td>0.045</td>
<td>0.045</td>
<td>0.045</td>
</tr>
</tbody>
</table>

108

Approved for Public Release
<table>
<thead>
<tr>
<th>Wavelength</th>
<th>Incidence Angle</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0°</td>
</tr>
<tr>
<td>1</td>
<td>0.25</td>
</tr>
<tr>
<td>2</td>
<td>0.075</td>
</tr>
<tr>
<td>3</td>
<td>0.065</td>
</tr>
<tr>
<td>4</td>
<td>0.050</td>
</tr>
<tr>
<td>5</td>
<td>0.045</td>
</tr>
</tbody>
</table>

Approved for Public Release
APPENDIX C

THERMOPHYSICAL AND OPTICAL PROPERTIES
OF GLACE MATERIALS

111

Approved for Public Release
The material properties employed in the analysis are tabulated in Tables C-I through C-V for fused silica, Vykor (96% silica), aluminosilicate, borosilicate, and soda lime glasses. These properties are stored as block data in the computer program. This allows temperatures to be computed for a window system containing any combination of the above five glaze materials without inputting glaze material property data.

Properties which are considered as temperature-dependent are:

1. Index of refraction, $n$;
2. Thermal conductivity, $k$;
3. Heat capacitance, $pc$; and
4. Absorption coefficient, $\gamma$.

The absorption coefficient is also spectrally dependent. Average values of $\gamma$ are presented for five finite wavelength bands within the spectral region (from 0.4 to 4.8 $\mu$) in which the glazes are considered to be semi-transparent.

The values of index of refraction, thermal conductivity and heat capacitance were obtained from Ref. 6 for the glaze materials used in the calculations. Spectral values of absorption coefficient were determined by Finch (Appendix A of Ref. 7) based on transmittance of glaze specimens of known thicknesses and taking into account the reflectance of the specimen surfaces.
### TABLE 5-1

**MATERIAL - FUSED SILICA**

<table>
<thead>
<tr>
<th>Temperature (<em>°K</em>)</th>
<th>Refractive Index</th>
<th>Conductivity (watts/cm·°K)</th>
<th>ρ₀ (watt sec/cm³·°K)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>1.45</td>
<td>0.021</td>
<td>1.216</td>
</tr>
<tr>
<td>200</td>
<td>1.45</td>
<td>0.011</td>
<td>1.216</td>
</tr>
<tr>
<td>400</td>
<td>1.45</td>
<td>0.0155</td>
<td>1.952</td>
</tr>
<tr>
<td>600</td>
<td>1.45</td>
<td>0.0805</td>
<td>2.282</td>
</tr>
<tr>
<td>800</td>
<td>1.45</td>
<td>0.0304</td>
<td>2.466</td>
</tr>
<tr>
<td>1,000</td>
<td>1.45</td>
<td>0.02207</td>
<td>2.567</td>
</tr>
<tr>
<td>1,200</td>
<td>1.45</td>
<td>0.02207</td>
<td>2.567</td>
</tr>
<tr>
<td>1,400</td>
<td>1.45</td>
<td>0.02207</td>
<td>2.567</td>
</tr>
<tr>
<td>1,700</td>
<td>1.45</td>
<td>0.02207</td>
<td>2.567</td>
</tr>
<tr>
<td>2,000</td>
<td>1.45</td>
<td>0.02207</td>
<td>2.567</td>
</tr>
</tbody>
</table>

**Absorption Coefficients (cm⁻¹)**

<table>
<thead>
<tr>
<th>Temperature (<em>°K</em>)</th>
<th>λ from 0.4 to 2.0 μ to 2.61 μ</th>
<th>λ from 2.61 μ to 3.8 μ</th>
<th>λ from 3.8 μ to 4.8 μ</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0.06</td>
<td>0.50</td>
<td>17.0</td>
</tr>
<tr>
<td>300</td>
<td>0.06</td>
<td>0.50</td>
<td>17.0</td>
</tr>
<tr>
<td>600</td>
<td>0.06</td>
<td>0.50</td>
<td>17.0</td>
</tr>
<tr>
<td>900</td>
<td>0.06</td>
<td>0.50</td>
<td>17.0</td>
</tr>
<tr>
<td>1,200</td>
<td>0.06</td>
<td>0.50</td>
<td>17.0</td>
</tr>
<tr>
<td>1,500</td>
<td>0.06</td>
<td>0.50</td>
<td>17.0</td>
</tr>
<tr>
<td>1,800</td>
<td>0.06</td>
<td>0.50</td>
<td>17.0</td>
</tr>
<tr>
<td>2,000</td>
<td>0.06</td>
<td>0.50</td>
<td>17.0</td>
</tr>
</tbody>
</table>

Emissivity at wavelength below 0.4 μ is 0.92.
Emissivity at wavelength above 4.8 μ is 0.922.
TABLE C-II

MATERIAL - VYCOR (98 PERCENT SILICA)

<table>
<thead>
<tr>
<th>Temperature (°K)</th>
<th>Refractive Index</th>
<th>Conductivity (watts/cm *°K)</th>
<th>gc (watt sec/cm² *°K)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>1.45</td>
<td>0.0133</td>
<td>1.34</td>
</tr>
<tr>
<td>200</td>
<td>1.45</td>
<td>0.0133</td>
<td>1.34</td>
</tr>
<tr>
<td>400</td>
<td>1.45</td>
<td>0.0162</td>
<td>1.946</td>
</tr>
<tr>
<td>600</td>
<td>1.45</td>
<td>0.01763</td>
<td>2.26</td>
</tr>
<tr>
<td>800</td>
<td>1.45</td>
<td>0.01885</td>
<td>2.49</td>
</tr>
<tr>
<td>1,000</td>
<td>1.45</td>
<td>0.0193</td>
<td>2.67</td>
</tr>
<tr>
<td>1,200</td>
<td>1.45</td>
<td>0.0193</td>
<td>2.67</td>
</tr>
<tr>
<td>1,400</td>
<td>1.45</td>
<td>0.0193</td>
<td>2.67</td>
</tr>
<tr>
<td>1,700</td>
<td>1.45</td>
<td>0.0193</td>
<td>2.67</td>
</tr>
<tr>
<td>2,000</td>
<td>1.45</td>
<td>0.0193</td>
<td>2.67</td>
</tr>
</tbody>
</table>

Absorption Coefficients (cm⁻¹)

<table>
<thead>
<tr>
<th>Temperature (°K)</th>
<th>λ from 0.4 to 2.2 μ</th>
<th>λ from 2.2 to 2.61 μ</th>
<th>λ from 2.61 to 2.9 μ</th>
<th>λ from 2.9 to 3.5 μ</th>
<th>λ from 3.5 to 4.8 μ</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0.05</td>
<td>0.45</td>
<td>17.0</td>
<td>1.35</td>
<td>19.0</td>
</tr>
<tr>
<td>300</td>
<td>0.05</td>
<td>0.45</td>
<td>17.0</td>
<td>1.35</td>
<td>19.0</td>
</tr>
<tr>
<td>600</td>
<td>0.05</td>
<td>0.45</td>
<td>17.0</td>
<td>1.35</td>
<td>19.0</td>
</tr>
<tr>
<td>900</td>
<td>0.05</td>
<td>0.45</td>
<td>17.0</td>
<td>1.35</td>
<td>19.0</td>
</tr>
<tr>
<td>1,200</td>
<td>0.05</td>
<td>0.45</td>
<td>17.0</td>
<td>1.35</td>
<td>19.0</td>
</tr>
<tr>
<td>1,500</td>
<td>0.05</td>
<td>0.45</td>
<td>17.0</td>
<td>1.35</td>
<td>19.0</td>
</tr>
<tr>
<td>1,800</td>
<td>0.05</td>
<td>0.45</td>
<td>17.0</td>
<td>1.35</td>
<td>19.0</td>
</tr>
<tr>
<td>2,000</td>
<td>0.05</td>
<td>0.45</td>
<td>17.0</td>
<td>1.35</td>
<td>19.0</td>
</tr>
</tbody>
</table>

Emissivity at wavelength below 0.4 μ is 0.914.
Emissivity at wavelength above 4.8 μ is 0.014.


<table>
<thead>
<tr>
<th>Temperature (°K)</th>
<th>Refractive Index</th>
<th>Conductivity (watts/m °K)</th>
<th>Conductivity (watt sec/cm² °K)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>1.54</td>
<td>0.01185</td>
<td>1.607</td>
</tr>
<tr>
<td>200</td>
<td>1.54</td>
<td>0.01185</td>
<td>1.607</td>
</tr>
<tr>
<td>400</td>
<td>1.54</td>
<td>0.01449</td>
<td>2.284</td>
</tr>
<tr>
<td>600</td>
<td>1.54</td>
<td>0.01469</td>
<td>2.677</td>
</tr>
<tr>
<td>800</td>
<td>1.54</td>
<td>0.01470</td>
<td>2.962</td>
</tr>
<tr>
<td>1,000</td>
<td>1.54</td>
<td>0.01471</td>
<td>3.192</td>
</tr>
<tr>
<td>1,200</td>
<td>1.54</td>
<td>0.01471</td>
<td>3.192</td>
</tr>
<tr>
<td>1,400</td>
<td>1.54</td>
<td>0.01471</td>
<td>3.192</td>
</tr>
<tr>
<td>1,600</td>
<td>1.54</td>
<td>0.01471</td>
<td>3.192</td>
</tr>
<tr>
<td>2,000</td>
<td>1.54</td>
<td>0.01471</td>
<td>3.192</td>
</tr>
</tbody>
</table>

Absorption Coefficients (cm⁻¹)

<table>
<thead>
<tr>
<th>Temperature (°K)</th>
<th>( \lambda ) from 0.4 to 2.2 ( \mu )</th>
<th>( \lambda ) from 2.2 to 2.61 ( \mu )</th>
<th>( \lambda ) from 2.61 to 2.9 ( \mu )</th>
<th>( \lambda ) from 2.9 to 3.5 ( \mu )</th>
<th>( \lambda ) from 3.5 to 4.8 ( \mu )</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0.107</td>
<td>0.3</td>
<td>6.0</td>
<td>5.0</td>
<td>14.0</td>
</tr>
<tr>
<td>300</td>
<td>0.107</td>
<td>0.3</td>
<td>6.0</td>
<td>5.0</td>
<td>14.0</td>
</tr>
<tr>
<td>600</td>
<td>0.107</td>
<td>0.3</td>
<td>6.0</td>
<td>5.0</td>
<td>14.0</td>
</tr>
<tr>
<td>900</td>
<td>0.107</td>
<td>0.3</td>
<td>6.0</td>
<td>5.0</td>
<td>14.0</td>
</tr>
<tr>
<td>1,200</td>
<td>0.107</td>
<td>0.3</td>
<td>6.0</td>
<td>5.0</td>
<td>14.0</td>
</tr>
<tr>
<td>1,500</td>
<td>0.107</td>
<td>0.3</td>
<td>6.0</td>
<td>5.0</td>
<td>14.0</td>
</tr>
<tr>
<td>1,800</td>
<td>0.107</td>
<td>0.3</td>
<td>6.0</td>
<td>5.0</td>
<td>14.0</td>
</tr>
<tr>
<td>2,000</td>
<td>0.107</td>
<td>0.3</td>
<td>6.0</td>
<td>5.0</td>
<td>14.0</td>
</tr>
</tbody>
</table>

Dissipation at wavelength below 0.4 \( \mu \) is 0.907.
Dissipation at wavelength above 4.8 \( \mu \) is 0.915.
### Table C-IV

**Material - Borosilicate**

<table>
<thead>
<tr>
<th>Temperature (°C)</th>
<th>Refractive Index</th>
<th>Conductivity (watts/cm °K)</th>
<th>( \rho_0 ) (watt sec/cm² °K)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>1.47</td>
<td>0.00021</td>
<td>1.444</td>
</tr>
<tr>
<td>200</td>
<td>1.47</td>
<td>0.00021</td>
<td>1.448</td>
</tr>
<tr>
<td>400</td>
<td>1.47</td>
<td>0.000269</td>
<td>1.459</td>
</tr>
<tr>
<td>600</td>
<td>1.47</td>
<td>0.000481</td>
<td>2.427</td>
</tr>
<tr>
<td>800</td>
<td>1.47</td>
<td>0.00756</td>
<td>2.500</td>
</tr>
<tr>
<td>1,000</td>
<td>1.47</td>
<td>0.00427</td>
<td>3.024</td>
</tr>
<tr>
<td>1,200</td>
<td>1.47</td>
<td>0.00427</td>
<td>3.024</td>
</tr>
<tr>
<td>1,400</td>
<td>1.47</td>
<td>0.00427</td>
<td>3.024</td>
</tr>
<tr>
<td>1,700</td>
<td>1.47</td>
<td>0.00427</td>
<td>3.024</td>
</tr>
<tr>
<td>2,000</td>
<td>1.47</td>
<td>0.00427</td>
<td>3.024</td>
</tr>
</tbody>
</table>

**Absorption Coefficients (cm⁻¹)**

<table>
<thead>
<tr>
<th>Temperature (°C)</th>
<th>( \lambda ) from 0.4 to 2.2 µ</th>
<th>( \lambda ) from 2.2 to 2.61 µ</th>
<th>( \lambda ) from 2.61 to 3.5 µ</th>
<th>( \lambda ) from 3.5 to 4.8 µ</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0.03</td>
<td>0.03</td>
<td>5.0</td>
<td>4.0</td>
</tr>
<tr>
<td>300</td>
<td>0.05</td>
<td>0.03</td>
<td>5.0</td>
<td>4.0</td>
</tr>
<tr>
<td>600</td>
<td>0.05</td>
<td>0.03</td>
<td>5.0</td>
<td>4.0</td>
</tr>
<tr>
<td>900</td>
<td>0.05</td>
<td>0.03</td>
<td>5.0</td>
<td>4.0</td>
</tr>
<tr>
<td>1,200</td>
<td>0.05</td>
<td>0.03</td>
<td>5.0</td>
<td>4.0</td>
</tr>
<tr>
<td>1,500</td>
<td>0.05</td>
<td>0.03</td>
<td>5.0</td>
<td>4.0</td>
</tr>
<tr>
<td>1,800</td>
<td>0.05</td>
<td>0.03</td>
<td>5.0</td>
<td>4.0</td>
</tr>
<tr>
<td>2,000</td>
<td>0.05</td>
<td>0.03</td>
<td>5.0</td>
<td>4.0</td>
</tr>
</tbody>
</table>

Emissivity at wavelength below 0.4 µ is 0.925.
Emissivity at wavelength above 4.8 µ is 0.921.
TABLE C-V

MATERIAL - SODA LIME

<table>
<thead>
<tr>
<th>Temperature (°K)</th>
<th>Refractive Index</th>
<th>Conductivity (watts/cm °K)</th>
<th>( \rho_c ) (watt sec/cm² °K)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>1.51</td>
<td>0.0113</td>
<td>2.51</td>
</tr>
<tr>
<td>200</td>
<td>1.51</td>
<td>0.0113</td>
<td>2.51</td>
</tr>
<tr>
<td>400</td>
<td>1.51</td>
<td>0.0113</td>
<td>2.51</td>
</tr>
<tr>
<td>600</td>
<td>1.51</td>
<td>0.0138</td>
<td>2.51</td>
</tr>
<tr>
<td>800</td>
<td>1.51</td>
<td>0.0165</td>
<td>2.51</td>
</tr>
<tr>
<td>1,000</td>
<td>1.51</td>
<td>0.0188</td>
<td>2.51</td>
</tr>
<tr>
<td>1,200</td>
<td>1.51</td>
<td>0.0188</td>
<td>2.51</td>
</tr>
<tr>
<td>1,400</td>
<td>1.51</td>
<td>0.0188</td>
<td>2.51</td>
</tr>
<tr>
<td>1,700</td>
<td>1.51</td>
<td>0.0188</td>
<td>2.51</td>
</tr>
<tr>
<td>2,000</td>
<td>1.51</td>
<td>0.0188</td>
<td>2.51</td>
</tr>
</tbody>
</table>

Absorption Coefficients (cm⁻¹)

<table>
<thead>
<tr>
<th>Temperature (°K)</th>
<th>λ from 0.4 to 2.0 µm</th>
<th>λ from 2.2 to 2.61 µm</th>
<th>λ from 2.61 to 3.9 µm</th>
<th>λ from 3.9 to 4.8 µm</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0.4</td>
<td>0.48</td>
<td>1.8</td>
<td>4.5</td>
</tr>
<tr>
<td>300</td>
<td>0.4</td>
<td>0.48</td>
<td>1.8</td>
<td>4.5</td>
</tr>
<tr>
<td>600</td>
<td>0.4</td>
<td>0.48</td>
<td>1.8</td>
<td>4.5</td>
</tr>
<tr>
<td>900</td>
<td>0.4</td>
<td>0.46</td>
<td>1.8</td>
<td>4.5</td>
</tr>
<tr>
<td>1,200</td>
<td>0.4</td>
<td>0.48</td>
<td>1.8</td>
<td>4.5</td>
</tr>
<tr>
<td>1,500</td>
<td>0.4</td>
<td>0.48</td>
<td>1.8</td>
<td>4.5</td>
</tr>
<tr>
<td>1,800</td>
<td>0.4</td>
<td>0.48</td>
<td>1.8</td>
<td>4.5</td>
</tr>
<tr>
<td>2,000</td>
<td>0.4</td>
<td>0.48</td>
<td>1.8</td>
<td>4.5</td>
</tr>
</tbody>
</table>

Emissivity at wavelength below 0.4 µ is 0.21.
Emissivity at wavelength above 4.8 µ is 0.21.
APPENDIX D

CORRELATIONS USED TO PREDICT IN-FLIGHT HEATING
INTRODUCTION

Various methods of computing the heat transfer to the window are used by the program, depending on the mission under consideration. Missions for which the window heating can be computed by the program include hypersonic flight, re-entry, supersonic flight, or orbital flight. The analytical methods employed are based on accepted correlations for predicting aerodynamic (convective) heating, radiative heating from a shock layer, and radiative heating from the sun. These correlations as used by Lis, Barile, and Ingholm for the single glass window program of Reference 1 are also employed in the subject multiple glass program. A description of equations used has been reproduced from Reference 1 for this Appendix.

A convective heating rate versus time can also be included in the input data. This allows the convective heat flux computed by any desirable method to be used in the program. A constant radiative heating rate can be described by input data if so desired by inputting a heat source temperature and emittance and an appropriate configuration factor. This option was used when computing glaze temperatures for comparison to those measured in the experimental heat transfer tests.

HYPERSONIC FLIGHT AND RE-ENTRY

For hypersonic flight and re-entry, the convective input to the window is expressed as a percentage of the stagnation point heat transfer rate. The stagnation point convective heating is computed using the correlation of Kemp and Riddell (Ref. 8) as written below:

\[
\frac{q''}{\text{watts/cm}^2} = 11.88 \left( \frac{V}{1,000} \right)^{3.25} \left( 1 - \frac{H}{H_{\text{stag}}} \right) \]  

(1)

where

\( R_N \) = nose radius (ft.)
\( \rho \) = free stream density (lb/ft\(^3\))
\( V \) = free stream velocity (fps)
\( H \) = enthalpy

120

Approved for Public Release
The percentage or ratio of convective heat transfer rate at the window to that at the stagnation point is generally determined by heat flux data obtained during wind tunnel tests using a model of the actual vehicle being designed.

Above a critical altitude (defined by input data), the convective heating rate for hypersonic flight is based upon stagnation point heat transfer in free molecular flow and may be expressed as (Ref. 8):

\[ q = 2.271 \times 10^{-5} \rho V^5 \] (watt/cm²) \hspace{1cm} (2)

where the density, \( \rho \), is taken as free stream density (lb/ft³) and the velocity, \( V \), is taken as free stream velocity (10³ fps). The critical altitude above which free molecular flow is considered is based on

\[ \frac{M}{Re} > 10 \]

where \( M \) is the mach number and \( Re \) is the Reynolds number. In this flow regime, the air is highly rarefied and consequently intermolecular collisions are insignificant compared to molecule-surface collisions. The molecular mean free path is of the same order of magnitude or larger than the length of the aerospace vehicle (Ref. 17).

Radiative heating of the window during hypersonic flight and re-entry is considered to be from the hot air in a normal shock layer of a thickness equal to the stand-off distance at the stagnation point. For high speed flight, the shock layer thickness, \( \delta^* \), is satisfactorily approximated by

\[ \delta^* = \frac{224}{5(K-1)} \] (3)

where \( R_N \) is the nose radius and \( K \) is the ratio of normal shock to free stream density (Ref. 16).

Greybody emissivities for shock heated air per unit thickness at densities and temperatures behind the normal shock are obtained from curve fits of the data of Klvel and Bailey (Ref. 9). These curves have been fitted by a logarithmic polynomial expansion of the form:

121

Approved for Public Release
\[ \log \epsilon/\delta^* = a_0 + a_1 \log T + a_2 \log^2 T + a_3 \log^3 T + a_4 \log^4 T \] (4)

where

\[ \epsilon/\delta^* \text{ = graybody emissivity per unit thickness (cm}^{-1}) \]

\[ a_0 \ldots a_4 \text{ = constants determined from the polynomial fit} \]

\[ \log \text{ = logarithm to the base } 10 \]

\[ T \text{ = absolute temperature (°K)} \]

A least-squares analysis was used to determine the constants \( a_0 \ldots a_4 \). The resulting values for the constants are shown in Tables D-I and D-II. As may be noted, one set of constants is applicable in the range \( 1,000 \leq T < 6,000^\circ \text{K} \), and the second set of constants is applicable in the range \( 6,000 \leq T \leq 18,000^\circ \text{K} \). To determine intermediate values, double logarithmic interpolation is performed between temperature and density values on both sides of the values required.

**TABLE D-I**

<table>
<thead>
<tr>
<th>Density ratio ( \rho/\rho_0^* )</th>
<th>( a_0 )</th>
<th>( a_1 )</th>
<th>( a_2 )</th>
<th>( a_3 )</th>
<th>( a_4 )</th>
</tr>
</thead>
<tbody>
<tr>
<td>10^{-6}</td>
<td>-6.905507</td>
<td>2.8251600</td>
<td>-2.5958484</td>
<td>0.19645565</td>
<td>0.065059480</td>
</tr>
<tr>
<td>10^{-5}</td>
<td>-5.7398626</td>
<td>-2.4645677</td>
<td>-0.78953310</td>
<td>0.29189669</td>
<td>0.000000000</td>
</tr>
<tr>
<td>10^{-4}</td>
<td>-16.4635100</td>
<td>5.3745600</td>
<td>-1.9453232</td>
<td>0.28488560</td>
<td>0.000000000</td>
</tr>
<tr>
<td>10^{-3}</td>
<td>-64.2241000</td>
<td>34.8338386</td>
<td>-5.9048120</td>
<td>-1.1711284</td>
<td>0.22668464</td>
</tr>
<tr>
<td>10^{-2}</td>
<td>-212.259832</td>
<td>7.3045176</td>
<td>-1.3141515</td>
<td>0.14599265</td>
<td>0.000000000</td>
</tr>
<tr>
<td>10^{-1}</td>
<td>-75.6995100</td>
<td>45.790509</td>
<td>-5.1229970</td>
<td>-1.4009835</td>
<td>0.27386652</td>
</tr>
<tr>
<td>10^{0}</td>
<td>49.0920400</td>
<td>-42.0400200</td>
<td>7.1221200</td>
<td>1.1666320</td>
<td>-0.26156223</td>
</tr>
<tr>
<td>10^{1}</td>
<td>104.74206</td>
<td>-79.760151</td>
<td>11.775116</td>
<td>2.3571884</td>
<td>-0.48591030</td>
</tr>
</tbody>
</table>

\( \rho_0^* \text{ is air density at sea level.} \)

122

Approved for Public Release
<table>
<thead>
<tr>
<th>Density ratio $\rho/\rho_o$</th>
<th>$a_0$</th>
<th>$a_1$</th>
<th>$a_2$</th>
<th>$a_3$</th>
<th>$a_4$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$10^{-5}$</td>
<td>-42.023078</td>
<td>5.7775731</td>
<td>0.38428980</td>
<td>1.1454587</td>
<td>-0.23198627</td>
</tr>
<tr>
<td>$10^{-4}$</td>
<td>-56.036130</td>
<td>-4.0042870</td>
<td>2.6224850</td>
<td>2.0830205</td>
<td>-0.43582661</td>
</tr>
<tr>
<td>$10^{-3}$</td>
<td>-60.699710</td>
<td>-4.5744890</td>
<td>2.9574360</td>
<td>2.5487885</td>
<td>-0.48503387</td>
</tr>
<tr>
<td>$10^{-2}$</td>
<td>-87.550665</td>
<td>7.6861740</td>
<td>0.48121000</td>
<td>2.8453919</td>
<td>-0.56508439</td>
</tr>
<tr>
<td>$10^{-1}$</td>
<td>-58.483046</td>
<td>-5.1711910</td>
<td>1.5907300</td>
<td>1.4969915</td>
<td>-0.28368548</td>
</tr>
<tr>
<td>$10^{0}$</td>
<td>-11.1572062</td>
<td>-0.04727720</td>
<td>-0.25287500</td>
<td>0.32303528</td>
<td>-0.024935496</td>
</tr>
<tr>
<td>$10^{1}$</td>
<td>0.13892374</td>
<td>-1.3337925</td>
<td>-0.31732664</td>
<td>-0.05633168</td>
<td>0.063322102</td>
</tr>
<tr>
<td>$10^{2}$</td>
<td>4.7345840</td>
<td>-1.6747281</td>
<td>-0.14927570</td>
<td>-0.19923154</td>
<td>0.069056794</td>
</tr>
</tbody>
</table>

* $\rho_o$ is the density at sea level.

The effective emissivity, $\epsilon_g$, of the shock heated air is obtained by scaling the emissivity, $\epsilon$, according to the exponential (Ref. 26):

$$\epsilon_g = \frac{\epsilon_p}{H} = 1 - e^{-\epsilon}$$

(1)

where

- $\epsilon_g = \text{graybody hot gas emissivity}$
- $\epsilon_p = \text{radiative flux}$
- $\sigma = \text{Stefan Boltzmann's constant}$
- $T_H = \text{hot gas absolute temperature behind the normal shock}$
- $\epsilon = \text{emissivity defined by equations (5) and (4)}$. 

128

Approved for Public Release
Equation (5) yields an effective emissivity of the shock-heated air accurate to within 20% of the exact solution as presented in Reference 20. The basic assumptions leading to Eq. (5) are that the radiating layer is planar (normal shock) of thickness \( d \) which is divided into infinitesimal slabs having an absorptivity per unit thickness equal to their emissivity per unit thickness. The results given are then integrated over the width of the slab. Values of \( T_g \) and \( \epsilon_g \) are used in the element heat balance equations when determining the radiation absorbed by the elements during a hypersonic flight or re-entry.

**SUPERSONIC FLIGHT**

For supersonic flight, the aerodynamic heating is computed from the heat transfer correlations of a flat plate at zero angle of attack (Ref. 10). The correlations are based on free stream conditions and are written as:

\[
N_{St} = 0.016 \left( \frac{\rho}{\rho_{in}} \right)^{0.245}
\]

and

\[
h = 0.961 \left( \frac{\rho}{\rho_{in}} \right)^{0.24} \left( \frac{T_s}{T_a} \right)^{-0.34}
\]

where

- \( N_{St} \) = Stanton Number = \( \frac{h_l}{\rho_c \mu} \)
- \( N_{Re} \) = Reynolds Number = \( \frac{U L}{\nu} \)
- \( N_{Ma} \) = Mach number
- \( T_s \) & \( T_a \) = surface and ambient temperatures, respectively
- \( h \) & \( h_l \) = the local and incompressible heat transfer coefficients, respectively
\( \rho_a = \) free stream density
\( C_p = \) specific heat at constant free stream pressure
\( V = \) free stream velocity
\( L = \) distance from the leading edge
\( \nu = \) kinematic viscosity at free stream conditions

Once the local heat transfer coefficient is determined, the convective heat transfer rate is computed by (Ref. 10):

\[
q_{\text{conv}} = h(T_w - T_s) \tag{8}
\]

where

\[
T_w = T_a \left(1 + 0.178 \frac{\rho_w}{\rho_a} \right)
\]

\( T_w \) = (the adiabatic wall temperature for a turbulent boundary layer)

No radiative heating is used for the supersonic case because the gaseous radiation is considered negligible. Since the emissivity of air is relatively low, gaseous radiation does not become significant until extreme airflow temperatures are reached such as those in the shock layer of hypersonic flight and re-entry.

ORBITAL FLIGHT

The orbital heating conditions or thermal environment for the window is programmed specifically for a 200-nautical-mile circular orbit. Convective heating is based on the correlation for stagnation point heat transfer in free molecular flow, which is discussed above for hypersonic flight above the critical altitude. Based on this correlation, a constant convective heating rate of \( 7.408 \times 10^{-4} \text{ watt/cm}^2 \) is used for the 200-nautical-mile circular orbit.
The radiative heating from the sun is approximated by using a solar temperature of 6,000°K and an appropriate form factor. The form factor is evaluated as:

\[ F = \frac{\text{solar constant}}{\sigma T_{\text{sun}}} = 1.882 \times 10^{-6} \]  \hspace{1cm} (9)

where the solar constant is that above the earth's atmosphere (Ref. 21). Since the solar radiation is collimated and the computer program analysis assumes the external radiation to be diffuse, solar heating of a window is only approximated.
APPENDIX II

SUPERPOSITION TESTS
Introduction

The experimental procedures that were used to verify the computer program are based in part on the so-called superposition technique. The primary advantage of this "additive" approach is that it required experimental tests to be run for only the two sets of boundary conditions shown in Figure 8-1, all-air and all-vacuum, and eliminated the need for any of the other possible test combinations illustrated in Figure 8-2.

Superposition Terminology

Heat is transferred by three different mechanisms: conduction, convection, and radiation. The idea of superposition implies that the total heat transfer in a system can be determined by evaluating the heat transfer for each mode separately and then superimposing the results. This procedure is generally followed in a thermal analysis, but can equally be used in experimental work.

Experimental Analysis of Superposition

The superposition method, when used properly, has always been found to agree with observations. The method becomes particularly simple and convenient in a system in which heat is transferred by conduction and radiation when the conducting medium is air or some other transparent gas. In order to meet contractual obligations, experiments were performed to show that superposition for this case can be used with confidence.

Two plates were placed parallel to each other. The upper plate was heated to a uniform temperature while the lower plate was maintained at a substantially lower uniform temperature. The upper plate consisted of the flat radial resistance heater that was developed, calibrated, and employed in the previous MHI Research for the Air Force Flight Dynamics Laboratory under Contract No. AF 33(657)-9138. The lower plate was a water-cooled copper disk designed for use in both the superposition equipment and the current version of the transparent boundary apparatus. The copper plate was instrumented with Hy-Cal heat flux gauges.*

* A comparison of heat flux measurements taken with the Hy-Cal gauges with those previously taken under similar conditions with the precision water calorimeter developed by MHI indicated that the two types of instruments were in very close agreement for the applicable range of heat fluxes.

128

Approved for Public Release
Figure K-1 - Selected Boundary Conditions

Figure K-2 - Boundary Conditions That Can Be Eliminated By Application of Superposition Principle
The apparatus was first operated in an evacuated chamber and the rate of thermal radiation was measured. Air was then introduced into the system and the resulting thermal conduction between the plates was computed from the measured temperature differences between the plates, the gap size, and the known values of thermal conductivity of air. The thermal conduction thus calculated was subtracted from the total heat flux measured by the hy-Cal gauges and the difference, thermal radiation, was compared to the vacuum values. These tests and the subsequent conclusions are described in detail below.

The heater was first placed 9/16 in. above the copper plate. At this distance the radiation configuration factor was calculated by form factor algebra to be 0.880. The heater was then operated in a vacuum at temperatures ranging from 1500°F to 2500°F and values of impinging radiation were measured. The resulting data are plotted in Figure E-5 and based on the least mean square curve, the effective emissivity was computed to be 0.035. The heater was then similarly operated at a gap distance of 8 in. Using an effective emissivity of 0.035, the configuration factor, F, was computed from the data plotted in Figure E-4. The average value of F was calculated to be 0.151, which agrees very closely with the value determined by form factor algebra. The results of these calculations further substantiate the high accuracy of the commercial heat flux gauges which were essential not only in the superposition tests, but also in the subsequent Phases I, II, and III heat transfer tests.

Tests were next run at a 9/16 in. heater height with air present. Thus, thermal conduction was superpositioned onto the thermal radiation mechanism. Since, under these conditions, the Rayleigh Number is considerably below the critical value of 1700, no convection currents are set up. For this case, Figure E-5 illustrates the superposition method applied to heat transfer between two parallel plates. When air is present there are two transfer paths in parallel conduction and radiation. When the air is removed (vacuum conditions) heat can only be transferred by radiation.
Figure 8-3 - Superposition Test in Vacuum With $h = 9/16$ In.
Figure 8-4 - Superposition Test in Vacuum With $h = 0.0$ in.
The rate of heat conduction was determined from:

\[ q = \frac{k}{x} (T_H - T_C) \]

where \( k \) is the thermal conductivity of air taken at the mean gap temperature, \( x \) is the gap distance, and \( T_H \) and \( T_C \) are the heater and cold plate temperature, respectively. The differences between the measured total heat and the calculated conduction were then compared (see Figure 3-6) with radiation data based on the vacuum tests. It is apparent that throughout the entire range of temperatures, approximately 1000°F to 1800°F, the superposition of air had no measurable effect on the thermal radiation. In these tests the amount of thermal conduction was significant but was considerably less than the heat transfer by radiation; however, the relative magnitudes were selected so as to be similar to those that were actually encountered in the Phases I, II, and III heat transfer tests. That is, the heater was operated at temperatures which were of prime interest for glass, and the 9/16 in. gap was chosen as it is a representative window spacing.

**Conclusions**

The experimental tests proved conclusively that superposition is valid and is applicable to this particular project. As shown from the experimental
Figure E-6 - Superposition Tests
data, the difference between the total heat rate measured in air and the conduction rate calculated is equal to the radiation heat transfer through the space between two plates measured when a vacuum existed. In order to show that this agreement was independent of the rate of radiation as well as the ratio of radiation to conduction, the tests were run over a wide temperature range. In all cases, heat transfer by radiation alone could be accurately computed from the experimental data taken under conditions where radiation and conduction were occurring simultaneously. Thus, the results show that the presence or absence of a transparent medium such as air in the experimental setups which were employed in the current project is of no consequence and can be properly accounted for by straightforward and accepted heat transfer procedures.

Having shown this for one gap between two plates at various temperatures, it follows that in case there are more than two plates stacked parallel to each other as in Phase III, the absence or presence of air between any two surfaces will not introduce a new factor which could invalidate the superposition method of calculation. For example, if in the arrangement shown in Figure 6-7, tests were first conducted with air between glass surfaces 3 and 4 and then without air in this space, the only change in the heat transfer through the gap below would be due to a change in $T_g$ and the net rate of radiation. Since, as shown by the experiments, the effect on the rate of conduction due to a change in $T_g$ can be calculated, irrespective of the amount of thermal radiation, the presence or absence of air in any other gap will not cause any problems in determining the desired radiation heat transfer.
Figure E-7 - Phase III Test Setup
APPENDIX F

EXPERIMENTAL RESULTS
Data Symbols

○ Temperature of upper surface of outer glaze

△ Temperature of lower surface of outer glaze

● Temperature of upper surface of inner glaze

▲ Temperature of lower surface of inner glaze

□ Heat flux from and through the glazes to the calorimeter

Glaze Coating Symbols

KEA High efficiency anti-reflection coating

UV-IR Ultraviolet-infrared reflecting coating

Note: The KEA and UV-IR coatings are multiple-layer, thin-film coatings designed and applied to the glaze test specimens by the Optical Coating Laboratory, Inc. (OCLI). The gold coating employed in the test specimens was also applied by OCLI and consists of multiple layers of gold and dielectric materials.
SINGLE GLAZE HEAT TRANSFER TEST

TEST NUMBER: 1-1 (AIR)
HEAT SOURCE: CONVECTION
GLAZE: 1/8" FUSED SILICA - NO COATINGS

GLAZE SURFACE TEMPERATURE (°F)

HEAT FLUX TO CALORIMETER (1000 BTU/HR-FT²)
SINGLE GLAZE HEAT TRANSFER TEST

TEST NUMBER: 1-6 (AIR)
HEAT SOURCE: RADIATION
GLAZE: 1/4" FUSED SILICA - NO COATINGS
SINGLE GLAZE HEAT TRANSFER TEST

TEST NUMBER: 1-7 (AIR)
HEAT SOURCE: CONVECTION
GLAZE: 1/4" FUSED SILICA - NO COATINGS
TEST NUMBER: 11-11 (AIR)
HEAT SOURCE: RADIATION
GLAZE: 1/4" VYCOR - NO COATINGS

GLAZE SURFACE TEMPERATURE (°F)

RADIANT HEATER TEMPERATURE (°F)

HEAT FLUX TO CALORIMETER (1000 BTU/HR-FT²)
SINGLE GLAZE HEAT TRANSFER TEST

TEST NUMBER: 1-14 (AIR)
HEAT SOURCE: RADIATION
GLAZE: 1/4" ALUMINOSILICATE - NO COATINGS

GLAZE SURFACE TEMPERATURE (°F)

RADIANT HEATER TEMPERATURE (°F)

HEAT FLUX TO CALORIMETER (1000 Btu/hr-ft²)
SINGLE GLAZE HEAT TRANSFER TEST

TEST NUMBER: 1-15 (AIR)
HEAT SOURCE: CONVECTION
GLAZE: 1/4" ALUMINOSILICATE - NO COATINGS

![Graph showing the relationship between heat flux and glaze surface temperature.](image-url)
SINGLE GLAZE HEAT TRANSFER TEST

TEST NUMBER: 11-69 (AIR)
HEAT SOURCE: RADIATION
GLAZE: 1/4" FUSED SILICA
HEA COATING ON INCIDENT SURFACE

[Graph showing the relationship between glaze surface temperature and radiant heater temperature]
SINGLE GLAZE HEAT TRANSFER TEST

TEST NUMBER: 11-82 (AIR)
HEAT SOURCE: CONVECTION
GLAZE: 1/4" FUSED SILICA
HEA COATING ON BOTH SURFACES

GLOZE SURFACE TEMPERATURE (°F)

HEAT FLUX TO CALORIMETER (1000 Btu/hr-ft²)

1400
1200
1000
800
600
400
200
0
0 1 2 3 4 5 6 7 8 9 10

10000 Btu/hr-ft²
SINGLE GLAZE HEAT TRANSFER TEST

TEST NUMBER: II-77 (AIR)
HEAT SOURCE: CONVECTION
GLAZE: 1/4" FUSED SILICA
GOLD ON INCIDENT SURFACE
HEA ON EMERGENT SURFACE
SINGLE GLAZE HEAT TRANSFER TEST

TEST NUMBER: 11-55
HEAT SOURCE: RADIATION
GLAZE: 1/4" FUSED SILICA
UV-IR COATING ON EMERGENT SURFACE

![Graph showing glaze surface temperature vs. radiant heater temperature](image-url)
SINGLE GLAZE HEAT TRANSFER TEST

TEST NUMBER: 54
HEAT SOURCE: CONVECTION
GLAZE: 1/4" FUSED SILICA
UV-IRR ON EMERGENT SURFACE

GLAZE SURFACE TEMPERATURE (°F)

HEAT FLUX TO CALORIMETER (1000 BTU/HR-FT²)
MULTIPLE GLAZE HEAT TRANSFER TEST

TEST NUMBER: III-31 (AIR)
HEAT SOURCE: RADIATION
OUTER GLAZE: 1/4" FUSED SILICA - NO COATING
INNER GLAZE: 1/8" Vycor - NO COATING

![Graph showing heat transfer test results.](image-url)
MULTIPLE GLAZE HEAT TRANSFER TEST

TEST NUMBER: III-57 (AIR)
HEAT SOURCE: CONVECTION
OUTER GLAZE: 1/4" FUSED SILICA - NO COATING
INNER GLAZE: 1/8" VYCOR - NO COATING

GLAZE SURFACE TEMPERATURE (°F)

HEAT FLUX TO CALORIMETER (1000 BTU/HR-FT²)
MULTIPLE GLAZE HEAT TRANSFER TEST

TEST NUMBER: III-68 (AIR)
HEAT SOURCE: RADIATION & CONVECTION
OUTER GLAZE: 1/4" FUSED SILICA - UNCOATED
INNER GLAZE: 1/8" VYCOR - UNCOATED

GLAZE SURFACE TEMPERATURE (°F)

HEAT FLUX TO CALORIMETER (1000 BTU/Hr-FT²)
MULTIPLE GLAZE HEAT TRANSFER TEST

TEST NUMBER: III-90 VACUUM
HEAT SOURCE: RADIATION
OUTER GLAZE: 1/4" FUSED SILICA — NO COATING
INNER GLAZE: 1/8" VYCOR — NO COATING

---

GLAZE SURFACE TEMPERATURE (°F)

HEAT FLUX TO CALORIMETER (1000 BTU/HR-FT²)

RADIANT HEATER TEMPERATURE (°F)
MULTIPLE GLAZE HEAT TRANSFER TEST

TEST NUMBER: III-24 (AIR)
HEAT SOURCE: RADIATION
OUTER GLAZE: 1/4" FUSED SILICA - NO COATING
INNER GLAZE: 3/8" FUSED SILICA - NO COATING
MULTIPLE GLAZE HEAT TRANSFER TEST

TEST NUMBER: III-23 (AIR)
HEAT SOURCE: CONVECTION
OUTER GLAZE: 1/4" FUSED SILICA - NO COATING
INNER GLAZE: 3/8" FUSED SILICA - NO COATING

![Graph showing heat transfer characteristics of glaze surfaces.](image-url)
MULTIPLE GLAZE HEAT TRANSFER TEST

TEST NUMBER: III-22 (AIR)
HEAT SOURCE: RADIATION & CONVECTION
OUTER GLAZE: 1/4" FUSED SILICA - NO COATING
INNER GLAZE: 3/8" FUSED SILICA - NO COATING
MULTIPLE GLAZE HEAT TRANSFER TEST

TEST NUMBER: III-104 (VACUUM)
HEAT SOURCE: RADIATION
INNER GLAZED: 1/4" FUSED SILICA - NO COATING
INNER GLAZED: 3/8" FUSED SILICA - NO COATING
MULTIPLE GLAZE HEAT TRANSFER TEST

TEST NUMBER: 111-79 (AIR)
HEAT SOURCE: RADIATION
OUTER GLAZE: 1/4" FUSED SILICA - NO COATING
INNER GLAZE: 1/4" ALUM. - NO COATING
MULTIPLE GLAZE HEAT TRANSFER TEST

TEST NUMBER: III-20 (AIR)
HEAT SOURCE: CONVECTION
OUTER GLAZE: 1/4" FUSED SILICA - NO COATING
INNER GLAZE: 1/4" ALUMINOSILICATE - NO COATING
MULTIPLE GLAZE HEAT TRANSFER TEST

TEST NUMBER: III-21 (AIR)
HEAT SOURCE: RADIATION & CONVECTION
OUTER GLAZE: 1/4" FUSED SILICA - NO COATING
INNER GLAZE: 1/4" ALUMINOSILICATE - NO COATING

GLAZE SURFACE TEMPERATURE (°F)

HEAT FLUX TO CALORIMETER (1000 BTU/HR-FT²)
MULTIPLE GLAZE HEAT TRANSFER TEST

TEST NUMBER: III-105 (VACUUM)
HEAT SOURCE: RADIATION
OUTER GLAZE: 1/4" FUSED SILICA - NO COATING
INNER GLAZE: 1/4" ALUMINOSILICATE - NO COATING

GLAZE SURFACE TEMPERATURE (°F)

RADIANT HEATER TEMPERATURE (°F)

HEAT FLUX TO CALORIMETER (1000 BTU/HR-FT²)
MULTIPLE GLAZE HEAT TRANSFER TEST

TEST NUMBER: III-28 (AIR)
HEAT SOURCE: RADIATION
OUTER GLAZE: 3/8" FUSED SILICA - NO COATING
INNER GLAZE: 1/8" VYCOR - NO COATING

GLAZE SURFACE TEMPERATURE (°F)

HEAT FLUX TO CALORIMETER (1000 BTU/HR-FT²)

RADIANT HEATER TEMPERATURE (°F)
MULTIPLE GLAZE HEAT TRANSFER TEST

TEST NUMBER: III-27 (AIR)
HEAT SOURCE: RADIATION
OUTER GLAZE: 1/4" ALUMINOSILICATE - NO COATING
INNER GLAZE: 3/8" ALUMINOSILICATE - NO COATING

GLAZE SURFACE TEMPERATURE (°F)

RADIANT HEATER TEMPERATURE (°F)

HEAT FLUX TO CALORIETER (1000 BTU/HR-FT²)
MULTIPLE GLAZE HEAT TRANSFER TEST

TEST NUMBER: IH-1B (AIR)
HEAT SOURCE: RADIATION
OUTER GLAZE: 3/8" FUSED SILICA - NO COATING
INNER GLAZE: 1/4" ALUMINOSILICATE - NO COATING

![Graph showing heat transfer test results.](image_url)
MULTIPLE GLAZE HEAT TRANSFER TEST

TEST NUMBER: III-56 (AIR)
HEAT SOURCE: RADIATION
OUTER GLAZE: 1/4" FUSED SILICA - UNCOATED
INNER GLAZE: 2/8" ALUMINOSILICATE - UNCOATED

GLAZE SURFACE TEMPERATURE (°F)

RADIANT HEATER TEMPERATURE (°F)

HEAT FLUX TO CALORIMETER (1000 BTU/HR-FT²)
MULTIPLE GLAZE HEAT TRANSFER TEST

TEST NUMBER: III-37 (AIR)
HEAT SOURCE: RADIATION
OUTER GLAZE: 1/4" FUSED SILICA - UV-IR ON EMERGENT SURFACE
INNER GLAZE: 1/8" VYCOR - NO COATING

---

Legend

- Open Circles
- Closed Circles
- Open Squares
- Closed Squares

---

Graph: Relationship between Glaze Surface Temperature (°F) and Radiant Heater Temperature (°F)
MULTIPLE GLAZE HEAT TRANSFER TEST

TEST NUMBER: III-36 (AIR)
HEAT SOURCE: CONVECTION
OUTER GLAZE: 1/4" FUSED SILICA - UV+IR ON EMERGENT SURFACE
INNER GLAZE: 1/8" VYCOR - NO COATING

GLAZE SURFACE TEMPERATURE (°F)

HEAT FLUX TO CALORIMETER (100 BTU/HR-FT²)
MULTIPLE GLAZE HEAT TRANSFER TEST

TEST NUMBER: III-25 (AIR)
HEAT SOURCE: RADIATION & CONVECTION
OUTER GLAZE: 1/4" FUSED SILICA - UV-IR ON EMERGENT SURFACE
INNER GLAZE: 1/8" YCOR - NO COATING

GALZ SURFACE TEMPERATURE (°F)

HEAT FLUX TO CALORIMETER (100 BTU/HR-FT²)
MULTIPLE GLAZE HEAT TRANSFER TEST

TEST NUMBER: III-88 (VACUUM)
HEAT SOURCE: RADIATION
OUTER GLAZE: 1/4" FUSED SILICA - UV-IR EMERGENT SURFACE
INNER GLAZE: 1/8" VYCOR - NO COATING

Graph showing the relationship between radiant heater temperature (°F) and glaze surface temperature (°F) with different symbols representing various conditions.
MULTIPLE GLAZE HEAT TRANSFER TEST

TEST NUMBER: III-12 (AIR)
HEAT SOURCE: RADIATION
OUTER GLAZE: 1/4" FUSED SILICA - UV-IR ON EMERGENT SURFACE
INNER GLAZE: 1/8" VYCOR - HEA ON BOTH SURFACES
MULTIPLE GLAZE HEAT TRANSFER TEST

TEST NUMBER: III-9 (AIR)
HEAT SOURCE: CONVECTION
OUTER GLAZE: 1/4" FUSED SILICA - UV-IR ON EMERGENT SURFACE
INNER GLAZE: 1/8" VYCOR - HEA ON BOTH SURFACES

![Graph showing heat flux to calorimeter vs. glaze surface temperature.](image-url)
TEST NUMBER: III-10 (AIR)
HEAT SOURCE: RADIATION & CONVECTION
OUTER GLAZE: 1/4" FUSED SILICA - UV-IR ON EMERGENT SURFACE
INNER GLAZE: 1/8" Vycor - HEA ON BOTH SURFACES

MULTIPLE GLAZE HEAT TRANSFER TEST

GLAZE SURFACE TEMPERATURE (°F)

HEAT FLUX TO CALORIMETER (100 BTU/HR-FT²)
MULTIPLE GLAZE HEAT TRANSFER TEST

TEST NUMBER: 111-103 (VACUUM)
HEAT SOURCE: RADIATION
OUTER GLAZE: 1/4" VYCOR - UV-IR ON EMERGENT SURFACE
INNER GLAZE: 1/8" VYCOR - HEA ON BOTH SURFACES
MULTIPLE GLAZE HEAT TRANSFER TEST

TEST NUMBER: III-42 (AIR)
HEAT SOURCE: RADIATION
OUTER GLAZE: 1/4" FUSED SILICA - HEA ON BOTH SURFACES
INNER GLAZE: 1/8" VYCOR - HEA ON BOTH SURFACES
MULTIPLE GLAZE HEAT TRANSFER TEST

TEST NUMBER: III-8 (AIR)
HEAT SOURCE: RADIATION & CONVECTION
OUTER GLAZE: 1/4" FUSED SILICA - HEA ON BOTH SURFACES
INNER GLAZE: 1/8" VYCOR - HEA ON BOTH SURFACES

GLAZE SURFACE TEMPERATURE (°F)

HEAT FLUX TO CALORIMETER (100 BTU/HR-FT^2)
MULTIPLE GLAZE HEAT TRANSFER TEST

TEST NUMBER: III-B1 (AIR)
HEAT SOURCE: RADIATION
OUTER GLAZE: 1/4" YCOR - UV-IR ON EMERGENT SURFACE
INNER GLAZE: 1/4" YCOR - GOLD ON INCIDENT - HEA ON EMERGENT SURFACE
MULTIPLE GLAZE HEAT TRANSFER TEST

TEST NUMBER: III-74 (AIR)
HEAT SOURCE: CONVECTION
OUTER GLAZE: 1/4" VYCOR - UV-IR ON EMERGENT SURFACE
INNER GLAZE: 1/4" VYCOR - GOLD ON INC., - HEA ON EMERGENT

1200
1000
800
600
400
200
0

GLAZE SURFACE TEMPERATURE (°F)

1 2 3 4 5 6 7 8 9 10 11 12

HEAT FLUX TO CALORIMETER (100 BTU/HR-Ft²)
MULTIPLE GLAZE HEAT TRANSFER TEST

TEST NUMBER: III-76 (AIR)
HEAT SOURCE: RADIATION & CONVECTION
OUTER GLAZE: 1/4" VYCOR - UV-IR ON EMERGENT SURFACE
INNER GLAZE: 1/4" VYCOR - GOLD ON INCIDENT - HEA ON EMERGENT SURFACE

Heat Flux to Calorimeter (100 BTU/HR-FT²) vs. Glaze Surface Temperature (°F)
MULTIPLE GLAZE HEAT TRANSFER TEST

TEST NUMBER: 111-99 (VACUUM)
HEAT SOURCE: RADIATION

OUTER GLAZE: 1/4" VYCOR - UV-IR EMERGENT SURFACE
INNER GLAZE: 1/4" VYCOR - GOLD INCIDENT SURFACE - HEA ON EMERGENT SURFACE

![Graph showing heat transfer test results with various glaze materials and radiant heater temperatures.](image-url)
REFERENCES


169


Activities at Wright-Patterson AFB, Ohio 45433

AFDRL (FDR/Library)
AFDRL (FDP/Stinfo)
AFDRL (FUC)
AFDRL (FDGR/Capt. J. R. Fruner)
AFDRL (FDGR/R. R. Davis)
AFDRL (FDGR/Z. G. Roberts)
AFDRL (FDMS/C. J. Cosenza)
APAL (AVG)
FALAL (AVZ)
APML (MAG)
APML (MAAE/R. E. Wittman)
APML (MAAM)
APML (MMAE/S. Allinikov)
APML (MAN)
APML (MATT)
AFIT (Tech Library)
AMRL (MSEE) {2 cys}
AMRL (MST/C. A. Dempsey)
AMRL (MSB)
AKL (ARIL)

Activities at Wright-Patterson AFB, Ohio 45433

ASD (ASS)
ASD (ASMD)
ASD (ASEP)
ASD (ASLE)
ASD (ASLE-6)
ASD (ASM)
ASD (ASM)
ASD (ASNFS)
ASD (ASNNW)
ASD (ASNM)
ASD (ASNM) {2 cys}
ASD (ASNM)
ASD (ASNR) {2 cys}
ASD (AST)
ASD (ASRM)
ASD (ASRF)
ASD (ASRM)
AIR FORCE

Air University Library
Maxwell AF, Alabama 36112

RSRO/Lt. Col. W. R. Wadsworth
Norton AFB, California 92409

Headquarters, USAF (AFOSI)
Washington, D. C. 20330

APSC (SCAP)
Andrews AFB
Washington, D. C. 20331

USAF (9th SEC/Lt. Col. Loper)
Brooks AFB, Texas 78235

Headquarters, USAF (AFRED)
Washington, D. C. 20330 (2 yrs)

APSC (SCIN)
Andrews AFB
Washington, D. C. 20331

DG (SCB)
Bolling AFB, D. C. 20332 (2 yrs)

APSER
1400 Wilson Boulevard
Arlington, Virginia 22203

GAMA (Tech. Library)
AP Unit Post Office
Los Angeles, California 90045

GAMA (Tech. Library)
Kirtland AFB, California 99409

NAVY

Commander
Naval Air Systems Command
Headquarters (AIR-804)
Washington, D. C. 20360

Commander
Naval Air Systems Command
Headquarters (AIR-8502)
Washington, D. C. 20360

Commanding Officer
Naval Air Engineering Center
Philadelphia, Pennsylvania 19112

US Navy
Attn: Code PID-23
17th & Constitution Avenue
Washington, D. C. 20000

ARMY

Commanding Officer
US Army Transportation Res. Command
Fort Eustis, Virginia 23604

US Army RAD Lab
Attn: Tech. Document Unit
Fort Belvoir, Virginia 22060

US Army Research Office-Durham
Attn: Scientific Sythesis Office
Box CM, Duke Station
Durham, North Carolina 27706

OTHER US GOVERNMENT AGENCIES

DOD-TIAS
Cameron Station
Alexandria, Virginia 22314 (20 yrs)

NASA
Scientific and Tech. Info. Facility
P. O. Box 35
College Park, Maryland 20740 (2 yrs)
OTHER US GOVERNMENT AGENCIES (Concluded)

NASA
Attn: HW-2
Washington, D. C. 20546

NASA
Attn: RAL
Washington, D. C. 20546

NASA (Tech. Library)
Langley Research Center
Hampton, Virginia 23685

NASA
Manned Spacecraft Center
Attn: Tech. Library
Houston, Texas 77058

NASA (Materials Research)
1550 N Street, N.W.
Washington, D. C. 20005

NASA
Manned Spacecraft Center
Attn: Edward Cemini
Head, Heat Transfer Section
EF-58
Houston, Texas 77058

NASA
Manned Spacecraft Center
Attn: G. Screwhall
R. G. Brown
Thermo-Structures Branch
Houston, Texas 77059

National Bureau of Standards
US Department of Commerce
Attn: Library
Washington, D. C. 20202

NON-GOVERNMENT AGENCIES

Aerojet-General Corporation
Attn: Tech. Library
P. O. Box 298
Azusa, California 91703

Aerojet-General Corporation
Attn: Tech. Library
9100 East Plair Drive
El Monte, California 91734

Aeronca, Incorporated
Attn: Engineering Department Librarian
1712 Germantown Road
Middletown, Ohio 45042

Aerospace Corporation
Attn: Reports Acquisition
P. O. Box 96285
Los Angeles, California 90045

American Optical Company
Attn: Research Division
52 Mechanics Street
Southbridge, Massachusetts 01551

Arthur D. Little Company
Attn: David Richardson
Room 20-544
Acorn Park
Cambridge, Massachusetts 02140

AVCO Research and Advanced Development Laboratory
Attn: Tech. Library
Wilmington, Massachusetts 01887

AVCO Corporation
Attn: Tech. Library
P. O. Box 210
Nashville, Tennessee 37202
AVCO Corporation
Research and Advanced Development Division
Attn: M. E. Izmat
Lowell Industrial Park
Lowell, Massachusetts 01851

Barber-Colman Company
Attn: Don Schande
Electro-Mechanical Products Division
Rockford, Illinois 61100

Battelle Memorial Institute
DMC, Attn: Tech. Library
306 King Avenue
Columbus, Ohio 43201

Battelle Memorial Institute
DMC, Attn: J. F. Lynch
505 King Avenue
Columbus, Ohio 43201

Bausch and Lomb Incorporated
8405 St. Paul Street
Rochester, New York 14602

Beach Aircraft Corporation
Attn: Engineering Department Librarian
9709 East Central Avenue
Wichita, Kansas 67201

Bell Aerospace Corporation
Attn: Engineering Department Librarian
P. O. Box 1
Buffalo, New York 14240

Bendix Corporation
Bendix Systems Division
Ann Arbor, Michigan 48107

The Boeing Company
Wichita Division
Attn: Engineering Department Librarian
Wichita, Kansas 67201

The Boeing Company
Aerospace Group
Attn: Tech. Library
P. O. Box 3707
Seattle, Washington 98124

The Boeing Company
Airplane Division
Attn: Tech. Library
Benton, Washington 98025

The Boeing Company
Attn: G. L. Brower/Doct. 6-2000
Mail Stop 50-88
Renton, Washington 98025

The Boeing Company
Aerospace Group
Attn: John McIndoe
Jim Kelson
P. O. Box 3996
Seattle, Washington 98124 (cves)

The Boeing Company
Aerospace Group
Attn: Earl Wiedekamp
Box 3707, Mail 28-81
Seattle, Washington 98124

Cornell Aeronautical Laboratory, Inc.
Attn: Tech. Library
P. O. Box 233
Buffalo, New York 14221

Corning Glass Works
Attn: Dr. M. G. Britton
Manager, Tech. Liaison
Corning, New York 14832

Approved for Public Release
Non-Government Agencies (Continued)

Bendix Corporation
Attn: Tech. Library
592 Sagamore Road
Midland, Michigan 48640

Emerson and Cuming, Inc.
Attn: Robert Schaffer
669 Washington Street
Canton, Massachusetts 02021

Ingleside Industries, Inc.
Attn: J. B. Claudford, Jr.
3005 N. Dixie Drive
Dayton, Ohio 45414

Fairchild Hiller Corporation
Aircraft Division
Attn: Tech. Library
Hagerstown, Maryland 21740

Fairchild Hiller Corporation
Republic Aviation Division
Attn: Non-Metallics Section, Structures
Farmingdale, Long Island
New York 11735

Fairchild Hiller Corporation
Attn: Tech. Library
Fairchild Drive
Springtown, Maryland 20767

General American Trans Corporation
M&I Division
Attn: S. J. Lies
7501 N. Marshes Avenue
Miles, Illinois 60648

General Electric Company
Missile and Space Division
Re-Entry System Department
Attn: Tech. Library
2390 Chestnut Street
Philadelphia, Pennsylvania 19101

General Electric Company
Lamp Glass Department
24400 N. Highland Road
Richmond Heights, Ohio 44121

General Dynamics Corporation
Astronautics Division
Attn: Tech. Library
Mail Zone 560-60X
F. O. Box 1128
San Diego, California 92112

General Dynamics Corporation
Fort Worth Division
Attn: Tech. Library
F. O. Box 746
Fort Worth, Texas 76101

Goodyear Aerospace Corporation
Attn: Engineering Department
Librarian
1210 Massillon Road
Akron, Ohio 44315

Goodyear Aerospace Corporation
Attn: D. C. Culley
1210 Massillon Road
Akron, Ohio 44315

Grumman Aircraft Engineering Corporation
Attn: Tech. Library
Bethpage, Long Island
New York 11714

Kaman Corporation
11-13 Brookside Drive
Wilmington, Delaware 19806

Hughes Aircraft Company
Aerospace Group
Attn: Tech. Library
Centinela and Toal Streets
Culver City, California 90230

Approved for Public Release
NON-GOVERNMENT AGENCIES (Continued)

IIT Research Institute
Attn: W. J. Christian
10 West 35th Street
Chicago, Illinois 60616

Libby-Owens-Ford Glass Company
Attn: P. L. Elton
1701 East Broadway
Toledo, Ohio 43605

Libby-Owens-Ford Glass Company
Liberty Mirror Division
631 Third Avenue
Brackenridge, Pennsylvania 15014

Ring-Tempo-Vought, Incorporated
Attn: Engineering Department Librarian
P. O. Box 5207
Dallas, Texas 75222

Lockheed Aircraft Corporation
Missiles and Space Division
Attn: Engineering Department Librarian
P. O. Box 504
Sunnyvale, California 94088

Lockheed Aircraft Corporation
Marietta Georgia Division
Attn: Engineering Department Librarian
Marietta, Georgia 30061

Lockheed Missle and Space Company
Technical Information Center
3051 Hanover Street
Palo Alto, California 94304

Lockheed Aircraft Corporation
Attn: Frank Morris
Building 63
Department 74a SST - Box 591
Burbank, California 91503

Lockheed Aircraft Corporation
Attn: Engineering Department Librarian
2555 North Hollywood Way
Burbank, California 91503

Margarit Corporation
Attn: Tech. Library
16555 Statonry Street
Van Nuys, California 91409

The Martin Company
Attn: Tech. Library
Friendship International Airport
Maryland 21240

The Martin Company
Attn: J. H. Fleshier
Department 2560, Mail No. 5057
Friendship International Airport
Maryland 21240

McDonnell Douglas Corporation
McDonnell Douglas Astronautics Company
333 West First Street
Attn: N. E. Pierce
Dayton, Ohio 45402

McDonnell Douglas Corporation
McDonnell Douglas Astronautics Company
Space Systems Center
Attn: A5-159 Library
501 Bales Avenue
Huntington Beach, California 92646

McDonnell Douglas Corporation
Douglas Aircraft Company
Attn: H. F. Kleckner
2555 Lakewood Boulevard
Long Beach, California 90802

Approved for Public Release
NON-GOVERNMENT AGENCIES (Continued)

McDonnell Douglas Corporation
Douglas Aircraft Company
Attn: H. M. Kneuth
3605 Lakewood Boulevard
Long Beach, California 90801

McDonnell Douglas Corporation
Douglas Aircraft Company (M&SSD)
Attn: A-260 Library
3000 Ocean Park Boulevard
Santa Monica, California 90406

McDonnell Douglas Corporation
Douglas Aircraft Company (M&SSD)
Attn: E. S. Lowe/Dept. A-260
3000 Ocean Park Boulevard
Santa Monica, California 90406

McDonnell Douglas Corporation
Douglas Aircraft Company
Attn: Tech. Library
3635 Lakewood Boulevard
Long Beach, California 90801

McDonnell Douglas Corporation
McDonnell Company
Attn: Tech. Library
P. O. Box 516
St. Louis, Missouri 63166

Midwest Research Institute
Attn: Tech. Library
425 Volker Boulevard
Kansas City, Missouri 64110

Midwest Research Institute
Attn: Gary Korb
425 Volker Boulevard
Kansas City, Missouri 64110 (2 cys)

Naraco Research and Development
Attn: Tech. Library
3540 Aero Court
San Diego, California 92123

Northrop Corporation
Norair Division
Attn: Tech. Information
3920-21
1001 East Broadway
 Hawthorne, California 90250

North American-Beckwell Corporation
Columbus Division
Attn: Tech. Library
4300 East Fifth Street
Columbus, Ohio 43216

North American Aviation, Inc.
Los Angeles Division
Attn: Tech. Library
International Airport
Los Angeles, California 90009

North American Aviation, Inc.
Space and Information Systems Division
Attn: Tech. Information Center
15514 Lakewood Boulevard
Downey, California 90241

North American Aviation, Inc.
Attn: Donald Koch
Los Angeles International Airport
Los Angeles, California 90009

North American Aviation, Inc.
Attn: James Nixon
Los Angeles International Airport
Los Angeles, California 90009

North American Aviation, Inc.
Attn: H. H. Crooksley
Los Angeles International Airport
Los Angeles, California 90009

North American Aviation, Inc.
Attn: High Haroldson, Department 56
Los Angeles International Airport
Los Angeles, California 90009 (2 cys)

Approved for Public Release
Non-Government Agencies (Continued)

Optical Costing Laboratory, Inc.
Attn: Dennis Morelli
2709 Griffin Avenue
Santa Rosa, California 95401 (2 cvs)

Philco-Ford Corporation
Space and Re-Entry Systems Division
Attn: Tech. Library
Ford Road
Newport Beach, California 92663

Pittsburgh Plate Glass Company
Glass Research Center
Box 11472
Pittsburgh, Pennsylvania 15222

Pittsburgh Plate Glass Company
Attn: C. R. Prownfelter
D. W. Ludwig
J. J. Chess
One Gateway Center
Pittsburgh, Pennsylvania 15222 (3 cvs)

The Rand Corporation
Attn: Tech. Library
1700 Main Street
Santa Monica, California 90401

Ryan Aeronautical Company
Attn: Tech Library
2701 Harbor Drive
San Diego, California 92112

The Sierracin Corporation
Attn: M. G. Partridge
12798 San Fernando Road
San Fernando Valley
Hymar, California 91342 (2 cvs)

Southwest Research Institute
Attn: Engineering Department Librarian
8500 Culebra Road
San Antonio, Texas 78200

Swedlow, Incorporated
Attn: Ken Granger
Aircraft Products
6066 Bandini Boulevard
Los Angeles, California 90000

Swedlow, Incorporated
Attn: William Yamaguchi
12606 Beach Boulevard
Garden Grove, California 92641

University of Illinois
Attn: R. G. Hering
Department of Mechanical and Industrial Engineering
Urbana, Illinois 61801

Vitae
Research and Development
2626 Hanover Street
Palo Alto, California 94304

Approved for Public Release
The severe thermal environment of future hypervelocity aerospace vehicles will place rigorous demands on direct vision window systems. At the high temperatures encountered, heat will be transferred within window materials by both conduction and radiation. This report describes the development and experimental verification of a computer program for predicting the temperature distribution and heat transfer through coated and uncoated, single or multiple glass window systems. The heat balance equations in the computer program account for emission, attenuation, and absorption of radiant energy within the glass. Reflection and transmission of glass surfaces having multilayer, thin-film coatings are computed. Window temperatures and heat flux can be predicted for transient conditions of individual and/or combined convective and radiative heating. The computer program was experimentally verified with heat transfer tests in which specimens of various glas materials and thicknesses were used. Typical aerospace reflection and antireflection coatings were employed on one and/or both surfaces of the test specimens. The work was performed in three phases. In the first phase the research was applicable to single uncoated glasses. In the second phase the scope was expanded to include coated single glasses, and in the third phase coated and uncoated multiple glasses were investigated. Good agreement between the analytical and experimental results was obtained. The computer program is written in FORTRAN IV language and for the IBM 7094 digital computer. A program user's manual is available as a separate publication.
<table>
<thead>
<tr>
<th>KEY WORDS</th>
<th>LINK A</th>
<th></th>
<th>LINK B</th>
<th></th>
<th>LINK C</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Aerospace Windows</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Heat Transfer Analysis</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Computer Program Developed</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Experimental Verification</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Semi-transparent Materials</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>