GEORGIA INSTITUTE OF TECHNOLOGY
Engineering Experiment Station

PROJECT INITIATION

Date: 3/7/72

Project Title: Ceramic Systems for Missile Structural Applications

Project No.: A-1403

Project Director: Mr. J. N. Harris

Sponsor: Naval Ordnance Systems Command, Washington, D. C. 20350

Effective March 1, 1972 Estimated to run until: December 31, 1972

Type Agreement: Contract No. N00014-72-C-1472

Reports/Data Required: Quarterly Progress Reports

Paced-Silica Design Manual

Final Comprehensive Report

Sponsor Contact Persons: Technical Authority
(Person not named)

Naval Ordnance Systems Command
Code GM-035
Washington, D. C. 20350

Administrative Matters
Mr. R. J. Whitcomb (RJO)

NIM Resident Representative
Campus

NOTE: Follow-on project to A-1215.


Assigned to High Temperature Materials Division

COPIES TO:

☐ Project Director

☐ Director

☐ Associate Director

☐ Assistant Director(s)

☐ Division Chiefs

☐ Branch Head

☐ General Office Services

☐ Engineering Design Services

☐ Photographic Laboratory

☐ Research Security Officer

☐ Accounting

☐ Purchasing

☐ Report Section

☐ Library

☐ Rich Electronic Computer Center

☐ __________________________
GEORGIA INSTITUTE OF TECHNOLOGY
Engineering Experiment Station

PROJECT TERMINATION

Date: August 23, 1973

PROJECT TITLE: Ceramic Systems for Missile Structural Applications

PROJECT NO: A-1403

PROJECT DIRECTOR: Mr. J. N. Harris

SPONSOR: Naval Ordnance Systems Command; Washington, D. C.

TERMINATION EFFECTIVE: August 31, 1973 (approved Design Manual due.)

CHARGES SHOULD CLEAR ACCOUNTING BY: August 31, 1973

Contract Closeout Items Remaining: Distribute Approved Design Manual
Final Invoice & Closing Documents
Final Report of Inventions
Government Property Inventory & Cert.
 Classified Material Certificate

HIGH TEMPERATURE MATERIALS DIVISION

COPIES TO:
Project Director
Director
Associate Director
Assistant Directors
Division Chief
Branch Head
Accounting
Engineering Design Services

General Office Services
Photographic Laboratory
Purchasing
Report Section
Library
Security
Rich Electronic Computer Center
FUSED SILICA SLIP REQUIREMENTS
FOR SLIP CASTING RADOMES

Technical Report No. 1

June 1972

By

J. N. Harris
E. A. Welsh

Prepared Under Contract N00017-70-C-4438

For

Naval Ordnance Systems Command
Weapons Dynamics Division (Code ORD-035)
Department of the Navy

By

Engineering Experiment Station
Georgia Institute of Technology
Atlanta, Georgia 30332

"Approved for public release; distribution unlimited."
FUSED SILICA SLIP REQUIREMENTS
FOR SLIP CASTING RADOMES

Technical Report No. 1

June 1972

By

J. N. Harris
E. A. Welsh

Prepared Under Contract N00017-70-C-4438

For

Naval Ordnance Systems Command
Weapons Dynamics Division (Code ORD-035)
Department of the Navy

By

Engineering Experiment Station
Georgia Institute of Technology
Atlanta, Georgia 30332

"Approved for public release; distribution unlimited."
ABSTRACT

This report consists of a material specification for a fused silica casting slip. The rationale behind the requirements for this specification is given.
# TABLE OF CONTENTS

<table>
<thead>
<tr>
<th>Section</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>I. PURPOSE</td>
<td>1</td>
</tr>
<tr>
<td>II. INTRODUCTION</td>
<td>2</td>
</tr>
<tr>
<td>III. SLIP QUALIFICATION REQUIREMENTS</td>
<td>5</td>
</tr>
<tr>
<td>A. Particle Size and Distribution</td>
<td>5</td>
</tr>
<tr>
<td>B. Chemical Compositions</td>
<td>6</td>
</tr>
<tr>
<td>C. Crystalline Phases</td>
<td>7</td>
</tr>
<tr>
<td>D. Water Content</td>
<td>7</td>
</tr>
<tr>
<td>E. Appearance</td>
<td>8</td>
</tr>
<tr>
<td>F. Viscosity and pH</td>
<td>8</td>
</tr>
<tr>
<td>G. Cristobalite Content</td>
<td>8</td>
</tr>
<tr>
<td>APPENDIX</td>
<td>9</td>
</tr>
<tr>
<td>REFERENCE</td>
<td>16</td>
</tr>
</tbody>
</table>
I. PURPOSE

The purpose of Contract No. N00017-70-C-4438 is to perform research and development directed towards the development of techniques to fully exploit the potential of readily available ceramic systems for use as structural components in hypersonic missile applications.
II. INTRODUCTION

Prior to the production of slip-cast fused silica radomes a broad comprehensive specification for the fused silica slip raw material must be developed.

Slip casting is normally accomplished by placing a suspension of solid material in a liquid medium (slip), into a porous mold. The liquid is drawn outward through the porous mold leaving a moist cake of solids on the wall of the porous mold. Fused silica casting slips differ from most other ceramic slips in that mill additions other than water and the fused silica raw material are not required. The term fused silica raw material as used in this report refers to an amorphous form of silica prepared either by the fusion of quartz or to "synthetic silica" prepared by the pyrolysis of silicon tetrachloride to give an amorphous form of silica.

The starting material is charged into a ball mill with water and the proper grinding media and ground until the desired particle size distribution is reached. This type of grinding gives a log-normal particle size distribution and produces a well suspended casting slip that requires no other additives.

There are a number of parameters that may vary in the production of a fused silica slip. Among these are: purity of raw material, liquid vehicle, per cent solids, particle size distribution, mean particle size, pH, and viscosity. These parameters and their interaction determine the characteristics of the final fused silica slip.

In the past when fused silica slip has been needed for the fabrication of radome hardware the slip has been procured on an acceptance test basis 1/.
A limited number of tests were performed by the purchaser on a sample from the slip lot. These included tests for slip stability (settling rate, viscosity, and pH), devitrification rate, and flexural strength of sintered test specimens. Acceptable ranges of property values were based on past experience in producing satisfactory radome hardware.

The acceptance test procedure is satisfactory for laboratory operations or for the manufacture of a few prototypes, especially if the source of slip is located close to the using agency. However, it is readily apparent that this qualification technique would not be acceptable for production operations where many batches of slip raw material would be required, the manufacturer did not have the testing facilities and/or the slip supplier was located at a considerable distance from the manufacturer.

What is needed by the manufacturer is a rigid specification for the raw material which will assure, with proper processing techniques, satisfactory production of acceptable radome hardware. At the same time such a specification should place the minimum number of testing requirements on the supplier to assure that each lot of slip will perform satisfactorily in processing.

The writing of a broad comprehensive specification is complicated by the end use requirements. That is, certain qualities of fused silica slip would provide satisfactory hardware for radomes operating up to Mach 3 or 4 at low levels, however, for operation at Mach 5 and higher more stringent requirements would have to be placed on the slip. The competency of the manufacturer and his equipment also influence the selection of criteria for a fused silica slip raw material specification. A manufacturer who can exercise very close temperature control in processing the slip-cast fused silica
can make satisfactory radome hardware with lower grades of fused silica slip than can a manufacturer who cannot exercise close control of his kilns and other processing steps. Therefore, the specification presented here will only qualify the best (highest purity) grades of fused silica available at the current time.

The following section presents the rationale for specifying the criteria necessary to qualify a fused silica slip for radome hardware.
III. SLIP QUALIFICATION REQUIREMENTS

A. Particle Size and Distribution

Fused silica slips prepared by wet ball milling will have a log-normal particle size distribution. However, the slope of the distribution curve will be influenced by the milling conditions, (i.e., the mill feed distribution, the ball charge volume and distribution, the volume of water and the mill speed). Therefore, it becomes necessary to specify that the slip producer provide a particle size distribution curve with each lot of slip. In addition the producer must measure the residue retained on a 325 mesh screen. No more than 5 weight per cent of the slip should be coarser than 44 micrometers (μm) to prevent rapid settling of the solids from the suspension.

Murphy 1/ found that slips with mean particle sizes of 5 to 11 μm could be used to make satisfactory radome hardware in the laboratory under carefully controlled conditions. This range is too broad for normal production fabrication, however. Slips with mean particle size ranges near 5 μm form dense castings that work well for thin wall structures but become increasingly difficult to dry without cracking as thickness approaches 0.75-inch. For thicknesses greater than 0.75-inch it is almost impossible to dry fine ground slips without cracking of the cast piece. Slips with a mean particle size near 11 μm can be used to cast very thick sections with little or no drying problems, however, the cast piece has a high porosity and requires considerably longer sintering times to achieve the same final density as a slip with a mean particle size near 5 μm. Also the larger particle size slips settle more rapidly. This results in problems of wall thickness gradients and problems of stoppages in hoses and pipes containing slip. For walls of 1/4 to 1/2-inch
in thickness the aforementioned casting problems should be minimized with a slip having a mean particle size of 6-1/2 to 8 \( \mu m \).

B. Chemical Compositions

Analyses of two technical grade and six high purity fused silica slips are shown in Table I. Analyses were made by emission spectroscopy, with the exception of the alkalies, which were determined from flame photometry. From these results it can be seen that the term "high purity" when used to describe fused silica type is somewhat of a misnomer. The designation "low alkaline earth" would be more descriptive. Based on total alkali content, there is no clear cut line between high purity and technical grade materials. With respect to alkaline earth oxide content, the lesser of the technical grade values is 0.44 per cent, while the maximum for high purity is 0.033 per cent which suggests a limit in the vicinity of 0.035 per cent alkaline earth oxide content for high purity fused silica slips. Perhaps the best difference is the sum of alkalis, alkaline earths and iron oxides. In this case, the difference between maximum high purity and minimum technical grade contents is 0.021 with the high purity materials having less than 0.060 per cent impurity, excluding aluminum and titanium oxides, which in small amounts seem to have less effect on devitrification behavior. The fact that devitrification rates for the two materials vary so greatly indicate that the slight changes in impurities have major effects on devitrification rates, or that the difference is more subtle; for instance remnant crystalline nuclei in the technical grade material.

Therefore a fused silica slip with chemical analysis indicating 99.5 per cent \( \text{SiO}_2 \) with not more than 50 parts per million (ppm) total alkali metals
**TABLE I**

**SPECTROGRAPHIC ANALYSIS OF FUSED SILICA CASTING SLIPS**

<table>
<thead>
<tr>
<th></th>
<th>Technical Grade</th>
<th></th>
<th>High Purity</th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>T1</td>
<td>T2</td>
<td>HP1</td>
<td>HP2</td>
<td>HP3</td>
<td>HP4</td>
<td>HP5</td>
<td>HP6***</td>
</tr>
<tr>
<td>Al₂O₃</td>
<td>0.340</td>
<td>0.340</td>
<td>0.310</td>
<td>0.340</td>
<td>0.370</td>
<td>0.420</td>
<td>0.300</td>
<td>0.248</td>
</tr>
<tr>
<td>Na₂O</td>
<td>0.008</td>
<td>0.002</td>
<td>0.008</td>
<td>0.008</td>
<td>0.008</td>
<td>0.001</td>
<td>0.001</td>
<td>0.004</td>
</tr>
<tr>
<td>K₂O</td>
<td>0.001*</td>
<td>0.010</td>
<td>0.001*</td>
<td>0.001*</td>
<td>0.001*</td>
<td>0.001*</td>
<td>0.001*</td>
<td>0.003</td>
</tr>
<tr>
<td>Li₂O</td>
<td>0.001*</td>
<td>0.001*</td>
<td>0.001*</td>
<td>0.001*</td>
<td>0.001*</td>
<td>0.001*</td>
<td>0.001*</td>
<td>*</td>
</tr>
<tr>
<td>MgO</td>
<td>0.014</td>
<td>0.011</td>
<td>0.011</td>
<td>0.008</td>
<td>0.009</td>
<td>0.006</td>
<td>0.011</td>
<td>0.014</td>
</tr>
<tr>
<td>CaO</td>
<td>0.030</td>
<td>0.050</td>
<td>0.022</td>
<td>0.010</td>
<td>0.004</td>
<td>0.015</td>
<td>0.015</td>
<td>0.003</td>
</tr>
<tr>
<td>Fe₂O₃</td>
<td>0.027</td>
<td>0.050</td>
<td>0.017</td>
<td>0.027</td>
<td>0.021</td>
<td>0.008</td>
<td>0.010</td>
<td>0.001</td>
</tr>
<tr>
<td>TiO₂</td>
<td>0.013</td>
<td>0.020</td>
<td>0.001</td>
<td>0.003</td>
<td>0.003</td>
<td>0.003</td>
<td>0.005</td>
<td>0.001</td>
</tr>
</tbody>
</table>

*Not detected (number indicates limit of detection).

**SiO₂ by difference.**

***HP6 is laboratory batch - all others commercial slips.***

and not more than 300 ppm total alkaline earth oxide should be satisfactory for production of radome hardware.

**C. Crystalline Phases**

X-ray analysis should be used to determine if crystalline phases of silica are present in the slip. The presence of minute quantities of quartz, cristobalite or tridymite may serve as a nucleation point for the growth of cristobalite, thus causing a high rate of devitrification.

**D. Water Content**

The reasons for specifying a water content of not more than 18 per cent
by weight are as follows. Too much water creates an economic problem from the standpoint of weight and shipping. Satisfactory casting slips can be handled with as little as 17 per cent water, however, most slips are of the order of 17.5 weight per cent water. Slight variations in water content change the rate of casting and the porosity of the cast piece. A dilute slip is more difficult to handle because there is more liquid to get rid of in the casting and drying process.

E. Appearance

The requirement for freedom from particles of dark colored material is brought about by the problem of bulk impurities when care is not exercised in processing the raw material into slip. Such dark colored impurities are usually iron from the size reduction process which was not removed by careful magnetic screening prior to ball milling.

F. Viscosity and pH

The requirements for pH and viscosity have purposely been left out of the specifications. Both of these properties are dependent on the three requirements specified, namely, particle size, chemical composition, and water content. If these three items are controlled pH and viscosity will be in the range required for a satisfactory casting slip.

G. Cristobalite Content

With high purity slips cristobalite growth rate is not a problem. Processing time and temperature can vary widely without excessive cristobalite formation. There is no need for specifying cristobalite content as a requirement for raw material procurement. However, cristobalite content of the processed hardware should be specified as part of the acceptance test criteria.
APPENDIX I

MATERIAL SPECIFICATION

CASTING SLIP, FUSED SILICA

1. SCOPE This specification covers the requirements for fused silica casting slip for applications involving cast wall thickness in the range 0.25 - 1.50 inches.

2. APPLICABLE DOCUMENTS

2.1 The following documents of the issue in effect on date of initiation for bids or request for proposal, form a part of this specification to the extent specified herein:

SPECIFICATIONS

MILITARY

MIL-M-15176 Mica (Extender Pigment)

STANDARDS

MILITARY

MIL-STD-129 Marking for Shipment and Storage

2.2 Other Publications. The following documents form a part of this specification to the extent specified herein. Unless otherwise indicated, the issue in effect on the date of invitation for bids or request for proposal shall apply:
American Society for Testing and Materials

C92  Test for Sieve Analysis and Water Content of Refractory Materials
D422  Particle Size Analysis of Soils
E137  Evaluation of Mass Spectrometer for Use in Chemical Analysis
E311  Practice for Sampling and Sample Preparation Techniques in Spectrochemical Analysis

(Application for copies should be addressed to the American Society for Testing and Materials, 1916 Race Street, Philadelphia, Pennsylvania 19103.)

Official Classification Committee

Uniform Freight Carrier Classification Rules

(Application for copies should be addressed to the Official Classification Committee, 1 Park Avenue at 33rd Street, New York 16, N.Y.)

3. REQUIREMENTS

3.1 Qualification. The material furnished under this specification shall be a product which has been tested and has passed the qualification tests specified herein. Any changes in composition or methods of manufacture of a qualified product shall require requalification as a new product.

3.1.1 Manufacturing Process Procedure. When required by the procuring activity, a titled, numbered and dated manufacturing inspection document containing the detailed, in-sequence operations used in manufacturing and for control of manufacturing variables shall be submitted by the contractor to the Government and its procuring activity for approval before production parts are delivered. After approval, the manufacturing document shall form a part of
this specification and copies shall be made available by the contractor for use by authorized personnel from the Government and its procuring activity in the contractor's plant. The manufacturing document shall not be changed without the approval of the Government and its procuring activity.

3.2 Material

3.2.1 General. The material shall be supplied in the form of a viscous suspension of fused silica in water.

3.2.2 Particle Size

3.2.2.1 Particle Size Distribution. Particle size distribution shall be determined as specified in 4.5.1.1. The mean particle diameter, when measured on a weight basis, shall be in the range 6.5-8.0 microns.

3.2.2.2 Coarse Particles. Residue retained on a Standard No. 325 (44 micron) sieve shall not exceed five per cent when the material is tested as specified in 4.5.1.2.

3.2.3 Chemical Composition. The chemical composition of the material shall be as follows: the material shall contain a minimum of 99.5 weight per cent silica, a maximum 50 parts per million total alkali metals (sodium, lithium, potassium), and a maximum 300 parts per million total alkaline earth oxides (calcium and magnesium); all percentages to be calculated on a moisture free basis.

3.2.4 Residual Crystalline Phases. All silica material should be amorphous. There should be no detectable crystalline forms of silica present in the slip.
3.2.5 Water Content. The water content of the material shall not exceed 18.0 per cent by weight.

3.2.6 Appearance. Both the material, and hardware subsequently fabricated therefrom, shall be a uniform off-white color, and shall be free from particles of dark colored material.

4. QUALITY ASSURANCE PROVISIONS

4.1 Responsibility for Inspection. Unless otherwise specified in the contract or purchase order, the supplier is responsible for the performance of all inspection and test requirements as specified herein. Except as otherwise specified, the supplier may utilize his own facilities or any commercial laboratory acceptable to the Purchaser. The Purchaser reserves the right to perform any of the inspections set forth in the specification where such inspections are deemed necessary to assure supplies and services conform to prescribed requirements.

4.2 Qualification Testing. The qualification of a supplier's product shall consist of meeting all the requirements specified in Section 3 using tests outlined in Section 4.

4.2.1 Qualification Samples. Unless otherwise specified, for purposes of qualification, at least one pound test sample shall be provided from each of three different manufactured lots as specified in 4.3.3.

4.2.2 Qualification Test Report. The formulator of the material components shall provide a test report showing actual test data covering all tests required in Section 3.
4.3 **Acceptance Tests.** The acceptance tests required for each lot of material shall be all tests as outlined in Section 3.

4.3.1 **Acceptance Test Report.** For each lot the supplier shall furnish a report of the test results for those tests performed to verify conformance with the acceptance requirements of this specification.

4.3.2 **Representative Sample.** Material for acceptance testing shall be adequate -- both in quantity and location -- for characterizing the material tested and to verify that material tested is typical of the material submitted for acceptance.

4.3.3 **Lot.** A lot shall consist of that material manufactured from one batch of raw material under identical processing conditions and submitted for acceptance at one time.

4.4 **Visual Inspection.** The fused silica material shall be visually examined with normal or corrected normal vision to verify that the materials, marking, packaging and workmanship shall be as specified.

4.5 **Test Methods.** The test specimens shall be conditioned and tested in accordance with the following methods.

4.5.1 **Particle Size.**

4.5.1.1 **Particle Size Distribution.** Particle size distribution will be determined in accordance with ASTM D422 except that prior to sampling the material container shall be roll agitated for 15 hours to insure thorough dispersion of solid particles. Results will be in the form of a
plot of weight per cent less than indicated diameter versus log particle
diameter for particle sizes greater than 1 micron. Mean particle diameter
shall be determined graphically as the diameter corresponding to the 50 per
cent level.

4.5.1.2 Residue retained on Standard 325 mesh sieve shall be determined
in accordance with MIL-M-15176, except that prior to testing the test sample
shall be roll agitated for 15 hours to disperse solid particles and a 100 gm
sample shall be used in a 100 ml beaker.

4.5.2 Chemical Composition. Chemical composition shall be determined
by comparative mass spectrometer methods after establishment of comparative
standards in accordance with ASTM E137, or by spectrochemical analysis
techniques in accordance with ASTM E311.

4.5.3 Water Content. The water content of the material shall be
measured in accordance with ASTM C92.

5. PREPARATION FOR DELIVERY

5.1 Packaging. Unless otherwise specified by the procuring activity,
the fused silica slurry shall be packaged in a manner that will ensure the
chemical purity is maintained throughout all handling, transportation and
storage activities. Containers shall meet Uniform Freight Classification
Rules or the regulations of other common carriers as applicable to the mode
of transportation.

5.2 Marking. In addition to any special marking required in the contract
or order, marking for shipment shall be in accordance with MIL-STD-129.
Markings shall include, but shall not be limited to, the following information:

a. Manufacturer's name, and his product designation.
b. Type of material.
c. Lot or batch number of material.
d. Purchase order number.
e. Quantity.
f. Precautionary Label-Do Not Freeze
REFERENCE

### DISTRIBUTION LIST

<table>
<thead>
<tr>
<th>NAVY</th>
<th>No. of Copies</th>
</tr>
</thead>
</table>
| Commander, Naval Ordnance Systems Command  
Department of the Navy  
Washington, D. C. 20360  
Attn: Code ORD-0333  
Code ORD-035  
Code ORD-55212  
Code ORD-035A  
Code ORD-04721 | 1 |
| Commander  
Naval Air Systems Command (AIR-320B)  
Washington, D. C. 20360 | 1 |
| Commander  
Naval Weapons Center  
Attn: J. L. Lankford (Code 323)  
China Lake, California 93557 | 1 |
| U.S. Naval Ordnance Laboratory  
Attn: J. L. Lankford (Code 323)  
White Oak, Silver Spring, Maryland 20910 | 1 |
| Chief of Naval Research  
Department of the Navy  
Washington, D. C. 20360  
Attn: Code 461  
Code 439  
Code 470 | 1 |
| Naval Research Laboratory  
Attn: Dr. M. R. Achter (Code 6340)  
Washington, D. C. 20390 | 1 |
| Superintendent  
Naval Postgraduate School  
Attn: Code 2124  
Monterey, California 93940 | 1 |

### AIR FORCE

<table>
<thead>
<tr>
<th>No. of Copies</th>
</tr>
</thead>
<tbody>
<tr>
<td>AIR FORCE</td>
</tr>
</tbody>
</table>
| Office of Aerospace Research  
Attn: Major Richard H. Hartke (D656)  
1400 Wilson Boulevard  
Arlington, Virginia 22029 | 1 |
<table>
<thead>
<tr>
<th>AIR FORCE (Continued)</th>
<th>No. of Copies</th>
</tr>
</thead>
<tbody>
<tr>
<td>AF Materials Laboratory</td>
<td></td>
</tr>
<tr>
<td>Attn: MAAM (B. R. Emrich)</td>
<td></td>
</tr>
<tr>
<td>Wright-Patterson Air Force Base, Ohio 45433</td>
<td>1</td>
</tr>
<tr>
<td>AFML/LLM (W. G. Ramke)</td>
<td></td>
</tr>
<tr>
<td>Wright-Patterson Air Force Base, Ohio 45433</td>
<td>1</td>
</tr>
<tr>
<td>AFML/LNE (George Schmitt)</td>
<td></td>
</tr>
<tr>
<td>Wright-Patterson Air Force Base, Ohio 45433</td>
<td>1</td>
</tr>
<tr>
<td>AFAL/TEM-3 (Richard A. Ireland)</td>
<td></td>
</tr>
<tr>
<td>Wright-Patterson Air Force Base, Ohio 45433</td>
<td>1</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>ARMY</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Commanding General</td>
<td></td>
</tr>
<tr>
<td>U.S. Army Missile Command</td>
<td></td>
</tr>
<tr>
<td>Attn: AMCPM-MDEM (Glen B. Nicholas)</td>
<td></td>
</tr>
<tr>
<td>Redstone Arsenal, Alabama 35809</td>
<td>1</td>
</tr>
</tbody>
</table>

| Commanding General |              |
| U.S. Army Missile Command |              |
| Attn: AMSMI-RLM (Phil Ormsby) |              |
| Building 5400 |              |
| Redstone Arsenal, Alabama 35809 | 1 |

<table>
<thead>
<tr>
<th>OTHER AGENCIES</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>NASA Scientific and Technical Inf. Facility</td>
<td></td>
</tr>
<tr>
<td>Attn: Acquisitions Branch-Foreign Exchange</td>
<td></td>
</tr>
<tr>
<td>P. O. Box 33</td>
<td></td>
</tr>
<tr>
<td>College Park, Maryland 20740</td>
<td>2</td>
</tr>
</tbody>
</table>

| Commander, Defense Documentation Center |              |
| Cameron Station |              |
| Alexandria, Virginia 22314 |              |
| Via: Commander, Naval Ordnance Systems Command |              |
| Department of the Navy |              |
| Attn: Code ORD-0632 |              |
| Washington, D. C. 20360 | 14 |
INDUSTRY

Aerospace Corporation
Attn: Dr. Robert L. Hallse
1111 East Mill Street
San Bernardino, California 92408

Ford Motor Company
Product Development Group
Attn: (E. A. Fisher, Turbine Research Dept.)
20000 Rotunda Drive
Dearborn, Michigan 48121

Applied Physics Laboratory
The Johns Hopkins University
Attn: Mr. L. B. Weckesser
8621 Georgia Avenue
Silver Spring, Maryland 20910

Battelle Memorial Institute
Defense Metals Information Center
Attn: H. D. Moran
505 King Avenue
Columbus, Ohio 43201

Brunswick Corporation
Technical Products Division
Attn: Robert Copeland
325 Brunswick Lane
Marion, Virginia 24354

Ceramic Finishing Company
Attn: Dr. Dennis R. Platts
P. O. Box 498
State College, Pennsylvania 16801

Coors Porcelain Company
Attn: Mr. Derald Whiting
Drawer 312
Golden, Colorado 80401

Emerson and Cuming, Inc.
Attn: E. J. Luoma
869 Washington Street
Canton, Massachusetts 02021

General Dynamics/Pomona
Attn: R. A. Miller
Mail Zone 6-56
Pomona, California 91766
<table>
<thead>
<tr>
<th>Company</th>
<th>Address</th>
<th>1</th>
</tr>
</thead>
<tbody>
<tr>
<td>Glasrock Products, Inc.</td>
<td>Attn: Mr. C. A. Murphy, Rt. 1, McDaniel Station Road, Calhoun, Georgia 30701</td>
<td>1</td>
</tr>
<tr>
<td>Hughes Aircraft Company</td>
<td>Attn: L. E. Gates, M.S. H-164, Culver City, California 90230</td>
<td>1</td>
</tr>
<tr>
<td>Lockheed Missiles &amp; Space Company</td>
<td>Technical Information Center, 3251 Hanover Street, Palo Alto, California 94034</td>
<td>1</td>
</tr>
<tr>
<td>Lockheed Missiles &amp; Space Company</td>
<td>Attn: Robert M. Beasley, Sr., Staff Scientist, Dept. 52-30, Bldg. 103, P.O. Box 504, Sunnyvale, California 94088</td>
<td>1</td>
</tr>
<tr>
<td>Los Alamos Scientific Laboratory</td>
<td>CMB-6 Ceramics Section, Attn: S. D. Stoddard, Box 1663, Los Alamos, New Mexico 87544</td>
<td>1</td>
</tr>
<tr>
<td>Martin-Marietta Corporation</td>
<td>Attn: Hyman Leggett (Mail Point 275), P.O. Box 5837, Orlando, Florida 32805</td>
<td>1</td>
</tr>
<tr>
<td>McDonnell-Douglas Astronautics Co. - W-D</td>
<td>Attn: Dept. A-263, 3000 Ocean Park Boulevard, Santa Monica, California 90406</td>
<td>1</td>
</tr>
<tr>
<td>Monsanto Company</td>
<td>Attn: Dr. H. Teicher, 800 N. Lindbergh Boulevard, St. Louis, Missouri 63166</td>
<td>1</td>
</tr>
<tr>
<td>Raytheon Company</td>
<td>Missle Systems Division, VB1-3, Attn: R. O. Howe, Hartwell Road, Bedford, Massachusetts 01730</td>
<td>1</td>
</tr>
<tr>
<td>INDUSTRY (Concluded)</td>
<td>No. of Copies</td>
<td></td>
</tr>
<tr>
<td>----------------------</td>
<td>--------------</td>
<td></td>
</tr>
<tr>
<td>Thermo Materials Corporation</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>Attn: Dr. W. J. Corbett</td>
<td></td>
<td></td>
</tr>
<tr>
<td>P. O. Box 47237</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Atlanta, Georgia 30348</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Union Carbide Corporation</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>Materials Systems Division</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Attn: Technical Library</td>
<td></td>
<td></td>
</tr>
<tr>
<td>P. O. Box 24166</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Indianapolis, Indiana 46224</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Whittaker Corporation</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>Nuclear Metals Division</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Attn: Document Custodian</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Box 125</td>
<td></td>
<td></td>
</tr>
<tr>
<td>West Concord, Massachusetts 01781</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
FUSED SILICA SLIP REQUIREMENTS FOR SLIP CASTING RADOMES

Technical Report No. 1, June 1972

Joe N. Harris and Earle A. Welsh

REPORT DATE
June 1972

TOTAL NO. OF PAGES
16

OTHER REPORT NUMBERS (Any other numbers that may be assigned this report)
A-1246

This report consists of a material specification for a fused silica casting slip. The rationale behind the requirements for this specification is given.
<table>
<thead>
<tr>
<th>KEY WORDS</th>
<th>LINK A</th>
<th>LINK B</th>
<th>LINK C</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fused Silica</td>
<td>ROLE</td>
<td>ROLE</td>
<td>ROLE</td>
</tr>
<tr>
<td>Slip Casting</td>
<td>WT</td>
<td>WT</td>
<td>WT</td>
</tr>
<tr>
<td>Raw Materials</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
PROCESSING REQUIREMENTS FOR
SLIP-CAST FUSED SILICA RADOMES

Technical Report No. 2

June 1972

By

J. N. Harris
E. A. Welsh

Prepared Under Contract N00017-70-C-4438

For

Naval Ordnance Systems Command
Weapons Dynamics Division (Code ORD-035)
Department of the Navy

By

Engineering Experiment Station
Georgia Institute of Technology
Atlanta, Georgia  30332

"Approved for public release;
distribution unlimited."
PROCESSING REQUIREMENTS FOR SLIP-CAST FUSED SILICA RADOMES

Technical Report No. 2

June 1972

By

J. N. Harris
E. A. Welsh

Prepared Under Contract N00017-70-C-4438

For

Naval Ordnance Systems Command
Weapons Dynamics Division (Code ORD-035)
Department of the Navy

By

Engineering Experiment Station
Georgia Institute of Technology
Atlanta, Georgia 30332

"Approved for public release; distribution unlimited."
ABSTRACT

This report consists of a process specification for slip-cast fused silica radomes. The rationale behind the requirements for this specification is given.
# TABLE OF CONTENTS

<table>
<thead>
<tr>
<th>Section</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>I. PURPOSE</td>
<td>1</td>
</tr>
<tr>
<td>II. INTRODUCTION</td>
<td>2</td>
</tr>
<tr>
<td>III. PROCESS QUALIFICATION REQUIREMENTS</td>
<td>3</td>
</tr>
<tr>
<td>A. Mold Material</td>
<td>3</td>
</tr>
<tr>
<td>B. Mold Release Agents</td>
<td>3</td>
</tr>
<tr>
<td>C. Slip Storage and Handling</td>
<td>4</td>
</tr>
<tr>
<td>D. Slip Casting</td>
<td>4</td>
</tr>
<tr>
<td>E. Drying</td>
<td>6</td>
</tr>
<tr>
<td>F. Sintering</td>
<td>9</td>
</tr>
<tr>
<td>G. Thermal Gradients During Sintering</td>
<td>10</td>
</tr>
<tr>
<td>H. Machining of Slip-Cast Fused Silica</td>
<td>15</td>
</tr>
<tr>
<td>REFERENCES</td>
<td>18</td>
</tr>
<tr>
<td>APPENDIX I.</td>
<td>19</td>
</tr>
</tbody>
</table>

This report contains 25 pages.
# LIST OF ILLUSTRATIONS

<table>
<thead>
<tr>
<th>Illustration Description</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Cast Wall Thickness versus Time of Casting for Fused Silica.</td>
<td>7</td>
</tr>
<tr>
<td>2. Bulk Density versus Sintering Time for High-Purity and Technical Grade Fused Silica Slips Sintered at 2100°F, 2250°F, and 2400°F.</td>
<td>11</td>
</tr>
<tr>
<td>3. Elastic Modulus versus Density for High-Purity and Technical Grade Slip-Cast Fused Silica.</td>
<td>12</td>
</tr>
<tr>
<td>4. Modulus of Rupture versus Density for High-Purity Slip-Cast Fused Silica.</td>
<td>13</td>
</tr>
<tr>
<td>5. Dielectric Constant of Slip-Cast Fused Silica versus Density Measured at X-Band.</td>
<td>14</td>
</tr>
<tr>
<td>6. Hold Time at 2000°F Necessary to Raise Backside Temperature to 1990°F, as a Function of Wall Thickness.</td>
<td>16</td>
</tr>
<tr>
<td>7. Heating Rate Necessary to Maintain 20°F Gradient Across Radome Wall on Heating from 2000°F to 2200°F.</td>
<td>17</td>
</tr>
</tbody>
</table>
I. PURPOSE

The purpose of Contract No. N00017-70-C-4438 is to perform research and development directed towards the development of techniques to fully exploit the potential of readily available ceramic systems for use as structural components in hypersonic missile applications.

Parts II and III of this report provide the rationale leading to the "Processing Specification for Slip-Cast Fused Silica Hardware" of Appendix I.
II. INTRODUCTION

The definition of a processing specification is more difficult than that for the raw materials. Sintering time-temperature is dependent on the starting material (i.e., synthetic fused silica or fused quartz). Different results are usually obtained in sintering slip-cast fused silica in gas fired and electrically heated kilns even though the same time-temperature firing schedule is followed. It is generally assumed that normally there is more moisture in the kiln atmosphere of a gas fired kiln than there is in an electrically fired kiln. If this is the case this could account for the difference in sintering rate. Less significant variations have even been seen between firings in different electrically heated kilns for the same time-temperature sintering conditions. Differences in moisture in the firing atmosphere, placement of the hardware to be fired in relation to the heating elements and placement of controlling thermocouples, within the kiln can be causes for variations in firing conditions between two kilns. Therefore, each manufacturer must establish a particular time-temperature sintering condition to produce the desired density and mechanical properties ahead of time. Guidelines are given in this report based on several years of experience at the Georgia Institute of Technology using several different kilns.

A processing specification can only place broad requirements on such items as mold materials, storage and handling of the fused silica slip, handling and proper drying of the freshly cast ware, and sintering to the final desired properties. These requirements, and the rationale behind their inclusion in a fused silica hardware processing specification are discussed in the following section.
III. PROCESS QUALIFICATION REQUIREMENTS

A. Mold Material

Fleming 1/ has reported that different plasters produce varying degrees of surface devitrification in slip-cast fused silica. However, he notes that these differences in surface devitrification seemed to have no effect on bulk devitrification or sintering behavior. For this reason, any commercially available pottery plaster should be suitable for use.

Inert materials such as porous ceramics and resin bonded grain have shown promise in high volume production areas such as sanitary ware and dinnerware production 2,3/. They are suitable for use in radome production, but introduce additional design problems, such as mold shrinkage during cure or sintering. Their use can only be recommended in cases where the longer mold life is sufficient to offset the greatly increased mold manufacturing cost.

B. Mold Release Agents

A mold release agent is a thin film between the mold and the fused silica casting. This film aids in removing the cast piece from the porous mold. Three mold release agents have been used at Georgia Tech, namely graphite, ammonium alginate, and sodium alginate. No reductions in strength have been observed with either but it is felt that the sodium alginate should be avoided since alkalies increase devitrification rates greatly 1/. As a general rule mold release agents should be avoided since they tend to produce uneven, rough surfaces. When used they should be held to as small a thickness as possible.
C. Slip Storage and Handling

Fused silica casting slip should be stored in polyethylene or similar polymeric containers, or in polyethylene lined metal drums. The slip should not be in contact with any metal. Containers should be continuously rolled or otherwise agitated to prevent settling. Slip should not be allowed to freeze since this apparently precipitates silicic acid from the slip, and prevents casting of a dense body. The slip generally contains a small portion of -4 +10 mesh material which is slightly smaller than the interstices in the grinding media bed. This material should be screened, usually to -40 mesh, at the time the plaster mold is filled. Slips should be used as soon as possible after milling. No aging problems have been noted with commercially available technical grade and high purity casting slips, but one manufacturer producing slip for in-house use has reported that the slip tends to gel after 3 to 4 weeks.

D. Slip Casting

Molds for slip-casting are usually prepared from pottery plaster using procedures recommended by the manufacturer. A plaster/water mix of 50/40 has been found best for slip-casting silica. For pressure casting, the walls of the plaster mold should be thick enough to withstand the internal pressure. For casting large shapes (up to 50-inch long radomes), a 3-inch plaster wall thickness has been satisfactory for pressures up to 20 psi. The outer contour of the mold should conform as closely as possible to the inner or casting surface. For example, an ogive radome could be cast in a conical mold or even a mold with its outer surface formed by portions of two cones.
The uniform wall thickness aids in obtaining a uniform wall thickness in the casting. In slip-casting, an aqueous suspension of finely ground particles (casting slip) is poured into a porous mold which defines the shape of the object to be produced. Capillary action draws water from the slip into the porous mold, increasing the solids content of the slip adjacent to the plaster, forming a solid wall. The water eventually evaporates from the mold. The thickness of the wall increases with the time the slip is left in the mold. When sufficient thickness has built up, the excess slip is drained out by vacuum or gravity leaving a dense but somewhat leathery shape in the mold.

The rate of wall build-up follows the parabolic filtration equation. The expression

$$W = 0.048 \sqrt{\theta} - 2.7 - 0.0207$$  \hspace{1cm} (1)$$

where $W =$ wall thickness in inches

$\theta =$ casting time in minutes

has proved satisfactory for estimating casting times at atmospheric pressure. Long casting times should be avoided due to problems such as settling of the slip in the mold. As an alternative, the slip may be pressurized and casting times drastically reduced. In this case the expression

$$W = 0.012 \sqrt{\theta P} - 0.047$$  \hspace{1cm} (2)$$

where $P =$ gage pressure - psi

may be used to estimate casting times. Figure 1 shows data for both expressions graphically. In either case, casting at atmospheric or at
increased pressure, the time for a given wall thickness may be estimated from a trial casting by the relationship

\[ \frac{W_1^2}{W_2^2} = \frac{\Theta_1}{\Theta_2} \]  

(3)

where \( W_1 \) = wall thickness at time \( \Theta_1 \)  
\( W_2 \) = wall thickness at time \( \Theta_2 \).

In this way casting times necessary to produce a given wall thickness may be readily determined. These curves are generally accurate to within ± 10 percent for slips with 7 micrometer (\( \mu m \)) mean particle diameters. Coarser slips will cast more rapidly while finer grinds will cast more slowly.

Since the coarse fractions of most fused silica slips settle to some extent, it is advisable to use pressure casting to hold casting times to a reasonable value, (i.e., 6 hours). From Equation (2), it can be seen that a wall of 0.97 inches roughly C-band can be reached in 6 hours at 20 psi pressure. X-band and higher frequency radomes could be cast in correspondingly shorter times.

E. Drying

Drying is a critical portion of the fabrication process, particularly for large shapes. At the end of casting, the pore spaces in the cast part are filled with water, and a thin film of water surrounds each particle. Since the particles are not in direct contact, but are cushioned by a water layer, the cast part has very little strength and will slump slightly if removed from the mold. At this point castings from slips with 7-8 \( \mu m \) mean particle
Figure 1. Cast Wall Thickness versus Time of Casting for Fused Silica.
diameter silica slips indicate drying shrinkages in the range from 0.05 to 0.1 per cent. Since these measurements were referenced to model size, rather than actual mold size, the linear drying shrinkage is more probably in the range from 0.2 to 0.4 per cent, assuming that the plaster mold is approximately 0.2 per cent oversize as a result of expansion on settling. This small shrinkage corresponds to a small moisture reduction on the order of 0.5 to 0.7 per cent. At this point, and certainly by the time 1.0 per cent moisture has been removed from the cast part, the part may be safely removed from the mold. It should be noted that since there is no convenient method of measuring the moisture content of the part in the mold, the simplest method of determining when the part may be safely removed from the mold is to measure the inside or outside diameter of the part from time to time. When shrinkage ceases, the part may be removed safely.

The two most important points in drying large slip-cast fused silica shapes are then,

(1) Drying should be carried out in the mold until the moisture content drops below the critical point (from 0.5 to 1 per cent loss).

(2) Drying rate during this time should be slow enough that moisture gradients across the cast wall are not large enough to cause cracking from differential shrinkage. These conditions are difficult to estimate or define from existing data and must be determined by trial and error for the particular part and mold configuration used. (Drying rate is also restricted by mean particle diameter. More finely ground slips will form cast parts with smaller and therefore less permeable pores.)
After the critical moisture content is reached, the part may be removed from the mold and dried more rapidly. Small shapes have been successfully dried at 350°F, but for most shapes it is recommended that drying temperatures be kept below 125°F. After the moisture content has been reduced to 1 or 2 per cent, the part should be dried to at least 250°F, and preferably 350°F for a minimum of 4 hours before sintering.

F. Sintering

Sintering is the most important single aspect of processing slip-cast fused silica hardware. The temperature and duration of sintering, along with the purity and particle size of the slip determine the physical properties of the finished item. During sintering particles tend to consolidate resulting in an increase in strength and bulk density. With increasing time the sintering rate slows until an end point density, directly proportional to sintering temperature is reached. At the same time, the vitreous silica is devitrifying to form cristobalite, which due to a phase change, causes a loss of strength when cooled to room temperature. At some point in sintering, the strengthening effect of sintering is balanced by the weakening effect of cristobalite growth and property values begin to fall.

Due to differences in particle size in slips, and sintering characteristics in furnaces, and properties required for finished hardware items, it is difficult to specify an optimum time and temperature for sintering. Therefore, sintering times and temperatures must be established by trial and error. Since this specification is concerned with hardware which is intended primarily for EM window or radome applications, the dielectric constant of
the sintered product must be maintained within specified limits. For a
given purity of fused silica the dielectric constant is dependent entirely
on density. Therefore, density seems to be a reasonable property choice
for establishing sintering schedules. Figure 2 shows bulk density as a function
of time and temperature for a typical fused silica slip of the type specified
for radome production.

Test firings should be made on either full size shapes or similar shapes.
For instance a radome may be approximated by a closed end cylinder. Although
the maximum bulk density increases with temperature, within limits, properties
such as Young's modulus and modulus of rupture, and dielectric constant are
density dependent, as shown in Figures 3, 4, and 5, while others such as
thermal expansion and specific heat are independent of density.

G. Thermal Gradients During Sintering

Boland 7/ has established guidelines for establishment of heating rates
for slip-cast fused silica hardware. In this he establishes 20° F as the
maximum temperature gradient tolerable in a cast part. From his sample
problems, one can easily calculate both the soak time at 2000° F necessary
to bring the backside temperature of a radome from room temperature to
1900° F, and the maximum permissible heating rates from 2000° F to the
vicinity of 2200° F, which will allow no more than a 20° F lag in backside
temperature. Plots of these functions with respect to wall thickness are
shown in Figures 6 and 7. From these it is seen that the soak time at
2000° F is short enough to be ignored for wall thickness under 0.25-inch.
Similarly, on heating to final temperature, the heating time becomes low
enough for thick walled radomes, that a compromise maximum rate of 700° F
Figure 2. Bulk Density versus Sintering Time for High-Purity and Technical Grade Fused Silica Slips Sintered at 2100°F, 2250°F, and 2400°F. (Reference 4, page 18.)
Figure 3. Elastic Modulus versus Density for High-Purity and Technical Grade Slip-Cast Fused Silica. (Reference 5.)
Figure 4. Modulus of Rupture versus Density for High-Purity Slip-Cast Fused Silica. (Reference 5)
Figure 5. Dielectric Constant of Slip-Cast Fused Silica versus Density Measured at X-Band. (Reference 6.)
per hour must be used to prevent excessive sintering and devitrification of the outside surface of the wall.

H. Machining of Slip-Cast Fused Silica

Although slip-cast fused silica parts can be precision cast to tolerances of the order of ± 0.005-inch, some degree of finish machining is often required. Diamond grinding with low (1000-2000 surface feet per minute, sfm) wheel speeds and low material feed rates has proven a satisfactory method of finish machining. Some manufacturers report satisfactory results with dense silicon carbide wheels. Machining should be carried out in such a manner as to prevent contamination of the part. For this reason distilled water is the preferred coolant. In addition, tooling fixtures which come in contact with the silica should be made from non-ferrous materials. Feed rates are limited by the thickness of the part, since comparatively low grinding pressure can cause tensile failure at the back side of the part. Conical shapes with 0.076-inch walls have been successfully machined, but it is felt that this approaches a lower limit on wall thickness. After machining, parts should be dried, and if size permits, leached with dilute (3:1) aqua regia to remove all traces of grinding wheel debris. Drying followed by heating to 1000°F is usually sufficient to remove most organic contaminants such as grease.

NOTE: The above discussion has been directed expressly towards the requirements of the specification attached as Appendix I. For a more comprehensive treatment of slip-cast fused silica radome fabrication techniques and properties the reader is referred to Reference 5.
Figure 6. Hold Time at 2000°F Necessary to Raise Backside Temperature to 1990°F, as a Function of Wall Thickness.
Figure 7. Heating Rate Necessary to Maintain 20° F Gradient Across Radome Wall on Heating from 2000° to 2200° F.
REFERENCES


APPENDIX I

PROCESS SPECIFICATION

Hardware, Slip-Cast Fused Silica

1. SCOPE: This specification covers requirements and guidelines for fabrication of finished hardware from fused silica casting slip.

2. APPLICABLE DOCUMENTS

2.1 The following documents of the issue in effect on date of initiation for bids or request for proposal, form a part of this specification to the extent specified herein:

SPECIFICATIONS

1. "Fused Silica Slip Requirements for Slip Casting Radomes."
2. "Acceptance Criteria for Slip-Cast Fused Silica Radomes."

3. REQUIREMENTS

3.1 Qualification the material processed in accordance with this specification shall be a product which has been tested and has passed the qualification tests specified herein. Any changes in composition or methods of manufacture of a qualified product shall require requalification as a new product.

3.1.1 Manufacturing Process Procedure. When required by the procuring activity, a titled, numbered, and dated manufacturing inspection document containing the detailed, in sequence operations used in manufacture and control of manufacturing variables, as
specified herein, shall be submitted by the contractor to the Government and its procuring activity for approval before production parts are delivered. After approval, the manufacturing document shall become a part of this specification and copies shall be made available by the contractor for use by authorized personnel from the Government and its procuring activity in the contractor's plant. The manufacturing document shall not be changed without the approval of the Government and its procuring activity.

3.2 Material

3.2.1 Starting Material the starting material for products processed under this specification shall be fused silica casting slip meeting the requirements of "Fused Silica Slip Requirements for Slip Casting Radomes" and "Acceptance Criteria for Slip-Cast Fused Silica Radomes."

3.2.2 Finished Product Finished products processed under this specification shall further satisfy the requirements of the applicable Materials Test Specification.

3.3 Processing

3.3.1 General Processing as specified herein is oriented toward reducing or eliminating contamination of the material with impurities which will contribute to excessive devitrification in further processing or in end use.
3.3.2 Slip Casting

3.3.2.1 Mold Material Plaster of paris shall be an acceptable mold material. Other porous permeable materials such as resin bonded inorganic grain or sintered ceramics shall be acceptable provided products capable of meeting the requirements of "Acceptance Criteria for Slip-Cast Fused Silica Radomes" can be produced.

3.3.2.2 Mold Release Agents Where mold release problems are present, milled graphite slurry or ammonium alginate may be used as mold release agents. Other materials may be used provided that it is demonstrated by comparison of flexural strength of not less than ten test specimens cast with and without mold release agent, that such agent has no significant effect on flexural strength. Flexural specimens shall be in the form of 1/2 x 1 x 5 inch bars broken in quarter point loading, 4-inch span.

3.3.2.3 Casting Slip Storage and Preparation Casting slip will be stored at temperatures above freezing and will be discarded if frozen. The casting slip will be roll agitated for 48 hours prior to use. The slip will be screened to -20 mesh prior to pouring in the mold or slip reservoir.
3.3.2.4 Pressure Assisted Casting  Where wall thickness of the cast part is such that it cannot be drain cast within 6 hours, pressure assistance shall be used. Pressure assisted casting shall be acceptable for any cast wall thickness.

3.3.3 Drying  Freshly cast parts, particularly large radome shapes shall be dried slowly in the mold until drying shrinkage is complete. At this point the part may be removed and dried in a conventional manner. Cracking of a part in the mold or after removal shall be considered evidence of too rapid drying and insufficient drying in the mold respectively, and will require adjustment of the drying schedule.

3.3.4 Sintering

3.3.4.1 General  Sintering will be carried out in such a way as to reach bulk density and strength requirements as required by the applicable acceptance test specification, and in such a way as to minimize thermal gradients within the cast shape.

3.3.4.2 Kiln Requirements  Any type of kiln is satisfactory provided temperature over the entire volume occupied by the cast shape can be held within ± 10 degrees Farenheit of the control temperature.
3.3.4.2 Heating Rates To insure minimal thermal gradients in the cast shape prior to final sintering, the casting shall be held at 2000°F for the indicated time according to wall thickness, as follows: up to 0.25-inch - no hold; 0.26-0.50-inch - 30 minutes; 0.51-0.75-inch - 60 minutes; 0.76-1.00-inch - 100 minutes; 1.01-1.25-inch - 160 minutes; 1.26-1.50-inch - 220 minutes. To further insure uniform heat treatment, heating rates from 2000°F to the final sintering temperature shall be no greater than 100°F/hr for parts with wall thickness greater than 0.500-inch, while parts with thinner wall sections may be heated at any rate.

3.3.5 Machining Machining shall be carried out with diamond or silicon carbide abrasives, using distilled or deionized water as a coolant. Jigs and holding fixtures shall be constructed in such a way that only stainless steel or non-ferrous materials shall be in contact with fused silica.

4. QUALITY ASSURANCE PROVISIONS

4.1 Unless otherwise specified in the contract or purchase order, the supplier is responsible for the performance of all inspection and test requirements as specified herein. The Purchaser reserves the right to perform any of the inspections set forth in the specification where such specifications are deemed necessary to assure processing conforms to prescribed requirements.
4.2 Qualification Requirements The qualification of a supplier's process shall consist of meeting all the requirements specified in Section 3 using documentation outlined in Section 4.

4.2.1 Process Qualification Report The supplier shall provide a report showing actual process parameters covering all items required in Section 3.

4.3 Process Acceptance Requirements The acceptance requirements for each lot of material processed shall be all requirements as outlined in Section 3.

4.3.1 Process Acceptance Report For each lot of material processed the supplier shall furnish a report of the process parameters for those items necessary to verify conformance with the acceptance requirements of this specification.

4.3.2 Lot A lot shall consist of those radomes fabricated from one lot of slip.

4.4 Process Documentation

4.4.1 Material The starting material will be noted by vendors lot number.

4.4.2 Casting Each casting shall be identified as to mold, time and pressure of casting, and cast wall thickness.

4.4.3 Drying A log of temperature conditions and drying time will be maintained.
4.4.4 Sintering Schedule A log of time and temperature during sintering will be maintained to insure meeting the requirements of 3.3.4.2.

4.4.4.1 Kiln Characterization A log of time and temperature at furnace centerline elevations corresponding to the top, center and bottom of the casting shall be maintained during the soak period to demonstrate compliance with 3.3.4.1 above. (This requirement for qualification only.)
DISTRIBUTION LIST

NAVY

Commander, Naval Ordnance Systems Command
Department of the Navy
Washington, D. C. 20360
Attn: Code ORD-0333 1
Code ORD-035 2
Code ORD-55212 1
Code ORD-035A 1
Code ORD-04721 1

Commander
Naval Air Systems Command (AIR-320B)
Washington, D. C. 20360 1

Commander
Naval Weapons Center
Attn: Code 4062
China Lake, California 93557 1

U.S. Naval Ordnance Laboratory
Attn: J. L. Lankford (Code 323)
White Oak, Silver Spring, Maryland 20910 1

Chief of Naval Research
Department of the Navy
Washington, D. C. 20360
Attn: Code 461 1
Code 439 1
Code 470 1

Naval Research Laboratory
Attn: Dr. M. R. Achter (Code 6340)
Washington, D. C. 20390 1

Superintendent
Naval Postgraduate School
Attn: Code 2124
Monterey, California 93940 1

AIR FORCE

Office of Aerospace Research
Attn: Major Richard H. Hartke (D686)
1400 Wilson Boulevard
Arlington, Virginia 22029 1
<table>
<thead>
<tr>
<th>Agency</th>
<th>Contact Information</th>
<th>No. of Copies</th>
</tr>
</thead>
<tbody>
<tr>
<td>AIR FORCE</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
| AF Materials Laboratory | MAAM (B. R. Emrich)  
Wright-Patterson Air Force Base, Ohio 45433                                      | 1             |
| AFML/LLM (W. G. Ramke) |  
Wright-Patterson Air Force Base, Ohio 45433                                        | 1             |
| AFML/LNE (George Schmitt) |  
Wright-Patterson Air Force Base, Ohio 45433                                         | 1             |
| AFAL/TEM-3 (Richard A. Ireland) |  
Wright-Patterson Air Force Base, Ohio 45433                                         | 1             |
| ARMY                |                                                                                      |               |
| Commanding General  | U.S. Army Missile Command  
Attn: AMCPM-MDEM (Glen B. Nicholas)  
Redstone Arsenal, Alabama 35809                                                   | 1             |
| Commanding General  | U.S. Army Missile Command  
Attn: AMSMI-RLM (Phil Ormsby)  
Building 5400  
Redstone Arsenal, Alabama 35809                                                   | 1             |
| OTHER AGENCIES      |                                                                                      |               |
| NASA Scientific and Technical Inf. Facility |  
Attn: Acquisitions Branch-Foreign Exchange  
P. O. Box 33  
College Park, Maryland 20740                                                      | 2             |
| Commander, Defense Documentation Center  
Cameron Station  
Alexandria, Virginia 22314                                                           |               |
| Via: Commander, Naval Ordnance Systems Command  
Department of the Navy  
Attn: Code ORD-0632  
Washington, D. C. 20360                                                              | 14            |
<table>
<thead>
<tr>
<th>INDUSTRY</th>
<th>No. of Copies</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aerospace Corporation</td>
<td>1</td>
</tr>
<tr>
<td>Attn:  Dr. Robert L. Hallse</td>
<td></td>
</tr>
<tr>
<td>1111 East Mill Street</td>
<td></td>
</tr>
<tr>
<td>San Bernardino, California 92408</td>
<td></td>
</tr>
<tr>
<td>Ford Motor Company</td>
<td>1</td>
</tr>
<tr>
<td>Product Development Group</td>
<td></td>
</tr>
<tr>
<td>Attn:  (E. A. Fisher, Turbine Research Dept.)</td>
<td></td>
</tr>
<tr>
<td>20000 Rotunda Drive</td>
<td></td>
</tr>
<tr>
<td>Dearborn, Michigan 48121</td>
<td></td>
</tr>
<tr>
<td>Applied Physics Laboratory</td>
<td>1</td>
</tr>
<tr>
<td>The Johns Hopkins University</td>
<td></td>
</tr>
<tr>
<td>Attn:  Mr. L. B. Weckesser</td>
<td></td>
</tr>
<tr>
<td>8621 Georgia Avenue</td>
<td></td>
</tr>
<tr>
<td>Silver Spring, Maryland 20910</td>
<td></td>
</tr>
<tr>
<td>Battelle Memorial Institute</td>
<td>1</td>
</tr>
<tr>
<td>Defense Metals Information Center</td>
<td></td>
</tr>
<tr>
<td>Attn:  H. D. Moran</td>
<td></td>
</tr>
<tr>
<td>505 King Avenue</td>
<td></td>
</tr>
<tr>
<td>Columbus, Ohio 43201</td>
<td></td>
</tr>
<tr>
<td>Brunswick Corporation</td>
<td>1</td>
</tr>
<tr>
<td>Technical Products Division</td>
<td></td>
</tr>
<tr>
<td>Attn:  Robert Copeland</td>
<td></td>
</tr>
<tr>
<td>325 Brunswick Lane</td>
<td></td>
</tr>
<tr>
<td>Marion, Virginia 24354</td>
<td></td>
</tr>
<tr>
<td>Ceramic Finishing Company</td>
<td>1</td>
</tr>
<tr>
<td>Attn:  Dr. Dennis R. Platts</td>
<td></td>
</tr>
<tr>
<td>P. O. Box 498</td>
<td></td>
</tr>
<tr>
<td>State College, Pennsylvania 16801</td>
<td></td>
</tr>
<tr>
<td>Coors Porcelain Company</td>
<td>1</td>
</tr>
<tr>
<td>Attn:  Mr. Derald Whiting</td>
<td></td>
</tr>
<tr>
<td>Drawer 312</td>
<td></td>
</tr>
<tr>
<td>Golden, Colorado 80401</td>
<td></td>
</tr>
<tr>
<td>Emerson and Cuming, Inc.</td>
<td>1</td>
</tr>
<tr>
<td>Attn:  E. J. Luoma</td>
<td></td>
</tr>
<tr>
<td>869 Washington Street</td>
<td></td>
</tr>
<tr>
<td>Canton, Massachusetts 02021</td>
<td></td>
</tr>
<tr>
<td>General Dynamics/Pomona</td>
<td>1</td>
</tr>
<tr>
<td>Attn:  R. A. Miller</td>
<td></td>
</tr>
<tr>
<td>Mail Zone 6-56</td>
<td></td>
</tr>
<tr>
<td>Pomona, California 91766</td>
<td></td>
</tr>
<tr>
<td>INDUSTRY (Continued)</td>
<td>No. of Copies</td>
</tr>
<tr>
<td>----------------------</td>
<td>--------------</td>
</tr>
<tr>
<td>Glasrock Products, Inc.</td>
<td>1</td>
</tr>
<tr>
<td>Attn: Mr. C. A. Murphy</td>
<td></td>
</tr>
<tr>
<td>Rt. 1</td>
<td></td>
</tr>
<tr>
<td>McDaniel Station Road</td>
<td></td>
</tr>
<tr>
<td>Calhoun, Georgia 30701</td>
<td></td>
</tr>
<tr>
<td>Hughes Aircraft Company</td>
<td>1</td>
</tr>
<tr>
<td>Attn: L. E. Gates, M.S. H-164</td>
<td></td>
</tr>
<tr>
<td>Culver City, California 90230</td>
<td></td>
</tr>
<tr>
<td>Lockheed Missiles &amp; Space Company</td>
<td>1</td>
</tr>
<tr>
<td>Technical Information Center</td>
<td></td>
</tr>
<tr>
<td>3251 Hanover Street</td>
<td></td>
</tr>
<tr>
<td>Palo Alto, California 94034</td>
<td></td>
</tr>
<tr>
<td>Lockheed Missiles &amp; Space Company</td>
<td>1</td>
</tr>
<tr>
<td>Attn: Robert M. Beasley, Sr., Staff Scientist</td>
<td></td>
</tr>
<tr>
<td>Dept. 52-30, Bldg. 103</td>
<td></td>
</tr>
<tr>
<td>P. O. Box 504</td>
<td></td>
</tr>
<tr>
<td>Sunnyvale, California 94088</td>
<td></td>
</tr>
<tr>
<td>Los Alamos Scientific Laboratory</td>
<td>1</td>
</tr>
<tr>
<td>CMB-6 Ceramics Section</td>
<td></td>
</tr>
<tr>
<td>Attn: S. D. Stoddard</td>
<td></td>
</tr>
<tr>
<td>Box 1663</td>
<td></td>
</tr>
<tr>
<td>Los Alamos, New Mexico 87544</td>
<td></td>
</tr>
<tr>
<td>Martin-Marietta Corporation</td>
<td>1</td>
</tr>
<tr>
<td>Attn: Hyman Leggett (Mail Point 275)</td>
<td></td>
</tr>
<tr>
<td>P. O. Box 5837</td>
<td></td>
</tr>
<tr>
<td>Orlando, Florida 32805</td>
<td></td>
</tr>
<tr>
<td>McDonnell-Douglas Astronautics Co. - W-D</td>
<td>1</td>
</tr>
<tr>
<td>Attn: Dept. A-263</td>
<td></td>
</tr>
<tr>
<td>3000 Ocean Park Boulevard</td>
<td></td>
</tr>
<tr>
<td>Santa Monica, California 90406</td>
<td></td>
</tr>
<tr>
<td>Monsanto Company</td>
<td>1</td>
</tr>
<tr>
<td>Attn: Dr. H. Teicher</td>
<td></td>
</tr>
<tr>
<td>800 N. Lindbergh Boulevard</td>
<td></td>
</tr>
<tr>
<td>St. Louis, Missouri 63166</td>
<td></td>
</tr>
<tr>
<td>Raytheon Company</td>
<td>1</td>
</tr>
<tr>
<td>Missile Systems Division, VB1-3</td>
<td></td>
</tr>
<tr>
<td>Attn: R. O. Howe</td>
<td></td>
</tr>
<tr>
<td>Hartwell Road</td>
<td></td>
</tr>
<tr>
<td>Bedford, Massachusetts 01730</td>
<td></td>
</tr>
<tr>
<td>Company</td>
<td>Attention</td>
</tr>
<tr>
<td>----------------------------------------------</td>
<td>--------------------</td>
</tr>
<tr>
<td>Thermo Materials Corporation</td>
<td>Dr. W. J. Corbett</td>
</tr>
<tr>
<td>Union Carbide Corporation</td>
<td>Technical Library</td>
</tr>
<tr>
<td>Whittaker Corporation</td>
<td>Document Custodian</td>
</tr>
</tbody>
</table>
**PROCESSING REQUIREMENTS FOR SLIP-CAST FUSED SILICA RADOMES**

This report consists of a process specification for slip-cast fused silica radomes. The rationale behind the requirements for this specification is given.
<table>
<thead>
<tr>
<th>KEY WORDS</th>
<th>LINK A</th>
<th>LINK B</th>
<th>LINK C</th>
</tr>
</thead>
<tbody>
<tr>
<td>Slip-Cast Fused Silica</td>
<td>ROLE</td>
<td>ROLE</td>
<td>ROLE</td>
</tr>
<tr>
<td>Radomes</td>
<td>WT</td>
<td>WT</td>
<td>WT</td>
</tr>
<tr>
<td>Processing</td>
<td>ROLE</td>
<td>ROLE</td>
<td>ROLE</td>
</tr>
<tr>
<td></td>
<td>WT</td>
<td>WT</td>
<td>WT</td>
</tr>
</tbody>
</table>
ACCEPTANCE CRITERIA FOR
SLIP-CAST FUSED SILICA RADOMES

Technical Report No. 3

June 1972

By

J. N. Harris
E. A. Welsh

Prepared Under Contract N00017-70-C-4438

For

Naval Ordnance Systems Command
Weapons Dynamics Division (Code ORD-035)
Department of the Navy

By

Engineering Experiment Station
Georgia Institute of Technology
Atlanta, Georgia 30332

"Approved for public release; distribution unlimited."
ACCEPTANCE CRITERIA FOR
SLIP-CAST FUSED SILICA RADOMES

Technical Report No. 3

June 1972

By

J. N. Harris
E. A. Welsh

Prepared Under Contract N00017-70-C-4438

For

Naval Ordnance Systems Command
Weapons Dynamics Division (Code ORD-035)
Department of the Navy

By

Engineering Experiment Station
Georgia Institute of Technology
Atlanta, Georgia 30332

"Approved for public release; distribution unlimited."
# TABLE OF CONTENTS

<table>
<thead>
<tr>
<th>Section</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>I. PURPOSE</td>
<td>1</td>
</tr>
<tr>
<td>II. INTRODUCTION</td>
<td>1</td>
</tr>
<tr>
<td>III. ACCEPTANCE TESTING REQUIREMENTS</td>
<td>2</td>
</tr>
<tr>
<td>A. Mechanical Properties</td>
<td>2</td>
</tr>
<tr>
<td>1. Tensile Strength</td>
<td>2</td>
</tr>
<tr>
<td>2. Modulus of Rupture</td>
<td>2</td>
</tr>
<tr>
<td>B. Physical Properties</td>
<td>3</td>
</tr>
<tr>
<td>1. Density</td>
<td>3</td>
</tr>
<tr>
<td>2. Cristobalite Content</td>
<td>3</td>
</tr>
<tr>
<td>3. Thermal Conductivity</td>
<td>3</td>
</tr>
<tr>
<td>4. Specific Heat</td>
<td>3</td>
</tr>
<tr>
<td>5. Thermal Expansion</td>
<td>4</td>
</tr>
<tr>
<td>C. Dielectric Properties</td>
<td>4</td>
</tr>
<tr>
<td>D. Physical Dimensions</td>
<td>4</td>
</tr>
<tr>
<td>1. Wall Thickness</td>
<td>4</td>
</tr>
<tr>
<td>2. Concentricity and Prescribed Contour</td>
<td>4</td>
</tr>
<tr>
<td>E. Cracks and Voids</td>
<td>5</td>
</tr>
<tr>
<td>APPENDIX I. ACCEPTANCE TEST CRITERIA RADOME, SLIP-CAST FUSED SILICA.</td>
<td>6</td>
</tr>
<tr>
<td>APPENDIX II. PROCEDURE FOR DETERMINING BULK $\alpha$-CRISTOBALITE CONTENTS BY X-RAY DIFFRACTION TECHNIQUES.</td>
<td>10</td>
</tr>
<tr>
<td>REFERENCES.</td>
<td>21</td>
</tr>
</tbody>
</table>

This report contains 21 pages.
ABSTRACT

This report consists of an acceptance criteria specification for slip-cast fused silica radomes. The rationale behind the requirements for this specification is given.
I. PURPOSE

The purpose of Contract No. N00017-70-C-4438 is to perform research and development directed towards the development of techniques to fully exploit the potential of readily available ceramic systems for use as structural components in hypersonic missile applications.

II. INTRODUCTION

In order to determine whether a delivered radome or a radome blank meets particular specifications for the intended final use certain acceptance tests and measurements must be made. Material tests must be; either non-destructive, accomplished on material removed from an excess portion of the radome, or accomplished on separate material processed from start to finish at the same time and in the same manner as the radome. Acceptance tests should be simple to accomplish and should not be expensive or time consuming. The tests may be conducted by the supplier, the receiver, or jointly.

It must be remembered that acceptance tests are only a measure of the material under the specified test conditions and do not necessarily represent stress failure levels, etc. that may be experienced under actual flight conditions. The complete response (mechanical, electrical, and thermal) of a radome is intimately related to its particular mission and can only be determined by a detailed experimental and/or analytical study for each individual missile system.

To ensure that tests whether conducted by the supplier or the receiver, are standardized ASTM specifications have been cited wherever possible.
III. ACCEPTANCE TESTING REQUIREMENTS

A. Mechanical Properties

The strength of slip-cast fused silica increases with temperature to approximately 2000° F. Therefore, testing at room temperature represents a minimum strength and should be satisfactory for all acceptance tests.

1. Tensile Strength

In most radome shapes the simplest and easiest test specimen to prepare from the extended portion of the radome skirts is a machined ring. Several rings can be machined and subjected to a hydrostatic tensile test using equipment similar to that designed by Sedlacek 1/. At the same time the tensile test rings can be instrumented with strain gages to determine tensile elastic modulus and Poisson's ratio.

2. Modulus of Rupture

Depending on radome wall thickness and diameter, rectangular modulus of rupture specimens can be machined from the skirt section. If the diameter and wall thickness are sufficient, specimens can be cut from both the horizontal and vertical directions of the skirt section. Prior to breaking these specimens, modulus of elasticity can also be determined using a sonic resonance method as specified in ASTM C623 and/or by measuring the deflection of the modulus of rupture specimen as specified in ASTM E111. The modulus of rupture specimen is to be broken transversely, using four point loading to prevent wedging effects and to subject a larger volume of material to maximum stress.
B. Physical Properties

1. Density

Bulk density, porosity and water absorption can be determined on samples of sufficient size cut or broken from the skirt-section of the radome using the procedures of ASTM C373. In addition, determinations should be made on several samples taken from the base, middle and tip area of one radome from each lot.

2. Cristobalite Content

At least one bulk density sample from the skirt and one sample from each area of the test radome from each lot should be examined for bulk cristobalite content using x-ray diffraction comparison techniques as outlined in Appendix II.

3. Thermal Conductivity

The thermal conductivity of slip-cast fused silica is directly related to its porosity $2/,$ $3/$. If the density and porosity are known, thermal conductivity can be estimated as close as the limits of experimental error in actual measurements. Therefore, there is no need to measure thermal conductivity on material from each radome.

4. Specific Heat

The specific heat does not vary with processing variations. Therefore, there is no need for determination of specific heat on each radome. Acceptable values for specific heat are given in the Fused Silica Design Manual $4/$ published during this program.
5. Thermal Expansion

Thermal expansion should be determined on material from each radome using the procedures of ASTM E228.

C. Dielectric Properties

Dielectric constant and loss tangent should be measured from room temperature to 1000 °C at the frequency(ies) to be used in service using the procedures of ASTM D2520.

D. Physical Dimensions

1. Wall Thickness

Wall thickness should be measured with a suitable device such as deep throttled calipers or a specially constructed device such as that described by Poulos, et al., 5/. Sufficient measurements should be made vertically and circumferentially to be certain there are no variations in the wall thickness which exceed the prescribed tolerances.

2. Concentricity and Prescribed Contour

Concentricity should be measured using a suitable measuring technique to insure that the radome meets specifications. Out-of-roundness can occur in slip-cast fused silica radomes during slip casting and firing operations. Out-of-roundness should be removed during machining operations. However, if vacuum chucks are used, it is possible to machine a thin wall radome to a perfectly round condition and then have it go out of shape when the vacuum is removed. Radome contour should also be determined at several points to insure compliance with specifications.
E. Cracks and Voids

The translucent nature of slip-cast fused silica allows it to be inspected for cracks and voids using a visual technique. By illuminating the interior with a 300 watt bulb and soaking the outside with isopropyl alcohol any cracks or voids become visible. Ten power magnification will aid in discovering small cracks or voids.
1.0 Scope

This document outlines the procedures and equipment to be used in the Quality Acceptance testing of Radome Blanks as a demonstration of compliance to the performance requirements.

2.0 Applicable Documents and Drawings

ASTM C373
ASTM C674
ASTM D2520
ASTM E111
ASTM E132
ASTM E137
ASTM E228


3.0 Test Conditions

Unless otherwise specified herein, or in the applicable test procedures, the acceptance testing of the Radome Blank will be performed at standard ambient conditions as defined below:

- Temperature: 25° C ± 10° C (77° F ± 18° F)
- Relative Humidity: 90 per cent Max with no Minimum
- Barometric Pressure: 29 to 32 inches of Hg
- Test Equipment Warm-Up Time: 2 hours Minimum
4.0 Test Equipment

Test equipment meeting the requirements of the documents listed in 2.0 shall be deemed satisfactory.

5.0 Preliminary Instructions

5.1 The test technician shall read and understand each test procedure prior to testing the Radome Blank, or associated test specimens.

5.1.1 Verify that the item is the correct serial number, and proper configuration.

5.1.2 Verify that test instruments used are within calibration dates stated on calibration tag, or are properly calibrated where such calibration is necessary prior to each use.

5.1.3 Record appropriate calibration dates and/or data on all applicable test data sheets.

5.1.4 Record all test results on the applicable data sheets.

5.2 All test results shall be within the limits specified on the applicable data sheets.

6.0 Acceptance Inspection Tests

6.1 The following paragraphs detail procedures for demonstrating performance requirements for material to be used in radome
manufacture. All measurements with the exception of chemical analysis are to be made on suitable test specimens processed under the same conditions as deliverable radomes.

6.1.1 **Composition.** Chemical analysis conforming with ASTM E137 shall be furnished by the material vendor. Cristobalite content shall be determined by X-ray diffraction, as specified by Georgia Tech method "Procedure for Determining Bulk α-Cristobalite Content by X-ray Diffraction Techniques."

6.1.2 **Bulk Density.** Bulk density shall be determined from a minimum of five (5) test samples per ASTM C373.

6.1.3 **Modulus of Rupture.** A minimum of three (3) test specimens shall be diamond ground from a suitable slip-cast fused billet, using distilled water as a coolant. Samples will be broken according to ASTM C674, with the exception that quarter point loading shall be used.

6.1.4 **Tensile Strength.** Tensile strength shall be determined by a hydrostatic test on a minimum of two (2) rings machined from the skirt section of the radome blank. Testing shall be performed with suitably sized equipment and with procedures conforming to the recommendations of Sedlacek and Halden.

6.1.5 **Poisson's Ratio.** Poisson's Ratio shall be measured utilizing strain gages attached to the hoop tensile specimen.
6.1.6 **Modulus of Elasticity.** Young's Modulus shall be determined at room temperature utilizing strain gages on the hoop-tensile specimen.

6.1.7 **Dielectric Properties.** Dielectric constant and loss tangent shall be measured at the frequency(ies) to be used in service from 20° to 1000° C in accordance with ASTM D2520.

6.1.8 **Thermal Expansion.** Thermal expansion shall be determined per ASTM E228 at temperatures from 20° to 1000° C.

6.2 The following paragraphs detail procedures for demonstrating compliance with the Quality Conformance Inspection.

6.2.1 **Wall Thickness.** Wall thickness shall be measured at a minimum of 20 points spaced 90 degrees apart around the circumference of the radome.

6.2.2 **Cracks and Voids.** The radome shall be soaked with isopropyl alcohol, illuminated from within with a 300 watt light bulb, and inspected visually at 10X magnification for the presence of cracks and voids.

6.2.3 **External Dimensions.** The external dimensions shall be measured with either pi tape, or engraved steel rule to the maximum accuracy obtainable with the particular measuring device.

6.2.4 **Roundness.** Roundness measurements will be made using a suitable rotational device.
APPENDIX II

PROCEDURE FOR DETERMINING BULK $\alpha$-CRISTOBALITE CONTENTS BY X-RAY DIFFRACTION TECHNIQUES

This procedure is presented to serve as a guide to installations which desire to utilize this technique for the determination of $\alpha$-cristobalite in slip-cast fused silica.

$\alpha$-Cristobalite Standard

Since no absolute X-ray standard exists for $\alpha$-cristobalite, the many x-ray diffraction studies of $\alpha$-cristobalite have always utilized an $\alpha$-cristobalite reference or standard prepared from some other form of silicon dioxide. The starting materials in these preparations have ranged from well crystallized quartz to silicic acid. According to the work of Floerke 6/, the quantitative analysis of $\alpha$-cristobalite by x-ray diffraction requires special care to relate the calibration or reference material to the estimated $\alpha$-cristobalite phase. This requirement was further emphasized by the experimental studies of Foster et al. 7/; the starting form of silicon dioxide which produces the $\alpha$-cristobalite standard should be made of material similar to that being analyzed. Also, the standard should be produced at a temperature level at which the specimens to be analyzed will be devitrified. The following procedure describes preparation of one standard.

The $\alpha$-cristobalite standard was prepared from fused silicon dioxide obtained by the fusion of quartz sand in an electric arc. The material is typical of that used in the fabrication of slip-cast fused silicon dioxide bodies. A slip-cast cylindrical specimen was sintered for 60 hours at 2500°F in an electric furnace with an air atmosphere. The specimen was subsequently crushed and ground to minus 325 mesh powder.
Sizing and Packing

Test samples for α-cristobalite content determinations are crushed and screened through a 325 mesh screen to preclude preferred orientation due to overly large particles. The samples are packed against a frosted glass slide to help maintain random orientation of the powder and provide for a reproducible "roughness" of the sample surface. Repacking studies have shown that when this procedure is used the variations from sample to sample due to preferred orientation and to surface roughness are quite small. In addition, no variation in diffracted beam intensity with packing density has been observed.

Scanning

Scanning from 21 to 22.67 degrees two-theta (2θ) is sufficient for the measurement of the (101) α-cristobalite reflection (2θ = 21.94 degrees).

Basis

The integrated intensity is used, since it is relatively insensitive to the crystallite sizes and the residual inhomogeneous strains in the crystals. The integrated intensity is a most convenient index since it has been found to be directly proportional to the percentage of the standard prepared by mixing known quantities of standard and fused silicon dioxide over the range 0.5 to 20.0 per cent of the standard cristobalite sample. The overlapping of Kα₁ and Kα₂ lines is avoided when integrated intensities are used.

Data Reduction

Diffractometer traces are made on both the standard and the test sample. A background curve can be established to eliminate those portions of the
spectra which do not constitute the $\alpha$-cristobalite (101) reflection intensity. The $\alpha$-cristobalite (101) reflection occurs atop a broad "hump" which is characteristic of fused silicon dioxide. Subjective judgment is involved in the placement of the background curve for low $\alpha$-cristobalite contents. The subjectivity can be limited by background curve templates which fit the fused 100 per cent silicon dioxide hump in the traces for various incident intensities and scale factors. The traces from the standard and the sample can be measured with a planimeter to obtain integrated intensity data. Graphical representation of the integrated intensity is the area bounded by the diffraction trace and the background curve, expressed as the per cent "apparent $\alpha$-cristobalite content" for the standard. For known amounts of standard mixed with fused silicon dioxide the apparent $\alpha$-cristobalite content was found to be reproducible for measurements to about 20 per cent.

A second technique to limit the subjectivity of placing a background curve is to use an "artificial background curve" in the form of a straight line segment. In place of the conformal background curve, a straight line segment joining two convenient points on the trace is used. The points on the diffraction traces corresponding to a $2\theta$ angle of 21.00 degrees and 22.67 degrees have been selected, and the apparent $\alpha$-cristobalite content is simply based on the areas bounded by the diffraction traces and the straight line segments.

The technique has the advantage of area measurement under the diffraction peak from the integrated-count data which most x-ray units provide. For proper utilization of the integrated-count technique a correction method must be developed which allows separation of the diffracted energy associated
with the amorphous hump. Such a correction method was developed using mechanical mixtures of fused silicon dioxide and the cristobalite standard. The "apparent $\alpha$-cristobalite content" of each of these mixtures was the integrated count for each mixture expressed as a percentage of the integrated count for the cristobalite standard. These apparent $\alpha$-cristobalite contents were plotted as a function of the known content of cristobalite for the mixtures. This plot is used to estimate the $\alpha$-cristobalite content of any test specimen from the integrated counts on the specimen and the cristobalite standard.

It must be emphasized, that the correction curve is not independent of the materials, procedures and equipment employed. Other laboratories must establish such a correction curve using the materials, procedures, and equipment which they employ.

Analysis Procedure

The following machine settings are used:

- **Tube**: Cu
- **Filter**: Ni
- **Tube Voltage**: 40KV
- **Tube Current**: 20 ma
- **Time Constant**: 0.5
- **Scanning Rate**: 2°/min
- **Divergent Slit**: 1°
- **Receiving Slit**: 0.003"
- **Scatter Slit**: 1°
- **Diff-Int Switch**: Diff.
The diffracted beam intensity from the cristobalite standard is amplified to a maximum by adjusting the Detector #2 Fine Voltage setting with the goniometer set at 21.94 degrees. The following procedure is used to obtain the $\alpha$-cristobalite content of a sample, relative to the cristobalite standard.

1. With the unknown sample in place the goniometer is set at 21.00 degrees, and the count for a fixed time of 10 seconds is recorded.

2. The goniometer is operated at 2 degrees/min scanning rate, and the count for a fixed time of 50 seconds is recorded (total scan of 1.67 degrees two-theta).

3. At the end on the 50 second run of step 2 the goniometer setting is 22.67 degrees. At this setting the count for a fixed time of 10 seconds is recorded.

4. A "corrected count" is obtained by adding the two counts from steps 1 and 3, multiplying by 2.5, and subtracting from the number obtained in step 2. Graphically this corrected count represents the area bounded by the diffraction trace and the straight line segment for the test sample.

5. The "corrected count" for the cristobalite standard, which represents the area bounded by the diffraction trace and the straight line segment for the cristobalite standard, is obtained by repeating steps 1 through 4 with a cristobalite standard specimen.
6. The apparent $\alpha$-cristobalite content is obtained by multiplying the corrected count for the sample by 100 and dividing by the corrected count for the cristobalite standard.

7. The $\alpha$-cristobalite content, relative to the cristobalite standard, is obtained by reading the corrected value corresponding to the apparent $\alpha$-cristobalite content obtained in step 6.

**Sample Calculation**

For a typical sample, the 10 second and end-counts at 21.00 and 22.67 degrees were 76 and 70, respectively; the 50 second count accumulated between 21.00 and 22.67 degrees was 460. For the cristobalite standard, the respective counts were 55, 45, and 1364. Thus:

The corrected count, test sample = 460 - 2.5 (76 + 70) = 95;
The corrected count, cristobalite standard = 1364 - 2.5 (55 + 47) = 1109;
The apparent $\alpha$-cristobalite content = $\frac{95}{1109} \times 100 = 8.6$ v/o; and
The $\alpha$-cristobalite content, relative to the standard as 100 per cent = 7.7 v/o.

**Reporting Results**

It has been the practice to report the interval expected to contain the $\alpha$-cristobalite content of a test material at the 95 per cent confidence level which requires multiple determinations on a given sample; and, generally, two determinations are made on the A-4 standard for comparison.

**Confidence Limits for $\alpha$-Cristobalite Determinations**

Suppose $n$ diffraction measurements are made on a given sample and two diffraction measurements are performed on the cristobalite standard, one
before and one after the measurements on the sample being analyzed. Let

\[ A_i = \text{corrected count, cristobalite standard, } i = 1,2 \]  
(1)

\[ X_i = \text{corrected count, test sample, } i = 1,2,\ldots,n \]  
(2)

Then the sample variances would be

\[ S_X^2 = \frac{\sum_{i=1}^{n} x_i^2 - (\sum x_i)^2}{n(n-1)} \]  
(3)

and

\[ S_A^2 = \frac{2 \sum_{i=1}^{n} A_i^2 - (\sum A_i)^2}{2} \]  
(4)

for the sample count and the cristobalite standard count, respectively. The apparent \( \alpha \)-cristobalite content, \( C \), in the sample would be

\[ \overline{X} - \frac{S_X}{\sqrt{n}} t_{n-1, \alpha} \times 100 \leq C \leq \overline{X} + \frac{S_X}{\sqrt{n}} t_{n-1, \alpha} \times 100, \text{ with 95% confidence} \]  
(5)

\[ \frac{\overline{A}}{\overline{X}} \pm \frac{S_A}{\overline{X}} \sqrt{2} t_{n-1, \beta} \leq C \leq \frac{\overline{A}}{\overline{X}} \pm \frac{S_A}{\overline{X}} \sqrt{2} t_{n-1, \beta} \]

where \( \alpha \beta = 0.025 \) and

\[ \overline{X} = \frac{1}{n} \sum_{i=1}^{n} x_i \]  
(6)
\[ \bar{A} = \frac{1}{2} \sum_{i=1}^{n} A_i. \] (7)

It is conservative to choose \( \alpha = \beta = 0.158 \) so that:

\[
\frac{X - \frac{X}{\sqrt{n}} t_{n-1, 0.158}}{\frac{S}{\sqrt{2}}} \times 100 \leq C \leq \frac{X + \frac{X}{\sqrt{n}} t_{n-1, 0.158}}{\frac{S}{\sqrt{2}}} \times 100, \text{ with 95\% confidence} \] (8)

The values of \( t_{n-1, 0.158} \) appear below:

<table>
<thead>
<tr>
<th>( n )</th>
<th>( t_{n-1, 0.158} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>1.87</td>
</tr>
<tr>
<td>3</td>
<td>1.02</td>
</tr>
<tr>
<td>4</td>
<td>0.93</td>
</tr>
<tr>
<td>5</td>
<td>0.91</td>
</tr>
</tbody>
</table>

**Computer Program**

To reduce the mathematical exercise required by the statistical calculations for a 95 per cent confidence interval, a computer program was prepared which contains a best fit curve for the correction factor to be used for \( \alpha \)-cristobalite determination.
Language - ALGOL

N = number of measurement/sample

\( A_1, A_4 = 10 \) second count at 21.00 degrees for A-4 standard

\( A_2, A_5 = 50 \) second scan count from 21.00 to 22.67 degrees for A-4 standard

\( A_3, A_6 = 10 \) second count at 22.67 degrees for A-4 standard

\( X_1, X_4 = 10 \) second count at 21.00 degrees for unknown

\( X_2, X_5 = 50 \) second scan count from 21.00 to 22.67 degrees for unknown

\( X_3, X_6 = 10 \) second count at 22.67 degrees for unknown

N = sample code number

BEGIN

COMMENT CRISTOBALITE CONTENT N=2;

INTEGER N, A1, A2, A3, A4, A5, A6, X1, X2, X3, X4, X5, X6;

REAL A, X, B, Y, Li, L2, L, H1, H2, E1, E, F1, F2, F3, F4, F5, F6, G1, G2, G3, L4, H4, E4, A7, A8, X7, X8;

FILE IN PBIN (2,10);

FILE OUT PBOUT 6 (2,15);

FORMAT OUT FT1(X10,"CRISTOBALITE CONTENT N-2"///);

FORMAT OUT FT2(X4, I6, X8, F7.2, X6, "TO", F9, 2, X10, F7.2,/);

FORMAT OUT FT3(X8,"SAMPLE", X8, "PER CENT CRISTOBALITE", /,
X9, "CODE", X9, " (NINETY-FIVE PER CENT", X10,
"EXPECTED", /, S8, "NUMBER", X8, "CONFIDENCE"
"INTERVAL)", X11, "VALUE", /);
LABEL BIGDADDY, FINISHED;
WRITE (PBOUT, FT1);
WRITE (PBOUT, FT3);
BIGDADDY: READ (PBIN, /, A1, A2, A3, A4, A5, A6, N, X1, X2, X3, X4, X5, X6) [FINISHED];
A7 - A2 - (2.5) x A1 - (2.5) x A3;
A8 - A5 - (2.5) x A4 - (2.5) x A6;
X7 - X2 - (2.5) x X1 - (2.5) x X3;
X8 - X5 - (2.5) x X4 - (2.5) x X6;
A - (0.5) x A7 + (0.5) x A8;
X - (0.5) x X7 + (0.5) x X8;
B - ABS(A7 - A8);
Y - ABS(X7 - X8);
L1 - (100) x X - (93.3) x Y;
L2 - A + (0.933) x B;
L - L1 / L2;
H1 - (100) x X + (93.3) x Y;
H2 - A - (0.933) x B;
H - H1 / H2;
E1 - (100) x X;
F1 - ABS(L - 7.5);
F2 - ABS(H - 7.5);
F3 - ABS(E - 7.5);
F4 - SQRT(F1);
F5 - SQRT(F2);
F6 - SQRT(F3);
G1-(34.2) / (F4 + 7);
G2-(34.2) / (F5 + 7);
G3-(34.2) / (F6 + 7);
L4=L-G1-(0.0097)xL+3;
H4=H-G2-(0.0097)xH+3;
E4=E-G3-(0.0097)xE+3;
WRITE (PBOUT,FT2,N,L4,H4,E4);

GO TO BIGDADDY:

FINISHED: END.

CRISTOBALITE CONTENT N=2

<table>
<thead>
<tr>
<th>SAMPLE CODE NUMBER</th>
<th>PER CENT CRISTOBALITE (NINETY-FIVE PER CENT CONFIDENCE INTERVAL)</th>
<th>EXPECTED VALUE</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1.66 to 2.34</td>
<td>1.99</td>
</tr>
<tr>
<td>3</td>
<td>0.95 to 1.09</td>
<td>1.02</td>
</tr>
<tr>
<td>4</td>
<td>3.37 to 3.61</td>
<td>3.49</td>
</tr>
</tbody>
</table>
REFERENCES


21
DISTRIBUTION LIST

NAVY

Commander, Naval Ordnance Systems Command
Department of the Navy
Washington, D. C. 20360
Attn: Code ORD-0333
Code ORD-035
Code ORD-55212
Code ORD-035A
Code ORD-04721

1
2
1
1
1

Commander
Naval Air Systems Command (AIR-320B)
Washington, D. C. 20360

1

Commander
Naval Weapons Center
Attn: Code 4062
China Lake, California 93557

1

U.S. Naval Ordnance Laboratory
Attn: J. L. Lankford (Code 323)
White Oak, Silver Spring, Maryland 20910

1

Chief of Naval Research
Department of the Navy
Washington, D. C. 20360
Attn: Code 461
Code 439
Code 470

1
1
1

Naval Research Laboratory
Attn: Dr. M. R. Achter (Code 6340)
Washington, D. C. 20390

1

AIR FORCE

Office of Aerospace Research
Attn: Major Richard H. Hartke (D6S6)
1400 Wilson Boulevard
Arlington, Virginia 22029

1
AIR FORCE (Continued)

AF Materials Laboratory
Attn: MAAM (B. R. Emrich)
Wright-Patterson Air Force Base,
Ohio 45433

AFML/LLM (W. G. Ramke)
Wright-Patterson Air Force Base,
Ohio 45433

AFML/LNE (George Schmitt)
Wright-Patterson Air Force Base,
Ohio 45433

AFAL/TEM-3 (Richard A. Ireland
Wright-Patterson Air Force Base,
Ohio 45433

<table>
<thead>
<tr>
<th>Army</th>
</tr>
</thead>
<tbody>
<tr>
<td>Commanding General</td>
</tr>
<tr>
<td>U.S. Army Missile Command</td>
</tr>
<tr>
<td>Attn: AMCPM-MDEM (Glen B. Nicholas)</td>
</tr>
<tr>
<td>Redstone Arsenal, Alabama 35809</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Other Agencies</th>
</tr>
</thead>
<tbody>
<tr>
<td>NASA Scientific and Technical Inf. Facility</td>
</tr>
<tr>
<td>Attn: Acquisitions Branch-Foreign Exchange</td>
</tr>
<tr>
<td>P. O. Box 33</td>
</tr>
<tr>
<td>College Park, Maryland 20740</td>
</tr>
<tr>
<td>Commander, Defense Documentation Center</td>
</tr>
<tr>
<td>Cameron Station</td>
</tr>
<tr>
<td>Alexandria, Virginia 22314</td>
</tr>
<tr>
<td>Via: Commander, Naval Ordnance Systems Command</td>
</tr>
<tr>
<td>Department of the Navy</td>
</tr>
<tr>
<td>Attn: Code ORD-0632</td>
</tr>
<tr>
<td>Washington, D. C. 20360</td>
</tr>
</tbody>
</table>
INDUSTRY

Aerospace Corporation
Attn: Dr. Robert L. Hallse
1111 East Mill Street
San Bernardino, California 92408

Ford Motor Company
Product Development Group
Attn: (E. A. Fisher, Turbine Research Dept.)
20000 Rotunda Drive
Dearborn, Michigan 48121

Applied Physics Laboratory
The Johns Hopkins University
Attn: Mr. L. B. Weckesser
8621 Georgia Avenue
Silver Spring, Maryland 20910

Battelle Memorial Institute
Defense Metals Information Center
Attn: H. D. Moran
505 King Avenue
Columbus, Ohio 43201

Brunswick Corporation
Technical Products Division
Attn: Robert Copeland
325 Brunswick Lane
Marion, Virginia 24354

Ceramic Finishing Company
Attn: Dr. Dennis R. Platts
P. O. Box 498
State College, Pennsylvania 16801

Coors Porcelain Company
Attn: Mr. Derald Whiting
Drawer 312
Golden, Colorado 80401

Emerson and Cuming, Inc.
Attn: E. J. Luoma
869 Washington Street
Canton, Massachusetts 02021

General Dynamics/Pomona
Attn: R. A. Miller
Mail Zone 6-56
Pomona, California 91766
<table>
<thead>
<tr>
<th>Industry</th>
<th>No. of Copies</th>
</tr>
</thead>
<tbody>
<tr>
<td>Glasrock Products, Inc.</td>
<td>1</td>
</tr>
<tr>
<td>Attn: Mr. C. A. Murphy</td>
<td></td>
</tr>
<tr>
<td>Rt. 1</td>
<td></td>
</tr>
<tr>
<td>McDaniel Station Road</td>
<td></td>
</tr>
<tr>
<td>Calhoun, Georgia 30701</td>
<td></td>
</tr>
<tr>
<td>Hughes Aircraft Company</td>
<td>1</td>
</tr>
<tr>
<td>Attn: L. E. Gates, M.S. H-164</td>
<td></td>
</tr>
<tr>
<td>Culver City, California 90230</td>
<td></td>
</tr>
<tr>
<td>Lockheed Missiles &amp; Space Company</td>
<td>1</td>
</tr>
<tr>
<td>Technical Information Center</td>
<td></td>
</tr>
<tr>
<td>3251 Hanover Street</td>
<td></td>
</tr>
<tr>
<td>Palo Alto, California 94034</td>
<td></td>
</tr>
<tr>
<td>Lockheed Missiles &amp; Space Company</td>
<td>1</td>
</tr>
<tr>
<td>Attn: Robert M. Beasley, Sr., Staff Scientist</td>
<td></td>
</tr>
<tr>
<td>Dept. 52-30, Bldg. 103</td>
<td></td>
</tr>
<tr>
<td>P. O. Box 504</td>
<td></td>
</tr>
<tr>
<td>Sunnyvale, California 94088</td>
<td></td>
</tr>
<tr>
<td>Los Alamos Scientific Laboratory</td>
<td>1</td>
</tr>
<tr>
<td>CMB-6 Ceramics Section</td>
<td></td>
</tr>
<tr>
<td>Attn: S. D. Stoddard</td>
<td></td>
</tr>
<tr>
<td>Box 1663</td>
<td></td>
</tr>
<tr>
<td>Los Alamos, New Mexico 87544</td>
<td></td>
</tr>
<tr>
<td>Martin-Marietta Corporation</td>
<td>1</td>
</tr>
<tr>
<td>Attn: Hyman Leggett (Mail Point 275)</td>
<td></td>
</tr>
<tr>
<td>P. O. Box 5837</td>
<td></td>
</tr>
<tr>
<td>Orlando, Florida 32805</td>
<td></td>
</tr>
<tr>
<td>McDonnell-Douglas Astronautics Co. - W-D</td>
<td>1</td>
</tr>
<tr>
<td>Attn: Dept. A-263</td>
<td></td>
</tr>
<tr>
<td>3000 Ocean Park Boulevard</td>
<td></td>
</tr>
<tr>
<td>Santa Monica, California 90406</td>
<td></td>
</tr>
<tr>
<td>Monsanto Company</td>
<td>1</td>
</tr>
<tr>
<td>Attn: Dr. H. Teicher</td>
<td></td>
</tr>
<tr>
<td>800 N. Lindbergh Boulevard</td>
<td></td>
</tr>
<tr>
<td>St. Louis, Missouri 63166</td>
<td></td>
</tr>
<tr>
<td>Raytheon Company</td>
<td>1</td>
</tr>
<tr>
<td>Missile Systems Division, VB1-3</td>
<td></td>
</tr>
<tr>
<td>Attn: R. O. Howe</td>
<td></td>
</tr>
<tr>
<td>Hartwell Road</td>
<td></td>
</tr>
<tr>
<td>Bedford, Massachusetts 01730</td>
<td></td>
</tr>
</tbody>
</table>
INDUSTRY (Concluded)

Thermo Materials Corporation
Attn: Dr. W. J. Corbett
P. O. Box 47237
Atlanta, Georgia 30348

Union Carbide Corporation
Materials Systems Division
Attn: Technical Library
P. O. Box 24166
Indianapolis, Indiana 46224

Whittaker Corporation
Nuclear Metals Division
Attn: Document Custodian
Box 125
West Concord, Massachusetts 01781

No. of Copies
1
1
1
# ACCEPTANCE CRITERIA FOR SLIP-CAST FUSED SILICA RADOMES

## Technical Report No. 3, June 1972

### Authors
Joe N. Harris, Earle A. Welsh

### Report Date
June 1972

### Contract or Grant No.
N00017-70-C-4438

### Project No.
A-1246

### Distribution Statement
Approved for public release; distribution unlimited.

### Abstract
This report consists of an acceptance criteria specification for slip-cast fused silica radomes. The rationale behind the requirements for this specification is given.
<table>
<thead>
<tr>
<th>KEY WORDS</th>
<th>LINK A</th>
<th>LINK B</th>
<th>LINK C</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>ROLE</td>
<td>WT</td>
<td>ROLE</td>
</tr>
<tr>
<td>Slip-Cast Fused Silica</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Radomes</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Testing</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>