AIM

Association for Information and Image Management

1100 Wayne Avenue, Suite 1100
Silver Spring, Maryland 20910
301/587-8202

Centimeter

Inches

MANUFACTURED TO AIM STANDARDS
BY APPLIED IMAGE, INC.

Antenna Dielectric Sealing Process Characterization

Kansas City Division

M. L. Busby and
S. S. Yerganian

KCP-613-5318

Published April 1994

Final Report

Approved for public release; distribution is unlimited.

Prepared Under Contract Number DE-ACO4-76-DP00613 for the
United States Department of Energy

DISTRIBUTION OF THIS DOCUMENT IS UNLIMITED

DISCLAIMER

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise, does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

Printed in the United States of America.

This report has been reproduced from the best available copy.

Available to DOE and DOE contractors from the Office of Scientific and Technical Information, P. O. Box 62, Oak Ridge, Tennessee 37831; prices available from (615) 576-8401, FTS 626-8401.

Available to the public from the National Technical Information Service, U. S. Department of Commerce, 5285 Port Royal Rd., Springfield, Virginia 22161

A prime contractor with the United States
Department of Energy under Contract Number
DE-ACO4-76-DP00613.

AlliedSignal Inc.
Kansas City Division
P.O. Box 419159
Kansas City, Missouri
64141-6159

Approved for public release; distribution is unlimited.

ANTENNA DIELECTRIC SEALING PROCESS CHARACTERIZATION

M. L. Busby and
S. S. Yerganian
Department 852

KCP-613-5269

Distributed September 1993

M. L. Busby and W. R. Sceiford, Project Leaders

Project Team:
T. R. Jespersen
J. F. Mahoney
R. S. Sanders
T. K. Stringer
E. G. Wenski
S. S. Yerganian

Technical Communications
Kansas City Division

MASTER

AlliedSignal
A E R O S P A C E

Contents

<i>Section</i>	<i>Page</i>
Abstract	9
Summary	9
Discussion	11
Scope and Purpose	11
Activity	12
Analysis of Stresses at the Bonding Interface	12
Finite Element Modeling Analysis	17
Process Variables Evaluation	59
Primer Evaluation	62
Process Controls	72
Accomplishments	77
References	79

Illustrations

<i>Figure</i>		<i>Page</i>
1	Radar Window Thermal Expansion	14
2	Test Data From One Tensile Test Specimen	17
3	Stresses on Bond Interface as Dielectric and RTV Shrink or Expand in Relation to Housing	18
4	First $\frac{1}{4}$ Symmetry Model, RTV and Dielectric	21
5	Finest Mesh, $\frac{1}{8}$ Symmetry Model, RTV Only	21
6	First $\frac{1}{4}$ Symmetry Model, 0.48 Poisson's Ratio	23
7	First $\frac{1}{8}$ Symmetry Model, 0.48 Poisson's Ratio	23
8	First $\frac{1}{4}$ Symmetry Model, 0.49 Poisson's Ratio	25
9	First $\frac{1}{8}$ Symmetry Model, 0.49 Poisson's Ratio	25
10	Second $\frac{1}{8}$ Symmetry Model, Two Elements Thick	29
11	Third $\frac{1}{8}$ Symmetry Model	29
12	Final $\frac{1}{4}$ Symmetry Model	31
13	Final $\frac{1}{4}$ Symmetry Model, Deformation Exaggerated	33
14	Final Model, Normal Stress XX	37
15	Final Model, Normal Stress YY	39
16	Final Model, Normal Stress ZZ	39
17	Final Model, Shear Stress XZ	41
18	Final Model, Shear Stress YZ	43
19	Final Model, Shear Stress XY	43
20	Final Model, Von Mises Stress	45
21	Final Model, Maximum Shear Stress	45

22	First Model, $\frac{1}{4}$ Symmetry, Normal Stress XX	47
23	Bonding Fixture and Tensile Test Specimen	51
24	Final Model, Normal Stress YY, 0.48 Poisson's Ratio	53
25	Final Model, Shear Stress XZ, 0.48 Poisson's Ratio	53
26	Final Model, Increased Thickness, Normal Stress YY	57
27	Final Model, Increased Thickness, Shear Stress XZ	57
28	Bonding Evaluation	60
29	Primer and RTV Cure Time Effects	64
30	Comparison of Lap Shear Strengths, Part 1, 2, and 3	66
31	Current Dielectric Sealing Process Steps	68
32	Cause and Effect Diagram of Variables That Can Affect Yields	69
33	Ranking of Process Variables	70
34	Dielectric Sealing Process Record Sheet	75
35	Proposed Dielectric Sealing Process Steps	76

Tables

<i>Number</i>	<i>Page</i>
1 Panel Shear Test Data, Part 1	61
2 Panel Shear Test Data, Part 2	63
3 Panel Shear Test Data, Part 3	65

Abstract

An antenna assembly experienced leak test failures during TMS testing. The leaks were occurring between the dielectric and housing. The antenna assembly dielectric is sealed into a nickel-plated aluminum housing using a tin catalyzed condensation cure silicone (RTV). In preparation for sealing, the dielectric and housing are chemically cleaned and then plasma cleaned. The surfaces to be sealed are primed, RTV is applied, and the RTV is cured in a humidity chamber. This report is an evaluation of the production process and includes FEM analysis and process characterization and control (PC&C) data.

Summary

An antenna assembly TMS lot experienced leak test failures caused by areas of nonadherence between the dielectric RTV sealing material and the housing wall. The assembly cumulative leak test failure rate for leaks around the dielectric was 19.5%. The antenna design was similar to an earlier antenna, using the same dielectric sealing process but with a dielectric made from a different material. The earlier version completed production with a 2.9% cumulative leak test failure rate, including weld joint leak failures.

A study was conducted to determine the root cause of the current antenna dielectric seal leak failures. The root cause was determined to be the performance of the primer used to enhance the RTV adhesion when the dielectric is sealed into the housing. The primer formulation had changed over time; that problem was coupled with a primer cure time that was marginal. The study has shown that changing to another primer and increasing the primer cure time has corrected the problem.

Performance to date is 100% yield on over 90 units assembled and tested. The process flow is shown when the study was initiated and then again with the recommended changes. Finite element modeling (FEM) analysis of the design and shear test specimens shows that the bond strengths predicted are within those provided by the process. The FEM study also indicated that additional margin could be realized by redesign.

Discussion

Scope and Purpose

The antenna assembly contains a dielectric piecepart that is sealed into a nickel-plated aluminum housing using a two-part RTV material. The dielectric sealing process was the same as an earlier antenna that completed production with a 2.9% cumulative defect rate for leaks in the dielectric seal. The difference in the two assemblies was the type of material used to make the dielectric. The current TMS evaluation group failure rate was 12% at the first leak test after sealing the dielectric, 2.4% at the second leak test after preconditioning, and 4.8% after E-test. The cumulative leak test failure rate for the current assembly was 19.5%, compared to the 2.9% for the earlier version. The TMS results were considered unacceptable, so the production definition and production processes were reviewed to determine the cause of failure.

The antenna leaks appeared to be keyed to process groups that were processed on a given day. Because no new process changes were made and a different operator built the antennas, the problem was believed to be related either to operator training or possibly a malfunction of the plasma cleaner. An operator qualification requirement was added to the production traveler, and three operators were trained and qualified to install the dielectrics. Changes were made to the procedure for operation of the plasma cleaner and a re-TMS was planned.

The second TMS group was fabricated using the process improvements identified. The first leak test failure rate was 8.7% and the second leak test failure rate was 4.3%; the post E-test and D-test failure rates were 0%. While the results were improved, the first and second leak rates were still considered to be too high. The assembly was made conditionally acceptable based upon the good post E-test/D-test results. The requirements for removal of the conditional acceptance status were as follows:

1. That the bonding process would be re-characterized by studies directed by the production and design agency engineers. From these studies would come changes to the process that would produce acceptable product with a high yield.
2. The process would be proven by the completion of 30 consecutive units without an RTV bond line failure, including E-test.

Activity

Analysis of Stresses at the Bonding Interface

Reason for the Analysis

This analysis was conducted to determine the types and magnitudes of stresses involved in the components of the antenna assembly as it undergoes temperature changes. The components of the antenna system are the dielectric molded from glass fiber reinforced polyphenylene sulfide and the electroless nickel-plated aluminum window housing. The dielectric is only slightly smaller than the opening in the housing and is sealed in the housing by the RTV silicone. The clearance between the inside surface of the aluminum housing and the dielectric is filled with the RTV material and is referred to as the gap in this stress analysis. Strains are experienced by the RTV as it shrinks upon itself and as the dielectric shrinks at the cold temperature of the thermal cycle. Stresses are generated as the assembly undergoes these strains because of the thermocycling process. These stresses occur in the RTV material, at the bond interfaces between the RTV and housing, and between the RTV and dielectric. The purpose of this analysis was to determine the stresses created in the RTV and its bonds in comparison to their strength.

Assumptions and Dimensions

- Temperature Range: -55 to 75°C
- Pressure of Helium: 815 mm Hg plus or minus 25 mm Hg at room temperature
- Dimensions of Dielectric: (consult product drawing)
- Dimensions of Housing Opening: (consult product drawing)
- Gap Between the Dielectric and Housing along the Longest Side: one-half the difference between the length of the housing opening and the length of the dielectric
- Gap Between the Dielectric and Housing on the Ends: one-half the difference between the width of the housing opening and the width of the dielectric

- Coefficient of Thermal Expansion of Aluminum = $\alpha_{alum} = \frac{23.4(10^{-6})}{^{\circ}\text{C}}$

This number was found in the 1991 Materials Selector issue of Materials Engineering Magazine.¹

- Coefficient of Thermal Expansion of RTV = $\alpha_{RTV} = \frac{300(10^{-6})}{^{\circ}\text{C}}$

The vendor literature listed the RTV expansion coefficient as $298(10^{-6})/^{\circ}\text{C}$. The 1991 Materials Selector issue listed a number of $300(10^{-6})/^{\circ}\text{C}$. The number was rounded up from 298 to 300 for simplicity.

- Coefficient of Thermal Expansion of Dielectric in Direction of its Length = $\alpha_{DL} = \frac{29.7(10^{-6})}{^{\circ}\text{C}}$
- Coefficient of Thermal Expansion of Dielectric in Direction of its Width = $\alpha_{DW} = \frac{45.7(10^{-6})}{^{\circ}\text{C}}$
- Coefficient of Thermal Expansion of Dielectric in Direction of Thickness = $\alpha_{DT} = \frac{56.5(10^{-6})}{^{\circ}\text{C}}$

The dielectric coefficients of expansion vary with temperature and orientation within the material. The values used in the analysis were chosen from measurements previously taken of the dielectric. This data is shown in Figure 1, with the X, Y, and Z directions referring to the length, width, and thickness of the dielectric, respectively. The largest average expansion coefficients for each direction in the -55 to $+75^{\circ}\text{C}$ temperature range were used in the analysis.

Notation

α = coefficient of thermal expansion

L = length of dielectric and opening in housing

W = width of dielectric and opening in housing

t = thickness of dielectric

T = temperature

gap = spacing on a side between the dielectric and the housing

ΔL = change in length

ΔW = change in width

Δt = change in thickness

ΔT = change in temperature

Δgap = change in spacing on a side between the dielectric and the housing

ϵ = engineering normal strain

Figure 1. Antenna Window Thermal Expansion

σ = engineering normal stress

τ = engineering shear stress

E = Young's Modulus

ν = Poisson's Ratio

P = pressure (absolute)

A = cross-sectional area over which pressure or stress acts (perpendicular to normal stresses and pressure, tangent to shear stresses)

Change in Gap Between Dielectric and Housing Because of Temperature Changes

- Along the Length: $\Delta gap_L = (\alpha_{DL} - \alpha_{alum}) \left(\frac{L}{2} \right) (\Delta T)$

$$\Delta gap_{L_H} = (29.7 - 23.4)(10^{-6}) \left(\frac{L}{2} \right) (22 - 75) \text{ (closing of gap at high temperature)}$$

$$\Delta gap_{L_C} = (29.7 - 23.4)(10^{-6}) \left(\frac{L}{2} \right) (22 + 55) \text{ (opening of gap at low temperature)}$$

- Along the Width: $\Delta gap_W = (\alpha_{DW} - \alpha_{alum}) \left(\frac{W}{2} \right) (\Delta T)$

$$\Delta gap_{W_H} = (45.7 - 23.4)(10^{-6}) \left(\frac{W}{2} \right) (22 - 75) \text{ (closing of gap at high temperature)}$$

$$\Delta gap_{W_C} = (45.7 - 23.4)(10^{-6}) \left(\frac{W}{2} \right) (22 + 55) \text{ (opening of gap at low temperature)}$$

Linear Strain in RTV Because of Increase in Gap Between Housing and Dielectric at Cold Temperature

Because the dielectric and aluminum housing are so much more rigid than the RTV, the RTV was assumed to have no ability to create strains in the dielectric or housing. The estimate of the strain in the RTV was equal to the change in the gap between the aluminum and dielectric divided by the original thickness of the RTV (original gap between dielectric and housing).

- Along the Length: $\epsilon_{gapL} = \frac{\Delta gapL_C}{gapL} = 0.104$
- Across the Width: $\epsilon_{gapW} = \frac{\Delta gapW_C}{gapW} = 0.076$

Linear Strain in RTV Because of its Own Shrinkage at Cold Temperature

- For any Direction: $\epsilon_{RTV} = \alpha_{RTV}(\Delta T) = 300(10^{-6})(-55-22) = -0.023$ (*shrinkage*)

Total Linear Strain in RTV Because of its Own Shrinkage and Gap Widening

- Total Strain of RTV: $\epsilon_{RTV(Total)} = \epsilon_{gap} - \epsilon_{RTV}$
- Along the Length: $\epsilon_{L_{RTV(Total)}} = \epsilon_{gapL} - \epsilon_{RTV} = 0.104 + 0.023 = 0.127$
- Across the Width: $\epsilon_{W_{RTV(Total)}} = \epsilon_{gapW} - \epsilon_{RTV} = 0.076 + 0.023 = 0.099$

Constitutive Relationship

A constitutive relationship was needed to determine the stresses in the bond interfaces between the RTV and housing or dielectric caused by the RTV strains. The relationship between stress and strain for elastomers such as this RTV is known to be extremely nonlinear when viewed over its entire elastic range. The strain of the RTV in this analysis makes up only a small portion of the RTV elastic curve (0.127 estimated strain of RTV versus a total possible strain of 3.0 from the 300% elongation at failure material property). To determine if the constitutive behavior of the RTV was linear for this limited 0 to 0.127 range, five tensile specimens were tested ² from a strain range of 0 to 0.25. All five samples were found to be very consistent, and they were linear in the 0 to 0.25 range tested. A copy of the test data from one of the samples is shown in Figure 2. Based on this data, the RTV was modeled as an isotropic linear elastic material. The elastic modulus values calculated from the test data were 284, 272, 281, 283, and 288 psi. The largest value (288 psi) was used.

Two independent material constants are needed to describe an isotropic linear elastic material. By knowing the elastic modulus (Young's modulus for elastic materials), either the shear modulus or Poisson's ratio needed to be determined as the other independent material property. The vendor suggested that most of their products have a Poisson's ratio in the 0.48 to 0.49 range, usually near the 0.49 value, and that using 0.49 was recommended for analysis purposes.

Determination of Stresses on Bond Interface Between RTV and Housing at Cold Temperature

Both shear stresses and normal stresses exist at the bond interfaces. Emphasis was placed on the bond between the RTV and housing because the observed failures occurred at this interface. An illustration of these stresses and their notation is shown in Figure 3. A finite

Figure 2. Test Data From One Tensile Test Specimen

element analysis was made to determine these stresses.

Finite Element Modeling Analysis

Finite Element Modeling Approach for Finding Stresses in RTV and Bond Interfaces

Four separate finite element models of the RTV and dielectric were created by taking advantage of the symmetry of the assembly. The experience gained from a comparison of the first three models was used as a guide to the formulation of the final model. A brief summary of the various models in the order in which they were performed is shown below:

1. 1/4 symmetry model of RTV and dielectric.
2. 1/8 symmetry model of RTV only, with much finer mesh.
3. 1/8 symmetry model of RTV only, with somewhat finer mesh and using two elements through thickness.

Figure 3. Stresses on Bond Interface as Dielectric and RTV Shrink or Expand in Relation to Housing

4. 1/4 symmetry model of RTV only, with somewhat finer mesh.

The RTV and dielectric meshes were modeled as being flat, thereby neglecting the large radius along the length of the dielectric. The surfaces of the RTV that are bonded to the aluminum housing were modeled as a fixed boundary condition in all directions. All coefficients of expansion used were made relative to aluminum by subtracting away the expansion coefficient of aluminum. The solid model and analysis code used was PATRAN3, version 1.1A, using the P3/FEA solver supplied with this software. The elements used in all models were referred to by PATRAN as Hex 20s (20 noded brick-shaped elements). The RTV material was modeled as a linear elastic isotropic material for the small range of strain expected, based on the previous test data. The dielectric in the first model was assumed to be an orthotropic material because its thermal expansion coefficients were dependent on the direction of the axes. A static stress analysis was run on all models, with the original temperature at 22°C (72°F) and then cooled to -55°C (-67°F).

Description of the Finite Element Models

1/4 Symmetry Model of RTV and Dielectric. The first 1/4 symmetry model was developed by dividing the assembly at the centerlines along its length and width with appropriate boundary conditions along these centerlines (centerline along the X-axis constrained in the Y direction with rotations constrained about the X and Z axes, and centerline along the Y-axis constrained in the X direction with rotations constrained about the Y and Z axes). A finite element mesh was made of both the RTV and dielectric. The outside and bottom surfaces of

the RTV which are bonded to the aluminum housing were modeled as a fixed boundary condition in all directions. The RTV mesh used one element across its thickness and four elements along its height. The RTV and dielectric mesh consisted of 676 elements (132 RTV and 544 dielectric) with 3654 total nodes and was as shown in Figure 4.

1/8 Symmetry Model of RTV Only, With Much Finer Mesh. This model was created to determine if significant errors were incurred by the geometry of the RTV elements used in the first 1/4 symmetry model. Because of the thin width of the RTV material, the aspect ratio of the width of the RTV elements in the first model with respect to the other two dimensions was nearly 1:5. The new model was created using a 1/8 symmetry approach. This model was only one-half as tall as the first 1/4 symmetry model and took advantage of the final (X-Y) plane of symmetry which cuts the model into only half its original height. The appropriate boundary condition to reflect symmetry by constraining the bottom surface of the 1/8 symmetry model only in the Z direction (up and down) was applied. A mesh was created of only the RTV elements, with the effects of the dielectric modeled as a displacement field applied along the RTV-to-dielectric bond surface. The magnitude of the displacement field in any given direction equaled the coefficient of expansion (relative to aluminum in that direction of the dielectric material) multiplied by the temperature change and distance from the centerline. By using 1/8 symmetry and eliminating the dielectric mesh, a reasonably sized model was created with many more RTV elements that were nearly cubical in geometry (1008 elements and 7729 nodes). This RTV mesh is shown in Figure 5. This model does not accurately represent the actual antenna assembly because its symmetry implies that both the top and bottom of the RTV are free (in the actual case, the top is free and the bottom is bonded to the aluminum housing). To compare the first 1/4 symmetry model to this model, the boundary conditions of the first 1/4 symmetry model were altered (the fixed boundary condition representing the bottom RTV bond was removed).

When both models were run with a Poisson's ratio of 0.48, the shape and magnitude of the normal stress distributions in the X direction were compared and found to be similar between the two models with a difference in the maximum value of only about 6.5% (403 psi for the 1/4 symmetry model versus 429 for the 1/8 symmetry model). The results of these two runs are shown in Figures 6 and 7.

When both models were run with a Poisson's ratio of 0.49, both the shape and magnitude of the normal stress distributions in the X direction were found to differ much more. The stress distribution of the 1/8 symmetry model was consistent with the previous results, and the normal stress values nearly doubled. The stress distribution of the 1/4 symmetry model was very inconsistent with the previous results of either model, and the normal stress values were not as large as predicted by the 1/8 symmetry model. The magnitude of the maximum normal stress in the X direction for the 1/8 symmetry model was 29% larger than the 1/4 symmetry model (839 psi for the 1/8 symmetry model versus 652 psi for the 1/4 symmetry model). The results of the two models run with a Poisson's ratio of 0.49 are shown in Figures 8 and 9. The discrepancy between these models and the inconsistency of the first 1/4 symmetry model when run at a Poisson's ratio of 0.49 were believed to be caused by either too few nodes through the thickness of the RTV or too few elements along the RTV height. The next 1/8 symmetry model was generated to determine if the inconsistency in the first 1/4 symmetry model was caused by a lack of sufficient nodes through the thickness of the RTV material.

Figure 4. First 1/4 Symmetry Model, RTV and Dielectric

Figure 5. Finest Mesh, 1/8 Symmetry Model, RTV Only

Figure 6. First 1/4 Symmetry Model, 0.48 Poisson's Ratio

Figure 7. First 1/8 Symmetry Model, 0.48 Poisson's Ratio

Figure 8. First 1/4 Symmetry Model, 0.49 Poisson's Ratio

Figure 9. First 1/8 Symmetry Model, 0.49 Poisson's Ratio

1/8 Symmetry Model of RTV Only, With Somewhat Finer Mesh and Using Two Elements Through Thickness. Because of the thin width of the RTV material, the first 1/4 symmetry model and the first 1/8 symmetry model were modeled with only one element through the thickness. This provided only one internal node to resolve the internal displacements of the RTV (three nodes across the thickness with the two outside nodes attached to either the aluminum housing or dielectric). To determine if more internal nodes would affect the solution, a new 1/8 symmetry model was developed with two 20-noded elements across the RTV thickness. This created three nodes through the thickness of the RTV. The mesh consisted of 352 elements and 2325 nodes. This RTV mesh is shown in Figure 10. The same constraints because of symmetry and displacement field representation of the effects of the dielectric used with the previous 1/8 symmetry model were applied. As with the other 1/8 symmetry model, this model also includes an error caused by an implied free surface at the bottom. The model was run with a Poisson's ratio of 0.49. A comparison between the shape and magnitude of the normal stress distributions in the X direction of the two 1/8 symmetry models showed no significant difference because of the number of internal nodes across the thickness of the RTV. There was no significant change in results with the addition of the internal nodes through the thickness. The maximum stress value in the X direction for the model with two elements across the thickness was about 1% lower than the first 1/8 symmetry model (829 psi versus 839 psi for the previous 1/8 symmetry model). The result of this run is shown in Figure 11 and was compared to the results shown previously in Figure 9. Using the experience gained from the first three models, the final model was developed to include more elements along the height, with only one element through the thickness.

1/4 Symmetry Model of RTV Only, With Somewhat Finer Mesh. The final mesh was created of only the RTV material using 1/4 symmetry with one element across the RTV thickness and 10 elements along its height. This combined the advantages of creating more RTV elements (especially along the height) by using field displacement boundary conditions to represent the dielectric with the ability to correctly model the bottom bond of the RTV to the housing by using the 1/4 symmetry model. The RTV mesh consisted of 1000 elements and 7553 nodes. The addition of elements along the height greatly improved the 1/4 symmetry model. The results of this model were very similar to both 1/8 symmetry models. The normal stresses were nearly identical to the 1/8 symmetry models in magnitude and distribution. The normal stress distribution was also very consistent, based on runs made with Poisson's ratios of 0.48 and 0.49. The values of these stresses were nearly cut in half when the Poisson's ratio was reduced to the 0.48 value. This behavior is identical to that of the first 1/8 symmetry model. The stress results of the finite element modeling are based on this final 1/4 symmetry model. The mesh and shape of deformation are shown in Figures 12 and 13 (note that the magnitude of the deformation in Figure 13 is exaggerated for visualization; the actual deformations were much smaller).

Results and Verification Tests of the Final Finite Element Model

The stresses along the bond interface between the housing and RTV consisted of large normal stresses in all three orthogonal directions because of the near incompressibility of the RTV material. The shear stresses were smaller in comparison. The near incompressibility of the material resulted in normal stresses in all three directions (σ_{xx} , σ_{yy} , σ_{zz}) nearly identical in magnitude and distribution. The values of these stresses were very dependent on the value chosen for Poisson's ratio. Based on the analysis and the tests performed to verify the finite

Figure 10. Second $\frac{1}{8}$ Symmetry Model, Two Elements Thick

Figure 11. Third $\frac{1}{8}$ Symmetry Model

Final Model 1/4 Symmetry
RTV Finite Element Mesh

Figure 12. Final 1/4 Symmetry Model

Deflection Plot 10 31 RES 11 F3 PATRAN R12 DISPLACEMENT F3 FEA 17 Jun 93 09
10 31 00 00 00

Final Model 1/4 Symmetry RTV Deformation Shape

Figure 13. Final 1/4 Symmetry Model, Deformation Exaggerated

element model, the normal stresses on the RTV bond surfaces ranged from about 572 to 847 psi, with the largest stresses at the far ends of the housing. The largest shear stresses along the bond surfaces were in the Z direction (τ_{xz} , τ_{yz}), with the maximum shear of about 179 psi on the top edge at the end of the housing. The shear stress in the X or Y directions (τ_{xy}) was much lower, with a worst case maximum value of about 24 psi. The stresses on the bond interface between the RTV and Housing were as shown in Figures 14 through 19. These high tensile stresses acting together in the RTV (nearly a hydrostatic stress state) do not create a stress condition likely to fail the RTV material based on both the Von Mises and maximum shear stress failure criteria. The material specifications require it to have a tensile strength above 500 psi. This 500 psi uniaxial tensile stress corresponds to a Von Mises stress of 500 psi (for uniaxial tension, the Von Mises stress equals the tensile stress) and a maximum shear stress of 250 psi (for uniaxial tension, the maximum shear stress is one-half the tensile stress). The worst case magnitude of the Von Mises stress was about 313 psi, and the worst case maximum shear stress was about 180 psi. The maximum shear stresses and Von Mises stresses are shown in Figures 20 and 21.

The magnitude of the normal stresses were larger than expected. In a further effort to gain insight into the validity of the finite element model, four separate comparison tests were conducted. The tests helped to reinforce the validity of the final finite element model. These tests were as listed below:

- **Comparison to a Simple One-Dimensional Uniaxial Tensile Model.** Before the first 1/4 symmetry finite element model was developed, the normal stresses in the RTV at the ends of the dielectric were calculated using a simple uniaxial tensile model. The normal stresses found by these calculations were only 37 psi (much lower than those found by the three-dimensional finite element analysis). These calculations were made as follows:

$$\sigma = E\varepsilon (\text{Hooke's law for uniaxial loading of a linearly elastic material})$$

$$\sigma = (288 \text{ psi})(0.127) = 37 \text{ psi}$$

This result emphasized the three-dimensional nature of the RTV stress state and the inability of this simplified analysis to accurately determine these stresses. To compare the first 1/4 symmetry finite element model to the one-dimensional calculations, the Poisson's ratio of the RTV was changed to 0.01 (creating a one-dimensional finite element model by virtually eliminating the effects of the other dimensions). The normal stress from this model was found to be about 35 psi in the area at the ends of the dielectric. This proved that if the finite element model was forced to behave in a one-dimensional nature, it agreed with the calculations of a simplified model. The results of this analysis are shown in Figure 22.

- **Comparison to a Simplified Two-Dimensional Plane Strain Model.** A comparison was made between the results of the finite element model and calculations made by assuming plane strain conditions (a body undergoing normal strains on two orthogonal faces, with zero strains in the other orthogonal direction). The zero strain in the third direction is achieved by either constraining movement in this direction or by negligible strains created if this third direction is extremely large when compared to the other two dimensions. This has some similarity to the actual case because the RTV experiences

Figure 14. Final Model, Normal Stress XX

Figure 15. Final Model, Normal Stress YY

Figure 16. Final Model, Normal Stress ZZ

Figure 17-31: PPS 21 PATRA/PAIR 1 (Gauss 2.0) 1317A 17 Jan 93 09:01:53
170.2

Final Model 1/4 Symmetry
RTV Shear Stress XZ (psi) $\nu=.49$

155.6

132.1

113.7

84.91

61.77

37.7

14.19

0.39

2.9

16.53

89.12

100.7

114.3

129.9

174.4

Figure 17. Final Model, Shear Stress XZ

Figure 18. Final Model, Shear Stress YZ

Figure 19. Final Model, Shear Stress XY

Figure 20. Final Model, Von Mises Stress

Figure 21. Final Model, Maximum Shear Stress

Figure 22. First Model, 1/4 Symmetry, Normal Stress XX

normal strains in two dimensions (along its length and thickness) and is constrained by its bond to the housing at the bottom. The top of the RTV is not constrained, however, but the height of the RTV is very large in comparison to its thickness. Based on these similarities, the plane strain assumption should be a good approximation of the actual case. The assumptions made with this approximation were that the RTV experiences uniform strains in tension in the direction of its thickness and length. The strain in the direction of its thickness was caused by the addition of the widening of the gap between the dielectric and housing and by the RTV shrinking on itself. The strain in the direction of the RTV length was caused only by the RTV shrinkage. The equation used in this calculation was equation 4.1.33 from Continuum Mechanics by T. J. Chung.³

- $$\sigma_{XX} = \left[\frac{E}{(1+\nu)(1-2\nu)} \right] [(1-\nu)\epsilon_{XX} + \nu\epsilon_{YY}]$$
- $$\sigma_{XX} = \left[\frac{288}{(1+0.49)(1-0.98)} \right] [(1-0.49)(0.127) + (0.49)(0.023)] = 735 \text{ psi}$$
- $$\sigma_{YY} = \left[\frac{E}{(1+\nu)(1-2\nu)} \right] [(1-\nu)\epsilon_{YY} + \nu\epsilon_{XX}]$$
- $$\sigma_{YY} = \left[\frac{288}{(1+0.49)(1-0.98)} \right] [(1-0.49)(0.099) + (0.49)(0.023)] = 597 \text{ psi}$$

These calculations help to verify the magnitude of the stresses in the finite element model because they represent an assumed constant normal stress of about 597 to 735 psi. This helps to substantiate the magnitude of the normal stresses of the final finite element model which range from about 572 to 847 psi.

- **Comparison of Displacements to the Original Estimates and Constitutive Model.** The magnitude of the displacements found with the finite element model were compared to those estimated by the calculations of the widening of the gap between the housing and dielectric. They were found to be in agreement with the original calculations and the linear elastic constitutive model.
- **Comparison of the PATRAN Solver to a Solution Using ABAQUS.** This was the first practical use of the PATRAN-P3/FEA solver at KCD. To validate its solution, a comparison was made to a similar solution by the ABAQUS software package used by the finite element group. The PATRAN software was used to generate an ABAQUS input file of the first 1/4 symmetry finite element mesh with an RTV Poisson's ratio of 0.48. This model was then run by the finite element group. A comparison of the ABAQUS and PATRAN results showed them to be very similar in both stress magnitudes and distribution.

Determination of Shear Stress From Increase in Pressure at High Temperature

To check whether or not the RTV and its bond interfaces undergo significant stresses because of pressure created by the helium at high temperature, calculations were made using the ideal gas law. Assuming the helium within the assembly is an ideal gas, and taking advantage of the constant volume and mass of helium within the antenna assembly, the ideal gas law gives the relationship for the pressure at high temperature as a function of the ambient pressure and both high and ambient temperatures.

- $P_{a(max)} = 840 \text{ mm Hg} = 111.99 \text{ kPa}_{(absolute)} = 16.24 \text{ psi}_{(absolute)}$
- $T_H = 75^\circ\text{C} = 348^\circ\text{K} = 167^\circ\text{F}$
- $T_a = 22^\circ\text{C} = 295^\circ\text{K} = 72^\circ\text{F}$
- $\frac{P_H}{P_a} = \frac{T_H}{T_a}$

Therefore:

- $P_H = \frac{P_a T_H}{T_a} = \frac{(111.99 \text{ kPa})(348)}{295} = 132.11 \text{ kPa}_{(absolute)} = 19.16 \text{ psi}_{(absolute)}$

Assuming the worst case condition with zero pressure external to the antenna:

- $\tau_{yz} = \frac{P_H A_{Dielectric}}{A_{RTV}} = \frac{P_H (W)(L)}{2(t)[(L) + (W)]}$
- $\tau_{yz} = \frac{132.11 \text{ kPa} (W)(L)}{2(t)(L + W)} = 182.36 \text{ kPa} = 26.45 \text{ psi}$

Attempt to Test Tensile Bond Strength of RTV to Nickel-Plated Aluminum

An attempt was made to determine the adhesive strength of the RTV bond to nickel-plated aluminum under tensile stress (corresponding to the normal stresses in tension found by the finite element model). Five electroless nickel-plated aluminum tensile test specimens were tested in accordance with ASTM D-429-81.⁴ The test specimens were cylindrical with a one-square-inch cross section. The RTV material thickness between the two aluminum cylinders was 0.030 inch. The aluminum samples were placed in a bonding fixture similar to that specified in Figure 10 of ASTM D-429-81. Tests of the samples showed no bond failures. In all cases, the tensile tests failed the RTV material. The highest failure occurred at 405 psi. The RTV fails at a low value under this form of loading. The only conclusion gained from this test was that the bond strength is greater than 405 psi. A method is needed for testing the bond strength while subjecting the RTV to a nearly hydrostatic loading similar to the loading it actually experiences. The bonding fixture and test specimen are shown in Figure 23.

Figure 23. Bonding Fixture and Tensile Test Specimen

Sensitivity of the Stresses to Poisson's Ratio of the RTV

Because the RTV material is nearly incompressible, the magnitude of the stresses in the RTV and its bond interfaces changes dramatically with a small change in the Poisson's ratio of the RTV. The results of this analysis were based on a Poisson's ratio of 0.49. Comparison runs of each finite element model with a Poisson's ratio of 0.48 consistently resulted in the normal stresses being reduced to about one-half the values of those with a Poisson's ratio of 0.49. The results from the final finite element run with a 0.48 Poisson's ratio are shown in Figures 24 and 25.

Effects of Changing the Thickness of the RTV

Duplicates of both the first and the final 1/4 symmetry models were created with the thickness of the RTV material increased to three times its actual width. The expected result was that the normal stresses should decrease. This is caused by the independence of the thermal strain of the RTV to its width and by a strain decrease for a wider RTV undergoing the same displacements caused by the shrinkage of the dielectric. In both cases, the normal stresses

**Figure 24. Final Model, Normal Stress YY,
0.48 Poisson's Ratio**

**Figure 25. Final Model, Shear Stress XZ,
0.48 Poisson's Ratio**

were reduced to about one-half the value of the actual RTV thickness models. The shear stresses along the bond interfaces were also reduced significantly. The results of this evaluation are shown in Figures 26 and 27.

Conclusions From the Analysis of Bond Stresses

The magnitude of the tensile stresses on the RTV bonds was very dependent on the type of loading of the RTV and its material properties. The material is normally very flexible, as evidenced by the low Young's modulus at low strain (about 288 psi), but is nearly incompressible with a correspondingly high Poisson's ratio (about 0.49). The largest strains experienced by the RTV were caused by the dielectric shrinking in relation to the aluminum housing. The thermal strain of the RTV shrinking on itself was smaller in comparison (about 20% of the total strain). These strains created large normal stresses within the RTV and its bonds that were nearly equal in all directions (nearly hydrostatic stress condition). This is because of the near incompressibility of the RTV material coupled with its confinement when bonded within the antenna housing. The large normal stresses from the triaxial stress state occur throughout the RTV, with the largest magnitude of these stresses reaching about 847 psi. The shear stresses were near zero throughout most of the RTV, with values reaching a maximum of about 179 psi at the top edges of the RTV. The normal stresses can be much lower if the Poisson's ratio of the RTV is not 0.49. The normal stresses are cut in half if a Poisson's ratio of 0.48 is assumed for the material, but the best estimates from the material vendor are that the Poisson's ratio is close to 0.49.

The magnitude of the stresses calculated by the finite element model were compared to the minimum requirements of the RTV material specifications. The RTV material must meet a minimum 500 psi uniaxial tensile strength. The comparison between this minimum requirement and the stress state determined by the finite element model was made using both the Von Mises and maximum shear stress failure criteria. Although the normal stresses calculated by the finite element model were high, the nearly equal magnitude of these stresses in all three orthogonal directions is less detrimental to the material than a uniaxial tensile load. The largest Von Mises and maximum shear stresses from the finite element model were about two-thirds the values experienced by a 500 psi uniaxial tensile load. Based on this evaluation, the stresses determined by the finite element model will not cause the material to fail.

It is not known if the 847 psi tensile stresses calculated by the finite element analysis are near a level that will cause the RTV bonds to fail. The attempt to determine the tensile strength of the RTV bonds (using the method prescribed by ASTM D-429-81) was unsuccessful because of failures of the RTV material itself at 405 psi or less under this type of loading. The only conclusion drawn from this testing is that the bond strength is greater than 405 psi. Another method will need to be developed to test the tensile strength of the RTV bonds by better simulating the triaxial stresses experienced by the RTV within the antenna assembly.

The normal stresses in the RTV and its bonds can be lowered by increasing the RTV thickness within the antenna assembly. An analysis run with the RTV thickness increased to three times its original thickness showed the normal stresses to be cut in half.

Figure 26. Final Model, Increased Thickness, Normal Stress YY

Figure 27. Final Model, Increased Thickness, Shear Stress XZ

An analysis was made of the shear stresses caused by an increase in pressure within the antenna assembly as the helium reaches the highest temperature of the thermocycle. The pressure of the helium at high temperature was calculated using the ideal gas law. The force caused by this pressure was then calculated, with the known surface area of the dielectric as part of the calculation. The resulting shear stress on the RTV was evaluated and found to be insignificant.

Process Variables Evaluation

Nickel-plated panels were used to determine the effects that the identified independent process variables would have on the adherence of RTV to nickel plating (the same finish as the housing surface). Figure 28a is a picture of the aluminum panels with five fingers. These panels were used throughout the evaluation to determine changes in the RTV adherence. The panels were (1) chemically cleaned, (2) plasma cleaned, (3) primed with primer and cured, and (4) coated with RTV and cured in a fixture. Figure 28b shows the two panels bonded together with RTV. The panels were then separated into five specimens and shear tested, with the shear strength recorded. Figure 28c is a photo of the finger test specimen after pull testing. Sample #BD2 exhibits an adhesive failure (failure of the primer to adhere to the panel). Sample #BW3 exhibits a desired cohesive failure (failure within the RTV). Figure 28d shows the fixture used to provide an RTV bond line of 0.030 inches with an area of one square inch. The evaluation was divided into three parts. In part 1, shown in Table 1, the plasma cleaning, chemical cleaning, and primer thickness parameters were identified and varied to determine the changes in bond strength using the same primer material used for the TMS lot. The primer shelf life had been extended past the one-year limit by repeating the receiving inspection tests. The production chemical cleaning process definition required trichloroethylene ultrasonic cleaning followed by spray cleaning with trichloroethylene. The plasma cleaning process used argon and oxygen gases, at 0.4 torr and 0.1 torr, respectively. The plasma power used was 400 watts for 1 hour. In part 2, newly received current and proposed primers were evaluated along with plasma cleaning and primer and RTV cure times. Part 3 was a continuation of part 2, with the emphasis on longer primer cure times.

Part 1

The part 1 data shows that the current production definition yields panel lap shear strengths of approximately 100 psi; all failure modes were adhesive. Some higher readings in the upper 100s were obtained by plasma cleaning with pure oxygen or dry air, especially with higher powers and longer plasma cleaning times. However, none of these variables would provide enough RTV adhesion to tear the RTV (cohesive failure) during lap shear testing. The RTV vendor data shows the lap tensile strength to be 500 psi minimum; the expected lap shear strength would be approximately one-half the tensile strength. An alternate primer was also tried but provided about the same data. The shelf life of the alternate primer had also been extended past the one-year specification shelf life.

The dielectric leak problem was evaluated as a joint study by KCD and Sandia Laboratories, NM. The Sandia Project Engineer found that Sandia's supply of the alternate primer exhibited much better bond strengths than the primer used in the KCD Process Characterization

a. ALUMINUM PANELS

b. TWO PANELS BONDED WITH RTV

c. FINGER TEST SPECIMEN AFTER PULL TEST

d. RTV BOND LINE FIXTURE

Figure 28. Bonding Evaluation

Panel Shear Test Data													
Part 1													
Variables - 1) Plasma Cleaning, 2) Primer Thickness, 3) Solvent Cleaning, and 4) Primer vendor													
Exp #	Solvent Clean	Plasma Clean			Primer	RTV	Comments	Shear Strength Data					
		Gas	Power	Time	Vendor	Time	Days		Low	High	Sigma	Ave	
1	Trich/Vac Bake	Arg/Oxy	400 W	1 hr	2 Coat Current	1.5 hrs	5		44	116	38	81.8	
2	Trich/Vac Bake	Arg/Oxy	400 W	1 hr	1 Coats	1.0 hr	5		42	129	30.74	87	
3	Trich/Vac Bake	Arg/Oxy	400 W	1 hr	3 Coats	1.5 hrs	5		78	126	18.17	95	
4	Trich/Vac Bake	Arg/Oxy	400 W	1 hr	1 Coat Alcohol Diluted	1.5 hrs	5		0	24	12.4	16	
5	Alcohol Spray	Oxygen	400 W	1 hr	1 Coats	1.5 hrs	5		78	138	21.7	103	
6	Alcohol Spray	Oxygen	400 W	1 hr	2 Coat	1.5 hrs	5		72	108	22.18	78.6	
7	Alcohol Spray	Oxygen	400 W	1 hr	3 Coats	1.5 hrs	5		83	172	40.4	124	
8	Alcohol Spray	Oxygen	400 W	4 hrs	1 Coats	1.5 hrs	5		133	184	18.64	159	
11	Trich/Vac Bake	Arg/Oxy	400 W	2 hrs	1 Coats	1.5 hrs	5		46	135	38	95	
12	Alcohol Spray	Oxygen	400 W	2 hrs	1 Coats	1.5 hrs	5		24	76	20.8	58	
13	Trich/Vac Bake	Oxygen	800 W	1 hr	1 Coats	1.5 hrs	5		181	210	11	197	
15	Alcohol Spray	Oxygen	400 W	1 hr	1 Coats	1.5 hrs	5		61	167	41.27	123	
16	Alcohol Spray	Oxygen	400 W	1 hr	1 Coat Proposed	1.5 hrs	5		77	116	18.18	93	
18	Alcohol Spray	Oxygen	600 W	1 hr	1 Coats Current	1.5 hrs	5		133	179	21	151	
19	Alcohol Spray	Dry Air	400 W	1 hr	1 Coats	1.5 hrs	5		214	375	66	275	
20	Alcohol Spray	Oxygen	600 W	3 hrs	1 Coats	1.5 hrs	5		124	186	25	164	
22	Alcohol Spray	Oxygen	400 W	3 hrs	1 Coats	1.5 hrs	5		0	90	40	41	
24	Alcohol Spray	Dry Air	400 W	1 hr	1 Coats	1.5 hrs	5		114	254	68	173	
25	Alcohol Spray	Dry Air	400 W	3 hrs	1 Coats	1.5 hrs	5		114	221	39	174	
26	Alcohol Spray	None	0 W	0 hr	1 Coats	1.5 hrs	5		36	90	20	59	
28	Alcohol Spray	None	0 W	0 hr	1 Coats	1.5 hrs	5	2/22/93	41	59	7	48	
29	Alcohol Spray	Dry Air	800 W	1 hr	1 Coats	1.5 hrs	5	2/22/93	68	127	22	109	
30	Alcohol Spray	Oxygen	800 W	1 hr	1 Coats	1.5 hrs	5	2/22/93	54	120	28	78	
31	Alcohol Spray	Arg/Oxy	800 W	1 hr	1 Coats	1.5 hrs	5	2/22/93	57	87	12	66	
32	Alcohol Spray	Dry Air	600 W	2 hrs	1 Coats	1.5 hrs	5	2/25/93	165	225	38	209	
33	Alcohol Spray	Dry Air	600 W	2 hrs	1 Coats	1.5 hrs	5	2/25/93	100	108	6	105	
34	Alcohol Spray	None	0 W	0 hr	1 Coats	1.5 hrs	5	2/25/93	59	80	7	72	
35	Alcohol Spray	None	0 W	0 hr	1 Coats	1.5 hrs	5	2/25/93	39	63	10	54	
36	Alcohol Spray	None	0 W	0 hr	1 Coats	2.0 hrs	5	Air dry primer	29	94	26	74	
37	Alcohol Spray	None	0 W	0 hr	1 Coats	2.0 hrs	5	Air dry pri/RTV	0	0	0	0	
38	Alcohol Spray	None	0 W	0 hr	1 Coats	1.5 hrs	5	No RTV deair	87	122	15	100	
39	Brush Clean	None	0 W	0 hr	1 Coats	2.0 hrs	5	No RTV deair	60	111	26	81	

Table 1. Panel Shear Test Data, Part 1

part 1 study. The Sandia engineer had used a minimum of 2 hours primer cure time for his evaluation, whereas the part 1 KCD study had been done with the production drawing specified minimum primer cure time of 1.5 hours. A quantity of the Sandia Dow primer was obtained and evaluated with a 2-hour primer cure. The results were somewhat better than the KCD primer cured for 1.5 hours, but the results were not as high as the Sandia data.

Part 2

Quantities of two vendor's new primers in Receiving Inspection going through acceptance testing were obtained and used to determine if the primers evaluated in part 1 were acceptable for the application. Characterization data with the new primers is tabulated in Table 2. The first quart of primer was identified as D2 and the second quart obtained from production stores was identified as D3. The new primer was identified as G2. The parameters evaluated in part 2 were (1) primer cure time, (2) RTV cure time, and (3) repeat of some of the part 1 study parameters. The new Dow3 primer with 1.5 hours (experiment number 59) cure time did not look any better than the old GE primer. When the primer cure time was extended to 2 hours, the lap shear strength increased but most of the failure modes were still adhesive failures (peeling loose from the panel). Also, the new G2 data samples provided unacceptable results, so most of the characterization was done with the new D3 primer. When the primer cure time part of the experiment was completed, the 4 or more hours cure time provided the data that was needed. The average lap shear strength was in the 400 psi range, with cohesive failures (Figure 29).

Part 3

In part 3 of the study, the experiments were continued with 4 or more hours of primer cure time. These results are shown in Table 3. The new G2 primer was tried again with 4 hours cure and the results were still unacceptable. The 4 hours primer cure was considered a minimum cure time for the D3 primer and would be marginal with humidity near the 50% lower limit. The manufacturer states that "if the humidity is decreased by 1/2, the cure time must be doubled." To lengthen the primer cure time above 4 hours, an overnight cure would work best with the part processing. The cure times were lengthened to see if there were detrimental effects with the longer cure times. The results were very good. Figure 30 shows a graph of the part 1, 2, and 3 lap shear strength results for comparison.

Primer Evaluation

During development of the antenna, the current primer exhibited high shear strengths, even higher shear strengths than the proposed primer. The Sandia engineer repeated the evaluation using the new lot of current primer and the same type of anodized panels. The results showed the decrease in shear strength being experienced on the antenna evaluation. It appears that the formulation has changed over time since the evaluation was completed. This information explains why the leak rate on the antenna was so much higher.

Panel Shear Test Data												
Part 2												
Variables - 1) Primer Vendor, 2) Plasma Cleaning, and 3) Primer and RTV cure times												
Exp #	Solvent	Plasma Clean			Primer Ident.	RTV Time	Comments	Shear Strength Data				
		Gas	Power	Time				Low	High	Sigma	Ave	F. Mode
40	Alcohol	None	0	0	SNL SNL Current	2	5	KCD Bonded	72	198	43	153
41	Alcohol	Dry Air	600	2		2	5	KCD Bonded	173	259	37	226
42	Alcohol	None	0	0		2	5	New Lot				90
43	Alcohol	None	0	0		2	5	New Lot	193	426	92	350
44	Alcohol	Dry Air	600	2	Current	2	5	New GE	13	54	18	35
45	Alcohol	Dry Air	600	2		2	5	No Test, Operator error				
46	Alcohol	None	0	0		2	5	Eval Gas Type	51	156	44	91
47	Alcohol	Argon/Oxy	600	1		2	5	Eval Gas Type	18	54	16	39
48	Alcohol	Oxygen	600	1		2	5	No Test				
49	Alcohol	Dry Air	600	1		0.5	5	Eval Gas Type	54	66	8	59
50	Alcohol	Dry Air	600	1		1.5	5	Apply primer 0.5 hrs after plasma	75	137	25	108
51	Alcohol	Dry Air	600	1		1.5	5	Apply primer 3 hrs after plasma	60	96	13	79
52	Alcohol	Dry Air	600	1		0.5	5	Apply primer 0.5 hrs after plasma	7.2	78	34	38
53	Alcohol	None	0	0		2	5	Normal	81	275	76	163
54	Alcohol	None	0	0		2	5	Wipe-off Excess Primer	47	75	14	66
55	Alcohol	None	0	0		2	5	Cure RTV @ 25% RH - Did not cure.	0	0	0	0
56	Alcohol	None	0	0		2	3	Cure RTV 3 days, bench cure	24	50	8	36
57	Alcohol	None	0	0		2	5	Cure RTV 5 days, bench cure	45	77	13	62
58	Alcohol	None	0	0		2	7	Cure RTV 7 days, bench cure	84	117	14	93
59	Trichloro/Bake	Argon/Oxy	400	3		1.5	5	Control Sample, 3/30/93	66	135	28	96
60	Alcohol	None	0	0		0.5	7	0.5 Primer Cure	0	42	8	34
61	Alcohol	None	0	0		1	7	1.0 Primer Cure	55	69	5	63
62	Alcohol	None	0	0		2	7	2.0 Primer Cure	95	299	86	170
63	Alcohol	None	0	0		4	7	4.0 Primer Cure	263	354	44	337
64	Alcohol	None	0	0		1.5	6	Control sample, 3/30/93	174	221	19	192
65	Alcohol	Dry Air	400	1		2	5		139	278	51	205
66	Alcohol	Dry Air	400	2		2	5		167	286	45	225
67	Trichloro/Bake	Dry Air	400	3		1.5	5	Control sample, 3/31/93	84	115	15	100
69	Trichloro/Bake	Argon/Oxy	400	3		1.5	5	Control sample, 4/2/93	132	169	14	148
70	Alcohol	None	0	0		79	6	Cure primer over weekend	288	467	77	367
71	Alcohol	None	0	0		64	6	1st coat, weekend; 2nd coat, 4 hrs	333	494	63	384
72	Alcohol	None	0	0		4	14	Cure primer 4 hrs, RTV 14 days	386	492	42	429
73	Alcohol	None	0	0		4	7	Cure primer 4 hrs, RTV 7 days	233	339	44	295
75	Trichloro/Bake	Argon/Oxy	400	3		8	5	process, overnight cure	230	511	106	397
76	Trichloro/Bake	Argon/Oxy	400	3		8	5	process, overnight cure	368	456	45	418
77	Trichloro/Bake	Argon/Oxy	400	3		8	5	process, overnight cure	336	416	31	380
78	Trichloro/Bake	Argon/Oxy	400	3		8	5	process, overnight cure	281	318	15	300

Table 2. Panel Shear Test Data, Part 2

Primer
Cleaning - Alcohol wipe. Plasma - Dry Air, 400 W., 1 hr
Overnight primer cure - RH approx. 70%

Primer
5 day RTV Cure Time - RH approx. 70%
No Plasma Cleaning

Figure 29. Primer and RTV Cure Time Effects

Panel Shear Test Data													
Part 3													
Variables - 1) Plasma Cleaning, and 2) Primer and RTV cure times													
EXP #	Solvent	Plasma Clean			Primer		RTV	Comments	Shear Strength Data				
		Gas	Power	Time	Vendor	Time	Time		Low	High	Sigma	Ave	F. Mode
79	Alcohol Wipe	Dry Air	400	1		4	5	4 hr primer cure, 5 day RTV cure.	370	458	35	427	85% Cohes.
80	Alcohol Wipe	Dry Air	400	1		4	5	4 hr primer cure, 5 day RTV cure.	330	464	50	382	80% Cohes.
81	Alcohol Wipe	Dry Air	400	1		4	5	4 hr primer cure, 5 day RTV cure.	288	504	90	384	95% Cohes.
82	Alcohol Wipe	Dry Air	400	1		4	5	4 hr primer cure, 5 day RTV cure.	440	522	35	484	85% Cohes.
83	Tri. V. Bake	Argon/Oxy	400	3		4	5	Control Sample 4/16/93, 5 day RTV	328	420	33	378	90% Cohes.
84	Alcohol	None	0	0		4	4	4 day RTV cure time	376	446	28	409	90% Cohes.
85	Alcohol	None	0	0		4	5	Specimen had no strength	0	0	0	0	100% Adhes.
86	Tri. V. Bake	Argon/Oxy	400	3		18	7	Control Sample 4/20/93, 7 day RTV	430	489	19	456	85% Cohes.
87	Tri. V. Bake	Argon/Oxy	400	3		18	6	Control Sample 4/21/93, 6 day RTV	388	430	18	408	85% Cohes.
88	Alcohol	None	0	0		4	5	5 Day RTV Cure	360	540	81	418	95% Cohes.
89	Alcohol	None	0	0		5	5	5 Day RTV Cure	0	0	0	0	100% Adhes.
90	Alcohol	Argon/Oxy	400	3		18	5	5 day RTV cure, overnight primer cure	504	642	60	599	90% Cohes.
91	Alcohol	Dry Air	400	3		18	5	5 day RTV cure, overnight primer cure	360	540	69	451	95% Cohes.
92	Alcohol	Dry Air	400	3		18	5	5 day RTV cure, overnight primer cure	360	540	67	468	85% Cohes.
93	Alcohol	Dry Air	400	3		18	5	5 day RTV cure, overnight primer cure	340	536	81	428	95% Cohes.
94	Tri. V. Bake	Argon/Oxy	400	3		18	6	Control Sample 4/28/93, 6 day RTV	344	496	67	408	85% Cohes.
95	Alcohol	Dry Air	400	3		16	3	RTV cure study, 3 day cure	250	416	73	324	95% Cohes.
96	Alcohol	Dry Air	400	3		16	4	RTV cure study, 4 day cure	227	485	100	394	95% Cohes.
97	Alcohol	Dry Air	400	3		16	5	RTV cure study, 5 day cure	366	518	57	442	95% Cohes.
98	Alcohol	Dry Air	400	3		16	9	RTV cure study, 9 day cure	319	516	79	455	95% Cohes.
99	Alcohol	None	0	0		22	5	Cure Primer, Workbench, 30-40%RH	108	198	38	133	10% Cohes.

Table 3. Panel Shear Test Data, Part 3

99 PSI

Figure 30. Comparison of Lap Shear Strengths, Part 1, 2, and 3

Process Characterization

A process characterization study was initiated. The goal was to define changes and controls to the design and processes required to provide high yields. A flowchart of the assembly process (Figure 31) was prepared to provide an understanding of the processes involved in sealing the dielectric into the housing. Also, a cause and effect diagram, shown in Figure 32, was prepared to identify dependent variables in the process that could affect the RTV bonding process yields. The independent variables believed to be most important were identified before and again after the study. These variables are shown in Figure 33. Each of the process steps was reviewed to see if process improvements could be identified. Following are the review results for each process step.

Chemical Cleaning. The defined production cleaning process was to ultrasonic clean the housing and dielectric for 20 minutes in trichloroethylene followed by a spray clean with trichloroethylene. Then the parts were vacuum baked to drive off the halogens before beginning the plasma cleaning process. Because the plant directive is to eliminate trichloroethylene from all processes by July 1993, another suitable cleaning solvent was needed. Because alcohol seemed to be the best substitute from a handling standpoint, it was tried first as a replacement for trichloroethylene. Tables 1, 2, and 3 (process evaluation study parts 1, 2, and 3) show the results obtained when the current cleaning process was used and when parts were spray cleaned with alcohol without the vacuum bake process.

- From the experiments, the conclusions were as follows.

No changes were detected between panels cleaned with the current cleaning process and with the new proposed process using alcohol without vacuum baking. The recommended process is

1. Solvent wipe or spray clean with alcohol, and
2. Eliminate vacuum bake.

Plasma Cleaning. The housing and dielectric are placed into the plasma cleaner for surface cleaning. A plasma gas consisting of argon at 0.4 torr pressure and oxygen at 0.1 torr was used with a plasma power of 400 watts for 1 hour. The plasma cleaning variables identified to evaluate were gas type, power, and time. The two primers available for the study had just passed incoming tests to have the shelf life extended beyond the one-year requirement for six months.

Figure 29 shows the results of varying the plasma cleaning parameters.

- From the study, the following conclusions were drawn.

1. Dry air and oxygen were somewhat more effective than argon/oxygen as a cleaning gas. Because dry air, a single gas, requires less safety controls than oxygen and is just as effective, changing to dry air as the plasma gas is recommended.
2. Longer cleaning times and higher plasma power tend to improve results, but not significantly.

Figure 31. Current Dielectric Sealing Process Steps

Figure 32. Cause and Effect Diagram of Variables That Can Affect Yields

PROCESS: DIELECTRIC SEALING

RANK: NUMBER RANKING WITH 1 BEING THE HIGHEST

MACHINE/PROCESS

Dependent	Leak Integrity	
	Before Study	After Study
Primer Vendor	5	1
Primer Cure Time		2
Primer Cure Relative Humidity	6	3
Primer Thickness	4	10
Plasma Cleaning Gas Type	1	7
Plasma Cleaning Treatment Time	2	8
Plasma Cleaning Gas Chamber Pressure		
Plasma Cleaning Power Level	3	9
RTV Cure Time		4
RTV Cure Relative Humidity	7	5
RTV Mix Ratio	8	
RTV Mix Uniformity	9	6
Chemical Cleaning Solvent	10	
Dielectric Movement During RTV Cleanup		

Figure 33. Ranking of Process Variables

Primer Cure. As stated earlier, joint studies at Sandia using the primer exhibited much better bond strengths than the primer used in the KCD process characterization study, with lap shear strengths greater than 300 psi. Experiments were outlined to characterize the process and to identify changes required to achieve the higher shear strengths. In the part 1 study, only a few of the pull test samples averaged a pull strength above 150 pounds and

were showing some RTV cohesive failure indications. The new results shown in Table 3 as D2 and D3 with 2-hour cure times were improved with pull strengths of some samples greater than 200 pounds and cohesive failures greater than 50%. Some new primer, identified as G2, was also obtained from Receiving Inspection, and the results are shown in Table 2. The results of the G2 primer were not as good as the original primer used in part 1 (Table 1). A decision was made to continue the studies with only the new D3 primer.

Cure Time. The primer cure time was varied from 0.5 hours to 80 hours. The results of varying the cure time are shown in Figure 29. The results indicate that a minimum of 4 hours is needed to obtain near maximum shear test results.

- This conclusion was drawn:

The currently defined cure time of 1.5 hours minimum should be extended to at least 4 hours.

Thickness. The technical notes supplied by the primer manufacturer stated, "apply a thin coat of primer to the surface to be bonded." One coat was applied to a panel, and the thickness measured was 0.0005 inches (1/2 mil). In the plasma cleaning studies of Tables 1 and 2 (experiment 71), two coats were applied without any significant degradation in pull strength. One panel was primed and the excess was removed with a dry Q-tip swab to simulate a very thin coat (Table 2, experiment 54). The results showed a significant reduction in pull strength.

- This conclusion was drawn:

One coat of primer is preferred, but primer buildup when an antenna is reworked and all of the first primer coat is not removed should not cause a significant reduction of RTV adhesion.

Relative Humidity. The technical note recommends using humidity to cure the primer, stating that cure time should be doubled for every halving of the humidity. Because the RTV technical note recommends 50% minimum, most of the testing was done using the 50% minimum requirement. Experiment number 89 (Table 3) was conducted by curing the primer in the factory open air (which has a relative humidity of 20 to 25%) to see if humidity has an impact on the RTV pull strengths. The resultant pull strengths were 0 psi, indicating the primer had not cured. To see if longer cure times at the lower humidity level would improve the results, the primer was cured overnight in experiment number 99 (Table 3) with 30 to 40% relative humidity; the results were improved but still unacceptable.

- This conclusion was drawn:

A relative humidity of 50% minimum is required for primer curing.

RTV Cure. The RTV used is a two-part mix sold as a base and catalyst. The RTV is an organo-tin catalyzed condensation cure system which does not require moisture or other outside agent to cure, according to the manufacturer's literature.

Relative Humidity. Experiments were performed to see if humidity was required to cure the RTV by curing the panels in the factory open air environment; after 10 days the RTV had not completed its cure. The humidity was 20 to 25% in the factory. The panels were then placed into the humidity cabinet to cure, but the RTV still remained tacky after several days of cure. Other panels were cured with humidity between 50 and 90% with no differences noted.

- This conclusion was drawn:

The RTV must be cured in a humidity cabinet with a minimum humidity of 50%.

Cure Time. Studies were run with cure times of 3, 4, 5, and 9 days. The data shown in Figure 29 indicated 5 days cure time has adequate margin.

- The recommendation is to cure the RTV for a minimum of 5 days.

Process Controls

The part I Characterization Study identified changes in the process parameters that would improve the primer/RTV bond strength. This section will discuss the process controls needed to ensure that repeated results are obtained from the antenna sealing process and identify areas where documentation is needed.

Primer Acceptance

During the part 1 evaluation (Table 1), both primers did not provide acceptable adhesion to the nickel-plated panels. Both primers' shelf lives had been extended, and primer degradation over time was thought to be the failure cause. To see if the old material would pass the incoming acceptance tests again, panels normally used to perform incoming acceptance tests on the primer were sent to Receiving Inspection for retesting of the primer. These test panels are different from the panels used in parts 1, 2, and 3 studies in that they are aluminum with a sandblasted surface to enhance adhesion. After being retested, the panels were prepared for bonding by rinsing them in an acid solution to further promote acceptable bonding. Again, the primer passed Receiving Inspection testing with plenty of margin. Future studies to establish the proper shelf life for the primer are recommended.

- The following changes are recommended.

Materials engineering was asked and agreed to make a special drawing to

1. Qualify the primer for the antenna nickel-plated application and restock the primer under a new stores number,
2. Repackage the primer in smaller containers, and
3. Shorten the primer shelf life until studies can be completed that support a longer shelf life.

Primer Cure

The humidity requirement in the bonding specification called for a humidity cabinet with a 50% relative humidity. The cabinet being used was of plexiglass construction with cups of water containing lint-free cloths as wicks to disperse the moisture. The humidity indicator used was moisture-sensitive strips that have spots that change color. The spots are at 10% RH increments, and the humidity is read by seeing which spot is lavender (between pink and blue). These indicators are not very accurate, and the operator may not notice that the humidity has fallen below 50% during the 5-day cure.

- The changes recommended are as follows.
  1. Add a circulating fan to the cabinet to keep the air moving and to promote evaporation of moisture from the wicks.
  2. Modify the shelving to allow air to move more freely around the cabinet.
  3. Add a permanent humidity recorder to provide a permanent record of the cabinet humidity for verification that the specification requirements were satisfied.
  4. Replace the door with a door with top and bottom latches to provide a better seal.

RTV Mixing/Evacuation

There are four variables in the mixing process that could affect the overall RTV mixing results: mix ratio, mix consistency, evacuation, and mix time before use. These items were reviewed to see if controls are required for consistently acceptable results.

Mix Ratio. The mix ratio is defined as a 10:1 mix. The Sandia engineer did some evaluation of the proper mix ratio. His conclusion was that the 10:1 mix was still the preferred mix. There was not any data available to support the tolerance needed for the RTV mix. The bonding specification did not call out a tolerance. Materials Engineering was contacted and recommended a product tolerance $\pm 1\%$ by weight for each part of the mix. The 1% applied to the 3 grams of catalyst is difficult for the operators to obtain. The 1% tolerance will be accepted with further study recommended to relax the tolerance of the catalyst.

- The following action was recommended and incorporated.

A programmable scale was located and programmed to require the $\pm 1\%$ by weight for the base material before the scale accepts the reading and asks for the catalyst to be added to the mix, also with a $\pm 1\%$ requirement. When the mix requirements are satisfied, the scale prints out the weight of each material and the final mix. The RTV information is retained and attached to a process record sheet to be kept in the department as a permanent record. The process sheet will be covered later in the report.

Mix Consistency. The RTV parts are very stiff to mix and because so little of the catalyst is used, the complete mixing of the catalyst into the base is very important. To accomplish thorough mixing, the RTV material is scraped from the spatula into the mix occasionally and the material against the container wall is also scraped away from the wall and included in the

mix to ensure that all the mix is consistent. The spatula is again cleaned before the RTV is removed from the container with the spatula and applied to the antenna and dielectric.

- The change recommended is to revise the traveler to provide more detailed instructions to the operators on how to properly mix the RTV.

Evacuation Process. The purpose of the evacuation process is to remove air from the RTV mix that could later cause a leak around the antenna. The process was reviewed and found to be acceptable. The traveler instructed the operator to spread the material out around the wall of the container to provide a thinner layer of material that will give up air more readily when the vacuum is pulled.

Mix Time. The drawing specifies a 2-hour life after the RTV is mixed. The traveler covered this requirement, and when the process was observed, the operators applied the RTV to the units as soon as the mix was completed. Usually, two operators are used to complete the job more quickly.

RTV Application. The process was reviewed and changes are not recommended.

Dielectric Installation. The dielectric is installed into the housing, and by dimensional control, the RTV bond line thickness is approximately 0.010 inches. The material provides the alignment. Some setscrews located on the sides of the dielectric provide enough restraint to keep the dielectric in position but do not provide alignment.

- The change recommended is as follows.

Change the traveler to emphasize to the operators that they must be careful, when cleaning the excess RTV from around the dielectric, to not apply pressure on the dielectric and cause movement.

RTV Curing. The RTV curing requirement defined by the bonding specification was to cure for 5 days minimum at a relative humidity of 50% minimum. This requirement is acceptable and no controls are recommended, other than the controls stated in the "Primer Cure" section.

Sealing Process Record

With increased emphasis on process controls and verification, a permanent record of the processes performed by date, time, and operator was needed for future reference. The dielectric sealing record sheet was developed and incorporated to provide a permanent record of the process used. This process record is shown in Figure 34. Figure 35 is a flowchart of the proposed dielectric sealing process steps.

Process Verification Panel

With each group of antennas bonded, it is recommended that control panels be bonded together (see Figure 28) and pull tested as part of the process verification to be certain the process and materials are acceptable. The results from the pull test would be used to validate the process for that group of antennas.

DIELECTRIC SEALING PROCESS RECORD

Issue Date: 08/18/93

DATE

S/N

1 ALCONOL CLEAN

START TIME

CHECK
HERE IF
REWORKED

2 PLASMA CLEAN

START TIME

FINISH TIME

1 HR (New Units)
2 HRS (Reworked Units)

3 PRIMER CURE TIME and LOT NO.

START TIME

FINISH TIME

LOT NO.

12 hrs (minimum)

4 MDX RTV

TAPE SCALE PRINTOUT HERE

6 EVACUATE RTV

START TIME

FINISH TIME

7 SEALING OPERATION

START TIME

FINISH TIME

8 RTV CURE TIME and LOT NO.

START TIME

FINISH TIME

LOT NO.

9 PROCESS TIME VERIFICATION

TIME #1 SUBTRACT STEP 7 FINISH TIME FROM STEP 1 FINISH TIME
REQUIREMENT = 32 HRS MAXIMUM

TIME #2 SUBTRACT STEP 7 FINISH TIME FROM STEP 5 PRINTOUT TIME
REQUIREMENT = 2 HRS MAXIMUM

HRS MIN

Figure 34. Dielectric Sealing Process Record Sheet

Figure 35. Proposed Dielectric Sealing Process Steps

Accomplishments

The antenna assembly TMS lot experienced areas of nonadherence between the dielectric and housing. The root cause was determined to be the performance of the primer used to enhance the RTV adhesion when the dielectric is sealed into the housing. The primer formulation had changed over time, coupled with a primer cure time that was marginal. The study has shown that changing to another primer and increasing the primer cure time has corrected the problem.

Performance to date is 100% yield on over 90 units assembled and tested. FEM analysis of the design and shear test specimens shows that the bond strengths predicted are within those provided by the process. The FEM study also indicates that additional margin could be realized by redesign.

References

¹ *Materials Engineering, Materials Selector 1991 Issue*. Penton Publishing, Inc., Cleveland, Ohio, December 1990.

² ASTM D-412-87, "Standard Test Methods for Rubber Properties in Tension." approved 1987.

³ T. J. Chung, *Continuum Mechanics*. Prentice Hall, Inc., Englewood Cliffs, New Jersey, 1988, p 116.

⁴ ASTM D-429-81, "Standard Test Methods for Rubber Property-Adhesion to Rigid Substrates." approved 1981, re-approved 1988.

**DATE
FILMED**

8/24/94

END