"WORMHOLE" FORMATION IN RSRM NOZZLE JOINT BACKFILL

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Abstract

The RSRM nozzle uses a barrier of RTV rubber upstream of the nozzle O-ring seals. Post flight inspection of the RSRM nozzle continues to reveal occurrence of "wormholes" into the RTV backfill. The term "wormholes", sometimes called "gas paths", indicates a gas flow path not caused by pre-existing voids, but by a little-understood internal failure mode of the material during motor operation. Fundamental understanding of the mechanics of the RSRM nozzle joints during motor operation, nonlinear viscoelastic characterization of the RTV backfill material, identification of the conditions that predispose the RTV to form wormholes, and screening of candidate replacement materials is being pursued by a joint effort between Thiokol Propulsion, NASA, and the Army Propulsion & Structures Directorate at Redstone Arsenal.

The performance of the RTV backfill in the joint is controlled by the joint environment. Joint movement, which applies a tension and shear load on the material, coupled with the introduction of high pressure gas in combination create an environment that exceeds the capability of the material to withstand the wormhole effect. Little data exists to evaluate why the material fails under the modeled joint conditions, so an effort to characterize and evaluate the material under these conditions was undertaken.

Viscoelastic property data from characterization testing will anchor structural analysis models. Data over a range of temperatures, environmental pressures, and strain rates was used to develop a nonlinear viscoelastic model to predict material performance, develop criteria for replacement materials, and quantify material properties influencing wormhole growth.

Three joint simulation analogs were developed to analyze and validate joint thermal barrier (backfill) material performance. Two exploratory tests focus on detection of wormhole failure under specific motor operating conditions. A "validation" test system provides data to "validate" computer models and predictions. Finally, two candidate replacement materials are being screened and "validated" using the developed test systems.

INTRODUCTION

Each reusable solid rocket motor (RSRM) uses an ablative nozzle to provide thrust control and guidance for the Space Shuttle system during launch. The nozzle's function in the RSRM motor is to contain and direct the combustion products in a controlled manner. The nozzle is made up of a myriad of materials including insulating and ablating carbon cloth, glass cloth, and silica cloth phenolic parts, supported by a structure of steel and aluminum housings. Internal motor pressures can be nearly 1000 psi in locations around the nozzle. The nozzle rotates about two axes to steer the Space Shuttle. A flex bearing of steel and rubber connects the housings to the motor case to allow this movement.

The nozzle is assembled out of several subassemblies, each containing multiple parts. These assemblies are joined by either bonding or bolting. There are several internal sealing joints in the RSRM nozzle. The joints are backfilled with a room temperature vulcanizing (RTV) silicone rubber. The specific material used is DC 90-006 RTV supplied by Dow Corning.

WORMHOLING IN RSRM NOZZLE JOINTS

To backfill a nozzle joint, RTV is injected into the assembled joint and allowed to cure. Postflight inspection of the joint reveals that the DC 90-006 permits "wormholes" to form through the material during motor operation. Changes to processing procedures eliminated trapped air-formed "gas paths", but the continued occurrence of "wormholes" has prompted further study of the DC 90-006 material.

The term "wormholes", sometimes called "gas paths", denotes a gas flow path into or through the material. The cause of wormholes is not pre-existing voids, but a little-understood internal failure mode of the material during motor operation. Previous testing demonstrated that meandering voids can be induced in the RTV material when high-pressure gas is injected into an RTV-filled gap. The test set up, dubbed the "Crook Blowpath", consists of two 6-inch square plates with a 0.050" gap filled with RTV between them (reference Figure 1). The plates were compressed, and 900-psi nitrogen was injected through the middle of the bottom plate. The pressure was varied on the plates to determine at what pressure the RTV would allow gas paths to form. It was discovered that with 200-psi compression or less on the plates, RTV would allow gas paths to form and to find their way through to the outer edge of the gap. It was observed that the failure of the RTV was not an adhesive failure between the RTV and the plate, but rather a cohesive failure in the material. Additionally, the development of these meandering voids, called "wormholes" did not require high temperature to form. A material with higher tensile strength was sought to replace DC 90-006 as a backfill material. Lacking any data to support tensile strength as the only criteria for selecting an alternative material, and lacking sufficient data to understand why DC 90-006 fails in this manner prompted a study of DC 90-006 mechanical properties. The approach to analyzing this material is shown in the flow chart, Figure 2.

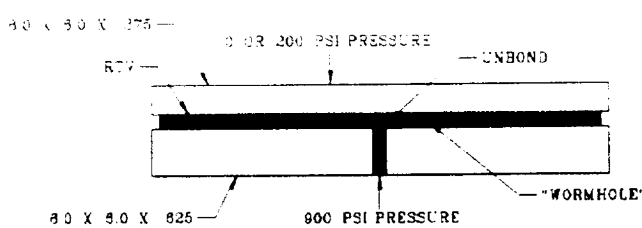


Figure 1 Crook Blowpath Configuration

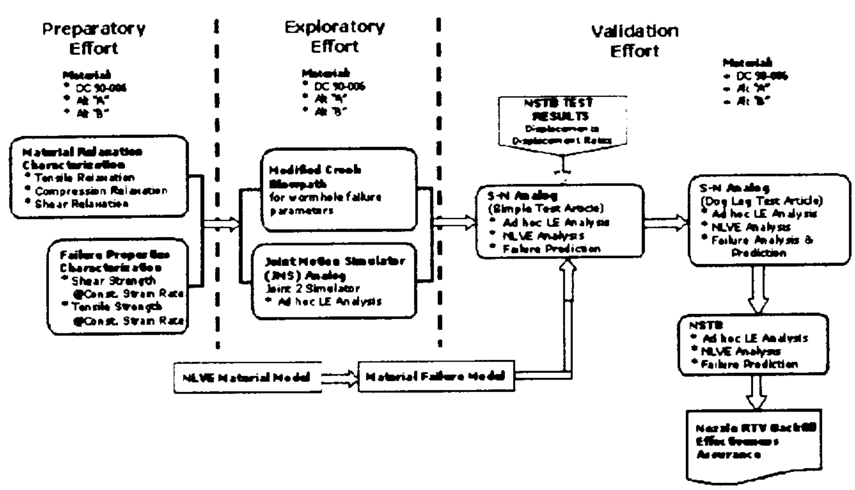


Figure 2 Task Logic Flow for NLVE Characterization of DC 90-006 and Analog Testing

DC 90-006 MATERIAL CHARACTERIZATION AND MODELING

As a silicone-based polymer, it was expected that DC 90-006 would exhibit some nonlinear viscoelastic (NLVE) material characteristics. The extent of nonlinearity and viscoelasticity was not known, so a test matrix was developed to determine tensile and shear strength and tensile, compression, and shear relaxation moduli. Some of the tensile strength testing and all of the relaxation testing was performed in a pressure chamber with an environmental pressure of 900 psig to determine if pressure affected the viscoelastic properties.

MATERIAL PROPERTY /TEST SPECIMEN	TEST PRESSURE (psig)	TEST TEMPERATURES (degrees F)	STRAIN or STRAIN RATE or CROSSHEAD RATE
Tensile Relaxation	1000	40, 75, 110	0.05 in/in
JANNAF Class A Dogbones			0.15. 0.25,
1 x 3 x .50			0.35, 0.45
Compressive Relaxation	1000	40, 75, 110	0.05 in/in
Compression Cylinder			0.15, 0.25
1" diameter x 1 " long			0.35, 0.45
Shear Relaxation	1000	40, 75, 110	0.05 in/in
Quadruple Lap Shear (QLS)			0.15, 0.25
2 x 1 x .10			0.35, 0.45
Tensile Strength	0	40, 75, 110	2 in/min
(Constant Strain Rate)			20, 200
JANNAF Class C 1/2 scale Dogbone	250	40, 75, 110	2 in/min
.50 x 2.5 x .25			20, 200
	500	40, 75, 110	2 in/min
			20, 200
	1000	40, 75, 110	2 in/min
			20, 200
Shear Strength	0	40, 75, 110	0.2 in/min
Quadruple Lap Shear			2.0 in/min
2 x 1 x .10			20.0 in/min

Table 1 Material Characterization Matrix for DC 90-006 and Two Replacement Materials

Because the NASA MSFC does not have a tensile test machine coupled to a pressure chamber to perform this testing, a cooperative agreement was made to use the "High Rate Tester" at the Army materials test lab on Redstone Arsenal. Testing was conducted from June to August 1999.

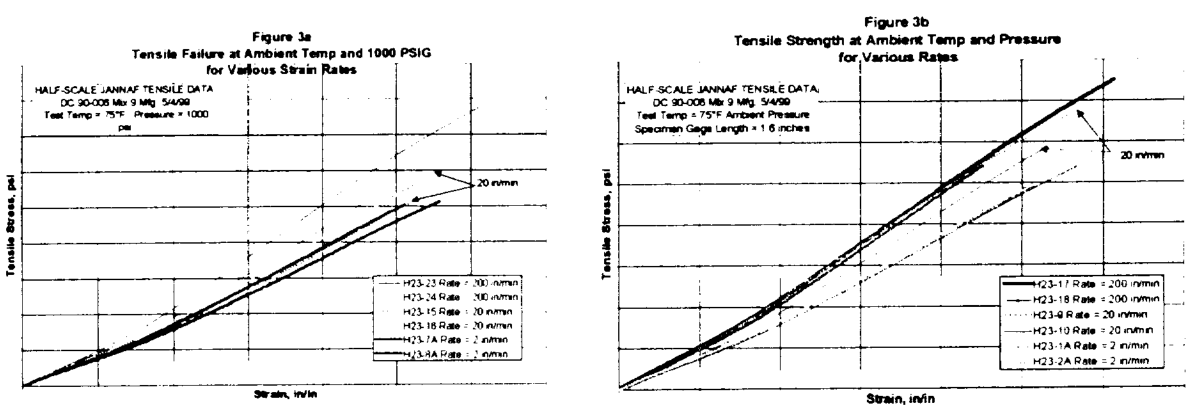


Figure 3 Selected Data: A) Tensile Failure at Ambient Temperature and 1000 psig for Various Strain Rates B) Tensile Strength at Ambient Temperature and Pressure for Various Strain Rates

Results of the testing from the above test matrix indicate that DC 90-006 is not very sensitive to temperature or pressure, but does show sensitivity to strain rate. Temperature sensitivity was also measured to very low temperatures using a Rheometrics RMS 810 thermomechanical analyzer. Properties were stable to very low temperatures. Further research revealed that silicone materials such

as RTV are often used as a standard for this type of testing because of their known thermal stability. Sensitivity to strain rate confirms the viscoelastic nature of the material.

A mathematical model of RTV characteristics was developed from the characterization data. Because the RTV was not as sensitive to pressure and temperature as earlier anticipated, a simplified approach to modeling the nozzle joint was taken rather than requiring a full NLVE model. An essentially linear model is used with subroutines to handle the nonlinear response of the material to strain rate. Using the mathematical model, a prediction for the performance of the DC 90-006 in special test tooling was made. Test runs were made with a new batch of RTV in a test analog. The mathematical model overpredicted the modulus of the material by a factor of 2 to 1. Investigation into this disparity revealed a time-related increase in hardness and modulus for the first 8 to 10 weeks after the material is mixed. Testing with material aged for 8 to 10 weeks showed good agreement between the model and test data (reference Figure 4). Further characterization may need to be done to adjust the model if further study reveals the actual hardness to be slightly less than the lab cured material.

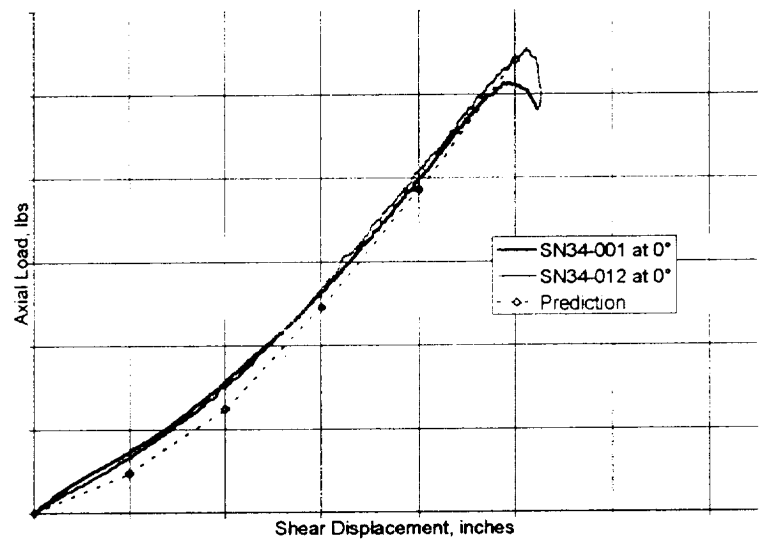


Figure 4 Comparison of Actual Stevens-Nelson Analog Test Data vs. Prediction from Characterized DC 90-006

JOINT MECHANICS EFFECT ON RTV

An understanding of the joint dynamics was required before test devices and alternative material criteria could be developed. The performance of the RTV backfill is controlled by the joint movement and gas pressure. Joint movement is not well known, and is currently approximated by computer models. The joint is approximately 2 inches long with a .050" thick bondline of backfill material. There is a 45° dogleg approximately ¼" long about ½" radially outward from the ID of the joint. Earlier models were primarily 2D axisymetric models, and did not necessarily have good agreement between different model approaches. Two independent 3D models were generated in May and June of 1999. These models revised the expectations of joint movement and were in fairly good agreement with each other.

A full scale RSRM nozzle structural test bed (NSTB) is being developed by Thiokol Propulsion to measure nozzle joint deflections. Data from the NSTB will be used to establish induced load and strain criteria for joint simulation in the lab. The NSTB is expected to begin test operations in the fall of 2000. Additionally, some instrumentation for nozzle joint 2 was included in FSM-8, a full scale static test motor which fired in February 2000. Data from the FSM-8 motor indicated that the analytical model predictions bounded the actual test data. Data from both the NSTB and FSM-8 will greatly enhance our limited knowledge of joint dynamics.

LABSCALE TEST DEVICES DEVELOPED

Full scale testing of the joint and the performance of the material in the joint specifically regarding wormhole development is costly, time consuming, and prohibitively complex. Lab scale test devices to validate the accuracy of the mathematical material model were developed in conjunction with test devices to identify the physical conditions that predispose the RTV to fail in this peculiar mode.

Wormholes are believed to be caused by localized micromechanical failure of the RTV due to induced gas pressure from motor operation. The localized failure stress state inflicted on the RTV by the pressurized gas is little understood. Figure 5 shows a typical postflight wormhole and the results of earlier Crook Blowpath testing.

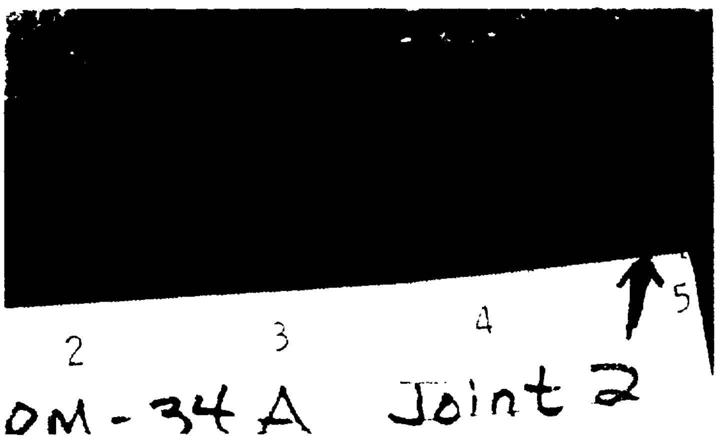


Figure 5 A) Nozzle "Wormhole" B) Crook Blowpath "Wormhole"

The localized stress state of the RTV is also greatly influenced by the joint movement, as mentioned before. Because of these two contributing factors two exploratory "analogs", or test systems, were developed to independently test the material for 1) propensity to form wormholes because of injected gas, and 2) failure of the material due to the tension and shear forces induced by the joint movement.

The exploratory analogs were first used in an attempt to identify :

a. The differential pressure at the localized site of failure in wormhole formation
b. The minimum compressive stress that would allow wormholes to form
c. The response of the material to joint movement

The exploratory analogs are also used in another phase of this program to evaluate whether other, alternative replacement materials will also have a propensity to form wormholes and if those materials will be able to withstand the predicted movement of the joint. Finally, the analogs, especially the "validation" analog, will be used to help evaluate the accuracy of the mathematical material models developed from the material characterization phase of this program.

THE MODIFIED CROOK BLOWPATH TEST SYSTEM

The first test article was named the "modified Crook Blowpath" analog, and uses essentially the same concept as the original Crook Blowpath test article (reference Figure 6). The modified Crook Blowpath utilizes two different methods for attempting to determine how a wormhole forms. The first method uses pressure sensitive tactile indicating film between the top of the RTV and the top plate. The indicating film records the pressure experienced by the RTV during compression by the plate ends and during injection of 900 psi GN_2 through the bottom center plate. The indicating film is observed through a borescope during the test and the image of the growing wormhole is recorded by video for later analysis. After testing, the indicating film is removed and analyzed by the film vendor to provide a maximum pressure distribution plot experienced by the RTV during test.

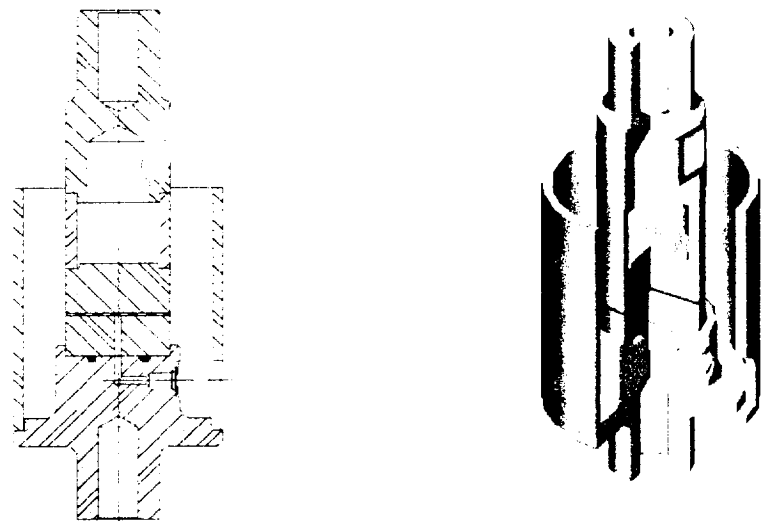


Figure 6 The modified Crook Blowpath Test System (Analog)

It was discovered that the rate of wormhole growth is dependent on the existence of a crack initiating flaw. Test articles without an initiating flaw were tested and were able to maintain a seal even at the high pressurization rates experienced in the motor. Test articles with the initiating flaw, an unbond area approximately 0.5 inches in diameter at the injection site, performed very similarly to the original Crook Blowpath tests. The test articles with an initiating flaw rapidly formed wormholes and "blew out" within 30 seconds at a compression of 150 psi. Higher compression levels produced slower growing wormholes, and wormholing was negligible when the compression exceeded approximately 180 psi.

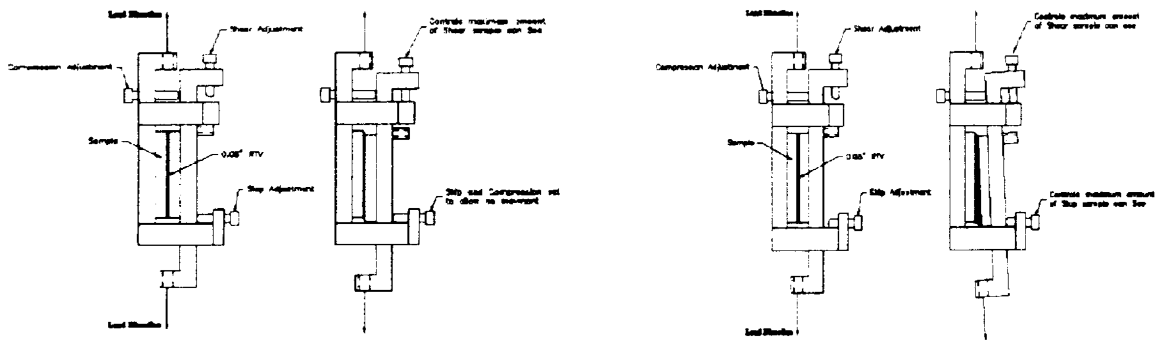
In another configuration, modified Crook Blowpath Option 2, metal adherends adapted to pull in tension provide a hydrostatic tension force in the center of the test specimen. Wormhole growth is inspected post test by injecting a dye-containing grease into the bottom port at low pressure to fill the voids created by the high pressure GN_2. The sample is then pulled apart and inspected. Figure 5B shows Crook Blowpath wormholes produced by this method. This set up is similar to another test used by Thiokol called the "Poker Chip" tensile test. Poker Chip testing is primarily used for adhesives, not sealants, so data did not exist for RTV in this configuration. Because the Poker Chip test article is capable of producing streses more relevant to nozzle joint movement conditions, the Poker Chip test was selected as a screening test for alternative materials. The main difference between the Poker Chip test article hardware and the modified Crook Blowpath Option 2 test hardware other than injected gas is the diameter of the adherends.

It is expected that all elastomers will exhibit some form of wormholing under the appropriate conditions. The question remains to what extent. The modified Crook Blowpath test article designed to pull in tension enables us to evaluate alternative materials under tension to simulate the joint tensile state and determine if the alternative material will meet and exceed performance requirements of the joint.

THE JOINT MOTION SIMULATOR (JMS) TEST SYSTEM

The second exploratory analog, the "Joint Motion Simulator", or JMS test fixture, investigates the stresses induced on the material due to joint movement and attempts to demonstrate the limits of the material's ability to withstand joint movement. Screws on the fixture frame allow technicians to adjust the movement of the test plates if different stress states or movement sequences are indicated by full-scale tests. The test article consists of a 0.050-inch thick layer of RTV bonded to two plates (reference Figure 7). The JMS test fixture can be set up with either flat plates or test articles that simulate the joint

"dogleg" contour. The configuration that allows shear and tension simulates the joint movement conditions when a joint bolt "skips" suddenly, a condition known to exist, but difficult to model and predict. Joint "skip" is experienced when the forces on the joint suddenly overcome the friction keeping the joint together.



Sample in Pure Shear

Sample in Shear and Tension

Figure 7 Joint Motion Simulator (JMS) Test Fixture

THE STEVENS-NELSON VALIDATION ANALOG

A third analog, called the "Stevens-Nelson" analog, or S-N Analog, was developed as a "validation" analog. This analog combines controlled gap movement with pressurized gas introduction to evaluate the formation of wormholes under simulated joint conditions (reference Figure 8). This test article is used to validate the computer predictions for material performance such as stress and strain capability, and to validate predictions for wormhole formation in the material under specific conditions.

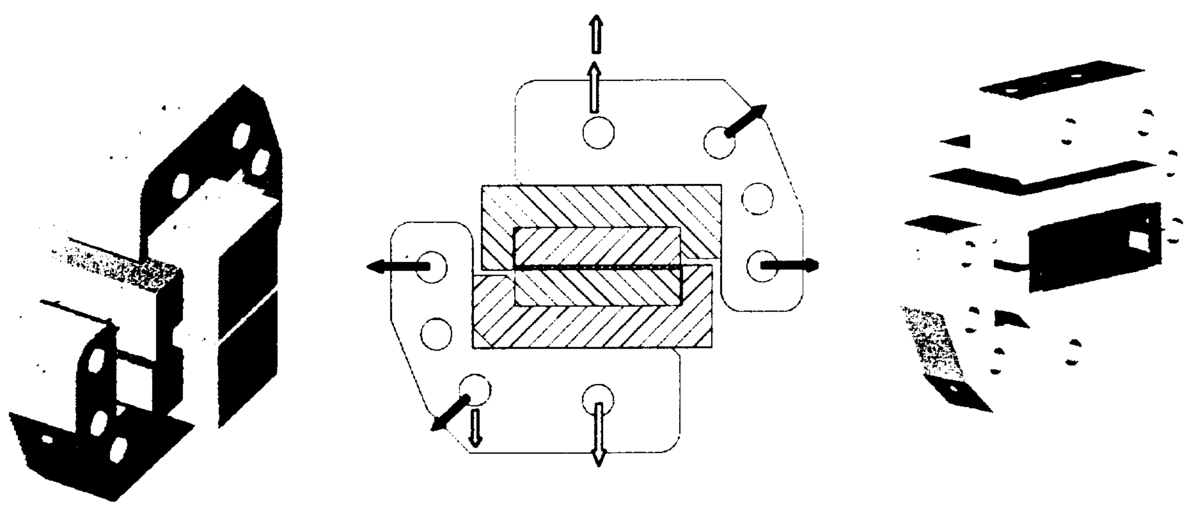


Figure 8 Stevens-Nelson Analog for combined Joint Motion Simulation and Blowpath Growth

This analog uses a 0.050-inch thick layer of RTV bonded between two plates which are pulled at specified angles to simulate desired stress combinations in the material. This test article was originally designed to simulate joint movement conditions that impose both tensile and compressive stresses on the test article. The load on the test article can be applied either in-line or offset from center to apply a varying load across the bondline. It was determined after initial testing with the analog, and further analysis of joint movement, that testing off center was not required to model the joint. Nevertheless, the analog is useful for validating the material model prediction. It can be used with either flat plates or a

simulated dogleg joint, and can be tested in the High Rate Tester. Alternatively, it can be retrofitted with a Crook Blowpath injection port in the bottom plate and run as a combination JMS/Crook Blowpath test.

Failure mode evaluation of the Stevens-Nelson analog for wormhole formation propensity is to be by posttest NDE of the test articles. Several methods were screened to determine the extent of failure of test articles- Computed Tomography (CT), Ultrasonic inspection (UT), and X-ray. Results of this testing indicated that both CT and X-Ray can give accurate indications of voids in the test article. Alternatively, a dye-containing grease (silicone grease with Carbon Black) can be injected into the port at low pressure (30 psig) to fill the wormhole voids. The test article is then carefully pulled apart, and the grease-filled wormholes revealed and photographed. This is the inspection method used by Crook earlier.

Further testing and development revealed that testing with both gas injection and shear-tension stress states are not required to fully understand the wormholing phenomenon or to evaluate the current and alternative material performance and mathematical models. A simple Stevens-Nelson analog is all that is required to evaluate the performance of the material to the components of the joint movement stresses. While the JMS is useful in evaluating these stresses, it is not rigid enough to prevent unwanted movement. Testing at 45° and 22.5° pull with the current material demonstrates the propensity of the material to resist movement in tension and to move in shear. To date, the simple Stevens-Nelson test without introduced gas pressure has been used to validate the material models with acceptable results. The Stevens-Nelson analog in combination with the modified Crook Blowpath in tension test have been sufficient test beds to provide the needed data to understand and predict the wormholing phenomenon.

Data from the analogs support and validate material model development. Data from the analogs provide the parameters by which wormhole formation is likely for a given material. From this, the suitability of an alternative material to replace DC 90-006 can be predicted and materials screened.

ANALOG TESTING, MODEL VALIDATION, AND ALTERNATIVE MATERIAL CRITERIA

Inspection of the test article in the JMS test fixture reveals that the DC 90-006 may fail locally in the joint if the joint skips. This condition, coupled with the propensity of the material to form wormholes while under a pressure differential indicates that an alternative material will need to have a higher tensile strength, higher shear strength, and possibly, a lower Poisson's Ratio than the DC 90-006.

Testing with the modified Crook Blowpath analog has demonstrated that blowpaths can be induced in DC90-006 RTV, but are dependent on the stress in the material and the pressure of the injected gas. In comparing the expected joint movement and the observed growth of blowpaths under certain conditions, it may be surmised that blowpaths do not ordinarily form unless the joint movement is on the extreme end of the model prediction. This can occur when the nozzle bolt "skips". A contributing factor to this may be stress concentrations that decrease the material's resistance to tearing. A potential cause of stress concentrations may be a cured-in, lapped surface contour from the material injection process. A lapped surface contour may act as a notch to promote material tear.

Tear strength was included on the short list of critical material properties required for screening testing. A tear strength test using ASTM D624 Die C specimens with and without a notch in the "knee" of the specimen revealed significantly decreased tear strength of the DC 90-006 RTV when notched. The potential of the RTV for forming the lapped surface contour at a bolt skip site is still under investigation. Other potential causes of stress concentrations are under evaluation. Any new replacement material is required to perform better than the current material regarding resistance to tear at stress concentrations.

A propensity of the plasticizer to migrate out to the surface of the material was observed during processing and testing of the RTV . It has been theorized that the loss of plasticizer may create microvoids. Wormholes may follow the microvoids to the inside of the joint if the material is mainly in tension. Crook Blowpath tests demonstrated that the high pressure injected air gets trapped between the RTV and the developer film. The bubble is not obvious when the test is terminated, but within one minute after pressure is released from the test article, a bubble forms between RTV and the developer film. It appears that the bubble grows for the next 10-15 minutes, and that the trapped air cannot find it's way back out. The bubble remains trapped even after 5 days. It was thought that the formation of

wormholes is possibly not a material failure, but rather a problem of gas diffusion through the material. In a solid rocket motor, with hot gases, the wormhole would tend to erode and allow more hot gas to flow through, permanently opening the path. Further investigation into backfill material permeability indicated that this is probably not the case; wormholes are mechanical failure in the material. While microvoids due to plasticizer migration is probable, joint mechanical movement and the low tear resistance of the material in the presence of an initiating flaw are likely overwhelmingly responsible for the wormhole phenomenon.

ALTERNATIVE MATERIAL SELECTION AND SCREENING

Ten vendors, including Dow Corning, GE, Monsanto, Du Pont, Master Bond, PRC/Courtaulds, and several others were contacted to provide potential alternative materials to the current backfill material. Rough screening criteria included mechanical/structural performance (elongation, shear strength, tensile strength, tear resistance), processing factors (slump, viscosity, pot life, cure duration, cure mechanism), and thermal resistance. Of over twenty materials surveyed, three materials were selected for a more rigorous screening and downselection activity. The three materials are DC 93-076, an RTV from Dow Corning, PR-1826, a polythiolether-based material from PRC/Courtalds, and UF 3363, a polysulfide-basedThiokol proprietary formulation. A forth material submitted late by Master Bond may also be an acceptable alternative, but was not received in sufficient time for inclusion in the screening and downselection test series. At the time of writing of this paper, the screening tests had not been completed. Early test results indicated that all three materials exceed DC 90-006 structural and ablative performance, and it may be difficult to downselect to just one recommendation.

CONCLUSIONS

The cause of wormhole formation has been investigated, and specific recommendations to eliminate wormholes in the RSRM nozzle have been identified. It is not possible to prevent DC 90-006 from wormholing in the nozzle joint, so alternative elastomeric backfill materials are being screened to replace DC 90-006. Test systems, also called "analogs", have been developed to investigate the causes of wormholes. The test analogs developed will also help in screening alternative replacement materials and for anchoring and validating mathematical computer material models for LE and NLVE analysis of the joint. The results from the models will be compared to full scale test data obtained from the NSTB and FSM-8.

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