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SOLID ROCKET BOOSTER JOINT SEAL ANALYSES

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TECHNICAL MEMORANDUM

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I. INTRODUCTION

This report documents O-ring seal response analyses. This analysis points to some failure possibilities in seal design which must be totally eliminated in systems, especially where human life is at stake. Thus, it is deemed necessary to communicate these in order that all possibilities can be refuted or that proper design techniques possibly will eliminate them. The study found that the key elements in a failure of a shell structure sealed with an O-ring to be joint opening and rotation, assembly out of roundness, and O-ring seal response. The Solid Rocket Booster (SRB) field joint and O-ring was chosen as a baseline configuration for this study.

II. MATH MODELING OF THE O-RING

The modeling and analysis of the O-ring made use of proven in-house NASA analysis tools which could be turned around quickly with the available computer resources. The main analysis tool used for this analysis was a NASA and Lockheed developed finite element code called SPAR. Its most important advantages over Cosmic NASTRAN are that it uses about one-fifth the computer resources of NASTRAN and has interactive plotting and data display capability. Thus, SPAR was ideal for quick, online, emergency analyses.

The O-ring seal was modeled with wedge solid elements in SPAR. The model was limited to a 0.1-deg segment of the 6-ft radius O-ring with the proper axisymmetric boundary conditions. The solid elements have a linear displacement function and depend on many elements to converge to a proper solution. Taking the derivatives of the linear displacement function to obtain the strain terms results in only a constant. Thus, these elements can only model a constant element strain or stress for their enclosed region. The above restriction again shows the need for large numbers of elements to reasonably model the stress distribution. The analysis assumed a linearly elastic material. Actually, the Viton seal material is highly nonlinear and has a large time dependency. O-ring relaxation resiliency data are plotted in Figure 1. Nonlinear stiffness due to large strains and corresponding deflections and nonlinear material behavior are not defined in the present seal model. Although. linear elastic analysis has major limitations for the analysis of the highly nonlinear O-ring, an important understanding of the seal dynamic response is obtained from the results.

III. ENFORCED DISPLACEMENTS

A two-dimensional slice of the O-ring cross section as modeled in SPAR using wedge solid elements is shown in Figure 2. The O-ring groove was modeled to provide a graphic display for reference and to aid the engineer in controlling the linear solution procedure to model a basically nonlinear problem involving contact (changing boundary conditions). This visual feedback allowed modeling of the O-ring as it was statically compressed into the O-ring groove for three different amounts of compression as shown in Figure 2.

The procedure to generate the compressed O-ring plots is as follows. The node point in contact at the bottom of the groove is constrained to zero displacements; then the topmost node is given an enforced displacement. The node points on the model are then displayed and any node points that cross the boundary defined by the tang or O-ring groove are moved back to rest on the boundary by enforced displacements. When the model displays the proper compression and conforms properly to the boundary, the reaction forces can be obtained and the initial conditions for O-ring response are defined.

Figure 2 gives the displacement shapes for three different states of compression of the O-ring. A nominal diameter O-ring (0.280 in.) is compressed in a maximum depth groove (0.216 in.). A tang-clevis contact boundary causes a steel-to-steel compression of the O-ring of 0.064 in., and the O-ring seals on the sides of the O-ring groove. In the fully compressed state, flow around the O-ring is restricted. As the gap opens during the SRM ignition transient, O-ring resiliency and the tang/O-ring flow boundary characterize the seal response.

IV. RESPONSE OF FULLY COMPRESSED O-RING

The response and sealing of the O-ring can be influenced by case out of roundness. This out of roundness can be induced by the railroad shipping of the propellant segments. Although 0.5-in. thick steel seems like a rigid structure, when it is a 12-ft in diameter, open-ended cylinder the sides will sag under their own weight. These segments are shipped loaded with a rubber like solid rocket propellant.

The condition of assembly out of roundness results in the O-ring being compressed lightly at two points while it is also compressed fully with the tang and clevis in steel-to-steel contact. Ignition of the SRBs causes a pressurization of the case which will cause an initial jump to reestablish roundness. This jump is largest at the fully compressed O-ring positions and can be as much as 0.030 in. at the seals. A theoretical investigation of the free response of a fully compressed O-ring was initiated. The transient response was obtained in SPAR by using an uncoupled linear analysis employing superposition of vibration mode shapes. A detailed nonlinear analysis which modeled the nonlinear material properties properly would have required a direct transient solution scheme.

The response of the seal after steel-to-steel compression of the tang and clevis was investigated using uncoupled modal transient response. Thirty modes of the O-ring cross section were used from 2,000 to 8,000 Hz. The suitability of this model approximation was tested by using mode superposition to generate the original compression state. The superposition initial conditions were plotted and the number of modes adjusted until the thirty modes provided the initial result shown in Figure 3. Pressure was applied to the O-ring cross section along the top 180 deg. The sides of the O-ring were considered sealed. A linear representation of the response is presented in Figure 4 for release of the fully compressed O-ring. The response plot, with a pressure of 936 psi, shows that the pressure drives the seal farther into the groove locking the O-ring in this position. For this case, tang-clevis gap sealing cannot occur. The linear assumptions show the seal being driven through the bottom of the groove while in fact this is not possible. The important and correct result is that the seal does not respond to any gap opening and is compressed into the groove by pressure. Additional response plots for the initial steel-to-steel compression of the O-ring are presented for pressures of 468 and 374 psi. The overall trend is to force the seal into the groove. These plots show a slight initial tendency to respond up. This response is due to the natural tendency for the top enforced flat on the O-ring to return to a circular configuration.

The exact transition pressure between holding the seal in and allowing the sides to unseal will vary with groove and O-ring tolerances and amount of tang and clevis grease. A pressure less than the transition pressure would allow pressure to get under the seal to allow it to respond as the pressure increases. The exact determination of the transition pressure requires a detailed nonlinear analysis taking into account nonlinear properties which vary with time and temperature. The tendency of the steel-to-steel compressed O-ring to seal on the sides could be corrected by increasing the width of the groove. The O-ring steel-to-steel compression response plots have a constant pressure load over the top 180 deg, which would not be the case the instant the seal sides unseal. The plots shown in Figure 4 investigate the tendency of the O-ring to lock in the groove. Note. seal damping was assumed to be equal for all pressure states given at 2 percent. Although the 2-percent damping is not valid for the Viton material, the results of the above study remain valid. Viton was later found to be highly over damped in this frequency range. The SPAR transient analysis software showed numerical instabilities for some overdamped cases. SPAR may presently only be designed to handle the underdamped case. The highly over damped phenomenon would only increase the possibility of the seal locking in the groove. The damping delays the unsealing of the sides and allows SRB pressure to build up while the sides remain sealed. If the pressure climbs above around 200 psi before the sides unseal, the O-ring will be compressed into the groove.

After this analysis was done, MSFC's Test Laboratory conducted Viton seal tests in a special test fixture. When the O-ring was compressed steel-to-steel and the joint opening and SRB pressure transient was simulated, the seal consistently failed at all temperatures 40°F and below. There is another factor which at low temperatures can contribute to the seal locking phenomenon. The O-ring groove, the tang, and the clevis are coated with grease which becomes stiff at low temperatures. This stiff grease would contribute to the delay of the unsealing of the O-ring sides and increase the potential for O-ring lockup.

V. RESPONSE OF O-RING COMPRESSED 0.046 in.

The SRB joint is subject to opening and rotation as the SRB ignites and the internal combustion chamber pressure increases. The joint, which is made up of a tang and clevis which are pinned together, has a greatly increased circumferential stiffness. The less stiff chamber walls balloon out inducing a change in slope or rotation of the joint. This rotation opens the joint at the seal locations at a rate which tracks the pressure rise. The maximum pressure induced opening for the aft joint was around 0.025 in. with a maximum rate of around 0.3 in. per second. It was necessary to analyze the O-ring response also for the case of nominal compression.

As in the previous response investigation, linear elastic uncoupled modal transient analysis techniques were used. The initially compressed 0.046 in. seal was modeled with modal superposition. This study assumed the tang-clevis combination to instantaneously be separated by 0.048 in. (Fig. 5). Sonic conditions at 400 psi were assumed at the top of the O-ring and the pressure distribution around the O-ring was calculated from area ratios. The downstream side of the O-ring was assumed to have separated flow, and the middle bottom of the O-ring was assumed sealed on the bottom of the groove. The flow velocity between the tang and clevis was 1,038 ft/sec. The first response plot (Fig. 6) shows the linear elastic response of the 0.046-in. compressed O-ring without pressure. Figure 7 shows the O-ring response of the pressure loading defined by the 0.048-in. tang-clevis separation. This pressure loading state speeds up the response. Although the linear elastic analysis shows very fast response, the nature of the material suggests this is not the case. These plots demonstrate that the dynamic inertia forces are very small.

Viton O-ring response test data confirmed that the material does not respond very fast. Figure 8 shows an initial O-ring response test result. It is interesting to note that at 25°F an O-ring which has been compressed 0.040 in. will only return 0.005 in. in one second after release. The plotted responses during the first few milliseconds are wrong because the testing machine was not lifting off the O-ring quickly enough. Later testing corrected this error and was important in the later theoretical characterization of the phenomenon.

The above material testing at 25°F indicated that if the O-ring was assumed to remain at the bottom of the O-ring groove it was impossible for Viton to seal the SRB joints with the opening deflections being experienced at the seal locations. If in fact the material is slow to restore to its original undeformed shape, it becomes necessary to depend on other sealing phenomenon for quick reaction. It should be remembered that the other SRB joints sealed properly even with the low temperatures.

An analysis was then done allowing the seal to free float to see if it would translate into a sealed position. This was done using the mode shapes of a free O-ring cross section. The first free cross section mode was 4,000 Hz. The response plot given in Figure 9 shows that the O-ring is capable of free floating into position at a faster rate than the tang-clevis gap opens. Note that this type of sealing is independent of slow material response.

VI. O-RING RESPONSE FINDINGS

1. Initial forces necessary to compress O-ring steel-to-steel (0.064 in.):

Viton E (psi)	Temperature (°F)	Compression Force (lbs/in.)
1240	70	52.8
1970	40	83.9
3170	25	135.0
16400	10	698.0

Note: The temperature/modulus relationship was based on early test data.

2. Steel-to-steel compression of the O-ring results in contact and sealing on the sides of the O-ring groove. This side groove sealing can couple with pressure forces to hold the seal in a fully compressed state making pressure sealing impossible.

3. If the seal is not sealed on the sides of the groove (as in the steel-to-steel case), the Bernoulli induced flow forces are sufficient to rigid body translate the O-ring to the sealed position faster than the gap opening transient. This rigid body translation of the seal to a sealing position is known as a free floating seal. It should

be noted that according to the Parker Seal Handbook, it is not recommended that a free floating seal be used for pressures over 200 psi. (SRB pressures are over 900 psi.)

4. Although linear elastic theory predicts a very fast snapback of the seal from the compressed state, the extreme time dependency of the Viton material makes response from a highly compressed state too slow to follow the gap opening transient. The seal must depend on a free floating translation for quick sealing of large gaps.

VII. LATER CHARACTERIZATION OF O-RING RESPONSE

The testing and theoretical analysis of the O-ring response has continued on at Marshall Space Flight Center. This additional testing and analysis has provided some additional insight into the response phenomenon.

Additional improved test results for the SRB Viton O-rings has been obtained from MSFC's Materials Laboratory. Analysis of these latest test results indicate that two different mechanisms are involved in the free response of the O-rings. The initial 2 to 3 milliseconds are dominated by an overdamped dynamic response, and the following response is then dominated by a classic creep equation as memory of the material tries to restore it to its original shape. In short, the viscoelastic materials take a set, which becomes a new short term equilibrium position, and then they slowly creep back toward the original position. This set position is influenced by time of compression and temperature. During the initial seconds and minutes of O-ring specimen compression, a recoverable viscoelastic creep takes place at a rate which is also reflected in the response creep recovery. There is an additional phenomenon which takes place during long term compression. This phenomenon seems to be a nonrecoverable creep which resembles a fluid flow. Low temperatures decrease the O-ring response rates. In general, lower temperatures increase the elastic damping while increasing the amount of material short term set and the amount of relaxed set. The creep recovery rate decreases with decreased temperature.

Additional information on O-ring response and analysis should be obtained by referring to the NASA report titled "SRB O-ring Free Response Analysis." Figures 10 and 11 are from this report and show a comparison of the current test results and the developed theoretical math model. Figure 10 gives the O-ring free response for 75°F while Figure 11 documents the response for 25°F. Comparing the two plots shows a very marked decrease in the response capability of Viton at the lower 25°F temperature.

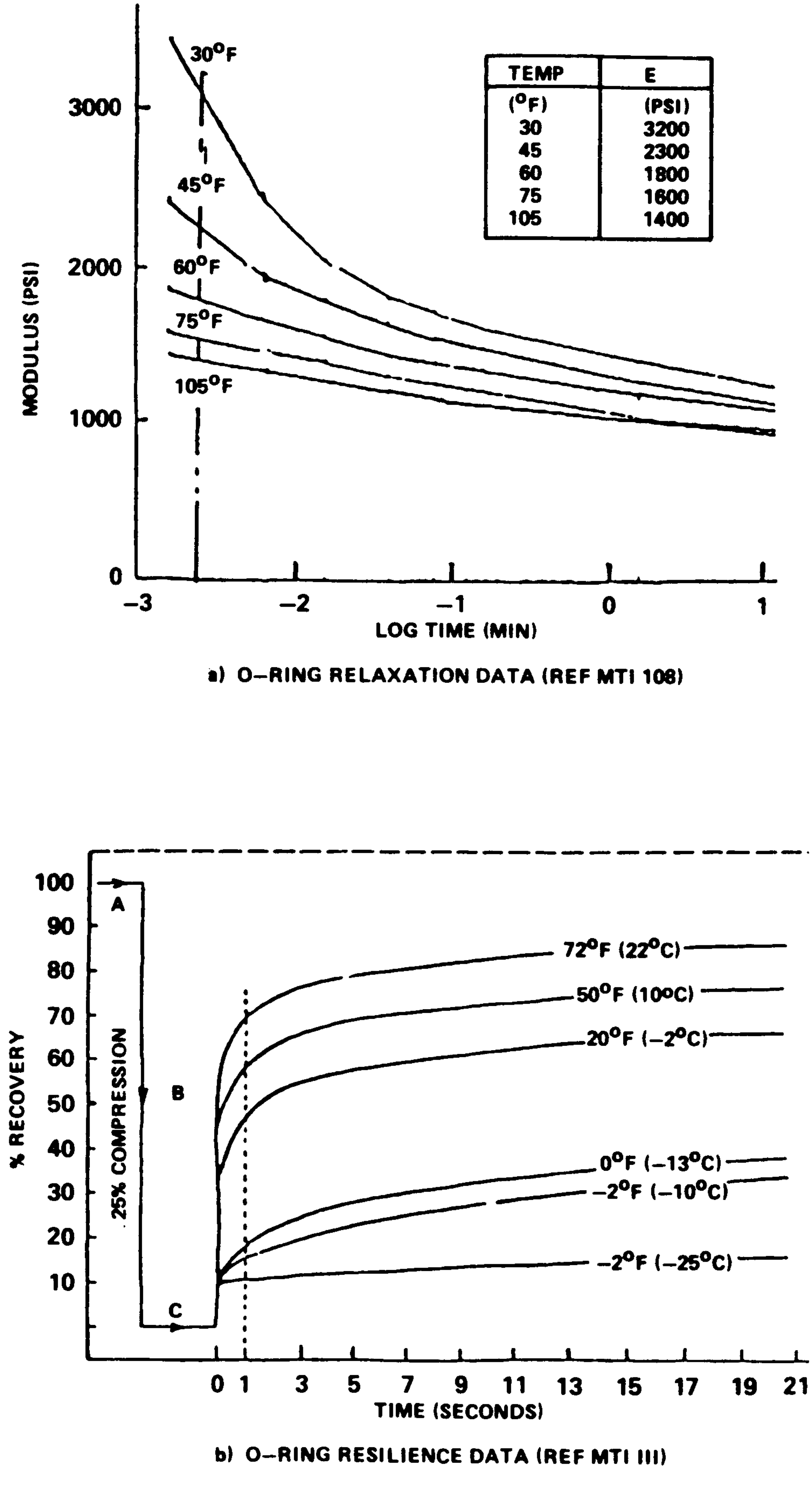


Figure 1. O-ring material property characteristics.

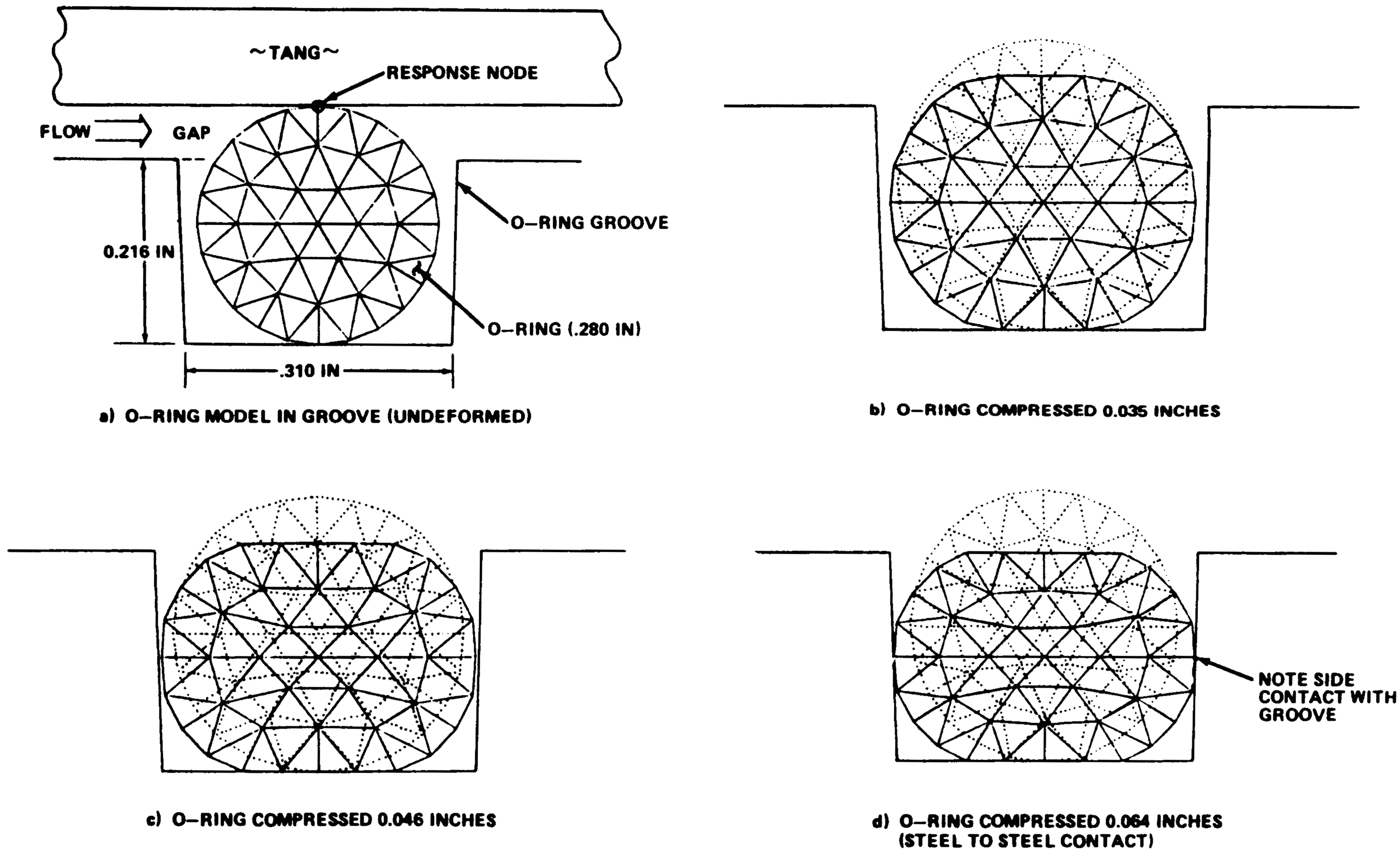


Figure 2. O-ring displacement shapes for various states of compression.

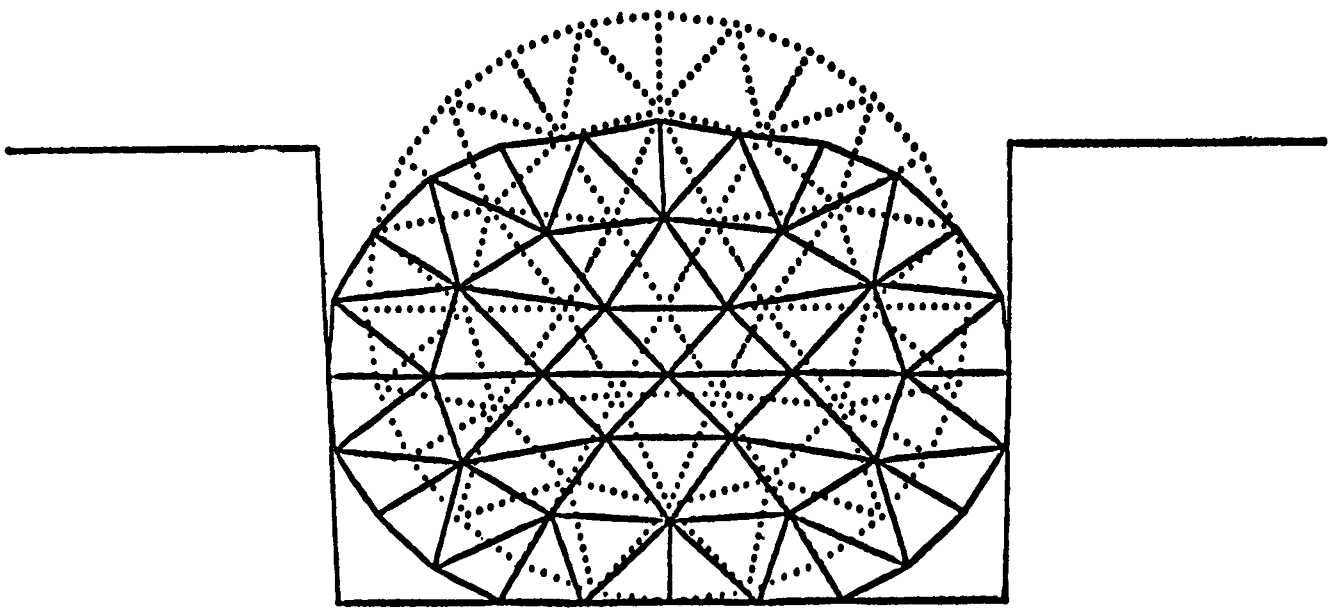


Figure 3. Initially compressed O-ring modeled with modal superposition (30 modes) steel-to-steel compression (0.064 in.).

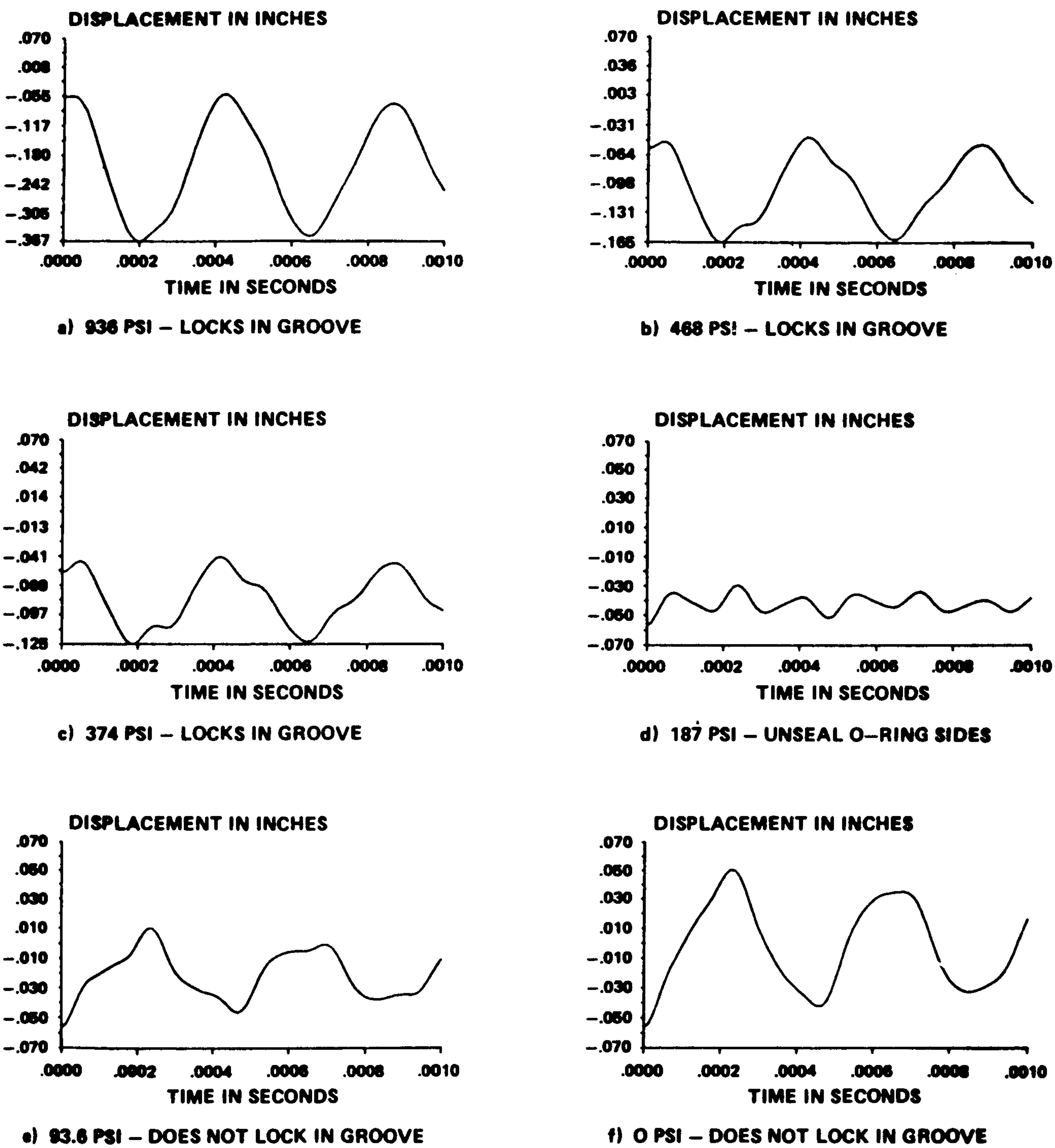


Figure 4. Response of steel-to-steel compressed O-ring at different flow pressures, linear elastic response.

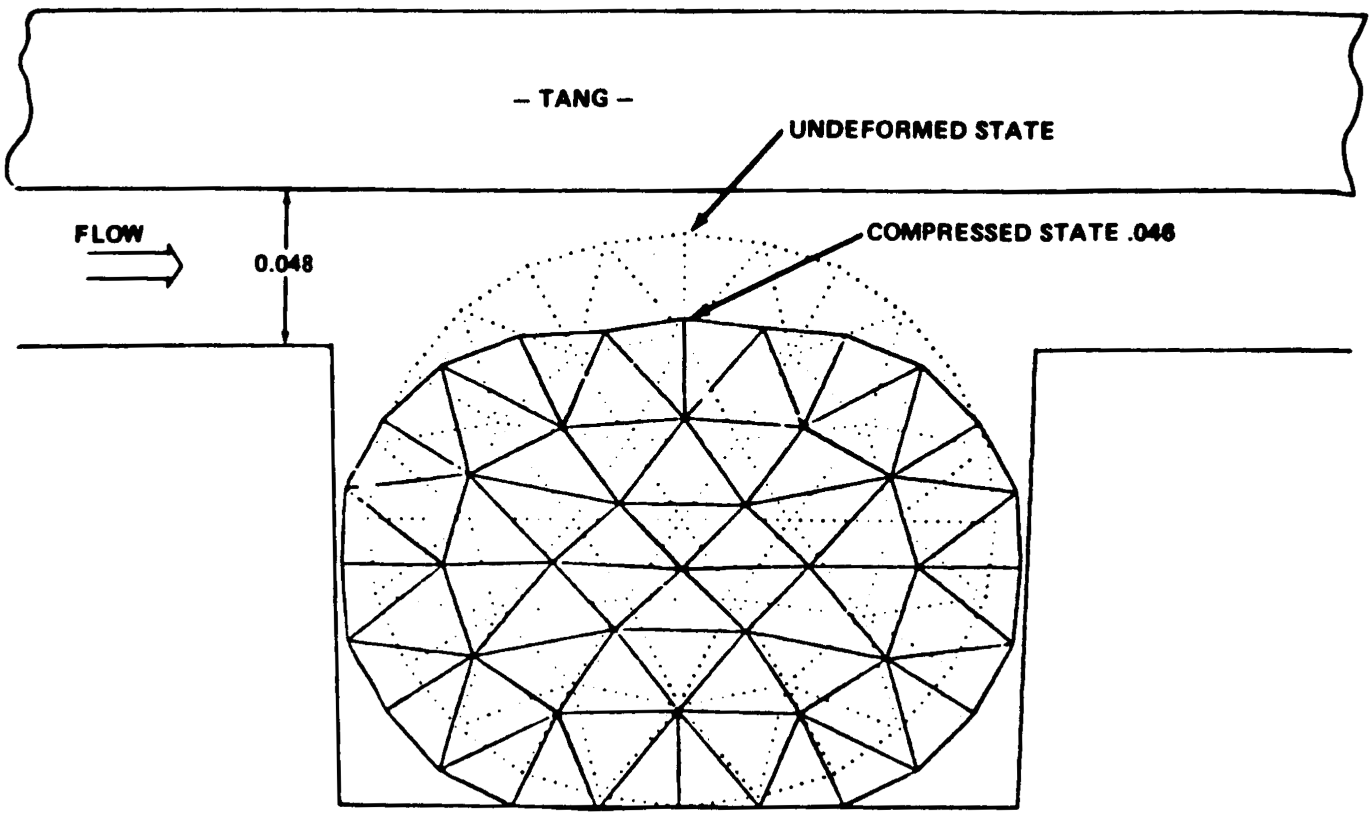


Figure 5. Compressed O-ring 0.046 in. model.

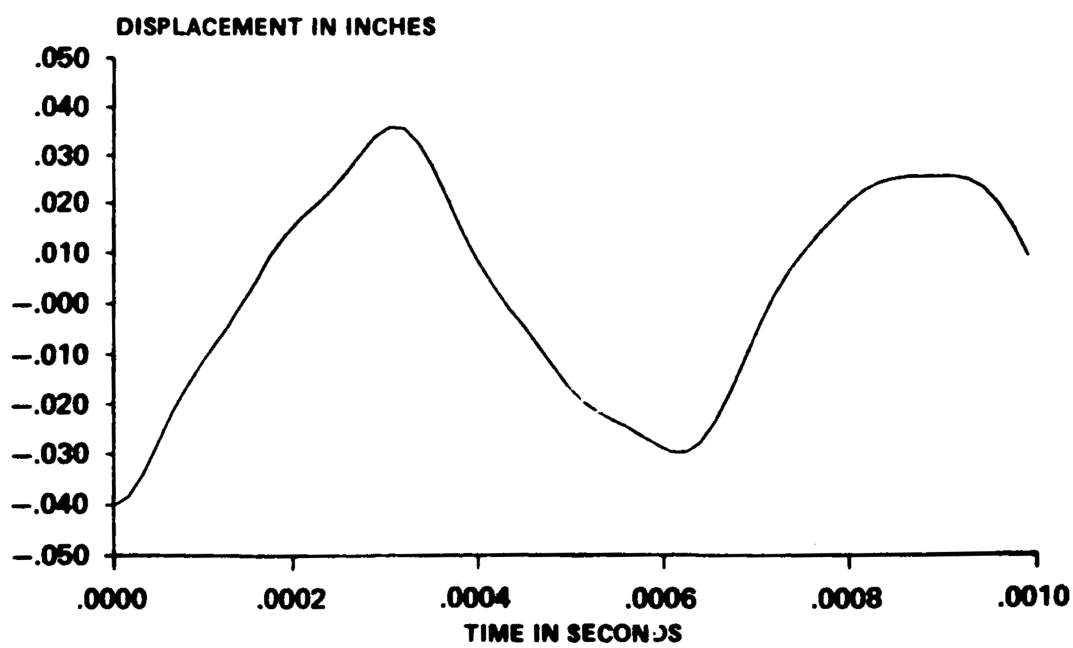
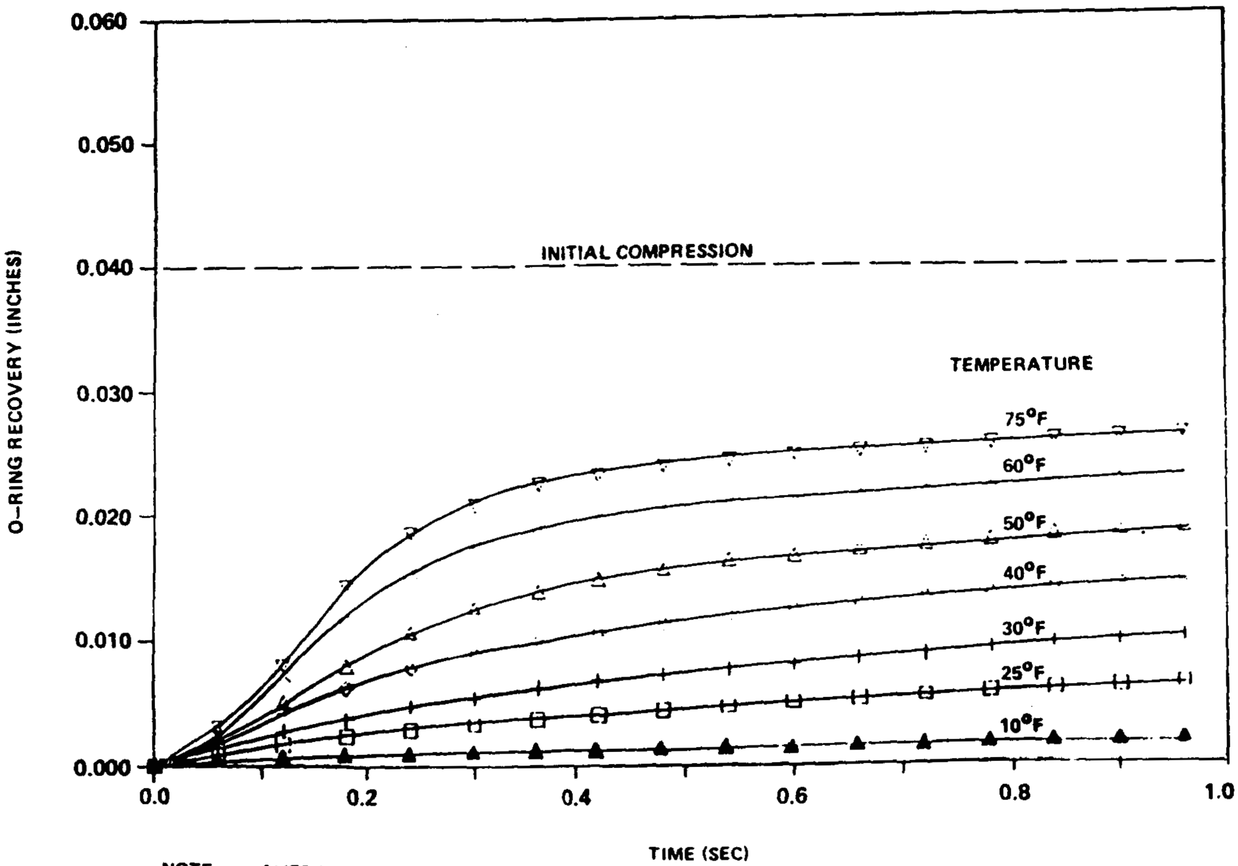


Figure 6. Response of O-ring compressed to 0.046 in.
(linear elastic response, no pressure).

Figure 7. Response of O-ring compressed to 0.046 in. (linear elastic response with pressure).



NOTE: AVERAGE O-RING RECOVERY AT VARIOUS TEST TEMPERATURES DURING FIRST SECOND AFTER LOAD RELEASE. INITIAL COMPRESSION OF 40 MILS WAS MAINTAINED FOR 2 HOURS.

Figure 8. Graph plots O-ring shape recovery in inches against time in seconds for a variety of temperatures.

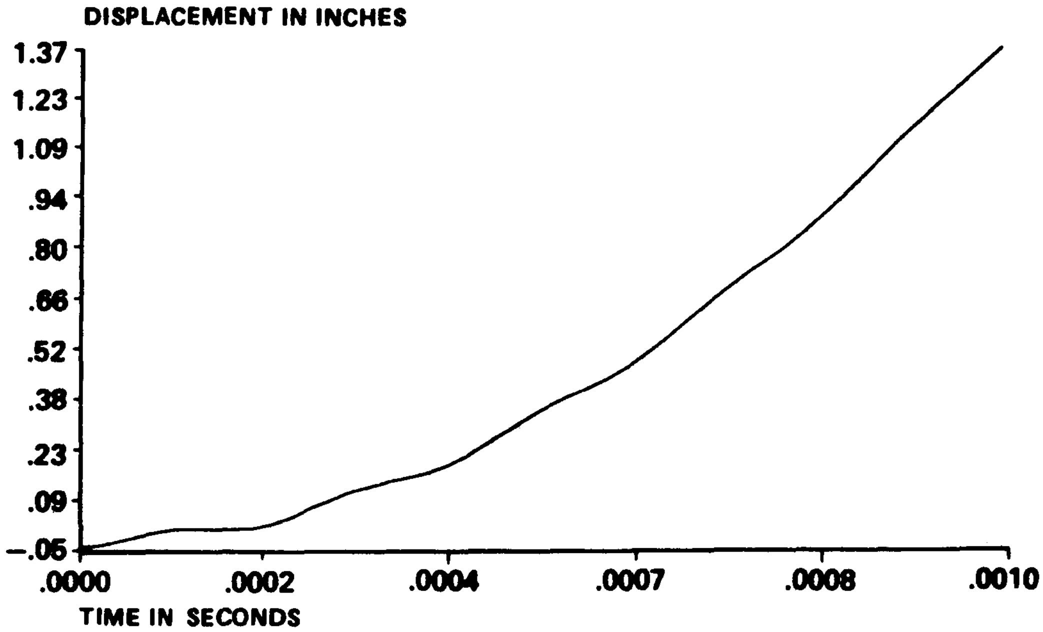


Figure 9. Response of free-floating O-ring compressed to 0.046 in. (linear elastic with pressure).

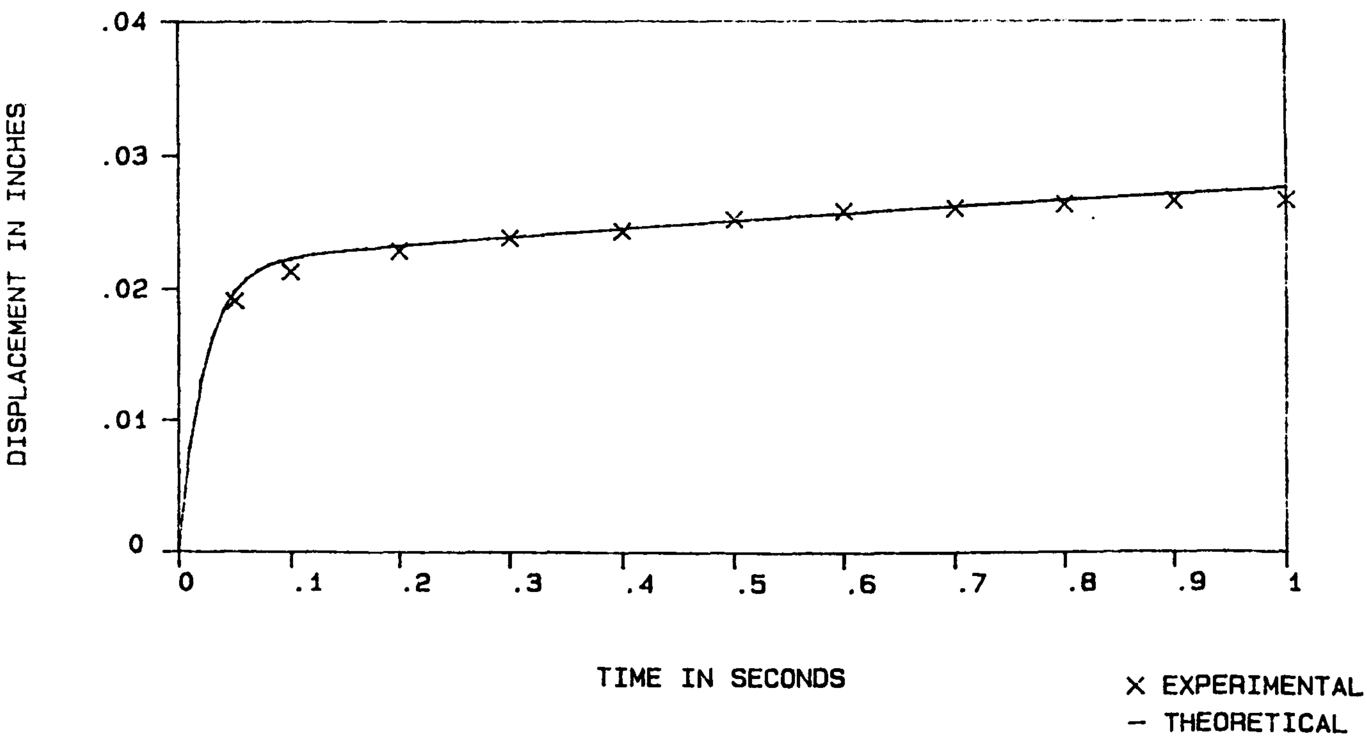


Figure 10. SRB O-ring free response, Viton O-ring compressed 0.04 in. for 2 hr, temperature 75°F.

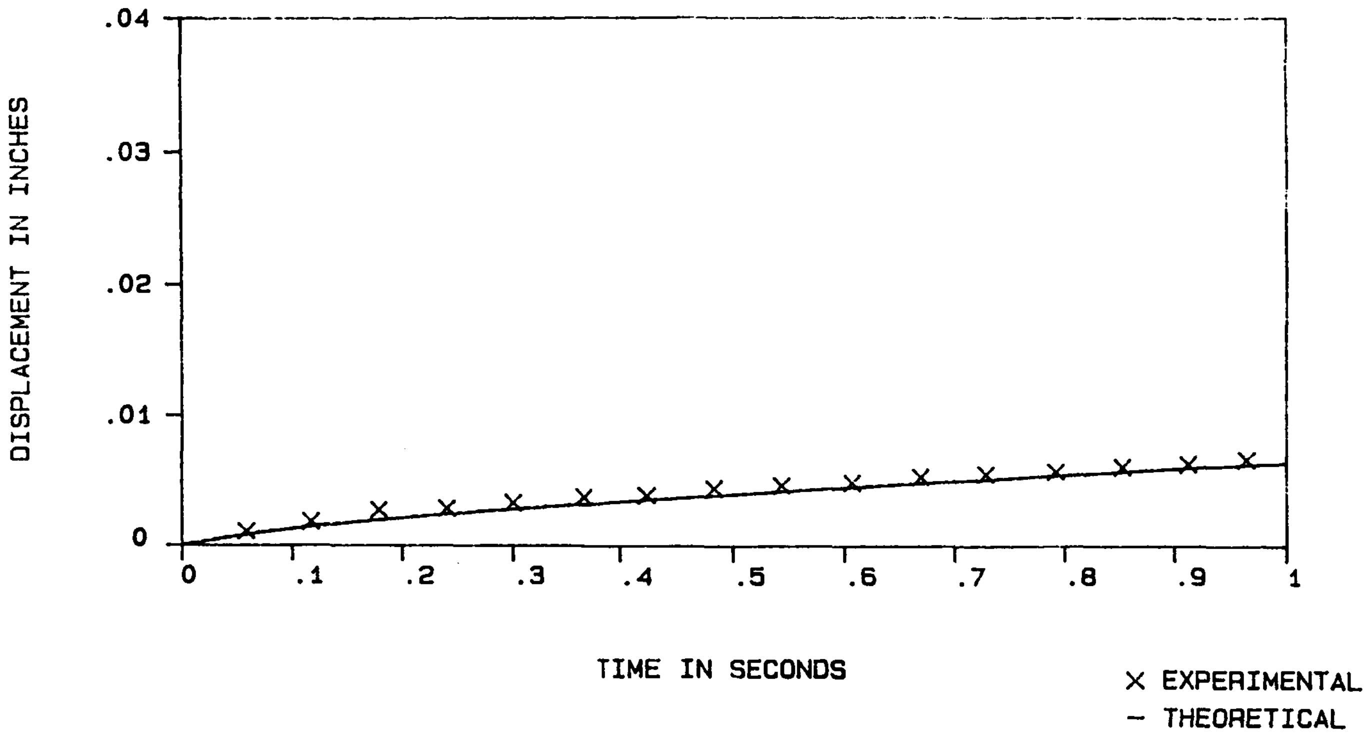


Figure 11. SRB O-ring free response, Viton O-ring compressed 0.04 in. for 2 hr, temperature 25°F.

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"SRB O-Ring Free Response Analysis," by Carleton J. Moore, MSFC-RPT 1337, October 1986.

"Parker Seal Handbook," Copyrighted 1982, Parker Seal Group, Lexington, KY.

APPROVAL

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The information in this report has been reviewed for technical content. Review of any information concerning Department of Defense or nuclear energy activities or programs has been made by the MSFC Security Classification Officer. This report, in its entirety, has been determined to be unclassified.

G. F. McDONOUGH
Director, Structures and Dynamics Laboratory

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16. ABSTRACT

This report documents O-ring response and sealing in pressurized shell structures. The study found that the key elements in the failure of the seal to be joint opening and rotation, assembly out of roundness, and O-ring seal response.

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