NASA TECHNICAL MEMORANDUM

NASA TM X-73303

SRM ATTRITION RATE STUDY OF THE AFT MOTOR CASE SEGMENTS DUE TO WATER IMPACT CAVITY COLLAPSE LOADING

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(NASA-TM-X-73303) SRM ATTRITION RATE STUDY OF THE AFT MOTOR CASE SEGMENTS DUE TO WATER IMPACT CAVITY COLLAPSE LOADING (NASA) 50 p HC $4.00 CSCL 21H

N76-24620

Unclas
G3/39 28247

May 1976

NASA

George C. Marshall Space Flight Center
Marshall Space Flight Center, Alabama

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INTRODUCTION

Cost optimum design of the Solid Rocket Motor (SRM) requires adequate assessment of attrition resulting from reuse. The critical attrition rate for the SRM results from the water impact cavity collapse loading. The attrition assessment treats these loadings probabilistically and determines if these loadings exceed the structural capabilities of the designed vehicle.

The cavity collapse loading is unique in that it drastically changes the shape of the pressure wave with water impact conditions. This requires a number of stress analyses to determine capability for each pressure distribution. For most other water impact loads, a single analysis is sufficient and the capability is linearly proportional to a load such as pressure.

A significant problem of computer economics (cost and schedule) was created in computing a capability for each load condition for three positional locations and for multiple configuration design options.

Resolution of the problems for preliminary assessment of the attrition rates of the SRM aft segments is discussed herein.

BACKGROUND

The attrition assessment of the aft segments of the SRM due to water impact requires the establishment of a correlation between loading occurrences and structural capability.

The critical loading for the aft segments of the SRM during water impact is the cavity collapse condition. Seventy-five discrete loading cases have been empirically determined as functions of vertical impact velocity (V_V), horizontal velocity (V_H), and impact angle (θ).

Each discrete load case as identified by the parameters $V_V/V_H/\theta$, varies longitudinally and radially in magnitude and distribution of the external pressure. The distributions are further required to be shifted forward or aft one-fourth the vehicle diameter to assure minimization of the effect of test instrumentation location for the load determinations. The asymmetrical load distributions result in large geometric nonlinearities in structural response. The critical structural response is progressive buckling of the case. Discrete stiffeners have been added to these aft segments to aid in gaining maximum structural capability for minimum weight addition for resisting these loads.

Structural capabilities (eigenvalues) have been calculated using the buckling of shells of revolution (BOSOR) program and scaled using nonlinear structural analysis of general shells (STAGS) program. These are converted to factor-of-safety values and used as input to the SPLASH program for attrition assessment.

Other methods described herein were evaluated progressively to arrive at the preferred solution. The preferred solution is considered to be more realistic than other methods investigated and yet inherently retains conservatism resulting from the use of constant minimum correction factors for each input matrix. Accuracy may be somewhat improved as results of a greater number of STAGS runs become available and as configuration changes and load revisions are completed; however, the results shown are not expected to change significantly.

LOADS

The load parameters utilized for the attrition assessment are documented in SE-019-057-2H, "Space Shuttle Solid Rocket Booster Design Loads, Revision A, September 12, 1975." All motor case analyses include a 2.0 psig superimposed, thermally induced vacuum shown in Figure 1.

Tables 1 and 2 list the magnitudes of the external cavity collapse pressure shown in the referenced document as a function of V_V, V_H, and θ.

Table 1 is a single matrix of the peak pressure which can fall on the motor case forward of the first clevis joint at station 1818.0, including those pressures whose distributional magnitude on the case would increase if shifted forward 36.5 in. This is a worst case pressure distribution and is the matrix initially used for design.

Table 2 shows three matrices of pressure, which define the limits of the pressure intensities as they are shifted fore and aft (Figure 2). Matrix 2 is the peak pressure shown in the reference forward of station 1818.0 (the nominal applied pressure). Matrix 1 is the pressure at the same station if the peak is shifted forward one-fourth the motor case diameter (36.5 in.). Matrix 3 is similar except peak pressures are assumed to be shifted aft.

These matrices of loads were the basis of the early attrition studies due to the ease of formulation of the matrices and the simplistic use of a single capability. Inherent weaknesses of the methods are discussed in paragraph Results.

CONFIGURATIONS

The design of the aft two segments of the SRM is defined as to length (120 in.), nominal wall thickness (0.5111 in.), and spacing and configuration of the bolt-on "T-rings." Figure 2 shows the spacing of the rings and their integral stubs for the aft two segments. Economics indicated commonality was preferable for these segments, the bolt-on rings, and their clevis (mating) joints. The relative positioning of the peak pressure of a representative load distribution is shown. Figure 3 shows the configuration of a typical clevis joint and the geometric properties used in the analysis. Figure 4 shows the bolt-on ring configuration and analysis properties. Each ring and its accessories weigh 185.6 lb.

The nominal skin thickness was set by prelaunch and flight load requirements, while the ring configuration, spacing, and segment length were dictated by the water impact cavity collapse loadings.

COMPUTER PROGRAM "SPLASH"

The computer program SPLASH[1] (SRB Probabilistic Loads for Attrition of Subsystem Hardware) was utilized to assess the attrition rate of the aft motor case subjected to the cavity collapse water impact loading. This program is a Monte Carlo analysis which treats the meteorological factors (wind, sea, etc.) and the strength of each element probabilistically.[1] In general, each

1. Duane N. Counter: SPLASH Evaluation of SRB Designs: NASA TM X-64910; MSFC, Alabama, October 1974.

defined criterion parameter (load or factor of safety) is programmed as a table of input data for variations of V_V, V_H, and θ. For each Monte Carlo trial, a water impact condition (V_V, V_H, θ) is randomly selected and the set of loads is computed by interpolation from the tables. The probability of strength is included in the analysis to increase or decrease the effective load. If a load exceeds its companion strength, a failure is tabulated. The percentage of failures is the attrition rate.

The above described procedure is similar for the selection of factors of safety as the criterion parameter. The only difference in the methodology is the adjustment of strength by the strength ratio.[2] For loads input, the strengths are multiplied by the inverse of the strength ratio.

A separate version of the SPLASH program was developed to assess the cavity collapse load. It includes the affect of shifting the load distribution with an equal probability of it lying anywhere within a bandwidth of one-fourth the motor diameter forward or aft of a critically determined station.

STRUCTURAL CAPABILITIES

The structural capability (lower limit of the ability of a structure to carry a defined critical loading) of the SRM aft segments for water impact is governed by the cavity collapse loads. The criterion for the assessment of the capability is the buckling load which would, if exceeded, result in damage to one or both of the aft segments.

The capability can be indexed in several ways such as a factor of safety (ratio of capability load to applied load), the capability load itself (applied load times the safety factor), or as variations of eigenvalues times correction factors.

An eigenvalue is a single-valued function which allows the arrangement or ordering of members of a set. As used in buckling analysis, it represents a load multiple. A factor of safety can be considered an eigenvalue; however, as used herein an eigenvalue is defined as a buckling value from either a linear STAGS or BOSOR analysis. The eigenvalue must be multiplied by a knock-down-factor (KDF) to determine the factor of safety. The KDF attempts to account for the nonlinearity of the buckling of a real physical system.

2. Thomas, Jerrell and Hanagud, S.: Reliability — Based Econometrics of Aerospace Structural Systems: Design Criteria and Test Options. NASA TN D-7646, June 1974.

STAGS nonlinear analysis results can be considered factors of safety directly.

For the attrition assessments using the pressures as the discriminator, the capability is defined as the critical factor of safety (nonlinear STAGS result) times the critical pressure peak of the distribution used. It is assumed constant for all conditions of $V_V/V_H/\theta$. For the attrition assessments using eigenvalues as the discriminator, the capabilities are determined for each condition and are expressed as a factor of safety.

BUCKLING ANALYSIS COMPUTER PROGRAMS

Primarily the BOSOR and STAGS computer programs have been utilized to date to assess the buckling behavior of the SRM case subjected to water recovery loadings. These programs were developed by the Lockheed Missiles and Space Company, Sunnyvale, California, with Government funding. The Government has also funded program improvement from time to time.

Early in the Shuttle program, a survey was made and testing performed to evaluate analytical tools for use in design and analysis of the SRM. Computer programs were needed which could analyze the asymmetric nonlinear buckling capability of Shuttle type motor cases reinforced by external rings, and/or segment joints, subjected to external asymmetric loads. The BOSOR and the STAGS program were assessed as having reasonably efficient computer utilization time, good agreement with test data, sufficient documentation, and user experience to shorten learning time, and could be made available to any Shuttle contractor at minimal expense. They were thus selected for SRM design analysis.

The BOSOR program is primarily limited in that it treats asymmetric loading in the radial direction as if they were symmetric. The STAGS (linear option) program is also limited in that it neglects the nonlinear interactions of the structural geometry. These program characteristics, in general, under estimate the buckling strengths and deflection magnitudes. These unconservatisms are increased as the degree of geometric (structure/load) nonlinearity, and asymmetry are increased. The disadvantages of BOSOR and STAGS (linear buckling) analysis are largely overcome by ease of programming and short running times (often less than 8 min on a UNIVAC 1108) provided a determinable correction factor can be obtained.

Previous experience indicated a correction KDF of 0.75 should be utilized. This resulted in reasonably good buckling results for those structures symmetrically loaded but subjected to small imperfection sensitivity and/or to those structures subjected to asymmetry of geometry or load. When judgments required a factor greater than 0.75, verification tests were established for the cases without high margins.

The nonlinear STAGS analysis is accurate enough to be used directly without a KDF. This characteristic can also be used to derive a KDF and thus use the more efficient linear analysis for the bulk of the evaluations. The numerical value of this factor ranges from 0.6 for extremely asymmetric cavity collapse loading distributions to 1.0 for symmetrical loadings. The lower bound of this ratio for the most critical design conditions is 0.605. This factor was assessed by Thiokol for the conditions 100/30/45, 80/15/-5, and 85/15/-5. The factor using BOSOR analysis results as the numerator of the KDF ratio is 0.65.

Figure 5 is a graphical comparison of linear and nonlinear STAGS analysis of percent load versus radial deflection at the critical longitudinal position of the peak cavity collapse pressure for the pressure distribution of condition $V_V/V_H/\theta$ (100/30/+5). Table 3 is a comparison of results of the analysis methods and the resulting ratios KDF. The nonlinear option of the STAGS program, while having the capability of adequately assessing the nonlinear asymmetric buckling response of the structure, limits the number of computer investigations due to running times of 3 to 7 h per solution. A workable solution to the dilemma was to use the linear analysis for studies and criticality assessments, followed by nonlinear analysis, for final results.

Due to the extensive number of buckling runs necessary to assess the critical load cases, with respect to configuration optimization, load updating, critical positioning, program debugging, and refinement etc., it was determined to use linear STAGS or BOSOR analysis for these early assessment for economy of computer resources, and to use the STAGS nonlinear option only for the final checks on the fewer selected critical cases.

Linear STAGS and BOSOR analysis was utilized for analysis economy to determine the critical loadings for each studied configuration. Figures 6 and 7 show graphically the results of the eigenvalue (BOSOR) analysis as utilized to determine the critical loadings as a function of vertical velocity, for the three-ring and two-ring configurations, respectively. The peak pressure and an estimated "STAGS nonlinear" value are also shown for each load case.

METHODOLOGY DEVELOPMENT

To develop the three positional matrices of factors of safety for attrition assessment, the following rationale was employed:

1. The minimum KDF, as determined by the ratio of analysis results of STAGS nonlinear to STAGS linear, would be the basis for the shift factors.

2. The KDF can be assumed to be composed of the product of three subfactors:

   a. A load shift factor.

   b. An imperfection factor of 0.75.

   c. An asymmetric factor of 0.9 determined by dividing the KDF by the product of subfactors for load shift and imperfections.

3. The forward shift factor is 0.9 and the aft shift factor is 1.111 as determined by BOSOR and STAGS linear analysis.

Using this rationale, the scale factors to be applied to the BOSOR analysis eigenvalues are for the loads "as shown" (matrix 2) :0.675, for loads in the forward position (matrix 1) :0.605, and for the loads shifted aft (matrix 3) :0.75. These factors are the product of the imperfection and asymmetric factor (0.675) times the shift factor (0.9 forward, 1.0 as shown, and 1.111 aft).

POSITIONAL (SHIFT) FACTOR

BOSOR preliminary analyses were used to select the critical conditions of $V_V/V_{II}/0$. For the conditions which indicated criticality, additional runs were made with the loads distributions shifted to the most critical axial location on the segment within the one-fourth diameter (36.5 in.) limitation. The determining of this critical location was initially a trial and error process. From this family of cases shown in Tables 4 and 5, a ratio of eigenvalues with the load as shown was determined for the three-ring and two-ring configurations, respectively. From these sets of data, a shift factor of 0.9 was representative of the increase of criticality of a forward shift of load for the three-ring configuration and 0.85 for the two-ring configuration. The reciprocal of 0.9 (1.111) was selected as the corresponding (improvement) factor for an aft shift for both configurations.

SUBFACTORS FOR IMPERFECTIONS AND ASYMMETRY

The use of a subfactor for imperfections and asymmetry was purely arbitrary. It was done to aid in resolution of the paradox of reverse trends resulting from the use of KDF. For symmetrical circumferential loading distribution, the KDF approaches one; however, conservative analysis historically has applied a correction factor of 0.75 to symmetrical buckling analysis to account for imperfection sensitivity as evidenced from testing. Analysis which can assess the sensitivity of arbitrarily introduced imperfects indicates that the 0.75 factor is significantly conservative. Analysis also indicates that highly asymmetrically loaded structures are nearly insensitive to imperfections. However, for asymmetrical loading, linear analysis is in error by a factor ranging to nearly 40 percent, as represented by the maximum KDF of 0.605 for the cavity collapse loads on the aft SRM segments.

It is noted that the product of these arbitrary subfactors is 0.675 and is of interest in comparison with the historical factor of 0.75. The product of these two subfactors has been utilized as a constant to develop the three positional matrices which only vary as a function of the shift factors.

Table 6 presents input minimum eigenvalues used to determine the effect on attrition of using a symmetrical 0.75 scale factor for the three symmetrical loading cases of 80/0/0, 100/0/0, and 120/0/0 and a factor of 0.605 for all other conditions.

VERTICAL VELOCITY/STRUCTURAL CAPABILITY DISCRIMINATORS

Tables 7 and 8 are the uncorrected (scale factor 1.0) BOSOR eigenvalue matrices as functions of $V_V/V_H/0$ for the cavity collapse water impact load distributions for the three-ring and two-ring configurations, respectively.

These results are for loads represented in matrix 2 of Table 2. These matrices form the basis for development of positional factor of safety matrices used for the attrition assessment.

Table 9 presents uncorrected BOSOR eigenvalues for the vertical velocity of 85 ft/s loadings. These values were used as checks on interpolations of values within the SPLASH program for vertical velocities between 80 and 100 ft/s.

Tables 10 and 11 present the adjusted (scale factor 0.605) BOSOR eigenvalue matrices as functions of $V_V/V_H/\theta$ for the condition of the cavity collapse load distribution shifted forward one-fourth the motor diameter for the three-ring and two-ring configurations, respectively. These results would correspond with loads represented in Table 1.

Tables 12 (three-ring) and 13 (two-ring) present the three positional matrices to assess the equal probability of the load shifted fore and aft 36.5 in. Matrix 1 (forward shift), matrix 2 (as shown), and matrix 3 (aft shift) are the eigenvalues shown in Tables 7 and 8, respectively, multiplied by the positional scale factors of 0.605, 0.675, and 0.75.

PROGRAM COSTS

Costs for trades were determined using total program costs of flight hardware and spares as stated in the current cost per flight document. The differential costs shown in Tables 14 through 18 result from water impact attrition only. Total program costs do reflect the total attrition; however, general attrition is a constant and its costs have been subtracted for differential trade consideration. All costs are in FY75 dollars.

LOSS OF ENTIRE SRB

Throughout this study it has been assumed that loss of an SRM cyclinder will not prevent recovery of the SRB, which is a baselined attrition analysis assumption. However, this assumption has major cost implications. Leakage in this area will not cause the SRB to sink, but it may prevent plugging of the nozzle and, thus, prevent recovery of the SRB. The critical factors are the size and location of the hole or crack generated, and whether the resulting log mode flotation angle will allow towing the SRB into the Indian River. An estimate of the cost if the plug cannot maintain a satisfactory log mode for towback is obtained by assuming that the ultimate capability of the case is 10 percent greater than the stability capability (the same criteria used for slapdown loads on the forward segments). These attrition rates for the loss of an "entire SRB" are assessed and discussed in the Results and Conclusions paragraph.

RESULTS AND CONCLUSIONS

Table 19 presents a summary and methodology comparison of the attrition rate assessments. Table 20 presents a comparison of the range of attrition values for the baselined velocity for evaluation of the sensitivity of the analysis methods. The attrition rates shown in the tables are due to water impact only. Figures 8 through 13 show the results of the attrition studies as progressively developed. Attrition rates (in percent) are shown for the V_V of 85 and 100 ft/s and for the three-ring and two-ring configurations. Four methods are identified: two methods using peak pressure and two methods using factors of safety (scaled eigenvalues).

The methods identified as "max ΔP" or "min eigen" use a maximized single matrix of the largest pressure or minimum factor of safety for each $V_V/V_H/\theta$ without positional probability considerations.

The methods identified as "3M ΔP" and "3M eigen" consider positional probabilities.

Due to the nonlinear structural response, the nonlinear peak load, and load distribution characteristics, the structural criticality is not proportional to the peak load. This necessitated the use of the minimum pressure capability within the arbitrarily defined envelope of conditions of $V_V/V_H/\theta$ of 100/45/±5. The use of this minimum pressure capability (nonlinear STAGS result times the peak pressure) for the max ΔP method results in highly conservative attrition rates. The conservatism is introduced from the neglect of the positional probabilities and, more significantly, the use of a single capability established by a low frequency of occurrence event (100/30/±5 or 80/15/-5). The 3M (ΔP) method reduces the conservatism, but still has the deficiency of using a single low frequency of occurrence pressure capability.

The eigenvalue methods are preferred; their single point of difficulty is the extensive analysis required. While a constant KDF is used for each matrix set, this improves the realism of the results since the asymmetry effect is similar for a high percentage of the load cases; each load event (V_V/ V_H/θ) capability is treated in accordance with its frequency of occurrence.

The 3M eigen method is conservative and is the best interim estimate of motor case attrition.

The method outlined in this report utilizing factor of safety matrices for load positioning as input to the SPLASH program will provide a compatible attrition rate assessment with other SRB assemblies. Using this method (3M eigen) the attrition rate of 0.4 percent for the three- or four-ring configuration and 1.3 percent for the two-ring configuration for the vertical velocity of 85 ft/s are determined. Table 14 assesses the program costs of the SRM aft segment cavity collapse rings for the four-, three-, and two-ring configurations. The study indicates a program saving of $1.9 million by removing the first cavity collapse ring. Removal of a second ring results in a program cost penalty of $1.1 million.

The absolute value of this attrition assessment for the four-or three-ring configuration is considered slightly conservative and may be further reduced as additional analysis results are provided. The attrition assessment for the two-ring configuration is considered slightly unconservative primarily because of the limited number of "nonlinear STAGS" investigations made.

The apparent 1.0 percent differences in attrition rates of the four- or three-ring configuration and the two-ring configuration indicates that the dollar value of weight reduction must be greater than $13/lb (added to a single SRB) per flight (of two SRB) for the removal of the third ring (185.6 lb of ring weight per SRB) to have a beneficial cost effect.

Table 15 compares the attrition rates of the ring configuration options at the baselined V_V of 85 ft/s with respect to structural verification testing. If structural verification testing is not performed, the attrition increase to 2.68 and 7.1 percent for the three/four-ring and two-ring configuration, respectively. Figure 16 shows a $7.6 million increase in program costs for the three-ring configuration if verification testing is not performed. The increase in program cost is $11.3 million for the two-ring configuration.

Table 18 shows the results of a sensitivity assessment of loss of an entire SRB (for the baselined vertical velocity), assuming the ultimate capability (point at which sinkage would occur) of the case is 10 percent greater than the stability capability. The losses of entire SRB attritions are 0.2 percent and 0.9 percent for the three-ring and two-ring configurations, respectively.

All analyses contained herein have retained the integral stubs on both aft segments, regardless of the number of stiffener rings employed. Their stiffness is required for the capabilities and attritions stated and segment commonality is desirable for economic reasons.

TABLE 1. SRM AFT SEGMENTS CAVITY COLLAPSE MAXIMUM DIFFERENTIAL PRESSURE (ΔP, PSIG), SHIFTED FORWARD (+36.5 INCHES)

CONDITION			MATRIX	CONDITION			MATRIX
V_V (FT/SEC)	V_H (FT/SEC)	THETA (DEGREES)	PRESSURE (PSIG)	V_V (FT/SEC)	V_H (FT/SEC)	THETA (DEGREES)	PRESSURE (PSIG)
80.	0.	−10.	.14500+03	100.	30.	5.	.25500+03
80.	0.	− 5.	.15000+03	100.	30.	10.	.11800+03
80.	0.	0.	.10200+03	100.	45.	−10.	.00000+02
80.	0.	5.	.15000+03	100.	45.	− 5.	.11000+03
80.	0.	10.	.14500+03	100.	45.	0.	.15000+03
80.	15.	−10.	.12000+03	100.	45.	5.	.24000+03
80.	15.	− 5.	.17500+03	100.	45.	10.	.25200+03
80.	15.	0.	.16500+03	100.	60.	−10.	.40000+02
80.	15.	5.	.82000+02	100.	60.	− 5.	.70000+02
80.	15.	10.	.17000+03	100.	60.	0.	.11500+03
80.	30.	−10.	.10000+03	100.	60.	5.	.15000+03
80.	30.	− 5.	.13200+03	100.	60.	10.	.19800+03
80.	30.	0.	.16500+03	120.	0.	−10.	.28500+03
80.	30.	5.	.18500+03	120.	0.	− 5.	.26500+03
80.	30.	10.	.95000+02	120.	0.	0.	.15000+03
80.	45.	−10.	.45000+02	120.	0.	5.	.26500+03
80.	45.	− 5.	.65000+02	120.	0.	10.	.28500+03
80.	45.	0.	.13000+03	120.	15.	−10.	.21500+03
80.	45.	5.	.15500+03	120.	15.	− 5.	.33000+03
80.	45.	10.	.18200+03	120.	15.	0.	.23500+03
80.	60.	−10.	.80000+02	120.	15.	5.	.14000+03
80.	60.	− 5.	.70000+02	120.	15.	10.	.26000+03
80.	60.	0.	.70000+02	120.	30.	−10.	.14500+03
80.	60.	5.	.10500+03	120.	30.	− 5.	.20500+03
80.	60.	10.	.15000+03	120.	30.	0.	.32000+03
100.	0.	−10.	.21400+03	120.	30.	5.	.30200+03
100.	0.	− 5.	.20000+03	120.	30.	10.	.15000+03
100.	0.	0.	.12500+03	120.	45.	−10.	.10000+03
100.	0.	5.	.20000+03	120.	45.	− 5.	.13000+03
100.	0.	10.	.21400+03	120.	45.	0.	.18000+03
100.	15.	−10.	.18000+03	120.	45.	5.	.31500+03
100.	15.	− 5.	.24200+03	120.	45.	10.	.30200+03
100.	15.	0.	.21800+03	120.	60.	−10.	.80000+02
100.	15.	5.	.10800+03	120.	60.	− 5.	.10000+03
100.	15.	10.	.19800+03	120.	60.	0.	.13500+03
100.	30.	−10.	.10000+03	120.	60.	5.	.20000+03
100.	30.	− 5.	.16500+03	120.	60.	10.	.30000+03
100.	30.	0.	.24500+03				

TABLE 2 SRM AFT SEGMENTS CAVITY COLLAPSE MAXIMUM DIFFERENTIAL PRESSURE (ΔP, PSIG) SHIFTED FORE AND AFT (±36.5 INCHES)

CONDITION			LOAD DIFFERENTIAL PRESSURE (PSIG)		
V_V (FT/SEC)	V_H (FT/SEC)	THETA (DEGREES)	MATRIX 1	MATRIX 2	MATRIX 3
80.	0.	−10.	.14500+03	.14000+03	.14500+03
80.	0.	− 5.	.15000+03	.10500+03	.13000+03
80.	0.	0.	.70000+02	.95000+02	.10000+03
80.	0.	5.	.15000+03	.10500+03	.13000+03
80.	0.	10.	.10500+03	.14000+03	.14500+03
80.	15.	−10.	.12000+03	.10000+03	.65000+02
80.	15.	− 5.	.15000+03	.17500+03	.15000+03
80.	15.	0.	.14590+03	.16500+03	.12000+03
80.	15.	5.	.75000+02	.80000+02	.60000+02
80.	15.	10.	.13000+03	.17000+03	.12500+03
80.	30.	−10.	.85000+02	.10000+03	.75000+02
80.	30.	− 5.	.11000+03	.12500+03	.10000+03
80.	30.	0.	.16500+03	.16000+03	.11000+03
80.	30.	5.	.16000+03	.18500+03	.11500+03
80.	30.	10.	.75000+02	.95000+02	.65000+02
80.	45.	−10.	.45000+02	.30000+02	.00000
80.	45.	− 5.	.65000+02	.50000+02	.50000+02
80.	45.	0.	.13000+03	.11000+03	.60000+02
80.	45.	5.	.15500+03	.15000+03	.11000+03
80.	45.	10.	.15500+03	.18000+03	.13000+03
80.	60.	−10.	.80000+02	.10000+02	.00000
80.	60.	− 5.	.70000+02	.20000+02	.00000
80.	60.	0.	.70000+02	.50000+02	.30000+02
80.	60.	5.	.10500+03	.95000+02	.70000+02
80.	60.	10.	.15000+03	.15000+03	.12000+03
100.	0.	−10.	.17500+03	.21500+03	.20500+03
100.	0.	− 5.	.13000+03	.15000+03	.20000+03
100.	0.	0.	.10000+03	.12500+03	.12500+03
100.	0.	5.	.13000+03	.15000+03	.20000+03
100.	0.	10.	.17500+03	.21500+03	.20500+03
100.	15.	−10	.15000+03	.18000+03	.13000+03
100.	15.	− 5.	.21000+03	.24000+03	.16500+03
100.	15.	0.	.20500+03	.21500+03	.16500+03
100.	15.	5.	.95000+02	.10500+03	.70000+02
100.	15.	10.	.14500+03	.17000+03	.20000+03
100.	30.	−10.	.10000+03	.95000+02	.65000+02
100.	30.	− 5.	.14500+03	.16500+03	.12000+03
100.	30.	0	.21500+03	.24500+03	.14500+03
100.	30.	5.	.21500+03	.25500+03	.21500+03
100.	30.	10.	.10000+03	.11500+03	.10000+03
100.	45.	−10.	.80000+02	.60000+02	.35000+02
100.	45.	− 5.	.11000+03	.10000+03	.65000+02
100.	45.	0.	.13000+03	.15000+03	.11000+03
100.	45.	5.	.21500+03	.24000+03	.17000+03
100.	45.	10.	.21500+03	.25200+03	.17000+03
100.	60.	−10.	.40000+02	.20000+02	.00000
100.	60.	− 5.	.70000+02	.20000+02	.00000
100.	60.	0.	.11500+03	.10500+03	.50000+02
100.	60.	5.	.15000+03	.15000+03	.13000+03
100.	60.	10.	.16500+03	.20000+03	.15000+03
120.	0.	−10.	.23000+03	.28500+03	.23000+03
120.	0.	− 5.	.22000+03	.26500+03	.24000+03
120.	0.	0.	.13000+03	.15000+03	.15000+03
120.	0.	5.	.22000+03	.26500+03	.24000+03
120.	0.	10.	.23000+03	.28500+03	.23000+03
120.	15.	−10.	.19500+03	.21500+03	.20000+03
120.	15.	− 5.	.30000+03	.33000+03	.28000+03
120.	15.	0.	.22500+03	.28500+03	.22500+03
120.	15.	5.	.13000+03	.14500+03	.13000+03
120.	15.	10.	.23500+03	.25500+03	.25000+03
120.	30.	−10.	.14500+03	.14000+03	.12500+03
120.	30.	− 5.	.20000+03	.20000+03	.16500+03
120.	30.	0.	.28500+03	.32000+03	.28500+03
120.	30.	5.	.25000+03	.30000+03	.25000+03
120.	30.	10.	.14500+03	.15000+03	.15000+03
120.	45.	−10.	.11000+03	.11000+03	.85000+02
120.	45.	− 5.	.13000+03	.11500+03	.10000+03
120.	45.	0.	.13000+03	.16500+03	.15000+03
120.	45.	5.	.28000+03	.30500+03	.26000+03
120.	45.	10.	.26500+03	.30500+03	.23000+03
120.	60.	−10.	.80000+02	.65000+02	.45000+02
120.	60.	− 5.	.10000+03	.95000+02	.65000+02
120.	60.	0.	.13500+03	.11500+03	.95000+02
120.	60.	5.	.17500+03	.20000+03	.17500+03
120.	60.	10.	.29000+03	.30000+03	.30000+03

TABLE 3 COMPARATIVE RESULTS OF CAVITY COLLAPSE BUCKLING ANALYSIS VERSUS PROGRAM OPTIONS

CONDITION	PEAK PRESSURE (PSIG)	BOSOR EIGENVALUE	STAGS LINEAR EIGENVALUE	STAGS NON-LINEAR % LOAD	KNOCKDOWN FACTORS	
		A.	B.	C.	A/C	B/C
3–RING						
100/30/+5	250	1.15	1.24	0.75	0.65	0.605
80/15/-5	175	1.67	1.75	1.06	0.63	0.605
85/30/+5	190	1.32	1.47	0.89	0.64	0.605
2–RING						
85/15/-5	185		1.63	1.02		0.63
85/0/0	106		1.39			

NOTE: 1. VALUES SHOWN IN COLUMNS B AND C HAVE BEEN PROVIDED BY THIOKOL INC. WITH EP-42 CONCURRENCE

TABLE 4. REPRESENTATIVE EIGENVALUES OF THE CAVITY COLLAPSE LOAD SHIFTED FORWARD FROM AS-SHOWN POSITION TO CRITICAL LOCATION (MAX + D/4, 36.5 IN.), THREE RINGS

CONDITION	EIGENVALUE		RATIO
	(A) LOAD SHIFTED	(B) LOAD AS SHOWN	A/B
80/0/0	2.488	2.704	0.92
80/15/-5	1.667	1.896	0.88
80/30/+5	1.748	1.969	0.89
100/0/0	2.184	2.513	0.87
100/0/-5	1.419	1.548	0.92
100/15/-5	1.310	1.410	0.93
100/30/+5	1.151	1.298	0.87
100/15/+10	1.429	1.548	0.92

USE SHIFT FACTOR 0.90 (MEAN)

TABLE 5. REPRESENTATIVE EIGENVALUES OF THE CAVITY COLLAPSE LOAD SHIFTED FORWARD FROM AS-SHOWN POSITION TO CRITICAL LOCATION (MAX + D/4, 36.5 IN.), TWO-RING

CONDITION	EIGENVALUE		RATIO
	(A) LOAD SHIFTED	(B) LOAD AS SHOWN	A/B
80/0/0	1.139	1.168	0.97
80/16/-5	1.612	1.896	0.85
80/30/+5	1.7481	1.945	0.90
100/0/0	1.441	1.710	0.84
100/0/-5	1.273	1.461	0.87
100/30/+5	0.639	1.298	0.49
100/15/+10	1.283	1.451	0.88
100/15/-5	1.269	1.410	0.90
80/0/-5	1.826	1.953	0.93

USE SHIFT FACTOR 0.85 (MEAN)

TABLE 6. SRM AFT SEGMENTS MINIMUM EIGENVALUE MATRIX CAVITY COLLAPSE, SCALE 0.605, SYMMETRICAL LOADS 120/0/0, 100/0/0 AND 80/0/0 SCALE 0.75, THREE-RING

	CONDITION		FACTOR SAFETY		CONDITION		FACTOR SAFETY
V_V (FT/SEC)	V_H (FT/SEC)	THETA (DEGREES)	MATRIX	V_V (FT/SEC)	V_H (FT/SEC)	THETA (DEGREES)	MATRIX
80.	0.	−10.	.12140+01	100.	30.	5.	.74300+00
80.	0.	− 5.	.11800+01	100.	30.	10	.19400-01
80.	0.	0.	.18180+01	100.	45.	−10.	.38450+01
80.	0.	5.	.11800+01	100.	45.	− 5.	.20810+01
80.	0.	10.	.12140+01	100.	45.	0.	.13720+01
80.	15.	−10.	.18680+01	100.	45.	5.	.90500+00
80.	15.	− 5.	.11520+01	100.	45.	10.	.76700+00
80.	15.	0.	.12820+01	100.	60.	−10.	.43600+01
80.	15.	5.	.25880+01	100.	60.	− 5.	.47390+01
80.	15.	10.	.14630+01	100.	60.	0.	.19440+01
80.	30.	−10.	.20100+01	100.	60.	5.	.13970+01
80.	30.	− 5.	.15440+01	100.	60.	10.	.55050+00
80.	30.	0.	.13630+01	120.	0.	−10.	.66800+00
80.	30.	5.	.19600+01	120.	0.	− 5.	.65400+00
80.	30.	10.	.20530+01	120.	0.	0.	.12230+01
80.	45.	−10.	.47250+01	120.	0.	5.	.65400+00
80.	45.	− 5.	.45280+01	120.	0.	10.	.66800+00
80.	45.	0.	.18517+01	120.	15.	−10.	.82400+00
80.	45.	5.	.14580+01	120.	15.	− 5.	.56400+00
80.	45.	10.	.10550+01	120.	15.	0.	.68040+00
80.	60.	−10.	.48600+01	120.	15.	5.	.12870+01
80.	60.	− 5.	.48600+01	120.	15.	10.	.54300+00
80.	60.	0.	.27340+01	120.	30.	−10.	.10970+01
80.	60.	5.	.19440+01	120.	30.	− 5.	.94000+00
80.	60.	10.	.13970+01	120.	30.	0.	.59230+00
100.	0.	−10.	.81200+00	120.	30.	5.	.63700+00
100.	0.	− 5.	.86200+00	120.	30.	10.	.11350+01
100.	0.	0.	.16970+01	120.	45.	−10.	.20110+01
100.	0.	5.	.86200+00	120.	45.	− 5.	.18230+01
100.	0.	10.	.81300+00	120.	45.	0.	.11640+01
100.	15.	−10.	.11150+01	120.	45.	5.	.59600+00
100.	15.	− 5.	.85600+00	120.	45.	10.	.64100+00
100.	15.	0.	.89200+00	120.	60.	−10.	.19440+01
100.	15.	5.	.15420+01	120.	60.	− 5.	.18830+01
100.	15.	10.	.86800+00	120.	60.	0.	.15800+01
100.	30.	−10.	.19400+01	120.	60.	5.	.90800+00
100.	30.	− 5.	.12370+01	120.	60.	10.	.53460+00

TABLE 7. SRM AFT SEGMENTS CAVITY COLLAPSE EIGENVALUE MATRIX, AS SHOWN, SCALE FACTOR 1.0, THREE RINGS

CONDITION V_V (FT/SEC)	V_H (FT/SEC)	THETA (DEGREES)	EIGENVALUE MATRIX	CONDITION V_V (FT/SEC)	V_H (FT/SEC)	THETA (DEGREES)	EIGNEVALUE MATRIX
80.	0.	–10.	.19980+01	100.	30.	5.	.12230+01
80.	0.	– 5.	.19530+01	100.	30.	10.	.31950+01
80.	0.	0.	.27040+01	100.	45.	–10.	.63300+01
80.	0.	5.	.19530+01	100.	45.	– 5.	.34260+01
80.	0.	10.	.19980+01	100.	45.	0.	.22590+01
80.	15.	–10.	.30750+01	100.	45.	5.	.14890+01
80.	15.	– 5.	.18960+01	100.	45.	10.	.12630+01
80.	15.	0.	.21100+01	100.	60.	–10.	.93000+01
80.	15.	5.	.42600+01	100.	60.	– 5.	.73000+01
80.	15.	10.	.24080+01	100.	60.	0.	.32000+01
80.	30.	–10.	.33100+01	100.	60.	5.	.23000+01
80.	30.	– 5.	.25410+01	100.	60.	10.	.14000+01
80.	30.	0.	.22440+01	120.	0.	–10.	.11000+01
80.	30.	5.	.19690+01	120.	0.	– 5.	.10800+01
80.	30.	10.	.33790+01	120.	0.	0.	.18120+01
80.	45.	–10.	.77780+01	120.	0.	5.	.10770+01
80.	45.	– 5.	.74540+01	120.	0.	10.	.11000+01
80.	45.	0.	.30480+01	120.	15.	–10.	.13560+01
80.	45.	5.	.24000+01	120.	15.	– 5.	.92900+00
80.	45.	10.	.17360+01	120.	15.	0.	.11200+01
80.	60.	–10.	.80000+01	120.	15.	5.	.21190+01
80.	60.	– 5.	.80000+01	120.	15.	10.	.10580+01
80.	60.	0.	.45000+01	120.	30.	–10.	.18100+01
80.	60.	5.	.32[illegible]0+01	120.	30.	– 5.	.15480+01
80.	60.	10.	.23000+01	120.	30.	0.	.97500+00
100.	0.	–10.	.13400+01	120.	30.	5.	.10480+01
100.	0.	– 5.	.14190+01	120.	30.	10.	.18690+01
100.	0.	0.	.25130+01	120.	45.	–10.	.33110+01
100.	0.	5.	.14190+01	120.	45.	– 5.	.30000+01
100.	0.	10.	.13380+01	120.	45.	0.	.19160+01
100.	15.	–10.	.18360+01	120.	45.	5.	.98100+00
100.	15.	– 5.	.14100+01	120.	45.	10.	.10560+01
100.	15.	0.	.14690+01	120.	60.	–10.	.32000+01
100.	15.	5.	.25380+01	120.	60.	– 5.	.31000+01
100.	15.	10.	.14290+01	120.	60.	0.	.26000+01
100.	30.	–10.	.32000+01	120.	60.	5.	.14940+01
100.	30.	– 5.	.20360+01	120.	60.	10.	.88000+00
100.	30.	0.	.13870+01				

TABLE 8. SRM AFT SEGMENTS CAVITY COLLAPSE EIGENVALUE MATRIX, AS SHOWN, SCALE FACTOR 1.0, TWO RINGS

CONDITION V_V (FT/SEC)	CONDITION V_H (FT/SEC)	THETA (DEGREES)	EIGENVALUE MATRIX	CONDITION V_V (FT/SEC)	CONDITION V_H (FT/SEC)	THETA (DEGREES)	EIGENVALUE
80.	0.	–10.	.14700+01	100.	30.	5.	.12230+01
80.	0.	– 5.	.19530+01	100.	30.	10.	.23510+01
80.	0.	0.	.11680+01	100.	45.	–10.	.28640+01
80	0.	5.	.19530+01	100.	45.	– 5.	.14000+01
80.	0.	10.	.14700+01	100.	45.	0.	.22590+01
80.	15.	–10.	.30750+01	100.	45.	5.	.14890+01
80.	15.	– 5.	.18960+01	100.	45.	10.	.12630+01
80.	15.	0.	.21100+01	100.	60.	–10.	.35000+01
80.	15.	5.	.38290+01	100.	60.	– 5.	.34000+01
80.	15.	10.	.23940+01	100.	60.	0.	.20000+01
80.	30.	–10.	.33120+01	100.	60.	5.	.15000+01
80.	30.	– 5.	.25410+01	100.	60.	10.	.13000+01
80.	30.	0.	.22440+01	120.	0.	–10.	.73300+00
80.	30.	5.	.19450+01	120.	0.	– 5.	.56400+00
80.	30.	10.	.33790+01	120.	0.	0.	.88700+00
80.	45.	–10.	.34880+01	120.	0.	5.	.56400+00
80.	45.	– 5.	.34420+01	120.	0.	10.	.73300+00
80.	45.	0.	.30480+01	120.	15.	–10.	.72100+00
80.	45.	5.	.24000+01	120.	15.	– 5.	.69200+00
80.	45.	10.	.17360+01	120.	15.	0.	.10330+01
80.	60.	–10.	.35000+01	120.	15.	5.	.20840+01
80.	60.	– 5.	.35000+01	120.	15.	10.	.55100+01
80.	60.	0.	.33000+01	120.	30.	–10.	.10500+01
80.	60.	5.	.20000+01	120.	30.	– 5.	.12770+01
80.	60.	10.	.15000+01	120.	30.	0.	.75700+00
100.	0.	–10.	.12470+01	120.	30.	5.	.93300+00
100.	0.	– 5.	.12820+01	120.	30.	10.	.98700+00
100.	0.	0.	.25130+01	120.	45.	–10.	.33040+01
100.	0.	5.	.12820+01	120.	45.	– 5.	.26860+01
100.	0.	10.	.12470+01	120.	45.	0.	.14740+01
100.	15.	–10	.18360+01	120.	45.	5.	.83800+00
100.	15.	– 5.	.14100+01	120.	45.	10.	.98800+00
100.	15.	0.	.14690+01	120.	60.	–10.	.20000+01
100.	15.	5.	.23660+01	120.	60.	– 5.	.19000+01
100.	15.	10.	.12740+01	120.	60.	0.	.26000+01
100.	30.	–10.	.31950+01	120.	60.	5.	.10180+01
100.	30.	– 5.	.20360+01	120.	60.	10.	.70000+00
100.	30.	0.	.13870+01				

TABLE 9. SRM AFT SEGMENT BOSOR EIGENVALUES FOR THE WATER IMPACT CAVITY COLLAPSE CONDITION (V_V = 85 FT/SEC), THREE-AND TWO-RING CONFIGURATION

LOAD CONDITION $V_V/V_H/\theta$	P_{MAX} (PSIG)	MINIMUM "BOSOR" EIGENVALUES AFT SEGMENTS CONFIGURATIONS	
		3-RING	2-RING
85/0/0	110	2.18737 (4)	1.12477 (5)
85/15/0	180	1.66903 (13)	1.66903 (13)
85/15/-5	190	1.46839 (12)	1.46839 (12)
85/30/0	190	1.59220 (13)	1.45636 (5)
85/30/+5	200	1.56665 (12)	1.56665 (12)
85/45/+5	180	1.66903 (13)	1.66903 (13)

NOTE: 1. ALL EIGENVALUES SHOWN ARE MINIMUM FOR THE CONDITION INDICATED FOR THE LOAD DISTRIBUTION SHIFTED FORWARD 36.5 INCHES (+ D/4)

2. NUMBER IN PARENTHESES IS EIGENVALUE BUCKLE WAVE INDEX.

TABLE 10. SRM AFT SEGMENTS CAVITY COLLAPSE MINIMUM EIGENVALUES, SHIFTED FORWARD (+36.5 INCHES) SCALE FACTOR 0.605, THREE RINGS

CONDITION			FACTOR SAFETY
V_V (FT/SEC)	V_H (FT/SEC)	THETA (DEGREES)	MATRIX
80.	0.	−10.	.12088+01
80.	0.	− 5.	.11816+01
80.	0.	0.	.16359+01
80.	0.	5.	.11816+01
80.	0.	10.	.12088+01
80.	15.	−10.	.18604+01
80.	15.	− 5.	.11471+01
80.	15.	0.	.12765+01
80.	15.	5.	.25773+01
80.	15.	10.	.14568+01
80.	30.	−10.	.20025+01
80.	30.	− 5.	.15373+01
80.	30.	0.	.13576+01
80.	30.	5.	.11912+01
80.	30.	10.	.20443+01
80.	45.	−10.	.47057+01
80.	45.	− 5.	.45097+01
80.	45.	0.	.18440+01
80.	45.	5.	.14520+01
80.	45.	10.	.10503+01
80.	60.	−10.	.48400+01
80.	60.	− 5.	.48400+01
80.	60.	0.	.27225+01
80.	60.	5.	.19360+01
80.	60.	10.	.13915+01
100.	0.	−10.	.81070+00
100.	0.	− 5.	.85849+00
100.	C.	0.	.15204+01
100.	0.	5.	.85849+00
100.	0.	10.	.80949+00
100.	15.	−10.	.11108+01
100.	15.	− 5.	.85305+00
100.	15.	0.	.88874+00
100.	15.	5.	.15355+01
100.	15.	10.	.86454+00
100.	30.	−10.	.19360+01
100.	30.	− 5.	.12318+01
100.	30.	0.	.83913+00

CONDITION			FACTOR SAFETY
V_V (FT/SEC)	V_H (FT/SEC)	THETA (DEGREES)	MATRIX
100.	30.	5.	.73991+00
100.	30.	10.	.19330+01
100.	45.	−10.	.38296+01
100.	45.	− 5.	.20727+01
100.	45.	0.	.13667+01
100.	45.	5.	.90084+00
100.	45.	10.	.76411+00
100.	60.	−10.	.48400+01
100.	60.	− 5.	.47190+01
100.	60.	0.	.19360+01
100.	60.	5.	.13915+01
100.	60.	10.	.84700+00
120.	0.	−10.	.66550+00
120.	0.	− 5.	.65340+00
120.	0.	0.	.10963+01
120.	0.	5.	.65158+00
120.	0.	10.	.66550+00
120.	15.	−10.	.82038+00
120.	15.	− 5.	.56204+00
120.	15.	0.	.67760+00
120.	15.	5.	.12820+01
120.	15.	10.	.64009+00
120.	30.	−10.	.10950+01
120.	30.	− 5.	.93654+00
120.	30.	0.	.58987+00
120.	30.	5.	.63404+00
120.	30.	10.	.11307+01
120.	45.	−10.	.20032+01
120.	45.	− 5.	.18150+01
120.	45.	0.	.11592+01
120.	45.	5.	.59350+00
120.	45.	10.	.63888+00
120.	60.	−10.	.19360+01
120.	60.	− 5.	.18755+01
120.	60.	0.	.15730+01
120.	60.	5.	.90387+00
120.	60.	10.	.53240+00

TABLE 11. SRM AFT SEGMENTS CAVITY COLLAPSE MINIMUM EIGENVALUES, SHIFTED FORWARD (+36.5 INCHES), SCALE FACTOR 0.605, TWO RINGS

CONDITION V_V (FT/SEC)	CONDITION V_H (FT/SEC)	CONDITION THETA (DEGREES)	FACTOR SAFETY MATRIX
80.	0.	−10.	.38935+00
80.	0.	− 5.	.11816+01
80.	0.	0.	.70664+00
80.	0.	5.	.11816+01
80.	0.	10.	.88935+00
80.	15.	−10.	.18604+01
80.	15.	− 5.	.11471+01
80.	15.	0.	.12765+01
80.	15.	5.	.23165+01
80.	15.	10.	.14484+01
80.	30.	−10.	.20038+01
80.	30.	− 5.	.15373+01
80.	30.	0.	.13576+01
80.	30.	5.	.11767+01
80.	30.	10.	.20443+01
80.	30.	−10.	.21102+01
80.	30.	− 5.	.20324+01
80.	45.	0.	.18440+01
80.	45.	5.	.14520+01
80.	45.	10.	.10503+01
80.	45.	−10.	.21175+01
80.	45.	− 5.	.21175+01
80.	60.	0.	.19965+01
80.	60.	5.	.12100+01
80.	60.	10.	.90750+00
100.	0.	−10.	.75443+00
100.	0.	− 5.	.77561+00
100.	0.	0.	.75443+00
100.	0.	5.	.77561+00
100.	0.	10.	.75443+00
100.	15.	−10.	.11108+01
100.	15.	− 5.	.85305+00
100.	15.	0.	.88874+00
100.	15.	5.	.14314+01
100.	15.	10.	.77077+00
100.	30.	−10.	.19330+01
100.	30.	− 5.	.12318+01
100.	30.	0.	.83913+00
100.	30.	5.	.73991+00
100.	30.	10.	.14224+01
100.	45.	−10.	.17327+01
100.	45.	− 5.	.84700+00
100.	45.	0.	.13667+01
100.	45.	5.	.90084+00
100.	45.	10.	.76411+00
100.	60.	−10.	.21175+01
100.	60.	− 5.	.20570+01
100.	60.	0.	.12100+01
100.	60.	5.	.90750+00
100.	60.	10.	.78650+00
120.	0.	−10.	.44346+00
120.	0.	− 5.	.34122+00
120.	0.	0.	.44346+00
120.	0.	5.	.34122+00
120.	0.	10.	.44346+00
120.	15.	−10.	.43620+00
120.	15.	− 5.	.41866+00
120.	15.	0.	.62496+00
120.	15.	5.	.12608+01
120.	15.	10.	.33335+00
120.	30.	−10.	.63525+00
120.	30.	− 5.	.77258+00
120.	30.	0.	.45798+00
120.	30.	5.	.56446+00
120.	30.	10.	.59713+00
120.	45.	−10.	.19989+01
120.	45.	− 5.	.16250+01
120.	45.	0.	.89177+00
120.	45.	5.	.50699+00
120.	45.	10.	.59774+00
120.	60.	−10.	.12100+01
120.	60.	− 5.	.11495+01
120.	60.	0.	.15730+01
120.	60.	5.	.61589+00
120.	60.	10.	.42350+00

TABLE 12. SRM AFT SEGMENTS CAVITY COLLAPSE EIGENVALUE MATRICES, SHIFTED FORE AND AFT (±36.5 INCHES), SCALE FACTORS 0.605, 0.675, 0.75, THREE RINGS

CONDITON			FACTORS OF SAFETY		
V_V (FT/SEC)	V_H (FT/SEC)	THETA (DEGREES)	MATRIX 1	MATRIX 2	MATRIX 3
80.	0.	−10.	.12088+01	.13486+01	.14985+01
80.	0.	− 5.	.11016+01	.13183+01	.14647+01
80.	0.	0.	.16359+01	.18252+01	.20280+01
80.	0.	5.	.11816+01	.13183+01	.14647+01
80.	0.	10.	.12088+01	.13486+01	.14985+01
80.	15.	−10.	.18604+01	.20756+01	.23062+01
80.	15.	− 5.	.11471+01	.12798+01	.14220+01
80.	15.	0.	.12765+01	.14242+01	.15825+01
80.	15.	5.	.25773+01	.28755+01	.31950+01
80.	15.	10.	.14568+01	.16254+01	.18060+01
80.	30.	−10.	.20025+01	.22342+01	.24825+01
80.	30.	− 5.	.15373+01	.17152+01	.19058+01
80.	30.	0.	.13576+01	.15147+01	.16830+01
80.	30.	5.	.11912+01	.13291+01	.14767+01
80.	30.	10.	.20443+01	.22808+01	.25342+01
80.	45.	−10.	.47057+01	.52501+01	.58342+01
80.	45.	− 5.	.45097+01	.20574+01	.55905+01
80.	45.	0.	.18440+01	.16200+01	.22860+01
80.	45.	5.	.14520+01	.11718+01	.18000+01
80.	45.	10.	.10503+01	.11718+01	.13020+01
80.	60.	−10.	.48400+01	.54000+01	.60000+01
80.	60.	− 5.	.48400+01	.54000+01	.60000+01
80.	60.	0.	.27225+01	.30375+01	.33750+01
80.	60.	5.	.19360+01	.21600+01	.24000+01
80.	60.	10.	.13915+01	.15525+01	.17250+01
100.	0.	−10.	.81070+00	.90450+00	.10050+01
100.	0.	− 5.	.85849+00	.95782+00	.10642+01
100.	0.	0.	.15204+01	.16963+01	.18848+01
100.	0.	5.	.85849+00	.95782+00	.10642+01
100.	0.	10.	.80949+00	.90315+00	.10035+01
100.	15.	−10.	.11108+01	.12393+01	.13770+01
100.	15.	− 5.	.85305+00	.95175+00	.10575+01
100.	15.	0.	.88874+00	.99157+00	.11017+01
100.	15.	5.	.15355+01	.17131+01	.19023+01
100.	15.	10.	.86454+00	.96457+00	.10718+01
100.	30.	−10.	.19360+01	.21600+01	.24000+01
100.	30.	− 5.	.12318+01	.13743+01	.15270+01
100.	30.	0.	.83913+00	.93622+00	.10402+01
100.	30.	5.	.73991+00	.82552+00	.91725+00
100.	30.	10.	.19330+01	.21566+01	.23962+01
100.	45.	−10.	.38296+01	.42727+01	.47475+01
100.	45.	− 5.	.20727+01	.23125+01	.25695+01
100.	45.	0.	.13667+01	.15248+01	.16943+01
100.	45.	5.	.90084+00	.10051+01	.11167+01
100.	45.	10.	.76411+00	.85252+00	.94725+00
100.	60.	−10.	.48400+01	.54000+01	.60000+01
100.	60.	− 5.	.47190+01	.52650+01	.58500+01
100.	60.	0.	.19360+01	.21600+01	.24000+01
100.	60.	5.	.13915+01	.15525+01	.17250+01
100.	60.	10.	.84700+00	.94500+00	.10500+01
120.	0.	−10.	.66550+00	.74250+00	.82500+00
120.	0.	− 5.	.65340+00	.72900+00	.81000+00
120.	0.	0.	.10963+01	.12231+01	.13590+01
120.	0.	5.	.65158+00	.72698+00	.80775+00
120.	0.	10.	.66550+00	.74250+00	.82500+00
120.	15.	−10.	.82038+00	.91530+00	.10170+01
120.	15.	− 5.	.56204+00	.62707+00	.69675+00
120.	15.	0.	.67760+00	.75600+00	.84000+00
120.	15.	5.	.12820+01	.14303+01	.15892+01
120.	15.	10.	.64009+00	.71415+00	.79350+00
120.	30.	−10.	.10950+01	.12217+01	.13575+01
120.	30.	− 5.	.93654+00	.10449+01	.11610+01
120.	30.	0.	.58987+00	.65812+00	.73125+00
120.	30.	5.	.63404+00	.70740+00	.78600+00
120.	30.	10.	.11307+01	.12616+01	.14017+01
120.	45.	−10.	.20032+01	.22349+01	.24832+01
120.	45.	− 5.	.18150+01	.20250+01	.22500+01
120.	45.	0.	.11592+01	.12933+01	.14370+01
120.	45.	5.	.59350+00	.66217+00	.73575+00
120.	45.	10.	.63888+00	.71280+00	.79200+00
120.	60.	−10.	.19360+01	.21600+01	.24000+01
120.	60.	− 5.	.18755+01	.20925+01	.23250+01
120.	60.	0.	.15730+01	.17550+01	.19500+01
120.	60.	5.	.90387+00	.10084+01	.11205+01
120.	60.	10.	.53240+00	.59400+00	.66000+00

TABLE 13. SRM AFT SEGMENTS CAVITY COLLAPSE EIGENVALUE MATRICES, SHIFTED FORE AND AFT (±36.5 INCHES), SCALE FACTORS 0.605, 0.675, 0.75, TWO RINGS

CONDITION			FACTORS OF SAFETY		
V_V (FT/SEC)	V_H (FT/SEC)	THETA (DEGREES)	MATRIX 1	MATRIX 2	MATRIX 3
80.	0.	−10.	.88935+00	.99225+00	.11025+01
80.	0.	− 5.	.11816+01	.13183+01	.14647+01
80.	0.	0.	.70664+00	.78840+00	.87600+00
80.	0.	5.	.11816+01	.13183+01	.14647+01
80.	0.	10.	.88935+00	.99225+00	.11025+01
80.	15.	−10.	.18604+01	.20756+01	.23062+01
80.	15.	− 5.	.11471+01	.12798+01	.14220+01
80.	15.	0.	.12765+01	.14242+01	.15825+01
80.	15.	5.	.23165+01	.25846+01	.28717+01
80.	15.	10.	.14484+01	.16159+01	.17955+01
80.	30.	−10.	.20038+01	.22356+01	.24840+01
80.	30.	− 5.	.15373+01	.17152+01	.19058+01
80.	30.	0.	.13576+01	.15147+01	.16830+01
80.	30.	5.	.11767+01	.13129+01	.14587+01
80.	30.	10.	.20443+01	.22808+01	.25342+01
80.	45.	−10.	.21102+01	.23544+01	.26160+01
80.	45.	− 5.	.20824+01	.23233+01	.25815+01
80.	45.	0.	.18440+01	.20574+01	.22860+01
80.	45.	5.	.14520+01	.16200+01	.18000+01
80.	45.	10.	.10503+01	.11718+01	.13020+01
80.	60.	−10.	.21175+01	.23625+01	.26250+01
80.	60.	− 5.	.21175+01	.23625+01	.26250+01
80.	60.	0.	.19965+01	.22275+01	.24750+01
80.	60.	5.	.12100+01	.13500+01	.15000+01
80.	60.	10.	.90750+00	.10125+01	.11250+01
100.	0.	−10.	.75443+00	.84172+00	.93525+00
100.	0.	− 5.	.77561+00	.86535+00	.96150+00
100.	0.	0.	.15204+01	.16963+01	.18848+01
100.	0.	5.	.77561+00	.86535+00	.96150+00
100.	0.	10.	.75443+00	.84172+00	.93525+00
100.	15.	−10.	.11108+01	.12393+01	.13770+01
100.	15.	− 5.	.85305+00	.95175+00	.10575+01
100.	15.	0.	.88874+00	.99157+00	.11017+01
100.	15.	5.	.14314+01	.15970+01	.17745+01
100.	15.	10.	.77077+00	.35995+00	.95550+00
100.	30.	−10.	.19330+01	.21566+01	.23962+01
100.	30.	− 5.	.12318+01	.13743+01	.15270+01
100.	30.	0.	.83913+00	.93622+00	.10402+01
100.	30.	5.	.73991+00	.82552+00	.91725+00
100.	30.	10.	.14224+01	.15869+01	.17633+01
100.	45.	−10.	.17327+01	.19332+01	.21480+01
100.	45.	− 5.	.84700+00	.94500+00	.10500+01
100.	45.	0.	.13667+01	.15248+01	.16943+01
100.	45.	5.	.90084+00	.10051+01	.11167+01
100.	45.	10.	.76411+00	.85252+00	.94725+00
100.	60.	−10.	.21175+01	.23625+01	.26250+01
100.	60.	− 5.	.20570+01	.22950+01	.25500+01
100.	60.	0.	.12100+01	.13500+01	.15000+01
100.	60.	5.	.90750+00	.10125+01	.11250+01
100.	60.	10.	.78650+00	.87750+00	.97500+00
120.	0.	−10.	.44346+00	.49477+00	.54975+00
120.	0.	− 5.	.34122+00	.38070+00	.42300+00
120.	0.	0.	.53663+00	.59872+00	.66525+00
120.	0.	5.	.34122+00	.38070+00	.42300+00
120.	0.	10.	.44346+00	.49477+00	.54975+00
120.	15.	−10.	.43620+00	.48667+00	.54075+00
120.	15.	− 5.	.41866+00	.46710+00	.51900+00
120.	15.	0.	.62496+00	.69727+00	.77475+00
120.	15.	5.	.12608+01	.14067+01	.15630+01
120.	15.	10.	.33335+00	.37192+00	.41325+00
120.	30.	−10.	.63525+00	.70875+00	.78750+00
120.	30.	− 5.	.77258+00	.86197+00	.95775+00
120.	30.	0.	.45798+00	.51097+00	.56775+00
120.	30.	5.	.56446+00	.62977+00	.69975+00
120.	30.	10.	.59713+00	.66622+00	.74025+00
120.	45.	−10.	.19989+01	.22302+01	.24780+01
120.	45.	− 5.	.16250+01	.18130+01	.20145+01
120.	45.	0.	.89177+00	.99495+00	.11055+01
120.	45.	5.	.50699+00	.56565+00	.62850+00
120.	45.	10.	.59774+00	.66690+00	.74100+00
120.	60.	−10.	.12100+01	.13500+01	.15000+01
120.	60.	− 5.	.11495+01	.12825+01	.14250+01
120.	60.	0.	.15730+01	.17550+01	.19500+01
120.	60.	5.	.61589+00	.68715+00	.76350+00
120.	60.	10.	.42350+00	.47250	.52500+00

TABLE 14. SRM AFT SEGMENT CAVITY COLLAPSE RING PROGRAM COST ASSESSMENT

CONFIGURATION	4-RING	3-RING (BASELINE)	2-RING
ATTRITION (%)	0.42 + 2.75 = 3.17	0.42 + 2.75 = 3.17	1.31 + 2.75 = 4.06
AFT CYLINDER COST (\$M)	57.586	57.586	60.236
RING COST (\$M)	7.53	5.65	4.09
TOTAL (\$M)	65.23	63.23	64.32
DELTA COST (\$M)	+1.88	0	+1.09

NOTES:
1. BREAK EVEN = 1,091,000/190 X 445 = \$12.9 PER POUND PER FLIGHT
2. TOTAL ATTRITION = ATTRITION WATER IMPACT + GENERAL ATTRITION
3. ESTIMATED WEIGHT OF BOLT-ON CAVITY COLLAPSE RING IS 190 POUNDS
4. VERTICAL VELOCITY (V_V) = 85 FT/SEC.

TABLE 15. SRM AFT SEGMENTS ATTRITION RATE ASSESSMENT

CONFIGURATION	ATTRITION (%) STD. TEST	NO TEST
3 OR 4 RINGS	0.42	2.68
2 RINGS	1.31	7.10

NOTES: 1. THE INTEGRAL STUDS ARE RETAINED.
2. FOR THE BASELINE VERTICAL VELOCITY OF 85 FT/SEC.

TABLE 16. SRM AFT SEGMENT CAVITY COLLAPSE TEST PROGRAM COST ASSESSMENT (THREE-RING CONFIGURATION)

	TEST	NO TEST
ATTRITION (%)	0.42 + 2.75 = 3.17	2.68 + 1.75 = 5.43
AFT CYLINDER COST ($M)	57.586	64.038
RING COST ($M)	5.647	6.818
TOTAL ($M)	63.233	70.856
DELTA ($M)	0	7.623

V_V = 85 FT/SEC

TABLE 17. SRM AFT SEGMENT CAVITY COLLAPSE TEST PROGRAM COST ASSESSMENT (TWO-RING BASELINE CONFIGURATION)

	TEST	NO TEST
ATTRITION (%)	1.31 + 2.75 = 4.06	7.10 + 2.75 = 9.85
AFT CYLINDER COST ($M)	60.236	69.461
RING COST ($M)	4.087	6.119
TOTAL ($M)	64.323	75.580
DELTA ($M)	0	11.257

V_V = 85 FT/SEC

TABLE 18. SENSITIVITY ASSESSMENT OF SRB ATTRITION/COST VERSUS SEGMENT ATTRITION/COST ASSUMING A 10 PERCENT INCREASE IN STRUCTURAL CRITICALITY

	WATER IMPACT TOTAL ATTRITION (%)	ATTRITION LOSS OF SEGMENTS ONLY (%)	ATTRITION LOSS ENTIRE SRM (%)	ATTRITION COST
TWO RINGS	1.3	0.4 COST $2.6 M	0.9 COST $24.7	$27.3 M
THREE RINGS	0.4	0.2 COST $1.2 M	0.2 COST $5.5 M	6.7 M
			DELTA	$14.8 M

NOTES: 1. ASSUME SINKAGE OR LOSS OF AN SRB OCCURS WHEN CAPABILITY IS 1.0/1.1 = .90 OF CURRENT CAPABILITY. (LOAD/POSITIONAL EFFECT IS 10 PERCENT GREATER THAN DESIGN VALUES)
2. ASSUMES STRUCTURAL VERIFICATION TESTING.

TABLE 19. METHODOLOGY COMPARISONS OF SRM AFT SEGMENTS ATTRITION RATE ASSESSMENT

VERTICAL VELOCITY (V_V) (FT/SEC)	METHOD	ATTRITION (%) 3-RING CASES STD TEST	3-RING CASES NO TEST	2-RING CASES STD TEST	2-RING CASES NO TEST
85	3M (Δ P) 2/	1.8		8.5	
	MAX Δ P 2/	4.5		16.3	
	3M (EIGEN) 1/	0.4	2.68	1.3	7.10
	MIN EIGEN	0.9		3.1	
100	3M (Δ P) 2/	13.5		35.5	
	MAX Δ P 2/	24.0		50.0	
	3M (EIGEN) 1/	5.2		7.7	
	MIN EIGEN	12.3		16.2	

1/ RECOMMENDED METHOD RESULTS

2/ CAPABILITY 3-RING (80/15/-5) 1.06 x 175 = 185.5 PSIG
(100/30/+5) 0.75 x 250 = 187.5 PSIG
2-RING (85/30/+5) 0.605 x 177 x 1.466 = 157.0 PSIG

TABLE 20. METHODOLOGY COMPARISONS OF SRM AFT SEGMENTS ATTRITION RATE ASSESSMENT FOR THE BASELINED VERTICAL VELOCITY (V_V) OF 85 FT/SEC

VERTICAL VELOCITY (V_V) (FT/SEC)	METHOD	ATTRITION (%) 3-RING CASES STD TEST	ATTRITION (%) 2-RING CASES STD TEST
85	PEAK PRESSURE MATRIX DISCRIMINATOR 2/	4.5	16.3
	POSITIONAL EFFECT AND STRUCTURAL CAPABILITY MATRIX DISCRIMINATOR 1/	0.4	1.3

1/ RECOMMENDED METHOD RESULTS

2/ 3-RING (80/15/5) 1.06 X 175 = 185.5 PSIG
(100/30/+5) 0.75 X 250 = 187.5 PSIG
2-RING (85/30/+5) 0.605 X 177 X 1.466 - 157.0 PSIG

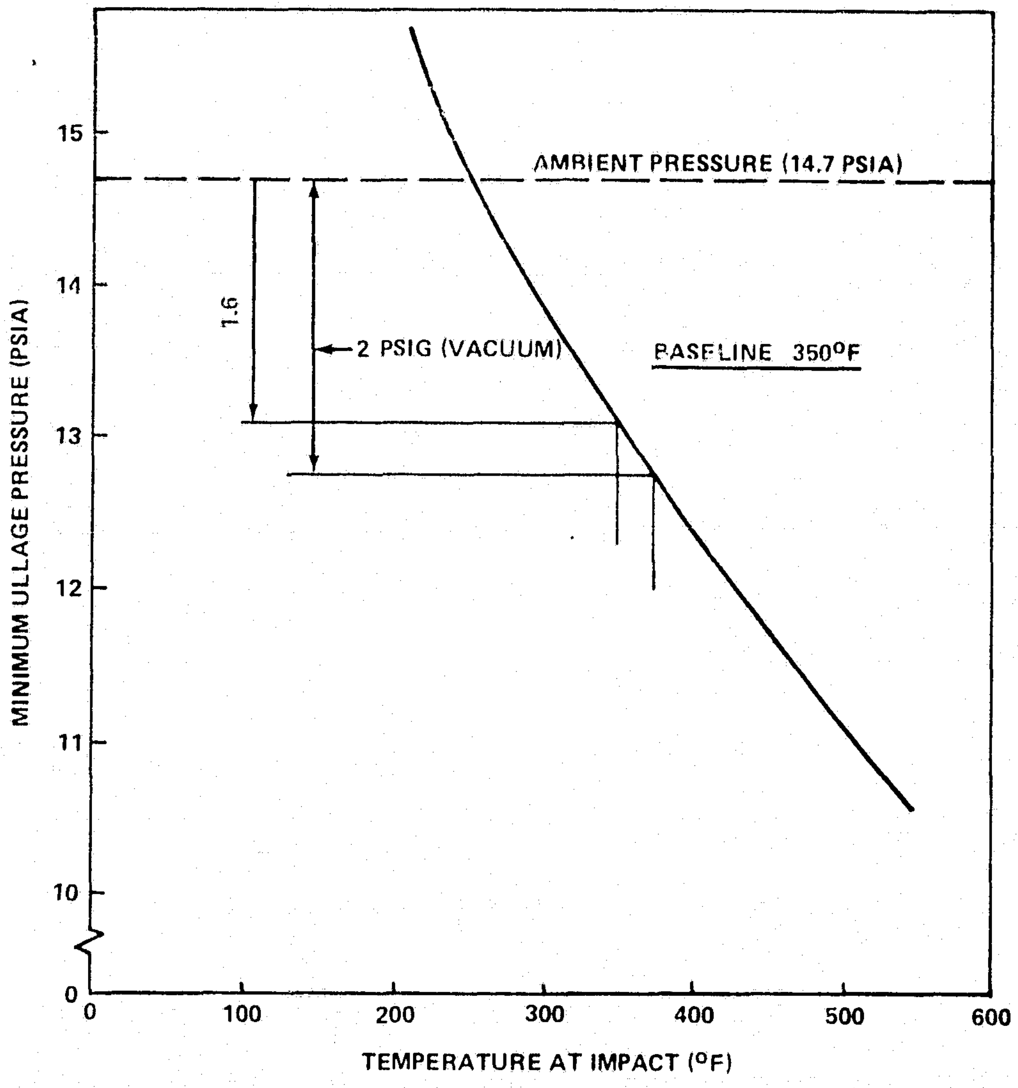


Figure 1. SRM ullage pressure as a function of ullage gas temperature at water impact.

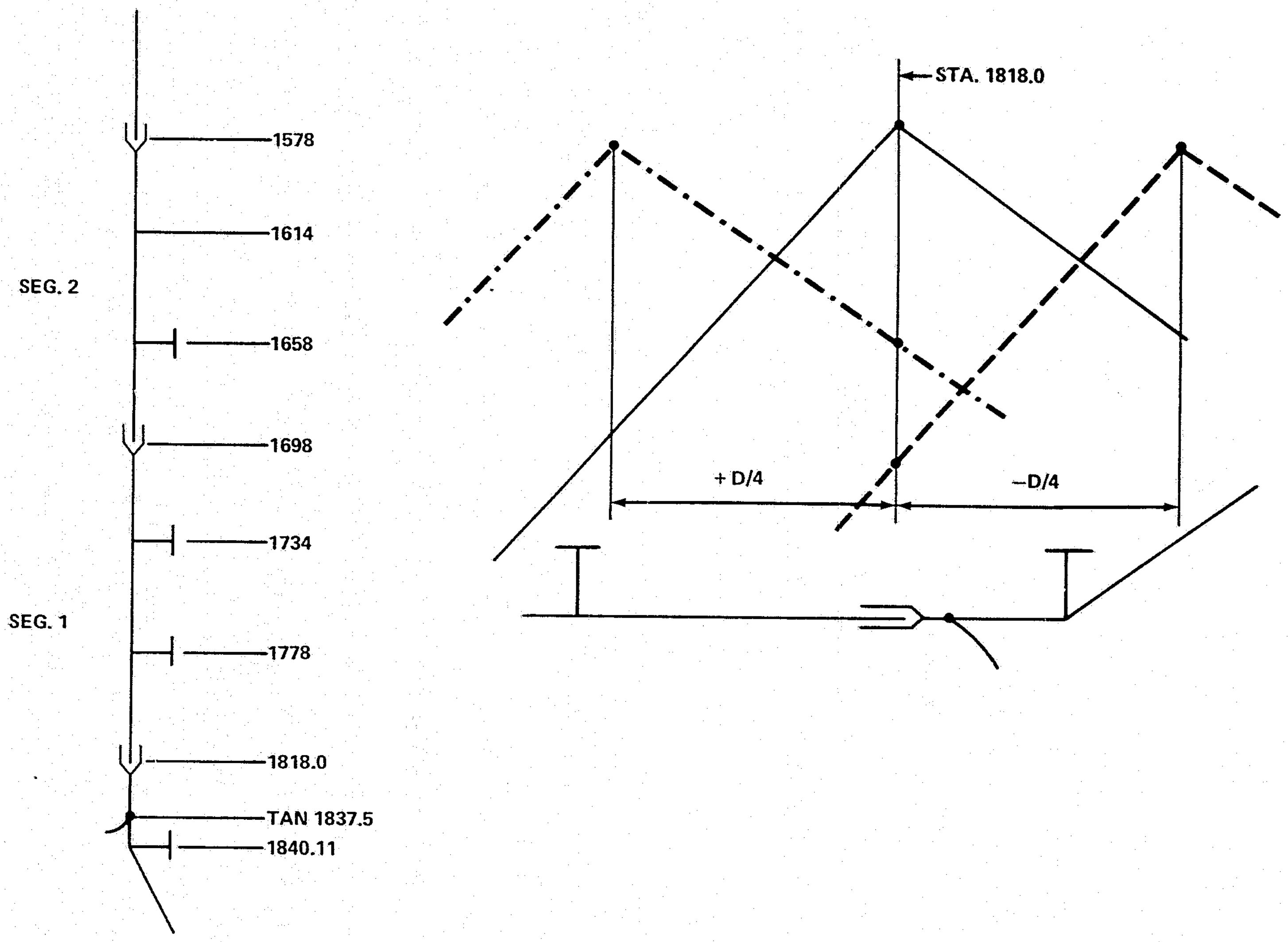
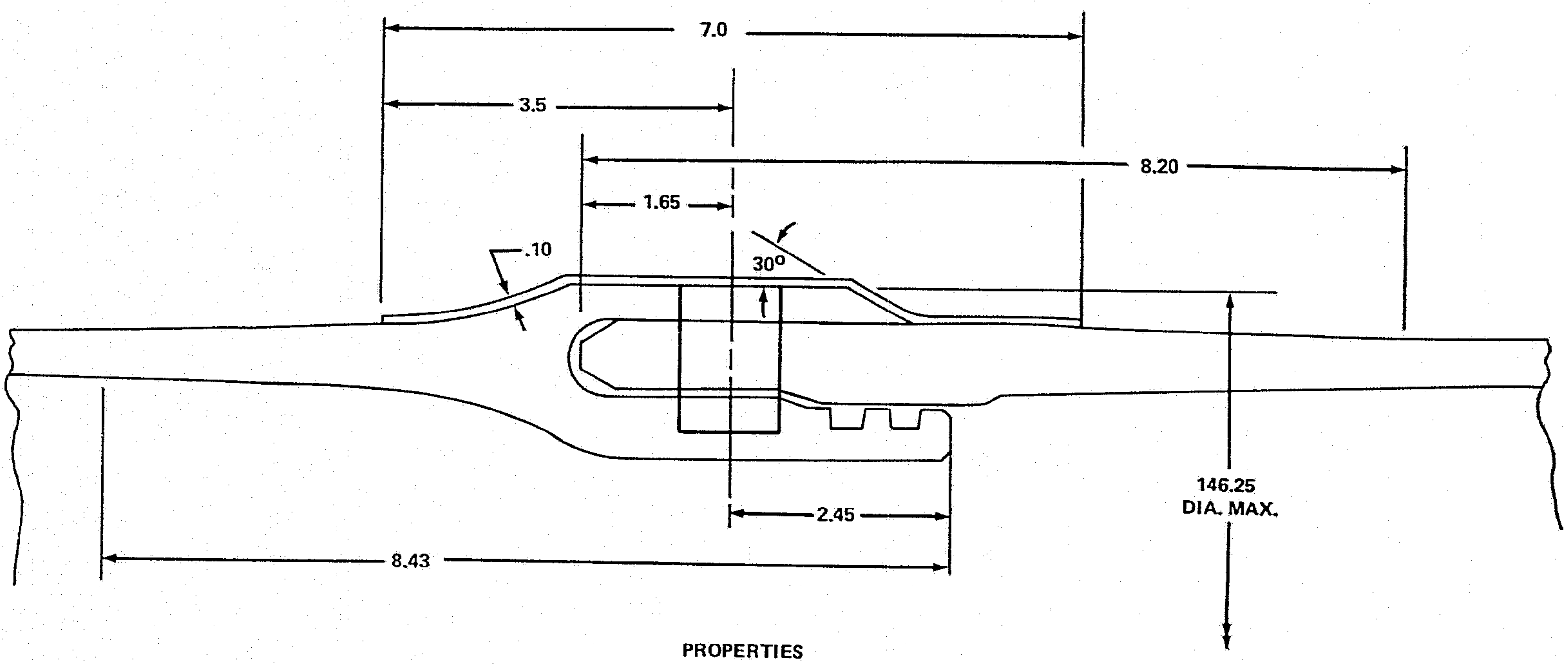


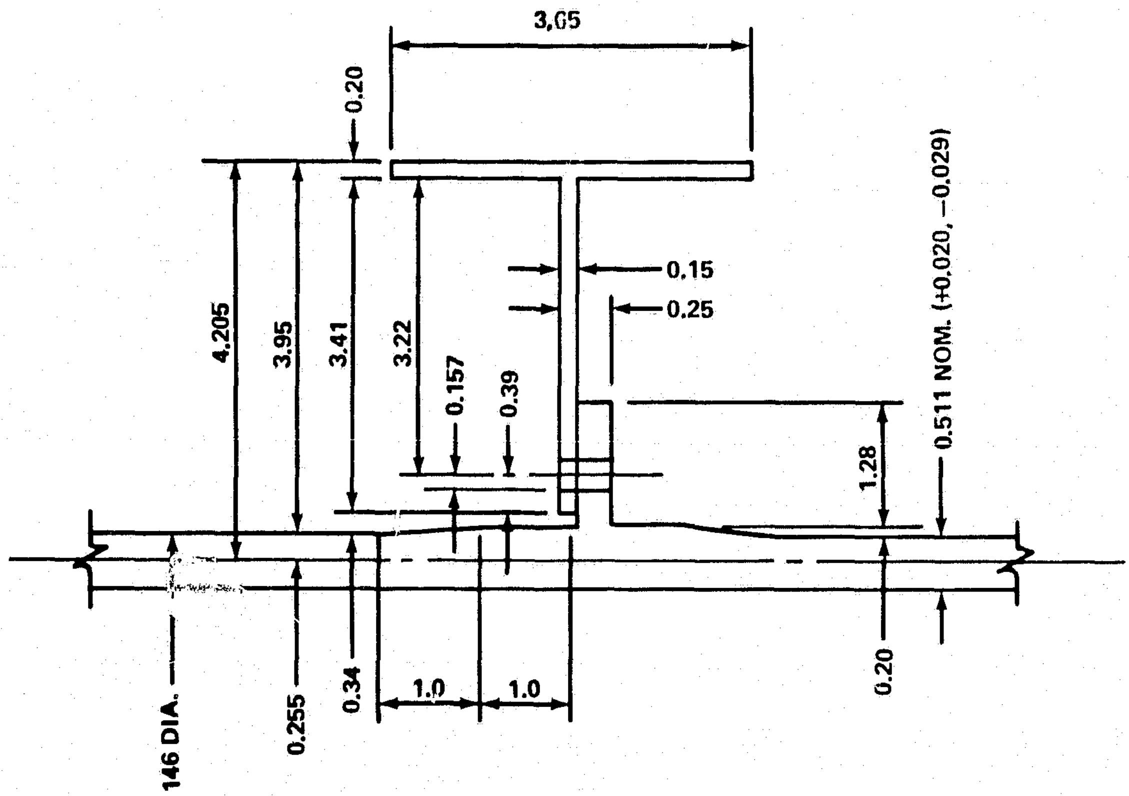
Figure 2. Aft motor case positional probability — equal probability of load peak within ± D/4 (36.5 in.) of as shown position.



PROPERTIES

AREA (SQ IN)		5.417
I	(IN^4)	1.519
$\overline{X}$	(IN)	0

Figure 3. Typical SRM clevis joint.



PROPERTIES		STUB	RING AND STUB
AREA	(SQ IN)	0.675	1.935
I	(IN^4)	0.129	4.60
$\bar{X}$	(IN)	0.695	2.362

Figure 4. Typical SRM aft segment cavity collapse bolt-on rings.

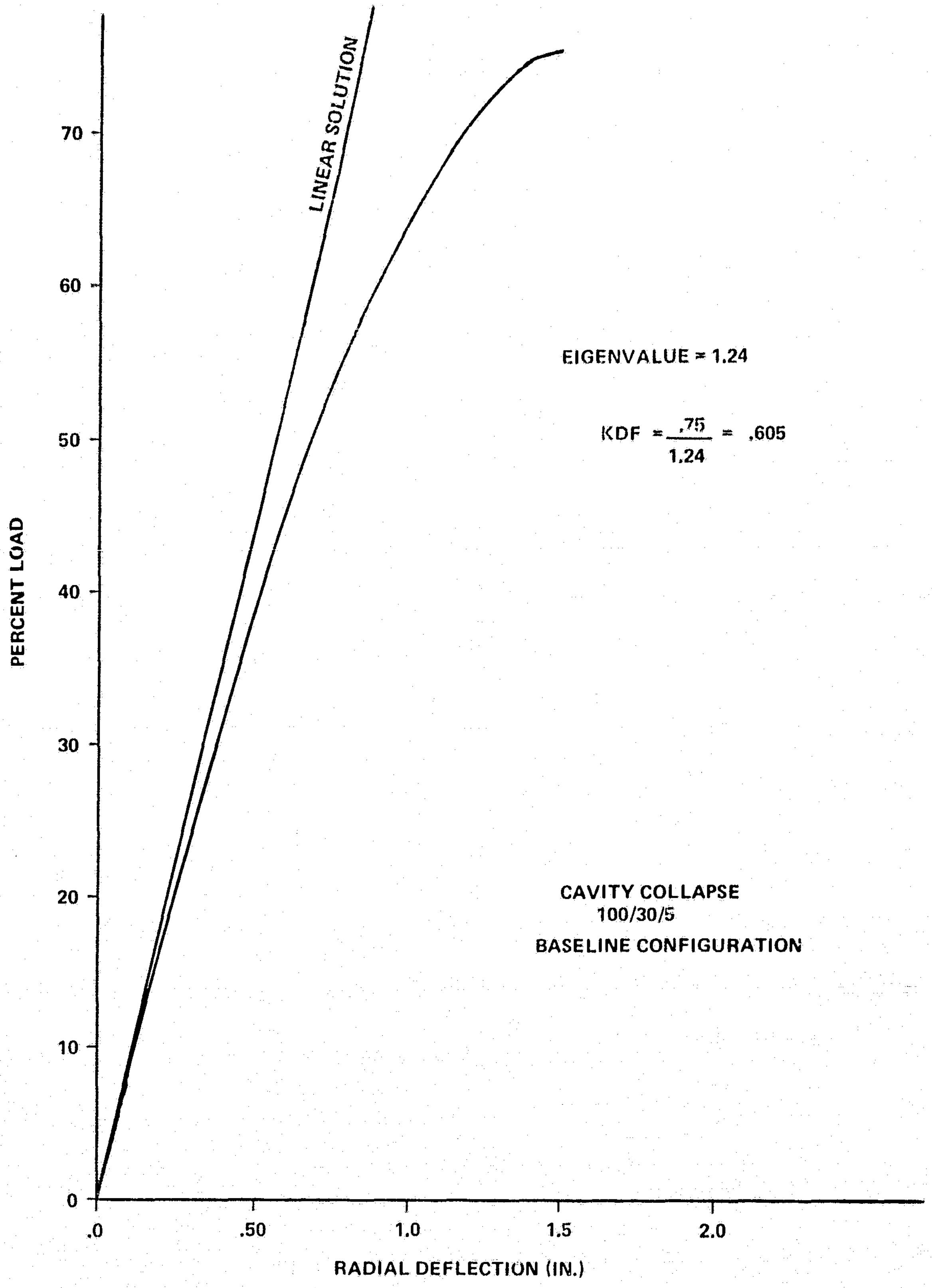


Figure 5. Comparison of STAGS linear and nonlinear buckling analysis.

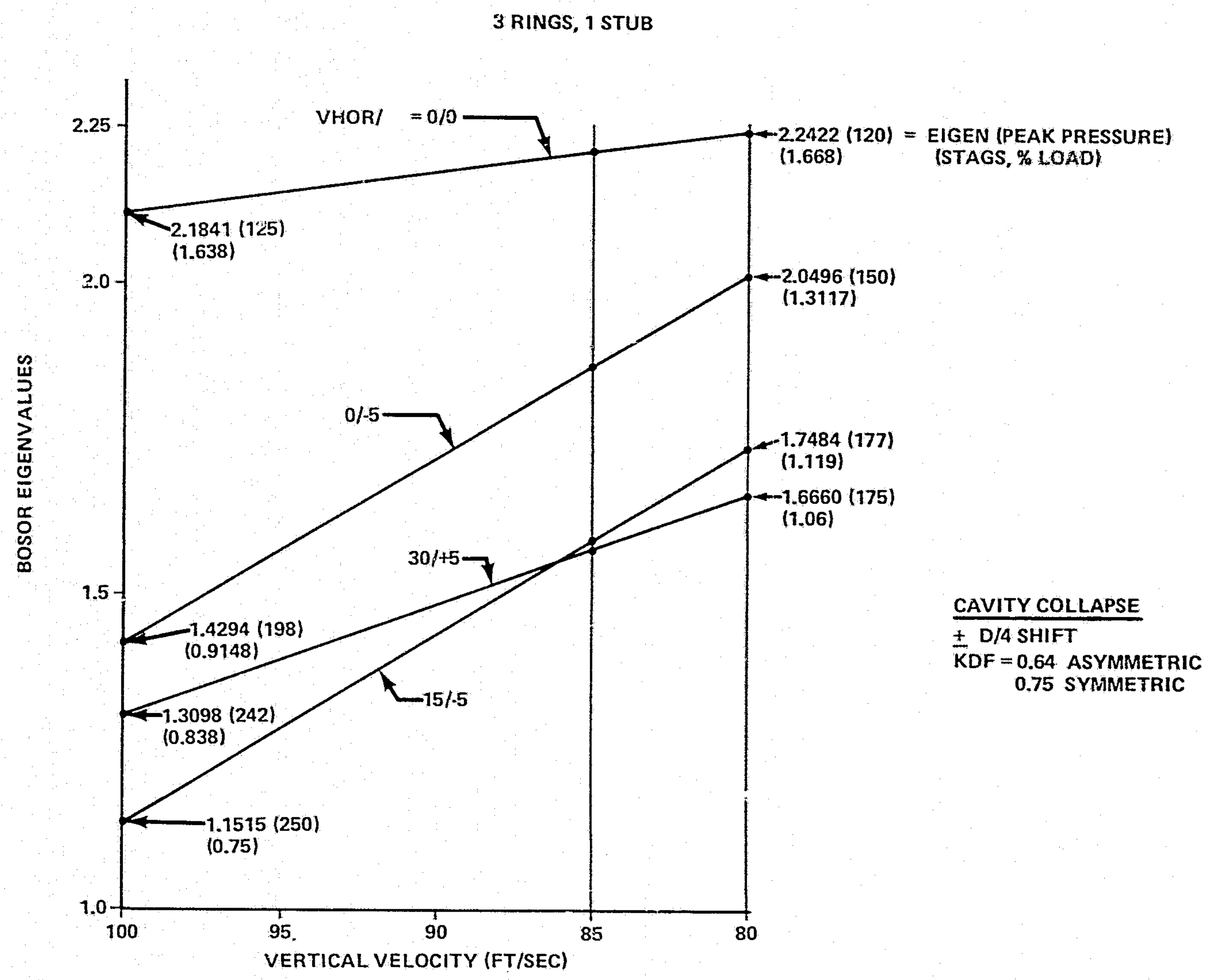


Figure 6. Comparison of critical cavity collapse SRM capabilities, three rings.

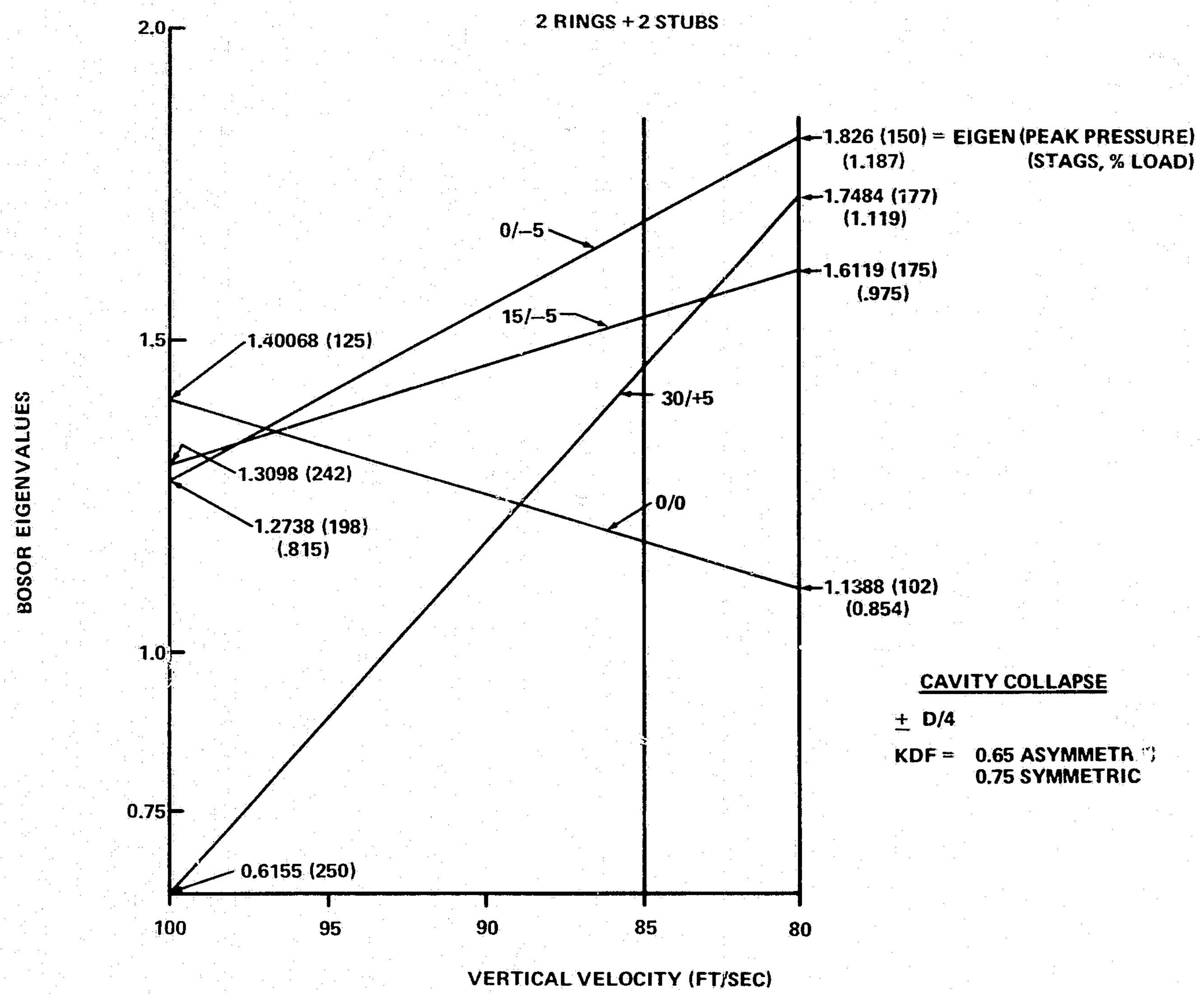


Figure 7. Comparison of critical cavity collapse SRM capabilities, two rings.

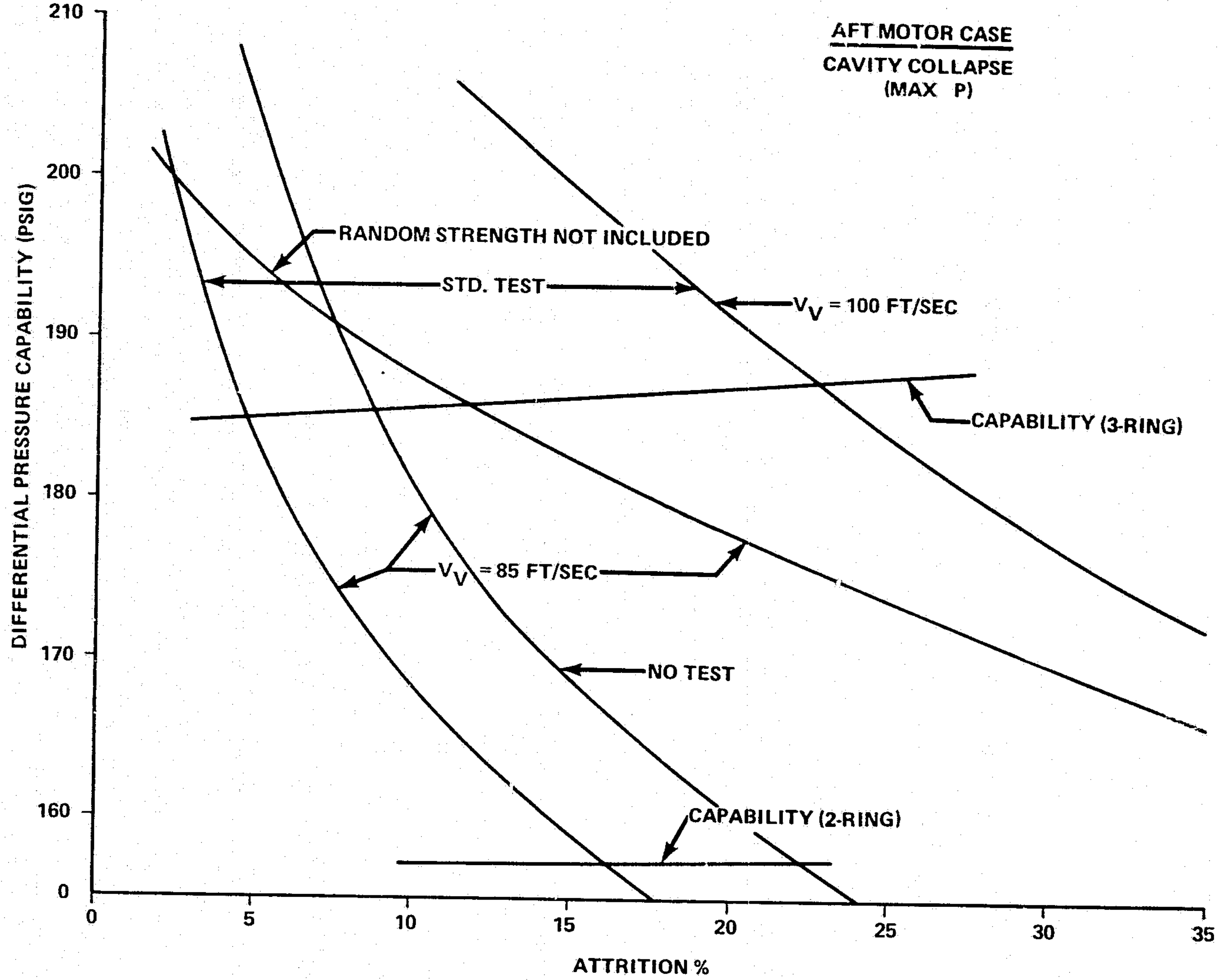


Figure 8. Aft motor case cavity collapse attrition rate, maximum differential pressure method.

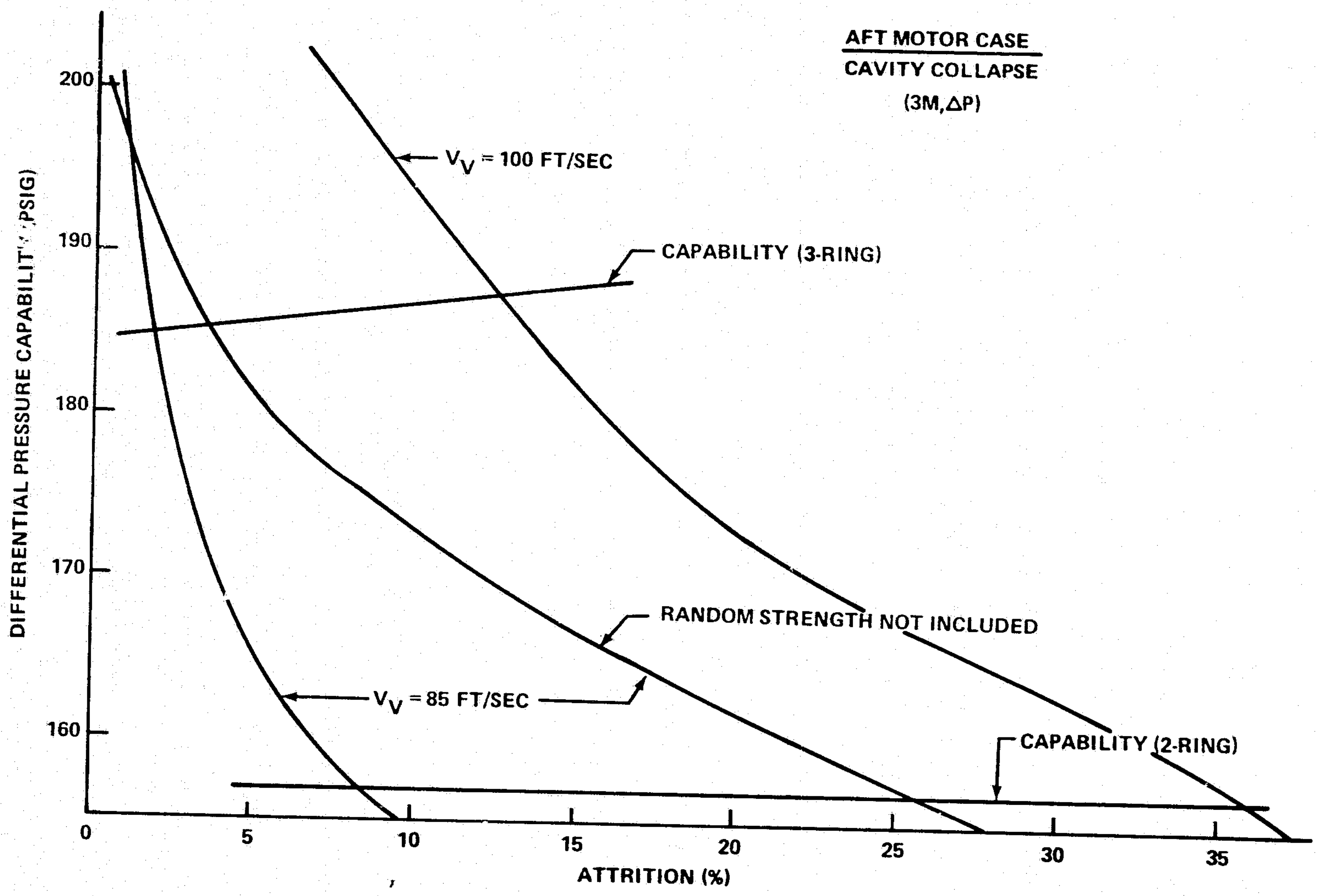


Figure 9. Aft motor case cavity collapse attrition rate, positional differential pressure (3M ΔP) method.

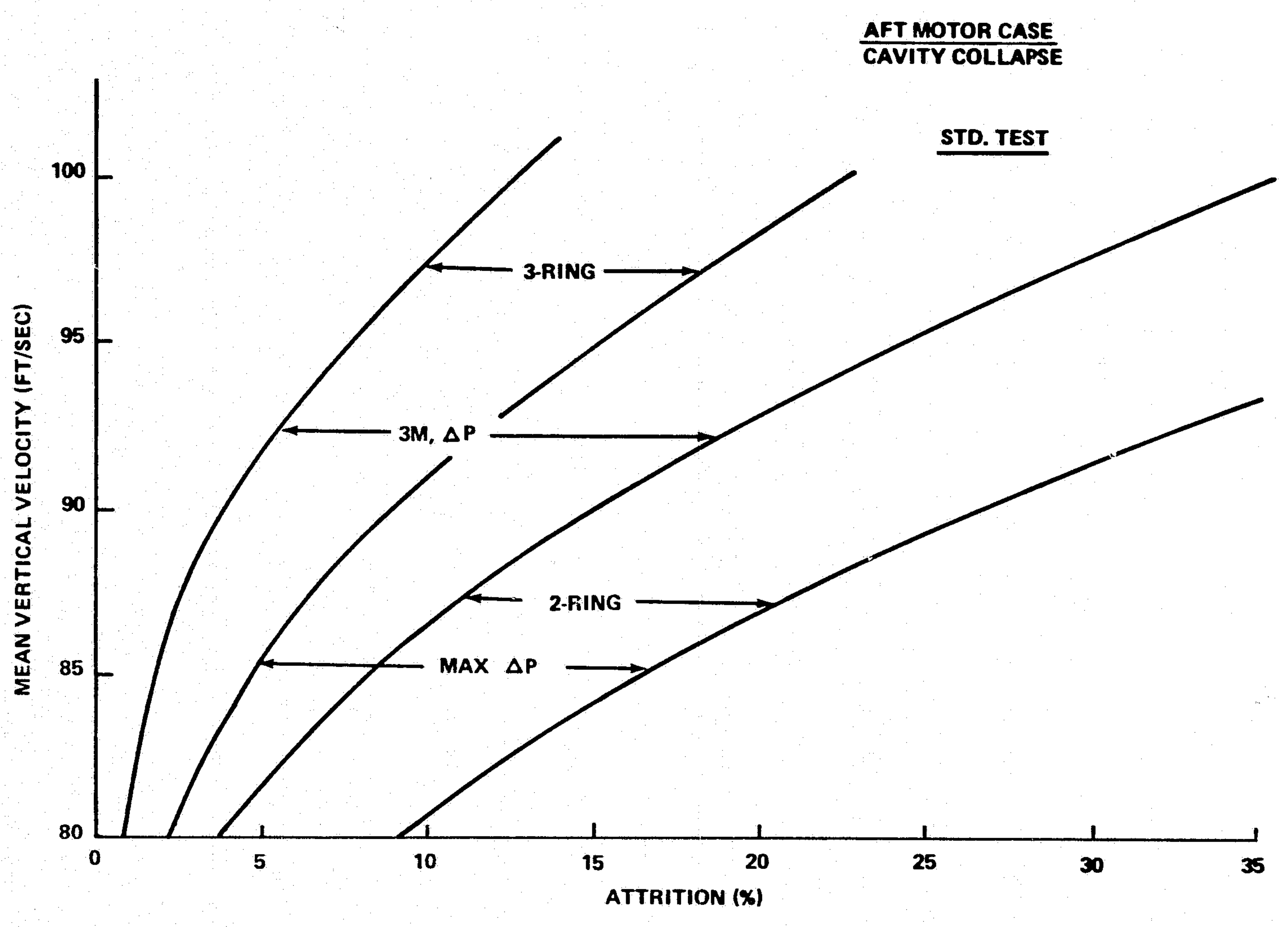


Figure 10. Aft motor case cavity collapse attrition rates versus V_V, differential pressure method.

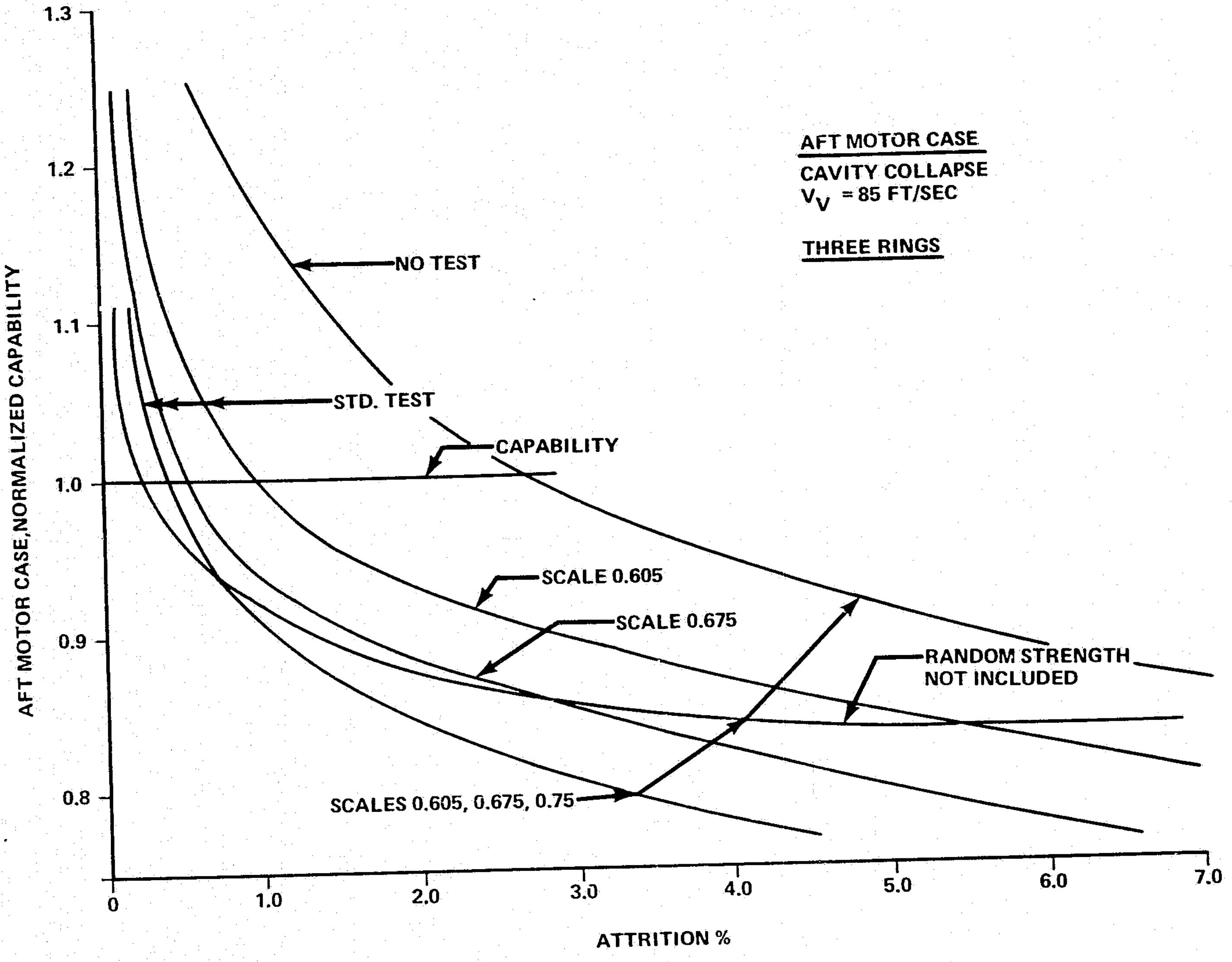


Figure 11. Aft motor case cavity collapse attrition rate methodology comparison, V_V 85 ft/sec, three rings, eigenvalues.

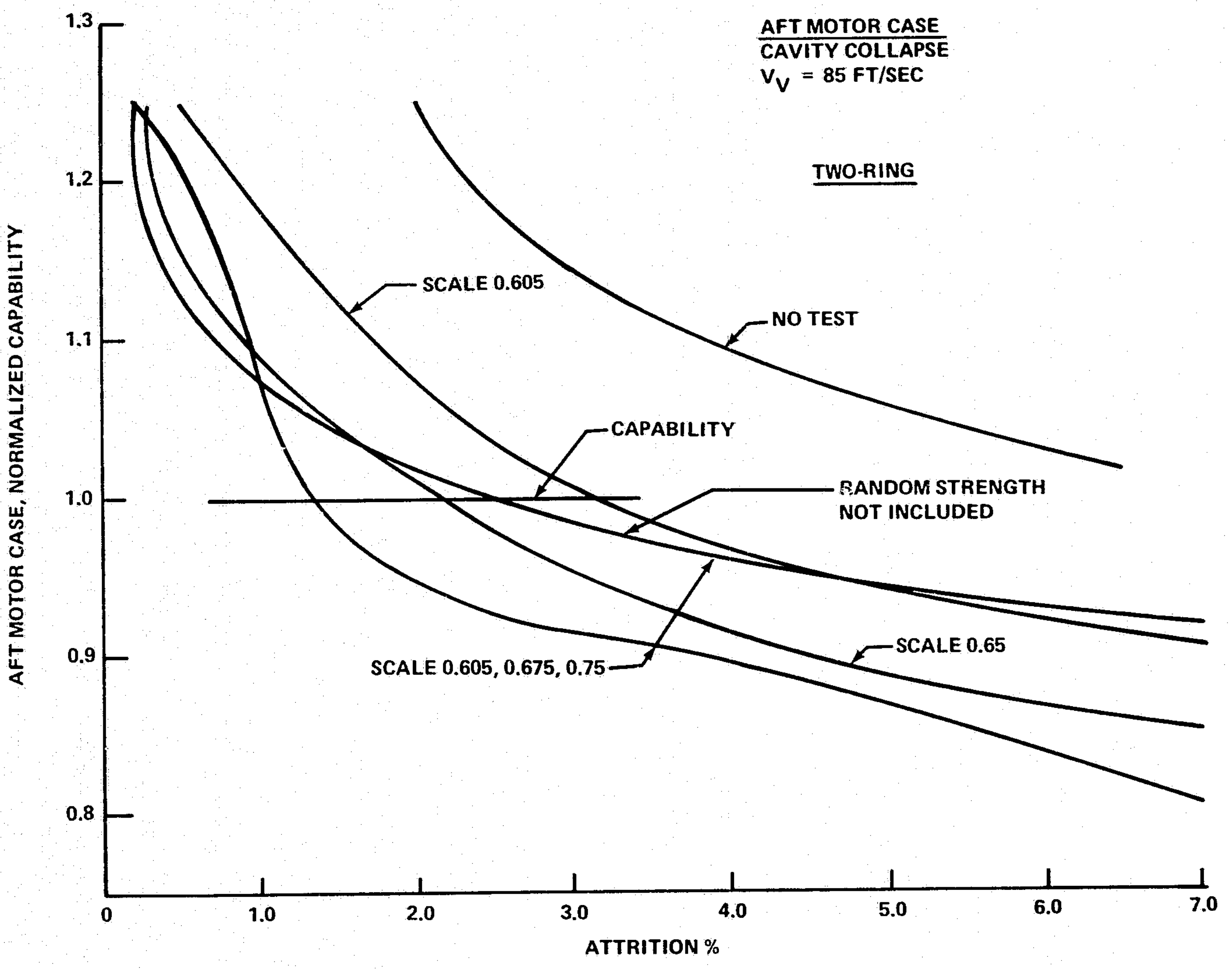


Figure 12. Aft motor case cavity collapse attrition rate methodology comparisons, V_V 85 ft/sec, two rings, eigenvalues.

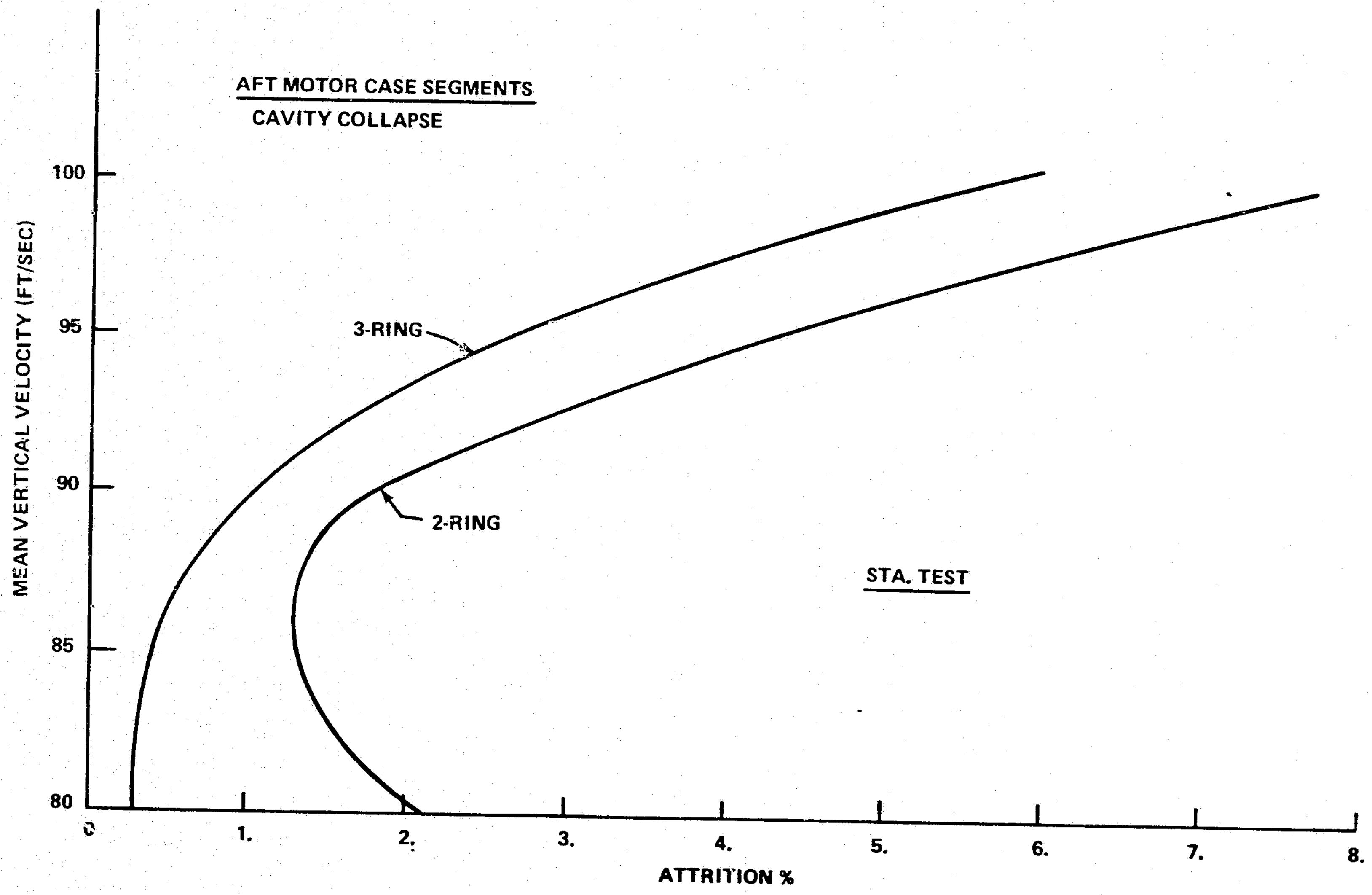


Figure 13. Aft motor case cavity collapse attrition rates versus V_V, eigenvalue method.

APPROVAL

SRM ATTRITION RATE STUDY OF THE AFT MOTOR CASE SEGMENTS DUE TO WATER IMPACT CAVITY COLLAPSE LOADING

By Charles D. Crockett

The information in this report has been reviewed for security classification. Review of any information concerning Department of Defense or Atomic Energy Commission programs has been made by the MSFC Security Classification Officer. This report, in its entirety, has been determined to be unclassified.

This document has also been review .d and approved for technical accuracy.

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