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**STRUCTURAL STABILITY ANALYSIS FOR THE
MIRROR FUSION TEST FACILITY
(MFTF) JACKET ASSEMBLY**

GENERAL DYNAMICS

Convair Division

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(MFTF) JACKET ASSEMBLY**

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SUMMARY

A structural analysis was performed for the unsupported MFTF jacket assembly. The STACS (Structural Analysis of General Shells) computer code was used to obtain linear and bifurcation buckling data for a one-quarter model considering all possible combinations of boundary conditions. The primary results are summarized below.

BASE LOAD (P_0) IN TOTAL CONDUCTOR BUNDLE

58 layers of conductor

24 windings per layer

600 lb initial winding tension

$$P_0 = 24 \times 58 \times 600 = 835,200 \text{ lb}$$

LOAD RELAXATION FACTOR (C_{relax}) DUE TO DEFORMATION OF JACKETASSEMBLY

$$C_{\text{relax}} = 0.50$$

ACTIVE LOAD (P_1) IN TOTAL CONDUCTOR BUNDLE

$$P_1 = C_{\text{relax}} \cdot P_0 = 417,600 \text{ lb}$$

MAX LINEAR DEFLECTION AND MIDDLE-SURFACE STRESS DUE TO $P_1 (=C_{\text{relax}} \cdot P_0)$

$$\text{Max } \Delta = 0.66 \text{ in.}$$

$$\text{Max } \sigma = -28,300 \text{ psi}$$

GOVERNING EIGENVALUES (λ_i) FOR GENERAL INSTABILITY MODES

$$\text{Min } \lambda = \text{Min } \lambda_{\text{sym/antisym}} = 3.24$$

$$\text{Min } \lambda_{\text{sym/sym}} = 11.22$$

$$(P_{\text{crit}})^{-1} = (\text{min } \lambda_i)^{-1} \cdot P_1$$

NONLINEAR MAGNIFICATION FACTOR (C_{mag})

$$C_{mag} = \frac{1}{1 - \frac{1}{\min \lambda_{sym/sym}}} = 1.10$$

MAGNIFIED DEFLECTIONS ARE LARGE BUT ACCEPTABLE

$$\text{Max } \Delta = 1.10 \times 0.66 = 0.73 \text{ in.}$$

Lawrence Livermore Laboratory can accept deflections up to approximately 1 inch in the region of this deformation.

MAGNIFIED MIDDLE-SURFACE STRESSES ARE ACCEPTABLE

$$\text{Max } \sigma = (1.10)(-28,300) = -31,100 \text{ psi}$$

$$\text{Material Yield Stress} = \pm 40,000 \text{ psi}$$

STRUCTURE IS STABLE

$$P_{cr} = \min \lambda_{sym/antisym} \cdot P_1 = 3.24 P_1$$

The calculated value for the load relaxation factor (C_{relax}) was a crucial element of the analysis. Were it not for this reduction, both the stresses and deflections from the linear analysis alone would have been excessive. In addition a large nonlinear magnification factor ($C_{mag} = 2.61$) would then apply and the occurrence of plastic instability would have been a possibility. In view of its importance to the analysis, a conservative approach was taken to establish the relaxation factor employed ($C_{relax} = 0.50$).

SECTION 1

INTRODUCTION

Fabrication of the MFTF jacket assembly involves the winding, under tension, of a conductor bundle onto the coil form while supported by a relatively stiff mounting adapter. Jacket covers are then welded to the structure after which the wound assembly is removed from the adapter. The loading introduced by the stretched conductor windings creates the possibility of a structural instability in the unsupported jacket assembly. A theoretical analysis was therefore performed to determine the internal load distribution and pre-buckling deformations in this condition and to establish whether or not a state of structural stability would exist.

The analysis was performed by means of the STAGS (Structural Analysis of General Shells) computer code developed by the Lockheed Palo Alto Research Laboratory under the primary sponsorship of the NASA Langley Research Center. This program employs finite-difference formulations of the nonlinear governing differential equations for a variety of shell shapes including the special cases of flat plates. By the technique commonly referred to as branching, these basic shapes can be assembled to model rather complicated configurations. In the case of the MFTF jacket assembly, more complex branching was required than is normally encountered in routine STAGS applications.

STAGS offers the user capability to assess structural stability either by small-deflection bifurcation buckling solutions or by incrementally tracking the nonlinear load-deflection path until a structural collapse is detected. The former alternative proved to be sufficient for the purposes of this study.

SECTION 2

ANALYSIS MODEL

The doubly symmetric configuration of the jacket assembly permitted the use of a STAGS model composed of only one fourth of the total structure. The quadrant selected for analysis is shown in Figure 1. As noted, the complete left and right boundaries of the quarter model are identified here as boundaries A and B, respectively. For the linear pre-buckling computations, conditions of symmetry were imposed around both of these cross sections. With regard to the incremental displacements that develop during buckling, it was necessary that the following four cases be analyzed separately:

<u>Boundary A</u>	<u>Boundary B</u>
Symmetric	Symmetric
Symmetric	Antisymmetric
Antisymmetric	Symmetric
Antisymmetric	Antisymmetric

2.1 BRANCHING

The structural model was constructed by assembling appropriate segments of annular plates and circular cylinders, both of which are generic shapes contained in the STAGS library. Figures 2 and 3 show the manner in which these fundamental elements were interconnected. These figures also present the STAGS identification numbers for the various branches, rows and columns of the finite-difference mesh, and the boundaries at junctures between the mating branches. The local coordinate systems used within the program are also shown.

2.2 DIMENSIONS

The dimensions of the model and its orientation within the STAGS global coordinate system (X_G, Y_G, Z_G) are given in Figure 4. Note that the thickness of the coil form is 1.0 inches whereas that of the jacket cover is 0.5 inches.

2.3 BOUNDARY CONDITIONS AND RIGID BODY CONSTRAINTS

Figures 5 through 8 depict the boundary conditions for the four combinations of interest. These are illustrated with respect to the global coordinate system. Also included are the single point constraints that were imposed in order to prevent rigid body motion.

2.4 FINITE DIFFERENCE MESH

To facilitate the finite difference numerical operations within STAGS, the user must select an appropriate arrangement of imaginary rows and columns whose points of intersection define the nodal positions. In general, the finer the mesh the more accurate is the solution.

Three different mesh configurations were employed in the subject investigation. The purpose of each configuration is described in Section 4, RESULTS. The essential features of the selected arrangements are listed in Table I and illustrated in Figures 9 and 10.

The column spacing shown in Figure 9 was common to all three mesh selections. Thirty equally spaced columns were used to subdivide the center region of the structure into twenty nine uniform angular spaces. For the end region, fifteen equally spaced columns were employed to provide fourteen uniform angular spaces. Each mesh column was continuous and therefore consisted of a complete trace of the rectangular cross section at the particular angular position.

The mesh lines referred to as rows were likewise continuous and were orthogonal to the columns. Therefore, the rows traced paths parallel to the exterior envelope outlined by the four corners of the rectangular cross section (see illustration with Table I). The row locations for each of the three mesh configurations are illustrated in Figure 10.

2.5 MATERIAL PROPERTIES

Both the coil form and jacket are made of 316L stainless steel. The conditions of interest to this study occur at room temperature. The corresponding material properties used in the analysis were as follows:

Ultimate Tensile Strength	:	$F_{tu} = 80 \text{ ksi}$
Tensile Yield Strength	:	$F_{ty} = 40 \text{ ksi}$
Compressive Yield Strength	:	$F_{cy} = 40 \text{ ksi}$
Young's Modulus	:	$E = 29.5 \times 10^6 \text{ psi}$
Shear Modulus	:	$G = 11.3 \times 10^6 \text{ psi}$
Poisson's Ratio	:	$\nu = 0.30$

For the conductors, the effective room temperature Young's modulus was taken to be $17 \times 10^6 \text{ psi}$.

SECTION 3

LOADING CONDITION

The source of loading on the jacket assembly is the tension in the conductor windings. For the STAGS model, the load was introduced as uniform pressure distributions on the two curved surfaces (branches 2 and 5) which react that tension.

The conductor bundle is built up as 58 layers, of 24 windings each, giving a total of 1392 windings. In the course of the winding operations, a tension of 600 pounds is applied to the conductor as it is stretched onto the coil form. If this initial tension were fully retained in each winding, the total bundle force P_0 would be

$$P_0 = 24 \times 58 \times 600 = 835,200 \text{ lb.}$$

However, in actuality the jacket assembly will deform to some degree during both the winding operations and subsequent release from the mounting adapter. A study was performed to establish the extent to which this behavior would relax the applied loading. The pressure magnitudes for the STAGS solutions include this reduction.

3.1 BASE VALUES

The STAGS pressure intensities were established by first computing base values to which relaxation factors were later applied. The base values were calculated as follows:

$$p_0 = \frac{P_0}{bR}$$

where

p_0 = Base pressure, psi

P_0 = Base load in total conductor bundle, lb.

b = Width of branch, in.

R = Radius of branch, in.

Branch 2:

$$P_0 = \frac{835,200}{14.62 \times 81.50} = 700.9 \text{ psi}$$

Branch 3:

$$P_0 = \frac{835,200}{35.75 \times 22.355} = 1,045 \text{ psi}$$

3.2 RELAXATION FACTOR

To arrive at an appropriate load relaxation factor, the following two situations were considered which bracket the actual conditions of fabrication:

- (a) The conductor windings were applied to the coil form while held completely fixed to an infinitely rigid mounting adapter. Subsequent to welding the jacket to the coil form, the entire assembly was released from the adapter.
- (b) The conductor windings were sequentially applied, total layer by total layer, with the coil form mounted on a zero stiffness adapter and prior to welding on the jacket.

In both cases, only the gross extensional ($\Delta = PL/AE$) deformations of the structure and conductors were considered. Local and gross bending deformations were ignored. The neglect of local bending should result in a conservatively high value for the final retained loading. It is assumed that the effects from omitting the gross bending should be minimal since they would average out over the cross sectional area. Some windings would experience increased tension while those on the other side of the neutral axis would undergo reduction of the pre-load.

For the purposes of these computations, the effective stiffness of a single conductor winding was established using the following values for area and Young's modulus:

$$A_c = 0.1643 \text{ in}^2$$

$$E_c = 17.0 \times 10^6 \text{ psi}$$

The calculations for the case of an infinitely rigid adapter were made as follows:

- (a) Stretch the entire conductor bundle such that it can just slip onto the coil form

- (b) After welding on the jacket, release the assembly from the adapter

where

$$L_c \approx L_s$$

A_s = Cross sectional area of jacket assembly, in²

E_s = Young's modulus for jacket assembly, psi

$$P_1 = \frac{P_0}{\left[1 + \frac{1,392 A_c E_c}{A_s E_s} \right]}$$

$$P_1 = 0.364 P_0$$

Hence, under this set of assumptions, a load relaxation of 63.6 percent (36.4% load retention) was obtained.

The calculations for the case of sequential layer application while mounted on a zero-stiffness adapter were made as follows:

- (a) At any interim stage of winding, just prior to the application of an additional conductor layer, the state of equilibrium could be represented as shown.

- (b) Immediately after the application of an additional conductor layer the state of loading is altered as shown.

$$24 \times 600 = 14,400$$

$$\Delta P_{\text{prior}} = \frac{14,400}{\left[1 + \frac{A_s E_s}{24 N_{\text{prior}} A_c E_c} \right]}$$

where

A_s = Cross sectional area of coil form, in²

E_s = Young's modulus for coil form, psi

N_{prior} = Number of conductor layers previously applied

Treating the conductors as being incapable of supporting compression, sequential numerical computations were made which tracked the winding process through the application of all 58 layers. The results showed a load relaxation of 49.7 percent (50.3 percent load retention).

3.3 APPLIED LOADING

The pressures used for the STAGS solutions were taken equal to the base values established in 3.1 multiplied by a relaxation factor of 0.50 to obtain

$$\text{Branch 2: } p = 700.9 \times 0.50 = 350 \text{ psi (crushing)}$$

$$\text{Branch 5: } p = 1,045 \times 0.50 = 523 \text{ psi (crushing)}$$

The resulting applied loading condition is depicted in Figure 11. Based on the information provided in 3.2 above, selection of the value 0.50 for the relaxation factor is considered to be a conservative choice.

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SECTION 4

RESULTS

Results were obtained for an active total conductor bundle load (P_1) of 417,600 lb. established as follows:

$$P_1 = C_{\text{relax}} \cdot P_0 = 0.50 \times 835,200 = 417,600 \text{ lb.}$$

where

C_{relax} = Load relaxation factor (0.50) established in
Sections 3.2 and 3.3.

P_0 = Base load ($24 \times 58 \times 600 = 835,200$) in total conductor
bundle composed of 58 layers, with 24 windings per
layer, and wound under an initial tension of 600 lb.

The jacket assembly was found to be stable, the maximum middle surface stresses were well below yield and the maximum deflections were large but acceptable.

4.1 ACCURACY OF STAGS MODELS

The final linear analysis results presented in this report were obtained using the finite difference mesh number 3 shown in Figure 10. On the other hand, all of the bifurcation buckling data were obtained using mesh number 1. The reasons for this and the consequent effects on the results are discussed below.

Mesh 1 was originally selected for this study on the basis of anticipated internal stress distributions and buckle wavelengths. The intent was to obtain reliable predictions of the linear stresses, linear deformations, and the eigenvalues.

In executing a STAGS bifurcation buckling solution, the run will automatically include a prerequisite linear solution in order to determine the pre-buckling internal load distribution. After completing the planned buckling runs, a review of the companion linear analysis data raised some question concerning the capability of the chosen mesh to adequately account for the effects of sharp curvature in the vicinity of the right hand

boundary (boundary B of Figure 1). It appeared quite likely that the row spacings near the cross section corner locations were too large to accurately represent the reduced efficiency of branches 5 and 8 under bending about axis A-A of Figure 10. The efficiency of such curved elements in this mode of deformation is a function of the parameter

$$\frac{tR}{b^2}$$

where

t = thickness, in.

R = radius of curvature, in.

b = width, in.

This parameter takes on the following values here:

$$\text{Branch 5: } \frac{tR}{b^2} = \frac{1.0 \times 22.4}{35.75^2} = 0.018$$

$$\text{Branch 8: } \frac{tR}{b^2} = \frac{0.5 \times 37.0}{35.75^2} = 0.014$$

From Figure 12 it is apparent that these branches will be extremely ineffective under the specified bending. It was further observed that this could well lead to the need for a variable row spacing that would be extremely fine at the corner locations. Therefore, two additional linear analyses (no bifurcation buckling) were performed using mesh configurations 2 and 3, respectively. The stress and deflection plots of Figure 13 were made using this output. The curves show that the model using mesh 1 did not provide fully converged data. On the other hand, the mesh 3 model was well converged. Therefore, the latter was used for all the linear analysis data presented in this report.

Since the STAGS bifurcation buckling runs were all performed using mesh 1, consideration was given to the possibility of repeating these solutions with a more refined row spacing. However, a study of the eigenvalues already obtained led to the conclusion that the consequent additional expense could not be justified. Based on the computations shown below, it was estimated that the eigenvalues from a well converged model would

be equal to about 70 percent of those values obtained from the mesh 3 runs. Even in the

LINEAR DEFLECTIONS

Mesh 1: Max $\Delta = 0.46$ in.

Mesh 3: Max $\Delta = 0.66$ in.

EFFECTIVE MOMENTS OF INERTIA

$$\text{Max } \Delta \propto \frac{1}{I_{\text{eff}}}$$

$$\frac{(I_{\text{eff}})_{\text{Mesh 3}}}{(I_{\text{eff}})_{\text{Mesh 1}}} = \frac{0.46}{0.66} = 0.70$$

CRITICAL LOADS

$$P_{\text{cr}} \propto I_{\text{eff}}$$

$$\frac{(P_{\text{cr}})_{\text{Mesh 3}}}{(P_{\text{cr}})_{\text{Mesh 1}}} = \frac{(I_{\text{eff}})_{\text{Mesh 3}}}{(I_{\text{eff}})_{\text{Mesh 1}}}$$

$$(P_{\text{cr}})_{\text{Mesh 3}} = 0.70 (P_{\text{cr}})_{\text{Mesh 1}}$$

highly unlikely case of a 50 percent (as opposed to the calculated estimate of 30 percent) reduction from the mesh 1 eigenvalues, the essential conclusions from the overall analysis would be unchanged. This extreme assumption would lead to

$$P_{\text{cr}} = 1.62 P_1$$

$$C_{\text{mag}} = 1.22$$

The structure would still be considered stable. In addition, the magnified pre-buckling stresses and deflections would still be acceptable. Hence, no reruns were made of the bifurcation buckling solutions and all of the buckling data presented in this report are from STAGS output using mesh 1.

4.2 LINEAR ANALYSIS

Results are given in this section for the STAGS linear analysis performed using mesh 3 of Figure 10. As noted above, this mesh provides well converged linear data.

The deflections and stresses presented here constitute base values to which nonlinear magnification factors must be applied to arrive at the pre-buckling deformed shape and stress distributions.

The orthogonal directions of interest are designated by the labels

TRANSVERSE

LATERAL

LONGITUDINAL

The orientations of these directions with respect to any cross section are illustrated in Figure 14.

4.2.1 DEFLECTIONS. The maximum linear deflection is a lateral displacement of 0.66 inches relative to the long centerline of symmetry. This occurs at one of the cross section corners. The deflection curve for this corner is given in Figure 14. The maximum transverse deflection is only 0.14 inches (relative to a point on the left boundary of the STAGS model). Since this is of little consequence, the displacements in this direction were not plotted.

4.2.2 STRESSES. The linear stresses of primary interest are the middle surface values associated with the running loads is N_x and N_y (lb/in) shown in Figure 15. These stresses are easily computed as follows:

$$\sigma_x = \frac{N_x}{t}$$

$$\sigma_y = \frac{N_y}{t}$$

Bending of the individual walls over the spans between corners of the cross section creates higher stress values but these are very localized and, for the purposes of this analysis, can be ignored. Material yielding in the regions of high localized bending will result in a redistribution of stress that will not significantly affect the conclusions drawn here.

Seven representative cross sections were selected for which the distribution of longitudinal middle surface stresses (σ_y) were plotted. The values for $\sigma_x (=N_x/t)$ are not displayed since they are all much lower than the peak longitudinal value. The locations of the selected cross sections are specified in terms of the coordinates θ and Φ as defined in Figure 16. The stress plots appear as Figures 17(a) through 17(g).

The maximum longitudinal middle surface stress is a compression of 28,300 psi. This occurs at a corner of the cross section located at $\Phi = 90^\circ$.

4.3 BIFURCATION BUCKLING

Results are presented in this section for the STAGS bifurcation buckling runs. As noted in 4.1 above, these solutions were all accomplished using mesh 1 of Figure 10. The output data were used for each of the following purposes:

- (a) To evaluate the jacket assembly structural stability.
- (b) To establish a nonlinear magnification factor for application as a multiplier to the linear analysis stresses and deformations.

In view of the doubly symmetric geometry and loading of the jacket assembly, the STAGS model consisted of only one fourth of the total structure. Hence, for the incremental displacements that develop during buckling, it was necessary to separately consider each of the following four combinations of boundary conditions:

SYMMETRIC/SYMMETRIC

SYMMETRIC/ANTISYMMETRIC

ANTISYMMETRIC/SYMMETRIC

ANTISYMMETRIC/ANTISYMMETRIC

However, in each case, SYMMETRIC/SYMMETRIC conditions were required for the companion linear analysis that established the pre-buckling internal load distribution.

4.3.1 EIGENVALUES. Eigenvalues (λ) obtained from bifurcation buckling solutions are constants of proportionality between the loading used in the analysis and the load values at which buckling will occur. In our case, the input loading is the relaxed total conductor bundle load $P_1 (= C_{\text{relax}} P_0 = 417,600 \text{ lb})$ as obtained earlier in this section.

Hence, for a particular set of boundary conditions identified through the subscript i, it follows that

$$(P_{cr})_i = (\min \lambda_i) \cdot P_1$$

An eigenvalue of 1.0 would therefore indicate that a structural instability occurs at the relaxed applied load level.

The eigenvalues obtained for each of the prescribed combinations of boundary conditions are listed in Table II. The primary data to be extracted from this table are the following:

$$\lambda_{\text{sym/antisym}} = 3.24$$

$$\lambda_{\text{sym/sym}} = 11.22$$

The former is the lowermost value obtained for any of the four sets of boundary conditions and therefore establishes the critical load level to be $3.24 P_1$. The associated mode is a general instability of the shape depicted in Figure 18. The latter eigenvalue (11.22) establishes the minimum load level corresponding to the occurrence of general instability in the symmetric/symmetric mode. This value was used to determine the nonlinear magnification factor that was applied to the linear stresses and deflections. The basis for this practice lies in the fact that the idealized pre-buckling state is a pure symmetric/symmetric condition. In addition, the applied loading is sufficiently below that for the critical symmetric/antisymmetric mode to preclude initiation of a transition into the latter state of deformation.

In order to identify the modes of instability, it was necessary to carefully examine the associated eigenvector data (incremental displacements) included in the STAGS output. It was usually possible to observe a distinct pattern of either local or general buckling. However, in a number of cases the relative magnitudes of the corner displacements and those at interior nodes were sufficiently close that it became questionable to definitively categorize the mode. For these cases the buckled shape is described in Table II as a mixed mode. In addition, these cases were conservatively considered to constitute general instability in the data evaluation process.

In order for one to view the eigenvalue data in a proper perspective, it should be observed that the STAGS computer code offers the user the option to assess structural stability by either a bifurcation buckling solution or a nonlinear collapse analysis. The major conceptual differences between these two approaches are illustrated in Figure 19. In a bifurcation buckling analysis, a search is made for the point at which an initial equilibrium path branches into two or more separate equilibrium states. Typically, the search is performed by the mathematical procedures of eigenvalue extraction. On the other hand, a nonlinear collapse analysis actually tracks a realistic nonlinear load deflection curve to detect a limiting load value. Depending upon the nature of the problem, these two approaches can give substantially different results. If the structural response involves considerable redistribution of internal loads, the lowermost bifurcation buckling level may be appreciably less than the collapse load. In other cases, the postbuckling equilibrium paths may be such that collapse could occur well below the bifurcation point. The latter possibility was of some concern in this study and the associated behavior is illustrated in Figure 20.

In a general sense, the overall MFTF jacket assembly can be looked upon as a segment of a deep circular ring whose primary loading consists of a hoop compression. Furthermore, the critical general instability mode is composed of a single half wave over an angular span in excess of 150 degrees. Based on our existing knowledge of postbuckling behavior of circular configurations, we are led to the conclusion that the loading, geometry, and critical mode shape for the jacket assembly are such that the related theoretical postbuckling equilibrium path would be essentially horizontal as shown in Figure 21. The actual load displacement path would have the characteristics illustrated by the dashed curve in the figure. Hence, the nonlinear collapse load and the critical bifurcation buckling load would virtually coincide. The eigenvalues obtained from the STAGS bifurcation buckling option are therefore considered to be sufficient for a reliable assessment of the jacket assembly structural stability. However, in evaluating the stresses and deflections prior to buckling, one must still account for the expected nonlinearity in the actual equilibrium path. This aspect of the problem is addressed in Section 4.3.2 below.

4.3.2 NONLINEAR MAGNIFICATION FACTOR. The following approximate relationship was used to establish a value for the nonlinear magnification factor (C_{mag}):

$$C_{mag} = \frac{1}{1 - \frac{P_1}{P_{cr}}}$$

where only the general instability modes are considered. In lieu of performing a complete nonlinear STAGS analysis, this factor was employed as a multiplier to the linear stress and deflection data presented in Section 4.2.

In view of the relationship

$$\min \lambda_i = \frac{(P_{cr})_i}{P_1}$$

it follows that

$$C_{mag} = \frac{1}{1 - \frac{1}{\min \lambda_i}}$$

In addition, if

- (a) the pre-buckling mode of deformation differs from the critical buckling mode

and

- (b) the applied loading is well below the critical buckling value, then the lowest eigenvalue corresponding to the pre-buckling mode shape can be used in the foregoing formula. Since the jacket assembly satisfies both of these conditions, the magnification factor used here was computed as follows:

$$C_{mag} = \frac{1}{1 - \frac{1}{\min \lambda_{sym/sym}}} = \frac{1}{1 - \frac{1}{11.22}} = 1.10$$

considering only the general instability modes.

SECTION 5

CONCLUSIONS

1. The jacket assembly is stable.
2. The middle surface stresses are the primary stresses of interest and these are all well below the material yield strength.
3. Stresses due to localized secondary bending exceed the material yield strength in some regions. This will result in minor stress redistributions that will not significantly affect the gross behavior.
4. The maximum deflections are large but within the acceptable limits of the Lawrence Livermore Laboratory.

Table I. Mesh Configurations

Mesh ID	Branch	Rows		Columns	
		Total Number	Distribution	Total Number	Distribution
1	1	6	Uniform ↓	30	Uniform ↓
	2	4		30	
	3	4		30	
	4	6		30	
	5	6		15	
	6	4		15	
	7	4		15	
	8	6	Uniform	15	Uniform
2	1	12	Uniform ↓	30	Uniform ↓
	2	8		30	
	3	8		30	
	4	12		30	
	5	12		15	
	6	8		15	
	7	8		15	
	8	12	Uniform	15	Uniform
3	1	14	Non-uniform ↓	30	Non-uniform ↓
	2	8		30	
	3	8		30	
	4	14		30	
	5	14		15	
	6	8		15	
	7	8		15	
	8	14	Non-uniform	15	Non-uniform

Table II. Eigenvalues from STAGS Bifurcation Buckling Runs

Sym/Sym		Sym/Antisym		Antisym/Sym		Antisym/Antisym	
λ	Mode	λ	Mode	λ	Mode	λ	Mode
5.46	Local	3.24	General	4.96	General	5.46	Local
5.58		5.46	Local	5.46	Mixed	5.56	Local
5.86		5.58		5.56	Local	5.90	Local
6.30		5.86		5.90	Mixed	6.28	Local
6.84		6.30		6.28	Mixed	6.78	Local
7.38		6.84	Local				
8.00							
8.74							
9.54							
10.38	Local						
11.22	Mixed						
12.06	Mixed						

NOTES:

1. Boundary condition designations give left-hand boundary first; e.g., ANTISYM/SYM denotes left boundary condition is antisymmetry and right is symmetry.
2. λ = Eigenvalue
3. $(P_{cr})_1 = \min \lambda_i \cdot P_1$
where P_1 is the relaxed value of loading (417,600 lb)

Type of Analysis	Boundary Conditions	
	Boundary A	Boundary B
Linear Pre-Buckling	Symmetric	Symmetric
Incremental (during buckling)	Symmetric	Symmetric
	Symmetric	Antisymmetric
	Antisymmetric	Symmetric
	Antisymmetric	Antisymmetric

Figure 1. Overall Features of STAGS Model

Figure 2. STAGS Branching Arrangement for Center Region of Jacket Assembly

Figure 3. STAGS Branching Arrangement for End Region of Jacket Assembly

Figure 4. Dimensions used for STAGS Model

Figure 5. Boundary Conditions and Rigid-Body Constraint for Symmetric/Symmetric Case

Figure 6. Boundary Conditions and Rigid-Body Constraints for Symmetric/Antisymmetric Case

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Figure 7. Boundary Conditions and Rigid-Body Constraints for Antisymmetric/Symmetric Case

Figure 8. Boundary Conditions and Rigid-Body Constraint for Antisymmetric/Antisymmetric Case

Figure 9. Spacing of Mesh Columns in STAGS Model

Figure 10. Spacing of Mesh Rows for STAGS Models

NOTE: The indicated pressure values include reductions due to a relaxation factor of 0.50.

APPLIED LOADS

Figure 11. Applied Loading for STAGS Solutions

Figure 12. Reduced Efficiency of Curved-Plate Frame Flanges

Figure 13. Effect of Mesh Size on Accuracy of Linear Analysis

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Figure 14. Linear Analysis Lateral Deflection Curve of Mesh Row Having Maximum Displacement

NOTES:

1. UNITS FOR N_x AND N_y ARE LB/IN.
2. N_x AND N_y POSITIVE AS SHOWN.
3. N_y AND THE ASSOCIATED STRESSES (N_y/t) ARE REFERRED TO AS LONGITUDINAL VALUES IN THIS REPORT.

Figure 15. Sign Convention and Orientation of Middle-Surface Running Loads

Figure 16. Coordinate System to Locate Stress-Plot Cross Sections

Figure 17. Distribution of Longitudinal Middle-Surface Stress ($\sigma_y = N_y / t$) from Linear Analysis

Figure 17. Distribution of Longitudinal Middle-Surface Stress ($\sigma_y = N_y/t$) from Linear Analysis (continued)

$$\theta = 52^\circ$$

(c)

Figure 17. Distribution of Longitudinal Middle-Surface Stress ($\sigma_y = N_y/t$) from Linear Analysis (continued)

(d)

Figure 17. Distribution of Longitudinal Middle-Surface Stress ($\sigma_y = N/t$) from Linear Analysis (continued)

Figure 17. Distribution of Longitudinal Middle-Surface Stress ($\sigma_y = N_y/t$) from Linear Analysis (continued)

Figure 17. Distribution of Longitudinal Middle-Surface Stress ($\sigma_y = N_y/t$) from Linear Analysis (continued)

Figure 17. Distribution of Longitudinal Middle-Surface Stress ($\sigma_y = N_y/t$) from Linear Analysis (concluded)

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Figure 18. Critical Buckling Mode ($\lambda = 3.24$)

Figure 19. Critical Load Criteria

Figure 20. Influence of Postbuckling Equilibrium Path on Collapse Load

Figure 21. Expected Behavior of MFTF Jacket Assembly