GENERAL DYNAMICS
Space Systems Division

NONLINEAR ANALYSIS OF POINT LOADS ON AN ELLIPTICAL BULKHEAD

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ABSTRACT

Nonlinear stress analysis was performed for point loads on an internally pressurized elliptical bulkhead. This bulkhead is the aft structure of the Centaur tank, a liquid hydrogen and liquid oxygen propellant rocket. Two 22,000 lb point loads are created by the engines on the aft bulkhead. Based on linear MSC/NASTRAN analysis, the aft bulkhead which was previously designed for two 16,500 lb engine thrust loads, required strengthening for the new upgraded engines. Subsequently, MSC/NASTRAN Solution 66 was used to account for material and geometric nonlinearities. The results of this analysis, which agreed with full-scale test results, showed no required strengthening.

INTRODUCTION

The Atlas/Centaur is an unmanned expendable launch vehicle. It consists of the Atlas lower stage and the Centaur upper stage. See Figure 1. This vehicle is currently being used to place government and commercial payloads into orbit. The unique propellant tanks in each stage are the primary structures of the Atlas/Centaur launch vehicle. These propellant tanks are fully monocoque, welded stainless steel structures. A common monocoque bulkhead is used to separate the two tanks in each stage. These tanks rely upon internal pressure to maintain structural stability. They are "steel balloons".

Two propellant tanks make up the primary Centaur structure. The forward tank contains liquid hydrogen (LH2); the aft, liquid oxygen (LOX). See Figure 2. On the Centaur aft bulkhead are two Pratt & Whitney engines fueled by liquid hydrogen and liquid oxygen. An enhancement to the Centaur structure currently under development is uprated extendable nozzle engines with increased thrust. This thrust increase is from 16,500 lbs/engine to a structural design of 22,000 lbs/engine.

The structural analysis for the increased thrust on the Centaur aft bulkhead was performed with MSC/NASTRAN. A NASTRAN model of the Centaur was created with SDRC/SUPERTAB on an APOLLO computer, and the analysis was performed on a CRAY computer. Results from linear analysis showed structural changes of the aft bulkhead were required. Subsequently, nonlinear NASTRAN analysis was performed to account for plasticity and nonlinear geometric effects. Results from this analysis showed positive margins in the aft bulkhead, and no changes were needed. These results also agreed with full-scale test results of the aft bulkhead. The comparisons thus validated the nonlinear analysis and eliminated the need for structural changes.

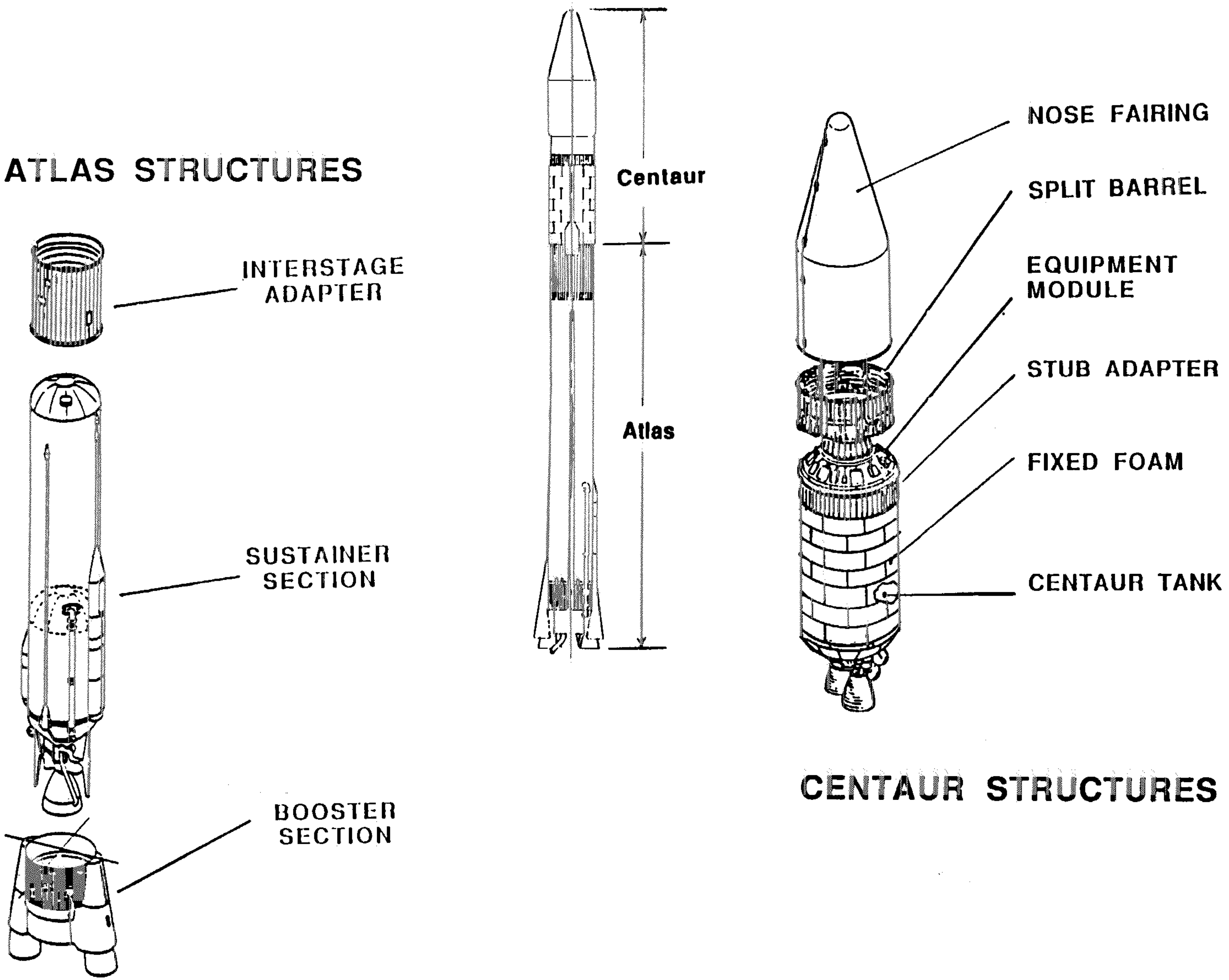
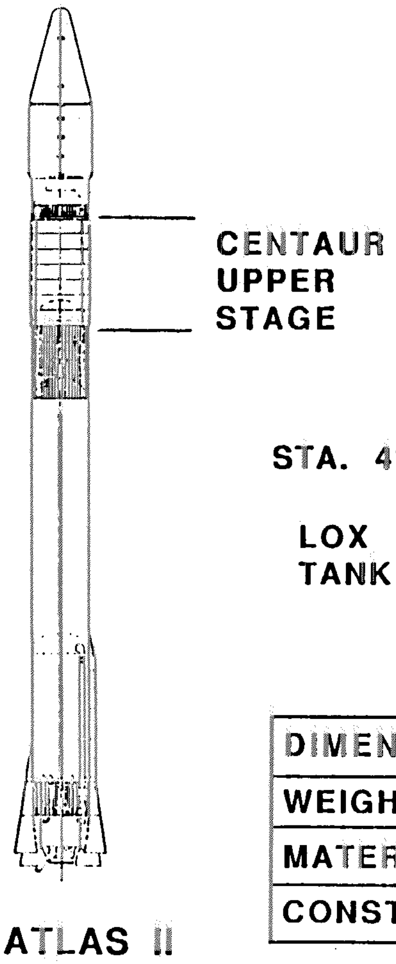
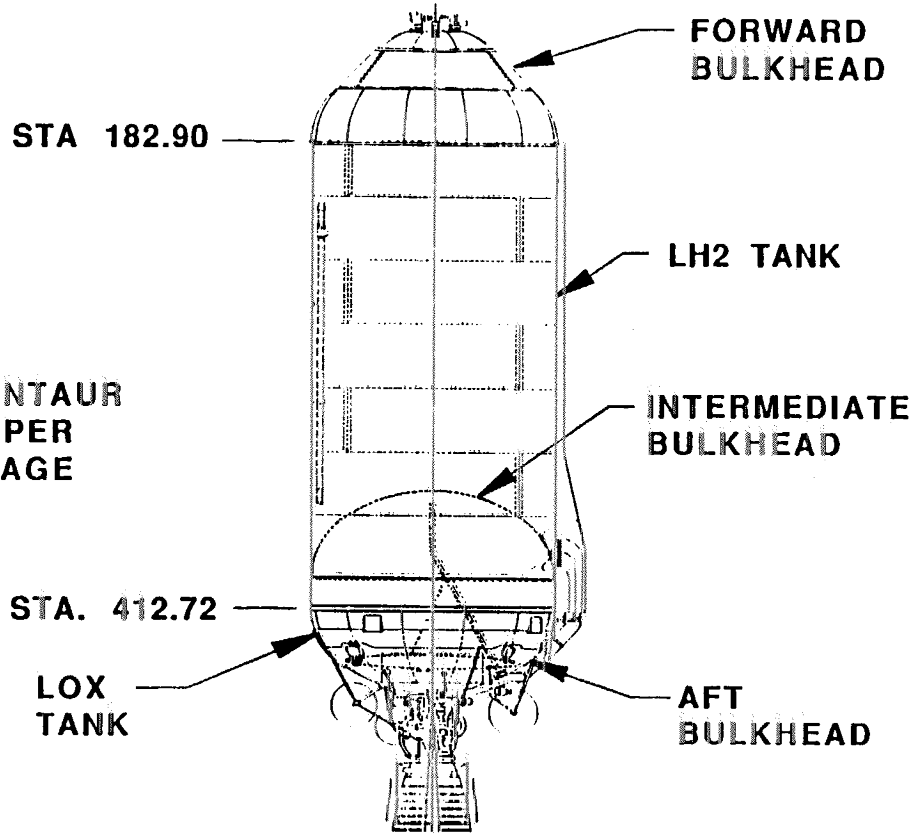


FIGURE 1 : THE ATLAS/CENTAUR LAUNCH VEHICLE





DIMENSIONS	10 FT DIA. X 32.5 FT
WEIGHT	2795 LB (DRY) 40,313 LB (WET)
MATERIAL	300 SERIES CRES
CONSTRUCTION	WELDED MONOCOQUE

FIGURE 2 : THE CENTAUR UPPER STAGE

STRUCTURAL DESCRIPTION

The aft bulkhead is a semi-ellipsoidal shell structure with a major radius of 60.0 inches and a minor radius of 43.5 inches. Stainless steel gores, 301 corrosion resistant steel 3/4H, are stretch-formed and buttwelded to this geometry. A 301 CRES splice doubler is spotwelded over each buttweld. This bulkhead serves as the aft end of the liquid oxygen propellant tank and reacts the engine thrust loads during Centaur flight. The two Centaur engines are externally mounted on gimbal blocks which are bolted to the aft bulkhead 180° apart.

Concentrated engine thrust loads are distributed by a thrust barrel mounted inside the aft bulkhead. See Figure 3. This thrust barrel is an aluminum skin-stringer frame cylinder. Mechanical fasteners are used to assemble the thrust barrel. The forward end of the barrel has a door membrane that serves to stabilize this end. An inverted T-shaped thrust ring is the interface between the thrust barrel and the aft bulkhead. See Figure 4. This ring is welded inside the aft bulkhead. The thrust barrel is then mechanically fastened to the thrust ring. This ring is machined from 321 CRES forging in the annealed state. Room temperature yield stress allowable of 321 CRES annealed is low at 30 ksi; ultimate stress allowable is 75 ksi. The bulkhead build-up that the thrust ring welds to is five layers with a total local thickness of 0.132 inches. The basic bulkhead skin gage is 0.020 inches thick.

Access to the LOX tank is through the LOX sump. The sump is a removable membrane that has two outlet elbows. LOX is fed through these elbows to the engines. The sump is constructed from chem-milled 321 CRES annealed membrane welded to a 321 CRES machined ring. A second 321 CRES ring is welded to the aft bulkhead which has a cutout with the same diameter as the inner diameter of this second ring. The sump is bolted to this aft bulkhead ring.

Structural integrity of both tanks is maintained by internal pressure. The LOX tank relies entirely on gaseous helium stored at high pressure in spherical bottles. These high pressure Helium bottles are externally mounted on the aft bulkhead with major loading designed to enter into the thrust ring. See Figures 5 and 6. One helium bottle is mounted on a quad I-II yoke; a second, on a quad III-IV yoke; and a third is supported with struts in quad III, adjacent to the second Helium bottle. In addition,

STRUCTURAL DESCRIPTION (con't)

small thrusters are mounted on the aft bulkhead to provide propellant settling prior to engine start, ensuring LH2 and LOX supply to the engines. Hydrazine is used to power these thrusters and is stored in one bottle. This bottle is also mounted on a quad III-IV yoke.

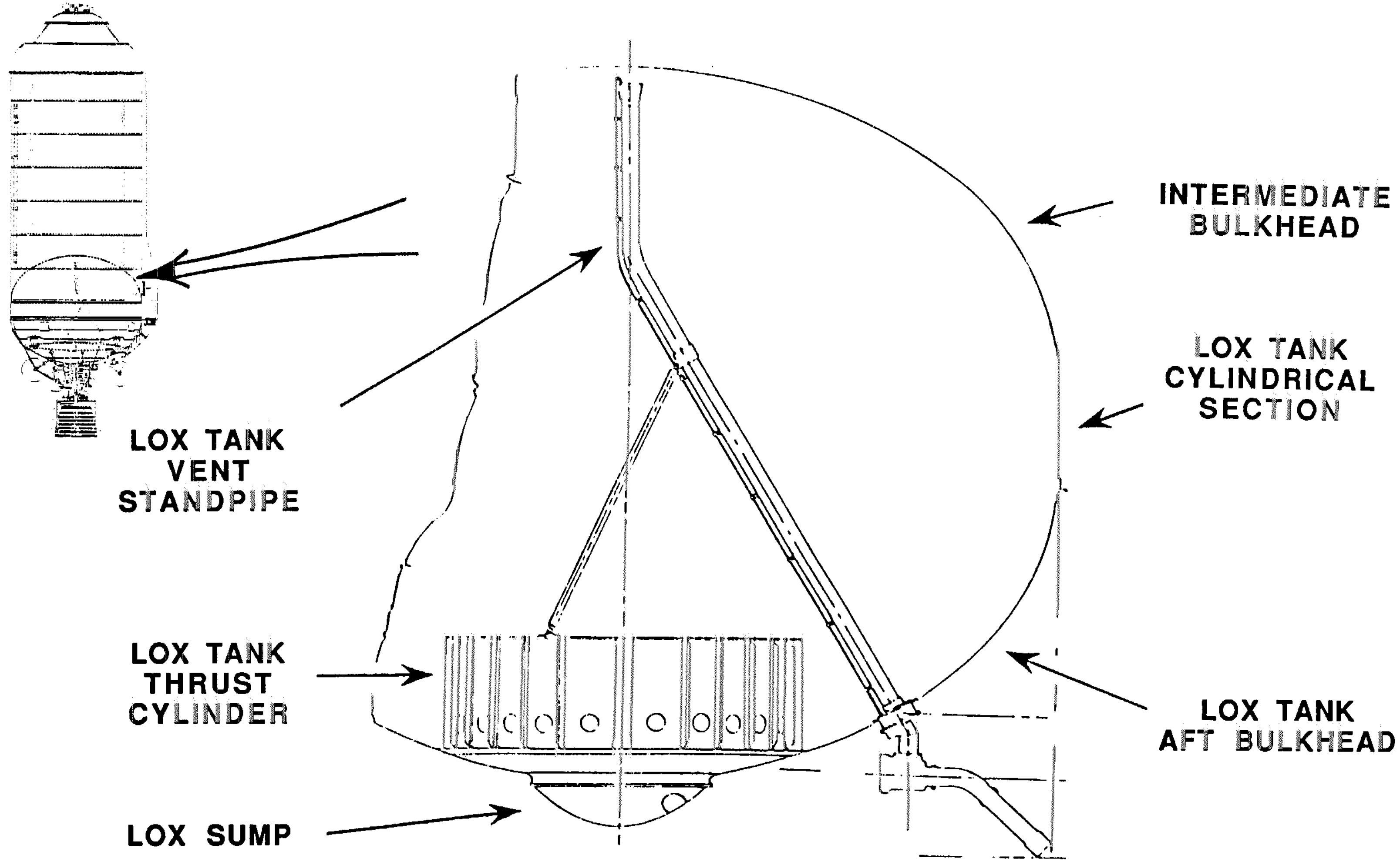


FIGURE 3 : LOX TANK THRUST CYLINDER

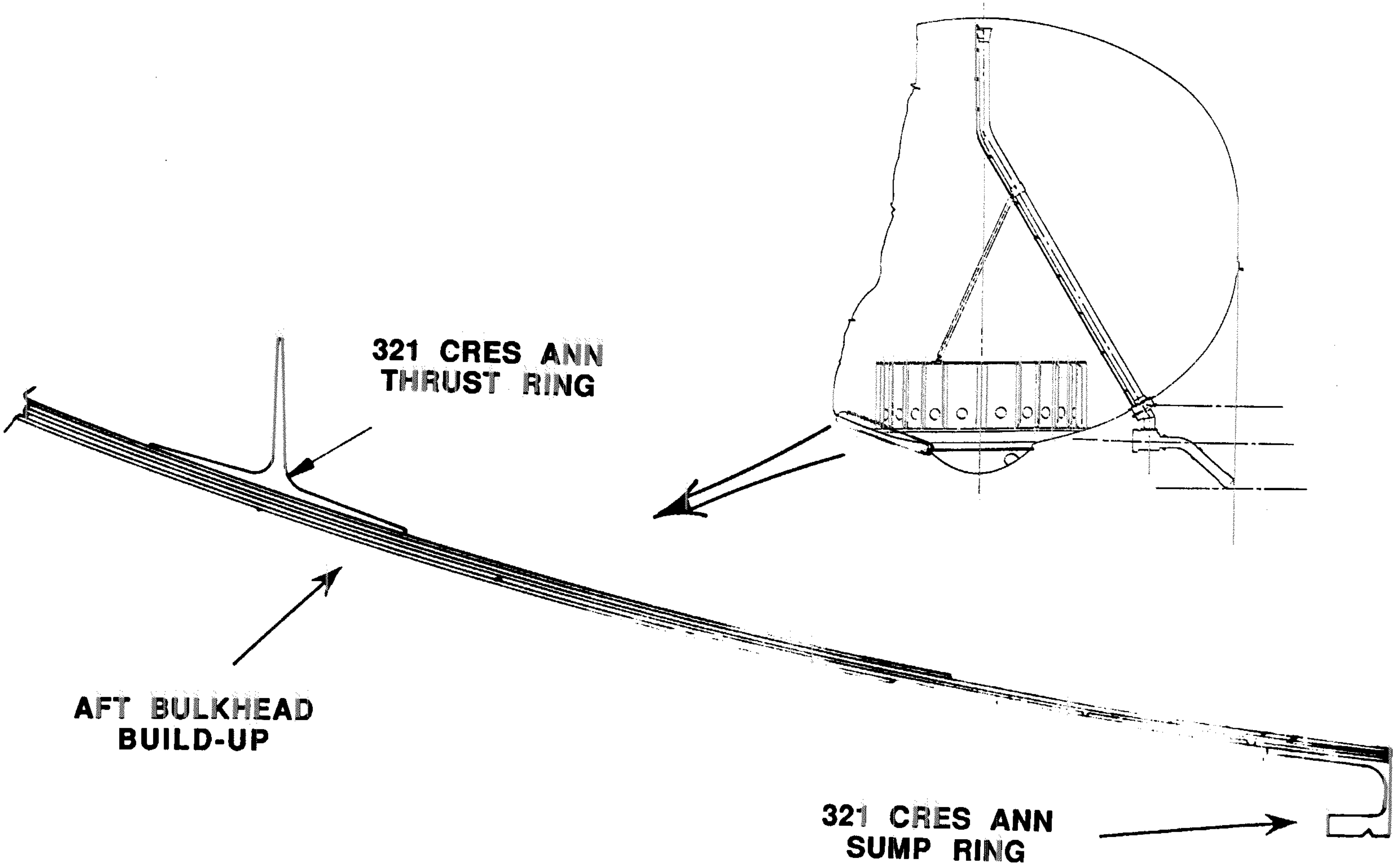


FIGURE 4 : CROSS SECTION OF AFT BHD BUILD-UP AND 321 CRES RINGS

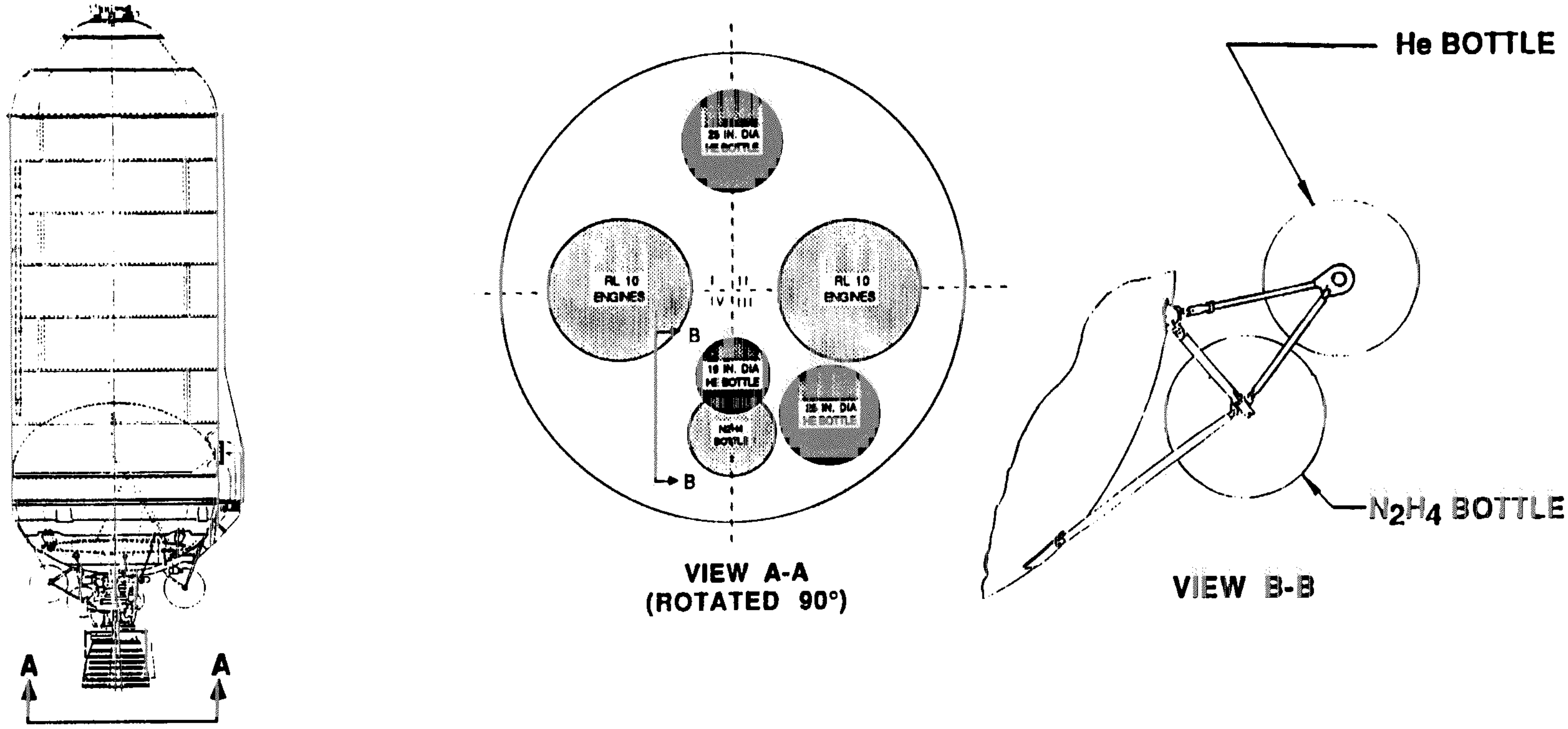


FIGURE 5 : BOTTLE ARRANGEMENT ON THE AFT BHD

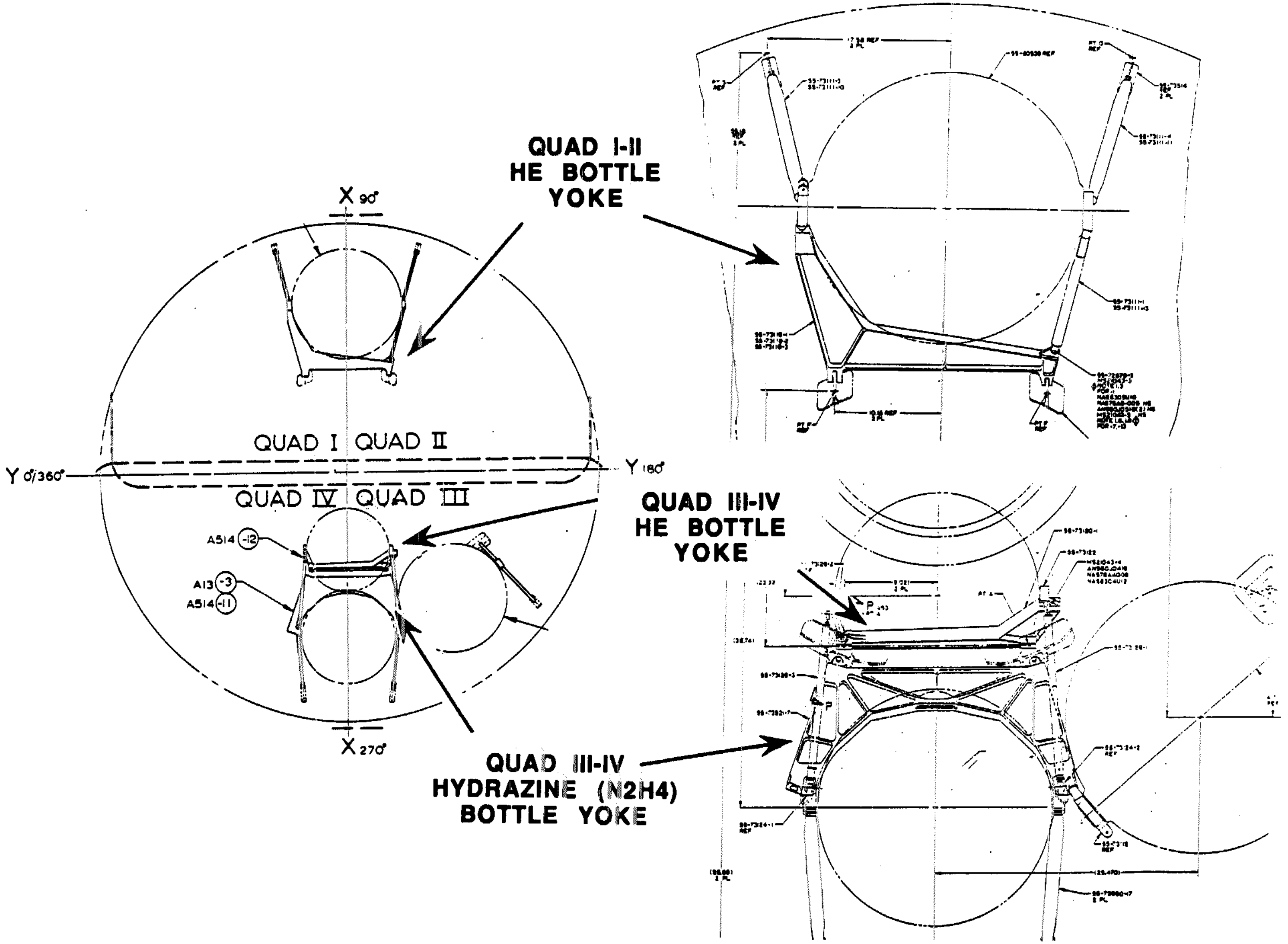


FIGURE 6 : CENTAUR BOTTLE SUPPORT STRUCTURES

NASTRAN MODEL

An MSC/NASTRAN finite element model was prepared that included the entire LOX tank and a portion of the LH2 tank. See Figures 7, 8, and 9. This model contains: the intermediate bulkhead, which separates the two tanks; the LOX tank cylindrical section; the aft bulkhead; the LOX sump and sump ring; the CRES 321 thrust ring; the thrust cylinder, including the thrust longerons and stiffeners; the forward cap ring and forward door membrane, which are fastened to the forward end of the thrust cylinder; and the Helium and Hydrazine bottle support structures.

SDRC/SUPERTAB on Space Systems Division APOLLO computer system was used to create the model and for postprocessing. Almost 3,000 grid points made up this model. The majority of the elements are QUAD4's, which are used for the tank skins, bulkheads, bottle support yokes and thrust cylinder skins. In addition, TRIA3 elements are used in these four areas. Beam elements make up the thrust ring, longerons, aft tank ring, sump and door rings; BAR elements are used for the stringers and bottle support structure. The limit structural design load of 22,000 lbs/engine is applied at the engine gimbal locations. Ultimate structural design load is 27,500 lbs/engine. The model is fixed at the forward end of the LH2 cylindrical section.

Grid spacing is driven by the desire to model accurately and in detail at the thrust ring load introduction points. Grids were placed at each of the thrust cylinder stringers and longerons. In addition, intermediate grids were used to further divide this stringer spacing. The thrust cylinder and aft bulkhead QUAD elements are then sized based on the grid spacing, with a limiting aspect ratio of 2.5.

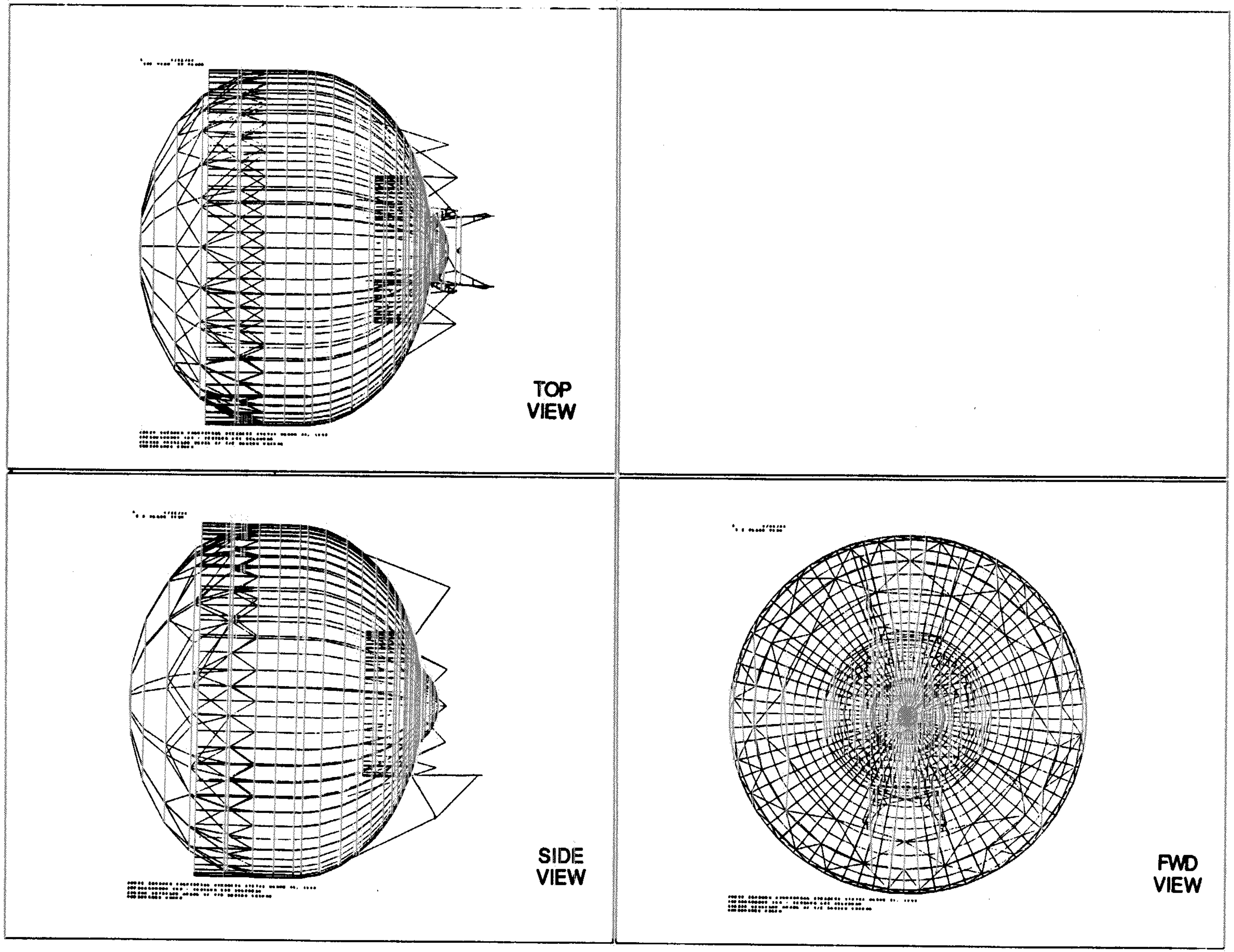


FIGURE 7 : OVERALL VIEWS OF NASTRAN MODEL

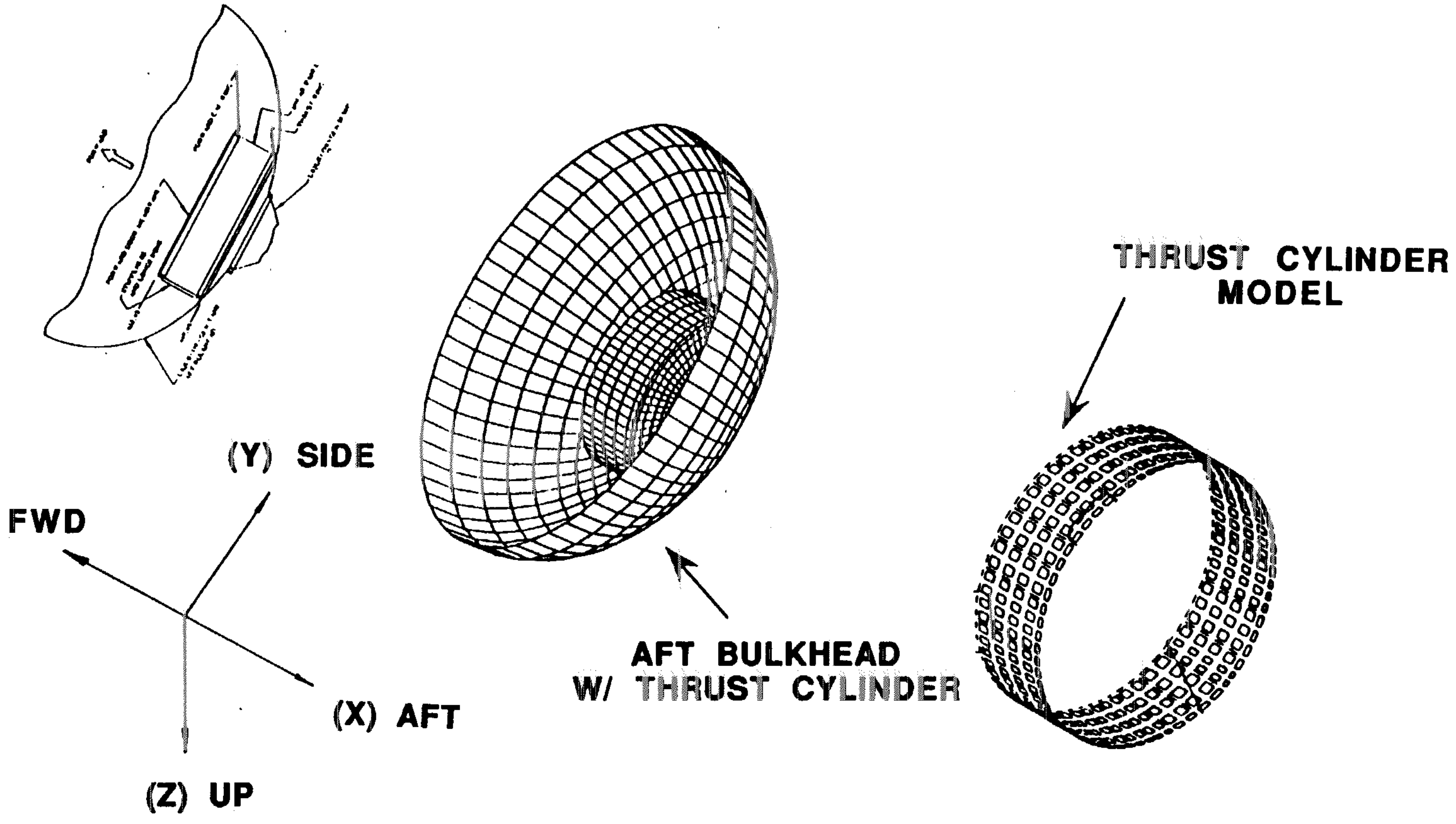


FIGURE 8 : NASTRAN MODEL OF AFT BHD/THRUST CYLINDER

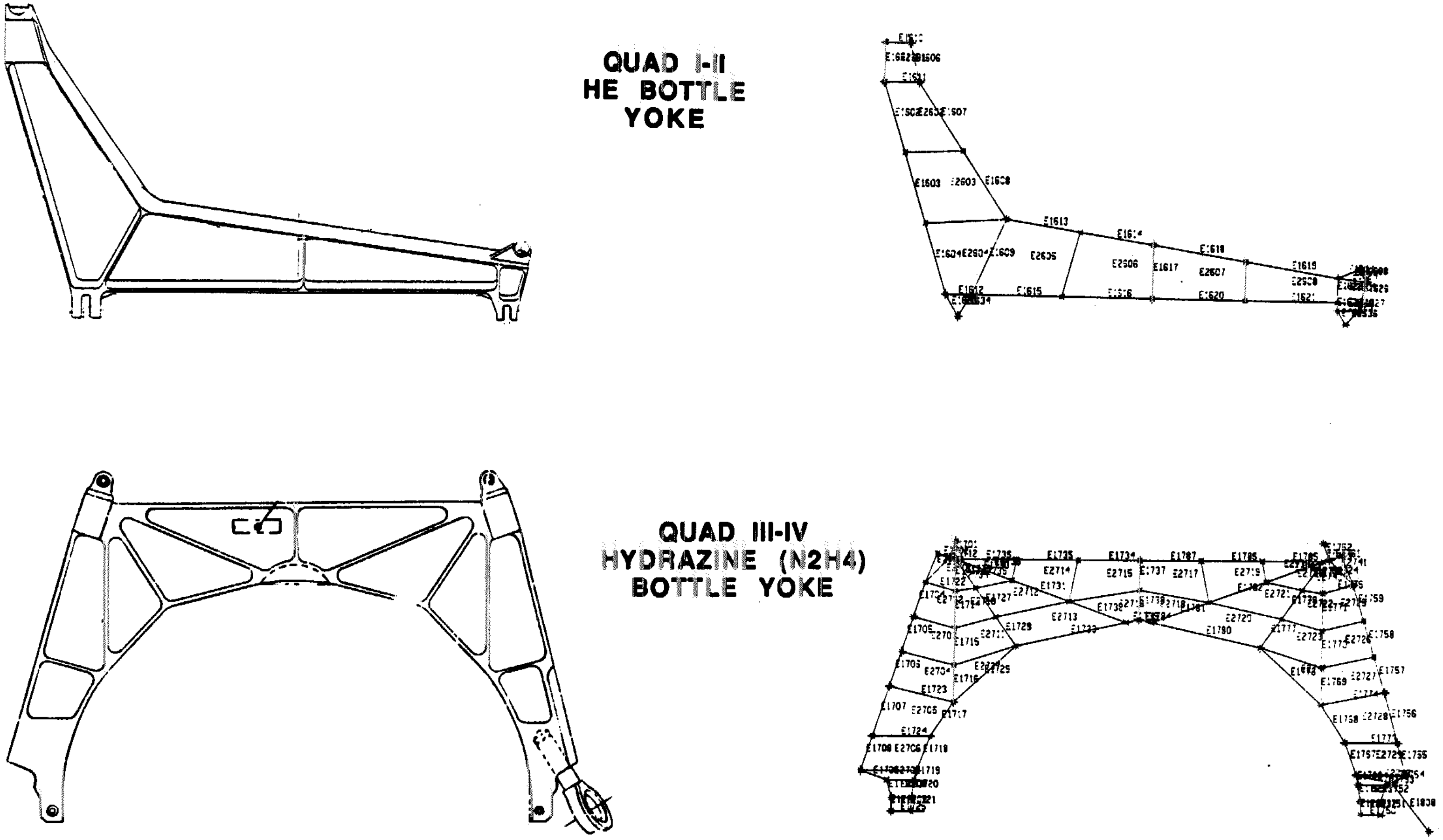


FIGURE 9 : NASTRAN MODEL OF BOTTLE SUPPORT STRUCTURES

LINEAR ANALYSIS

This 18,000 degree-of-freedom model is executed on General Dynamics Fort Worth Division CRAY computer. Linear analysis using MSC/NASTRAN'S SOL 61 took approximately 200 CPU seconds, costing about $100. High internal stresses were local to the engine mounting points. See Figures 10 and 11. This area of the thrust ring had negative margins of safety at 27,500 lbs/engine which would have necessitated local strengthening.

Strengthening the thrust ring locally would have required increases in the gages of the five layer, aft bulkhead-doubler build-up. The increased gage would improve the weld nugget penetration and also increase the spotweld strength. However, welding of thicker build-up is difficult, and the local skrinkage due to welding is aggravated. In addition, material allowables are decreased with the larger weld nuggets. Finally, each pound of Centaur structural weight added would decrease payload capability by a pound. Therefore, it is desirable to minimize structural weight increases as much as possible.

With a room temperature ultimate strain of over 0.25 in/in, 321 CRES annealed can sustain significant plasticity. The thrust ring can deform after yielding without large increases in stress. This deformation allows high local internal loads to be spread out over more of the thrust ring and the attached aft bulkhead and thrust cylinder. These conclusions were borne out in a full-scale structural test of the aft bulkhead performed in 1965. This test demonstrated an aft bulkhead load capability to 38,000 lbs/engine. With MSC/NASTRAN nonlinear analysis, this local yielding due to point loads on the aft bulkhead could now be analyzed. Faced with a redesign based upon conservative linear analysis, the decision was made to perform a nonlinear analysis to eliminate this conservatism, and also to compare the analysis results with the full-scale test results.

NONLINEAR ANALYSIS

Converting a linear model to a nonlinear model involved four separate items: defining superelements in the structure; inputting a stress-strain curve for material nonlinear analysis, and/or a PARAM,LGDISP, +1 card in the bulk data for geometric nonlinear analysis; setting a nonlinear iteration strategy; and defining a loading scheme. These four items are relatively easy to perform in MSC/NASTRAN, especially when starting with a linear model that has already been debugged.

Defining superelements allows the user to choose which part of the overall model will be analyzed for material and geometric nonlinearity in SOL 66. The nonlinear portion of the model is specified to be in superelement 0, or the residual superelement; the linear portion of the model is in the upstream superelements. This superelement definition can either be in field 9 of the grid card, or with an SESET card.

Inputting a stress-strain curve is through the MAT1, MATS1, and TABLES1 cards. The material ID specified in the element properties card (i.e. PBEAM) for the nonlinear elements is used in both the MAT1 and MATS1 cards. The MAT1 card is unchanged from linear analysis; the MATS1 card is added, containing the TABLES1 ID and the option for plastic or nonlinear elastic analysis (field 4). The TABLES1 card contains the data points for the stress-strain curve. A PARAM,LGDISP,+1 card in the bulk data is used to include geometric nonlinear analysis.

Setting the nonlinear iteration strategy is accomplished through the NLPARM card. An example of the NLPARM card is shown below:

NLPARM	1	2		AUTO			UPW	NO
1	2	3	4	5	6	7	8	9

The NLPARM bulkdata card is specified in the case control by its field 2 ID. The case control callout for this example is : NLPARM = 1. The number of load steps that the subcase's load is broken up into is specified in field 3. The load steps can be varied for both "coarse" and "fine" load steps depending on the sensitivity of the structure. The field 5 "AUTO" callout means the most efficient iteration scheme will be chosen

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by the computer--either a modified Newton-Raphson or "BFGS" quasi-Newton method. The field 8 "UPW" callout selects all three convergence criteria tests:` displacement, load, and work. The field 9 "NO" callout chooses no intermediate output for each load step increments specified in field 3. Fields 4, 6, and 7 were defaulted in this example.

Defining the loading scheme in SOL 66 is the most involved operation in converting from a linear model to a nonlinear model. Two bulk data cards are used:

LSEQ	900	110	1
1	2	3	4

CLOAD	1001	1.0	0.	110	0.	111	1.0	112
1	2	3	4	5	6	7	8	9

The LSEQ card renames load cards for nonlinear analysis. In the LSEQ example card above, the FORCE card with an ID of 1 (field 4) is renamed load 110 (field 3). This renamed ID of 110 is used in the CLOAD example card--(field 5 in the above CLOAD). The LSEQ ID of 900 is specified in the case control card: LOADSET = 900. The CLOAD card takes these renamed loads and multiplies them with the appropiate factors. For instance, load 110 (Force 1) is multiplied by 0 in field 4. All these loads are then multiplied by the overall factor of 1.0 specified in field 3. The field 2 ID of 1001 is called out by the case control card: CLOAD = 1001.

Fort Worth Division's CRAY computer was also used to perform nonlinear analysis. Each SOL 66 analysis took approximately 1650 CPU seconds, costing about $750 for nine load cases. The cost for nonlinear analysis was minimized because the nonlinear portion of the model was kept small. Only the thrust ring BEAM elements and aft bulkhead QUADs adjacent to the two engine mounting locations were included in the residual superelement.

As expected, the maximum stressess at the engine mounting locations were dramatically reduced. See Figures 10 and 11. The maximum nonlinear stress is one-

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half the linear stress. Now the thrust ring showed positive margins of safety at 27,500 lbs/engine. A redesign that would have been expensive and would have created manufacturing difficulties was not needed. The 321 thrust ring was shown to yield locally, spreading out the load over more of the ring and the adjacent aft bulkhead and thrust cylinder.

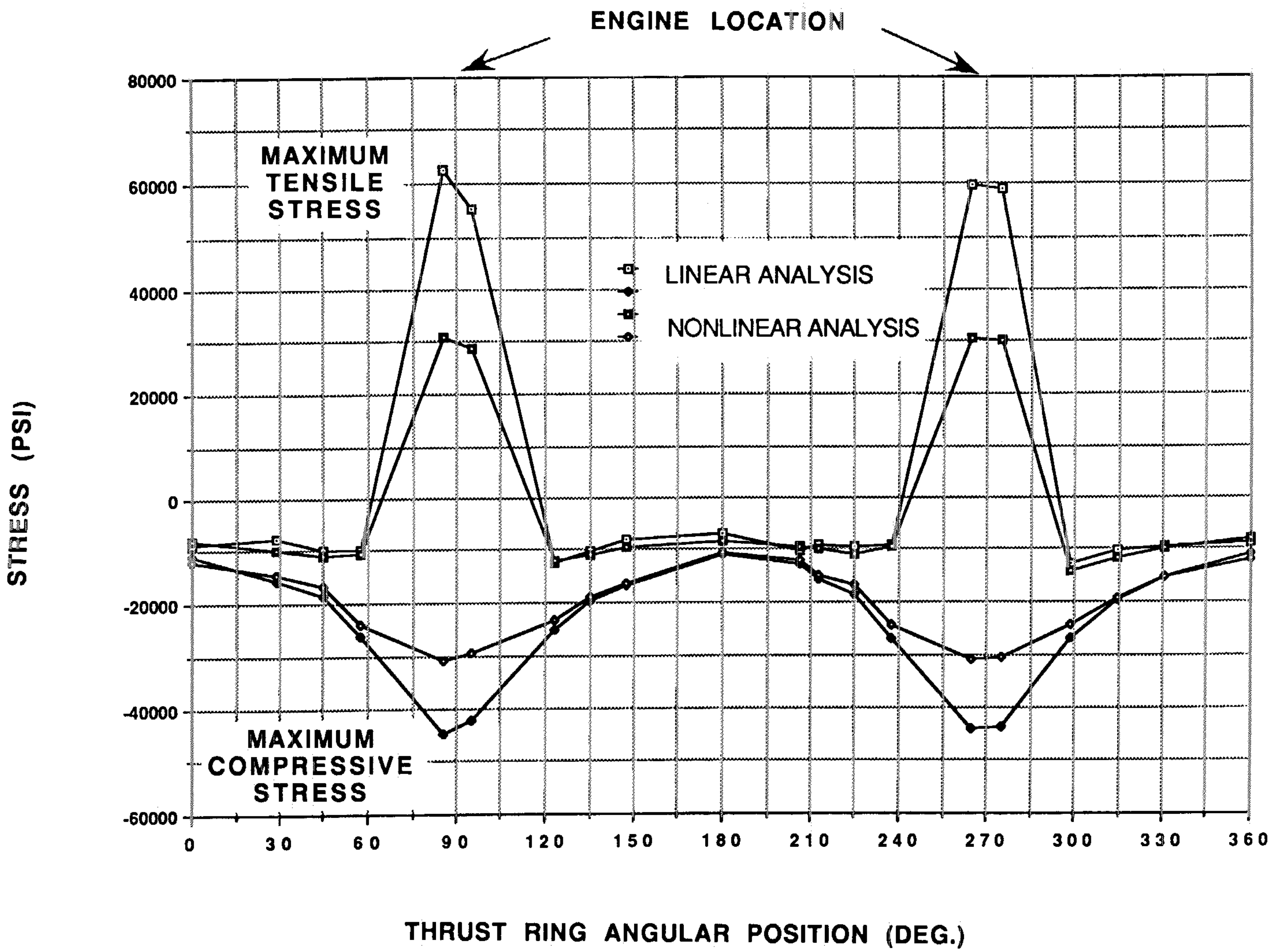

FIGURE 10 : MAXIMUM THRUST RING STRESSES -- 22 K THRUST PER ENGINE

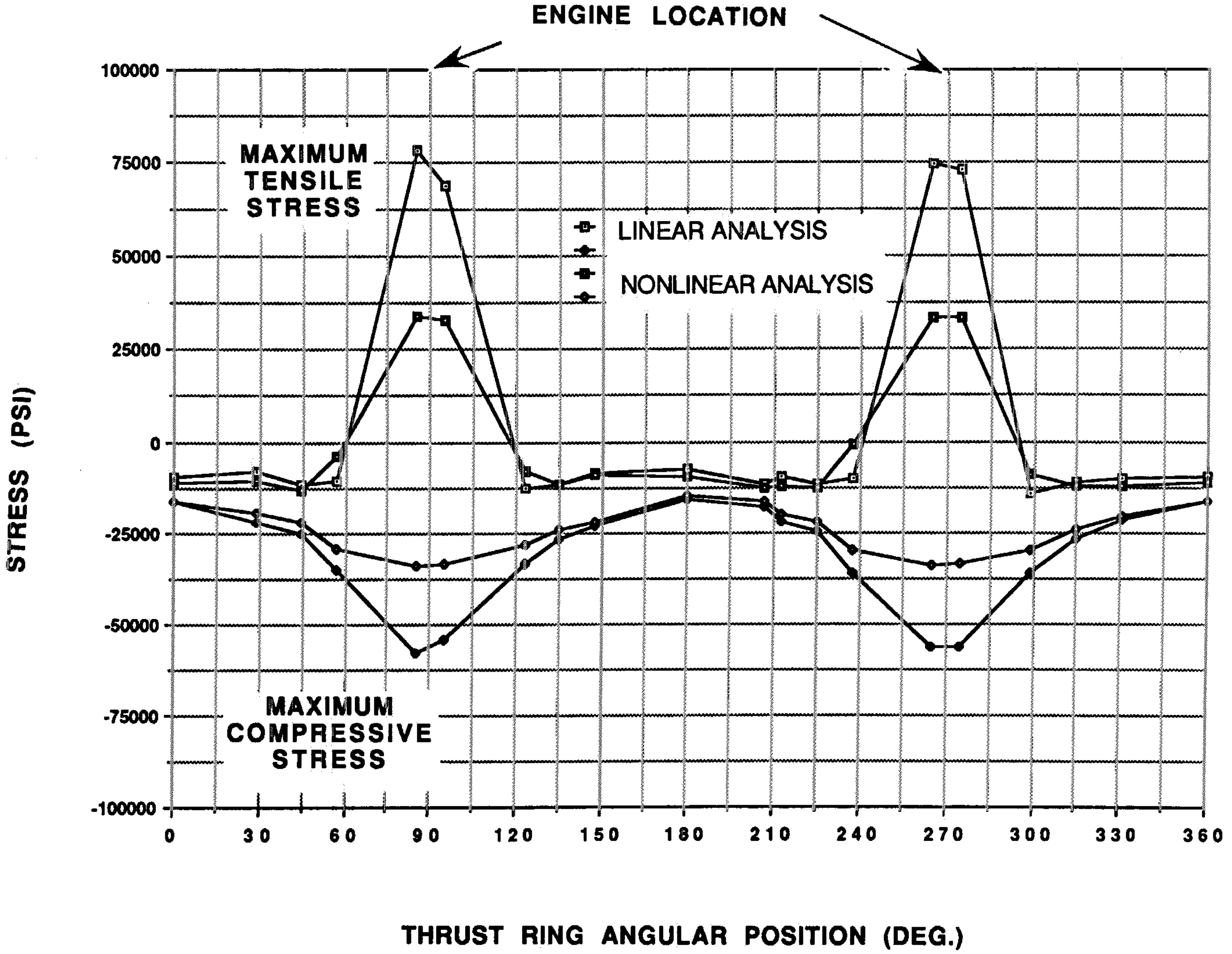

FIGURE 11 : MAXIMUM THRUST RING STRESSES -- 27.5 K THRUST PER ENGINE

COMPARISON WITH TEST

A full scale test of the Centaur aft bulkhead was performed in 1965 [1]. During this test, fore-aft loads were applied at the engine mounting locations to simulate engine loads. Included in the test load conditions were loads of 20K, 28K, and 38K lbs/engine. Deflections along the circumference of the thrust ring were recorded at these loads. These deflections were normalized with respect to the equator of the aft bulkhead. Plots of these deflections and SOL 66 NASTRAN analysis results are shown in Figures 12 to 14. As shown in these figures, agreement between the SOL 66 model results and test is excellent at 20K and 28K lbs/engine. Results were within 97% and 94%, respectively. However, as load increased beyond 28K lbs/engine, the nonlinear NASTRAN model's prediction of deflections deviated from test results. No additional efforts were made to investigate this as the current Centaur is designed for an ultimate load of 27.5K lbs/engine. A summary of maximum displacements is tabulated in Table 1.

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[1] GENERAL DYNAMICS/ASTRONAUTICS STRUCTURAL TEST REPORT, CENTAUR T-9 AFT BULKHEAD AND THRUST BARREL STATIC LOAD TEST, 9 NOV. 1965, REPORT NUMBER 55B-3379-3, FIGURE 27.

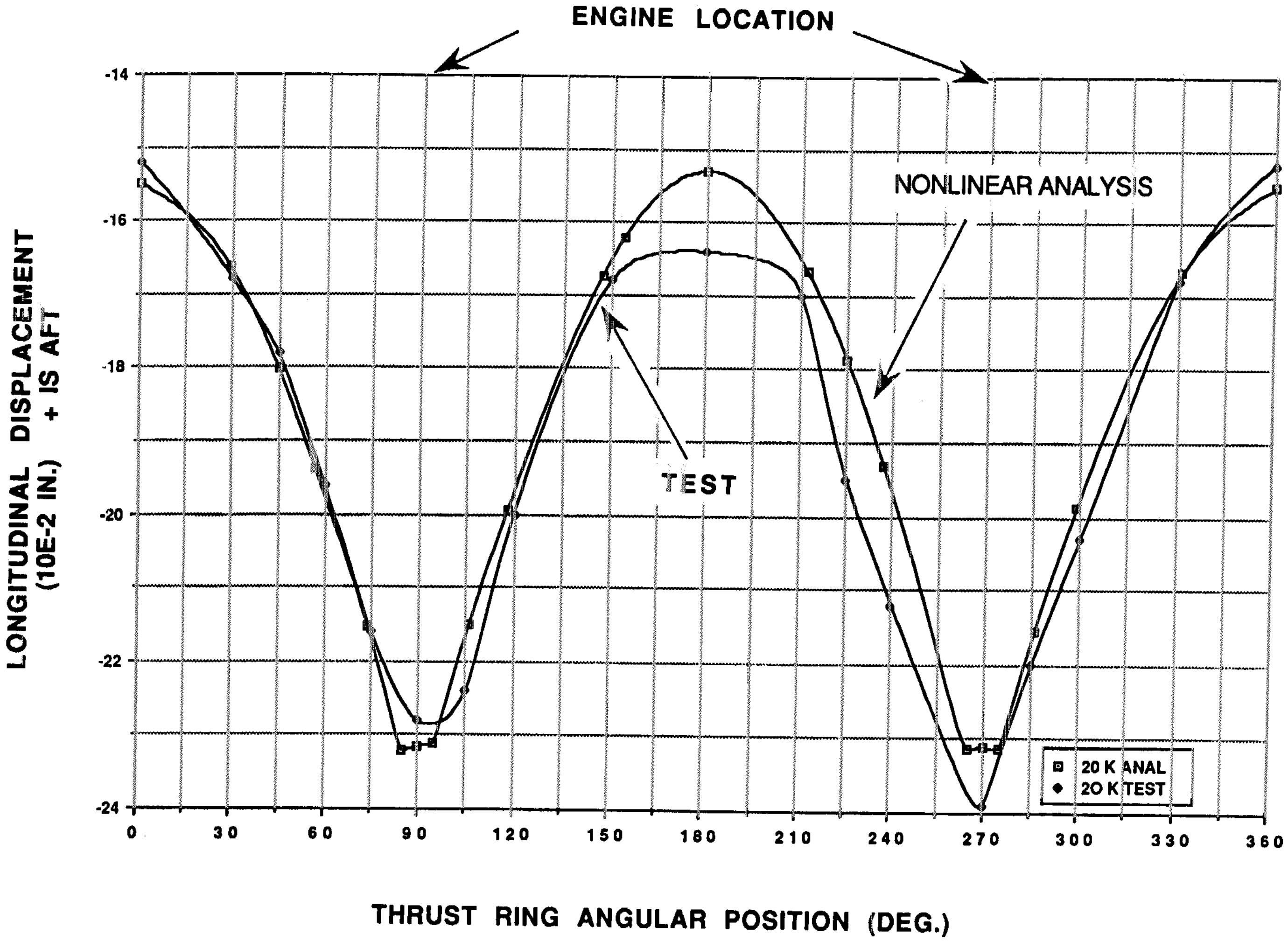

FIGURE 12 : MAXIMUM THRUST RING DISPLACEMENT -- 20 K THRUST PER ENGINE

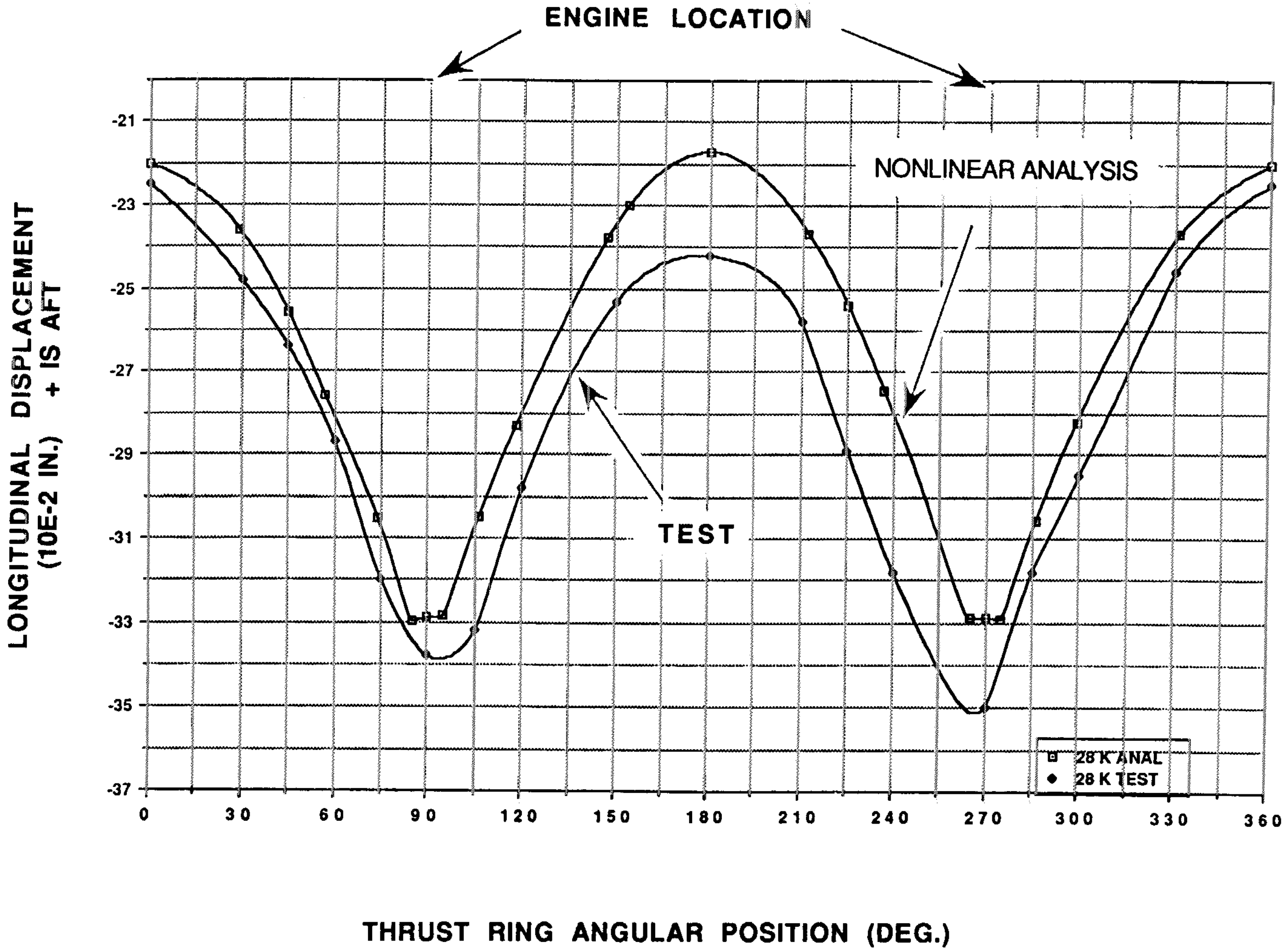

FIGURE 13: MAXIMUM THRUST RING DISPLACEMENT -- 28 K THRUST PER ENGINE

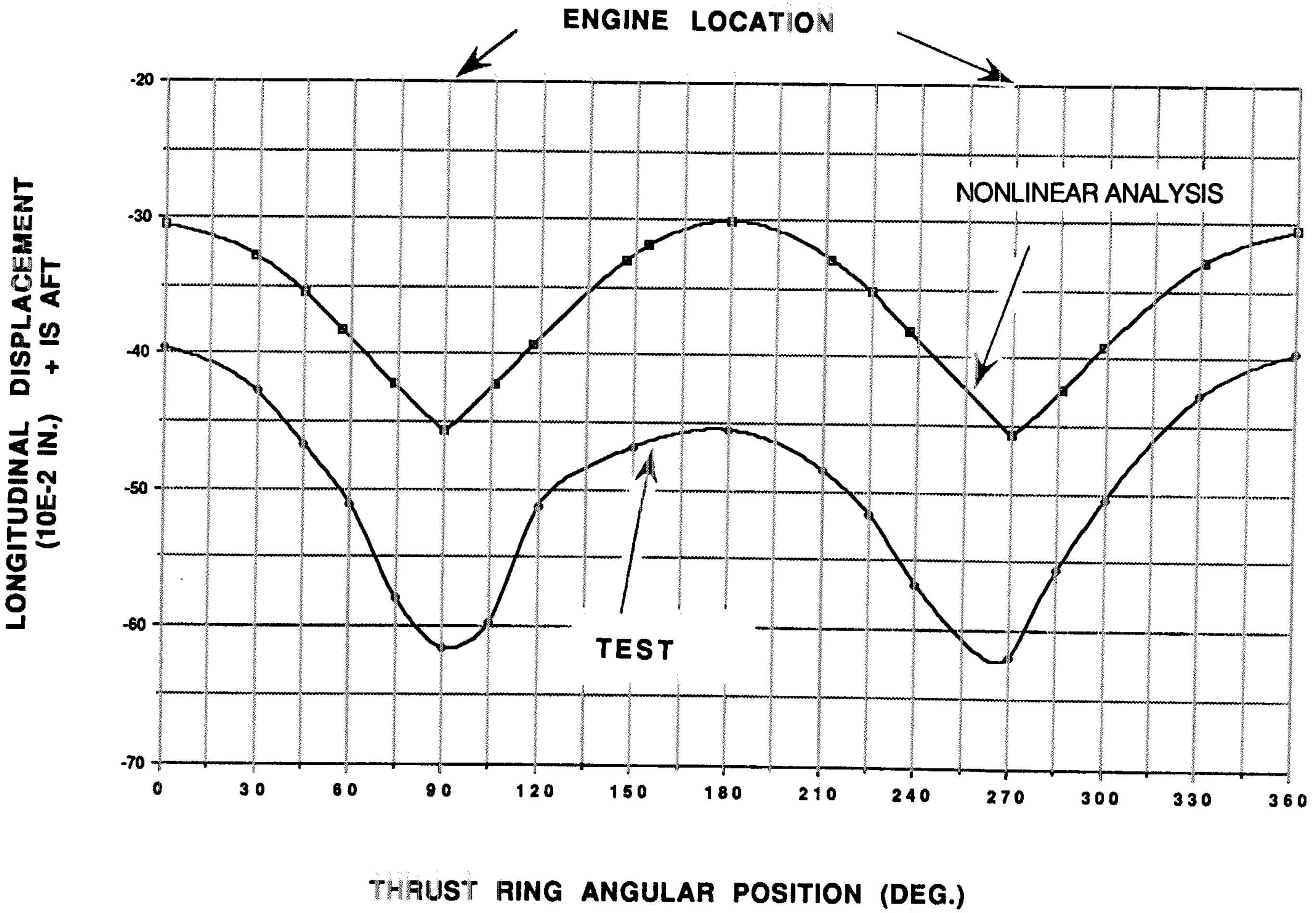

FIGURE 14 : MAXIMUM THRUST RING DISPLACEMENT -- 38 K THRUST PER ENGINE

TABLE 1 SUMMARY OF MAXIMUM DISPLACEMENTS

	LONGITUDINAL DISPLACEMENT (IN.)								
	20K/ENGINE			28K/ENGINE			38K/ENGINE		
Thrust Ring Location (Deg.)	Analysis	Test	Ratio**	Analysis	Test	Ratio**	Analysis	Test	Ratio**
90° *	-.232	-.228	1.02	-.329	-.338	.97	-.456	-.616	.74
270° *	-.231	-.239	.97	-.339	-.350	.94	-.456	-.620	.74

* ENGINE MOUNT LOCATION
** RATIO OF ANALYSIS TO TEST

SUMMARY

The analytical capability to account for the thrust ring's plasticity did not exist at the time of the Centaur aft bulkhead full-scale test. With MSC/NASTRAN SOL 66, the structural analyst can now compare both analytical stresses and deflections with test results. This ability to go beyond a conservative linear elastic analysis was instrumental in saving a structural change that would have been costly, difficult to manufacture, and would have reduced payload capacity. Previous testing had demonstrated excess capability in the aft bulkhead, and the nonlinear analysis results agreed with this testing.

Implementation of a geometric and material nonlinear analysis was relatively easy. Starting with a working linear elastic model, four changes were made: defining superelements; inputting a stress-strain curve; setting a nonlinear iteration strategy; and, defining a loading scheme. None of these four changes was difficult to implement. While nonlinear analysis is more expensive to execute than linear analysis, cost can be minimized by limiting the portion of the model that is nonlinear.

Linear analysis of the thrust ring showed stresses of 75 ksi and negative ultimate margins of safety. Nonlinear analysis for the same loads halved the maximum stresses to 35 ksi with positive ultimate margins of safety. At 20 K lbs/engine, the nonlinear analysis deflections were within 96% of the test deflections; at 28K lbs/engine, 94%; at 38K lbs/engine, 74%. This agreement demonstrates the validity of using SOL 66 for geometric and material nonlinear analysis.