OPTIMIZATION OF PROPELLANT TANKS SUPPORTED BY OPTIMIZED LAMINATED COMPOSITE TUBULAR STRUTS

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ABSTRACT

The propellant tank is a shell of revolution completely filled with liquid hydrogen (LH2). This propellant tank is to be launched into space. During launch it is subjected to high axial and lateral accelerations. The tank is supported by a system of struts that consist mainly of tubes with laminated composite walls. This strut-supported tank system is optimized via GENOPT/BIGBOSOR4 in the presence of two loading cases: (1) 10 g axial acceleration and 0 g lateral acceleration and (2) 0 g axial acceleration and 10 g lateral acceleration. In addition to the g-loading the tank has 25 psi internal ullage pressure and the tank wall is 200 degrees cooler than the wall of the launch vehicle from which it is supported by the struts. In the BIGBOSOR4 free vibration model the mass of the propellant is "lumped" into the tank wall, a conservative model. The tank/strut system is optimized in the presence of the following constraints: (1) the minimum free vibration frequency must be greater than a given value; (2) five stress components in each ply of the laminated composite wall of the strut tubes shall not exceed five specified allowables; (3) no strut tube shall buckle as a column; (4) no strut tube shall buckle as a thin cylindrical shell; (5) the maximum effective (vonMises) stress in the tank wall shall not exceed a specified value; (6) the tank wall shall not buckle; (8) the maximum force in a strut during the launch-hold phase of a mission shall not exceed a specified value. The objective to be minimized is in general a weighted combination of the normalized mass of the empty tank plus the normalized conductance of the support system: Objective= W x (normalized empty tank mass) + (1-W) x (normalized strut conductance), in which W is a user-selected weight between 0 and 1. Two propellant tank/strut systems are optimized: (1) a long tank with two "rings" of struts, an aft ring and a forward ring, and (2) a short tank with only one "ring" of struts. It is emphasized that the tank/strut combination is optimized as a single system. The flexibility of the propellant tank is accounted for and found to be significant for optimized tank/strut systems. The flexibility of the launch vehicle to which the tank/strut system is attached is neglected: the ends of the supporting struts attached to the launch vehicle are assumed to be attached to rigid "ground". For the long tank with two "rings" of struts a parameter study is conducted in which optimum designs are obtained as a function of the number of strut pairs attached at the aft and forward tank ends. Linear theory is used throughout. It is recommended that predictions for certain of the optimized tank/strut designs obtained here be compared to those from a general-purpose finite element code such as STAGS.

**************************** IMPORTANT NOTES ***********************************
1. Significant errors were found in the "tank" coding in February 2012. Also, the capability of GENOPT was enhanced to permit more than 50 decision variable candidates. Up to 98 decision variable candidates are now permitted by GENOPT. Because of the previously existing bugs in the "tank" software (bugs in "behavior" and

in "bosdec") the numerical results in this report no longer hold. However, they remain valuable for instructive purposes, that is, they demonstrate how GENOPT/BIGBOSOR4 is to be used for the generic case called "tank".

2. Before May 2012, all the loads in Load Case 1 and Load Case 2 were in what is commonly called “Load Set A”, meaning loads that are to be multiplied by the eigenvalue in buckling analyses. During May 2012 two load sets were established for buckling analyses: Load Set A and Load Set B. The loads in Load Set B are NOT multiplied by the buckling eigenvalue (load factor). Load Set A now contains only the components of acceleration, GAXIAL and GLATRL. Load Set B now contains the internal ullage pressure and the propellant tank cool down. The “BOSDEC” subroutines had to be modified in order to accommodate the new “Load Set A, Load Set B” formulation. New optimum designs were obtained with the new “Load Set A, Load Set B” formulation. These new optimum designs are different from those listed in this report. Software and results from the new “Load Set A, Load Set B” formulation are stored in the compressed “tar” file, tanktank2.tar.gz, which is located in the directory, …genopt/case/tank. NOTE: “tank” is the generic case name for the strut-supported propellant tank; “tank2” is the generic case name for the skirt-supported propellant tank.

3. A bug was discovered in BIGBOSOR4 having to do with "fixed" (non-eigenvalue) loading in a case for which INDIC = 4. This bug has been corrected. (See Item No. 38 in the file, ...bigbosor4/doc/bigbosor4.news).

4. TEMTUR = 0 instead of 170 degrees. Ring thermal loading was moved from Load Set A to Load Set B.

Files applicable to both specific cases, “test” and “test2” (stored in tanktank2/tank.paper/tankfiles):

```
-rw-r--r--   1 dave  staff  681841 May 18 08:43 addbosor4.density.var (“temporary” version of addbosor4)
-rw-r--r--   1 dave  staff  681449 May 18 08:43 addbosor4.regular (“permanent” version of addbosor4)
-rw-r--r--   1 dave  staff  153549 Feb 29 06:07 behavior.tank (“fleshed out” version of behavior.new)
-rw-r--r--@  1 dave  staff   12933 Jul 14 01:57 bigbosor4.input.test.BEHX.files.txt (explains *.BEHX files)
-rw-r--r--@  1 dave  staff   94295 Jul 14 01:31 bigbosor4.springs.txt (describes springs added to BIGBOSOR4)
-rw-r--r--   1 dave  staff  214446 Jun 10 14:51 bosdec.density.var (“varying density” version of bosdec)
-rw-r--r--   1 dave  staff  213982 Jun 10 14:51 bosdec.tank (“constant density” version of bosdec)
-rw-r--r--@  1 dave  staff   14081 Jul 14 01:58 computations.tank.txt (list of “chapter” computations)
-rw-r--r--@  1 dave  staff    1236 Jul 14 02:00 conductance.input.txt (input data for plotps for Fig.55(old))
-rw-r--r--@  1 dave  staff    1146 Jul 14 02:00 emptytankmass.input.txt (input data for plotps for Fig.56(old))
-rw-r--r--@  1 dave  staff     832 Jul 14 02:06 generic.tank.files.txt (list of file names for generic phase)
-rw-r--r--   1 dave  staff   68236 Mar  8 08:31 struct.tank (“fleshed out” version of struct.new)
-rw-r--r--   1 dave  staff  162271 Feb 29 06:08 tank.INP (input for the GENOPT processor, GENTEXT)
-rw-r--r--@  1 dave  staff   65953 Jul 14 02:24 tank.PRO.txt (prompting file generated by GENTEXT)
-rw-r--r--@  1 dave  staff   10422 Jul 14 02:23 tank.glossary.txt (variable names & definitions)
```

Files applicable to the specific cases, “test” (long propellant tank with aft & forward sets of struts) and “test2” (short propellant tank with only one set of struts; these files are stored in tanktank2/tank.paper/testtest2.input and tanktank2/tank.paper/testtest2.output:

1. Files stored in testtest2.input (input data for the specific cases, “test” and “test2”:

```
-rw-r--r--   1 dave  staff  18887 Feb 29 06:07 test.BEG (input for the GENOPT processor, BEGIN)
-rw-r--r--   1 dave  staff   9320 Feb 29 06:53 test.CHG (input for the GENOPT processor, CHANGE)
-rw-r--r--   1 dave  staff  17314 Feb 29 06:40 test.DEC (input for the GENOPT processor, DECIDE)
```

-rw-r--r-- 1 dave staff 1059 Feb 29 06:08 test.OPT (input for the GENOPT processor, MAINSETUP)
-rw-r--r-- 1 dave staff 9320 Mar 1 05:12 test.constdensity.chg (archived optimum design: constant density)
-rw-r--r-- 1 dave staff 9320 Mar 2 05:16 test.vardensity.chg (archived optimum design: varying density)
-rw-r--r-- 1 dave staff 14484 Mar 2 07:16 test2.BEG (input for the GENOPT processor, BEGIN)
-rw-r--r-- 1 dave staff 10754 Mar 2 07:17 test2.DEC (input for the GENOPT processor, DECIDE)
-rw-r--r-- 1 dave staff 1059 Mar 2 07:17 test2.OPT (input for the GENOPT processor, MAINSETUP)
-rw-r--r-- 1 dave staff 6345 Mar 3 05:56 test2.constdensity.chg (archived optimum design: constant density)
-rw-r--r-- 1 dave staff 6345 Mar 2 20:04 test2.vardensity.chg (archived optimum design: varying density)

2. Files stored in testtest2.output (output lists for the specific cases, "test" and "test2":
-rw-r--r-- 1 dave staff 131871 Mar 1 05:12 test.constdensity.opm (optimized design from "constant density")
-rw-r--r-- 1 dave staff 547052 Mar 1 05:01 test.constdensity.opp (output from optimization)
-rw-r--r-- 1 dave staff 483 Mar 1 05:21 test.constdensity.vib.bigbosor4.out (output from BIGBOSOR4)
-rw-r--r-- 1 dave staff 4830 Mar 1 06:01 test.constversusvaryingdensity.opm.diff
-rw-r--r-- 1 dave staff 132092 Jun 11 14:02 test.vardensity.feasible.loadaloadb.opm (optimum feasibledesign)
-rw-r--r-- 1 dave staff 131871 Mar 2 05:16 test.vardensity.opm (optimized design from "varying density")
-rw-r--r-- 1 dave staff 587381 Mar 2 05:04 test.vardensity.opp (output from optimization)
-rw-r--r-- 1 dave staff 91730 Mar 3 05:56 test2.constdensity.opm (optimized design, "constant density")
-rw-r--r-- 1 dave staff 358825 Mar 3 04:48 test2.constdensity.opp (output from optimization)
-rw-r--r-- 1 dave staff 515 Mar 3 06:04 test2.constdensity.vib.loadcase1.bigbosor4.out (BIGBOSOR4)
-rw-r--r-- 1 dave staff 515 Mar 3 06:08 test2.constdensity.vib.loadcase2.bigbosor4.out (BIGBOSOR4)
-rw-r--r-- 1 dave staff 5484 Mar 2 20:59 test2.constversusvaryingdensity.opm.diff
-rw-r--r-- 1 dave staff 91951 Jun 12 05:20 test2.vardensity.feasible.loadaloadb.opm (feasible design(
-rw-r--r-- 1 dave staff 91730 Mar 2 20:04 test2.vardensity.opm (optimized design from "varying density")
-rw-r--r-- 1 dave staff 557679 Mar 2 19:52 test2.vardensity.opp (output from optimization)
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VERY BRIEF SUMMARIES OF THE MAJOR SECTIONS OF THIS REPORT:

INTRODUCTION (summary)
References to previous similar work; comparison with the "dewar" program [6]; about the optimizer, ADS; two types of user.

SOME GEOMETRICAL AND OTHER DETAILS (summary)
Overall configuration of the propellant tank; local reinforcement by doubler plus discrete ring where struts are connected to the tank; modeling of the wall of the propellant tank; figures that show the tank/strut system.

MATERIAL PROPERTIES, OVERALL TANK DIMENSIONS,
FACTORS OF SAFETY AND ACCELERATION ARBITRARILY USED IN THIS STUDY (summary)
Arbitrarily selected conductivities, coefficients of thermal expansion, propellant tank support ring aspect ratio, propellant tank cool-down, single ply properties of the laminated composite strut tubes, strut tube curing temperature, overall propellant tank dimensions, factors of safety, minimum allowable free vibration frequencies, loading.

BEHAVIORS ACCOUNTED FOR DURING OPTIMIZATION CYCLES (summary)

Four free vibration modes, "lumping" the mass of the propellant into the tank wall, five maximum allowable stress components in each ply of the laminated composite strut tube wall, buckling of a strut tube as a column, buckling of a strut tube as a thin cylindrical shell, maximum effective stress in the wall of the propellant tank, buckling of the propellant tank, maximum allowable axial force in a strut during launch-hold.

TWO LOAD CASES (summary)
1. axial acceleration + internal pressure + tank cool-down,
2. lateral acceleration + internal pressure + tank cool-down

PLOTS PERTAINING TO THE OPTIMIZED LONG PROPELLANT TANK
WITH TWO SETS OF STRUTS WITH FOUR PAIRS OF STRUTS IN EACH SET (summary)
Figs. 19-31, strategy to the find "global" optimum design, design sensitivity of the optimized configuration (Figs. 32-54), description of the decision variables relating to ply thicknesses and ply layup angles in the laminated composite walls of the strut tubes, parameter study of empty tank mass and conductance of tank/strut system with increasing number of pairs of struts at each axial location (Figs. 55 and 56).

AN EXAMPLE OF A GENOPT/BIGBOSOR4 RUN STREAM (summary)
Table 1, set of commands used in GENOPT, description of valid input files for BIGBOSOR4 that can be used to obtain plots of various behaviors of optimized tank/strut systems (Table 11).

DECISION VARIABLE CANDIDATES (summary)
List of decision variables corresponding to the optimized long propellant tank with aft and forward "rings" of struts, names of several specific cases that were optimized.

TYPICAL DESIGN MARGINS (summary)
Design margins for Load Case 1 and Load Case 2 for an optimized tank/strut system with aft and forward sets of struts.

INFORMATION ABOUT GENOPT (summary)
Points to several files that contain general information about GENOPT.

INFORMATION ABOUT THE GENERIC CASE CALLED "tank" (summary)
Points to several files that contain information about the generic case called "tank",skeletal and "fleshed out" versions of the "struct" and "behavior" libraries, descriptions of the files, tank.INP, tank.PRO (Table 2), tank.DEF and the glossary of variables (Table 3), "temporary" and "permanent" versions of BIGBOSOR4 and BOSDEC.

RESULTS FROM MANY DIFFERENT CASES (summary)
List of compressed tar files where input and output are stored, long propellant tank, short propellant tank.

TWO BIGBOSOR4/BOSDEC MODELS OF "LUMPING" THE PROPELLANT MASS
INTO THE MIDDLE LAYER OF THE PROPELLANT TANK WALL (summary)
Effective added mass density, "regular" (permanent) and "temporary" versions of BIGBOSOR4 and BOSDEC, how to execute cases with either the "regular" or the "temporary" versions, warning about trying to use the "stand-alone" version of BIGBOSOR4 to predict free vibration frequencies for the GENOPT/BIGBOSOR4 model that employs the "temporary" versions of addbosor4 and bosdec.

FINDING THE OPTIMUM DESIGNS (summary)
Guideline on which model to use to obtain a reliable "global" optimum design, starting configuration of a second case is the optimized design of the first case and so on, anomalous cases called "test5" and "test1".

SOME DETAILS PERTAINING TO THE SPECIFIC CASE CALLED "test" (summary)
Long propellant tank with aft and forward sets of struts with 4 strut pairs in each set (Figs. 4 - 6, 19 - 28, 32 - 54), effect of propellant tank flexibility on the "effective" spring constants of struts, comparison of the prediction of free vibration frequencies from the "permanent" ("regular") and "temporary" versions of BIGBOSOR4/BOSDEC for the tank/strut system optimized with the use of the "temporary" version.

COMPARISON OF EMPTY TANK MASS AND TOTAL STRUT CONDUCTANCE
FOR THE LONG PROPELLANT TANK WITH TWO "RINGS" OF STRUTS (summary)
Results of a parameter study in which the number of strut pairs at each axial location (aft and forward) is varied from 2 to 8 strut pairs

OPTIMIZED SHORT PROPELLANT TANK WITH ONE "RING" OF STRUTS
WITH FOUR PAIRS OF STRUTS ATTACHED TO THAT RING (summary)
Results analogous to those from the long propellant tank that has aft and forward "rings" of struts, except there is no parameter study with respect to the number of strut pairs. (Figs. 7 - 10, 57 and 58; Tables 12 - 16).

PLOTS OF DECISION VARIABLES VERSUS DESIGN ITERATIONS
FOR THE LONG PROPELLANT TANK (specific case, "test") (summary)
An attempt is made to determine which of the many decision variables have the most influence on the several different converged local minima of the objective obtained during an execution of SUPEROPT.

PLOTS OF DECISION VARIABLES VERSUS DESIGN ITERATIONS
FOR THE SHORT PROPELLANT TANK (specific case, "test2") (summary)
An attempt is made to determine which of the many decision variables have the most influence on the several different converged local minima of the objective obtained during an execution of SUPEROPT. It is found that when the variable, ANGLE(5) (layup angle of one of the plies in the laminated composite strut tube), is removed as a decision variable the objective converges repeatedly to a unique minimum during an execution of SUPEROPT, not to multiple local minima. Figures 89 – 100 pertain to the short propellant tank.

MORE RESULTS GENERATED FOR THE OPTIMIZED SHORT TANK WITH ONE SET OF STRUTS
Figures 89 – 100 pertain to this section. All of these results are generated by GENOPT/BIGBOSOR4 after the February 2012 modifications.

SOME NOTES ABOUT RECENT CHANGES NOT REFLECTED IN THE FIGURES AND TABLES (summary)
Two notes are listed.

CONCLUSIONS (summary)
Fifteen conclusions are listed.

SUGGESTIONS FOR FURTHER WORK (summary)

Three suggestions are listed.

REFERENCES (summary)
Nineteen references are listed.

INTRODUCTION

A computer program system called "GENOPT/BIGBOSOR4" is used to obtain the optimum designs. GENOPT is a system of programs that can optimize anything [1] and BIGBOSOR4 [2], the successor to BOSOR4 [3], can analyze shells of revolution supported to ground by an arbitrary arrangement of springs [14]. The gradient-based optimizer used in GENOPT is called "ADS" [4,5]. ADS was created by Vanderplaats and his colleagues in the 1980s.

BIGBOSOR4 [2] is so named because it will handle complex shells of revolution with far more segments than will the original BOSOR4 program [3] from which it is derived. Also, BIGBOSOR4 permits the introduction of springs that connect any shell segment to rigid ground [14]. BOSOR4 does not have that capability.

The work reported here may be thought of as a more general approach to the solution of a strut-supported "dewar" payload described in [6]. In certain respects the model presented in [6] is more general than that presented here and in other respects the model in [6] is less general than that presented here:
(1) In [6] the launch vehicle is flexible and in the present model the launch vehicle is rigid and considered to be "ground".
(2) In [6] much attention is paid to an advanced type of strut with a thermal disconnect system (strut called "PODS"), and the support system is optimized for both orbital and launch conditions. Scant attention is paid to the "PODS" concept here. In that sense the present work is perhaps incomplete.
(3) In [6] clearance constraints are introduced that prevent supporting struts from passing through the dewar and that prevent supporting struts from passing through each other. Here it is up to the user of GENOPT/BIGBOSOR4 to provide upper and lower bounds of strut positions and angles so that most clearance constraints will automatically be satisfied or come close to being satisfied.
(4) The model used in [6] is more "primitive" (approximate) than that presented here. For example, the flexibilities of the dewar and launch vehicle from which the dewar is supported are obtained from a model that is greatly simplified and that is much too conservative for heavy payloads.
(5) The model used in [6] only permits three pairs of struts at each of two axial locations, whereas the model presented here permits any number of pairs of struts at each axial location.

Note that the "DEWAR" program [6] cannot be used for large payloads because its model in which the flexibility of the payload shell is accounted for is far too conservative to be practical. This unacceptable conservativeness of the "DEWAR" model leads to payload shell support rings the cross sections of which are unnecessarily huge, especially for heavy payloads.

In GENOPT the optimizer, ADS, is "hard-wired" in a so-called "1-5-7" mode: the "modified method of steepest descent". Constraint gradients are computed by finite differences of the behaviors of the "perturbed" design and the behaviors at the "current" design, in which the word, "behaviors" means free vibration or stress or buckling, etc.. A "perturbed" design is a design in which the value of one decision variable has been increased by a small amount (usually five per cent) from its "current" value. A constraint gradient matrix is generated by computing the change in each behavior caused by the perturbation of each decision variable. The values of the "behavioral" constraints and the constraint gradient matrix are inputs to the ADS optimizer by means of which a new "current" design is obtained by the modified method of steepest descent.

The GENOPT/BIGBOSOR4 system of computer programs has previously been used to obtain optimum designs of several structures that are comprised mainly of shells of revolution [2 and 7 - 10] or prismatic shells [11 - 13].

In the GENOPT system [1] there are two types of cases: generic and specific. In this work the generic case is called "tank", and the specific cases have names such as "test", "test1", "test2", "test3", etc. The specific cases are all members of the generic class, "tank". There are two types of user: the GENOPT user and the END user. The GENOPT user creates the software by means of which problems in the generic class (such as "tank") can be solved. The END user sets up and runs specific cases such as "test", "test1", "test2", etc. In the work reported here the GENOPT user and the END user are the same person: the writer of this report.

SOME GEOMETRICAL AND OTHER DETAILS

In this study the propellant tank consists of three sections:

(1) an aft dome (ellipsoidal head)
(2) a cylindrical portion
(3) a forward dome (ellipsoidal head)

The ellispoidal domes are each modeled as multi-segment shells in which the meridional curvature of each segment is constant. In [10] this device was found to be necessary in order to avoid partial finite element "locking", to which BIGBOSOR4 is susceptable in shell segments that have meridional curvature that varies along the meridian within any given shell segment. In this work twelve shell segments are used in the discretized model of each ellipsoidal dome.

The strut supports are arranged in a manner analogous to that displayed in Fig. 1 of [6]. (Also see Figs. 2 and 3 in this report.) In [6] only three pairs of "forward" and "backward" slanting struts are permitted at each of two axial locations. In the present model any number of pairs of "forward" and "backward" slanting struts are permitted at each axial "ring", and there may exist more than two axial "rings" of struts. (NOTE: the program system has been tested only for two axial "rings" of struts and one axial "ring" of struts. It may not work for more than two axial "rings" of struts because the total number of decision variable candidates and/or design margins may exceed the limits permitted by GENOPT.)

In the models used for the present work the ends of each "ring" of struts attached to the propellant tank are pinned to a reinforced axial section of the tank. This reinforcement consists of a tapered doubler centered about the axial location of each "ring" of struts plus a discrete ring of rectangular cross section. The pinned tank-end of each strut in the "ring" of struts is located at the centroid of the reinforcing ring. The reinforcing ring is considered to be attached to the reference surface of the tank shell wall, not to the outer surface of the tapered doubler. The material of the reinforcing doubler and the reinforcing ring therefore overlap in the short axial region where the doubler and ring material occupy the same space. See the sketch below:

```
  .---tank shell reference surface
 .
 |
|||
|||\
||| \<---tapered external doubler
|||  \
||------------
||     .     | <--discrete ring of rectangular cross section
||------------
|||  /  \\
||| /    \\
|||/      \\ <--pinned strut at propellant tank end of strut
|||        \\
|||         \\
|||
 |
```

Sketch of the propellant tank wall with a local reinforcement at the axial location where the tank-end of the "ring" of pinned struts is attached to the tank. Note: in this sketch the innermost "layer" of the propellant tank, which consists of an orthogrid with "smeared" stringers and rings, is not shown.

In the BIGBOSOR4 models of the propellant tank, the tank wall in each shell segment consists of three "layers":

(1) The innermost "layer" represents an orthogrid of rings and stringers with rectangular cross sections. These uniformly spaced stiffeners are "smeared out" in the model. The thickness of this innermost layer is equal to the height of the orthogrid. The material properties of this layer are equal to the material properties of the orthogrid material multiplied by the ratio, (thickness of orthogrid stiffeners)/(orthogrid spacing). This innermost layer exists in all sections of the propellant tank and is of constant properties throughout (orthogrid height and effective stiffness and density are constant and the same in all three major segments of the propellant tank: aft dome, middle cylindrical portion, and forward dome). The fact that ellipsoidal or hemispherical end domes cannot be manufactured in this way is overlooked in this study, the purpose of which is to create a capability to obtain reasonably good PRELIMINARY tank/strut designs.

(2) The middle layer is of constant thickness in each of the three major segments of the propellant tank: aft dome, cylindrical portion, and forward dome. This constant thickness may be different (THKAFT, THKMID, THKFWD) in each of these three major segments. It is this constant-thickness middle layer of the tank wall into which is "lumped" the mass of the propellant in the free vibration model.

(3) The outermost layer is of variable thickness and represents the tapered doublers. In regions with no doublers the thickness of this outermost layer is zero.

The ends of each "ring" of struts attached to the launch vehicle are considered to be attached to rigid "ground". In [6] flexibility of the launch vehicle is included in an approximate way. Here the launch-vehicle-ends of the struts must be connected to rigid "ground" because the BIGBOSOR4 model in which springs exist [14] only permits springs connected to ground, not to another flexible shell segment.

The flexibility of the propellant tank is included in the model, of course, since the propellant tank is modeled by BIGBOSOR4 as an ordinary flexible, segmented shell of revolution.

Figures 1 - 6 show the arrangement of struts for the starting design (Figs. 1-3) and for the optimized design (Figs. 4-6) of the long propellant tank/strut system supported by two "rings" of struts, aft and forward, for the specific case called "test", in which there are four pairs of struts attached to each of the two propellant tank support rings. The ends of the struts at the propellant tank are attached to rings located at the aft and forward dome/cylinder junctions.

Figures 7 - 10 show the same for the starting design (Figs. 7,8) and for the optimized design (Figs. 9,10) of the short propellant tank/strut system supported by one "ring" of struts (called "aft") with four strut pairs attached at the midlength of the short cylindrical part of the propellant tank.

Figures 11 - 16 show plan views of the aft set of struts for the OPTIMIZED designs of the long propellant tank/strut system with aft and forward sets of struts for the specific cases, "test1" (two pairs of struts at each of the two axial locations), "test3" (three pairs of struts at each of the two axial locations), "test4" (five pairs of struts at each of the two axial locations), "test6" (six pairs of struts at each of the two axial locations), "test7" (seven pairs of struts at each of the two axial locations), "test8" (eight pairs of struts at each of the two axial locations).

Figure 17 shows a plan view of the aft set of struts and Fig. 18 shows the elevation view for the OPTIMIZED design of the long propellant tank/strut system with aft and forward sets of struts for the specific case, "test5" (five pairs of struts at each of the two axial locations). The ends of the struts at the propellant tank are attached within the aft and forward domes, not at the dome/cylinder junctions as holds for all the other long tank/strut systems. This optimum design is very poor, that is, the optimized empty tank mass and total conductance are very high compared to those for the designs in which the struts are joined to the tank at the dome/cylinder junctions.

MATERIAL PROPERTIES, OVERALL TANK DIMENSIONS, FACTORS OF SAFETY AND ACCELERATION ARBITRARILY USED IN THIS STUDY

Typical values of input variables are listed in Table 4.

The material properties used in this study are, in many instances, arbitrary. For example, the thermal conductivity along the fibers of each ply of the laminated composite strut tubes is taken to be 0.00727 BTU/(in-hr-deg.R) and the thermal conductivity transverse to the fibers is taken to be 0.00437 BTU/(in-hr-deg.R). These values were simply "lifted" from the end of Table 5 near the top of p.14 of the "dewar" paper [6]. No attempt was made in this work to differentiate these strut tube thermal conductivities at the cold end and at the warm end of a strut tube. The effect of strut tube cool-down is neglected throughout despite the fact that there is an input datum called "DTSUP", which implies inclusion of this phenomenon.

The coefficient of thermal expansion along the ply fibers is taken to be 0.1000000E-05 and transverse to the ply fibers is taken to be 0.1000000E-04, although the thermal expansion of the strut tube and its end fittings play no role in this work. The coefficient of thermal expansion of the strut tube end fittings is arbitrarily taken to be 0.1000000E-04. The coefficient of thermal expansion of the isotropic propellant tank material and the isotropic propellant tank support ring material is arbitrarily taken to be 0.1000000E-04. (See Table 4, for example.)

In models that include propellant tank support rings the height of each ring is arbitrarily constrained to be five times its thickness. In this work the combination of external tapered doubler and propellant tank support ring is assigned a "tank reinforcement type index". In the propellant tank models for which results are presented here there exists only a single "tank reinforcement type". Hence, in long tanks with two "rings" of struts, aft and forward, the doubler dimensions and propellant tank support ring cross section dimensions are the same at both aft and forward axial locations.

The propellant tank cool-down is arbitrarily taken to be -200 degrees and the maximum allowable launch-hold force in a strut is arbitrarily taken to be 15000 lb. If this maximum allowable force in a strut is set too low relative to the weight of the propellant-filled tank GENOPT cannot find a FEASIBLE or ALMOST FEASIBLE optimum design; the optimization simply does not work because all designs obtained during optimization cycles are either NOT FEASIBLE or unacceptable to GENOPT on some other grounds.

The material properties of each ply of the laminated composite strut tubes and the five maximum allowable stress components were arbitrarily taken from one of the papers related to the PANDA2 computer program for optimization of stiffened laminated composite panels and shells. (The writer forgets which paper!) See Table 4, for example. No consideration is given to the dependence of material properties on the temperature.

The curing temperature, TEMTUR, of a laminated composite strut tube is arbitrarily taken to be 170 degrees. Cases are run either with TEMTUR = 0 or TEMTUR = 170 degrees. (See Table 4, for example.)

The overall dimensions of the propellant tank are arbitrarily assigned: tank diameter equals 200 inches, overall long tank length equals 400 inches, overall short tank length equals 150 inches, end domes are 2:1 ellipsoidal shells. The diameter of the launch vehicle (considered to be rigid "ground" in this study) is arbitraily taken to be 300 inches. (See Table 4, for example.)

The factor of safety for each stress component in each ply of the laminated composite strut tubes is arbitrarily set to 1.5; the factor of safety for effective stress in the propellant tank is arbitrarily set to 1.0; the factor of safety for free vibration frequency is arbitrarily set to 1.2; the factor of safety for buckling of a strut as a column is arbitrarily set to 1.0; the factor of safety for buckling of a strut as a thin cylindrical shell is arbitrarily set to 2.0 (to compensate for imperfection sensitivity). (See Table 4, for example.)

The minimum allowable frequency is arbitrarily set to 10 cps (Table 4).

The axial and lateral acceleration components of the tank are respectively arbitrarily set to 10g in two separate load cases (Table 4). The tank is assumed to be oriented with its axis of revolution aligned with the axial component of acceleration of the launch vehicle.

BEHAVIORS ACCOUNTED FOR DURING OPTIMIZATION CYCLES

As mentioned above, optimization of the tank/strut system is constrained by the following "behaviors", such as free vibration, stress and buckling. The "behaviors" constraining the design in this work are:

BEHAVIOR(1) Four free vibration modes corresponding to axial motion, rolling motion, and two lateral-pitching modes computed from a BIGBOSOR4 model of the strut-supported propellant tank. The flexibility of the propellant tank is accounted for in the computation of the "effective" spring constants (axial stiffnesses) of the supporting struts in this free vibration model. The mass of the propellant is "lumped" into the middle layer of the three-layered propellant tank. The axial and rolling free vibration modes correspond to n = 0 circumferential waves around the circumference of the tank. The two lateral-pitching modes correspond to n = 1 circumferential wave. Vibration modes with n = 2, 3,...etc. are not computed and are not accounted for in this study. It is assumed here that only the modes of vibration in which the propellant tank and its propellant are moving approximately as a rigid body need be accounted for. See Figs. 19-22 for vibration modes of the optimized long tank supported as shown in Figs. 4-6 (the specific case called "test").

****** IMPORTANT NOTE REGARDING "LUMPING" PROPELLANT MASS ******
In a general shell of revolution the amount of propellant mass to be "lumped" into the propellant tank shell wall middle layer at a nodal point in a shell segment depends on the radius from the axis of revolution and on the rate of change of this radius with meridional arc length. Hence, in the aft and forward ellipsoidal domes the effective density of the middle tank layer varies along the meridian of each dome shell segment. However, BIGBOSOR4 cannot handle shell segments with meridionally varying material density. Therefore, so-called "temporary" versions of BIGBOSOR4 and BOSDEC (see below) were created that are valid only for the generic case, "tank". Optimized designs were obtained with either the "temporary" or the "permanent" versions of BIGBOSOR4 and BOSDEC. The "stand-alone" version of BIGBOSOR4 was not changed in any way. More complete explanations are given below in the section entitled
"TWO BIGBOSOR4/BOSDEC MODELS OF LUMPING..." and in APPENDIX 2.
******************* END OF IMPORTANT NOTE *******************

BEHAVIOR(2) Maximum of each of five components of stress in the laminated composite walls of the strut tubes. The five stress components in each unidirectional ply of the composite laminates are:
a. maximum tension along the fibers
b. maximum compression along the fibers
c. maximum tension transverse to the fibers
d. maximum compression transverse to the fibers
e. maximum in-plane shear stress
These 5 maximum stress components are computed from both a BIGBOSOR4 model and from a PANDA-type model [15] of the most highly loaded laminated composite strut tube at each axial location (aft and forward) of a ring of "n" pairs of struts. Maximum tensile and maximum compressive loading of any strut at each axial location (aft and forward) are both included in the determination of the most critical stress components.

(3) Buckling of the strut as a column (Euler buckling), computed from both a BIGBOSOR4 model and a simple Euler model of the most highly compressed laminated composite strut at each axial location (aft and forward) of a ring of "n" pairs of struts. In the BIGBOSOR4 column buckling model the flexibility of the propellant tank is not accounted for. In the simple Euler model the flexibility of the propellant tank is accounted for. Therefore, the simple Euler model yields the most critical estimate of column buckling in the work reported here.

(4) Buckling of the strut tube as a thin cylindrical shell computed from both a BIGBOSOR4 model and a PANDA-type model [15] of the most highly compressed strut at each axial location (aft and forward) of a ring of "n" pairs of struts. The BIGBOSOR4 shell buckling model does not account for the effect of transverse shear deformation (t.s.d.) nor for the anisotropic terms in the 6 x 6 integrated constitutive matrix, C(i,j). The PANDA model accounts for t.s.d. and shell wall anisotropy. Therefore, the PANDA model yields the most critical estimate of shell buckling in the work reported here.

(5) Maximum effective (vonMises) stress in the propellant tank computed from a BIGBOSOR4 model of the propellant tank in which the struts are replaced by concentrated loads applied to the propellant tank along the aft and forward propellant tank support rings to which the "n" pairs of struts are attached.

(6) Buckling of the propellant tank computed from a BIGBOSOR4 model of the propellant tank in which the aft and forward rings of "n" pairs of struts are replaced by concentrated loads applied to the propellant tank along the aft and forward propellant tank support rings to which the struts are attached.

(7) Maximum force in a strut generated during the launch-hold phase of a mission computed from a BIGBOSOR4 model of the tank/strut system subjected to a 1-g loading. The propellant tank axis is assumed to be aligned with the axial direction of the launch vehicle from which the tank is supported. The purpose of this behavioral constraint is to obtain an optimum design of the tank/strut system in which an advanced strut, such as a strut that includes a thermal disconnect, does not "short circuit" during the launch-hold phase of a mission. NOTE: if the End user sets the allowable maximum force in a strut at too low a level, GENOPT/BIGBOSOR4 cannot find a FEASIBLE or ALMOST FEASIBLE optimum design; the optimization simply does not work properly.

TWO LOAD CASES

Calculations of each of the types of "behavior" just listed are performed for each of the two load cases experienced by the tank/strut system:

(1) Load Case 1:
internal ullage pressure = 25 psi
axial acceleration of the launch vehicle, GAXIAL = 10 g
lateral acceleration of the launch vehicle, GLATRL = 0 g
propellant tank cool-down, TNKCOOL = -200 degrees

(2) Load Case 2:
internal ullage pressure = 25 psi
axial acceleration of the launch vehicle, GAXIAL = 0 g
lateral acceleration of the launch vehicle, GLATRL = 10 g
propellant tank cool-down, TNKCOOL = -200 degrees

Cool-down of the supporting struts is not accounted for.

PLOTS PERTAINING TO THE OPTIMIZED LONG PROPELLANT TANK

WITH TWO SETS OF STRUTS WITH FOUR PAIRS OF STRUTS IN EACH SET
(the specific case called "test")

Plots of several of the behaviors (free vibration modes, buckling modes and deformation) pertaining to the optimized long tank with two "rings" of supporting struts with four strut pairs at each "ring" of struts (the specific case called "test") are given in Figs. 19-28.

Plots can also be obtained of the objective, variables, and design margins versus design iterations during a SUPEROPT optimization. Examples of such plots are given in Figs. 29-31, for examples. Figure 29 demonstrates that during SUPEROPT optimization cycles the tank/strut system converges to several different local minima of the objective, WGT*(normalized empty tank mass) +(1-WGT)*(normalized conductance). This property makes it especially difficult to find a "global" optimum design.

In the previous paragraph "global" is in quotes because the strategy used in GENOPT cannot rigorously determine a true global optimum design. Instead GENOPT attempts to find a design that is likely to be near a global optimum by starting from many different points in design space during a single execution of SUPEROPT. Each new "starting" point is established randomly in a manner consistent with equality and inequality constraints. In Fig. 29 each "starting" point corresponds to a "spike" in the plot of objective versus design iterations.

*************************** NOTE ********************************
In the process of launching each execution of SUPEROPT the End user is prompted as follows:

Enter specific case name: **test**
Enter number of executions of OPTIMIZE
for each execution of AUTOCHANGE (5 or 6 or 7 or 8 or 9 or 10 or ....15): **6**
B (background), F (foreground): **b**
H (high) or L (low) priority: **l**

The responses of the End user are shown in boldface. In every execution of SUPEROPT during this study the End user (the writer) chose six executions of OPTIMIZE for every execution of AUTOCHANGE.
****

Figures 32-54 show "design sensitivity" plots corresponding to the optimized design of the specific case called "test". The order of the figures corresponds to the order of the decision variable candidates listed Table 8.

In all of the configurations studied in this particular report the thickness of each ply in the laminated composite wall of each aft strut tube is the same as that of all the other plies in that aft strut tube. The thickness of each ply in the laminated composite wall of each forward strut tube is the same as that of all the other plies in that forward strut tube. All strut tubes at a given axial level, aft or forward, are the same. The forward strut tubes differ from the aft strut tubes, however. The thicknesses in each aft strut tube wall are:
[THICK(1), THICK(2), THICK(3), THICK(4), THICK(5), THICK(6)]symmetric
The thicknesses in each forward strut tube wall are:
[THICK(7), THICK(8), THICK(9), THICK(10), THICK(11), THICK(12)]symmetric
In the "DECIDE" processor of GENOPT THICK(2), THICK(3), THICK(4),
THICK(5) and THICK(6) are all linked to THICK(1). Analogously, THICK(8),

THICK(9), THICK(10), THICK(11) and THICK(12) are all linked to THICK(7).
Hence, there exist in this work only two independent decision variables for ply thickness in strut tubes: THICK(1) (all aft struts) and THICK(7) (all forward struts).

The layup of each aft strut tube is as follows:
[ANGLE(1), ANGLE(2), ANGLE(3), ANGLE(4), ANGLE(5), ANGLE(6)]symmetric
The layup of each forward strut tube is as follows:
[ANGLE(7), ANGLE(8), ANGLE(9), ANGLE(10), ANGLE(11), ANGLE(12)]symmetric
In the "DECIDE" processor of GENOPT, ANGLE(2), ANGLE(4) and ANGLE(6)
are constrained (linked) to be equal to the negatives of ANGLE(1), ANGLE(3) and ANGLE(5), respectively.
Analogous linking is established for the plies in the wall of each strut tube in the forward set of struts.

Figure 54 shows the sensitivity of the design objective,
WGT*(normalized empty tank mass) +(1-WGT)*(normalized conductance),
with respect to the decision variable, ANGLE(3), which is the layup angle of the third and fourth and of the tenth and ninth layers of the symmetric laminated composite wall of each aft strut tube.

Figures 55 and 56 pertain to the long propellant tank with two "rings" of struts, the aft ring located at the junction of the aft end dome with the cylindrical portion of the propellant tank and the forward ring located at the junction of the forward end dome with the cylindrical portion of the tank. Figure 55 shows the conductance into the propellant tank as a function of number of strut pairs at each of the aft and forward axial locations. Figure 56 shows analogous plots of the empty tank mass. Perhaps the best tank/strut system is the one in which there are four strut pairs at each axial location.

There are two curves in each of Figs. 55 and 56. The upper curve in each figure corresponds to use of the "permanent" BIGBOSOR4/BOSDEC model, that is, the BIGBOSOR4/BOSDEC model in which the "lumped" mass of the propellant into the middle layer of the wall of the propellant tank is approximate, and the effective density of that layer is constant along the meridian of each shell segment, ellipsoidal domes as well as the cylindrical portion. The lower curve in each figure corresponds to use of the "temporary" BIGBOSOR4/BOSDEC model, that is, the BIGBOSOR4/BOSDEC model in which the "lumped" mass of the propellant into the middle layer of the wall of the propellant tank is "exact", that is, the effective material density of the middle layer of the tank wall varies along the meridian of the aft dome and along the meridian of the forward dome. See the two sections below:
1. TWO BIGBOSOR4/BOSDEC MODELS OF "LUMPING"...
2. APPENDIX 2
for more details with regard to the two different BIGBOSOR4/BOSDEC models: the "permanent" BIGBOSOR4/BOSDEC model and the "temporary" BIGBOSOR4/BOSDEC model.

****************** IMPORTANT NOTE ****************************
It is best to compare predictions from STAGS [16-19] with predictions for optimized tank/strut designs found with use of the "temporary" BIGBOSOR4/BOSDEC model because that model is the more accurate of the two BIGBOSOR4/BOSDEC models studied in this work.
****

AN EXAMPLE OF A GENOPT/BIGBOSOR4 RUN STREAM

A rather detailed example of a GENOPT/BIGBOSOR4 run stream executed during the present work is contained in Table 1. The run stream involves execution of the various GENOPT processors, which are listed near the beginning of Table 1 and repeated here for convenience:

GENOPT commands have been activated.

gentext GENOPT user generates a prompt file, tank.PRO (Table 2) and an information file, tank.DEF, that contains a glossary: Table 3. Skeletal libraries, behavior.new and struct.new, are created. These are to be "fleshed out" by the GENOPT user.

genprograms GENOPT user generates (makes) executables: begin, decide, mainsetup, optimize, change, chooseplot, and diplot.

begin End user provides starting data: test.BEG (Table 4).

decide End user chooses decision variables, bounds, linked variables, and inequality constraints: test.DEC (Table 5)

mainsetup End user sets up strategy parameters: test.OPT (Table 6 or Table 7).

optimize End user performs optimization or analyzes a fixed design (output listed in Table 8) or performs design sensitivity (Figs 32 - 54)

change End user changes,archives variables: test.CHG (Table 9).

autochange New values for decision variables are randomly computed: (See the "spikes" in the plot in Fig. 29)

superopt End user finds "global" optimum (autochange/optimize): (Fig. 29, 59, 59b, Table 8, Figs. 57, 58, 86, 88, Table 15)

superduperopt End user executes superopt/chooseplot x times: (Not used in this study because of the very long computer run times required for the particular cases studied here, but generally very useful for finding a "global" optimum)

chooseplot End user chooses which variable to plot vs. design iterations: test.CPL (Table 10)

diplot End user plots variables vs. iterations: (Figs. 29-31, 57,58)

insert GENOPT user adds parameters to the problem.

cleangen GENOPT user cleans up GENeric case files.

cleanspec End user cleans up SPECific case files.

Once one obtains an optimum design, one can then obtain various plots generated by BIGBOSOR4 as described next.

Table 11 describes files called "test.BEHX11", "test.BEHX21", "test.BEHX31", "test.BEHX41", "test.BEHX511", "test.BEHX611", "test.BEHX711", "test.BEHX811", "test.BEHX911", and more. These many files contain valid input data for the "stand-alone" version of BIGBOSOR4. They can be used, as described in Table 11, for obtaining various plots of various behaviors for configurations that have been optimized by GENOPT/BIGBOSOR4, in which the string, "BIGBOSOR4" used in connection with the string, "GENOPT", indicates the "permanent" or "temporary" versions of BIGBOSOR4/BOSDEC, not the “stand-alone” version of BIGBOSOR4. The latest versions of the test.BEHX*** files are stored in the compressed "tar" file, test.behx.tar.gz. This compressed "tar" file contains the following "stand-alone" BIGBOSOR4 input files, all of which pertain to the specific case called "test":

```
-----------------------------------------------------------------
-rw-rw-r-- 1 bush bush 101334 Jan 10 05:31 test.BEHX011
-rw-rw-r-- 1 bush bush 101334 Jan 10 05:31 test.BEHX012
-rw-rw-r-- 1 bush bush   5130 Jan 10 05:31 test.BEHX021
-rw-rw-r-- 1 bush bush   5130 Jan 10 05:31 test.BEHX022
-rw-rw-r-- 1 bush bush  68831 Jan 10 05:31 test.BEHX031
-rw-rw-r-- 1 bush bush  68831 Jan 10 05:31 test.BEHX032
-rw-rw-r-- 1 bush bush 101334 Jan 10 05:31 test.BEHX041
-rw-rw-r-- 1 bush bush 101334 Jan 10 05:31 test.BEHX042
-rw-rw-r-- 1 bush bush  59786 Jan 10 05:31 test.BEHX11
-rw-rw-r-- 1 bush bush  59786 Jan 10 05:31 test.BEHX12 (Figs.19-22)
-rw-rw-r-- 1 bush bush   4942 Jan 10 05:31 test.BEHX21
-rw-rw-r-- 1 bush bush   4942 Jan 10 05:31 test.BEHX22
-rw-rw-r-- 1 bush bush   5176 Jan 10 05:31 test.BEHX31
-rw-rw-r-- 1 bush bush   5176 Jan 10 05:31 test.BEHX32
-rw-rw-r-- 1 bush bush   5119 Jan 10 05:31 test.BEHX511
-rw-rw-r-- 1 bush bush   5119 Jan 10 05:31 test.BEHX512 (Fig. 25)
-rw-rw-r-- 1 bush bush   5353 Jan 10 05:31 test.BEHX521
-rw-rw-r-- 1 bush bush   5353 Jan 10 05:31 test.BEHX522
-rw-rw-r-- 1 bush bush   5406 Jan 10 05:31 test.BEHX611
-rw-rw-r-- 1 bush bush   5406 Jan 10 05:31 test.BEHX612 (Fig. 26)
-rw-rw-r-- 1 bush bush   5640 Jan 10 05:31 test.BEHX621
-rw-rw-r-- 1 bush bush   5640 Jan 10 05:31 test.BEHX622
-rw-rw-r-- 1 bush bush 101312 Jan 10 05:31 test.BEHX71
-rw-rw-r-- 1 bush bush 101312 Jan 10 05:31 test.BEHX72
-rw-rw-r-- 1 bush bush 107713 Jan 10 05:31 test.BEHX811 (Fig. 27)
-rw-rw-r-- 1 bush bush 107713 Jan 10 05:31 test.BEHX812 (Fig. 28)
-rw-rw-r-- 1 bush bush 107713 Jan 10 05:31 test.BEHX821
-rw-rw-r-- 1 bush bush 107713 Jan 10 05:31 test.BEHX822
-rw-rw-r-- 1 bush bush 107888 Jan 10 05:31 test.BEHX911 (Fig. 23)
-rw-rw-r-- 1 bush bush 107888 Jan 10 05:31 test.BEHX912 (Fig. 24)
-rw-rw-r-- 1 bush bush 107888 Jan 10 05:31 test.BEHX921
-rw-rw-r-- 1 bush bush 107888 Jan 10 05:31 test.BEHX922
---------------------------------------------------------------
```

DECISION VARIABLE CANDIDATES

Here is an example of decision variable candidates used during the optimization of the long tank/strut system with two "rings" of struts with 4 strut pairs at each "ring"(the specific case called "test"; see Figs. 4 - 6 for the optimized design listed here):

OPTIMIZED DESIGN FOUND WITH THE TEMPORARY VERSION OF BIGBOSOR4/BOSDEC AND WITH CURING TEMPERATURE, TEMTUR=170 DEGREES FOR THE LONG PROPELLANT TANK WITH TWO RINGS OF STRUTS

VALUES OF DESIGN VARIABLES CORRESPONDING TO BEST FEASIBLE DESIGN

VAR. NO.	CURRENT VALUE	DEFINITION
1	5.188E-02	thickness of the tank aft dome skin: THKAFT
2	4.527E-02	thickness of the tank cylinder skin: THKMID
3	5.320E-02	thickness of the forward tank dome skin: THKFWD
4	3.639E+00	spacing of the tank orthogrid stringers: STRSPC
5	4.446E+00	spacing of the tank orthogrid rings: RNGSPC
6	1.028E-01	thickness of the tank orthogrid stringers: STRTHK
7	9.806E-01	height of the tank orthogrid stringers: STRHI
8	1.762E-01	thickness of the tank orthogrid rings: RNGTHK
9	9.806E-01	height of the tank orthogrid rings: RNGHI
10	1.500E+02	global axial coordinate of tank support ring: ZTANK(1)
11	4.500E+02	global axial coordinate of tank support ring: ZTANK(2)
12	8.939E+01	global axial coordinate of "ground": ZGRND(1)
13	5.085E+02	global axial coordinate of "ground": ZGRND(2)
14	6.000E+00	circ.angle (deg.) to pinned tank end of strut: ATANK(1)
15	6.000E+00	circ.angle (deg.) to pinned tank end of strut: ATANK(2)
16	4.500E+01	circ.angle to pinned "ground" end of strut: AGRND(1)
17	4.500E+01	circ.angle to pinned "ground" end of strut: AGRND(2)
18	6.753E+00	inner diam. of support tube active at launch: IDTUBE(1)
19	6.856E+00	inner diam. of support tube active at launch: IDTUBE(2)
20	1.000E-06	height of mid-tank T-ring web: WEBHI
21	1.000E-06	thickness of mid-tank T-ring web: WEBTHK
22	1.000E-06	width (height) of mid-tank T-ring flange: FLGHI
23	1.000E-06	thickness of mid-tank T-ring flange: FLGTHK
24	3.000E+01	axial length of the propellant tank doubler: DUBAXL(1)
25	8.555E-01	max.thickness of the propellant tank doubler: DUBTHK(1)
26	3.498E-01	thickness of the tank reinforcement ring: TRNGTH(1)
27	1.749E+00	height of the tank reinforcement ring: TRNGHI(1)
28	7.271E-03	thickness of a lamina: THICK(1)
29	7.271E-03	thickness of a lamina: THICK(2)
30	7.271E-03	thickness of a lamina: THICK(3)
31	7.271E-03	thickness of a lamina: THICK(4)
32	7.271E-03	thickness of a lamina: THICK(5)
33	7.271E-03	thickness of a lamina: THICK(6)
34	7.250E-03	thickness of a lamina: THICK(7)
35	7.250E-03	thickness of a lamina: THICK(8)
36	7.250E-03	thickness of a lamina: THICK(9)
37	7.250E-03	thickness of a lamina: THICK(10)
38	7.250E-03	thickness of a lamina: THICK(11)
39	7.250E-03	thickness of a lamina: THICK(12)
40	1.992E+01	layup angle: ANGLE(1)
41	-1.992E+01	layup angle: ANGLE(2)
42	1.000E+01	layup angle: ANGLE(3)
43	-1.000E+01	layup angle: ANGLE(4)
44	6.042E+01	layup angle: ANGLE(5)
45	-6.042E+01	layup angle: ANGLE(6)

```
 46    1.537E+01  layup angle: ANGLE(7 )
 47   -1.537E+01  layup angle: ANGLE(8 )
 48    1.000E+01  layup angle: ANGLE(9 )
 49   -1.000E+01  layup angle: ANGLE(10)
 50    6.448E+01  layup angle: ANGLE(11)
 51   -6.448E+01  layup angle: ANGLE(12)
-------------------------------------------------------------------
```

The values just listed correspond to the optimum design of the specific case called "test". Figures 4 - 6, 19 - 28, and 32 - 54 pertain to this optimized tank/strut system.

************************* NOTE ***************************
The predictions from GENOPT/BIGBOSOR4 for this configuration, also listed in Table 8, should be compared with predictions from STAGS [16-19].
****

The list of decision variable names and definitions is the same for all of the specific cases that pertain to the long propellant tank with two "rings" of struts. These specific cases are called:

```
"test1" (2 pairs of struts in each "ring" of struts, Fig.11)
"test3" (3 pairs of struts in each "ring" of struts, Fig.12)
"test4" (5 pairs of struts in each "ring" of struts, Fig.13)
"test5" (5 pairs of struts in each "ring" of struts, Figs.17,18)
"test6" (6 pairs of struts in each "ring" of struts, Fig.14)
"test7" (7 pairs of struts in each "ring" of struts, Fig.15)
"test8" (8 pairs of struts in each "ring" of struts, Fig.16)
```

In all of the specific cases just listed, except the specific case called "test5", the strut ends at the propellant tank are pinned to aft and forward propellant tank support rings located at the aft and forward junctions of the cylindrical portion of the tank with the aft dome (axial station = 150 inches) and the forward dome (axial station = 450 inches). In the specific case called "test5" the strut ends at the the propellant tank are pinned to propellant tank support rings that occur within the aft end dome (axial station = 125 inches) and within the forward dome (axial station = 475 inches). (Figs. 17 and 18)

Of course, the values of the decision variables and linked variables for these additional specific cases will be different from those listed above for the specific case called "test" (4 pairs of struts in each "ring" of struts).

TYPICAL DESIGN MARGINS

During optimization, design margins are computed for each of the two load cases for each optimization cycle. In the work reported here design margins are computed for each of the two load cases listed above in the section entitled "TWO LOAD CASES".

For example, the design margins computed for the optimized tank/strut system for the long tank with two "rings" of struts, an aft "ring" of struts and a "forward" ring of struts, are as follows for the specific case called "test" (4 pairs of struts in each "ring" of struts):

DESIGN MARGINS FOR THE OPTIMIZED DESIGN FOR LOAD CASES 1 AND 2

```
 ***** RESULTS FOR LOAD SET NO.  (axial acceleration of 10g) ******
 MARGINS CORRESPONDING TO CURRENT DESIGN (F.S.= FACTOR OF SAFETY)

MARGIN CURRENT
 NO.     VALUE           DEFINITION
  1   -8.385E-03  (FREQ(1 ,1 )/FREQA(1 ,1 )) / FREQF(1 ,1 )-1; F.S.=  1.20
  2    2.416E-03  (FREQ(1 ,2 )/FREQA(1 ,2 )) / FREQF(1 ,2 )-1; F.S.=  1.20
  3    6.280E-02  (FREQ(1 ,3 )/FREQA(1 ,3 )) / FREQF(1 ,3 )-1; F.S.=  1.20
  4    1.108E-01  (FREQ(1 ,4 )/FREQA(1 ,4 )) / FREQF(1 ,4 )-1; F.S.=  1.20
  5    2.022E+01  (STRES1A(1 ,1 )/STRES1(1 ,1 )) / STRES1F(1 ,1 )-1; F.S.=  1.50
  6    2.023E+00  (STRES1A(1 ,2 )/STRES1(1 ,2 )) / STRES1F(1 ,2 )-1; F.S.=  1.50
  7    6.615E-01  (STRES1A(1 ,3 )/STRES1(1 ,3 )) / STRES1F(1 ,3 )-1; F.S.=  1.50
  8    4.043E+00  (STRES1A(1 ,5 )/STRES1(1 ,5 )) / STRES1F(1 ,5 )-1; F.S.=  1.50
  9    8.006E-01  (STRES2A(1 ,1 )/STRES2(1 ,1 )) / STRES2F(1 ,1 )-1; F.S.=  1.50
 10    4.386E+00  (STRES2A(1 ,2 )/STRES2(1 ,2 )) / STRES2F(1 ,2 )-1; F.S.=  1.50
 11    1.937E-02  (STRES2A(1 ,3 )/STRES2(1 ,3 )) / STRES2F(1 ,3 )-1; F.S.=  1.50
 12    1.173E+00  (STRES2A(1 ,5 )/STRES2(1 ,5 )) / STRES2F(1 ,5 )-1; F.S.=  1.50
 13    8.615E-01  (COLBUK(1 ,1 )/COLBUKA(1 ,1 )) / COLBUKF(1 ,1 )-1; F.S.=  1.00
 14    1.885E+04  (COLBUK(1 ,2 )/COLBUKA(1 ,2 )) / COLBUKF(1 ,2 )-1; F.S.=  1.00
 15    1.509E+00  (SHLBUK(1 ,1 )/SHLBUKA(1 ,1 )) / SHLBUKF(1 ,1 )-1; F.S.=  2.00
 16    7.995E+01  (SHLBUK(1 ,2 )/SHLBUKA(1 ,2 )) / SHLBUKF(1 ,2 )-1; F.S.=  2.00
 17    1.279E+00  (FORCEA(1 ,1 )/FORCE(1 ,1 )) / FORCEF(1 ,1 )-1; F.S.=  1.00
 18    1.085E-02  (FORCEA(1 ,2 )/FORCE(1 ,2 )) / FORCEF(1 ,2 )-1; F.S.=  1.00
 19    6.413E-03  (TNKSTRA(1 ,1 )/TNKSTR(1 ,1 )) / TNKSTRF(1 ,1 )-1; F.S.=  1.00
 20    6.413E-03  (TNKSTRA(1 ,2 )/TNKSTR(1 ,2 )) / TNKSTRF(1 ,2 )-1; F.S.=  1.00
 21    9.786E+00  (TNKBUK(1 ,1 )/TNKBUKA(1 ,1 )) / TNKBUKF(1 ,1 )-1; F.S.=  1.00
 22    9.786E+00  (TNKBUK(1 ,2 )/TNKBUKA(1 ,2 )) / TNKBUKF(1 ,2 )-1; F.S.=  1.00

 ***** RESULTS FOR LOAD SET NO.  2  (lateral acceleration of 10g) ******
 MARGINS CORRESPONDING TO CURRENT DESIGN (F.S.= FACTOR OF SAFETY)

MARGIN CURRENT
 NO.     VALUE           DEFINITION
  1    3.610E-03  (FREQ(2 ,1 )/FREQA(2 ,1 )) / FREQF(2 ,1 )-1; F.S.=  1.20
  2    5.705E-02  (FREQ(2 ,2 )/FREQA(2 ,2 )) / FREQF(2 ,2 )-1; F.S.=  1.20
  3    6.378E-02  (FREQ(2 ,3 )/FREQA(2 ,3 )) / FREQF(2 ,3 )-1; F.S.=  1.20
  4    1.111E-01  (FREQ(2 ,4 )/FREQA(2 ,4 )) / FREQF(2 ,4 )-1; F.S.=  1.20
  5    5.936E-01  (STRES1A(2 ,1 )/STRES1(2 ,1 )) / STRES1F(2 ,1 )-1; F.S.=  1.50
  6    2.898E-01  (STRES1A(2 ,2 )/STRES1(2 ,2 )) / STRES1F(2 ,2 )-1; F.S.=  1.50
  7   -1.760E-03  (STRES1A(2 ,3 )/STRES1(2 ,3 )) / STRES1F(2 ,3 )-1; F.S.=  1.50
  8    5.975E-01  (STRES1A(2 ,5 )/STRES1(2 ,5 )) / STRES1F(2 ,5 )-1; F.S.=  1.50
  9    7.299E-01  (STRES2A(2 ,1 )/STRES2(2 ,1 )) / STRES2F(2 ,1 )-1; F.S.=  1.50
 10    4.082E-01  (STRES2A(2 ,2 )/STRES2(2 ,2 )) / STRES2F(2 ,2 )-1; F.S.=  1.50
 11   -3.868E-05  (STRES2A(2 ,3 )/STRES2(2 ,3 )) / STRES2F(2 ,3 )-1; F.S.=  1.50
 12    1.094E+00  (STRES2A(2 ,5 )/STRES2(2 ,5 )) / STRES2F(2 ,5 )-1; F.S.=  1.50
 13   -5.725E-03  (COLBUK(2 ,1 )/COLBUKA(2 ,1 )) / COLBUKF(2 ,1 )-1; F.S.=  1.00
 14    2.094E-03  (COLBUK(2 ,2 )/COLBUKA(2 ,2 )) / COLBUKF(2 ,2 )-1; F.S.=  1.00
 15    4.052E-04  (SHLBUK(2 ,1 )/SHLBUKA(2 ,1 )) / SHLBUKF(2 ,1 )-1; F.S.=  2.00
 16    1.048E-03  (SHLBUK(2 ,2 )/SHLBUKA(2 ,2 )) / SHLBUKF(2 ,2 )-1; F.S.=  2.00
 17    1.402E+00  (FORCEA(2 ,1 )/FORCE(2 ,1 )) / FORCEF(2 ,1 )-1; F.S.=  1.00
 18    3.494E-02  (FORCEA(2 ,2 )/FORCE(2 ,2 )) / FORCEF(2 ,2 )-1; F.S.=  1.00
 19   -5.288E-03  (TNKSTRA(2 ,1 )/TNKSTR(2 ,1 )) / TNKSTRF(2 ,1 )-1; F.S.=  1.00
 20   -6.549E-03  (TNKSTRA(2 ,2 )/TNKSTR(2 ,2 )) / TNKSTRF(2 ,2 )-1; F.S.=  1.00
```

```
 21    9.647E+00  (TNKBUK(2 ,1 )/TNKBUKA(2 ,1 )) / TNKBUKF(2 ,1 )-1; F.S.=  1.00
 22    1.766E+01  (TNKBUK(2 ,2 )/TNKBUKA(2 ,2 )) / TNKBUKF(2 ,2 )-1; F.S.=  1.00
------------------------------------------------------------------------------
```

In the margin lists the following conventions apply:

Behavioral variable names:
FREQ means free vibration frequency
STRES means stress component in a ply of a composite strut tube
COLBUK means buckling of a strut as a column
SHLBUK means buckling of a strut as a thin shell
FORCE means force in a strut tube during launch-hold
TNKSTR means stress in the propellant tank wall
TNKBUK means buckling of the propellant tank

"A", "F", and "F.S.":
An "A" added to a behavioral variable name means "allowable"
An "F" added to a behavioral variable name means "factor of safety"
"F.S." means "factor of safety"

Indices, i,j,k:

FREQ(i,j): i = load case; j = vibration mode
j = 1 means first eigenvalue for n = 0 waves (usually the axial mode))
j = 2 means first eigenvalue for n = 1 waves (lateral-pitch mode no. 1)
j = 3 means second eigenvalue for n = 0 waves (usually the rolling mode)
j = 4 means second eigenvalue for n = 1 waves (lateral-pitch mode no. 2)

STRESSi(j,k): i = material no., j=load case, k = stress component
i = 1 means "material no. 1" which also means "strut type no. 1" (aft ring)
i = 2 means "material no. 2" which also means "strut type no. 2" (forward ring)
k = 1 means tension along the fibers of a ply
k = 2 means compression along the fibers of a ply
k = 3 means tension transverse to the fibers of a ply
k = 4 means compression transverse to the fibers of a ply
k = 5 means in-plane shear in a ply

COLBUK(i,j): i = load case; j = strut type
j = 1 means type of strut in the aft "ring" of struts
j = 2 means type of strut in the forward "ring" of struts

SHLBUK(i,j): i = load case; j = strut type
j = 1 means type of strut in the aft "ring" of struts
j = 2 means type of strut in the forward "ring" of struts

FORCE(i,j): i = load case; j = strut type
j = 1 means type of strut in the aft "ring" of struts

j = 2 means type of strut in the forward "ring" of struts

TANSTR(i,j): i = load case; j = meridian number
j = 1 means the stress in the tank is that along meridian no. 1
j = 2 means the stress in the tank is that along meridian no. 2

TANBUK(i,j): i = load case; j = meridian number
j = 1 means the buckling of the tank from stress along meridian no. 1
j = 2 means the buckling of the tank from stress along meridian no. 2

INFORMATION ABOUT GENOPT

Information about GENOPT is provided in the papers cited in the Introduction. Also, there are several files provided here, as follows: (The files listed next are contained in the compressed "tar" file, general.info.tar.gz)

FILES GIVING GENERAL INFORMATION ABOUT GENOPT AND ABOUT THE INTRODUCTION OF SPRINGS INTO BIGBOSOR4. (Struts are a kind of spring support). These files are located in the folder, tanktank2/generalinfo:

```
-rw-r--r--  1 bush bush  94295 Nov 24 08:53 bigbosor4.springs
-rw-r--r--  1 bush bush   5720 Nov 24 08:44 genopt.abstract
-rw-rw-r--  1 bush bush   2024 Nov 24 08:34 genopt.commands
-rw-rw-r--  1 bush bush   3234 Nov 24 08:35 genopt.files
-rw-r--r--  1 bush bush  93262 Nov 24 08:48 genopt.getting.started
-rw-rw-r--  1 bush bush   8909 Nov 24 08:39 genopt.information
-rw-rw-r--  1 bush bush    987 Nov 24 08:55 genopt.information.files
-rw-rw-r--  1 bush bush   2507 Nov 24 08:36 genopt.programs
-rw-r--r--  1 bush bush 251587 Nov 24 08:43 genopt.runstream
-rw-rw-r--  1 bush bush  11183 Nov 24 08:37 genopt.summary
-rw-rw-r--  1 bush bush   1077 Nov 24 08:38 genopt.variable.roles
```

**************** June 2012 NOTE ************** June 2012 NOTE ****************
The file, bigbosor4.springs, is also located in the directory, …genopt/case/tank
****

INFORMATION ABOUT THE GENERIC CASE CALLED "tank"

In the GENOPT universe there are two types of cases:

(1) A generic case (called "tank" in this work)

(2) Specific cases that fit within the generic set. These specific cases are called "test", "test1", "test2", "test3", "test4", "test5", "test6", "test7" and "test8" in the work reported here.

Corresponding to each of the two classes of case, generic and specific, there are possibly different users. The role of the GENOPT user is to create the software for setting up the GENERIC environment ("tank"). The End user exercises the GENERIC environment, "tank", for SPECIFIC cases, such as the cases called "test", "test1", "test2", "test3", "test4", "test5", "test6", "test7" and "test8".

The following files pertain to the GENERIC case, "tank":

FILES RELATED TO THE GENOPT USER'S "GENERIC CASE" PHASE OF THIS PROJECT

```
 149170 Dec  5 06:42 behavior.tank         ("fleshed-out" version)
 209589 Dec  4 15:12 bosdec.tank           ("permanent" version)
  67909 Dec  5 13:56 struct.tank           ("fleshed-out" version)
  39212 Nov 19 04:10 tank.DEF              (general information)
 155703 Nov 19 04:09 tank.INP              (input for GENTEXT)
  63078 Nov 19 04:09 tank.PRO (Table 2)    (prompting file)
  10105 Nov 17 03:59 tank.glossary (Table 3) (part of tank.DEF)
 679734 Dec 23 08:23 addbosor4.density.var ("temporary" version)
 679342 Dec 23 15:55 addbosor4.regular     ("permanent" version)
 210151 Dec 28 05:54 bosdec.density.var    ("temporary" version)
```

***************** June 2012 NOTE ************** June 2012 NOTE *****************
The files just listed are contained in the compressed “tar” file, tank.tar.gz, which is located in the directory, …genopt/case/tank. Analogous files for the generic case called “tank2” (propellant tank supported by skirts) are contained in the compressed “tar” file, tank2.tar.gz, which is also located in the directory, …genopt/case/tank.
****

Skeletal forms of the files, behavior.tank and struct.tank, are created automatically by GENOPT during the GENOPT user's long interactive session associated with the GENOPT command, GENTEXT. It is the responsibility of the GENOPT user to "flesh out" these skeletal libraries (called behavior.new and struct.new) so that they compute any "behaviors" (vibration, buckling, stress) that may constrain the optimum design.

The "fleshed out" versions of behavior.new and struct.new are contained in the two files, behavior.tank and struct.tank. The file, bosdec.tank, is entirely written by the GENOPT user. bosdec.tank generates valid input files for BIGBOSOR4, which is the shell-of-revolution analyzer that computes the various vibration, buckling, and stress behaviors that constrain the design during optimization cycles.

The three files, tank.INP, tank.PRO and tank.DEF, are created automatically by the GENOPT processor, GENTEXT. tank.INP contains an image of the GENOPT user's long interactive GENTEXT session; tank.PRO (Table 2) is a prompting file created automatically by GENTEXT from the input words, phrases, and paragraphs provided by the GENOPT user during his/her long interactive GENTEXT session; tank.DEF is a file created automatically by GENTEXT. It contains general information about GENOPT and a glossary of variable names, definitions and properties established by the GENOPT user during his/her interactive GENTEXT session. The file, tank.glossary (Table 3), is the glossary part of the file, tank.DEF.

The two files, addbosor4.density.var and bosdec.density.var, contain the "temporary" versions of bigbosor4 and bosdec in which there is an "exact" representation of the "lumped" propellant mass into the middle layer of the wall of the propellant tank for the purpose of obtaining a reasonably accurate (and conservative) computation of free vibration frequencies corresponding to tank axial motion, tank rolling, and two tank lateral/pitching modes. In the "temporary" version of bigbosor4 the density of the middle layer of the wall of the propellant tank varies along the meridian of the aft ellipsoidal dome and along the meridian of the forward ellipsoidal dome. The file, addbosor4.regular, contains the "permanent" version of bigbosor4. In the "permanent" version of bigbosor4 the density of the middle layer of the wall of the propellant tank is constant along the meridians of the aft and forward ellipsoidal domes. Please see the section entitled "TWO BIGBOSOR4/BOSDEC MODELS..." and APPENDIX 2 for more details about the "temporary" versions of BIGBOSOR4 and BOSDEC.

RESULTS FROM MANY DIFFERENT CASES

Results for several specific cases, "test", "test1", "test2", "test3", "test4", "test5", "test6", "test7" and "test8" are contained in the compressed tar files:

```
-rw-rw-r-- 1 bush bush 405102 Jan 13 05:50 case.test.tar.gz
-rw-rw-r-- 1 bush bush 210187 Jan  9 08:57 case.test1.tar.gz
-rw-rw-r-- 1 bush bush 462770 Jan 13 05:24 case.test2.tar.gz
-rw-rw-r-- 1 bush bush 748001 Jan  9 09:27 case.test3.tar.gz
-rw-rw-r-- 1 bush bush 537577 Jan  9 09:50 case.test4.tar.gz
-rw-rw-r-- 1 bush bush 193256 Jan  9 10:03 case.test5.tar.gz
-rw-rw-r-- 1 bush bush 361252 Jan  9 10:27 case.test6.tar.gz
-rw-rw-r-- 1 bush bush 369806 Jan  9 10:45 case.test7.tar.gz
-rw-rw-r-- 1 bush bush 376016 Jan  9 12:06 case.test8.tar.gz
```

Perhaps the most important results for the optimized long propellant tanks are plotted in Figs. 55 and 56. These two figures show the optimized values of conductance (Fig. 55) and empty tank mass (Fig. 56) as functions of the number of strut pairs at both the aft and forward locations in the long propellant tank with "rings" of struts attached at the aft and forward junctions of the cylindrical portion of the propellant tank with the aft and forward end domes.

There are two different types of examples:

(1) a long propellant tank with two sets of struts, an "aft" set and a "forward" set. (Figs. 1 – 56 except Figs. 7 - 10 and Tables 1 - 11).

(2) a short propellant tank with one set of struts (Figs. 7 – 10, 57 – 58 and 89 - 100 and Tables 12 - 16).

TWO BIGBOSOR4/BOSDEC MODELS OF "LUMPING" THE PROPELLANT MASS INTO THE MIDDLE LAYER OF THE PROPELLANT TANK WALL

The shell-of-revolution analyzer, BIGBOSOR4, does not handle problems in which the density of the wall material varies along the meridian of a given shell segment. However, in the free vibration BIGBOSOR4 "tank" model the mass of the propellant is "lumped" into one of the three layers (the middle layer) of the propellant tank wall. For the two ellipsoidal end domes the amount of propellant mass "lumped" into this middle layer (which has constant thickness) should vary along the meridian of each ellipsoidal dome because the radius from the axis of revolution to the shell wall reference surface varies along the meridian and the slope of the shell wall varies along the meridian.

The formula for the effective added mass density of the propellant, rho(add), for a shell of one layer is:

rho(add) = 0.5*(r/t) x sqrt[1.-(dr/ds)^2] x rho(fluid)

in which r = radius at a meridional point from the axis of revolution to the shell wall reference surface, t = wall thickness at that meridional point, dr/ds = derivative of r with respect to the meridional arc length "s", and rho(fluid) is the mass density of the fluid in the tank. The formula for the added mass density, rho(add), is valid for a point on the meridian, and rho(add) varies along any meridian of a shell segment in which the radius, r, varies along the meridian.

For this "tank" project only, so-called "temporary" versions of BIGBOSOR4 and SUBROUTINE BOSDEC were created. Optimized designs of most of the specific cases were found from two BIGBOSOR4/BOSDEC models:

(1) The "regular" model in which the "permanent" versions of BIGBOSOR4 and SUBROUTINE BOSDEC are used, that is, the model in which the effective density of shell wall and "lumped" propellant must be constant within each shell segment. This model is probably too conservative for a long propellant tank and is certainly too conservative for a short propellant tank.

(2) The "temporary" model in which the "temporary" versions of BIGBOSOR4 and SUBROUTINE BOSDEC are used, that is, the model in which the effective density of shell wall and "lumped" propellant can vary along the meridian within each shell segment.

APPENDIX 2 lists the FORTRAN differences between the "regular" (permanent) model and the "temporary" model.

When we refer to "permanent" and "temporary" BIGBOSOR4 models in this context we are referring ONLY to the version of BIGBOSOR4 that is used in connection with GENOPT, that is, in what is called in this report the "GENOPT/BIGBOSOR4" complex. The version of BIGBOSOR4 that is used in connection with the many files with names such as "test.BEHX11", "test.BEHX12", etc. is the "stand-alone" version. The "stand-alone" version is never changed; it is the version of BIGBOSOR4 that is distributed to users around the world.

The "regular" BIGBOSOR4 model in the GENOPT/BIGBOSOR4 complex is stored in the files called addbosor4.regular and bosdec.tank. The "temporary" model is stored in the files called addbosor4.density.var and bosdec.density.var.

In order to execute GENOPT/BIGBOSOR4 with the "regular" (permanent) model, type the following:

```
cp /home/progs/genopt/case/tank/addbosor4.regular /home/progs/bosdec/sources/addbosor4.src
cp /home/progs/genopt/case/tank/bosdec.tank /home/progs/bosdec/sources/bosdec.src
```

then, in the "genoptcase" directory, execute the GENOPT processor called "genprograms" as follows:

/home/progs/genoptcase/genprograms

then run the specific case with use of the "regular" model that has been compiled by the GENOPT processor called "genprograms".

In order to execute GENOPT/BIGBOSOR4 with the "temporary" model, type the following:

cp /home/progs/genopt/case/tank/addbosor4.density.var /home/progs/bosdec/sources/addbosor4.src
cp /home/progs/genopt/case/tank/bosdec.density.var /home/progs/bosdec/sources/bosdec.src

then execute "genprograms" as follows:

/home/progs/genoptcase/genprograms

then run the specific case with use of the "temporary" model that has been compiled by the GENOPT processor called "genprograms".

*************** IMPORTANT NOTE *******************
The temporary versions of BIGBOSOR4 and BOSDEC, when executed with ITYPE = 2 (fixed design) in the *.OPT file, produce the files, *.BEHXxxx, just as do the permanent versions of BIGBOSOR4 and BOSDEC. However, it is emphasized that the two files pertaining to free vibration of the tank/strut system, *.BEHX11 and *.BEHX12, when used as input files for the "stand-alone" version of BIGBOSOR4 in the analyses described in the file, bigbosor4.input.test.BEHX.files, produce inappropriate results because the effective mass of the tank wall does not include the "lumped" mass of the propellant whenever the *.BEHX11 and *.BEHX12 files have been generated via the temporary versions of BIGBOSOR4 and BOSDEC. Therefore, what you must NEVER do is generate the *.BEHX11 and *.BEHX12 files with use of the temporary BIGBOSOR4 and BOSDEC, then run the "stand-alone" BIGBOSOR4 (which is always the permanent version of BIGBOSOR4 that is distributed worldwide) using those *.BEHX11 and *.BEHX12 files as input to the stand-alone version of BIGBOSOR4. All of the other *.BEHXxxx files generated via the temporary versions of BIGBOSOR4 and BOSDEC are okay because those models do not involve "lumping" the propellant mass into the middle layer of the tank wall. In order to get appropriate plots of the free vibration modes, you must generate appropriate *.BEHX11 and *.BEHX12 files by first copying the "permanent" versions of addbosor4 (addbosor4.regular) and bosdec (bosdec.tank) into ../bosdec/sources/addbosor4.src and ..bosdec/sources/bosdec.src, respectively, then run "genprograms", and then execute the case called "*" with use of ITYPE=2 in the *.OPT file.

Then, when you follow the directions listed in the file, bigbosor4.input.test.BEHX.files, you will obtain the plots you want.
****

FINDING THE OPTIMUM DESIGNS

The following points pertain to optimization of the tank/strut system:

1. The objective function is in general a compound objective as follows:

objective = W x (empty tank mass)/(nominal empty tank mass)
(1.-W) x (total strut conductance)/(nominal conductance)

in which W, (nominal empty tank mass) and (nominal conductance) are input variables supplied by the End user during the "BEGIN" interactive session. See the test.BEG file listed in Table 4. In Table 4 "W" is called "WGT", (nominal empty tank mass) is called "TNKNRM", and (nominal conductance) is called "CONNRM". (NOTE: In the input file, test.BEG (Table 4), there is a small error: the quantity, TNKNRM, is defined as "empty tank weight" when it should be defined as "empty tank mass". This error has been corrected in the generic input file, tank.INP. Therefore, future cases started from scratch will have the correct definition of TNKNRM.) If W (that is, WGT) equals zero the objective is simply the (total strut conductance), which is called CONDCT in the output. The "total strut conductance" is the conductance of one strut in each strut set times the number of struts in that strut set summed over the number of strut sets [either one strut set or two strut sets (aft and forward) in this work].

2. Optimization is carried out with W (that is, WGT) equal to 0.5. The curing temperature, TEMTUR, of a laminated composite strut tube is arbitrarily taken to be 170 degrees. Experience with optimizing tank/strut systems during this effort demonstrated that, for some unknown reason, the use of a non-zero value of TEMTUR seems to lead to a "global" optimum design with a smaller (better) objective than does the use of TEMTUR = 0. Therefore, in future optimizations of tank/strut systems, please always use a significant non-zero value for the variable called TEMTUR.

3. The GENOPT processor called SUPEROPT is executed. If there are two sets, aft and forward, of struts one SUPEROPT execution allowed to run to completion (about 470 design iterations) requires a little more than 24 hours on the writer's very fast computer. However, SUPEROPT executions may be terminated early in order to save calendar time. This was done in most of the specific cases because the writer felt that a good "global" optimum design had already been found. He did not want to wait 24 hours for the SUPEROPT process to finish on its own.

4. In this study GENOPT often has a difficult time finding a "global" optimum design. The SUPEROPT process often converges several times to objectives that are significantly higher than that corresponding to the "best" design, that is, the lowest objective for a design that is either "FEASIBLE" or "ALMOST FEASIBLE". Figures 29, 57, 58, 59, 59b and 86 demonstrate this characteristic.

5. The "global" optimum design of the tank/strut system with two sets of struts and with four pairs of struts at each axial location, aft and forward, was determined first. In this specific case, called "test", the SUPEROPT execution was allowed to run to a natural completion (470 design iterations, about 24 hours). Optimum designs were then determined for other specific cases in a sequence such as the following:

a. The specific case called "test4" (two sets of struts with five pairs of struts at each axial location). Except for the values of AGRND(1) and AGRND(2), the starting design of "test4" is the optimum design of "test" (two sets of struts with 4 pairs of struts at each axial location). AGRND(1) and AGRND(2), defined in the test.BEG file as 'circ.angle to pinned "ground" end of strut', are each changed from 45 degrees (which is the upper bound required for proper clearance when there are 4 pairs of struts at each axial location) to 36 degrees (which is the upper bound required for proper clearance when there are 5 pairs of struts at each axial location).

b. The specific case called "test6" (two sets of struts with six pairs of struts at each axial location). Except for the values of AGRND(1) and AGRND(2), the starting design of "test6" is the optimum design of "test5" (two sets of struts with 5 pairs of struts at each axial location). AGRND(1) and AGRND(2) are each changed from 36 degrees (which is the upper bound required for proper clearance when there are 5 pairs of struts at each axial location) to 30 degrees (which is the upper bound required for proper clearance when there are 6 pairs of struts at each axial location).

c. As with "a." and "b." for the specific cases called "test7" and "test8", except that starting values of AGRND(1) and AGRND(2) are each set to 25.7143 degrees in "test7" and to 22.5 degrees in "test8". The starting design for "test7" is the optimum design found for "test6", and the starting design for "test8" is the optimum design found from "test7".

d. The specific case called "test3" (two sets of struts with three pairs of struts at each axial location). Except for the values of AGRND(1) and AGRND(2), the starting design of "test3" is the optimum design of "test" (two sets of struts with 4 pairs of struts at each axial location). AGRND(1) and AGRND(2) are each changed from 45 degrees (which is the upper bound required for proper clearance when there are 4 pairs of struts at each axial location) to 60 degrees (which is the upper bound required for proper clearance when there are 3 pairs of struts at each axial location).

e. The case called "test5" is "anomalous" because the ends of the struts attached to the propellant tank are attached within the aft and forward domes rather than at the aft and forward dome/cylinder junctions. The optimum design of "test5" (five pairs of struts at each of the aft and forward axial locations) is very poor, that is, the empty tank mass and total conductance are unacceptably high, presumably because the struts are longer and therefore buckle as columns more easily and the dome is more flexible than the dome/cylinder junction.

f. The case called "test1" is somewhat "anomalous" because there are only two pairs of struts at each axial location, aft and forward. The optimum design with so few struts is very poor for two reasons: the empty tank mass and total conductance are unacceptably high, and there are significant clearance problems where each strut is joined to the propellant tank.

SOME DETAILS PERTAINING TO THE SPECIFIC CASE CALLED "test"

This case is for a long propellant tank supported by two sets of struts, an aft set located at the junction of the aft dome and the cylindrical portion of the tank and a forward set located at the junction of the forward dome and the cylindrical portion of the tank. There are 4 pairs of struts in the aft set and 4 pairs of struts in the forward set. Figures 4 - 6, 19 - 28, and 32 - 54 pertain to this optimized tank/strut system.

Of particular interest is the effect of propellant tank flexibility on the "effective" spring constant of the supporting struts. This effect can be ascertained from part of the output listed in Table 8:

For Load Case 1 (PRESS = 25 psi, GAXIAL = 10g, GLATRL = 0g, TNKCOOL=-200 degrees):

Spring constant for compound strut type 1 (aft strut set) = 1.8040E+05
Spring constant including tank flexibility: FKTOTL(JRING) = 0.8666E+05
Spring constant for compound strut type 2 (fwd strut set) = 1.9366E+05
Spring constant including tank flexibility: FKTOTL(JRING) = 1.3744E+05

For Load Case 2 (PRESS = 25 psi, GAXIAL = 0g, GLATRL = 10g, TNKCOOL=-200 degrees):
Spring constant for compound strut type 1 (aft strut set) = 1.8040E+05
Spring constant including tank flexibility: FKTOTL(JRING) = 1.1607E+05
Spring constant for compound strut type 2 (fwd strut set) = 1.9366E+05
Spring constant including tank flexibility: FKTOTL(JRING) = 1.1149E+05

The "Spring constant for compound strut type..." is the spring constant neglecting flexibility of the propellant tank. This is the spring constant of a three-segment (compound) strut: segment 1 is the end fitting at the propellant tank end of the strut; segment 2 is the laminated composite strut tube; segment 3 is the end fitting at the launch vehicle ("ground") end of the strut.

At the optimum the flexibility of the tank has a significant effect on the "effective" axial stiffness of the struts. Note that the effective stiffness of the struts (strut stiffness, FKTOTL, that includes the effect of flexibility of the propellant tank) depends on the loading. In the models for free vibration the first four design margins are different for Load Cases 1 and 2 because of this dependence of strut effective stiffness on loading.

Therefore, long propellant tanks with ellipsoidal domes that are similar to the case called "test" probably should be optimized with the use of the temporary versions of bigbosor4 (addbosor4.density.var) and bosdec (bosdec.density.var).

The files containing the string, "noring", correspond to a model in which there are very, very tiny propellant tank reinforcement rings (ring thickness=0.001 inch; ring height = 0.001 inch). These variables are no longer decision variables in this particular model.

The following list is a comparison for the specific case called "test" (long tank with aft and forward "rings" of struts, 4 strut pairs at each axial station) of free vibration frequencies from the model in which the density must be constant in each shell segment [BIGBOSOR4(permanent=addbosor4.regular); bosdec(permanent=bosdec.tank)] and the model in which the density may vary within a shell segment [BIGBOSOR4(temporary=addbosor4.density.var); bosdec(temporary=bosdec.density.var)] for the optimized design obtained with use of the temporary versions of BIGBOSOR4 and BOSDEC (the optimized design listed in the old version of Table 8, which is not included here.)
==
BIGBOSOR4 input file for: free vibration frequencies for Load Case 1 test.BEHX11

Permanent BIGBOSOR4 and BOSDEC used on the optimized configuration (old version of Table 8, which is not included here) determined with use of the temporary BIGBOSOR4 and BOSDEC:

```
 FREE VIBRATION FREQUENCIES AND MODES (BEHX1)
  1.1309E+01(n= 0 circ.waves)  1.7409E+01(n= 0 circ.waves)
  1.1025E+01(n= 1 circ.waves)  1.3678E+01(n= 1 circ.waves)
    1        11.30903      free vibration frequency (cps): FREQ(1 ,1 )
    2        11.02544      free vibration frequency (cps): FREQ(1 ,2 )
    3        17.40943      free vibration frequency (cps): FREQ(1 ,3 )
```

```
    4        13.67849      free vibration frequency (cps): FREQ(1 ,4 )
```

Temporary BIGBOSOR4 and BOSDEC used on the optimized configuration (old version of Table 8, which is not included here) determined with use of the temporary BIGBOSOR4 and BOSDEC:

```
 FREE VIBRATION FREQUENCIES AND MODES (BEHX1)
  1.2385E+01(n= 0 circ.waves)  1.7936E+01(n= 0 circ.waves)
  1.1969E+01(n= 1 circ.waves)  1.6021E+01(n= 1 circ.waves)
    1        12.38532      free vibration frequency (cps): FREQ(1 ,1 )
    2        11.96929      free vibration frequency (cps): FREQ(1 ,2 )
    3        17.93631      free vibration frequency (cps): FREQ(1 ,3 )
    4        16.02133      free vibration frequency (cps): FREQ(1 ,4 )
```

BIGBOSOR4 input file for: free vibration frequencies for Load Case 2 test.BEHX12

Permanent BIGBOSOR4 and BOSDEC used on the optimized configuration (old version of Table 8, which is not included here) determined with use of the temporary BIGBOSOR4 and BOSDEC:

```
 FREE VIBRATION FREQUENCIES AND MODES (BEHX1)
  1.0957E+01(n= 0 circ.waves)  1.6899E+01(n= 0 circ.waves)
  1.1222E+01(n= 1 circ.waves)  1.2663E+01(n= 1 circ.waves)
    1        10.95683      free vibration frequency (cps): FREQ(2 ,1 )
    2        11.22175      free vibration frequency (cps): FREQ(2 ,2 )
    3        16.89865      free vibration frequency (cps): FREQ(2 ,3 )
    4        12.66339      free vibration frequency (cps): FREQ(2 ,4 )
```

Temporary BIGBOSOR4 and BOSDEC used on the optimized configuration (old version of Table 8, which is not included here) determined with use of the temporary BIGBOSOR4 and BOSDEC:

```
 FREE VIBRATION FREQUENCIES AND MODES (BEHX1)
  1.1994E+01(n= 0 circ.waves)  1.7416E+01(n= 0 circ.waves)
  1.1991E+01(n= 1 circ.waves)  1.5089E+01(n= 1 circ.waves)
    1        11.99376      free vibration frequency (cps): FREQ(2 ,1 )
    2        11.99098      free vibration frequency (cps): FREQ(2 ,2 )
    3        17.41608      free vibration frequency (cps): FREQ(2 ,3 )
    4        15.08925      free vibration frequency (cps): FREQ(2 ,4 )
=================================================================
```

The free vibration frequencies from the permanent version of BIGBOSOR4 are significantly but not dramatically lower than those obtained with use of the temporary version of BIGBOSOR4.

COMPARISON OF EMPTY TANK MASS AND TOTAL STRUT CONDUCTANCE FOR THE LONG PROPELLANT TANK WITH TWO "RINGS" OF STRUTS

In the following table are compared the empty tank mass and the total conductance of the strut support system for the cases "test", "test1", "test3", "test4", "test5", "test6", "test7" and "test8" for the optimized designs.

All of these cases except for the case called "test5" pertain to the long propellant tank with two sets of struts, the aft set at the junction of the aft dome and the cylindrical part and the forward set at the junction of the forward dome and the cylindrical part (Fig.4). In the case, "test5" the strut ends at the propellant tank are located within the aft dome and within the forward dome (Fig. 9).

```
OLD RESULTS (BEFORE FEBRUARY 2012 MODIFICATIONS) FOR
EMPTY TANK MASS AND TOTAL STRUT SYSTEM CONDUCTANCE
FOR THE LONG PROPELLANT TANK WITH 2 SETS OF STRUTS
(AFT SET AND FORWARD SET), EACH SET LOCATED AT THE
JUNCTION OF THE MIDDLE CYLINDRICAL PART OF THE TANK
WITH ONE OF THE ELLIPSOIDAL END DOMES EXCEPT FOR
"test5", FOR WHICH THE TANK ENDS ARE WITHIN THE DOMES.
=====================================================
Case   Description    Empty tank        Conductance
                         mass
                      lb-sec^2/in       BTU/hr-deg.R
----------------------------------------------------
test optimized with permanent BIGBOSOR4 and BOSDEC:
(curing temperature of composite strut tubes, TEMTUR=0.)
test    4 strut pairs   9.3664          0.0025406
         (no rings)

test optimized with permanent BIGBOSOR4 and BOSDEC:
(curing temperature of composite strut tubes, TEMTUR=0.)
test    4 strut pairs   5.5513          0.0020818
         (with rings)

test optimized with permanent BIGBOSOR4 and BOSDEC:
(curing temperature of composite strut tubes, TEMTUR=170.)
test    4 strut pairs   5.5134          0.0021300
         (with rings)

test optimized with temporary BIGBOSOR4 and BOSDEC:
(curing temperature of composite strut tubes, TEMTUR=0.)
test    4 strut pairs   4.6516          0.0018227
         (with rings)

test optimized with temporary BIGBOSOR4 and BOSDEC:
(curing temperature of composite strut tubes, TEMTUR=170.)
test    4 strut pairs   4.6484          0.0018759
         (with rings)

test optimized with temporary BIGBOSOR4 and BOSDEC:
(curing temperature of composite strut tubes, TEMTUR=170.)
(Full execution of SUPEROPT, that is, 470 design iterations)
test    4 strut pairs   4.9142          0.0017692
         (with rings)

test2   4 strut pairs  (This is the short tank.
```

```
                 Therefore results for test2
                 are not listed in this table.)

test1 optimized with permanent BIGBOSOR4 and BOSDEC:
(curing temperature of composite strut tubes, TEMTUR=0.)
test1     2 strut pairs  24.784         0.0030873
          (with rings)

test3 optimized with permanent BIGBOSOR4 and BOSDEC:
(curing temperature of composite strut tubes, TEMTUR=0.)
test3     3 strut pairs  6.6057         0.0022085
          (with rings)

test3 optimized with temporary BIGBOSOR4 and BOSDEC:
(curing temperature of composite strut tubes, TEMTUR=0.)
test3     3 strut pairs  5.2435         0.0015765
          (with rings)

test3 optimized with permanent BIGBOSOR4 and BOSDEC:
(curing temperature of composite strut tubes, TEMTUR=0.)
test3     3 strut pairs  10.345         0.0017639
          (no rings)

test3 optimized with temporary BIGBOSOR4 and BOSDEC:
(curing temperature of composite strut tubes, TEMTUR=0.)
test3     3 strut pairs  7.0331         0.0016244
          (no rings)

test4 optimized with permanent BIGBOSOR4 and BOSDEC:
(curing temperature of composite strut tubes, TEMTUR=0.)
test4     5 strut pairs  5.6901         0.0023736
          (with rings)

test4 optimized with temporary BIGBOSOR4 and BOSDEC:
(curing temperature of composite strut tubes, TEMTUR=0.)
test4     5 strut pairs  4.8159         0.0022724
          (with rings)

test5 optimized with permanent BIGBOSOR4 and BOSDEC:
(curing temperature of composite strut tubes, TEMTUR=0.)
test5     5 strut pairs  33.316         0.013628
          (with rings)
     (strut ends in domes: a very poor design)

test6 optimized with permanent BIGBOSOR4 and BOSDEC:
(curing temperature of composite strut tubes, TEMTUR=0.)
test6     6 strut pairs  5.8447         0.0025809
          (with rings)
```

```
test6 optimized with temporary BIGBOSOR4 and BOSDEC:
(curing temperature of composite strut tubes, TEMTUR=0.)
test6     6 strut pairs  4.6439         0.0023467
          (with rings)

test7 optimized with permanent BIGBOSOR4 and BOSDEC:
(curing temperature of composite strut tubes, TEMTUR=0.)
test7     7 strut pairs  5.7369         0.0031424
          (with rings)

test7 optimized with temporary BIGBOSOR4 and BOSDEC:
(curing temperature of composite strut tubes, TEMTUR=0.)
test7     7 strut pairs  4.8114         0.0026498
          (with rings)

test8 optimized with permanent BIGBOSOR4 and BOSDEC:
(curing temperature of composite strut tubes, TEMTUR=0.)
test8     8 strut pairs  5.8744         0.0032227
          (with rings)

test8 optimized with temporary BIGBOSOR4 and BOSDEC:
(curing temperature of composite strut tubes, TEMTUR=0.)
test8     8 strut pairs  4.7139         0.0029841
          (with rings)
=================================================
```

The cases listed above that include the string, "no rings", correspond to models in which there are very, very tiny propellant tank reinforcement rings (ring thickness = 0.001 inch; ring height = 0.001 inch).

The following comments apply to this list:

1. Probably the best design is the specific case called "test" (4 strut pairs at each axial location) optimzed with curing temperature, TEMTUR = 170 degrees, with rings, with the full execution of SUPEROPT, and with use of the "temporary" version of BIGBOSOR4/BOSDEC
(the last entry for the specific case, "test":

```
test      4 strut pairs  4.9142         0.0017692
```

2. The last two entries for the specific case, "test", are:

```
test      4 strut pairs  4.6484         0.0018759
test      4 strut pairs  4.9142         0.0017692
```

The conditions under which these two different optimum designs were finally arrived at were the same (temporary BIGBOSOR4/BOSDEC, with rings, TEMTUR=170 degrees) but the paths to each of the two different optima were different. The first optimum (empty tank mass = 4.6484 lb-sec^2/in, conductance = 0.0018750 BTU/hr-deg.R) was arrived at by first optimizing with use of the permanent version of BIGBOSOR4/BOSDEC and with TEMTUR = 0 degrees, followed by further optimization with the temporary version of BIGBOSOR4/BOSDEC and with TEMTUR = 0 degrees, followed by yet more optimization with the

temporary version of BIGBOSOR4/BOSDEC and with TEMTUR = 170 degrees. In each of these three phases of optimization the starting design of a following phase was the optimum design from the current phase. The second optimum (empty tank mass = 4.9142 lb-sec^2/in, conductance = 0.0017692 BTU/hr-deg.R) was arrived at via a single complete execution of SUPEROPT with use of the same conditions throughout, that is, just one long (24-hour) execution on the computer. It turns out that the two different optima have essentially the same objective:
First optimum objective:
objective=0.5x(4.6484/10.) +(1.-0.5)x(0.0018759/0.002) = 0.70140
Second optimum objective:
objective=0.5x(4.9142/10.) +(1.-0.5)x(0.0017692/0.002) = 0.68801

3. Use of the temporary BIGBOSOR4/BOSDEC ("exact" representation of the "lumped" propellant mass) leads to a significantly better (smaller) objective than does use of the permanent BIGBOSOR4/BOSDEC ("constant density" representation of the "lumped" propellant mass). See the section above entitled "TWO BIGBOSOR4/BOSDEC MODELS OF LUMPING THE PROPELLANT MASS" and see APPENDIX 2 for details about the two different "propellant mass lumping" models. Comparisons of GENOPT/BIGBOSOR4 predictions for optimized designs with predictions from STAGS [16-19] should therefore be carried out for the optimized design listed in Table 8, that is, the optimum design obtained for the specific case called "test" obtained with the temporary BIGBOSOR4/BOSDEC model:

```
test      4 strut pairs  4.9142         0.0017692
```

4. The presence of propellant tank support rings is important. For the specific case, "test", optimization without rings leads to an empty tank mass of 9.3664, and with rings leads to a considerably lower empty tank mass of 5.5513 lb-sec^2/inch.

5. The tank/strut system should be designed such that the ends of the struts attached to the propellant tank occur at the junctions between the end domes and the cylindrical portion of the tank, not within the end domes.

6. The influence of curing temperature, TEMTUR, on the optimum objective and on the optimum design is minor. However, it seems to be much easier to reach a "global" optimum design with TEMTUR = 170 than with TEMTUR = 0. Therefore, in future optimizations of tank/strut systems always use a significantly non-zero value for TEMTUR.

OPTIMIZED SHORT PROPELLANT TANK WITH ONE "RING" OF STRUTS WITH FOUR PAIRS OF STRUTS ATTACHED TO THAT RING

Tables 12 - 16 and Figs. 7 – 10, 57, 58 and 89 - 100 pertain to this section. Tables 12 - 14 list input data for the GENOPT processors, BEGIN, DECIDE, and MAINSETUP, respectively. Table 15 lists the output for the optimized design from the GENOPT processor, OPTIMIZE, executed in a "fixed design" mode (ITYPE=2 in the test2.OPT file). Table 16 lists input data for the GENOPT processor, CHANGE, by means of which the optimized design is archived. Figures 7 - 10 show the configuration of the short tank with its single "ring" of struts for the starting design (Figs. 7 and 8) and for the optimized design (Figs. 9 and 10). Figure 57 shows the objective versus design iterations obtained with use of the temporary version of BIGBOSOR4/BOSDEC and Fig. 58 shows the same obtained with use of the permanent version of BIGBOSOR4/BOSDEC.

The optimum values of the decision variables and linked variables are as follows:

OPTIMIZED DESIGN FOUND WITH THE TEMPORARY VERSION OF BIGBOSOR4/BOSDEC AND WITH CURING TEMPERATURE, TEMTUR=170 DEGREES FOR THE SHORT PROPELLANT TANK WITH ONE RING OF STRUTS ATTACHED TO THE TANK AT THE SAME AXIAL STATION (CYLINDER MIDLENGTH) AS THAT OF THE TANK CENTER OF GRAVITY

```
---------------------------------------------------------------
  VALUES OF DESIGN VARIABLES CORRESPONDING TO BEST FEASIBLE DESIGN
 VAR.   CURRENT
 NO.     VALUE            DEFINITION
  1    2.135E-02  thickness of the tank aft dome skin: THKAFT
  2    6.672E-02  thickness of the tank cylinder skin: THKMID
  3    2.757E-02  thickness of the forward tank dome skin: THKFWD
  4    3.000E+00  spacing of the tank orthogrid stringers: STRSPC
  5    3.000E+00  spacing of the tank orthogrid rings: RNGSPC
  6    1.595E-01  thickness of the tank orthogrid stringers: STRTHK
  7    1.000E+00  height of the tank orthogrid stringers: STRHI
  8    1.634E-01  thickness of the tank orthogrid rings: RNGTHK
  9    1.000E+00  height of the tank orthogrid rings: RNGHI
 10    1.750E+02  global axial coordinate of tank support ring: ZTANK(1 )
 11    1.066E+02  global axial coordinate of "ground": ZGRND(1 )
 12    6.000E+00  circ.angle (deg.) to pinned tank end of strut: ATANK(1 )
 13    4.500E+01  circ.angle to pinned "ground" end of strut: AGRND(1 )
 14    6.277E+00  inner diam. of support tube active at launch: IDTUBE(1 )
 15    1.000E-06  height of mid-tank T-ring web: WEBHI
 16    1.000E-06  thickness of mid-tank T-ring web: WEBTHK
 17    1.000E-06  width (height) of mid-tank T-ring flange: FLGHI
 18    1.000E-06  thickness of mid-tank T-ring flange: FLGTHK
 19    3.000E+01  axial length of the propellant tank doubler: DUBAXL(1 )
 20    1.810E-01  max.thickness of the propellant tank doubler: DUBTHK(1 )
 21    1.000E-01  thickness of the tank reinforcement ring: TRNGTH(1 )
 22    5.000E-01  height of the tank reinforcement ring: TRNGHI(1 )
 23    5.000E-03  thickness of a lamina: THICK(1 )
 24    5.000E-03  thickness of a lamina: THICK(2 )
 25    5.000E-03  thickness of a lamina: THICK(3 )
 26    5.000E-03  thickness of a lamina: THICK(4 )
 27    5.000E-03  thickness of a lamina: THICK(5 )
 28    5.000E-03  thickness of a lamina: THICK(6 )
 29    1.726E+01  layup angle: ANGLE(1 )
 30   -1.726E+01  layup angle: ANGLE(2 )
 31    6.701E+01  layup angle: ANGLE(3 )
 32   -6.701E+01  layup angle: ANGLE(4 )
 33    1.000E+01  layup angle: ANGLE(5 )
 34   -1.000E+01  layup angle: ANGLE(6 )
----------------------------------------------------------------------
```

The values just listed correspond to the optimum design of the specific case called "test2". Figures 7 - 10 and 57 - 58 pertain to this optimized short tank/strut system.

************************ NOTE **************************
The predictions from GENOPT/BIGBOSOR4 for this configuration, also listed in Table 15, should be compared with predictions from STAGS [16-19].
****

During optimization, design margins are computed for each of the two load cases for each optimization cycle. In the work reported here design margins are computed for each of the two load cases listed above in the section entitled "TWO LOAD CASES".

For example, the design margins computed for the optimized tank/strut system for the short tank with one "ring" of struts are as follows for the specific case called "test2" (4 pairs of struts in each "ring" of struts):

DESIGN MARGINS FOR THE OPTIMIZED DESIGN FOR LOAD CASES 1 AND 2 (from Table 15)

```
-----------------------------------------------------------------
 ***** RESULTS FOR LOAD SET NO.  1 (axial acceleration = 10g) ******
 MARGINS CORRESPONDING TO CURRENT DESIGN (F.S.= FACTOR OF SAFETY)

MARGIN CURRENT
 NO.     VALUE            DEFINITION
  1    3.336E-01  (FREQ(1 ,1 )/FREQA(1 ,1 )) / FREQF(1 ,1 )-1; F.S.=  1.20
  2    1.577E-01  (FREQ(1 ,2 )/FREQA(1 ,2 )) / FREQF(1 ,2 )-1; F.S.=  1.20
  3    2.453E+00  (FREQ(1 ,3 )/FREQA(1 ,3 )) / FREQF(1 ,3 )-1; F.S.=  1.20
  4    2.454E+00  (FREQ(1 ,4 )/FREQA(1 ,4 )) / FREQF(1 ,4 )-1; F.S.=  1.20
  5    1.658E+01  (STRES1A(1 ,1 )/STRES1(1 ,1 )) / STRES1F(1 ,1 )-1; F.S.=  1.50
  6    1.072E+00  (STRES1A(1 ,2 )/STRES1(1 ,2 )) / STRES1F(1 ,2 )-1; F.S.=  1.50
  7    6.601E-01  (STRES1A(1 ,3 )/STRES1(1 ,3 )) / STRES1F(1 ,3 )-1; F.S.=  1.50
  8    3.348E+00  (STRES1A(1 ,5 )/STRES1(1 ,5 )) / STRES1F(1 ,5 )-1; F.S.=  1.50
  9    9.285E-01  (COLBUK(1 ,1 )/COLBUKA(1 ,1 )) / COLBUKF(1 ,1 )-1; F.S.=  1.00
 10    4.434E-01  (SHLBUK(1 ,1 )/SHLBUKA(1 ,1 )) / SHLBUKF(1 ,1 )-1; F.S.=  2.00
 11    5.237E+00  (FORCEA(1 ,1 )/FORCE(1 ,1 )) / FORCEF(1 ,1 )-1; F.S.=  1.00
 12   -4.748E-03  (TNKSTRA(1 ,1 )/TNKSTR(1 ,1 )) / TNKSTRF(1 ,1 )-1; F.S.=  1.00
 13    6.676E+00  (TNKBUK(1 ,1 )/TNKBUKA(1 ,1 )) / TNKBUKF(1 ,1 )-1; F.S.=  1.00

 ***** RESULTS FOR LOAD SET NO.  2 (lateral acceleration = 10g) ******
 MARGINS CORRESPONDING TO CURRENT DESIGN (F.S.= FACTOR OF SAFETY)

MARGIN CURRENT
 NO.     VALUE            DEFINITION
  1    1.538E-01  (FREQ(2 ,1 )/FREQA(2 ,1 )) / FREQF(2 ,1 )-1; F.S.=  1.20
  2    4.052E-03  (FREQ(2 ,2 )/FREQA(2 ,2 )) / FREQF(2 ,2 )-1; F.S.=  1.20
  3    2.413E+00  (FREQ(2 ,3 )/FREQA(2 ,3 )) / FREQF(2 ,3 )-1; F.S.=  1.20
  4    2.424E+00  (FREQ(2 ,4 )/FREQA(2 ,4 )) / FREQF(2 ,4 )-1; F.S.=  1.20
  5    8.521E-01  (STRES1A(2 ,1 )/STRES1(2 ,1 )) / STRES1F(2 ,1 )-1; F.S.=  1.50
  6    4.794E-01  (STRES1A(2 ,2 )/STRES1(2 ,2 )) / STRES1F(2 ,2 )-1; F.S.=  1.50
  7   -6.558E-04  (STRES1A(2 ,3 )/STRES1(2 ,3 )) / STRES1F(2 ,3 )-1; F.S.=  1.50
  8    1.412E+00  (STRES1A(2 ,5 )/STRES1(2 ,5 )) / STRES1F(2 ,5 )-1; F.S.=  1.50
  9   -2.890E-03  (COLBUK(2 ,1 )/COLBUKA(2 ,1 )) / COLBUKF(2 ,1 )-1; F.S.=  1.00
 10    1.532E-03  (SHLBUK(2 ,1 )/SHLBUKA(2 ,1 )) / SHLBUKF(2 ,1 )-1; F.S.=  2.00
 11    5.237E+00  (FORCEA(2 ,1 )/FORCE(2 ,1 )) / FORCEF(2 ,1 )-1; F.S.=  1.00
 12   -7.983E-03  (TNKSTRA(2 ,1 )/TNKSTR(2 ,1 )) / TNKSTRF(2 ,1 )-1; F.S.=  1.00
 13    6.927E+00  (TNKBUK(2 ,1 )/TNKBUKA(2 ,1 )) / TNKBUKF(2 ,1 )-1; F.S.=  1.00
-----------------------------------------------------------------------------
```

The following list, pertaining to the short propellant tank with one "ring" of struts, is analogous to a similar but much longer list above that pertains to the long propellant tank with two "rings" of struts.

OLD RESULTS (BEFORE FEBRUARY 2012 MODIFICATIONS) FOR
EMPTY TANK MASS AND TOTAL STRUT SYSTEM CONDUCTANCE
FOR THE SHORT PROPELLANT TANK WITH 1 SET OF STRUTS,
THAT SET LOCATED AT THE MIDLENGTH OF THE CYLINDRICAL
PART OF THE TANK

```
=================================================
Case    Description     Empty tank      Conductance
                           mass
                        lb-sec^2/in     BTU/hr-deg.R
------------------------------------------------------
test2 optimized with permanent BIGBOSOR4 and BOSDEC:
(curing temperature of composite strut tubes, TEMTUR=170.)
test2    4 strut pairs   3.0059          0.00077727
         (with rings)

test2 optimized with temporary BIGBOSOR4 and BOSDEC:
(curing temperature of composite strut tubes, TEMTUR=0.)
test2    4 strut pairs   1.7216          0.00056055
         (with rings)

test2 optimized with temporary BIGBOSOR4 and BOSDEC:
(curing temperature of composite strut tubes, TEMTUR=170.)
(Full execution of SUPEROPT, that is, 470 design iterations)
test2    4 strut pairs   1.7442          0.00055640
         (with rings)

test2 optimized with temporary BIGBOSOR4 and BOSDEC:
(curing temperature of composite strut tubes, TEMTUR=170.)
test2    4 strut pairs   2.6036          0.00059916
         (no rings)
=======================================================
```

The case listed above that includes the string, "no rings", corresponds to a model in which there is a very, very tiny propellant tank reinforcement ring (ring thickness=0.001 inch; ring height = 0.001 inch).

Of particular interest is the effect of propellant tank flexibility on the "effective" spring constant of the supporting struts. This effect can be ascertained from part of the output listed in Table 15:

For Load Case 1 (PRESS = 25 psi, GAXIAL = 10g, GLATRL = 0g, TNKCOOL=-200 degrees):
Spring constant for compound strut type 1 (aft strut set) = 1.2355E+05
Spring constant including tank flexibility: FKTOTL(JRING) = 1.1023E+05

For Load Case 2 (PRESS = 25 psi, GAXIAL = 0g, GLATRL = 10g, TNKCOOL=-200 degrees):
Spring constant for compound strut type 1 (aft strut set) = 1.2355E+05
Spring constant including tank flexibility: FKTOTL(JRING) = 0.82144E+05

The "Spring constant for compound strut type..." is the spring constant neglecting flexibility of the propellant tank. This is the spring constant of a three-segment (compound) strut: segment 1 is the end fitting at the propellant tank end of the strut; segment 2 is the laminated composite strut tube; segment 3 is the end fitting at the launch vehicle ("ground") end of the strut.

At the optimum the flexibility of the tank has a significant effect on the "effective" axial stiffness of the struts. Note that the effective stiffness of the struts (strut stiffness, FKTOTL, that includes the effect of flexibility of the propellant tank) depends on the loading. In the models for free vibration the first four design margins are different for Load Cases 1 and 2 because of this dependence of strut effective stiffness on loading.

There follows a comparison for the specific case called "test2" (short tank with one "ring" of struts at the cylinder midlength, 4 strut pairs at each axial station) of free vibration frequencies from the model in which the density must be constant in each shell segment [BIGBOSOR4(permanent=addbosor4.regular); bosdec(permanent=bosdec.tank)] and the model in which the density may vary within a shell segment [BIGBOSOR4(temporary=addbosor4.density.var); bosdec(temporary=bosdec.density.var)] for the optimized design obtained with use of the temporary versions of BIGBOSOR4 and BOSDEC (the optimized design listed in the old version of Table 15, which is not included here)
==
BIGBOSOR4 input file for: free vibration frequencies for Load Case 1
test.BEHX11

Permanent BIGBOSOR4 and BOSDEC used on the optimized configuration (the old version of Table 15, which is not included here) determined with use of the temporary BIGBOSOR4 and BOSDEC:

```
 FREE VIBRATION FREQUENCIES AND MODES (BEHX1)
  1.3297E+01(n= 0 circ.waves)  1.9391E+01(n= 0 circ.waves)
  1.0807E+01(n= 1 circ.waves)  1.2920E+01(n= 1 circ.waves)
    1        13.29678      free vibration frequency (cps): FREQ(1 ,1 )
    2        10.80678      free vibration frequency (cps): FREQ(1 ,2 )
    3        19.39077      free vibration frequency (cps): FREQ(1 ,3 )
    4        12.91987      free vibration frequency (cps): FREQ(1 ,4 )
```

Temporary BIGBOSOR4 and BOSDEC used on the optimized configuration (the old version of Table 15, which is not included here) determined with use of the temporary BIGBOSOR4 and BOSDEC:

```
 FREE VIBRATION FREQUENCIES AND MODES (BEHX1)
  1.7312E+01(n= 0 circ.waves)  2.2026E+01(n= 0 circ.waves)
  1.3721E+01(n= 1 circ.waves)  1.6808E+01(n= 1 circ.waves)
    1        17.31188      free vibration frequency (cps): FREQ(1 ,1 )
    2        13.72076      free vibration frequency (cps): FREQ(1 ,2 )
    3        22.02610      free vibration frequency (cps): FREQ(1 ,3 )
    4        16.80794      free vibration frequency (cps): FREQ(1 ,4 )
```

BIGBOSOR4 input file for: free vibration frequencies for Load Case 2
test.BEHX12

Permanent BIGBOSOR4 and BOSDEC used on the optimized configuration (the old version of Table 15, which is not included here) determined with use of the temporary BIGBOSOR4 and BOSDEC:

```
 FREE VIBRATION FREQUENCIES AND MODES (BEHX1)
  1.1623E+01(n= 0 circ.waves)  1.6794E+01(n= 0 circ.waves)
  9.3964E+00(n= 1 circ.waves)  1.1297E+01(n= 1 circ.waves)
    1        11.62337      free vibration frequency (cps): FREQ(2 ,1 )
    2        9.396413      free vibration frequency (cps): FREQ(2 ,2 )
    3        16.79353      free vibration frequency (cps): FREQ(2 ,3 )
    4        11.29723      free vibration frequency (cps): FREQ(2 ,4 )
```

Temporary BIGBOSOR4 and BOSDEC used on the optimized configuration (the old version of Table 15, which is not included here) determined with use of the temporary BIGBOSOR4 and BOSDEC:

```
 FREE VIBRATION FREQUENCIES AND MODES (BEHX1)
  1.4972E+01(n= 0 circ.waves)  1.9034E+01(n= 0 circ.waves)
  1.1892E+01(n= 1 circ.waves)  1.4593E+01(n= 1 circ.waves)
    1        14.97199      free vibration frequency (cps): FREQ(2 ,1 )
    2        11.89236      free vibration frequency (cps): FREQ(2 ,2 )
    3        19.03422      free vibration frequency (cps): FREQ(2 ,3 )
    4        14.59312      free vibration frequency (cps): FREQ(2 ,4 )
================================================================
```

The difference between predictions from the "permanent" and "temporary" versions of BIGBOSOR4 are more dramatic for the short tank than for the long tank.

PLOTS OF DECISION VARIABLES VERSUS DESIGN ITERATIONS FOR THE LONG PROPELLANT TANK (specific case, "test") (These results are from the old version that existed before the February 2012 modifications.)

Figure 29 shows the objective versus design iterations during a naturally completed execution of SUPEROPT (470 design iterations, about 24 hours on the computer) for the case in which the curing temperature of the laminated composite struts is 170 degrees. Figure 59 shows the same, except that the starting design is the best FEASIBLE design obtained from the SUPEROPT run corresponding to the results shown in Fig. 29, and the curing temperature, TEMTUR, is now 0 degrees. During this SUPEROPT execution the design converges to several different local minima. Why is that? The results (plots) given in this section represent a rather feeble attempt to explain this characteristic, which makes it especially difficult to find a "global" optimum design.

In order to attempt to throw some light on this characteristic plots of decision variables versus design iterations are given in Figs. 60 - 83. These plots correspond to the objective plotted in Fig. 59. Figures 84 and 85 show the margins corresponding to Load Case 1 (axial acceleration=10g) and Load Case 2 (lateral acceleration=10g), respectively.

The following list briefly describes Figs. 60 - 83 and comments on the correlation with Fig. 59:

Fig.60: THKAFT remains fairly constant; no correlation
Fig.61: THKMID bounces around somewhat; fairly strong correlation
Fig.62: THKFWD bounces around quite a bit: fairly strong correlation
Fig.63: STRSPC bounces arond so much that any correlation is obscured
Fig.64: STRTHK less bouncing around but weak correlation
Fig.65: STRHI stays near its upper bound of 1.0 inch; no correlation
Fig.66: ZGRND1 bounces around alot and no visible correlation
Fig.67: ZGRND2 bounces around alot and no visible correlation
Fig.68: ATANK1 stays near its lower bound of 6.0 deg.; no correlation
Fig.69: ATANK2 stays near its lower bound of 6.0 deg.; no correlation
Fig.70: AGRND1 stays near its upper bound of 45 deg.; no correlation
Fig.71: AGRND2 stays near its upper bound of 45 deg.; no correlation
Fig.72: IDTUBE1 less bouncing around and fair correlation
Fig.73: IDTUBE2 less bouncing around and fair correlation
Fig.74: DUBTHK1 more bouncing around and not much correlation
Fig.75: TRHGTH lots of bouncing around and no visible correlation
Fig.76: THICK1 not much bouncing around and some correlation
Fig.77: THICK7 not much bouncing around and some correlation
Fig.78: ANGLE1 not much bouncing around and fairly good correlation
Fig.79: ANGLE3 most iterations at upper bound (80 deg.); no correlation
Fig.80: ANGLE5 iterations at either upper or lower bounds; good correlation
Fig.81: ANGLE7 bouncing around at the optimum; fair correlation
Fig.82: ANGLE9 bouncing around at optimum; upper or lower bounds; some correlation
Fig.83: ANGLE11 most iterations at upper bound; fair correlation

Unfortunately, there is no one influence on the values of the local minima of the objective with respect to design iterations during the execution of SUPEROPT. The decision variables, THKMID, THKFWD, ANGLE(1) and ANGLE(5) seem to have the strongest influence.

Figure 59b is derived from the same conditions as Fig. 59 except that what were formerly decision variables, ANGLE(5) and ANGLE(11), are no longer decision variables and are now each constant at 10 degrees. Unfortunately, this strategy does not eliminate the existence of multiple local converged objective minima in the case of the long propellant tank with two "rings" of struts, aft and forward. See the next section for better behavior in the case of the short propellant tank with only one "ring" of struts.

Comparison of Figs. 84 and 85 demonstrate that the 10g lateral acceleration is associated with more critical margins than the 10g axial acceleration. FEASIBLE design are those with only very, very small negative margins. (For GENOPT to accept a design as FEASIBLE the most negative margin must be greater than -0.01.)

PLOTS OF DECISION VARIABLES VERSUS DESIGN ITERATIONS FOR THE SHORT PROPELLANT TANK (specific case, "test2") (These results are from the old version that existed before the February 2012 modifications.)

Figures 57 and 58 show the objective versus SUPEROPT design iterations for the BIGBOSOR4/BOSDEC model with the "exact" propellant mass "lumping" (use of the "temporary" versions of BIGBOSOR4 and BOSDEC, that is, varying density within a shell segment, Fig.57) and with the approximate propellant tank "lumping" (use of the "permanent" versions of BIGBOSOR4 and BOSDEC, that is, constant density within a shell segment, Fig. 58). Figure 86 is very similar to Fig. 57, except that the starting design is the best FEASIBLE design determined from the SUPEROPT execution for which the objective is plotted in Fig. 57.

In this case only a single plot of decision variable versus SUPEROPT design iterations is included: that displayed in Fig. 87. The decision variable, ANGLE(5), correlates very well with the higher and lower values of the converged objective: ANGLE(5) = 10 degrees corresponds mostly to the lower value of the converged objective, and ANGLE(5) = 80 degrees corresponds mostly to the higher value of the converged objective. This correlation indicates (but does not proove) that it may be the laminated composite strut tube layup angles, especially ANGLE(5), that give rise to multiple converged minima of the objective as a function of design iterations.

Figure 88, which was generated under the same conditions as Fig. 86 except that ANGLE(5) was fixed at 10 degrees, confirms this indication. In Fig. 88 every new "starting" design ("spike" in the plot) converges to the same "global" minimum objective, not to more than one local minimum objective as is displayed in Fig. 86 and in Figs. 57 and 58.

MORE RESULTS GENERATED FOR THE OPTIMIZED SHORT TANK WITH ONE SET OF STRUTS

Figures 89 – 100 pertain to this section. All of these results are generated by GENOPT/BIGBOSOR4 after the February 2012 modifications.

SOME NOTES ABOUT RECENT CHANGES NOT REFLECTED IN THE FIGURES AND TABLES

1. On January 15, 2012, the phrase that defines the objective

was changed from:

"total conductance into the tank: CONDCT"

to

"WGTxTOTMAS/TNKNRM +(1-WGT)xCONDCT/CONNRM: CONDCT"

The newer version is still illogical because it implies that the variable called "CONDCT" is equal to the quantity called "WGTxTOTMAS/TNKNRM +(1-WGT)xCONDCT/CONNRM", which it is not, of course. CONDCT remains equal to the total conductance into the tank. The objective is equal to "WGTxTOTMAS/TNKNRM +(1-WGT)xCONDCT/CONNRM", in which WGT is the weighting quantity, TOTMAS is the empty tank mass, TNKNRM is the normalizing empty tank mass and CONNRM is the normalizing total conductance into the tank. WGT, TNKNRM and CONNRM are End-user-supplied quantities listed in Table 4, for example.

Some of the plots (e.g. Fig. 54) retain the old phrase, "total conductance into the tank: CONDCT", but any new cases run will exhibit the new phrase, "WGTxTOTMAS/TNKNRM +(1-WGT)xCONDCT/CONNRM: CONDCT".
When you see the old phrase in some of the figures, please be aware that the actual value being plotted is "WGTxTOTMAS/TNKNRM +(1-WGT)xCONDCT/CONNRM". If WGT is equal to zero the actual value being plotted is CONDCT, the total heat conductance into the propellant tank via the strut supports.

2. The phrase, "empty tank weight" in some of the tables should read "empty tank mass". The phrase, "normalizing empty tank weight" should read, "normalizing empty tank mass".

CONCLUSIONS:

1. Short propellant tanks, such as that corresponding to the specific case called "test2", must be optimized with use of the "temporary" versions of bigbosor4 (addbosor4.density.var) and bosdec (bosdec.density.var) in addition (perhaps) to the "permanent" or "regular" versions of bigbosor4 (addbosor4.regular) and bosdec (bosdec.tank). The "regular" version of bigbosor4 does not handle shell segments the material density of which varies along the meridian of a given segment of the shell of revolution (the propellant tank). As listed in APPENDIX 2, a temporary "fix" is created that is valid only for the specific case of a propellant tank modeled as a three-layered shell of revolution. The three-layered model of the propellant tank shell wall is described above.

2. Long propellant tanks, such as that corresponding to the specific case called "test", should probably be optimized with use of the "temporary" versions of bigbosor4 and bosdec. As listed above, the "temporary" versions of bigbosor4/bosdec yield significantly better (smaller) objectives than do the "permanent" versions of bigbosor4/bosdec. However, the difference is not nearly as dramatic for the long tank as it is for the short tank. For directions on how to obtain optimum designs of the tank/strut system with use of the temporary versions of BIGBOSOR4 and BOSDEC see the section entitled, "TWO BIGBOSOR4/BOSDEC MODELS OF LUMPING...".

3. Important results for the optimized long propellant tank/strut systems are plotted in Figs. 55 and 56 as functions of the number of strut pairs at each of two axial locations, aft and forward. These figures show optimized conductance (Fig. 55) and empty tank mass (Fig.56) as functions of the number of strut pairs at each of the aft and forward axial locations. The "best" optimum is probably that with four pairs of struts at each of the two axial locations.

4. All the results in this report were obtained for arbitrarily assigned material properties, overall propellant tank dimensions and launch vehicle diameter, accelerations, and factors of safety. All the results presented here were obtained from only one value of each of these quantities. (See the values listed in Table 4, for example.) Further work should be done with the use of other values for these quantities.

5. The effect of cool-down of the supporting struts was not included in this study because the bigbosor4/bosdec software is not capable of including this effect.

6. The launch vehicle from which the propellant tank/strut system is supported is assumed to be rigid. BIGBOSOR4 cannot in its present form handle the presence of springs that connect different flexible shell segments to one another.

7. It is important in free vibration models to include the flexibility of the propellant tank when computing the effective axial stiffness of a supporting strut. The effective axial strut stiffness depends on the g-loading to which the propellant tank is subjected. Therefore, the free vibration frequencies depend on that loading.

8. There are no clearance constraints introduced into the present tank/strut model. It is up to the End user to specify upper and lower bounds of decision variables that do not allow struts to pass through eachother or through the propellant tank.

9. For the particular ply properties used for the laminated composite strut tubes in this study the curing temperature, TEMTUR, has a significant effect on the values of the maximum stress components in the laminated composite strut tube walls. However, the value of TEMTUR only has a minor effect on the design of the optimized tank/strut system.

10. It is often difficult to find a "global" optimum design because the GENOPT processor, SUPEROPT, converges to multiple local minima of the objective,
WGTx(TOTMAS/TNKNRM) +(1 WGT)x(CONDCT/CONNRM).
In a limited attempt to find which decision variables have the most influence on this unfortunate behavior, it is found that the layup angle of one of the strut tube plies, ANGLE(5), appears to eliminate that behavior in optimization of the short tank and has significant influence on that behavior, but does not eliminate it, in optimization of the long tank.

11. In optimizations the End user should always assign a significant non-zero value to the composite strut tube curing temperature, TEMTUR. TEMTUR = 170 degrees is used in this study.

12. Predictions from a general-purpose code such as STAGS [16-19] should be compared with predictions for the optimized long (Table 8) and short (Table 15) propellant tanks with 4 pairs of struts and derived from the TEMPORARY versions of BIGBOSOR4/BOSDEC.
****************** NOTE *********************
In the STAGS model it would be best to reinforce each propellant tank support ring with gussets located close to and on either side of the circumferential locations where each strut is connected to that propellant tank support ring. These gussets would be included in the STAGS model in order to prevent excessive local out-of-plane bending of each propellant tank support ring. A detail of this sort cannot, of course, be included in the shell-of-revolution (bigbosor4) model of the type used here for optimization, but can and should be included in the STAGS model.
****

13. Optimizations were obtained in the presence of two load cases: a first that includes a 10g axial acceleration and a second that includes a 10g lateral acceleration. The second load case generates many more critical design margins than the first. However, 10g lateral acceleration is probably much too severe. In future optimizations the lateral acceleration should be substantially reduced and perhaps the axial acceleration should be reduced somewhat.

14. The every case processed here the laminated composite strut tube walls have a total of 12 layers with a symmetric layup: [1,2,3,4,5,6,6,5,4,3,2,1]. This seems to be suitable for a heavy, long propellant tank subjected to high axial and especially high lateral accelerations. However, for short tanks and perhaps for both long and short tanks subjected to a milder environment, it might be best to optimize with strut tubes that have a total of only eight layers with a symmetric layup: [1,2,3,4,4,3,2,1].

15. Optimizations via SUPEROPT of the long propellant tank with two "rings" of struts, aft and forward, require about 24 hours on the writer's very fast computer.

SUGGESTIONS FOR FURTHER WORK

1. The results presented here for optimized designs should be compared with predictions from the STAGS computer program or some other general-purpose computer program [16-19]. The STAGS comparisons should be made with optimum designs obtained with use of the "temporary" versions of bigbosor4 (addbosor4.density.var) and bosdec (bosdec.density.var). The best cases to start with are the optimized specific case called "test" (Table 8) and the optimized specific case called "test2" (Table 15). In each of these cases there exist four pairs of struts at each axial location.

****************** NOTE *********************
In the STAGS model it would be best to reinforce each propellant tank support ring with gussets located close to and on either side of the circumferential locations where each strut is connected to that propellant tank support ring. These gussets would be included in the STAGS model in order to prevent excessive local out-of-plane bending of each propellant tank support ring. A detail of this sort cannot, of course, be included in the shell-of-revolution (bigbosor4) model of the type used here for optimization, but can and should be included in the STAGS model.
****

2. A version of BIGBOSOR4 should be created in which springs are permitted to connect two different shell segments. Presently, one end of each spring can be connected to a shell segment but the other end of that spring must be connected to rigid ground. Then this proposed new version of BIGBOSOR4 should be used to optimize payload/strut systems in which both ends of each strut are connected to flexible shells of revolution.

3. Little has been done here to handle struts with a thermal disconnect feature (called "PODS" in [6]) or to optimize for both launch (Phase 1) and orbital (Phase 2) conditions. Perhaps new decision variables should be introduced with respect to the "thermal disconnect part" of a strut. These would typically be the ply thicknesses and layup angles of an inner laminated strut tube that has a much lower conductivity than the much bigger launch tube part of the strut. Then the tank/strut system would have to be optimized for conditions in orbit as well as for launch conditions and for launch-hold conditions.

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APPENDIX 1

The file called "computations.tank" describes the various computations performed during each analysis of the strut-supported propellant tank. The paragraphs in that file are included in the output list (*.OPM file, in which "*" denotes the End-user- selected specific name of the case, such as "test" or "test2" or "test3" or "test4") if the print index, NPRINX, is greater than or equal to 2. Here follows the contents of the file, "computations.tank":

The FORTRAN coding in SUBROUTINE STRUCT and in SUBROUTINES BEHXi, i = 1,2,...9 includes "CHAPTER" headings with brief descriptions of the calculations that follow the CHAPTER headings, as listed here:

```
=======================================================
 CHAPTER 1 (BEHX01x, x = 1,2,...; x=load case):
  Find the lengths of struts and the axial loads in the
  struts from a BIGBOSOR4 model of the propellant tank
  supported by springs with an arbitrarily assigned spring
  constant. The flexibility of the propellant tank is
  neglected, the strut end fittings are neglected, and the
  propellant tank is loaded by ullage pressure, PRESS, tank
  cool-down, TNKCOOL, axial acceleration, GAXIAL, and lateral
  acceleration, GLATRL. This is a first approximation.
  The BIGBOSOR4 model is stored in *.BEHX01x, x = 1, 2...,
  in which "x" represents the load case.
----------------------------------------------------------

  CHAPTER 2:
  Optain PostScript plot files, *.PL6.ps, *.PL7.ps, *.PL8.ps,
```

which contain a plan view of the AFT set of struts (*.PL6.ps), a plan view of the FORWARD set of struts (*.PL7.ps, if any), and an elevation view of both AFT and FORWARD sets of struts (*.PL8.ps). The FORTRAN software is "borrowed" from the "DEWAR" system (SUBROUTINE STPLOT and the subroutines called by STPLOT). These FORTRAN subroutines are part of the bosdec.tank library.

CHAPTER 3 (BEHX02x, x=1,2,...; x=load case):

1. Fill the "DEWAR" labelled common blocks with the proper quantities so that buckling load factors of the strut launch tubes (buckling as thin shells) and so that the 5 stress components in composite laminate plies can be determined from "PANDA-type" of analyses similar to those analyses that are used in the "DEWAR" system for buckling and stress of the strut launch tubes.

2. Compute from SUBROUTINE GETCIJ the 6 x 6 constitutive stiffness matrix for each type of strut tube. SUBROUTINE GETCIJ is very like a subroutine of the same name in PANDA2.

3. Find the axial stiffnesses of aft and forward strut tubes. These strut tube stiffnesses are to be used in the computation of spring constants associated with each strut in the AFT set of struts and associated with each strut in the FORWARD set of struts (if any). In the "DO 20" loop of SUBROUTINE STRUCT, I = 1 corresponds to the AFT set of struts and I = 2 corresponds to the FORWARD set of struts.

CHAPTER 4 (BEHX03x, x = 1,2,...; x=load case):

Compute the linear static response of the propellant tank to concentrated loads applied by the struts (springs) to the tank along the tank support ring no. 1 (aft strut set) and along the tank support ring no. 2 (forward strut set). In this BIGBSOSOR4 model of the propellant tank the springs (struts) are replaced by concentrated loads obtained from the CHAPTER 1 computations. The concentrated loads are modeled in BIGBOSOR4 as line loads with little triangular "pulses" centered about the circumferential angles where the struts are pinned to the propellant tank and at the global axial coordinates that corresponds to the global axial coordinates of the centroids of the aft and forward propellant tank support rings. The circumferential distributions of the line loads are expanded in Fourier series, and the static response to each Fourier component is superposed by BIGBOSOR4 in what is called in BIGBOSOR4 jargon an "INDIC=3" type of analysis.

Sixty Fourier terms are used in the Fourier series expansion.

The purpose of this calculation is to find the maximum displacement of the propellant tank wall in the same direction as the axis of one of the struts: 1. the strut associated with the greatest tank wall displacement produced by the AFT strut set and 2. the strut associated with the greatest tank wall displacement produced by the FORWARD strut set. These two maximum local tank wall displacements are used in the determination of the spring constants to be associated with each of the AFT struts and with each of the FORWARD struts in the models in which the flexibility of the propellant tank is accounted for in the computation of the behavior(e.g.vibration)

In this BIGBOSOR4 model there exist "fake" springs, that is, springs with zero axial stiffness. These "fake" springs have no influence on the behavior.

CHAPTER 5 (BEHX04x, x = 1, 2,...; x = load case):
Repeat the CHAPTER 1 type of computations with the new (significantly smaller) spring constants that now account for the flexibility of the propellant tank. The purpose of this computation is to determine more accurate values of the loads in each strut (spring) caused by the loads, PRESS, GAXIAL, GLATRL, and TNKCOOL. The updated strut loads are used in the following computations:

1. Buckling of the most highly compressed strut of each type (type 1 = "AFT"; type 2 = "FORWARD") as a column (BEHX5) and as a shell (BEHX6).
2. Maximum of each of five stress components in each type of strut (BEHX2 for AFT struts and BEHX3 for FORWARD struts).
3. Maximum stress in the propellant tank due to loading by the AFT and FORWARD sets of struts and by the loads, PRESS, GAXIAL, GLATRL, and TNKCOOL (BEHX8).
4. Minimum buckling of the propellant tank under the AFT and FORWARD sets of struts and by the loads, PRESS, GAXIAL, GLATRL, and TNKCOOL (BEHX9).

CHAPTER 6: Free vibration analysis-BEHX1x, x=1,2; x=load case)
This is a BIGBOSOR4 model of the propellant tank with springs (pinned struts) attached. There is no loading. The mass of the propellant is "lumped" into the middle wall of the three-layered wall (inner layer = smeared orthogrid; middle layer= propellant tank wall of constant thickness; outer layer= tapered doubler centered on the global axial coordinate where each set of struts (AFT and FORWARD) are pinned to the tank.

The strut (spring) stiffness takes into account the
flexibility of the propellant tank wall.

CHAPTER 7: strut stress analysis-BEHX2x, x=1,2; x=load case)
This is the stress analysis from both BIGBOSOR4 and from a PANDA2-type of laminate analysis of the most highly loaded strut of the AFT set of struts (struts of type 1). The struts are tubes made of composite laminate. The most highly loaded strut under both axial tension and equal axial compression is analyzed. The tensile/compressive load to which the most highly loaded strut is subjected is derived in the computation under CHAPTER 5. The five stress "behavioral" constraints computed here correspond to:

1. tension along the fibers of a ply,
2. compression along the fibers of a ply,
3. tension transverse to the fibers of a ply,
4. compression transverse to the fibers of a ply,
5. in-plane shear stress in a ply.

Recorded as 5 behavioral constraints are the maximum values of each of the five components just listed from tension or compression and from a BIGBOSOR4 or a PANDA2-type of model. In other words, only the worst (highest) stress component from four computations (tension BIGBOSOR4,compression BIGBOSOR4, tension PANDA2, compression PANDA2) is recorded as each component behavioral constraint.

CHAPTER 8: strut stress analysis-BEHX3x, x=1,2; x=load case)
This is the stress analysis from both BIGBOSOR4 and from a PANDA2-type of laminate analysis of the most highly loaded strut of the FWD set of struts (struts of type 2). The struts are tubes made of composite laminate. The most highly loaded strut under both axial tension and equal axial compression is analyzed. The tensile/compressive load to which the most highly loaded strut is subjected is derived in the computation under CHAPTER 5. The five stress "behavioral" constraints computed here correspond to:

1. tension along the fibers of a ply,
2. compression along the fibers of a ply,
3. tension transverse to the fibers of a ply,
4. compression transverse to the fibers of a ply,
5. in-plane shear stress in a ply.

Recorded as 5 behavioral constraints are the maximum values of each of the five components just listed from tension or compression and from a BIGBOSOR4 or a PANDA2-type of model. In other words, only the worst (highest) stress component from four computations (tension BIGBOSOR4,compression BIGBOSOR4, tension PANDA2, compression PANDA2) is recorded as each component behavioral constraint.

CHAPTER 9: Buckling of strut as a column
-BEHX5xy, x=1,2 x=strut type; y=1,2 y=load case
Only the most highly axially compressed strut in the strut set "x" is included in the analysis. Two models are used:

1. a BIGBOSOR4 model of the strut. n = 1 circumferential wave corresponds to buckling of the strut as a column. The effect of propellant tank flexibility is NOT included in this BIGBOSOR4 model.
2. an Euler buckling model of the strut. This model is analogous to the column buckling model used in "DEWAR". The effect of propellant tank flexibility IS included.

The Euler buckling model usually gives the lower buckling load factor, mainly because of propellant tank flexibility. The buckling constraint is based on the minimum column buckling load factor obtained from the two models just listed.

CHAPTER 10: Buckling of strut as a shell
-BEHX6xy, x=1,2 x=strut type; y=1,2 y=load case
Only the most highly axially compressed strut in the strut set "x" is included in the analysis. Two models are used:

1. a BIGBOSOR4 model of a sub-length of the strut. A search is conducted over the number n of circumferential waves in the buckling mode to determine the critical buckling load factor. The effect of propellant tank flexibility is not relevant in this analysis.
2. a PANDA2-type buckling model of the strut. This model is analogous to the shell buckling model used in "DEWAR". The effect of propellant tank flexibility is not relevant.

The PANDA2-type buckling model usually gives the lower buckling load factor, mainly because of the effect of transverse shear deformation (t.s.d.) and the effect of the anisotropic terms, D16 and D26, that BIGBOSOR4 cannot handle. The buckling constraint is based on the minimum shell buckling load factor obtained from the two models just listed.

CHAPTER 11: Launch-hold force in a strut
-BEHX7x, x=1,2; x=load case
If the propellant tank is oriented vertically in the launch vehicle all the struts in each strut set experience the same launch-hold force. The launch-hold force in the AFT struts may differ from that in the FORWARD struts. Behavioral

constraints are computed for each set of struts. The behavioral constraint is called "FORCE(i,j)", in which i = the load case number and j =the strut set number (strut type).

FORCE(i,j) is computed from a BIGBOSOR4 model of the propellant tank with struts (springs) attached to it. The spring constants include the effect of the flexibility of the propellant tank. The tank is loaded by PRESS, GAXIAL=1g, and TNKCOOL. The maximum allowable strut launch-hold force is provided for each load case by the End user. The behavioral constraint, FORCE(i,j), must be less than the maximum allowable, FORCEA(i,j). The End user must supply FORCEA(i,j) at a small enough value so that if the struts contain a disconnect feature they will not "short out" during the launch-hold phase of a mission.

CHAPTER 12: Maximum effective stress in the isotropic propellant tank - BEHX8xy, x=1,2 x=meridian; y=1,2 y=load case
This is a BIGBOSOR4 model in which the springs (struts) are replaced by concentrated loads. The model is analogous to that described in CHAPTER 4 (*.BEHX03x, x=1,2; x=load case).
The propellant tank is loaded by PRESS, GAXIAL, GLATRL, and TNKCOOL. The modeling of the concentrated loads that replace the springs (struts) is described in CHAPTER 4. The purpose of this model is to compute the maximum effective stress in the propellant tank, which is assumed to be fabricated of isotropic material. This is an "INDIC=3" BIGBOSOR4 model.

CHAPTER 13: Buckling of the isotropic propellant tank
- BEHX9xy, x=1,2 x=meridian; y=1,2 y=load case
This is a BIGBOSOR4 model in which the springs (struts) are replaced by concentrated loads. The model is analogous to that described in CHAPTER 12 (*.BEHX8xy) except that in this case we are interested in buckling rather than maximum stress.
The propellant tank is loaded by PRESS, GAXIAL, GLATRL, and TNKCOOL. The modeling of the concentrated loads that replace the springs (struts) is described in CHAPTER 4. The purpose of this model is to compute the minimum buckling load of the propellant tank, which is assumed to be fabricated of isotropic material. This is an "INDIC=4" BIGBOSOR4 model.

CHAPTER 14: Computation of the objective:
In general the objective has the form:

objective =

```
       WGT*(normalized weight of empty tank)
 +(1.-WGT)*(normalized total strut conductance)

 in which (normalized weight of empty tank) =    TOTMAS/TNKNRM
 and      (normalized total strut conductance) = CONDCT/CONNRM
 and WGT, TNKNRM, CONNRM are input variables provided by the
 End user during his/her interactive "BEGIN" session (*.BEG).

 If WGT = 0, then the objective is simply the total strut
 conductance, CONDCT. Note that the listed definition of the
 objective is always "total conductance into the tank: CONDCT".
=============================================================
```

APPENDIX 2

Temporary changes in SUBROUTINE BOSDEC and in the library, addbosor4.src, the purpose of which is to determine the effect on free vibration frequencies of accounting for the fact that the "lumped" mass of the propellant into the propellant tank shell wall leads to density that varies along shell walls in shell segments in which the radius of the tank varies along a shell segment. This is the case for the aft and forward ellipsoidal domes. The formula for the effective added mass density, rho(add), for a shell of one layer is as follows:

rho(add) = 0.5*(r/t)x sqrt[1.-(dr/ds)^2] x rho(fluid)

in which r = radius at a meridional point from the axis of revolution to the shell wall reference surface, t = wall thickness at that meridional point, dr/ds = derivative of r with respect to the meridional arc length, and rho(fluid) is the mass density of the fluid in the tank.

The permanent version of BIGBOSOR4 cannot account for variations of shell wall density along the meridian of a given shell segment. BIGBOSOR4 was modified temporarily for the specific propellant tank case. The modifications are not valid for any shell of revolution; hence they are TEMPORARY modifications. made for obtaining the free vibration frequency comparisons listed in this "tank" document.

===
Temporary modifications to SUBROUTINE BOSDEC (bosdec.src library):

```
C=DECK      BOSDEC
C
C  PURPOSE IS TO SET UP BIGBOSOR4 INPUT FILES FOR "tank",
C  A PROGRAM TO OPTIMIZE A STRUT-SUPPORTED PROPELLANT TANK.
C  This work was done late in 2011 and early in 2012.
C  BIGBOSOR4 is used in connection with GENOPT.
C
      SUBROUTINE BOSDEC(INDX,IFIL14,ILOADX,INDIC,JSTRUT)

(lines skipped to save space)
```

```
      COMMON/ITRIPX/ITRIP
C BEG DEC 2011
      COMMON/DENMLX/DENMLT,DENFLD
C END DEC 2011
C
      common/caseblock/CASE

(lines skipped to save space)

         THKSKN = THKMID
         IF (ISEG.LE.NSEGDM) THKSKN = THKAFT
         IF (ISEG.GT.(NSEGS-NSEGDM)) THKSKN = THKFWD
         NRS = 0
C BEG DEC 2011
         DENMLT = 0.
         DENFLD = DENPRP/GRAV
C END DEC 2011
         SKNDEN = SMSKIN(ISEG)
C     The following SKNDEN is accurate for a cylindrical segment,
C     and is used here for all segments (including ellipsoidal)
C     for ease in writing bosdec. The added fluid mass is used only
C     for the free vibration model. Since the frequency varies as the
C     square root of the ratio, stiffness/mass, this approximation is
C     not horribly conservative. (conservative by about 20 per cent
C     if the entire propellant tank is spherical, less if the
C     propellant tank has a significant cylindrical portion).
C BEG DEC 2011
C   bosdec.tank (permanent) version (remove the "C" in col. 1
C   on the following two lines to get the permanent version):
C        IF (INDX.EQ.6)
C    1    SKNDEN = SMSKIN(ISEG) + 0.25*AFTDIA*(DENPRP/GRAV)/THKSKN
C
C   bosdec.src (temporary) version (set col. 1 to "C" in the
C   following line to get the permanent version, bosdec.tank):
         IF (INDX.EQ.6) DENMLT = 1.0
C END DEC 2011
C
---------------------------------------------------------------
```

Temporary modifications to ADDBOSOR4.SRC (addbosor4.src library):

```
(lines skipped to save space)

C
C=DECK      CFB4
```

(lines skipped to save space)

```
  120 CONTINUE
      ZREF = 0.
C BEG OCT 2011 and DEC 2011
      CALL CFBL(NLAY,ZREF,E1L,E2L,GL,U12L,RHOL,TL,ZETL,CX,
     1     A1L,A2L,THERMX,TMS,TD,A1L1,A1L2,A2L1,A2L2,
     1     CONDT,CON1L,CON2L,RAD(IPOINT),RADD(IPOINT),4)
C END OCT 2011 and DEC 2011
      DZREF = Z - TD/2.
      CALL CSHIFT(CX,DZREF,CNEW,THERMX,THMSFT)
      SMPA = TMS
```

(lines skipped to save space)

```
C=DECK      CFBL
C BEG OCT 2011 and DEC 2011
      SUBROUTINE CFBL(NLAY,ZREF,E1L,E2L,GL,U12L,RHOL,TL,ZETL,CCC,
     1                A1L,A2L,THERM,TMS,TD,A1L1,A1L2,A2L1,A2L2,
     1                CONDT,CON1L,CON2L,RAD,RADD,ICALL)
C END OCT 2011 and DEC 2011
C
C  PURPOSE IS TO CALCULATE C(i,j) AND THERM(J) FOR ONE MULTI-LAYERED
C  SKIN.
C
C BEG OCT 2011
      DIMENSION CON1L(*),CON2L(*)
C END OCT 2011
C BEG DEC 2011
      COMMON/DENMLX/DENMLT,DENFLD
C END DEC 2011
      DIMENSION E1L(99),E2L(99),GL(99),ZETL(99),U12L(99),RHOL(99)
```

(lines skipped to save space)

```
      S(L) = E1L(L)/UD
      TD = TD+TL(L)
C BEG DEC 2011
      IF (L.NE.2.OR.DENMLT.EQ.0.0)  TMS = TMS+TL(L)*RHOL(L)
      IF (L.EQ.2.AND.DENMLT.NE.0.0) TMS = TMS+TL(L)*(RHOL(L)
     1       +0.5*(RAD/TL(L))*SQRT(1.-RADD**2)*DENFLD)
   10 CONTINUE
C END DEC 2011
C
      ECCREF = (0.5*TD - ZREF)
      IF (ZREF.EQ.0.) ECCREF = 0.
```

(lines skipped to save space)

```
C=DECK      CFB9

(lines skipped to save space)

  120 CONTINUE
      ZREF = 0.
C BEG OCT 2011 and DEC 2011
      CALL CFBL(NLAY,ZREF,E1L,E2L,GL,U12L,RHOL,TL,ZETL,CX,
     1     A1L,A2L,THERMX,TMS,TD,A1L1,A1L2,A2L1,A2L2,
     1     CONDT,CON1L,CON2L,RAD(IPOINT),RADD(IPOINT),9)
C END OCT 2011 and DEC 2011
      SMPA = TMS
      DZREF = Z - TD/2.
      CALL CSHIFT(CX,DZREF,CNEW,THERMX,THMSFT)
----------------------------------------------------------
```

****************** IMPORTANT NOTES***********************
The “permanent” version of BIGBOSOR4 to be used in connection with GENOPT is stored in the file, /home/progs/genopt/case/tank/addbosor4.regular . This same FORTRAN coding is also stored in the file, /home/progs/genopt/case/sources/addbosor4.src

The “temporary” version of BIGBOSOR4 to be used in connection with GENOPT is stored in the file, /home/progs/genopt/case/tank/addbosor4.design.var

The “permanent” version of the BOSDEC library to be used in connection with GENOPT is stored in the file, /home/progs/genopt/case/tank/bosdec.tank.

The “temporary” version of the BOSDEC library to be used in connection with GENOPT is stored in the file, /home/progs/genopt/case/tank/bosdec.design.var
***.

Effect of the temporary modification to SUBROUTINE BOSDEC on the input file, test8.ALL, for the BIGBOSOR4 free vibration analysis (test8.ALL = test8.BEHX11 after execution of the BIGBOSOR4 processor called "cleanup"):

```
dave-> diff orig11.all test8.ALL
73c73
<   0.5647800E-02 $ mass density (e.g. lb-sec**2/in. Aluminum=.00025), DENS(  2)
---
>   0.2500000E-03 $ mass density (e.g. lb-sec**2/in. Aluminum=.00025), DENS(  2)
871c871
<   0.6228397E-02 $ mass density (e.g. lb-sec**2/in. Aluminum=.00025), DENS(  4)
---
>   0.2500000E-03 $ mass density (e.g. lb-sec**2/in. Aluminum=.00025), DENS(  4)
1185c1185
<   0.1433431E-01 $ mass density (e.g. lb-sec**2/in. Aluminum=.00025), DENS(  5)
---
>   0.2500000E-03 $ mass density (e.g. lb-sec**2/in. Aluminum=.00025), DENS(  5)
```

The "<" entries above correspond respectively to the aft dome, cylindrical portion, and forward dome of the propellant tank WITH the propellant mass lumped into layer no. 2 of the propellant tank wall in the original version, that is, the version that was used for optimization.

The ">" entries above correspond respectively to the aft dome, cylindrical portion, and forward dome of the propellant tank WITHOUT the propellant mass lumped into layer no. 2 of the propellant tank wall in the modified version. In the modified version the mass of the propellant is lumped into layer no. 2 of the propellant tank wall inside SUBROUTINE CFBL. (See the file, addbosor4.density.var).
==