OPTIMIZATION OF PROPELLANT TANKS SUPPORTED BY ONE OR TWO OPTIMIZED LAMINATED COMPOSITE SKIRTS

David Bushnell, Ph.D., Fellow of the AIAA, Fellow of ASME
February 2012, revised March 2012, re-revised June 2012

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 one or two conical skirts each of which consists of five segments: two short segments near each end of the skirt and a central long segment that has a laminated composite wall. Each of the short segments nearest the ends of the skirt has an isotropic one-layered wall with tapered thickness. Each short segment next to each short end segment is multi-layered with the innermost and outermost layers consisting of tapered isotropic material and the remaining layers consisting of the same laminated composite wall as the long central segment. This skirt-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 conical skirt. In the BIGBOSOR4 free vibration model the mass of the propellant is "lumped" into the tank wall, a conservative model. The tank/skirt system is optimized in the presence of the following constraints: (1) the minimum free vibration frequency of the tank/skirt system must be greater than a given value; (2) five stress components in each ply of the laminated composite wall of the conical skirt shall not exceed five specified allowables; (3) the conical skirt shall not buckle as a thin shell; (4) the maximum effective (vonMises) stress in the tank wall shall not exceed a specified value; (5) the tank wall shall not buckle. Linear theory is used throughout. 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.

****************************** IMPORTANT NOTES **************************************
1. Significant errors were found in the "tank2" 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 "tank2" 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 "tank2".

2. The "tank2" software was modified in April, 2012 in order to account approximately for the prebuckling in-plane shear resultant, Nxy, that is maximum in Load Case 2 (lateral acceleration) along the meridian at circumferential location, theta = 90 degrees. Two PANDA2-type models are now used in addition to the

BIGBOSOR4 model in order to account for buckling under a load set in which Nxy is present and in order to account for anisotropic terms D16, D26. The modifications were made to SUBROUTINE BEHX7 of the behavior.tank2 library.

3. The factors of safety for stress in the propellant tank wall were increased from 1.0 to 1.5, and the factors of safety for buckling were increased from 1.0 to 2.0. As a result the optimized weights of the tank/skirt systems, "oneskirt" and "twoskirt" are significantly greater than those that existed at the time this "paper" was originally written.

4. 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.

5. 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).

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

********** NEW OUTPUT IN THE *.OPM FILE RELATED TO “IMPORTANT NOTE” No. 2 **********
The following sample output from twoskirt.vardensity.loadaloadb.opm explains the “Nxy” part of the April 2012 modification:

```
 PANDA2-type buckling predictions corresponding to the
 prebuckled state along the skirt meridian at theta=  9.0000E+01
degrees...
 In this buckling analysis there are two PANDA2 models:
 Model 1: The full length of the effective cylindrical shell
          is included and Nx,Ny,Nxy at the midlength of the
          skirt are considered to be the prebuckled state
          which is uniform over the entire PANDA2 model.
 Model 2: 1/4th of the length nearest the large-diameter end
          of the conical skirt is included, and Nx,0.,Nxy
          ten nodal points from the large-diameter end are
          considered to be the uniform prebuckled state.
 We use the minimum of the two buckling load factors from
 PANDA2 Model 1 and PANDA2 Model 2 as the buckling load
 obtained from a PANDA2 analysis.
 Listed next are the assumed prebuckled state, length and
```

```
 radius of the effective cylindrical shell, buckling mode,
 (MSKIN,NSKIN,SLOPE), and buckling load factor for Model 1:
 Buckling load factor predicted from a PANDA2-type model of
 the aft skirt for Load Case  2:
 Average Load Set A prebuckling resultants used in the PANDA2 model:
 Average axial resultant over meridian length,NXAVE =  2.7994E+00
 Average hoop  resultant over meridian length,NYAVE = -1.6108E-06
 Average in-plane shear resultant,            NXYAVE=  3.0702E+02
 Average Load Set B prebuckling resultants used in the PANDA2 model:
 Average axial resultant over meridian length,NXFIX =  1.1309E+03
 Average hoop  resultant over meridian length,NYFIX =  5.9039E-01
 Length of the equivalent cylindrical shell,  FLEFF =  1.3761E+02
 Radius of the equivalent cylindrical shell,  RAVE  =  1.3417E+02
 Critical buckling mode:
 Number of axial half-waves over shell length,MSKIN =   1
 Number of circ. half-waves over 180 degrees, NSKIN =  20
 Slope of the buckling nodal lines,           SLOPE =  2.7372E-01
 SLOPE=dy/dx in Fig. 9(b) of 1987 "Theoretical Basis paper.
 "Bump-up" factor to adjust for milder imperfection
  sensitivity factor when in-plane shear is significant  1.5000E+00
 The actual buckling load factor,EIGLOC*FKNOCK/RATIO=  1.3242E+00

 PANDA2-type buckling predictions corresponding to the
 prebuckled state along the skirt meridian at theta=  9.0000E+01
degrees...
 Model 2: 1/4th of the length nearest the large-diameter end
          of the conical skirt is included, and Nx,0.,Nxy
          ten nodal points from the large-diameter end are
          considered to be the uniform prebuckled state.
 We use the minimum of the two buckling load factors from
 PANDA2 Model 1 and PANDA2 Model 2 as the buckling load
 obtained from a PANDA2 analysis.
 Listed next are the assumed prebuckled state, length and
 radius of the effective cylindrical shell, buckling mode,
 (MSKIN,NSKIN,SLOPE), and buckling load factor for Model 2:
 Buckling load factor predicted from a PANDA2-type model of
 the aft skirt for Load Case  2:
 Average Load Set A prebuckling resultants used in the PANDA2 model:
 Average axial resultant over meridian length,NXAVE =  2.3848E+00
 Average hoop  resultant over meridian length,NYAVE =  0.0000E+00
 Average in-plane shear resultant,            NXYAVE=  2.3122E+02
 Average Load Set B prebuckling resultants used in the PANDA2 model:
 Average axial resultant over meridian length,NXFIX =  9.6325E+02
 Average hoop  resultant over meridian length,NYFIX =  0.0000E+00
 Length of the equivalent cylindrical shell,  FLEFF =  3.4404E+01
 Radius of the equivalent cylindrical shell,  RAVE  =  1.6100E+02
 Critical buckling mode:
 Number of axial half-waves over shell length,MSKIN =   1
```

```
 Number of circ. half-waves over 180 degrees, NSKIN =  40
 Slope of the buckling nodal lines,           SLOPE =  5.6758E-01
 SLOPE=dy/dx in Fig. 9(b) of 1987 "Theoretical Basis paper.
 "Bump-up" factor to adjust for milder imperfection
  sensitivity factor when in-plane shear is significant  1.5000E+00
 The actual buckling load factor,EIGLOC*FKNOCK/RATIO=  2.9852E+00

 Minimum buckling load from PANDA2 Models 1 & 2, EIGMIN=  1.3242E+00
 For the buckling load factor, GENOPT/SKIRT uses the minimum
 buckling load from PANDA2 for the aft and forward (if any)
 skirt(s) and the buckling load from the BIGBOSOR4 model.
 The buckling load from the BIGBOSOR4 model is EIGCRT=  1.8033E+01

 The "buckling load factor" printed next may not be the
 actual buckling load factor, but may be the "bumped-up"
 buckling load factor from the PANDA2 model. GENOPT/SKIRT
 uses the minimum of the buckling load factors from
 BIGBOSOR4, the "bumped-up" PANDA2 model of the aft skirt
 and the "bumped-up" PANDA2 model of the forward skirt.
 The "bumped-up" buckling load factor from the PANDA2 model
 for skirt number 1 is SHLBC2( 1) =  1.9864E+00
---------------------------------------------------------------------
*******************************************************************************
```

The latest files (generated after all known errors were found and after the aforementioned improvement in GENOPT's capability) for the generic case called “tank2” and for two specific cases, "oneskirt" and "twoskirt", are stored in three folders located in the folder, tanktank2/tank2paper: tank2files (generic “tank2” files), onetwoskirt.input (input data for the two specific cases, oneskirt and twoskirt) and onetwoskirt.output (output data for the two specific cases, oneskirt and twoskirt):

1. Files for the generic case called “tank2” (located in the folder, tanktank2/tank2paper/tank2files):

```
-rw-r--r--   1 dave  staff  681449 May 18 08:37 addbosor4.regular (“permanent” version of BIGBOSOR4)
-rw-r--r--   1 dave  staff  682711 May 18 08:21 addbosor4.tank2.density.var (varying density BIGBOSOR4)
-rw-r--r--   1 dave  staff  103689 May  7 03:58 behavior.tank2 (“fleshed out” version of behavior.new)
-rw-r--r--   1 dave  staff  182548 May 16 13:13 bosdec.tank2 (constant density version of SUB. BOSDEC)
-rw-r--r--   1 dave  staff  183100 May 16 13:14 bosdec.tank2.density.var (varying density BOSDEC)
-rw-r--r--   1 dave  staff   27044 Feb 26 18:23 struct.tank2 (“fleshed out” version of struct.new)
-rw-r--r--   1 dave  staff  121887 Feb 26 18:23 tank2.INP (input file for the GENTEXT processor)
-rw-r--r--@  1 dave  staff   47462 Jul 14 03:03 tank2.PRO.txt (prompting file created by GENTEXT)
-rw-r--r--@  1 dave  staff    8725 Jul 14 03:02 tank2.glossary.txt (glossary of variables & definitions)
```

2. Files of input data for the specific cases called “oneskirt” and “twoskirt” (located in the folder, tanktank2/tank2paper/onetwoskirt.input):

```
-rw-r--r--   1 dave  staff   44433 May 16 15:43 aftskirt.ALL (BIGBOSOR4 model; V(LoadA), V(LoadB))
-rw-r--r--   1 dave  staff  130473 May 17 14:21 afttwoskirtgenopt.INDIC=4.all (linear BIGBOSOR4)
-rw-r--r--   1 dave  staff  269832 May 17 13:59 afttwoskirtnon.INDIC=-2.all (nonlinear BIGBOSOR4)
-rw-r--r--   1 dave  staff  269793 May 16 16:01 afttwoskirtnon.INDIC=1.all
```

```
-rw-r--r--   1 dave  staff   13056 May 10 02:07 oneskirt.BEG (input for the GENOPT processor, BEGIN)
-rw-r--r--   1 dave  staff   12633 Apr 24 03:45 oneskirt.DEC (input for the GENOPT processor, DECIDE)
-rw-r--r--   1 dave  staff    1059 Apr 24 03:45 oneskirt.OPT (input for the GENOPT processor, MAINSETUP)
-rw-r--r--   1 dave  staff    1686 Apr 27 04:59 oneskirt.itype3.cpl (input for CHOOSEPLOT, itype=3 case)
-rw-r--r--   1 dave  staff     629 Apr 27 04:56 oneskirt.opt3 (input for MAINSETUP, itype = 3 case)
-rw-r--r--   1 dave  staff    6520 Apr 27 03:25 oneskirt.vardensity.chg (archived optimum design)
-rw-r--r--   1 dave  staff    6520 May 18 08:36 oneskirt.vardensity.loadaloadb.chg (archived optimum design)
-rw-r--r--   1 dave  staff   15509 Jun  8 19:40 twoskirt.BEG (input for the GENOPT processor, BEGIN)
-rw-r--r--   1 dave  staff   20628 Apr 21 04:39 twoskirt.DEC (input for the GENOPT processor, DECIDE)
-rw-r--r--   1 dave  staff    1059 Apr 21 04:39 twoskirt.OPT (input for the GENOPT processor, MAINSETUP)
-rw-r--r--   1 dave  staff   10370 Jun  8 19:44 twoskirt.almostfeasible.chg (archived almost feasible optimum)
-rw-r--r--   1 dave  staff   10370 Jun  8 19:43 twoskirt.feasible.chg (archived feasible optimum design)
-rw-r--r--   1 dave  staff    1819 Jun  9 06:45 twoskirt.itype3.cpl (input for CHOOSEPLOT, itype=3 case)
-rw-r--r--   1 dave  staff   10370 Jun  9 08:35 twoskirt.vardensity.loadaonly.chg (archived old optimum design)
```

3. Files of output data for the specific cases called “oneskirt” and “twoskirt” (located in the folder, tanktank2/tank2paper/onetwoskirt.output):

```
-rw-r--r--   1 dave  staff    1849 May 16 15:48 aftskirt.loadfactors.out (“aftskirt” is a BIGBOSOR4 model)
-rw-r--r--   1 dave  staff   12382 May 16 15:51 aftskirt.prebuck.out
-rw-r--r--   1 dave  staff    2018 May 17 14:19 afttwoskirtgenopt.INDIC=4.loadfactors.out (linear theory)
-rw-r--r--   1 dave  staff  474914 May 17 13:54 afttwoskirtnon.INDIC=-2.out (nonlinear theory)
-rw-r--r--   1 dave  staff    1876 May 16 16:04 afttwoskirtnon.INDIC=1.loadfactors.out
-rw-r--r--   1 dave  staff   39163 May 16 16:10 afttwoskirtnon.INDIC=1.prebuck.out
-rw-r--r--   1 dave  staff  130949 Jun  9 06:42 oneskirt.vardensity.loadaloadb.opm (optimized design)
-rw-r--r--   1 dave  staff  204697 Jun  9 06:35 twoskirt.almostfeasible.opm (almost feasible optimum)
-rw-r--r--   1 dave  staff  204888 Jun  9 04:49 twoskirt.feasible.opm (feasible optimum design)
-rw-r--r--   1 dave  staff  673300 Jun  4 05:37 twoskirt.vardensity.opp (output from optimization)
*********************************************************************************
```

INTRODUCTION AND SOME GEOMETRICAL DETAIL

In this work the generic case is called "tank2" and the two specific cases optimized here are called "oneskirt" and “twoskirt”. The "oneskirt" case has only one supporting skirt (Figs. 1 – 21). The “twoskirt” case has two supporting skirts, one aft and the other forward (Figs. 22 – 30). In order to optimize tanks with two skirts, aft and forward, GENOPT had to be modified rather extensively to permit more than 50 decision variable candidates.

The technology on which this work is based is described in [1] and in the papers and reports referenced in [1]. The overall aspect of the geometry of the propellant tank is the same as that described in [1]. In the “oneskirt” case the conical skirt is attached to the tank at the axial coordinate that corresponds to that of the center of gravity of the propellant tank. In the "twoskirt" case the conical skirts are attached to the propellant tank at the aft and forward junctions of the cylindrical part of the tank with the aft and forward ellipsoidal end domes.

The geometry of each tank/skirt junction is the same as that shown in the sketch near the beginning of [1] and repeated here:

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

Sketch of the propellant tank wall with a local reinforcement at the axial location where the tank-end of the conical skirt 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.

The conical skirt consists of five segments as shown here:

```
----- <-- propellant tank support ring
  \
   \  <-- skirt seg.5 (one tapered isotropic layer)
    \
   ------ <--wall thicknesses of seg.4 & seg.5 match
      \
       \  <--skirt seg.4 (n+2 layers; the outer and
        \      inner layers are tapered isotropic and
      -------    the interior n layers are the same as
          \       in segment 3)
           \
            \
             \
              \
               \
                \  <--skirt seg.3 (n composite plies
                 \     as with each strut tube described
                  \     in [1])
                   \
                    \
                     \
                   ------ <--wall thicknesses of
                       \      segment 2 and segment 3 match
```

```
                              \  <--skirt seg.2 (n+2 layers,
                               \     n internal composite plies)
                             ------ <-- wall thicknesses of
                                 \       seg. 1 and seg. 2 match
                                  \ <--skirt seg.1 (one tapered
                                   \            isotropic layer)
                                 ------ "ground"
```

The conical skirt support consists of five segments, two short segments at each end and a central long segment.

Segment 2 has the wall shown schematically here:

```
                   |               |
                   |    Seg. 3     |
Segment 3 ---->    |  n composite  |
                   |     plies     |
                   |               |
                   -----------------
                  /|               |\
Segment 2 ---->  / |               | \
                /  |               |  \
inner tapered  /   |               |   \ <--outer tapered
isotropic     /    |               |    \   isotropic layer
layer----->  /     |  n composite  |     \  called "prong"
called      /      |  plies, as    |      \ below
"prong"    /       |  with Seg.3   |       \
below     /        |               |        \
         /         |               |         \
        ---------------------------------------
        Segment 1: one-layered, tapered isotropic
```

Schematic of wall constructions of skirt segments 2 and 3

Segment 4 has the wall shown schematically here:

```
        Segment 5: one-layered, tapered isotropic
          ___________________________________
          \        |               |        /
           \       |               |       /
            \      |  n composite  |      /
             \     |  plies, as    |     /
inner tapered \    |  with Seg.3   |    / <--outer tapered
isotropic layer\   |               |   /    isotropic layer
                \  |               |  /     called "prong"
Segment 4 ---->  \ |               | /      below
                  \|               |/
                   -----------------
```

```
                           |                |
                           |     Seg. 3     |
Segment 3 ---->            |  n composite   |
                           |     plies      |
```

Schematic of wall constructions of skirt segments 3 and 4

The wall of the propellant tank is modeled as consisting of three layers as described in [1]. The same material properties in the tank wall and skirt are used here as those in the tank wall and struts in [1]. The two loading cases are the same here as those used in [1]. The run stream used to obtain the optimized configuration is analogous to that described in [1].

The decision variable candidates are the same as those described in [1] except that there are the following additional decision variable candidates:

1. tank-end length of one-layered skirt part: LNGTNK1(i)
2. tank-end thickness of tapered skirt part: THKTNK1(i)
3. tank-end length of tapered prongs: LNGTNK2(i)
4. tank-end thickness of one tapered prong: THKTNK2(i)
5. "ground" end length of one-layered skirt part: LNGVEH1(i)
6. "ground"-end thickness of tapered skirt part: THKVEH1(i)
7. "ground"-end length of tapered prongs: LNGVEH2(i)
8. "ground"-end thickness of one tapered prong: TNKVEH2(i)

in which i = 1 for the aft skirt and i = 2 for the forward skirt.

The "tank-end" quantities correspond to skirt segments 4 and 5. The "ground-end" quantities correspond to skirt segments 1 and 2. By "length" is meant "slant length", that is, the length measured along the meridian of the conical reference surface. The innermost and outermost layers of Segments 2 and 4 are of the same isotropic material as Segments 1 and 5 and of the same isotropic material as the propellant tank. The thicknesses of the outer surface and inner surface tapered "prongs" are the same. The "prongs" in Segment 2 have different dimensions from the "prongs" in Segment 4. The purpose of the prongs is to contain the composite laminate at either end of the skirt. This geometry has been used previously in other successful Lockheed Martin projects (e.g. WISE).

DECISION VARIABLE CANDIDATES

Decision variable candidates are listed here for the case called “oneskirt”. In this case the laminated composite section of the skirt has a symmetric angle-ply layup, as is the case for each strut tube described in [1]. As in [1] there is only one ply thickness that is a decision variable. All other ply thicknesses are linked to this decision variable.

Optimized "variable density" design of the specific case, "oneskirt":

```
==========================================================================
  VALUES OF DESIGN VARIABLES CORRESPONDING TO BEST FEASIBLE DESIGN
```

```
 VAR.   CURRENT
 NO.     VALUE            DEFINITION
  1    1.251E-01  thickness of the tank aft dome skin: THKAFT
  2    6.482E-02  thickness of the tank cylinder skin: THKMID
  3    7.494E-02  thickness of the forward tank dome skin: THKFWD
  4    5.432E+00  spacing of the tank orthogrid stringers: STRSPC
  5    5.432E+00  spacing of the tank orthogrid rings: RNGSPC
  6    5.202E-01  thickness of the tank orthogrid stringers: STRTHK
  7    2.000E-01  height of the tank orthogrid stringers: STRHI
  8    5.202E-01  thickness of the tank orthogrid rings: RNGTHK
  9    2.000E-01  height of the tank orthogrid rings: RNGHI
 10    3.000E+02  global axial coordinate of tank support ring: ZTANK(1 )
 11    9.045E+01  global axial coordinate of "ground": ZGRND(1 )
 12    3.000E+01  axial length of the propellant tank doubler: DUBAXL(1 )
 13    7.693E-02  max.thickness of the propellant tank doubler: DUBTHK(1 )
 14    5.445E-02  thickness of the tank reinforcement ring: TRNGTH(1 )
 15    2.723E-01  height of the tank reinforcement ring: TRNGHI(1 )
 16    2.000E+00  tank-end length of one-layered skirt part: LNGTNK1(1 )
 17    1.532E-01  tank-end thickness of tapered skirt part: THKTNK1(1 )
 18    2.000E+00  tank-end length of tapered prongs: LNGTNK2(1 )
 19    3.127E-02  tank-end thickness of one tapered prong: THKTNK2(1 )
 20    2.000E+00  "ground" end length of one-layered skirt part: LNGVEH1(1 )
 21    1.951E-01  "ground"-end thickness of tapered skirt part: THKVEH1(1 )
 22    2.000E+00  "ground"-end length of tapered prongs: LNGVEH2(1 )
 23    4.219E-02  "ground"-end thickness of one tapered prong: THKVEH2(1 )
 24    8.798E-03  thickness of a lamina: THICK(1 )
 25    8.798E-03  thickness of a lamina: THICK(2 )
 26    8.798E-03  thickness of a lamina: THICK(3 )
 27    8.798E-03  thickness of a lamina: THICK(4 )
 28    8.798E-03  thickness of a lamina: THICK(5 )
 29    8.798E-03  thickness of a lamina: THICK(6 )
 30    3.374E+01  layup angle: ANGLE(1 )
 31   -3.374E+01  layup angle: ANGLE(2 )
 32    7.635E+01  layup angle: ANGLE(3 )
 33   -7.635E+01  layup angle: ANGLE(4 )
 34    2.483E+01  layup angle: ANGLE(5 )
 35   -2.483E+01  layup angle: ANGLE(6 )
================================================================================
```

Design margins of the optimized tank/skirt system for the specific case, "oneskirt"
Both load sets include 25 psi ullage pressure and -200 degrees tank cool-down.

```
================================================================================
 ***** RESULTS FOR LOAD SET NO.  1  ****** (10 g axial, 0 g lateral)
 MARGINS CORRESPONDING TO CURRENT DESIGN (F.S.= FACTOR OF SAFETY)

 MARGIN CURRENT
 NO.     VALUE            DEFINITION
  1    7.330E-01  (FREQ(1 ,1 )/FREQA(1 ,1 )) / FREQF(1 ,1 )-1; F.S.=  1.20
  2   -1.013E-03  (FREQ(1 ,2 )/FREQA(1 ,2 )) / FREQF(1 ,2 )-1; F.S.=  1.20
  3    1.186E+00  (FREQ(1 ,3 )/FREQA(1 ,3 )) / FREQF(1 ,3 )-1; F.S.=  1.20
  4    1.911E-01  (FREQ(1 ,4 )/FREQA(1 ,4 )) / FREQF(1 ,4 )-1; F.S.=  1.20
```

```
  5   -6.309E-03  (TNKSTRA(1 ,1 )/TNKSTR(1 ,1 )) / TNKSTRF(1 ,1 )-1; F.S.=  1.00
  6   -6.309E-03  (TNKSTRA(1 ,2 )/TNKSTR(1 ,2 )) / TNKSTRF(1 ,2 )-1; F.S.=  1.00
  7   -2.372E-03  (TNKBUK(1 ,1 )/TNKBUKA(1 ,1 )) / TNKBUKF(1 ,1 )-1; F.S.=  1.00
  8   -2.372E-03  (TNKBUK(1 ,2 )/TNKBUKA(1 ,2 )) / TNKBUKF(1 ,2 )-1; F.S.=  1.00
----------------------------------------------------------------------------------
 ***** RESULTS FOR LOAD SET NO.  2  ****** (0 g axial, 10 g lateral)
 MARGINS CORRESPONDING TO CURRENT DESIGN (F.S.= FACTOR OF SAFETY)

 MARGIN CURRENT
 NO.     VALUE           DEFINITION
  1    7.330E-01  (FREQ(2 ,1 )/FREQA(2 ,1 )) / FREQF(2 ,1 )-1; F.S.=  1.20
  2   -1.013E-03  (FREQ(2 ,2 )/FREQA(2 ,2 )) / FREQF(2 ,2 )-1; F.S.=  1.20
  3    1.186E+00  (FREQ(2 ,3 )/FREQA(2 ,3 )) / FREQF(2 ,3 )-1; F.S.=  1.20
  4    1.911E-01  (FREQ(2 ,4 )/FREQA(2 ,4 )) / FREQF(2 ,4 )-1; F.S.=  1.20
  5    2.869E-02  (TNKSTRA(2 ,1 )/TNKSTR(2 ,1 )) / TNKSTRF(2 ,1 )-1; F.S.=  1.00
  6    2.805E-03  (TNKSTRA(2 ,2 )/TNKSTR(2 ,2 )) / TNKSTRF(2 ,2 )-1; F.S.=  1.00
  7    7.005E-01  (TNKBUK(2 ,1 )/TNKBUKA(2 ,1 )) / TNKBUKF(2 ,1 )-1; F.S.=  1.00
  8    7.734E-01  (TNKBUK(2 ,2 )/TNKBUKA(2 ,2 )) / TNKBUKF(2 ,2 )-1; F.S.=  1.00
==================================================================================
```

Notice that in this "oneskirt" case the free vibration frequencies are independent of the loading and the margins corresponding to maximum stress in the tank/skirt system, TANKSTR(i,j) are critical. (i=Load Case; j = meridian selected for stress) Also, buckling of the tank/skirt system, TNKBUK, is critical for Load Case 1 but not critical for Load Case 2. The name of the buckling variable, TNKBUK, remains the same as in the generic case called "tank" [1]. However, in the generic case called "tank2" TNKBUK signifies the buckling of the tank/skirt system. In other words, in "tank2" buckling may occur either in one or more of the segments of the propellant tank or in one or more of the segments of the supporting skirt(s). It turns out that for the optimized designs presented here buckling of the supporting skirt is slightly more critical than buckling of the upper 2:1 ellipsoidal dome of the propellant tank. For example, the oneskirt.OPM file for the optimized design obtained with the "temporary" (varying density) versions of bosdec and addbosor4 (in this case the oneskirt.OPM file is called oneskirt.vardensity.opm) includes the following list:

```
 BUCKLING OF THE PROPELLANT TANK (BEHX9) (Load Case 1; CIRCANG(JCOL) = 0. deg.)
  1.0087E+00(n=   3 circ.waves); IFAILD= 0 <--first minimum: aft skirt buckling
  1.0108E+00(n=   5 circ.waves); IFAILD= 0    oneskirt.vardensity.tnkbuk11.n3.ps
  1.0140E+00(n=   7 circ.waves); IFAILD= 0
  1.0180E+00(n=   9 circ.waves); IFAILD= 0
  1.0229E+00(n=  11 circ.waves); IFAILD= 0
  1.0284E+00(n=  13 circ.waves); IFAILD= 0
  1.0323E+00(n=  15 circ.waves); IFAILD= 0
  1.0225E+00(n=  17 circ.waves); IFAILD= 0
  9.9804E-01(n=  19 circ.waves); IFAILD= 0
  9.9763E-01(n=  21 circ.waves); IFAILD= 0 <--second minimum: aft skirt buckling
  1.0112E+00(n=  23 circ.waves); IFAILD= 0    oneskirt.vardensity.tnkbuk11.n21.ps
  1.0328E+00(n=  25 circ.waves); IFAILD= 0
  1.0528E+00(n=  27 circ.waves); IFAILD= 0
  1.0752E+00(n=  29 circ.waves); IFAILD= 0
  1.1049E+00(n=  31 circ.waves); IFAILD= 0
  1.1479E+00(n=  33 circ.waves); IFAILD= 0
  1.2043E+00(n=  35 circ.waves); IFAILD= 0
```

```
  1.2630E+00(n=  37 circ.waves); IFAILD= 0
  1.3285E+00(n=  39 circ.waves); IFAILD= 0
  1.4042E+00(n=  41 circ.waves); IFAILD= 0
  1.4928E+00(n=  43 circ.waves); IFAILD= 0
  1.5728E+00(n=  45 circ.waves); IFAILD= 0
  1.6538E+00(n=  47 circ.waves); IFAILD= 0
  1.7364E+00(n=  49 circ.waves); IFAILD= 0
  1.8209E+00(n=  51 circ.waves); IFAILD= 0
  1.9072E+00(n=  53 circ.waves); IFAILD= 0
  1.9954E+00(n=  55 circ.waves); IFAILD= 0
  2.0856E+00(n=  57 circ.waves); IFAILD= 0
  2.0680E+00(n=  59 circ.waves); IFAILD= 0
  2.0433E+00(n=  61 circ.waves); IFAILD= 0
  2.0263E+00(n=  63 circ.waves); IFAILD= 0
  2.0163E+00(n=  65 circ.waves); IFAILD= 0
  2.0127E+00(n=  67 circ.waves); IFAILD= 0 <--third minimum: fwd dome buckling
  2.0147E+00(n=  69 circ.waves); IFAILD= 0    oneskirt.vardensity.tnkbuk11.n67.ps
  2.0219E+00(n=  71 circ.waves); IFAILD= 0
  2.0340E+00(n=  73 circ.waves); IFAILD= 0
  2.0504E+00(n=  75 circ.waves); IFAILD= 0
  2.0709E+00(n=  77 circ.waves); IFAILD= 0
  2.0953E+00(n=  79 circ.waves); IFAILD= 0
  2.1233E+00(n=  81 circ.waves); IFAILD= 0
  2.1547E+00(n=  83 circ.waves); IFAILD= 0
  2.1894E+00(n=  85 circ.waves); IFAILD= 0
  2.2271E+00(n=  87 circ.waves); IFAILD= 0
  2.2677E+00(n=  89 circ.waves); IFAILD= 0
  2.3112E+00(n=  91 circ.waves); IFAILD= 0
  2.3574E+00(n=  93 circ.waves); IFAILD= 0
  2.4061E+00(n=  95 circ.waves); IFAILD= 0
  2.4574E+00(n=  97 circ.waves); IFAILD= 0
  2.511+00(n=  99 circ.waves); IFAILD= 0
 Critical buckling load factor from BIGBOSOR4, TNKBUK=  9.9763E-01
 Critical number of axial half-waves (BIGBOSOR4), NWVCRT=   21
   21       0.9976277      propellant tank buckling load factor: TNKBUK(1 ,1 )
```

The list of buckling eigenvalues above contains the string, "IFAILD". If IFAILD is equal to 1 the eigenvalue extraction subroutine used in BIGBOSOR4 (called EBAND2) failed to converge to an acceptable value. (The "stand-alone" version of BIGBOSOR4 was also modified to include "IFAILD" in its output file, *.OUT.)

********************* IMPORTANT NOTE ********************************
Notice that the factors of safety for buckling of the tank/skirt system are set to 1.0; see the last four lines of the oneskirt.BEG file (Table 3):

```
1     $ factor of safety for tank buckling: TNKBUKF(  1,  1)
1     $ factor of safety for tank buckling: TNKBUKF(  2,  1)
1     $ factor of safety for tank buckling: TNKBUKF(  1,  2)
1     $ factor of safety for tank buckling: TNKBUKF(  2,  2)
```

This is not a good practice in the generic case called "tank2" (tank/skirt system) because it does not allow for the inevitable presence of initial imperfections, especially with regard to buckling of the skirt. In future optimizations the factors of safety should probably be set to 2.0.

However, a comparison with predictions from STAGS should still be made for the optimized design listed in the file, oneskirt.vardensity.opm , even though the buckling factors of safety are set too low in BEGIN.

STAGS may well predict significantly lower buckling load factors than those listed above because:

1. BIGBOSOR4 cannot obtain buckling load factors that include the effect of prebuckling in-plane shear loading, which is present in Load Case 2 especially at circumferential coordinate, theta = 90 deg.

2. BIGBOSOR4 cannot handle the effect of shell wall anisotropy.

3. BIGBOSOR4 does not account for the effect of transverse shear deformation (t.s.d.)

The best thing presently would be to compensate for these shortcomings in BIGBOSOR4 by setting appropriate factors of safety for buckling of the tank/skirt system.
****

DESIGN MARGINS LISTED IN THE oneskirt.OPP FILE

In the table below is listed part of the oneskirt.OPP file pertaining to the margins corresponding to the "BEST FEASIBLE" design. There are two aspects of this list that are emphasized here:

1. The margins for both Load Case 1 and Load Case 2 are combined, those corresponding to Load Case 1 the first 22 margins and those corresponding to Load Case 2 margins 23 - 44.

2. Margins 1 - 4 (Load Case 1) and 23 - 26 (Load Case 2) are generated from the "fleshed out" "behavior" routine, SUBROUTINE BEHX1. (See the file, behavior.tank2.) These margins are the same as the corresponding margins listed in the first and second parts of the above list.

3. Margins 19 and 20 (Load Case 1) and 41 and 42 (Load Case 2) are generated from the "fleshed out" "behavior" routine, SUBROUTINE BEHX6. (See the file, behavior.tank2.) These margins are the same as the corresponding margins listed in the first and second parts of the above list.

4. Margins 21 and 22 (Load Case 1) and 43 and 44 (Load Case 2) are generated from the "fleshed out" "behavior" routine, SUBROUTINE BEHX7. (See the file, behavior.tank2.) These margins are the same as the corresponding margins listed in the first and second parts of the above list.

5. There are many more margins listed below (44 margins) than are listed above for both Load Case 1 and Load Case 2 (16 margins). These "extra" margins listed below are all very, very high. That is because they are generated from the following SKELETAL "behavior" routines:

Margins 5 - 9 (Load Case 1) and 27 - 31 (Load Case 2) are generated from the SKELETAL SUBROUTINE BEHX2. (See the file, behavior.tank2.)

Margins 10 - 14 (Load Case 1) and 32 - 36 (Load Case 2) are generated from the SKELETAL SUBROUTINE BEHX3. (See the file, behavior.tank2.)

Margins 15 and 16 (Load Case 1) and 37 and 38 (Load Case 2) are generated from the SKELETAL SUBROUTINE BEHX4. (See the file, behavior.tank2.)

Margins 17 and 18 (Load Case 1) and 39 and 40 (Load Case 2) are generated from the SKELETAL SUBROUTINE BEHX5. (See the file, behavior.tank2.)

The SKELETAL "behavior" routines, BEHX2, BEHX3, BEHX4 and BEHX5, do nothing presently. Therefore, the design margins associated with them remain at their initialized values, which are automatically set very high by the GENOPT system. The initialized values are set very high so that these uncomputed margins will not affect the evolution of the optimum design during design iterations.

The question arises: why do these SKELETAL "behavior" routines and their associated uncomputed margins exist at all? The answer: Originally I had plans to "flesh out" BEHX2, BEHX3, BEHX4 and BEHX5. I have now decided to put that off to the future or not to do it at all. No computer time is used for execution of these SKELETAL "behavior" routines. Therefore, there is no harm in leaving them in place.

MARGINS LISTED NEAR THE END OF THE oneskirt.OPP FILE CORRESPONDING TO THE "BEST FEASIBLE" DESIGN

```
=================================================================================
 MARGINS CORRESPONDING TO THE DESIGN (F.S.= FACTOR OF SAFETY)
 MAR.   CURRENT
 NO.     VALUE            DEFINITION
  1     7.330E-01  (FREQ(1 ,1 )/FREQA(1 ,1 )) / FREQF(1 ,1 )-1; F.S.=  1.20
  2    -1.001E-03  (FREQ(1 ,2 )/FREQA(1 ,2 )) / FREQF(1 ,2 )-1; F.S.=  1.20
  3     1.186E+00  (FREQ(1 ,3 )/FREQA(1 ,3 )) / FREQF(1 ,3 )-1; F.S.=  1.20
  4     1.912E-01  (FREQ(1 ,4 )/FREQA(1 ,4 )) / FREQF(1 ,4 )-1; F.S.=  1.20
  5     9.371E+14  (STRES1A(1 ,1 )/STRES1(1 ,1 )) / STRES1F(1 ,1 )-1; F.S.=  1.
  6     6.981E+14  (STRES1A(1 ,2 )/STRES1(1 ,2 )) / STRES1F(1 ,2 )-1; F.S.=  1.
  7     7.038E+13  (STRES1A(1 ,3 )/STRES1(1 ,3 )) / STRES1F(1 ,3 )-1; F.S.=  1.
  8     9.686E+13  (STRES1A(1 ,4 )/STRES1(1 ,4 )) / STRES1F(1 ,4 )-1; F.S.=  1.
  9     4.193E+13  (STRES1A(1 ,5 )/STRES1(1 ,5 )) / STRES1F(1 ,5 )-1; F.S.=  1.
 10     9.371E+14  (STRES2A(1 ,1 )/STRES2(1 ,1 )) / STRES2F(1 ,1 )-1; F.S.=  1.
 11     6.981E+14  (STRES2A(1 ,2 )/STRES2(1 ,2 )) / STRES2F(1 ,2 )-1; F.S.=  1.
 12     7.038E+13  (STRES2A(1 ,3 )/STRES2(1 ,3 )) / STRES2F(1 ,3 )-1; F.S.=  1.
 13     9.686E+13  (STRES2A(1 ,4 )/STRES2(1 ,4 )) / STRES2F(1 ,4 )-1; F.S.=  1.
 14     4.193E+13  (STRES2A(1 ,5 )/STRES2(1 ,5 )) / STRES2F(1 ,5 )-1; F.S.=  1.
 15     5.000E+09  (SHLBUK(1 ,1 )/SHLBUKA(1 ,1 )) / SHLBUKF(1 ,1 )-1; F.S.=  2.
 16     5.000E+09  (SHLBUK(1 ,2 )/SHLBUKA(1 ,2 )) / SHLBUKF(1 ,2 )-1; F.S.=  2.
 17     1.500E+14  (FORCEA(1 ,1 )/FORCE(1 ,1 )) / FORCEF(1 ,1 )-1; F.S.=  1.00
 18     1.500E+14  (FORCEA(1 ,2 )/FORCE(1 ,2 )) / FORCEF(1 ,2 )-1; F.S.=  1.00
 19    -6.393E-03  (TNKSTRA(1 ,1 )/TNKSTR(1 ,1 )) / TNKSTRF(1 ,1 )-1; F.S.=  1.
 20    -6.393E-03  (TNKSTRA(1 ,2 )/TNKSTR(1 ,2 )) / TNKSTRF(1 ,2 )-1; F.S.=  1.
```

```
 21   -2.391E-03  (TNKBUK(1 ,1 )/TNKBUKA(1 ,1 )) / TNKBUKF(1 ,1 )-1; F.S.=  1.
 22   -2.394E-03  (TNKBUK(1 ,2 )/TNKBUKA(1 ,2 )) / TNKBUKF(1 ,2 )-1; F.S.=  1.
 23    7.330E-01  (FREQ(2 ,1 )/FREQA(2 ,1 )) / FREQF(2 ,1 )-1; F.S.=  1.20
 24   -1.001E-03  (FREQ(2 ,2 )/FREQA(2 ,2 )) / FREQF(2 ,2 )-1; F.S.=  1.20
 25    1.186E+00  (FREQ(2 ,3 )/FREQA(2 ,3 )) / FREQF(2 ,3 )-1; F.S.=  1.20
 26    1.912E-01  (FREQ(2 ,4 )/FREQA(2 ,4 )) / FREQF(2 ,4 )-1; F.S.=  1.20
 27    9.371E+14  (STRES1A(2 ,1 )/STRES1(2 ,1 )) / STRES1F(2 ,1 )-1; F.S.=  1.
 28    6.981E+14  (STRES1A(2 ,2 )/STRES1(2 ,2 )) / STRES1F(2 ,2 )-1; F.S.=  1.
 29    7.038E+13  (STRES1A(2 ,3 )/STRES1(2 ,3 )) / STRES1F(2 ,3 )-1; F.S.=  1.
 30    9.686E+13  (STRES1A(2 ,4 )/STRES1(2 ,4 )) / STRES1F(2 ,4 )-1; F.S.=  1.
 31    4.193E+13  (STRES1A(2 ,5 )/STRES1(2 ,5 )) / STRES1F(2 ,5 )-1; F.S.=  1.
 32    9.371E+14  (STRES2A(2 ,1 )/STRES2(2 ,1 )) / STRES2F(2 ,1 )-1; F.S.=  1.
 33    6.981E+14  (STRES2A(2 ,2 )/STRES2(2 ,2 )) / STRES2F(2 ,2 )-1; F.S.=  1.
 34    7.038E+13  (STRES2A(2 ,3 )/STRES2(2 ,3 )) / STRES2F(2 ,3 )-1; F.S.=  1.
 35    9.686E+13  (STRES2A(2 ,4 )/STRES2(2 ,4 )) / STRES2F(2 ,4 )-1; F.S.=  1.
 36    4.193E+13  (STRES2A(2 ,5 )/STRES2(2 ,5 )) / STRES2F(2 ,5 )-1; F.S.=  1.
 37    5.000E+09  (SHLBUK(2 ,1 )/SHLBUKA(2 ,1 )) / SHLBUKF(2 ,1 )-1; F.S.=  2.
 38    5.000E+09  (SHLBUK(2 ,2 )/SHLBUKA(2 ,2 )) / SHLBUKF(2 ,2 )-1; F.S.=  2.
 39    1.500E+14  (FORCEA(2 ,1 )/FORCE(2 ,1 )) / FORCEF(2 ,1 )-1; F.S.=  1.00
 40    1.500E+14  (FORCEA(2 ,2 )/FORCE(2 ,2 )) / FORCEF(2 ,2 )-1; F.S.=  1.00
 41    2.873E-02  (TNKSTRA(2 ,1 )/TNKSTR(2 ,1 )) / TNKSTRF(2 ,1 )-1; F.S.=  1.
 42    2.844E-03  (TNKSTRA(2 ,2 )/TNKSTR(2 ,2 )) / TNKSTRF(2 ,2 )-1; F.S.=  1.
 43    7.005E-01  (TNKBUK(2 ,1 )/TNKBUKA(2 ,1 )) / TNKBUKF(2 ,1 )-1; F.S.=  1.
 44    7.734E-01  (TNKBUK(2 ,2 )/TNKBUKA(2 ,2 )) / TNKBUKF(2 ,2 )-1; F.S.=  1.
```

==

MINOR INCONSISTENCY IN FILE NAMING IN THE GENERIC CASE CALLED "tank2"

In the generic case "tank2" (tank/skirt system) the following "behavioral" subroutines exist: BEHX1 (free vibration), BEHX2 (skeletal), BEHX3 (skeletal), BEHX4 (skeletal), BEHX5 (skeletal), BEHX6 (stress in the tank/skirt system) and BEHX7 (buckling of the tank/skirt system). The output file, oneskirt.OPM (called oneskirt.vardensity.opm here) contains the following lines:

```
 CHAPTER 12: Maximum effective stress in the propellant tank/
 skirt system - BEHX8xy, x=1,2 x=meridian; y=1,2 y=load case
 The tank/skirt system is loaded by PRESS, GAXIAL, GLATRL, and
 TNKCOOL. The purpose of this model is to compute the maximum
 effective stress in the isotropic propellant tank and the
 maximum stress in the supporting skirt(s), which consist of
 five segments each of combined isotropic and laminated
 composite material. This is an "INDIC=3" BIGBOSOR4 model.


 BIGBOSOR4 input file for load case  1:
 maximum stress in propellant tank/skirt system from the
 prebuckling load distribution on the meridian at angle,
 CIRCANG(JCOL)=  0.0000E+00 in which JCOL = 1
oneskirt.BEHX811
```

----

and

```
 CHAPTER 13: Buckling of the propellant tank/skirt system
 - BEHX9xy, x=1,2 x=meridian; y=1,2 y=load case
 This tank/skirt 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/skirt system is loaded by PRESS, GAXIAL,
 GLATRL and TNKCOOL. The purpose of this model is to compute
 the minimum buckling load in the propellant tank/skirt system.
 This is an "INDIC=4" BIGBOSOR4 model.


 BIGBOSOR4 input file for load case  1:
 buckling in the propellant tank/skirt system from the
 prebuckling load distribution on the meridian at angle,
 CIRCANG(JCOL)=  0.0000E+00 in which JCOL = 1
oneskirt.BEHX911
```

Actually, the maximum stresses in the tank/skirt system "tank2" are computed in SUBROUTINE BEHX6, not in SUBROUTINE BEHX8, and the buckling loads in the tank/skirt system "tank2" are computed in SUBROUTINE BEHX7, not in SUBROUTINE BEHX9 as are implied in the above lines of "oneskirt" output. However, I kept the terminology, "BEHX8xy" and "BEHX9xy", "erroneous" for the generic "tank2" case, because they are the same as those in the generic case, "tank", for which that terminology is correct. I kept the same names of the BEHXxxx files because then the file, bigbosor4.input.test.BEHX.files, still applies for "tank2". Files in the "tank2" specific cases with the same "BEHXxxx" names as those used in the "tank" specific cases therefore have the same purpose, compute the same things.

ACCURATE RESULT FOR FREE VIBRATION MODELS WITH "LUMPED" PROPELLANT MASS

In APPENDIX 2 of [1] are listed modifications to bosdec and addbosor4 required in order to obtain an accurate "lumping" of the propellant mass into the middle layer (Layer No. 2) of the propellant tank. The modified version of bosdec is called "bosdec.density.var" and the modified version of addbosor4 is called "addbosor4.density.var". These names reflect the property that for shells of revolution other than cylindrical shells the "lumped" density of the propellant varies within each shell segment, a property that BIGBOSOR4 cannot handle. The modified versions of bosdec and addbosor4 are called "temporary" versions in [1] because they are valid only for the generic case called "tank", not for shells with any type of wall construction.

Analogous modifications to bosdec and addbosor4 must be made for the generic case, "tank2", in which a propellant tank is supported by one or two skirts. However, these analogous modifications are not identical. For the generic case called "tank2" the variable called DENMLT must be an array, DENMLT(295), in which 295 is the maximum number of shell segments permitted in a BIGBOSOR4 model. The modifications are very like those listed in APPENDIX 2 of [1] except that everywhere DENMLT appears it is an array and the shell segment number, ISEG, must be introduced into the argument list of SUBROUTINE CFBL.

The modified bosdec and addbosor4 files are called: bosdec.tank2.density.var and addbosor4.tank2.density.var .

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

cp /home/progs/genopt/case/tank/addbosor4.tank2.density.var   /home/progs/bosdec/sources/addbosor4.src

cp /home/progs/genopt/case/tank/bosdec.tank2.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".

HOW THE STRESS CONSTRAINTS ARE COMPUTED FOR THE GENERIC "tank2" CASE

The generic case, "tank2", is fundamentally different from the generic case, "tank" in that in "tank2" the entire structure, propellant tank plus supporting skirt(s) is one BIGBOSOR4 model. In contrast, in "tank" [1] separate BIGBOSOR4 models exist for the unsupported propellant tank and for a sample strut. The five stress components in the sample strut are computed from a BIGBOSOR4 model containing only that strut. Stresses in the propellant tank are computed from a BIGBOSOR4 model containing only the propellant tank, with the struts being replaced by the concentrated loads that they apply to the tank.

In the "tank2" model BIGBOSOR4 finds the maximum stress components anywhere in the tank/skirt system. For example, for the optimized specific case called "oneskirt", Load Case 1 (10 g axial acceleration, 25 psi ullage pressure, -200 degrees propellant tank cool-down; the BIGBOSOR4 input file is called "oneskirt.BEHX811") the list output from the BIGBOSOR4 stress analysis (BIGBOSOR4 output file is called "oneskirt.OUT") contains the following:

From the BIGBOSOR4 output list for optimized vardensity case (BIGBOSOR4 input file = oneskirt.BEHX811):

```
==========================================================================================
****** (ALLOWABLE STRESS)/(ACTUAL STRESS) ********
  1  3.6054E+00 effect. stress: matl=1 ,  A , seg=4 , node=2 , layer=1 ,z=-0.05  ;FS=  1.00
  2  5.1397E+01 fiber tension : matl=2 ,  A , seg=2 , node=1 , layer=11,z= 0.04  ;FS=  1.00
  3  4.2492E+00 fiber compres.: matl=2 ,  A , seg=4 , node=13, layer=13,z= 0.05  ;FS=  1.00
  4  2.2908E+00 transv tension: matl=2 ,  A , seg=3 , node=91, layer=8 ,z= 0.02  ;FS=  1.00
  5  1.0799E+01 in-plane shear: matl=2 ,  A , seg=3 , node=92, layer=1 ,z=-0.05  ;FS=  1.00
  6  9.9369E-01 fiber tension : matl=3 ,  A , seg=17, node=8 , layer=1 ,z=-0.26  ;FS=  1.00
  7  2.8139E+00 fiber compres.: matl=3 ,  A , seg=21, node=51, layer=1 ,z=-0.23  ;FS=  1.00
  8  1.3974E+00 transv tension: matl=3 ,  A , seg=18, node=6 , layer=1 ,z=-0.03  ;FS=  1.00
  9  1.8388E+00 transv compres: matl=3 ,  A , seg=23, node=1 , layer=1 ,z=-0.24  ;FS=  1.00
 10  1.5450E+00 effect. stress: matl=4 ,  A , seg=17, node=3 , layer=2 ,z=-0.06  ;FS=  1.00
 11  1.5188E+00 effect. stress: matl=5 ,  A , seg=19, node=2 , layer=3 ,z= 0.03  ;FS=  1.00
 12  1.3104E+00 effect. stress: matl=6 ,  A , seg=18, node=5 , layer=2 ,z= 0.03  ;FS=  1.00
```

```
 13  1.5674E+00 effect. stress: matl=7 ,  A , seg=23, node=1 , layer=2 ,z=-0.04  ;FS=  1.00
 ****************************************************

 ****** MAX. NORMAL DISPLACEMENT, LOAD SET A ************
 WWWMAX(1)=  7.9681E-01, LOCATW(1)=1000*ISEG+I=  6001
 ********************************************************

 ****** MAX. EFF. STRESS IN ISOTROPIC WALL,LOAD A ******
 STRMAX(1)=  1.1141E+04, LOCATS(1)=1000*ISEG+I=  5013
 ******************************************************
==========================================================================================
```

The top part of the above list [labelled "ALLOWABLE STRESS)/(ACTUAL STRESS)] is generated from the shell segments for which the wall type, NWALL = 9. Segments 1 - 5 represent the one supporting skirt, and the rest of the segments (6 - 33) represent the propellant tank. The end of the above list:

```
 ****** MAX. EFF. STRESS IN ISOTROPIC WALL,LOAD A ******
 STRMAX(1)=  1.1141E+04, LOCATS(1)=1000*ISEG+I=  5013
 ******************************************************
```

is generated from the shell segments for which the wall type, NWALL = 2 (isotropic material). In the "oneskirt" model this means Segments 1 and 5.

The GENOPT/BIGBOSOR4 "behavior" routine, SUBROUTINE BEHX6, generates the single maximum stress quantity, TNKSTR(1,1), needed for computation of the design margin called:

```
(TNKSTRA(1,1)/TNKSTR(1,1))/TNKSTRF(1,1)-1; F.S.= 1.00
```

SUBROUTINE BEHX6 computes TNKSTR(1,1) using the data listed above. Output listed in the oneskirt.OPM file generated by SUBROUTINE BEHX6 is listed here:

from GENOPT/BIGBOSOR4 output list for optimized vardensity case (listed in the file, oneskirt.OPM):

```
==========================================================================================
BIGBOSOR4 input file for load case  1:
 maximum stress in propellant tank/skirt system from the
 prebuckling load distribution on the meridian at angle,
 CIRCANG(JCOL)=  0.0000E+00 in which JCOL = 1
oneskirt.BEHX811

 ***** MAX. NORMAL DISP.: PROPELLANT TANK *******

 ****** MAX. NORMAL DISPLACEMENT, LOAD SET A ************
 WWWMAX(1)=  7.9681E-01, LOCATW(1)=1000*ISEG+I=  6001
 ********************************************************

 ****** (ALLOWABLE STRESS)/(ACTUAL STRESS) ********
  1  3.6054E+00 effect. stress: matl=1 ,  A , seg=4 , node=2 , layer=1 ,z=-0.05  ;FS=  1.00
  2  5.1397E+01 fiber tension : matl=2 ,  A , seg=2 , node=1 , layer=11,z= 0.04  ;FS=  1.00
  3  4.2492E+00 fiber compres.: matl=2 ,  A , seg=4 , node=13, layer=13,z= 0.05  ;FS=  1.00
  4  2.2908E+00 transv tension: matl=2 ,  A , seg=3 , node=91, layer=8 ,z= 0.02  ;FS=  1.00
  5  1.0799E+01 in-plane shear: matl=2 ,  A , seg=3 , node=92, layer=1 ,z=-0.05  ;FS=  1.00
  6  9.9369E-01 fiber tension : matl=3 ,  A , seg=17, node=8 , layer=1 ,z=-0.26  ;FS=  1.00
  7  2.8139E+00 fiber compres.: matl=3 ,  A , seg=21, node=51, layer=1 ,z=-0.23  ;FS=  1.00
  8  1.3974E+00 transv tension: matl=3 ,  A , seg=18, node=6 , layer=1 ,z=-0.03  ;FS=  1.00
  9  1.8388E+00 transv compres: matl=3 ,  A , seg=23, node=1 , layer=1 ,z=-0.24  ;FS=  1.00
```

```
 10  1.5450E+00 effect. stress: matl=4 ,  A , seg=17, node=3 , layer=2 ,z=-0.06  ;FS=  1.00
 11  1.5188E+00 effect. stress: matl=5 ,  A , seg=19, node=2 , layer=3 ,z= 0.03  ;FS=  1.00
 12  1.3104E+00 effect. stress: matl=6 ,  A , seg=18, node=5 , layer=2 ,z= 0.03  ;FS=  1.00
 13  1.5674E+00 effect. stress: matl=7 ,  A , seg=23, node=1 , layer=2 ,z=-0.04  ;FS=  1.00
 ****************************************************
 Stress=  2.7350E+03 fiber tension : matl=2 ,  A , seg=2 , node=1 , layer=11,z= 0.04  ;FS=  1.00
 Stress=  5.0317E+04 fiber tension : matl=3 ,  A , seg=17, node=8 , layer=1 ,z=-0.26  ;FS=  1.00
 Stress=  2.4643E+04 fiber compres.: matl=2 ,  A , seg=4 , node=13, layer=13,z= 0.05  ;FS=  1.00
 Stress=  1.7769E+04 fiber compres.: matl=3 ,  A , seg=21, node=51, layer=1 ,z=-0.23  ;FS=  1.00
 Stress=  4.6084E+03 transv tension: matl=2 ,  A , seg=3 , node=91, layer=8 ,z= 0.02  ;FS=  1.00
 Stress=  3.5781E+04 transv tension: matl=3 ,  A , seg=18, node=6 , layer=1 ,z=-0.03  ;FS=  1.00
 Stress=  2.7192E+04 transv compres: matl=3 ,  A , seg=23, node=1 , layer=1 ,z=-0.24  ;FS=  1.00
 Stress=  5.8244E+02 in-plane shear: matl=2 ,  A , seg=3 , node=92, layer=1 ,z=-0.05  ;FS=  1.00
 Stress=  1.3868E+04 effect. stress: matl=1 ,  A , seg=4 , node=2 , layer=1 ,z=-0.05  ;FS=  1.00
 Stress=  3.2363E+04 effect. stress: matl=4 ,  A , seg=17, node=3 , layer=2 ,z=-0.06  ;FS=  1.00
 Stress=  3.2921E+04 effect. stress: matl=5 ,  A , seg=19, node=2 , layer=3 ,z= 0.03  ;FS=  1.00
 Stress=  3.8157E+04 effect. stress: matl=6 ,  A , seg=18, node=5 , layer=2 ,z= 0.03  ;FS=  1.00
 Stress=  3.1901E+04 effect. stress: matl=7 ,  A , seg=23, node=1 , layer=2 ,z=-0.04  ;FS=  1.00
 Modified maximum stress components for Load Case  1 STRESS2(i),i=1,6=
     5.0317E+04     1.7769E+04     3.5781E+04     2.7192E+04     4.6299E+03     3.8157E+04
     fiber tension  fiber compres. transv tension transv compres in-plane shear effect. stress

 ***** MAX. STRESS IN THE PROPELLANT TANK *******

 ****** MAX. EFF. STRESS IN ISOTROPIC WALL,LOAD A ******
 STRMAX(1)=  1.1141E+04, LOCATS(1)=1000*ISEG+I=  5013
 ******************************************************

 ****** MAX. EFF. STRESS IN ISOTROPIC WALL,LOAD A ******
 STRMAX(1)=  1.1141E+04, LOCATS(1)=1000*ISEG+I=  5013
 ******************************************************

 ****** MAX. EFF. STRESS IN NWALL =9 SEGS, LOAD A ******
 STRESS=     5.0317E+04
fiber tension : matl=3 ,  A , seg=17, node=8 , layer=1 ,z=-0.26  ;FS=  1.00
 ******************************************************
   19        50317.44      maximum stress in the propellant tank: TNKSTR(1 ,1 )
============================================================================================
```

The list above contains the following three lines:

```
Modified maximum stress components for Load Case  1 STRESS2(i),i=1,6=
     5.0317E+04     1.7769E+04     3.5781E+04     2.7192E+04     4.6299E+03     3.8157E+04
     fiber tension  fiber compres. transv tension transv compres in-plane shear effect. stress
```

One or more of the stress components listed just above these three lines has to be modified because the maximum allowable stress components for a ply of the laminated composite skirt are different from the maximum allowable stress, TNKSTRA(1,1). In the example presented here the "in-plane shear" component is the only critical component that requires modification because all the other maximum stress components correspond to stress in a metallic part of the structure for which the maximum allowable stress is equal to TNKSTRA(1,1).

The part of the FORTRAN coding in SUBROUTINE BEHX6 that generates the "oneskirt.OPM" output listed above is as follows:

```
          DO 78 I = 1,6
            STRESS2(ILOADX,I) = 0.
            DO 75 J = 1,ICONST
```

```
            ILET = INDEX(STRWRD(J),STRING(I))
            IF (ILET.NE.0.AND.STRRAT(J).NE.0.0) THEN
               ILET2 = INDEX(STRWRD(J),'matl=2')
               IF (ILET2.NE.0) THEN
                IF (JCOL.EQ.1) THEN
                  STRESS3(ILOADX,I) = STRES1A(ILOADX,I)/STRRAT(J)
                  RATIO(I) = TNKSTRA(ILOADX,JCOL)/STRES1A(ILOADX,I)
                ENDIF
                IF (JCOL.EQ.2) THEN
                  STRESS3(ILOADX,I) = STRES2A(ILOADX,I)/STRRAT(J)
                  RATIO(I) = TNKSTRA(ILOADX,JCOL)/STRES2A(ILOADX,I)
                ENDIF
               ELSE
                STRESS3(ILOADX,I) = TNKSTRA(ILOADX,JCOL)/STRRAT(J)
                RATIO(I) = 1.0
               ENDIF
               IF (NPRINX.GE.2) WRITE(IFILE,'(A,1PE12.4,1X,A)')
     1         ' Stress=',STRESS3(ILOADX,I),STRWRD(J)(1:76)
               STRESS2(ILOADX,I) =
     1            MAX(STRESS2(ILOADX,I),STRESS3(ILOADX,I)*RATIO(I))
C234567890123456789012345678901234567890123456789012345678901234567890123456789012
            ENDIF
   75     CONTINUE
   76     CONTINUE
   78   CONTINUE
C
      IF (NPRINX.GE.2) THEN
       WRITE(IFILE,'(A,I2,A,/,1P6E15.4)')
     1 ' Modified maximum stress components for Load Case ',ILOADX,
     1 ' STRESS2(i),i=1,6=',(STRESS2(ILOADX,I),I=1,6)
       WRITE(IFILE,'(5X,A,1X,A,1X,A,1X,A,1X,A,1X,A)') (STRING(I),I=1,6)
      ENDIF
```

The maximum stress components are modified by the quantity called "RATIO(I)".

FILES PERTAINING TO THE GENERIC CASE, "tank2", AND THE SPECIFIC CASE, "oneskirt"

The following files pertain to the GENERIC case, "tank2":

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

  86604 Feb 27 10:01 behavior.tank2              ("fleshed-out" version)
 180559 Feb 27 08:45 bosdec.tank2                ("permanent" version)
  27044 Feb 24 13:20 struct.tank2                ("fleshed-out" version)
  37971 Feb 12 18:42 tank2.DEF                   (general information)
```

```
 121887 Feb  5 03:33 tank2.INP                      (input for GENTEXT)
  47462 Feb 12 18:42 tank2.PRO      (Table 2)    (prompting file)
   8725 Feb 12 18:43 tank2.glossary (Table 1)    (glossary of variables)
 681340 Feb 26 06:55 addbosor4.tank2.density.var ("temporary" version)
 680079 Feb 26 06:38 addbosor4.regular           ("premanent" version)
 181111 Feb 27 08:38 bosdec.tank2.density.var    ("temporary" version)
```

RESULTS FOR THE GENERIC CASE, "tank2", AND THE SPECIFIC CASE, "oneskirt"

The glossary of variable names and definitions for the generic case called "tank2" is given in Table 1. Table2 lists the prompting file, tank2.PRO, generated automatically by the GENOPT processor called "GENTEXT" with use of the GENOPT user's input listed in the tank2.INP file (input for GENTEXT).

Please see the files starting with the string, “oneskirt”, that are listed under the headings, **“2. / 3. Files of input / output data for the specific cases called “oneskirt” and “twoskirt” (located in the folders, tanktank2/tank2paper/onetwoskirt.input / tanktank2/tank2paper/onetwoskirt.output)”**.

Input data for the specific case, "oneskirt" are listed in Tables 3, 4, 5 and 8. Results from the optimized design are listed in Table 6 and the optimum design is archived in Table 7. The discretized BIGBOSOR4 model of the optimized "oneskirt" design is displayed in Fig. 1. Figure 2a shows the evolution of the objective versus design iterations during an execution of SUPEROPT with use of the “temporary” versions of bosdec (bosdec.tank2.density.var) and addbosor4 (addbosor4.tank2.density.var). Figure 2b shows the same with use of the “permanent” versions of bosdec (bosdec.tank2) and addbosor4 (addbosor4.regular). Figures 3 – 6 show modal vibration results from the optimized “oneskirt” design obtained with use of the “permanent” versions of bosdec and addbosor4. Figures 7 - 13 show results obtained from the "stand-alone" BIGBOSOR4 for the optimized design with use of the "temporary" versions of bosdec (bosdec.tank2.density.var) and addbosor4 (addbosor4.tank2.density.var). All of these results should be compared with predictions from STAGS.

Figures 14 - 21 (pertaining to the old optimum design determined before certain errors were found in the “tank2” software, behavior.tank2, bosdec.tank2, and bosdec.tank2.density.var) show the design margins as functions of certain selected decision variables. These results are obtained from a "design sensitivity" analysis of the optimized "oneskirt" configuration (ITYPE=3 in the oneskirt.OPT file).

NOTE: Figures 14 - 21 were generated with the old optimum design obtained before certain corrections were made to the “tank2” software: behavior.tank2, bosdec.tank2 and bosdec.tank2.density.var. Please think of these figures only as a demonstration of the capability of GENOPT/BIGBOSOR4 to perform design sensitivity analyses of the sort shown here.

RESULTS FOR THE GENERIC CASE, "tank2", AND THE SPECIFIC CASE, "twoskirt"

Please see the files starting with the string, “twoskirt”, that are listed under the headings, **“2. / 3. Files of input / output data for the specific cases called “oneskirt” and “twoskirt” (located in the folders, tanktank2/tank2paper/onetwoskirt.input / tanktank2/tank2paper/onetwoskirt.output)”**.

Input data for the specific case, "twoskirt" are listed in the files, twoskirt.BEG, twoskirt.DEC, and twoskirt.OPT. The optimum design obtained with use of the “temporary” versions of bosdec (bosdec.tank2.density.var) and addbosor4 (addbosor4.tank2.density.var) is listed in the file, twoskirt.vardensity.opm, and this optimum design is archived in the file, twoskirt.vardensity.chg.

Figures 22 – 30, pertaining to the “twoskirt” configuration, are more or less analogous to Figs. 2 – 13, which pertain to the “oneskirt” configuration.

Decision variable candidates for the case called "twoskirt" (These values correspond to the optimum design determined from a partial execution of SUPEROPT. See the file called "twoskirt.vardensity.opm".)

```
 ===============================================================================
VALUES OF DESIGN VARIABLES CORRESPONDING TO BEST FEASIBLE DESIGN
 VAR.   CURRENT
 NO.     VALUE            DEFINITION
  1    7.334E-02  thickness of the tank aft dome skin: THKAFT
  2    5.196E-02  thickness of the tank cylinder skin: THKMID
  3    6.255E-02  thickness of the forward tank dome skin: THKFWD
  4    7.111E+00  spacing of the tank orthogrid stringers: STRSPC
  5    7.111E+00  spacing of the tank orthogrid rings: RNGSPC
  6    2.741E-01  thickness of the tank orthogrid stringers: STRTHK
  7    2.983E-01  height of the tank orthogrid stringers: STRHI
  8    2.741E-01  thickness of the tank orthogrid rings: RNGTHK
  9    2.983E-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    2.108E+01  global axial coordinate of "ground": ZGRND(1 )
 13    6.500E+02  global axial coordinate of "ground": ZGRND(2 )
 14    3.000E+01  axial length of the propellant tank doubler: DUBAXL(1 )
 15    1.455E-01  max.thickness of the propellant tank doubler: DUBTHK(1 )
 16    3.155E-02  thickness of the tank reinforcement ring: TRNGTH(1 )
 17    1.577E-01  height of the tank reinforcement ring: TRNGHI(1 )
 18    2.128E+00  tank-end length of one-layered skirt part: LNGTNK1(1 )
 19    2.128E+00  tank-end length of one-layered skirt part: LNGTNK1(2 )
 20    4.132E-02  tank-end thickness of tapered skirt part: THKTNK1(1 )
 21    5.173E-02  tank-end thickness of tapered skirt part: THKTNK1(2 )
 22    2.128E+00  tank-end length of tapered prongs: LNGTNK2(1 )
 23    2.000E+00  tank-end length of tapered prongs: LNGTNK2(2 )
 24    1.000E-02  tank-end thickness of one tapered prong: THKTNK2(1 )
 25    1.064E-02  tank-end thickness of one tapered prong: THKTNK2(2 )
 26    2.108E+00  "ground" end length of one-layered skirt part: LNGVEH1(1 )
 27    2.000E+00  "ground" end length of one-layered skirt part: LNGVEH1(2 )
 28    1.341E-02  "ground"-end thickness of tapered skirt part: THKVEH1(1 )
 29    1.958E-02  "ground"-end thickness of tapered skirt part: THKVEH1(2 )
 30    2.080E+00  "ground"-end length of tapered prongs: LNGVEH2(1 )
 31    2.000E+00  "ground"-end length of tapered prongs: LNGVEH2(2 )
 32    1.080E-02  "ground"-end thickness of one tapered prong: THKVEH2(1 )
 33    1.000E-02  "ground"-end thickness of one tapered prong: THKVEH2(2 )
 34    5.000E-03  thickness of a lamina: THICK(1 )
 35    5.000E-03  thickness of a lamina: THICK(2 )
```

```
 36    5.000E-03  thickness of a lamina: THICK(3 )
 37    5.000E-03  thickness of a lamina: THICK(4 )
 38    5.000E-03  thickness of a lamina: THICK(5 )
 39    5.000E-03  thickness of a lamina: THICK(6 )
 40    5.027E-03  thickness of a lamina: THICK(7 )
 41    5.027E-03  thickness of a lamina: THICK(8 )
 42    5.027E-03  thickness of a lamina: THICK(9 )
 43    5.027E-03  thickness of a lamina: THICK(10)
 44    5.027E-03  thickness of a lamina: THICK(11)
 45    5.027E-03  thickness of a lamina: THICK(12)
 46    6.768E+01  layup angle: ANGLE(1 )
 47   -6.768E+01  layup angle: ANGLE(2 )
 48    5.723E+01  layup angle: ANGLE(3 )
 49   -5.723E+01  layup angle: ANGLE(4 )
 50    5.660E+01  layup angle: ANGLE(5 )
 51   -5.660E+01  layup angle: ANGLE(6 )
 52    6.375E+01  layup angle: ANGLE(7 )
 53   -6.375E+01  layup angle: ANGLE(8 )
 54    6.384E+01  layup angle: ANGLE(9 )
 55   -6.384E+01  layup angle: ANGLE(10)
 56    6.400E+01  layup angle: ANGLE(11)
 57   -6.400E+01  layup angle: ANGLE(12)
======================================================================
```

Margins corresponding to the optimized design just listed

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

 MARGIN CURRENT
 NO.     VALUE            DEFINITION
  1    3.129E-01  (FREQ(1 ,1 )/FREQA(1 ,1 )) / FREQF(1 ,1 )-1; F.S.=  1.20
  2    9.676E-02  (FREQ(1 ,2 )/FREQA(1 ,2 )) / FREQF(1 ,2 )-1; F.S.=  1.20
  3    1.189E+00  (FREQ(1 ,3 )/FREQA(1 ,3 )) / FREQF(1 ,3 )-1; F.S.=  1.20
  4    1.052E+00  (FREQ(1 ,4 )/FREQA(1 ,4 )) / FREQF(1 ,4 )-1; F.S.=  1.20
  5   -2.512E-03  (TNKSTRA(1 ,1 )/TNKSTR(1 ,1 )) / TNKSTRF(1 ,1 )-1; F.S.=  1.00
  6   -2.512E-03  (TNKSTRA(1 ,2 )/TNKSTR(1 ,2 )) / TNKSTRF(1 ,2 )-1; F.S.=  1.00
  7    3.359E-01  (TNKBUK(1 ,1 )/TNKBUKA(1 ,1 )) / TNKBUKF(1 ,1 )-1; F.S.=  1.00
  8    3.359E-01  (TNKBUK(1 ,2 )/TNKBUKA(1 ,2 )) / TNKBUKF(1 ,2 )-1; F.S.=  1.00

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

 MARGIN CURRENT
 NO.     VALUE            DEFINITION
  1    3.129E-01  (FREQ(2 ,1 )/FREQA(2 ,1 )) / FREQF(2 ,1 )-1; F.S.=  1.20
  2    9.676E-02  (FREQ(2 ,2 )/FREQA(2 ,2 )) / FREQF(2 ,2 )-1; F.S.=  1.20
  3    1.189E+00  (FREQ(2 ,3 )/FREQA(2 ,3 )) / FREQF(2 ,3 )-1; F.S.=  1.20
  4    1.052E+00  (FREQ(2 ,4 )/FREQA(2 ,4 )) / FREQF(2 ,4 )-1; F.S.=  1.20
  5    1.641E-01  (TNKSTRA(2 ,1 )/TNKSTR(2 ,1 )) / TNKSTRF(2 ,1 )-1; F.S.=  1.00
  6    1.300E-01  (TNKSTRA(2 ,2 )/TNKSTR(2 ,2 )) / TNKSTRF(2 ,2 )-1; F.S.=  1.00
  7    4.069E-01  (TNKBUK(2 ,1 )/TNKBUKA(2 ,1 )) / TNKBUKF(2 ,1 )-1; F.S.=  1.00
```

```
  8    8.549E-01  (TNKBUK(2 ,2 )/TNKBUKA(2 ,2 )) / TNKBUKF(2 ,2 )-1; F.S.=  1.00
============================================================
```

Optimized objective:

```
===============================================================

******************** DESIGN OBJECTIVE *******************
 *************                             ***********
    CURRENT VALUE OF THE OBJECTIVE FUNCTION:

 VAR.   CURRENT
 NO.     VALUE            DEFINITION
  1    1.180E+00  WGTxTOTMAS/TNKNRM +(1-WGT)xCONDCT/CONNRM: CONDCT

 *************                          ************
 ******************** DESIGN OBJECTIVE *******************
 ******************************************************
 ***********  ALL 2 LOAD CASES PROCESSED ***********
 ==================================================================
```

CONCLUSIONS:

1. The GENOPT/BIGBOSOR4 "tank2" model seems to work. Comparisons of predictions from STAGS and GENOPT/BIGBOSOR4 should be made, however, because it is possible that horrible errors may still lurk in the software used to generate the results presented here.

2. The GENOPT software in the directory ../genopt/sources was significantly modified to permit more than 50 decision variable candidates. The maximum number of decision variable candidates has been raised from 50 to 98.

3. Predictions from GENOPT/BIGBOSOR4 should be compared with predictions from STAGS.

4. BIGBOSOR4 does not handle the effect of buckling under in-plane shear loading, which is present especially at the circumferential coordinate, theta = 90 degrees in the supporting skirt in Load Case 2 (10g lateral acceleration). In order to compensate for this an approximate PANDA2-type model has been introduced into the "tank2" software in order to predict with reasonable accuracy buckling of the laminated composite skirt(s).

5. The reader should read [1] in order to obtain much background information required for a fuller understanding of how GENOPT/BIGBOSOR4 works.

6. ********************* IMPORTANT NOTE ********************************
The figures labeled "old" that go with this text are now out of date because of software modifications made in behavior.tank2, bosdec.tank2 and bosdec.tank2.density.var during February, 2012. However, these figures and tables are still of some value because they demonstrate what GENOPT/BIGBOSOR4 does. The figures labeled "new" were obtained from results generated after the modifications to the software were implemented.

****

REFERENCE

[1] David Bushnell, Optimization of propellant tanks supported by optimized laminated composite tubular struts, unpublished report, February 2012