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# THE DETERMINATION OF EQUIVALENT BEARING LOADING FOR THE BSMT THAT SIMULATE SSME HIGH PRESSURE OXIDIZER TURBOPUMP CONDITIONS USING THE SHABERTH/SINDA COMPUTER PROGRAMS


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# THE DETERMINATION OF EQUIVALENT BEARING LOADING FOR THE BSMT THAT SIMULATE SSME HIGH PRESSURE OXIDIZER TURBOPUMP CONDITIONS USING THE SHABERTH/SINDA COMPUTER PROGRAMS

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## ABSTRACT

The MSFC bearing seal material tester (BSMT) can be used to evaluate the SSME high pressure oxygen turbopump (HPOTP) bearing performance. The four HPOTP bearings have both an imposed radial and axial load. These radial and axial loads are caused by the HPOTP's shaft, main impeller, preburner impeller, turbine and by the LOX coolant flow through the bearings respectively. These loads coupled with bearing geometry and operating speed can define bearing contact angle, contact Hertz stress and heat generation rates. The BSMT has the capability of operating at HPOTP shaft speeds, provide proper coolant flowrates but presently, can only apply an axial load. Due to the inability to operate the bearings in the BSMT with an applied radial load, it is important to develop an equivalency between the applied axial load and the actual HPOTP loadings.

In this study, the objective was to use the SHABERTH/SINDA (shaft-bearing-thermal) computer code to simulate the BSMT bearing-shaft geometry and thermal-fluid operating conditions. This study was performed at two shaft speeds using two coolants, LN2 and LOX. A simulation of the HPOTP was also generated by SRS/System Division using current operating conditions from the SSME HPOTP. Then, a comparison of the bearing contact stresses and heat generation rates of these two simulations was attempted to establish the equivalence between the BSMT axial load and the HPOTP loads.

## ACKNOWLEDGEMENTS

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I would especially like to thank my colleagues Mr. Henry P. Stinson and Mr. James P. Cannon who were valuable in formulating this project and providing the necessary technical assistance. A special appreciation is extended to Mr. Fredrick Bachtel and Mr. Glenn E. Wilmer of NASA/MSFC who greatly assisted in the author's operation and understanding of the SHABERTH/SINDA codes and provided the necessary technical background resources.

Also, a grateful appreciation is extended to Mr. Joe Cody of SRS/System Division, whose notes provided needed information for the program's input file, and Mr. Dave Marty of SRS/System Division, whose interest in the project constantly aided this author with the parametric study. Dave also performed execution of SHABERTH/SINDA, the construction of the appropriate files and the execution of the HPOTP simulation.

A special thanks to Ms. Sandra Gallik of Boeing Computer Support Services, who assisted the author in the use of the SPERRY/UNIVAC computer and to Ms. Gloria Gideon who diligently typed this manuscript. I would like to thank Mr. Loren Gross and all members of his Turbomachinery and Combustion Devices Branch for making this an enjoyable and productive summer experience.

## INTRODUCTION

In the Space Shuttle Main Engine (SSME) High Pressure Oxygen Turbopump (HPOTP), four ball bearings support a turbopump shaft, a main impeller, preburner impeller and turbine. Throughout the flight history of the SSME, these bearings have been subject to various degrees of damaging wear. Two possible causes for this wear are insufficient lubrication resulting in frictional heat generation and large contact (Hertz) stresses between the balls and the inner and outer races due to loading and bearing geometry variations. Even though these causes will be addressed in this study, numerous scenario's based on test data can be formulated to address the HPOTP bearing wear problem. The main source of test data is from instrumentation measurements of the HPOTP. However, due to the expense of this process, viable alternatives to predict bearing behavior must be established. One alternative is the use of the NASA-Marshall Space Flight Center (MSFC) Bearing Seal Material Tester (BSMT). Another relatively inexpensive alternative is to develop a computer model to simulate the bearing environment. A general program called SHABERTH (Shaft-Bearing-Thermal) developed originally by SKF Industries and later greatly modified by SRS Technologies/System Division exists and will be used to attempt this simulation. In addition to SHABERTH which analyzes the bearings and shaft, a code named SINDA (System Improved Numerical Differencing Analyzer) will be coupled to SHABERTH to perform the temperature calculations. Thus, this code will be referred to as SHABERTH/SINDA.

The major unknown in this study of bearing behavior is loading. From experimental studies on the HPOTP, Figure 1 shows the best estimate of the loads applied to the shaft due to the preburner impeller, main impeller and turbine that the bearings support. In addition to these radially applied loads, there also exists axially applied loads due to the pressure*area (PA loads) of the liquid oxygen (LOX) coolant that flows through the bearings. These PA loads are of particular importance when the turbopump throttles its speed.

Figure 2 shows a schematic of the bearing-shaft arrangement and the flow paths through the BSMT. To reproduce HPOTP conditions at this time is not possible since the tester has a different flow path than the HPOTP, the working fluid in the tester is LN2 (liquid nitrogen) not LOX, and most importantly, there can be only an applied axial load in the tester to simulate PA loading and preloading. Thus, presently, no radially load can be applied to simulate the radial HPOTP loads.

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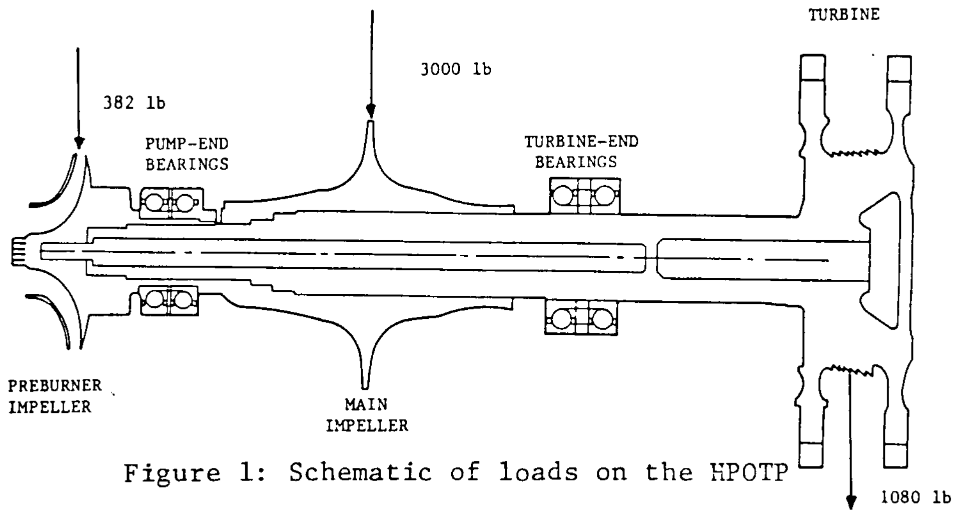


Figure 1: Schematic of loads on the HPOTP

The purpose of this study is to attempt to use SHABERTH/SINDA programs to model the BSMT. This model will only have applied axial loads on the shaft and will be used in conjunction with a model of the HPOTP that was conducted by Spectra Research Systems (SRS) to compare heat generation rates and Hertezian stresses. Hopefully, this study will establish which applied axial loads for the BSMT model corresponds to the combined radial and axial loads for the SRS HPOTP model. From the comparison of heat generation rates and contact stresses, a so-called "equivalent" load can be stated for the BSMT based on HPOTP loading cases. Note that several important parameters as coolant flow rate, bearing geometry changes, coefficient of friction, coolant inlet temperature and pressure drop will be held fixed in this study. This was done to limit the problem's scope not to infer the insignificance of these parameter's affect on bearing behavior. In this study, only shaft speed will be varied along with type of coolant used (LOX vs. LN2). Recall, LOX is the coolant of the HPOTP, however LN2 is the current working fluid for the BSMT. The BSMT is currently undergoing redesign changes to eventually use LOX as the working fluid again. So, equivalent loads will be established using both fluids for the BSMT to simulate HPOTP loading.

## OBJECTIVES

As previously stated, the purpose of this project is to simulate the BSMT conditions using the SHABERTH/SINDA computer code. Using this model of the tester and a turbopump simulation using SHABERTH/SINDA performed by SRS, a comparison of the heat generation rates and Hertz stresses will be made to attempt to correlate the axial load applied

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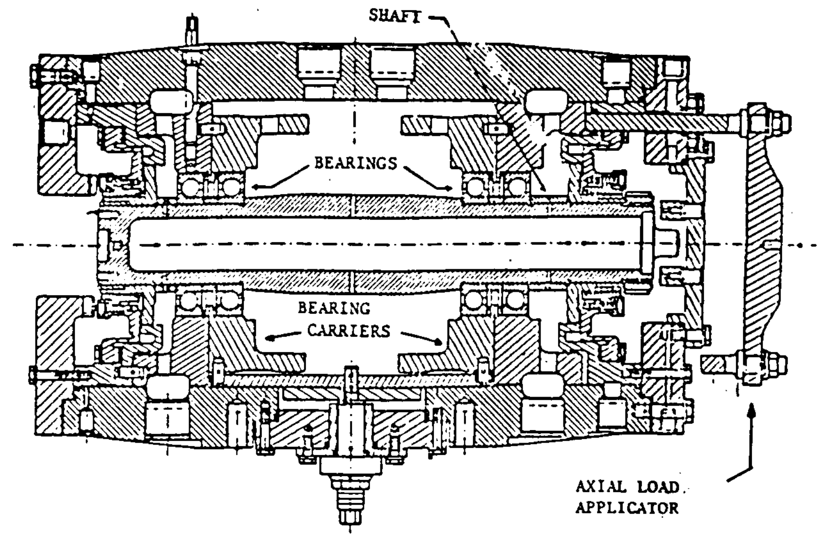
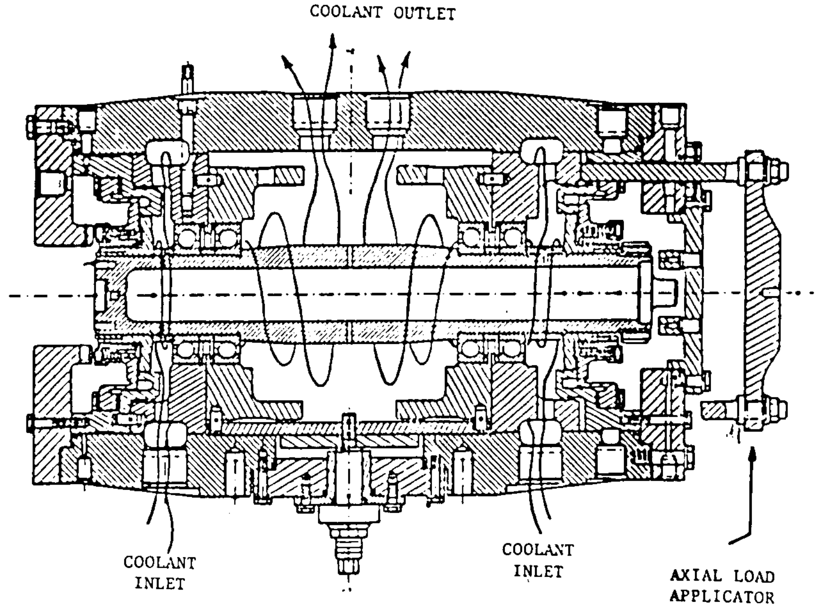



CURRENT BSMT LN2 (002) BUILD •1 CONFIGURATION

The Bearing Seals and Materials Tester




CURRENT BSMT LN2 (002) BUILD •1 CONFIGURATION

. The BSMT flow paths

Figure 2: The current BSMT and its flow paths

in the tester model to the axial-radial load combination that exists in the turbopump simulation. The objectives of this project were.

1. To develop the input data necessary for modelling the BSMT using LN2 and LOX and perform a parametric study.

2. To obtain SHABERTH/SINDA models of the turbopump from SRS/System Division.

3. To compare for two different shaft speeds for both LN2 and LOX, the heat generation rates and contact Hertz stresses of two models to correlate the loadings applied to the tester simulation to those applied in the turbopump simulation.

## SHABERTH/SINDA Computer Models

The SHABERTH program is structured in four sections: thermal, bearing dimensional equilibrium, shaft-bearing system load equilibrium and bearing rolling element and cage load equilibrium. A detailed account of these sections, bearing equations that are used, flowcharts of program structure, and sample input and output are described in reference (3). The bearing theory used in this problem is based on reference (1) by Harris. When SHABERTH was modified for the HPOTP by SRS, it was decided not to use the SHABERTH thermal model but to replace it with SINDA. SHABERTH uses an assumed set of temperatures given by a user then calculates all the bearing forces and moments, Hertz stresses, bearing geometry changes and heat generation rates. SINDA uses the calculated heat generation rates from SHABERTH to compute a temperature distribution. A UNIVAC computer runstream which controls the program flow replaces the assumed temperatures with the newly calculated SINDA temperatures. These temperatures that are being compared are of the shaft, inner ring, inner race, ball, outer race, outer ring, housing, bulk fluid temperature respectively. This iteration process between SHABERTH and SINDA continues until thermal convergence to 2$^{\circ}$F occurs, or thermal runaway to 1000$^{\circ}$F diverges the solution or when 15 iterations occur usually related to an oscillating solution. Maximum runtime or maximum number of pages usually is associated with a divergence or oscillating solution. A good indicator of this type solution is when SINDA cannot reach an energy balance. For these cases of divergence, the SHABERTH/SINDA simulation will terminate. For convergence,

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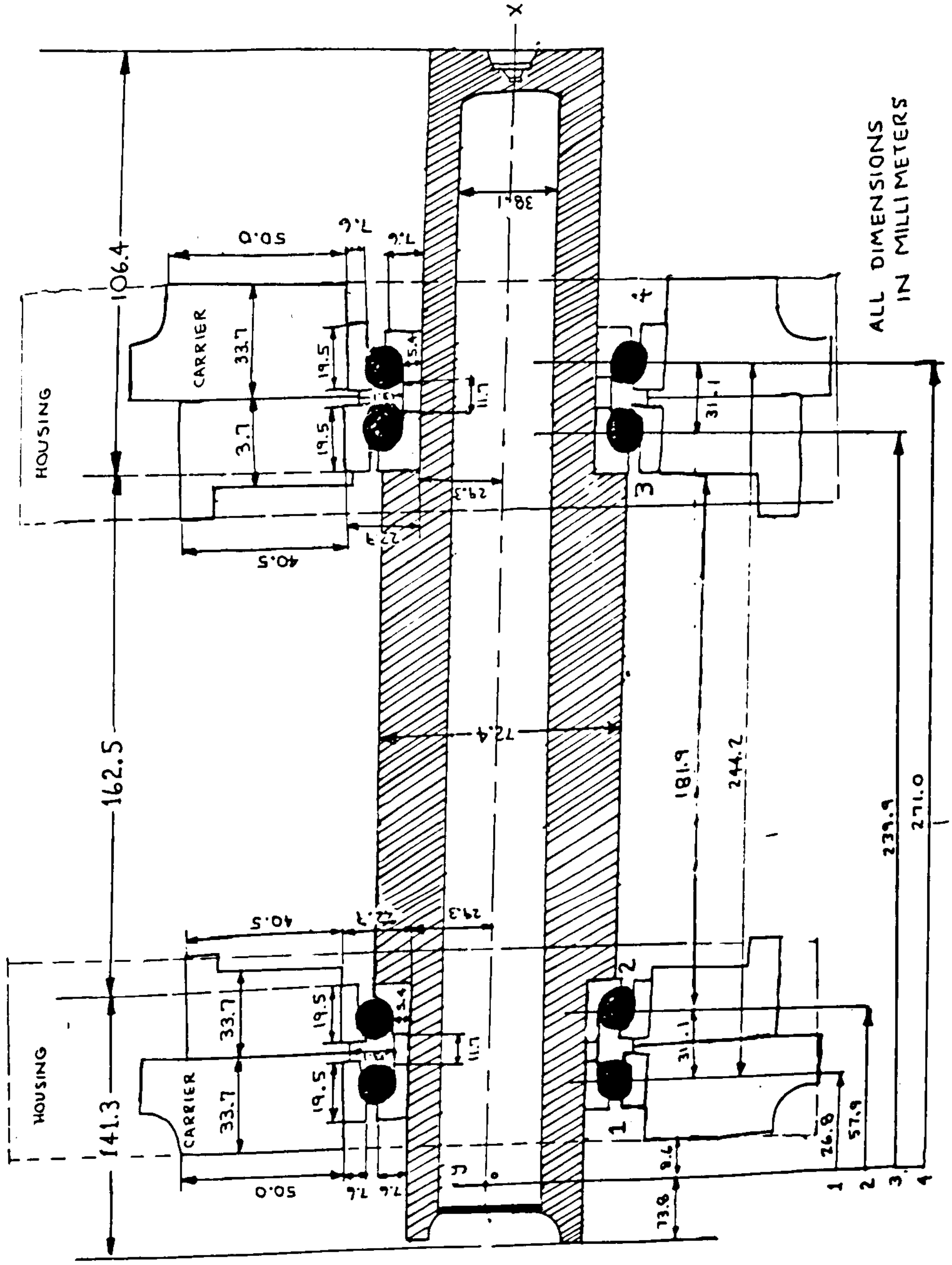


Figure 3: A schematic of bearing dimensions and shaft locations of the BSMT simulation

the SHABERTH/SINDA simulation usually iterates 4 to 7 times depending on values of the initial temperatures assumed in SHABERTH. The computer run time of a converged solution is from 45 minutes to 1 hour.

The input data to the SHABERTH model in general is discussed in reference (3). The Appendices to this reference are particularly helpful since it shows the formatting and structure of the input information and a listing of typical output. The input data that SRS added for their modifications to SHABERTH is described in (14). Much effort was expended to learn and verify analytically many of the inputs to SHABERTH and the source data in SINDA. However, some of inputs are based on experimental tester data. For instance, shaft dimensions and bearing locations, shown schematically in Figure 3, were found from the BSMT drawings. Fluid properties used for LN2 were found by interpolating at 480 psia, the tester pressure, using reference (5). In the same manner, fluid properties for LOX were found using reference (6). Cage load and viscous heat generation inputs were extensively calculated by myself based on J.C. Cody's notes from SRS Technologies. These calculations are based on the theory in reference (12). Cage heat generation rates based on the cage loads are found in a table in reference (14) as a function of coefficient of friction.

In the Appendices of this report, a representative listing of SHABERTH input and references to the lines of SINDA code that are to be changed by the user are given for both LN2 and LOX. When shaft speed was varied, the inputs that must be varied were viscous heat generation rates for bearings 3 & 4 (VQBRG1, VQBRG2), shaft speed (SHAFTS), cage speed (CAGESP), ball spin (BSPEED), and ball spin speed (BALLSP). If other parameters as coolant inlet temperature, cage load, pressure drop, and coolant flowrate need to be varied, reference (14) states the affected inputs to SHABERTH/SINDA that must also be varied. These parameters will be considered fixed in this study.

The SHABERTH inputs indicate a four-bearing system being modeled. However, due to the arbitrarily choosen small initial contact angle $\alpha_0$ to be $+ 5^{\circ}$ and zero diametrical clearance, bearings 1 & 2 are dummy bearings in this model. Since the BSMT has four 57 mm bearings shown schematically in Figure 2, symmetry was used and only 2 of the 4 bearings are actually analyzed by SHABERTH. Therefore, bearings 1 and 2 (the pump end bearings for HPOTP) are the dummy bearings and bearings 3 and 4 (the turbine end bearings for HPOTP) are analyzed. The SINDA model was written only for bearing #3. The grid generation and nodal numbering was performed similiar to the process shown in (8,9 and 13) for the 45 mm pump-end bearings. The user need only be concerned with SINDA's coolant inlet and saturation temperatures (lines 697-709), cage heat (line 757), half of the viscous heat generation rates for bearing #4 (lines 760-761 for nodes 2 and 3) and for bearing #3 (lines 763-764 for nodes 5 & 6) and coolant flowrate per ball (lines 2228-2236). Also, specific heat vs. temperature lines 2293-2300 of SINDA, must be changed when using different coolants. Notice in the initial nodal temperature guess in the SHABERTH input, only the 3rd line representing bearing #3 has been deviated from an initial value of $-170^{\circ}$F. These temperatures represent the shaft, inner ring, inner race, ball, outer race, outer ring, housing and fluid bulk temperatures. These initial temperatures will change with each iteration of SHABERTH/SINDA until either convergence or divergence occurs. Also, change the modulus of elasticity and thermal expansion coefficients to match the initial temperatures of bearing #3. They will also be updated in the iteration process.

Axial preload can be included by setting the diametrical clearance of bearing #3 and #4 to a non-zero value. In the Appendices, a table is presented relating the amount of axial preload to the diametrical clearance. This was generated by running SHABERTH only at steady state temperature and denoting the Fx (x force reaction) in the output. Therefore, the amount of diametrical clearance inputted is related to the Fx force reaction which is the axial preload on bearings #3 and #4. These results are independent of coolant used and flowrate based on the simulation.

In this study, the coefficient of friction was set at 0.2, tester pressure was 480 psia, saturated temperature for LN2 was $-233.8^{\circ}$F and for LOX was $-200.8^{\circ}$F and the coolant flowrate was 6.4 lbm/sec. The axial preload was set at 1000 lbs by setting the diametrical clearance input to be 0.013 mm on bearings #3 and #4.

## RESULTS

Due to input parameter problems and UNIVAC down-time, the study of the BSMT axial load variation producing heat generation rates and contact stresses that were compared to a HPOTP simulation was abandoned at a shaft speed of 20,000 rpm. At 30,000 rpm, a coolant flowrate of 4.6 lbm/sec was used initially for both the BSMT LN2 and LOX simulations.

This was the coolant flowrate used in the HPOTP simulation. At this flowrate for both LN2 and LOX coolants, the solutions diverged. The range of applied axial loads were from 1000 lbs to 3000 lbs with a fixed preload of 1000 lbs for these cases. As the axial load increased, the ball temperature accelerated toward 1000$^{o}$F in 3 to 4 iterations before divergence was declared. Based on these initial results, it was decided to increase the coolant flowrate to 6.4 lbm/sec for both LN2 and LOX BSMT models. In this process, however, several errors were found in the SINDA source data. Specifically, lines 2293-2300 were not changed in the LOX SINDA file. These lines list the specific heat vs. temperature of the coolant used. So, the LOX SINDA file was still using LN2 data. Also, in the SHABERTH input file, the LN2 fluid properties of specific heat, thermal conductivity, and Prandtl number had to be adjusted at the saturated temperatures. Since the tester operating pressure of 480 psi is near the critical pressure of LN2 of 493 psi, the variation in these properties were held at a constant value at the saturation temperature. This should stabilize the heat transfer conductance calculations according to SRS. So, these two problems could have played a part in the divergence of the solution at a flowrate of 4.6 lbm/sec.

The above changes were made to the SHABERTH/SINDA input files and with the coolant flowrate value changed to 6.4 lbm/sec, another series of program executions were performed. From this series of computer runs, Tables 1 and 2 show the converged results of the heat generation rates and Hertz stresses in bearings 3 & 4. As shown, for both heat generation rates and Hertz stresses, there is no significant difference between using LN2 or LOX coolants for the range of axial loads. From Table 1, for bearing #3, there is a reasonable agreement between the BSMT and HPOTP simulations. For bearing #4, the BSMT simulation under predicts the HPOTP simulation by a factor of 1/2. This effect may be caused by the HPOTP simulation having a SINDA model of both bearings 3 & 4 whereas, the BSMT model only has bearing #3 thermally modelled. In Table 2, again, there is no significant difference in Hertz stress for bearings #3 and #4 due to the coolant used in the BSMT model. The results from Table 2 show a reasonable agreement of outer and inner race Hertz stresses for the BSMT and HPOTP simulation for bearing #3; however, the BSMT model again underestimates Hertz stresses by about one-fourth compared to the HPOTP simulation. From these results, it is difficult to predict how much axial load could exactly predict the HPOTP simulation results. Further studies are necessary to attempt to establish an equivalent load relationship.

Table 1: Total Heat Generation Rates of the BSMT & HPOTP Simulations (Preload 1000 lbs) in Watts

| Axial Load | BSMT Simulation | | | | HPOTP Simulation | |
|---|---|---|---|---|---|---|
| | LN2 | | LOX | | | |
| N (lb) | Bearing 3 | Bearing 4 | Bearing 3 | Bearing 4 | Bearing #3 | Bearing #4 |
| 2223.3 (500) | 4489 | 1978 | 5018 | 2288 | | |
| 3334.9 (750) | 5389 | 2009 | 5877 | 2275 | 5396 | 4833 |
| 4446.5 (1000) | 7311 | 2541 | 6898 | 2330 | | |

Table 2: Hertz Contact Stresses of the BSMT & HPOTP Simulation (Preload-1000 lbs) in $N/mm^2$

| Axial Load N (lb) | BSMT Simulation | | | | | | | | HPOTP Simulation | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | LN2 | | | | LOX | | | | | | | |
| | Bearing 3 | | Bearing 4 | | Bearing 3 | | Bearing 4 | | Bearing 3 | | Bearing 4 | |
| | Outer | Inner | Outer | Inner | Outer | Inner | Outer | Inner | Outer | Inner | Outer | Inner |
| 2223.8 (500) | 2074 | 2284 | 1787 | 1720 | 2126 | 2370 | 1826 | 1810 | | | | |
| 3334.9 (750) | 2159 | 2422 | 1791 | 1729 | 2197 | 2487 | 1825 | 1807 | 2541 | 3014 | 2459 | 2896 |
| 4446.5 (1000) | 2307 | 2656 | 1858 | 1878 | 2276 | 2609 | 1832 | 1822 | | | | |

## CONCLUSIONS AND RECOMMENDATIONS

Based on my limited results, no relationship can be established at this time between the BSMT simulation and the HPOTP simulation loadings. In the BSMT simulation, no axial load above 1000 lbs (4446.5N) would result in a stable thermally converging solution at a shaft speed of 30,000 rpm. Based on this study, several recommendations for future research in this area are as follows.

1. The continuation of this study at a lower shaft speed to determine it's effect on the comparison of heat generation rates contact stresses and on enabling the use of higher axial loads.

2. The study of the effects of coolant flowrates and coefficient of friction on the comparison between BSMT simulation axial loads and HPOTP simulation loads.

3. The investigation of other bearing parameters that need be included besides heat generation rates and contact stress in the equivalency of BSMT and HPOTP loading.

4. The correlation of BSMT simulation axial load results to actual BSMT tester data for both LN2 and coolants.

Hopefully, from these recommendations, an equivalency between BSMT axial loads and HPOTP loadings can be found. However, the possibility exists that an applied axial load only may never produce equivalent HPOTP conditions in the bearing tester. So, the logical alternative may be to incorporate a workable radial load capability to the bearing tester and to the SHABERTH BSMT simulation. The alternative would lead to a matching of both axial and radial load conditions between the tester and turbopump to hopefully generate the same mechanical and thermal environment for the bearings.

For SHABERTH's results to be a reliable predictor of bearing performance, it must have reliable inputs based upon both experimental data and analytical formulation. SHABERTH is also constantly being modified and updated by SRS to make it more versatile in its simulation of a shaft bearing system by including more bearing theory. Eventally, SHABERTH could become an important analytic tool for both the current HPOTP or BSMT configuration and for any future alternative configurations that may be developed.

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APPENDICES

SHABERTH/SINDA INPUTS
FOR $LN_2$

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RUNKLEBIN197*SHABOLD(1).SHAB57DUMP(0)
     57MM TESTER USING LN2  OUTLET PRESS=480       2 MATCHED BRG. (57 & 57)
        30000.    4        5                                                  11
     B1        440C                440C                3.       3.      0.
        81.026        13      .0000      -5.00                  0
         12.70
           .53       .55
          .014      .014      .014       2.        2.       2.
            -1    87.884      3.01     0.381     0.635      .02
        .07112     -.079     38.91     19.46     19.46    33.50
         38.10   57.2567     70.83     90.59   103.124    203.0
       2.353E5   2.106E5   2.106E5   2.106E5   2.075E5
            .3        .3        .3        .3        .3
         8.193     7.667     7.667     7.667     8.193
      11.16E-6  9.150E-6  9.150E-6  9.150E-6 11.444E-6
                                        0.20
```

Bearing #1

```
     B2        440C                440C                3.       3.      0.
        81.026        13      .0000      -5.00                  0
         12.70
           .53       .55
          .014      .014      .014       2.        2.       2.
            -1    87.884      3.01     0.381     0.635      .02
        .07112     -.079     38.91     19.46     19.46    33.50
         38.10   57.2567     70.83     90.59   103.124    203.0
       2.353E5   2.108E5   2.108E5   2.108E5   2.075E5
            .3        .3        .3        .3        .3
         8.193     7.667     7.667     7.667     8.193
      11.16E-6  9.150E-6  9.150E-6  9.150E-6 11.444E-6
                                        0.20
```

Bearing #2

```
     B3        440C                440C                3.       3.      0.
        81.026        13      .0130      22.14                  0
         12.70
           .53       .55
          .014      .014      .014       2.        2.       2.
            -1    87.884      3.01     0.381     0.635      .02
        .07112     -.079     38.91     19.46     19.46    33.50
         38.10   57.2567     70.83     90.59   103.124    203.0
       2.346E5   2.079E5   2.015E5   2.088E5   2.076E5
            .3        .3        .3        .3        .3
         8.193     7.667     7.667     7.667     8.193
      11.16E-6 10.072E-6 12.576E-6  9.793E-6 11.409E-6
                                        0.20
```

Bearing #3

```
     B4        440C                440C                3.       3.      0.
        81.026        13      .0130     -22.14                  0
         12.70
           .53       .55
          .014      .014      .014       2.        2.       2.
            -1    87.884      3.01     0.381     0.635      .02
        .07112     -.079     38.91     19.46     19.46    33.50
         38.10   57.2567     70.83     90.59   103.124    203.0
       2.353E5   2.108E5   2.108E5   2.108E5   2.075E5
            .3        .3        .3        .3        .3
         8.193     7.667     7.667     7.667     8.193
      11.16E-6  9.150E-6  9.150E-6  9.150E-6 11.444E-6
                                        0.20
```

Bearing #4

```
                                   1
     -170.-170.-170.-170.-170.-170.-170.-170.
     -170.-170.-170.-170.-170.-170.-170.-170.
     -150. -98. -98.  65.-116.-116.-166.-170.
     -170.-170.-170.-170.-170.-170.-170.-170.
```

Initial
Temperatures

```
     1          0         0      38.10         0     57.33   2.346E5
     1      67.40     38.10      38.10     57.33     72.40   2.346E5
     1     100.00     38.10      38.10     72.40     72.40   2.346E5
     1     150.00     38.10      38.10     72.40     72.40   2.346E5          Shaft Dimensions
     1     200.00     38.10      38.10     72.40     72.40   2.346E5
     1     229.40     38.10      38.10     72.40     57.33   2.346E5
     1     296.80     38.10          0     57.33         0   2.346E5
     2      26.81         0                    0
     2      58.05         0                    0
     2     238.75         0                    0
     2     269.99         0                    0
     3      34.04    0000.0          0         0         0    0000.0
     3     224.50    0000.0          0         0         0    2223.3
                                                                            Axial Load
     3

 THE ADDITIONAL DATA IS FOR THE CONDUCTANCE CALCULATIONS (SRS)
  $BRGNUM
   LOUT=3
  $END
  $CONDAT
   IDENT='57MM ', SHAFTS=3141.59, CAGESP=1365.0, FILM=.TRUE.,DELP=32.,
     DIA=.0417,HF1=-28.384,HS2=  0.573,HFG=  7.73,TF=-274.,TS1=-228.3,
     HS1= 8.73  , CAGEH=169.3,HFG2=25.61, VOBRG1=2842.1, VOBRG2=752.5
  $END
  $COOLNT
   FLUID='LN2', FLOW=6.40
   TFLUID=-300.,-255.,-245.,-240.,-234.,-233.,-232.,-231.,
   VISCOW=8.23E-5,2.43E-5,1.34E-5,1.04E-5,0.78E-5,.945E-5,1.29E-5,
           1.87E-5,1.92E-5,
   SHEATF=0.493, 0.633, .782, .997, 1.40, 1.40, 1.40, 1.40
  $END
  $OUTER
   HCODEO=1, PRESSO=480., TSATO=-233.8,
   TEMPO= -300., -240., -230., -229., -225., -100., 100., 500., 1000.,
   DENSO= 47.61, 32.35, 22.63, 17.62, 10.91,  5.19, 3.32, 2.10,  1.46,
   SHEATO= .493, 1.24,  1.400, 1.400, 1.400,  .341, .281, .259,  .256,     Outer Race
   KO =   .0684, .0352, .0750, .0710, .0168, .0111, .0129, .0171, .0220,   Fluid Properties
   VISCOO=8.23E-5, 2.43E-5, 1.34E-5, 1.04E-5, 0.811E-5, 0.82E-5, 1.01E-5,
            1.35E-5, 1.72E-5,
   PRO =   2.13,  2.48, 2.48,  2.48, 2.47, 0.90, 0.778, 0.735, 0.720,
   VARO1= O.,O.,O.,O.,O.,O.,O.,O.,O.,
   VARO2= O.,O.,O.,O.,O.,O.,O.,O.,O.
  $END
  $INNER
   HCODEI=1, PRESSI=480., TSATI=-233.8,
   TEMPI= -300., -240., -230., -229., -225., -100., 100., 500., 1000.,
   DENSI= 47.61, 32.35, 22.63, 17.62, 10.91,  5.19, 3.32, 2.10,  1.46,
   SHEATI= .493, 1.24,  1.400, 1.400, 1.400,  .341, .281, .259,  .256,
   KI =   .0684, .0352, .0750, .0710, .0168, .0111, .0129, .0171, .0220,   Inner Race
   VISCOI=8.23E-5, 2.43E-5, 1.34E-5, 1.04E-5, 0.811E-5, 0.82E-5, 1.01E-5,  Fluid Properties
            1.35E-5, 1.72E-5,
   PRI =   2.13,  2.48, 2.48,  2.48, 2.47, 0.90, 0.778, 0.735, 0.720,
   VARI1= O.,O.,O.,O.,O.,O.,O.,O.,O.,
   VARI2= O.,O.,O.,O.,O.,O.,O.,O.,O.
  $END
  $BALL
   BSPEED= 130., BALLSP=9425., HCODEB=3,
   TEMPB= -300., -240., -230., -229., -225., -100., 100., 500., 1000.,
   DENSB= 47.61, 32.35, 22.63, 17.62, 10.91,  5.19, 3.32, 2.10,  1.46,
```

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```
        SHEATB= .493, 1.24,  1.400, 1.400, 1.400,  .341, .281, .259,  .256,
        KB =   .0684, .0352, .0750, .0710, .0168, .0111, .0129, .0171, .0220,
        VISCOB=8.23E-5, 2.43E-5, 1.34E-5, 1.04E-5, 0.811E-5, 0.82E-5, 1.01E-5,
                1.35E-5, 1.72E-5,                                              Ball
        PRB =   2.13,  2.48, 2.48,  2.48, 2.47, 0.90, 0.778, 0.735, 0.720,     Fluid Properties
        VARB1= 0.,0.,0.,0.,0.,0.,0.,0.,0.,
        VARB2= 0.,0.,0.,0.,0.,0.,0.,0.,0.
       $END

@XQT SHABOLD.RUNTESTER


@ADD.P SHABOLD.SHAB57DUMP
```

SINDA inputs

| | |
|---|---|
| lines 697-709 | |
| coolant inlet temperatures | -274 F nodes 1-8,998,-999,-997,-993 |
| saturation temperature | -233.8 F node 19 |
| line 757 | |
| cage heat (note: ½ the value is in SHABERTH, ½ is in SINDA) total: 338.6 Btu/hr | 169.3 Btu/hr |
| lines 760-761 | 1421.1 Btu/hr ball |
| add together = VQBRG1 in SHABERTH | 1421.1 Btu/hr ball |
| lines 763-764 | 376.3 Btu/hr ball |
| add together = VQBRG2 in SHABERTH | 376.3 Btu/hr ball |
| lines 2228-2236 | 1772.3 lb/hr ball |
| coolant flowrate | (nodes 12,23,34,45,56,67,78,9981,999998) |

$$\text{flowrate} = 6.4\ \frac{\text{lb}}{\text{sec}} \cdot 3600\ \frac{\text{sec}}{\text{hr}} = 23040\ \text{lb/hr} / 13 \text{ balls in a bearing} = 1772.3\ \text{lb/hr ball}$$

lines 2296-2301
specific heat vs temperature at 480 psia for LN2 at node 27 (see reference (5))

# SHABERTH/SINDA INPUTS
# FOR LOX



```
RUNKLEBIN197*SHABOLD(1).SHAB57DUMP(O)
     57MM TESTER USING LOX  OUTLET PRESS=480       2 MATCHED BRG. (57 & 57)
        30000.    4          5                                                 11
     B1         440C                   440C                  3.       3.        O.
        81.026          13     .0000      -5.00                       0
         12.70
           .53        .55
          .014       .014       .014        2.        2.        2.
            -1     87.884       3.01     0.381     0.635       .02
        .07112      -.079      38.91     19.46     19.46     33.50
         38.10    57.2567      70.83     90.59   103.124     203.0
       2.353E5    2.100E5    2.106E5   2.106E5   2.075E5
            .3         .3         .3        .3        .3                          Bearing #1
         8.193      7.667      7.667     7.667     8.193
     11.16E-6   9.150E-6   9.150E-6  9.150E-6 11.444E-6
                                         0.20
     B2         440C                   440C                  3.       3.        O.
        81.026          13     .0000      -5.00                       0
         12.70
           .53        .55
          .014       .014       .014        2.        2.        2.
            -1     87.884       3.01     0.381     0.635       .02
        .07112      -.079      38.91     19.46     19.46     33.50
         38.10    57.2567      70.83     90.59   103.124     203.0
       2.353E5    2.108E5    2.108E5   2.108E5   2.075E5                          Bearing #2
            .3         .3         .3        .3        .3
         8.193      7.667      7.667     7.667     8.193
     11.16E-6   9.150E-6   9.150E-6  9.150E-6 11.444E-6
                                         0.20
     B3         440C                   440C                  3.       3.        O.
        81.026          13     .0130      22.14                       0
         12.70
           .53        .55
          .014       .014       .014        2.        2.        2.
            -1     87.884       3.01     0.381     0.635       .02
        .07112      -.079      38.91     19.46     19.46     33.50              Bearing #3
         38.10    57.2567      70.83     90.59   103.124     203.0
       2.346E5    2.079E5    2.015E5   2.088E5   2.076E5
            .3         .3         .3        .3        .3
         8.193      7.667      7.667     7.667     8.193
     11.16E-6  10.072E-6  12.576E-6  9.793E-6 11.409E-6
                                         0.20
     B4         440C                   440C                  3.       3.        O.
        81.026          13     .0130     -22.14                       0
         12.70
           .53        .55
          .014       .014       .014        2.        2.        2.
            -1     87.884       3.01     0.381     0.635       .02              Bearing #4
        .07112      -.079      38.91     19.46     19.46     33.50
         38.10    57.2567      70.83     90.59   103.124     203.0
       2.353E5    2.108E5    2.108E5   2.108E5   2.075E5
            .3         .3         .3        .3        .3
         8.193      7.667      7.667     7.667     8.193
     11.16E-6   9.150E-6   9.150E-6  9.150E-6 11.444E-6
                                         0.20
                                   1
     -170.-170.-170.-170.-170.-170.-170.-170.
     -170.-170.-170.-170.-170.-170.-170.-170.
     -150. -98. -98.  65.-116.-116.-166.-170.                                   Initial
     -170.-170.-170.-170.-170.-170.-170.-170.                                   Temperatures
```

```
     1         0         0     38.10         0     57.33   2.346E5
     1     67.40     38.10     38.10     57.33     72.40   2.346E5
     1    100.00     38.10     38.10     72.40     72.40   2.346E5
     1    150.00     38.10     38.10     72.40     72.40   2.346E5
     1    200.00     38.10     38.10     72.40     72.40   2.346E5
     1    229.40     38.10     38.10     72.40     57.33   2.346E5
     1    296.80     38.10         0     57.33         0   2.346E5
     2     26.81         0               0
     2     58.05         0               0
     2    238.75         0               0
     2    269.99         0               0
```

Shaft Dimensions

```
     3     34.04    0000.0         0         0         0    0000.0
     3    224.50    0000.0         0         0         0    2223.3
```

Axial Load

```

     3

 THE ADDITIONAL DATA IS FOR THE CONDUCTANCE CALCULATIONS (SRS)
  $BRGNUM
   LOUT=3
  $END
  $CONDAT
   IDENT='57MM ', SHAFTS=3141.59, CAGESP=1365.0, FILM=.TRUE.,DELP=32.,
     DIA=.0417,HF1=-41.228,HS2=-13.150,HFG= 47.40,TF=-260.,TS1=-196.,
     HS1= -11.34  , CAGEH=169.3,HFG2=50.01, VOBRG1=4973.1, VOBRG2=910.44
  $END
  $COOLNT
   FLUID='LOX', FLOW=6.40
   TFLUID=-230.,-220.,-210.,-201.,-200.,-195.,-190.,-185.,
   VISCOW=14.22E-5,7.23E-5,4.29E-5,1.18E-5,1.21E-5,1.29E-5,1.47E-5,
           1.56E-5,1.63E-5,
   SHEATF=0.475, 0.516, .587, .774, .702, .546, .470, .423
  $END
  $OUTER
   HCODEO=1, PRESSO=480., TSATO=-200.8,
   TEMPO= -300., -250., -201., -200., -100., -50.,  50., 100., 450.,
   DENSO= 72.06, 62.69, 47.89,  9.13,  5.55,  4.89, 4.02, 3.71,  2.46,
   SHEATO= .401, .434,  .774, .702, .303,  .285, .253, .246,  .231,
   KO =    .0897, .0681, .0429, .0158, .0128, .0131, .0138, .0142, .0176,
   VISCOO=14.22E-5, 7.23E-5, 4.29E-5, 1.17E-5, 1.14E-5, 1.17E-5, 1.25E-5,
            1.295E-5, 1.61E-5,
   PRO =   2.29,  1.66, 2.79,  1.88, 0.969, 0.896, 0.826, 0.807, 0.757,
   VARO1= 0.,0.,0.,0.,0.,0.,0.,0.,0.,
   VARO2= 0.,0.,0.,0.,0.,0.,0.,0.,0.
  $END
```

Outer Race
Fluid Properties

```
  $INNER
   HCODEI=1, PRESSI=480., TSATI=-200.8,
   TEMPI= -300., -250., -201., -200., -100., -50.,  50., 100., 450.,
   DENSI= 72.06, 62.69, 47.89,  9.13,  5.55,  4.89, 4.02, 3.71,  2.46,
   SHEATI= .401, .434,  .774, .702, .303,  .285, .253, .246,  .231,
   KI =    .0897, .0681, .0429, .0158, .0128, .0131, .0138, .0142, .0176,
   VISCOI=14.22E-5, 7.23E-5, 4.29E-5, 1.17E-5, 1.14E-5, 1.17E-5, 1.25E-5,
            1.295E-5, 1.61E-5,
   PRI =   2.29,  1.66, 2.79,  1.88, 0.969, 0.896, 0.826, 0.807, 0.757,
   VARI1= 0.,0.,0.,0.,0.,0.,0.,0.,0.,
   VARI2= 0.,0.,0.,0.,0.,0.,0.,0.,0.
  $END
```

Inner Race
Fluid Properties

```
  $BALL
   BSPEED= 130., BALLSP= 9425., HCODEB=3,
   TEMPB= -300., -250., -201., -200., -100., -50.,  50., 100., 450.,
   DENSB= 72.06, 62.69, 47.89,  9.13,  5.55,  4.89, 4.02, 3.71,  2.46,
```

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```
SHEATB= .401, .434, .774, .702, .303, .285, .253, .246, .231,
KB =    .0897, .0681, .0429, .0158, .0128, .0131, .0138, .0142, .0176,
VISCOB=14.22E-5, 7.23E-5, 4.29E-5, 1.17E-5, 1.14E-5, 1.17E-5, 1.25E-5,
        1.295E-5, 1.61E-5,
PRB =   2.29, 1.66, 2.79, 1.88, 0.969, 0.896, 0.826, 0.807, 0.757,
VARB1= 0.,0.,0.,0.,0.,0.,0.,0.,0.,
VARB2= 0.,0.,0.,0.,0.,0.,0.,0.,0.
$END
```

Ball
Fluid Properties

```
@XQT SHABOLD.RUNTESTER

@ADD.P SHABOLD.SHAB57DUMP
```

SINDA inputs

| | |
|---|---|
| lines 697-709 | |
| coolant inlet temperatures | -260 F nodes 1-8,998,-999,-997,-993 |
| saturation temperature | -200.8 F node 19 |
| line 757 | |
| cage heat (note: ½ the value is in SHABERTH, ½ is in SINDA total: 338.6 Btu/hr | 169.3 Btu/hr |
| lines 760-761 | |
| add together = VQBRG1 in SHABERTH | 2486.5 Btu/hr ball<br>2486.5 Btu/hr ball |
| lines 763-764 | |
| add together = VQBRG2 in SHABERTH | 455.2 Btu/hr ball<br>455.2 Btu/hr ball |
| lines 2228-2236 | |
| coolant flowrate | 1772.3 lb/hr ball<br>(nodes 12,23,34,45,56,67,78,9981,999998) |

flowrate $= 6.4 \frac{lb}{sec} \cdot 3600 \frac{sec}{hr} = 23040$ lb/hr / 13 balls in a bearing = 1772.3 lb/hr

lines 2296-2301
specific heat vs temperature at 480 psia for LOX at node 27 (see reference (6))

Diametrical Clearance vs Axial Preload

| Diametrical Clearance Input to SHABERTH (mm) | Axial preload on bearing pair (N) | (lb) |
| --- | --- | --- |
| 0.0043 | 5137 | 1155.3 |
| 0.009 | 4750 | 1068.3 |
| 0.013 | 4450 | 1000.8 |
| 0.0148 | 4315 | 970.4 |
| 0.025 | 3651 | 821.1 |
| 0.05 | 2466 | 554.6 |