Calibration for Thrust and Airflow Measurements in the CE-22 Advanced Nozzle Test Facility

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Summary

CE-22 facility procedures and measurements for thrust and airflow calibration obtained with choked-flow ASME nozzles are presented. Six calibration nozzles are used at an inlet total pressure from 20 to 48 psia. Throat areas are from 9.9986 to 39.986 in.^{2}. Throat Reynolds number varies from 1.8 to 7.9 million. Nozzle gross thrust coefficient (CFG) uncertainty is 0.25 to 0.75 percent, with smaller uncertainly generally for larger nozzles and higher inlet total pressure. Nozzle discharge coefficient (CDN) uncertainty is 0.15 percent or less for all the data. ASME nozzle calibrations need to be done before and after research model testing to achieve these uncertainties. In addition, facility capability in terms of nozzle pressure ratio (NPR) and nozzle airflow are determined. Nozzle pressure ratio of 50 or more is obtainable at 40 psia for throat areas between 20 and 30 in.^{2}. Also presented are results for two of the ASME nozzles vectored at 10°, a dead-weight check of the vertical (perpendicular to the jet axis) force measurement, a calibration of load cell forces for the effects of facility tank deflection with tank pressure, and the calibration of the metric-break labyrinth seal.

Nomenclature

CDN	Nozzle Discharge Coefficient
CFG	Nozzle Gross Thrust Coefficient
ERB	Engine Research Building
ESP	Electronically Scanned Pressure
NPR	Nozzle Pressure Ratio
WP	Primary Weight Flow (lbm/sec)

Introduction

Procedures used to calibrate the CE-22 Advanced Nozzle Test Facility for nozzle model thrust and airflow are presented along with calibration measurements. Multiple calibration steps are performed, each building upon the previous. For the final calibration, choked-flow ASME nozzles are used. The calibration data will provide a data base to which future calibrations in the facility can be compared. The ASME nozzle data is processed with the calibration coefficients and compared to the ASME nozzle reference values for determination of the measurement uncertainty. Nozzle pressure ratio (NPR) limits of the facility were also determined. The information presented in this report will provide guidance to facility users in the selection of model sizing, instrumentation, and test conditions.
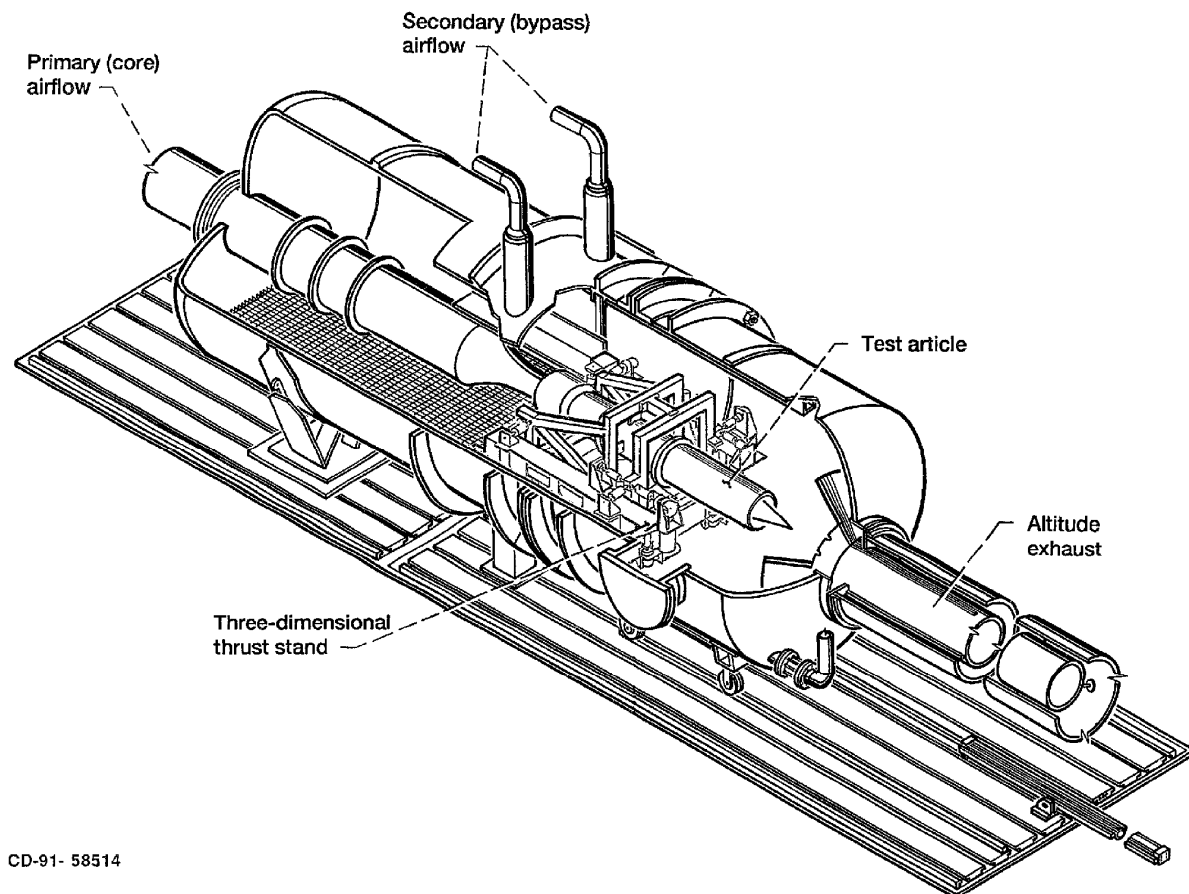
CD-91- 58514

Figure 1.—CE-22 Advanced Nozzle Test Facility.

Facility

The CE-22 Advanced Nozzle Test Facility (Fig. 1) is one of the seven Flow Physics Labs in the Engine Research Building (ERB) at the NASA Glenn Research Center. The CE-22 facility provides economical testing of 1/4-scale models incorporating advanced nozzle concepts. Model throat Reynolds numbers can range between 1.8 and 7.9 million at inlet pressures of 20 to 48 psia. The NPR range is from about 1.2 to 60. The facility can measure forces and moments in all three axes. The test chamber pressure can be controlled to simulate altitude conditions. The primary air can be heated to 370 °F. Secondary air at 40, 125, or 450 psig is available and can be heated to 250 °F. Unheated air temperature for primary and secondary flow is 65 to 85 °F depending on ambient conditions. The facility also has an inlet vane device for primary air swirl and a color Schlieren system for quantitative nozzle exit airflow analysis. Detailed descriptions of the facility are given in References 1 to 3 and a description of the six-component thrust stand and force interaction calibration is given in Reference 3. Appendix A lists all of the constants, averages, and calculations used for facility data reduction including the calibrations.

A 49-in. long, 28-in. inside diameter cylindrical altitude exhaust collector is used for this calibration program. Inlet duct length from the thrust stand mount to the ASME nozzle inlet is 24.75 in. The collector and inlet configurations remained the same throughout the program. Instrumentation in the primary flow stream as well as calculated variables based on this instrumentation are organized by station, illustrated in Figure 2, and named according to the convention shown in Figure 3.

Primary airflow is measured using total-to-static differential pressure transducers between stations 2 and 5 three transducer ranges are used in the facility—1, 2, and 5 psid. Four transducers at a time are installed for each range; but of these, one 1-psid, one 2-psid, and three 5-psid transducers were not included in the data reduction because of a large disagreement with each other and with separate measurement of static and total pressure by the electronically scanned pressure (ESP) system. A description of the ESP system is given in Reference 4.
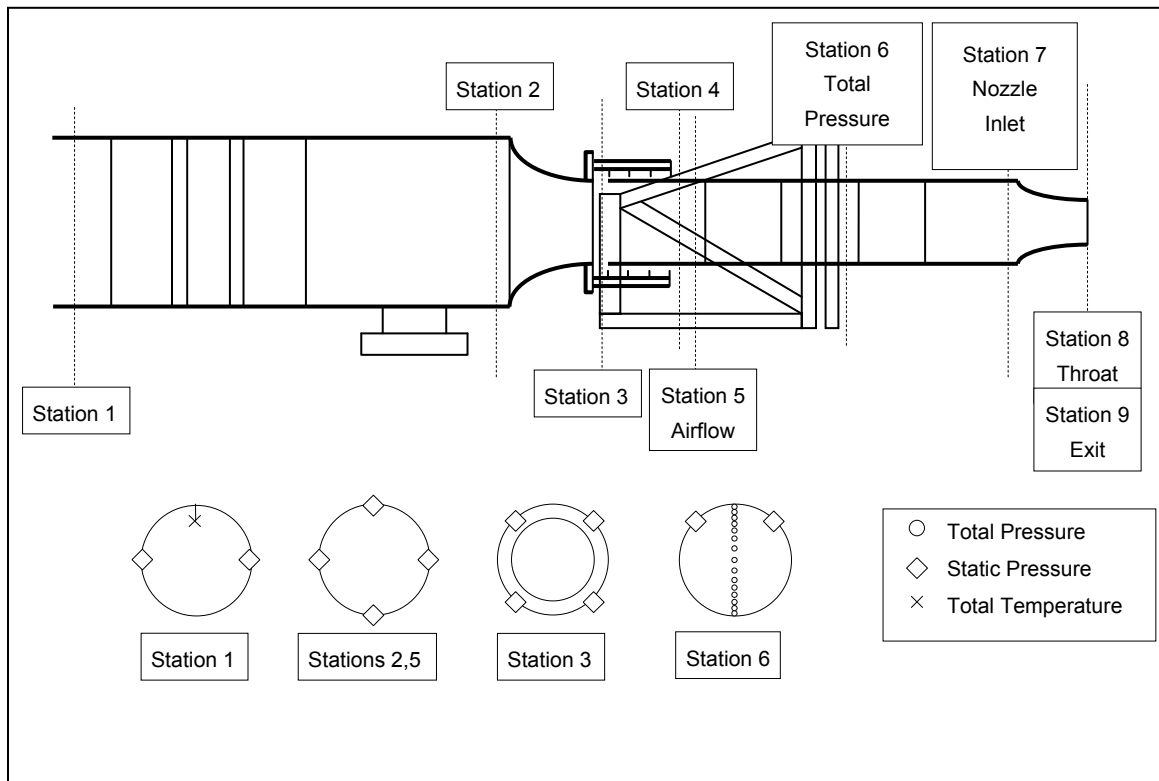

Figure 2.—Station designations in primary air stream.

Figure 3.—Measurement variable naming convention.

Maximum Nozzle Pressure Ratio

The ASME flow calibrations were done in October and November of 2005. The NPR limits for each nozzle with inlet pressure are empirically determined and are shown on Figure 4 versus primary airflow. NPR as high as 60 is measured. The limits of the total-to-static differential pressure transducer ranges used at station 5 are also shown in Figure 4.

Six-Component Thrust Stand

Figure 5 depicts the thrust stand including force and moment sign convention. Reference 3 gives a detailed description of the thrust stand and the in-stand calibration procedure. The thrust stand is a redundant system having a total of eight reaction load cells—two axial, two lateral, and four vertical. The redundancy is resolved by summing the two axial load cells together and combining the four vertical load cell together two different ways (front-back and right-left). The axial load cells can be summed because of an elastic hinge feature in the stand design. Two 5x5 matrices are generated and are transformed into the interaction coefficients. The interaction coefficients and the reaction load cell measurement combinations are then used to calculate the test stand forces and moments. Load cell sizes are 4000 lbf for both axial cells, 2000 lbf for the forward lateral, 4000 lbf for the aft lateral, and 2000 lbf for the four vertical load cells.

Reference 3 Errata

Five typographic errors can be found on page 8 of Reference 3. In Table III, row two and column two, replace *FZ* with *FX;* and for paragraph four, lines five and six, replace (*CX1* and *CX2*) and (*CX3* and *CX4*) with (*CZ1* and *CZ2*) and (*CZ3* and *CZ4*).
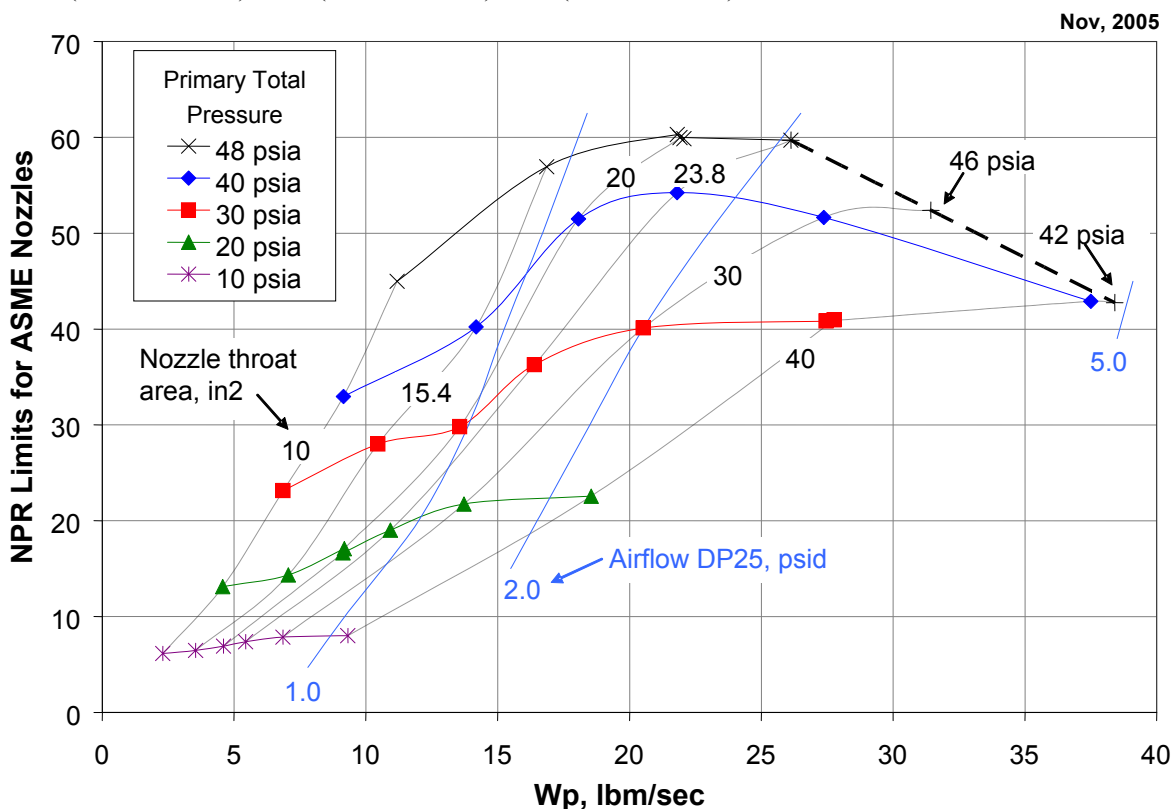

Figure 4.—NASA CE-22 facility nozzle pressure ratio NPR versus primary airflow.
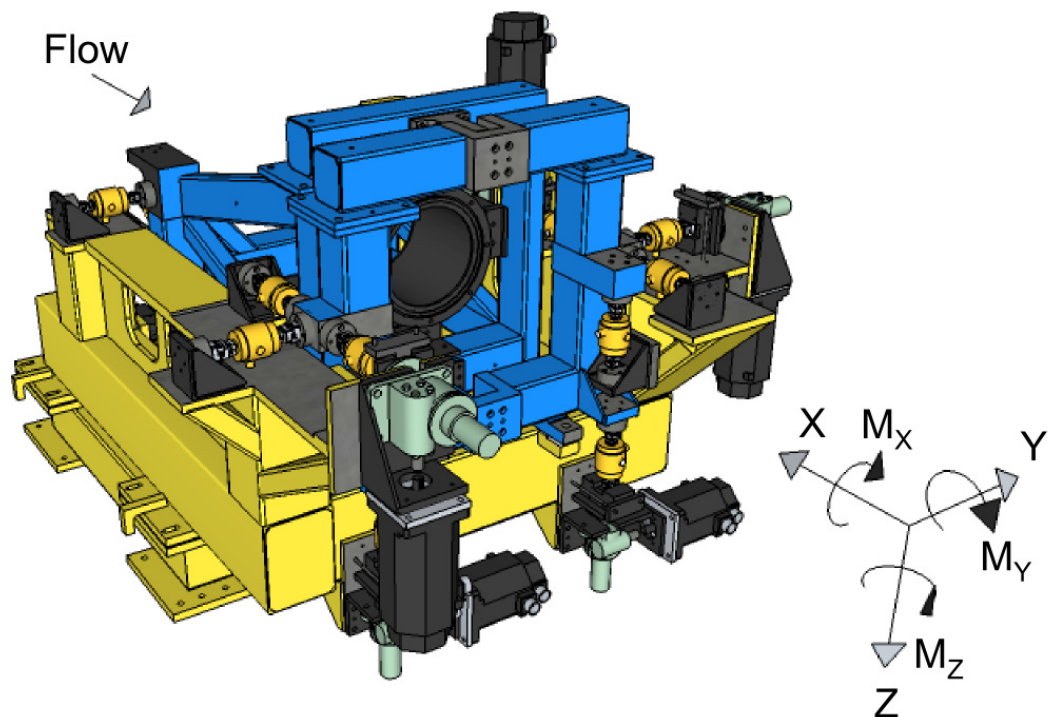
Figure 5.—Six component thrust stand.

Load Cell Installation Procedures

Load cells are calibrated in a calibration laboratory. Before installation in the thrust stand, the load cells are laid inside the CE-22 test cell and wired to the signal conditioners using the normal connections. The excitation voltage is applied and the load cells are allowed to "cook" for about 48 hr. Venting of the reaction load cells is then verified by closing the tank, electronically zeroing and spanning the loadcells (using the knobless conversion command of the data acquisition system, hereafter referred to as a "knobless calibration" of the load cells), and evacuating the chamber to vacuum exhaust conditions; vented load cells should not have any zero shifts with altitude exhaust pressure variation. Any preservative gel inside the load cells must be removed to prevent clogging the vent holes. The load cells are now mounted in the thrust stand.

Interaction Coefficients

Before each set of force or moment calibration loadings, a knobless calibration is performed. Coefficients from laboratory calibration are used with the knobless measurements to determine load cell slopes for converting output electrical signals into lbf units. The in-stand calibration is performed as outlined in Reference 3. In-stand calibration results are shown on nine figures in Appendix B. These results are very good with all of the reactions being linear and having no slope changes through the zero load point. The slope values are used to determine the interaction matrix coefficients.

Dead Weight Check

After the interaction matrix coefficients are set as constants in the data reduction program, the vertical downward (positive) force measurement is checked with dead weights. A fixture for hanging the weights is mounted on the airflow supply duct of the thrust stand. Weights are applied in steps of 50 lbm up to a total of 250 lb. The fixture has a slot allowing a 5-in forward-aft movement of the weight loading. Also, two duct pieces with a total length of 15 in. are installed between the stand and the fixture for additional axial locations for applying the weights loadings. The 9.625-in. distance to the centroid is obtained by putting weights directly on the aft portion of the thrust stand. Vertical force measurement results are shown in Figure 6.

Vertical force measurements are within 1 lbf of the weights for lengths of 9.625, 35.125, and 40.125 in. Measurement differences are greater than 1 lbf for weights of 100 lb and higher at 50.125 and 55.125-in. lengths. The effect of this distance is illustrated by replotting the vertical force measurements against axial length (Fig. 7). Dial indicators were placed between the live and the ground frames of the thrust stand and no deflections were observed during loading of the weights. An inclinometer was also located on the calibration fixture, and the deflection angle measurements are given in Figure 8. Deflection angle increased with length and loading. A maximum of 0.065° for downward deflection of the fixture was measured. These two results indicate that the angular deflection with weight is caused by a deflection of the tank, which supports the entire thrust stand structure, rather than a deflection between the live and ground frames of the thrust stand.

Correction for the dead weight check is not made in the data reduction program. For flow vectored at 10° at 40 in. from the thrust stand centroid, a correction of the force vector angle would be less than 0.1°. The effects of the dead weight check on the other measured forces and moments are shown on five figures in Appendix C.
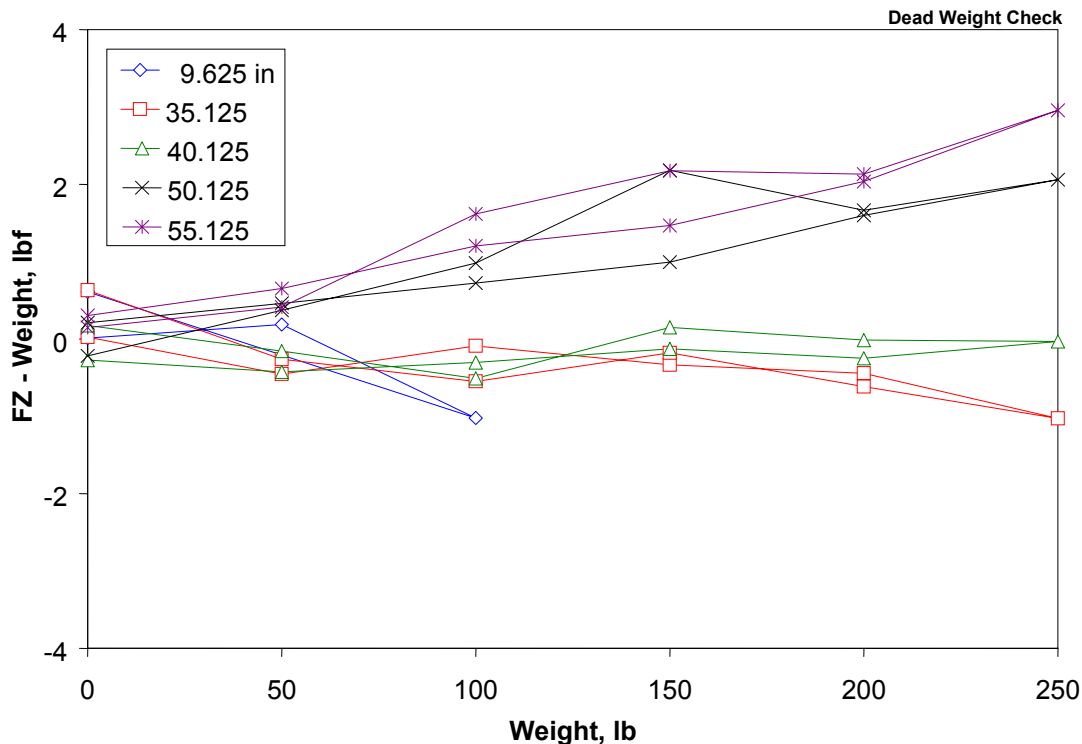

Figure 6.—Vertical force FZ resulting from a dead weight check. Axial distance aft of the x-y centroid of the thrust stand is varied from 9.625 to 55.125 in.
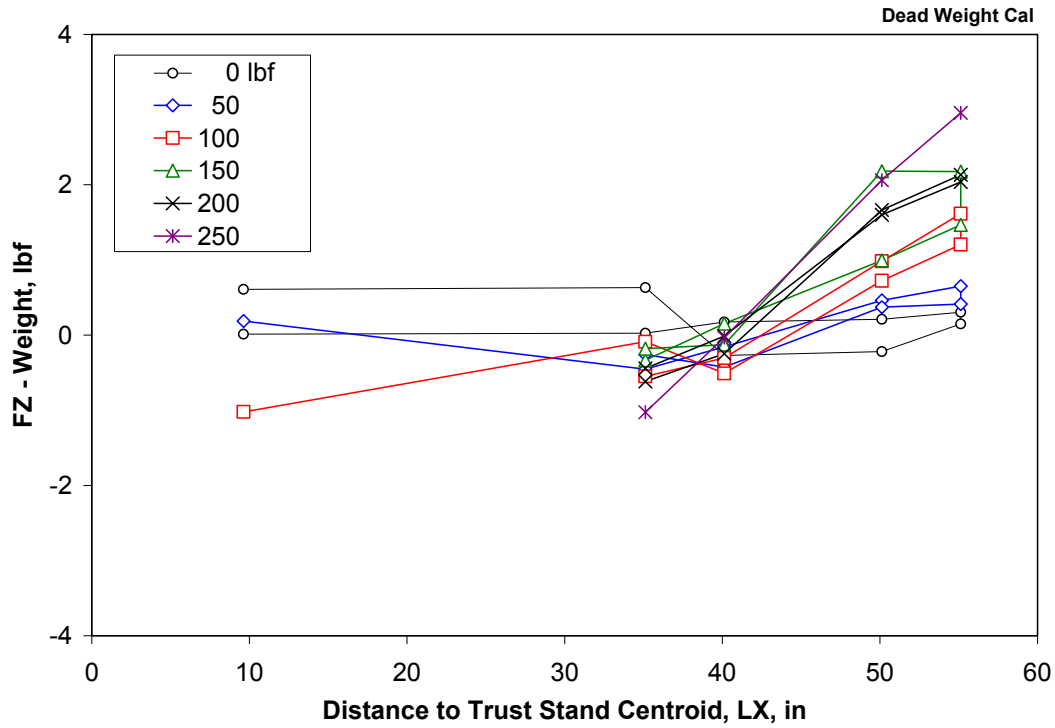
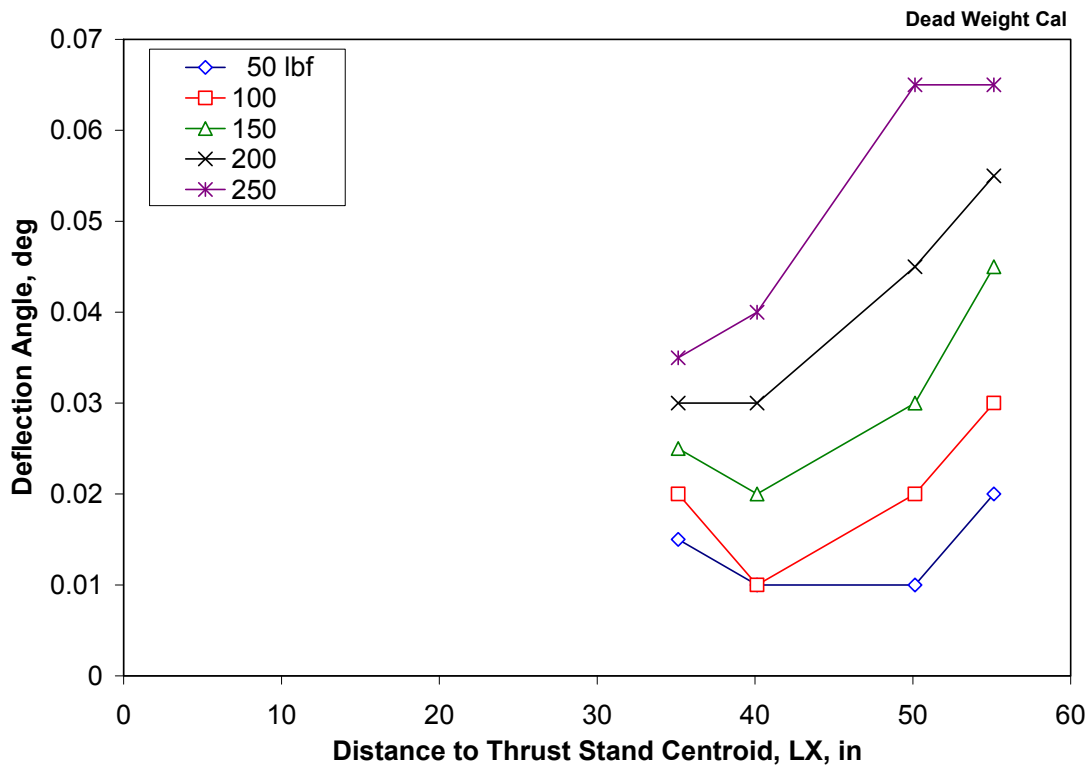Figure 7.—Vertical force FZ resulting from a dead weight check versus distance to the thrust stand centroid.

Figure 8.—Angular deflection measurement of the dead weight check fixture with vertical load.

Test Chamber Pressure Effects

Reaction load cell loadings as caused by evacuating the test chamber to vacuum pressure conditions are shown in Figure 9 and the effects of pressure on combinations of load cells are shown in Figure 10. These figures show typical responses of the vented load cells in the CE-22 facility. The loadings are caused by test chamber deflections. The load cell reactions are most significant in the vertical (z) direction. Consequently, the corrections for these forces, developed in the next paragraphs, will be greatest in the z direction. The thrust bed is "exercised" and a knobless load cell calibration is applied before decreasing the test cell pressure, $P0$.
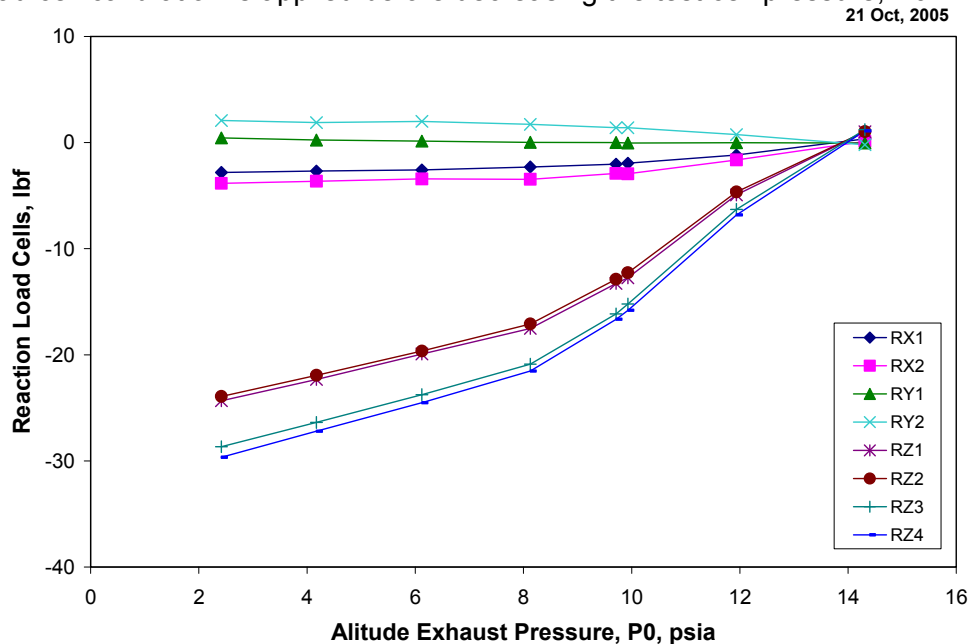

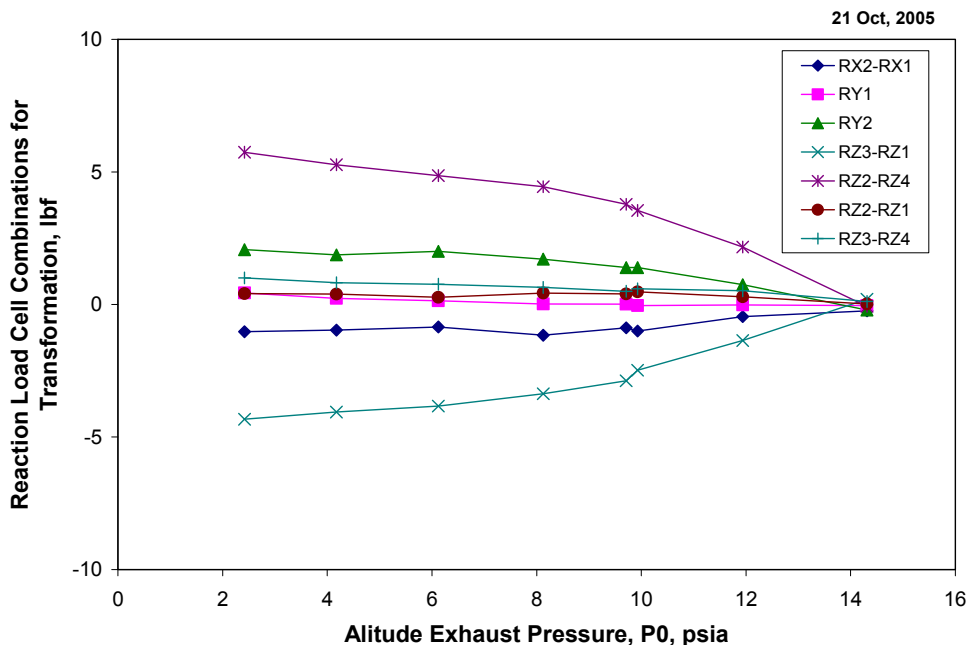Figure 9.—Reaction load cell response to altitude exhaust pressure.

Figure 10.—Response of combinations of reaction load cells to altitude exhaust pressure.

The forces and moments produced by P0 effects are given in Figures 11 and 12. The equations for the data reduction corrections of the exhaust pressure effects are shown in the figures. Slopes of the linear curve fits are used. P0KNOB is a recording of the P0 chamber pressure when a knobless calibration of the load cells is performed. These corrections (FXP0, FYP0, etc.) are subtractions in the calculations (Equations F051 to F054, Appendix A). There is no difference whether the calibration (and knobless) begins at sea level pressure and goes to altitude or starts at altitude exhaust pressure and goes to sea level.
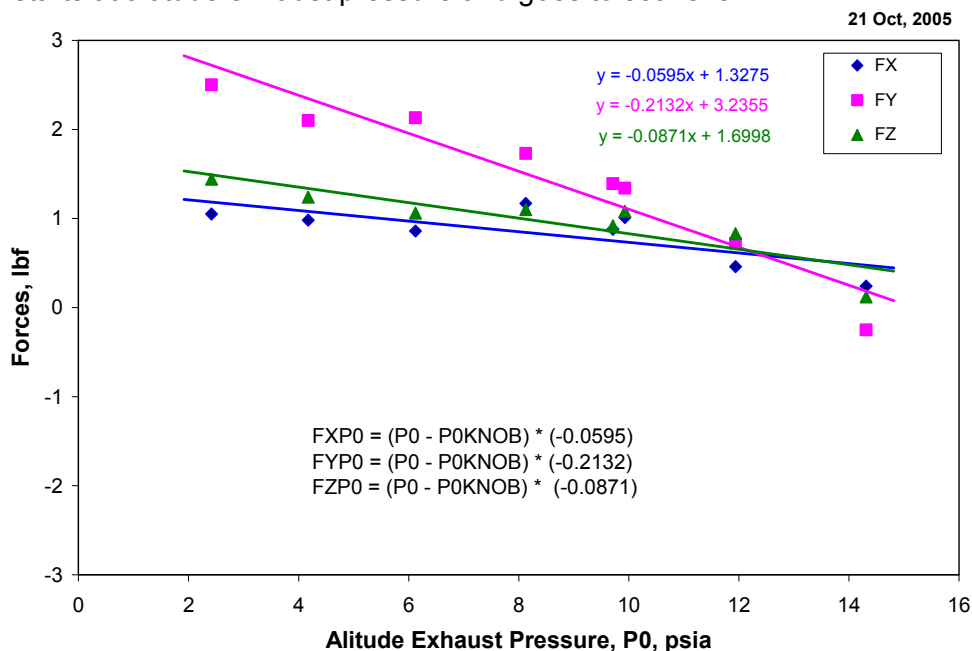

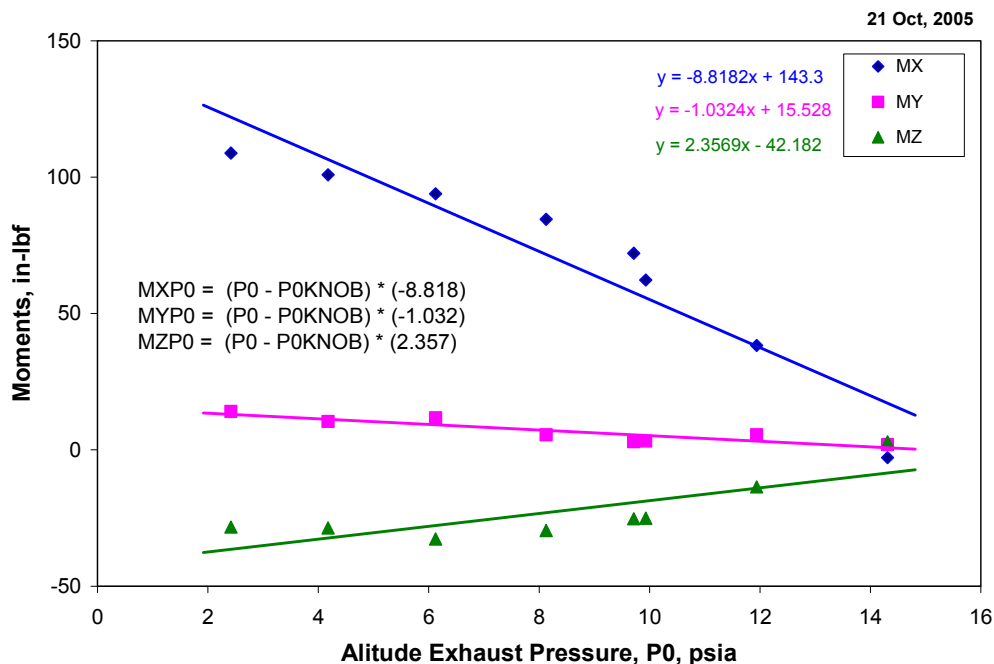Figure 11.—Thrust stand force corrections for altitude exhaust effects.

$$FXP0 = (P0 - P0KNOB) * (-0.0595)$$
$$FYP0 = (P0 - P0KNOB) * (-0.2132)$$
$$FZP0 = (P0 - P0KNOB) * (-0.0871)$$

Figure 12.—Thrust stand moment corrections for altitude exhaust effects.

$$MXP0 = (P0 - P0KNOB) * (-8.818)$$
$$MYP0 = (P0 - P0KNOB) * (-1.032)$$
$$MZP0 = (P0 - P0KNOB) * (2.357)$$

Labyrinth Seal Force Calibration

The labyrinth seal force calibration, which is also called the A∆P calibration or the blank-off plate calibration, results in the FTARE term in the axial force summation (calculation F052 in Appendix A). This calibration is achieved by blanking off the primary airflow duct and maintaining constant pressure in the duct while increasing the altitude exhaust pressure from the vacuum tare condition. This calibration is another area-delta-pressure term in the force equation and is used to balance out the pressure-area forces with the load cell forces at static conditions. The calibration calculation is given by Equations F069 and F070 in Appendix A. The same fixture used for the dead weight check is used to blank off the duct.

A knobless load cell calibration is recorded at vacuum conditions and then the duct is pressurized to a desired level (PT5). Altitude exhaust pressure is then increased with duct pressure held constant, and data is recorded at various PS3/P0 ratios. PS3 is the pressure inside the seal cavity upstream of the labyrinth seal. Since a small amount of airflow goes through the seal, PS3 will read slightly lower than pressures inside the primary airflow duct. After completing a PS3/P0 sweep, the conditions are returned to vacuum; a knobless calibration is recorded; and the procedure is repeated for another PT5 pressure level. With the blank-off plate installed, a zero pressure differential across the plate at vacuum tare is very hard to achieve for a knobless calibration. Therefore an additional term, FXKNOB, is included in the calculations to cancel out the small axial force loading from the pressure differential during the knobless calibration. Calibration results for the seal are shown in Figure 13 in the form of measured effective labyrinth seal area (ALS3M) as a function of the pressure ratio PS3/P0.
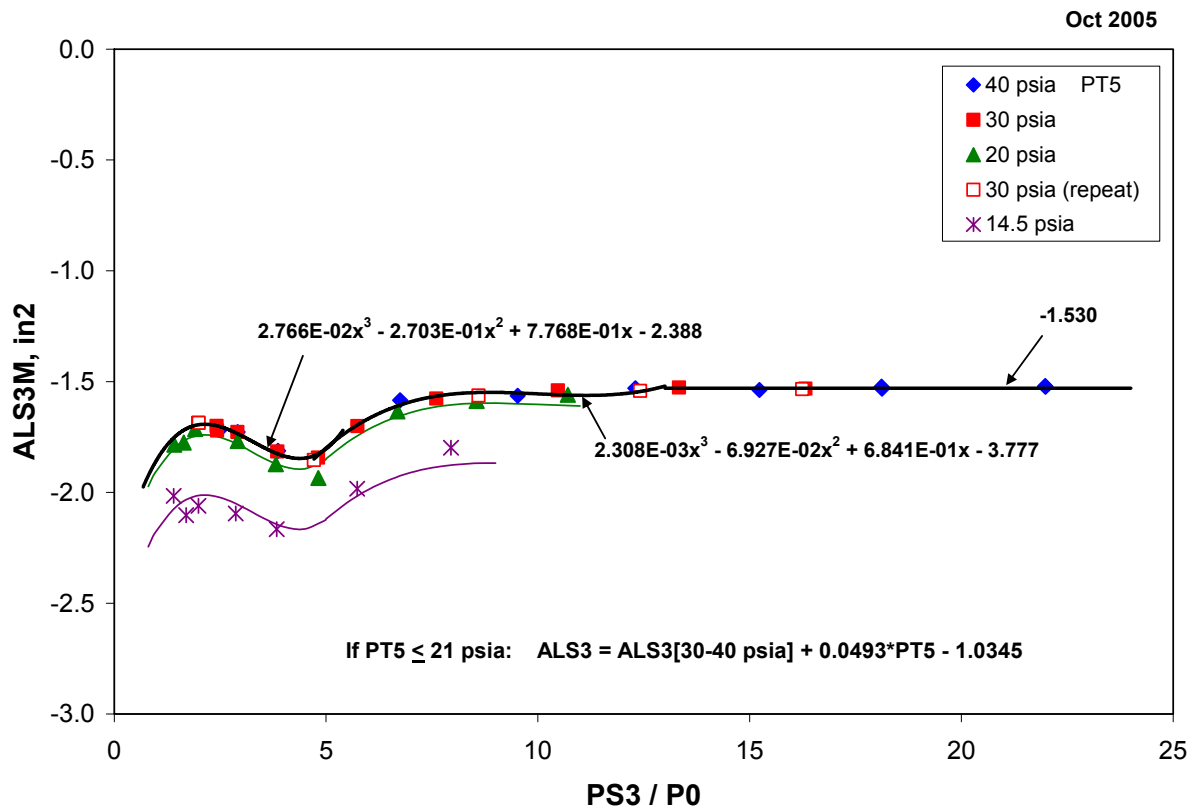

Figure 13.—Labyrinth seal calibration.

Figure 13 shows that the 30 and 40-psia PT5 data as well as a repeat 30-psia calibration all fall on the same curve. This curve is divided into three segments for the curve fits, and the resulting equations are shown on the figure. This same curve but with an intercept adjustments is used for the 20 and 14.5 psia data. A second curve fit is done for the intercepts (plot not included) and the resulting equation for duct pressures below 21 psia is also included in Figure 13.

Choked-Flow ASME Nozzle Calibration

The CE-22 facility airflow and inlet momentum are measured at station 5, and the respective calibration coefficients are determined using choked-flow ASME nozzles for the airflow and thrust calibration values. The ASME equations are based on Reference 5 and are given in Appendix A, calculations F071 to F077. The CV velocity coefficient calculation is modified to use an industry recommendation of 0.109 instead of 0.107 for a constant in the equation.

ASME Nozzle Description

The calibration nozzles are ASME long-radius flow nozzles as shown in Reference 6, page 217. The smallest of the nozzles (9.9986 in.[2]) is a low β nozzle having a throat-to-inlet diameter ratio of 0.408. The other five nozzles are high β nozzles with β ranging from 0.506 to 0.815. A schematic of the 19.990-in.[2] nozzle is given in Figure 14; this figure also shows a modification at the nozzle outlet. The nozzle exit contour goes radial outward and then forward (upstream) in 1/8-in. steps and then angles forward at 45°. The modification is an industry recommendation that improves thrust calibration.
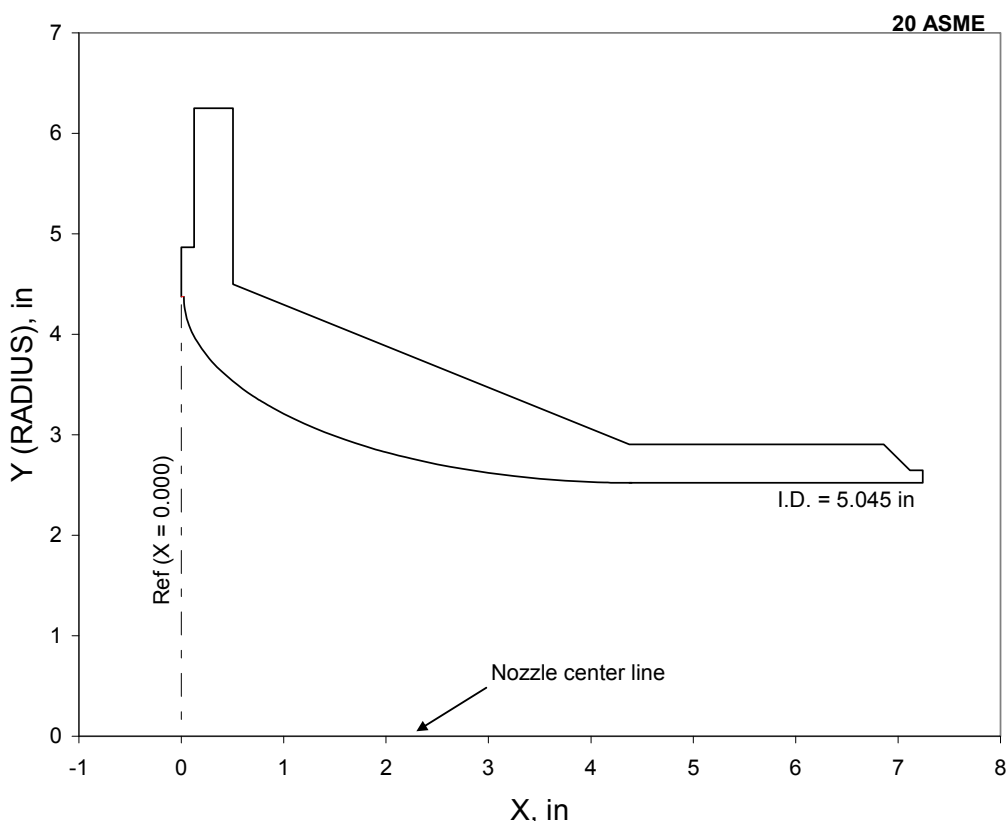

Figure 14.—Cross section of 19.990-in.[2] ASME nozzle.

ASME Nozzle Calibration Procedure

On each day prior to a run, the thrust stand load cells are exercised in all three axes with force loadings from the in-stand calibration system. The test chamber is taken to minimum exhaust pressure for the vacuum tare; a knobless calibration is taken and a data point is recorded. The inlet pressure is set to a desired level after which the exhaust pressure is increased until the first NPR value is obtained. The first NPR will be the highest of an NPR sequence. NPR is reduced by increasing the exhaust pressure until the sequence is completed. Standard deviations of online averages of test conditions and force measurements are monitored until an acceptable low deviation is observed and then a data point is recorded. Upon completion of an NPR sequence, the facility is returned to the vacuum tare condition and a data point is recorded; the force and airflow values (load cells and transducers) are reviewed for zero shifts. This procedure, beginning with a knobless calibration at vacuum, is repeated for subsequent NPR sequences at other total pressure levels. This same procedure is used during research model testing.

Hysteresis error is eliminated by always reducing NPR—if a point is missed the sequence is continued without reversing direction. The ASME force and airflow values will calibrate out the nonlinearity of the load cells and pressure transducers. If a load cell is replaced during a test program, then a complete calibration including the force interaction coefficients, lab seal, and ASME has to be redone. A pressure transducer replacement would only require a repeat of the ASME nozzle calibration or a reprocessing of the original data with a new DP25 average.

ASME Calibration Results

Figures 15 to 17 give the results of the momentum station CF5 calibrations for 1.0-, 2.0-, and 5.0-psid DP25 differential pressure transducers. Data taken at 3, 4.5, and 6 NPR is averaged together to reduce data scatter. These points for averaging are purely arbitrary and other averages better suited for the research tests could be used—perhaps 3 or more points at 2.0 NPR, etc. The DP25 transducer data was reviewed during data processing for inconsistent trends, etc. For this report, one each of the 1.0- and 2.0-psid transducers were removed from the calculations and three of the four 5.0-psid transducers were not used. This is an important step to reduce CF5 fluctuations in the plots and improve the calibration. The CF5 data is plotted against the ideal Mach number at station 5, M5ID. M5ID is primarily a function of nozzle throat area.

Figures 18 to 20 show NPR corrections that are applied to the CF5 averages. A limited amount of data was taken for NPR above 7.5; therefore, the repeat set of nozzle data taken with 2.0-psid DP25 transducers was included to better define the 2.0-psid NPR corrections. ASME nozzle calibrations should duplicate all the NPR values of the research test plan to correctly calibrate the facility. These corrections will vary depending on what averages are used for the for the CF5 plots. If the research model has screens at the model inlet, then PT5/P0 should be used instead of NPR.

Figures 21 to 23 present the CD5 airflow calibrations for the three transducer ranges. CD5 does not vary with NPR and averages for CD5 and M5ID using all the choked-flow NPR data can be used.
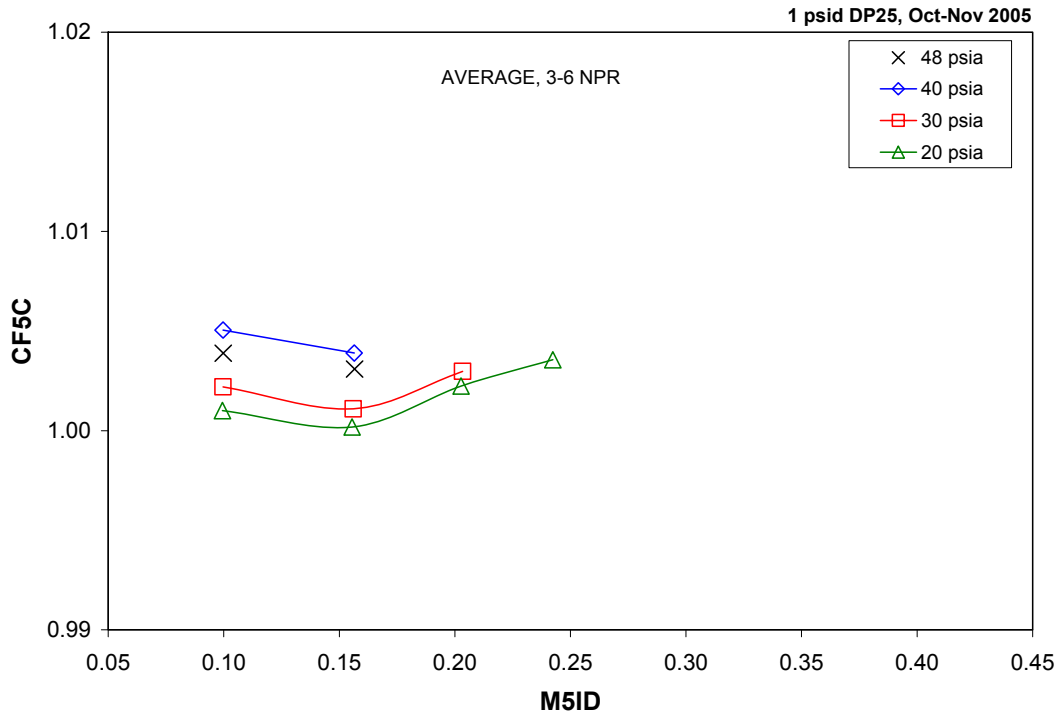
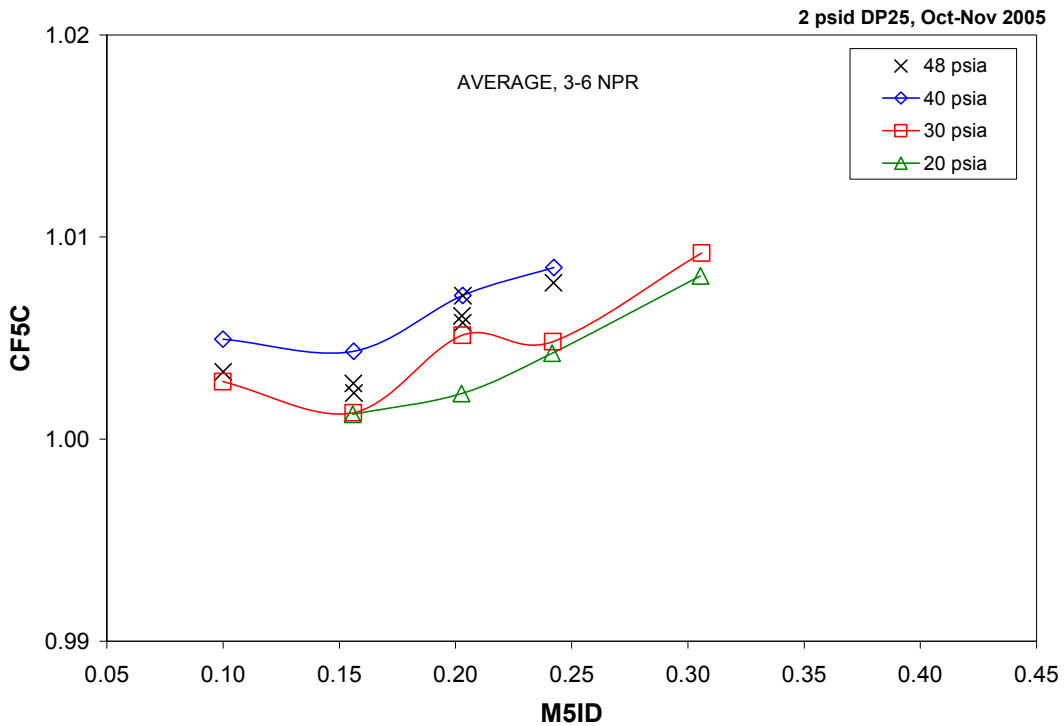Figure 15.—Station 5 force coefficient CF5 calibrations, 1-psid DP25 transducers.

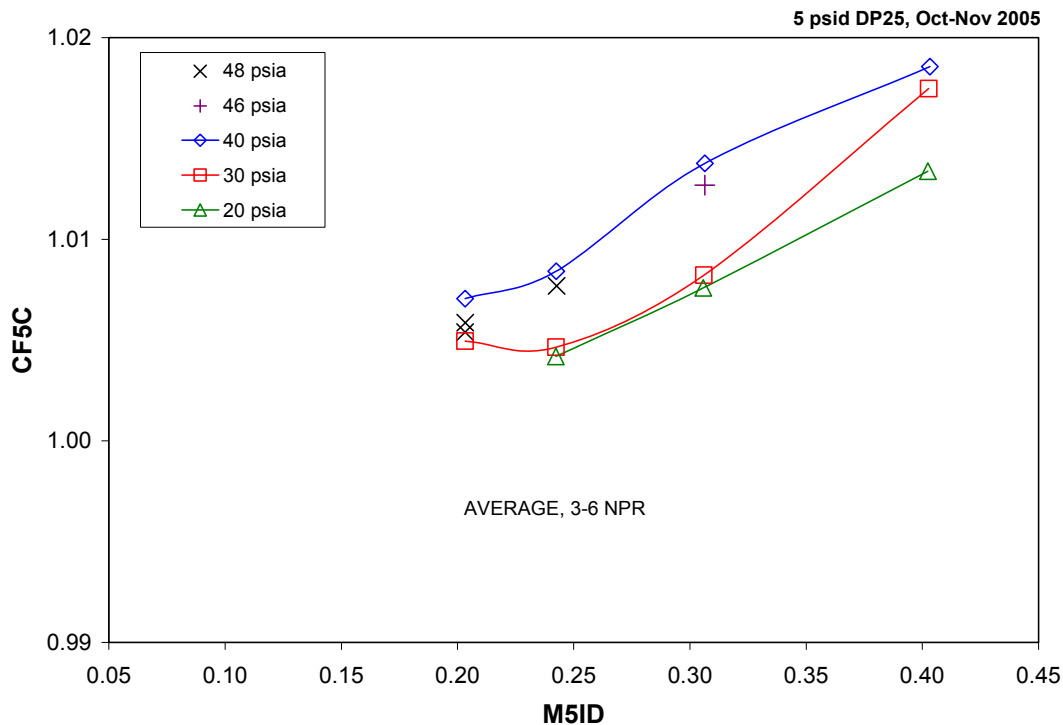Figure 16.—Station 5 force coefficient CF5 calibrations, 2-psid DP25 transducers.

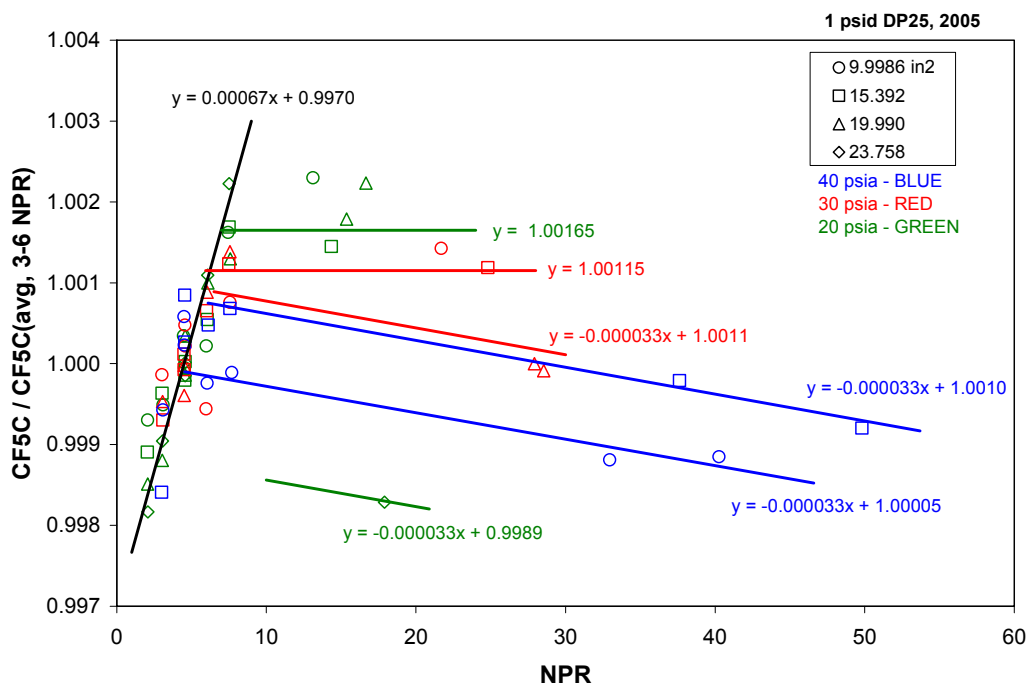Figure 17.—Station 5 force coefficient CF5 calibrations, 5-psid DP25 transducers.

Figure 18.—CF5 correction for NPR effects, 1-psid DP25 transducers.
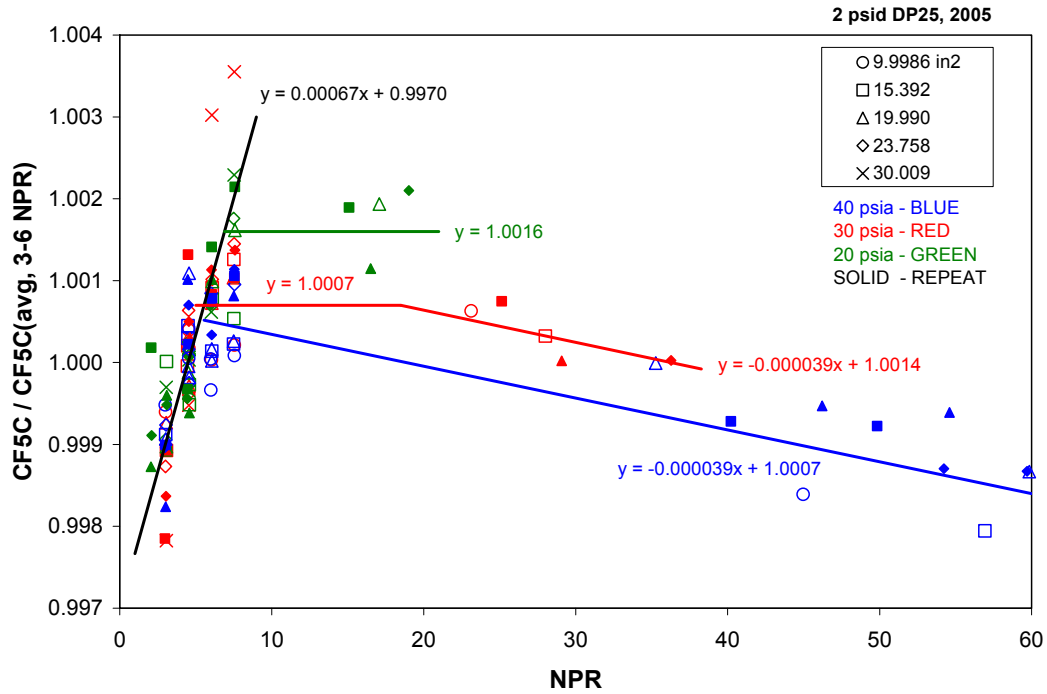
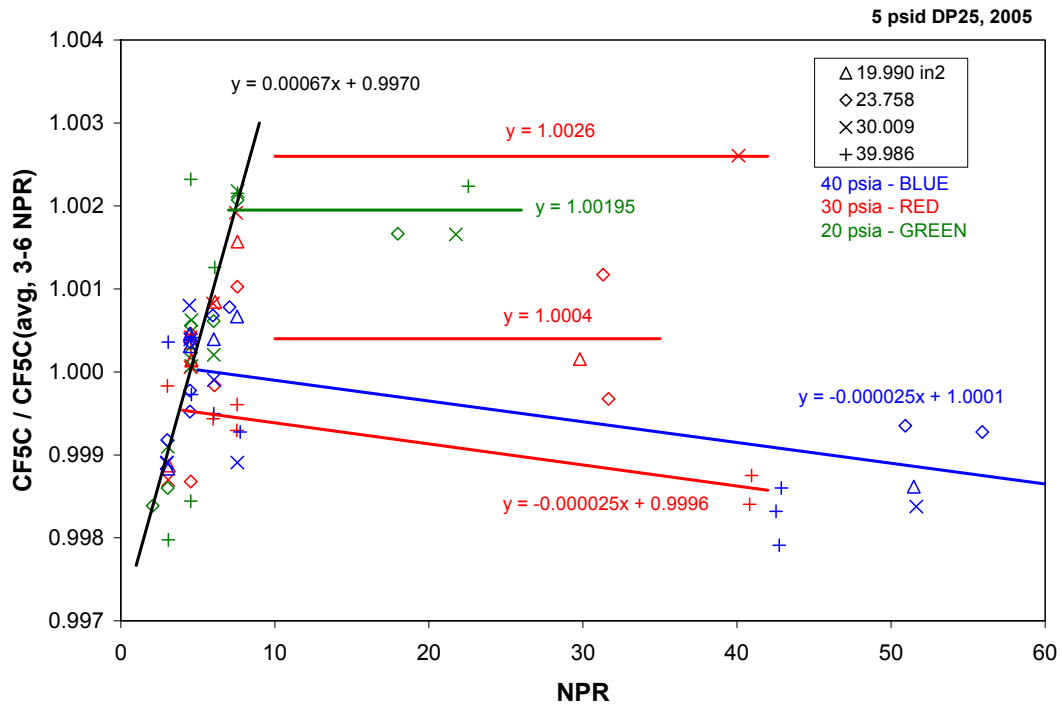Figure 19.—CF5 correction for NPR effects, 2-psid DP25 transducers.

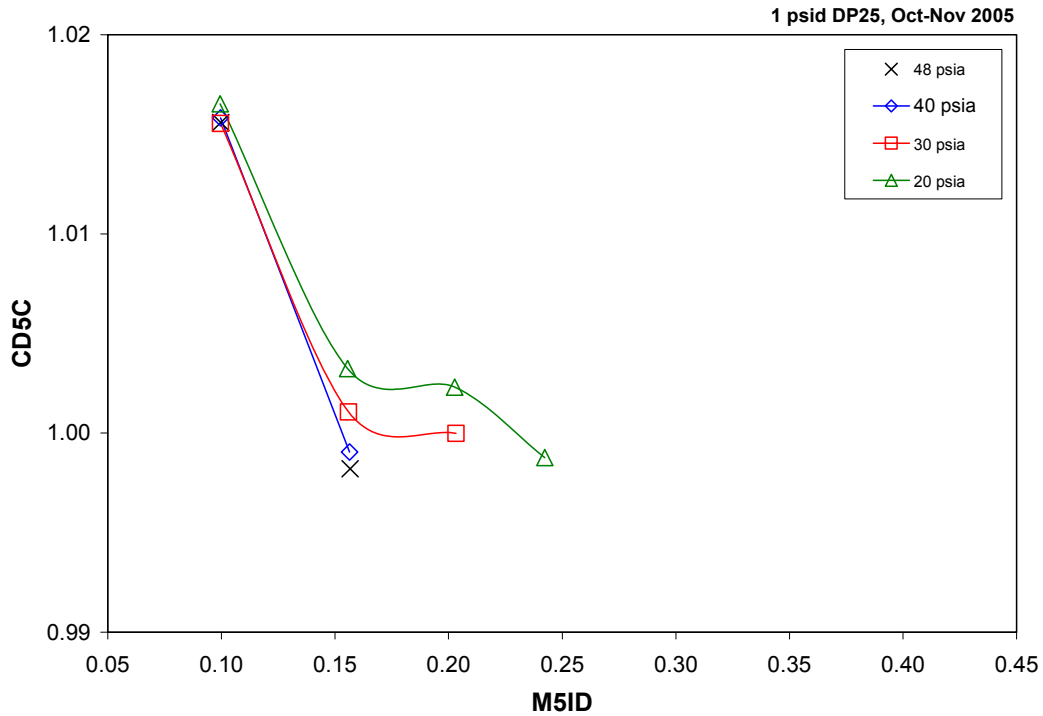Figure 20.—CF5 correction for NPR effects, 5-psid DP25 transducers.

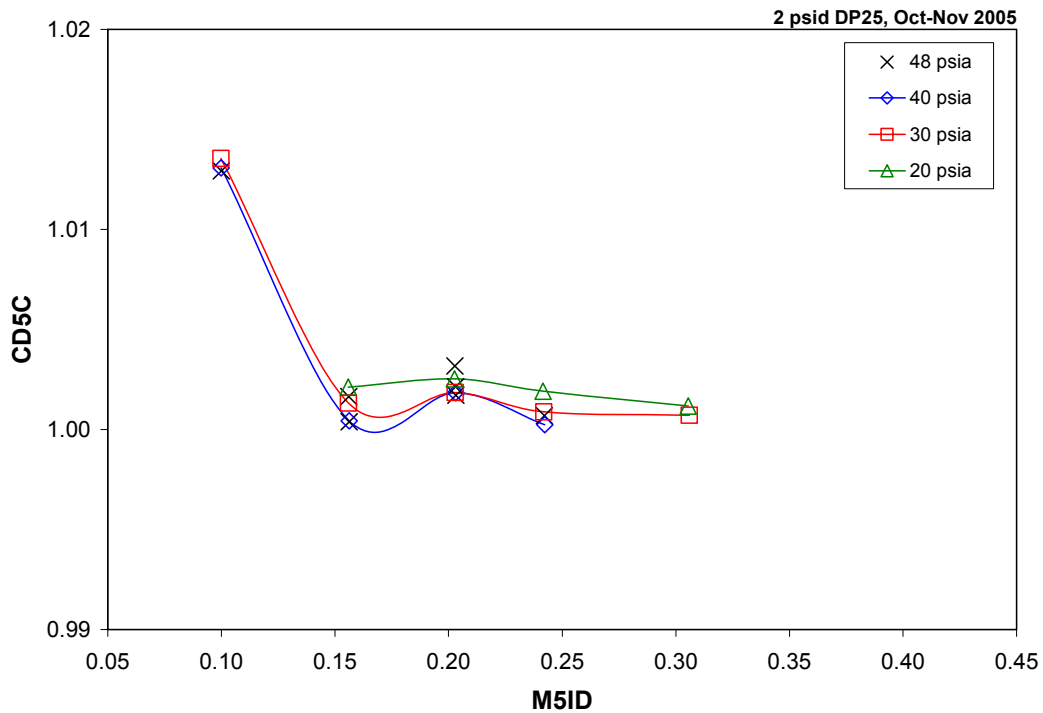Figure 21.—Station 5 airflow coefficient CD5 calibrations, 1-psid DP25 transducers.

Figure 22.—Station 5 airflow coefficient CD5 calibrations, 2-psid DP25 transducers.
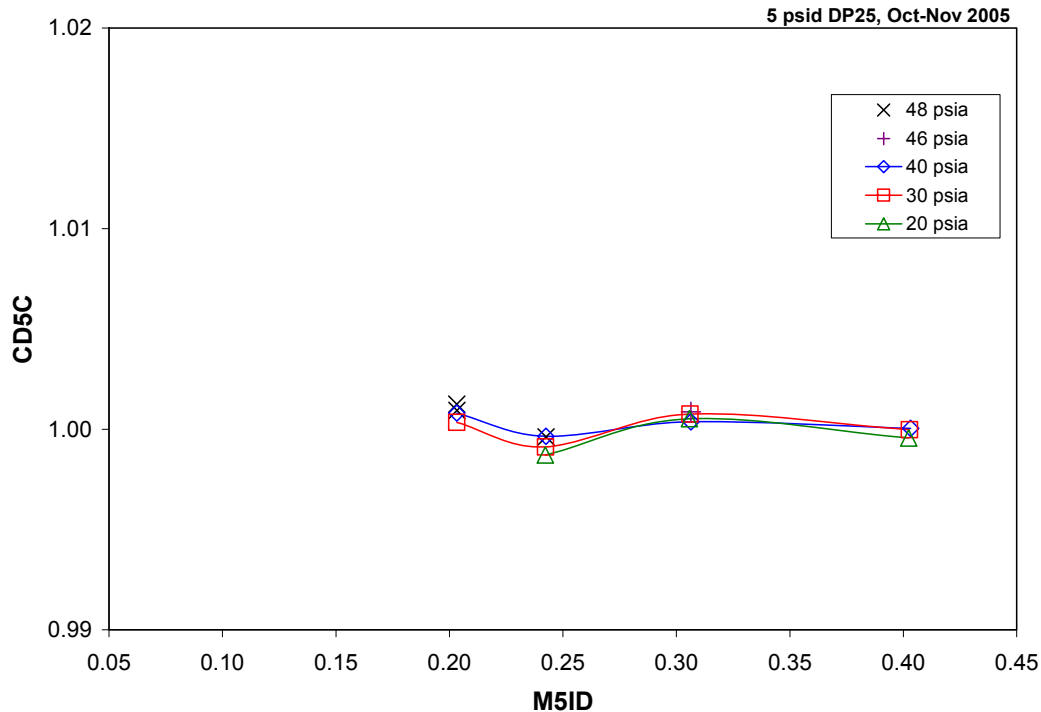
Figure 23.—Station 5 airflow coefficient CD5 calibrations, 5-psid DP25 transducers.

Thrust and Airflow Uncertainty

Thrust and airflow as represented by nozzle gross thrust coefficient CFG_{meas} and nozzle flow coefficient CDN_{meas} (calculations F057.1 and F038, Appendix A) are calculated for the ASME nozzles using facility measurements and the CF5 and CD5 calibrations. The percent difference to ASME predictions of CFG_{asme} and CDN_{asme} (CFGP, calculation F077, and CDP, calculation F071, Appendix A) is plotted versus NPR and presented in Appendix D. The percent difference in the nozzle performance coefficients for all throat areas and DP25 transducers is less than 0.25 for most of the force measurements and less than 0.13 percent for all of the airflow measurements.

At the end of the calibration program, repeat data was taken with 2.0-psid transducers and nozzle throat areas of 15.392-, 19.990-, and 23.758-in.^{2}—the most used transducer range and nozzle areas for the facility. The thrust and flow coefficients are processed as above using only the first set of 2.0-psid calibrations. Results are presented in Figures 24 and 25 that show a percent difference comparison as high as 1.1 percent for thrust and 0.23 percent for airflow.

The second set of data (post cal) was processed for CF5 and CD5 calibration values and these are shown in Figures 26 and 27 along with the original calibration (pre cal). The lines in these figures are for the average of the two calibrations. All the 2-psid data for the three nozzles was processed again using the average calibration coefficients, and results versus NPR are given in Figures 28 and 29.
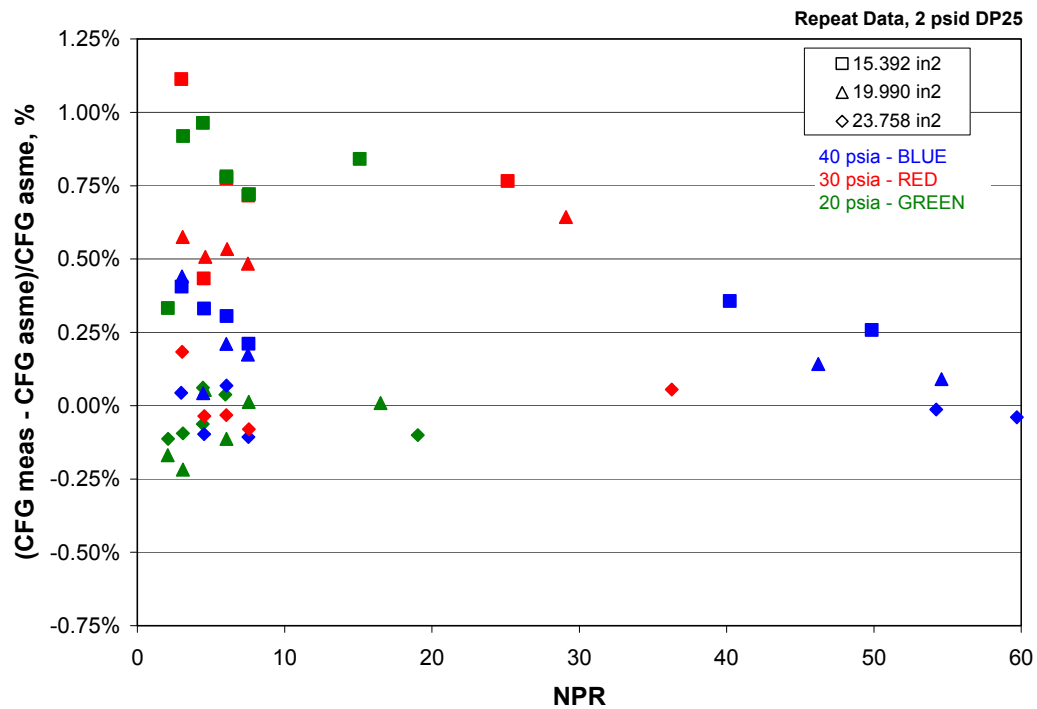
Figure 24.—ASME nozzle gross thrust coefficient CFG uncertainty of repeat data using pre-run CF5 calibrations.
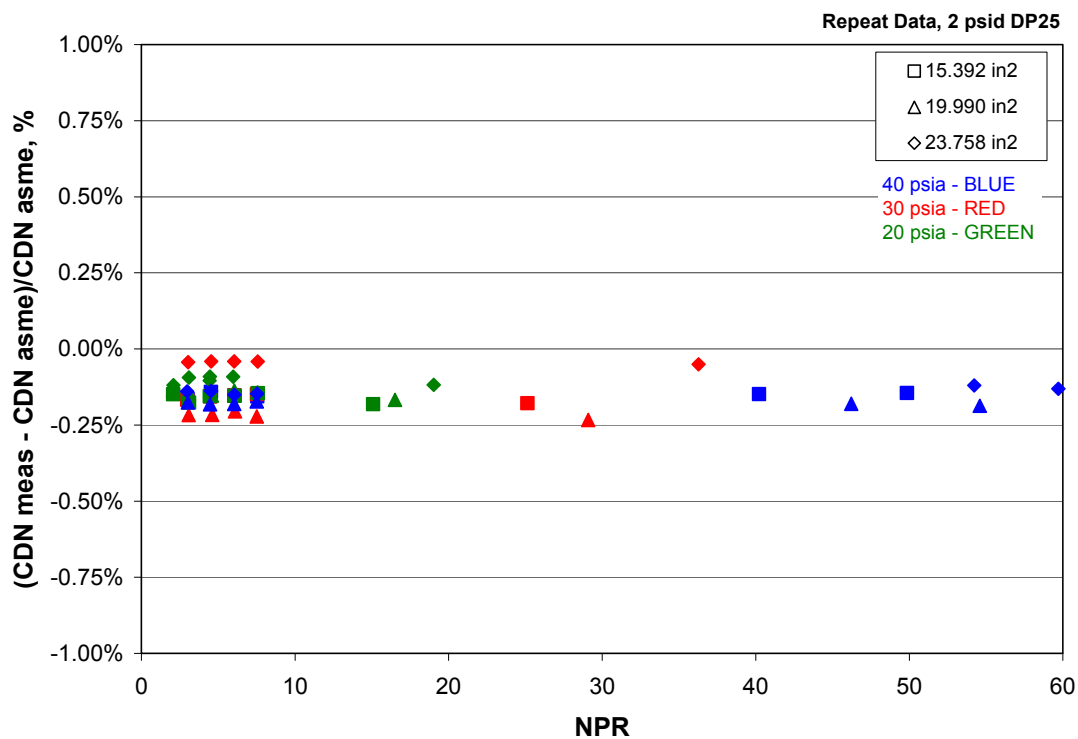

Figure 25.—ASME nozzle gross flow coefficient CDN uncertainty of repeat data using pre-run CD5 calibrations.
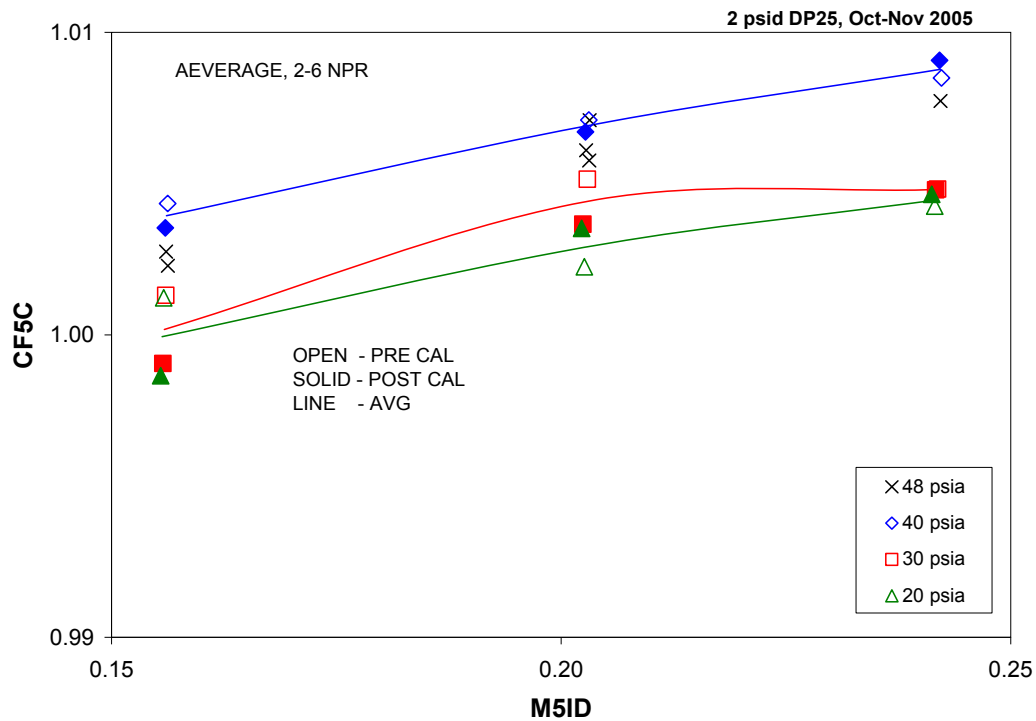
Figure 26.—Average of station 5 force coefficient CF5 pre and post calibrations, 2-psid DP25 transducers.

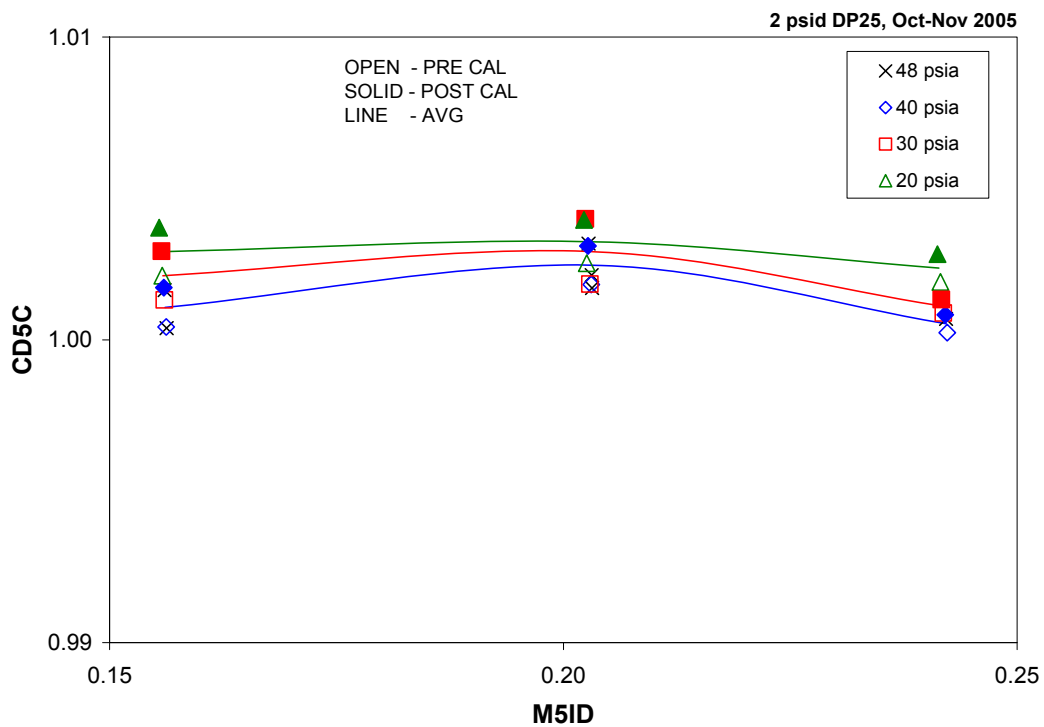Figure 27.—Average of station 5 flow coefficient CD5 pre and post calibrations, 2-psid DP25 transducers.
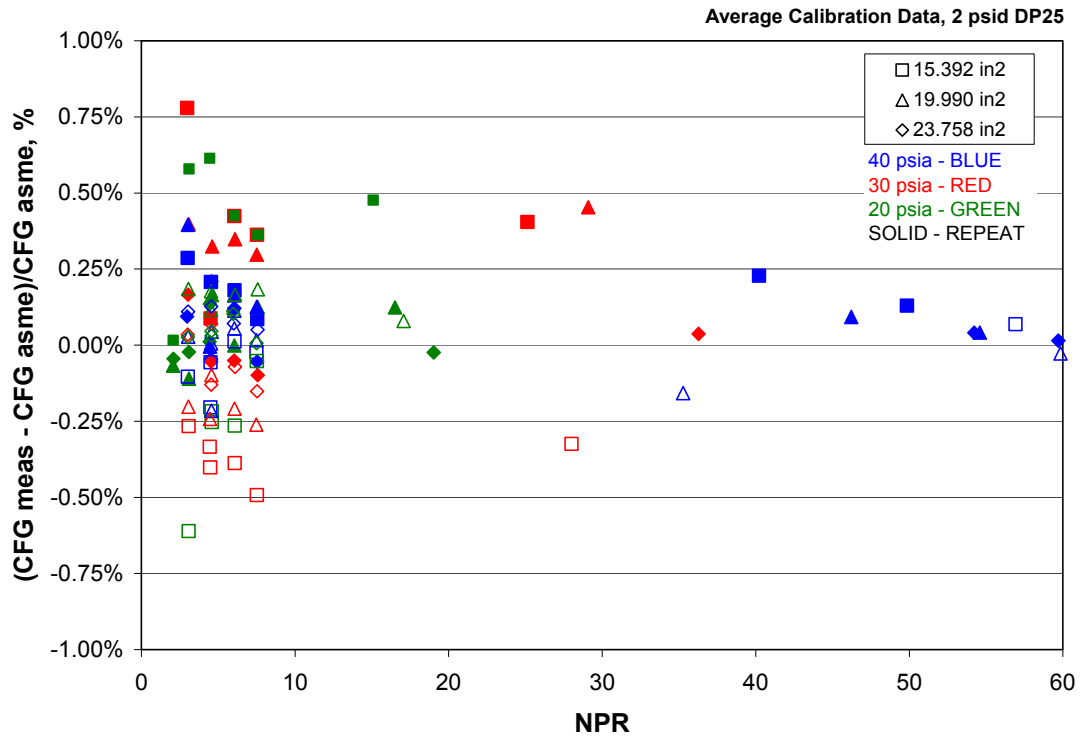
Figure 28.—ASME nozzle gross thrust coefficient CFG uncertainty of all data using average of pre and post CF5 calibrations, 2-psid DP25 transducers.
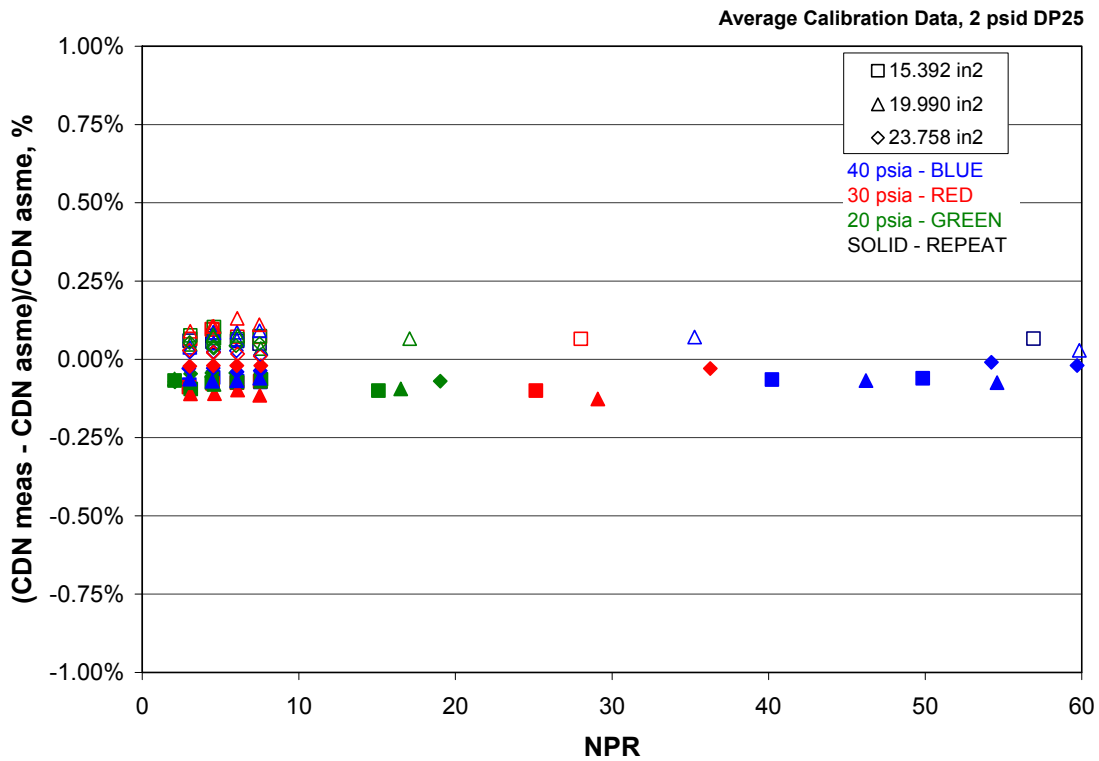

Figure 29.—ASME nozzle flow coefficient CDN uncertainty of all data using average of pre and post CD5 calibrations, 2-psid DP25 transducers.
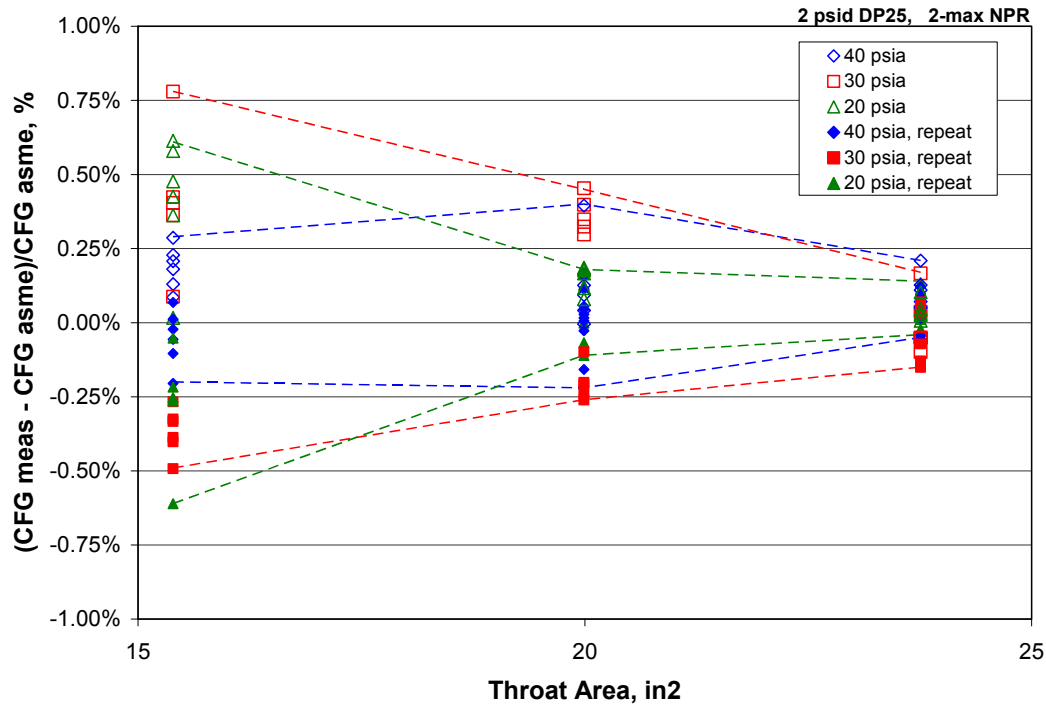
Figure 30.—ASME nozzle gross thrust CFG uncertainty using the average CF5 calibrations for each ASME nozzle area, 2-psid DP25 transducers.

Figure 28 gives 0.75-percent agreement with ASME predictions for thrust and Figure 29 have 0.13-percent agreement for airflow. The thrust data from Figure 28 are shown versus nozzle throat area in Figure 30. Here, there is 0.25-percent agreement for all pressures at 23.758 in.[2], 0.50-percent agreement at 19.990 in.[2] and 0.75-percent agreement at 15.392 in.[2]. Except for two points, the 40 psia data is in agreement with the ASME values for all areas and the 20 psia data is also within 0.25-percent agreement at 19.990 in.[2]. Total time duration of two weeks was between the two sets of 2-psid DP25 data. Between these tests the 5.0-psid calibrations were done, and then the 2.0-psid transducers were reinstalled.

Research Model Testing

For best results, a research model should have the same throat area has one of the ASME nozzles. Also, an ASME nozzle calibration needs to be done upon completion of a research program and averaged with the pre-run calibration for final data processing. Six weeks of research testing would be about an ideal time period. Research programs lasting much longer than 2 months should consider having an ASME nozzle calibration near the middle of testing. Future programs will determine the time between calibrations and if only the calibration coefficient values are required or if the NPR effects also need to be recalibrated.

Research nozzles with area expansion will produce thrust somewhere between the ASME force and the nozzle exit ideal force (calculation F039, Appendix A). Figure 31 shows the forces for the maximum NPR points at 30 and 40 psia. As the nozzle throat area is increased, the thrust stand FX force decreases while the ASME force increases. Also shown is the maximum nozzle force at each nozzle area for ideal expansion. The station 5 ideal momentum force F5ID increases slightly with the increase in airflow. Figure 32 gives the percent increase expected for the load cell measurements with the ideal expansion. At a nozzle area of 40 in.[2], the axial load cell measurement force increases up to 30 percent of its ASME value. Axial load cell nonlinearity may affect the nozzle thrust measurement uncertainty since the area expansion
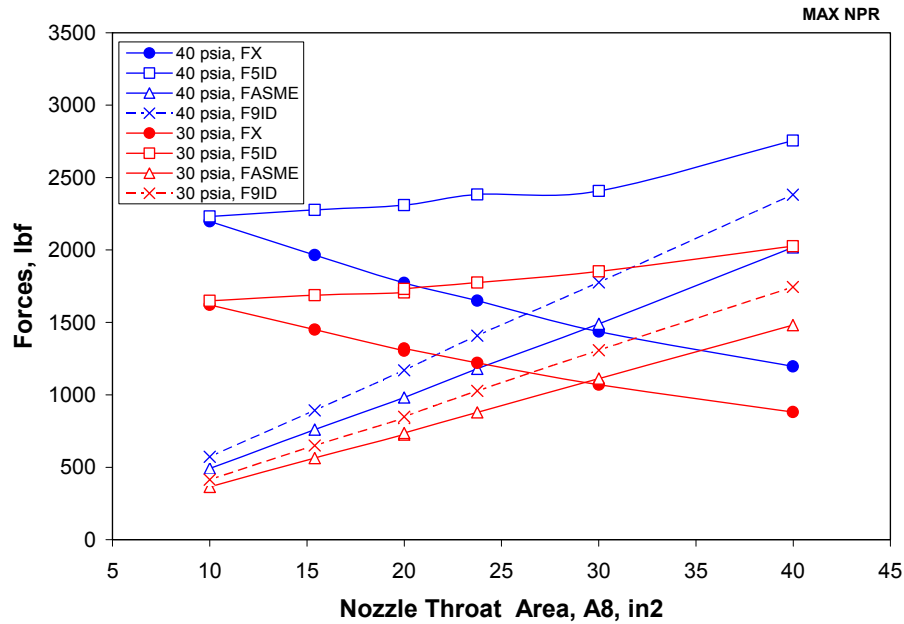
Figure 31.—Comparison of forces at maximum NPR, 30 and 40 psia.
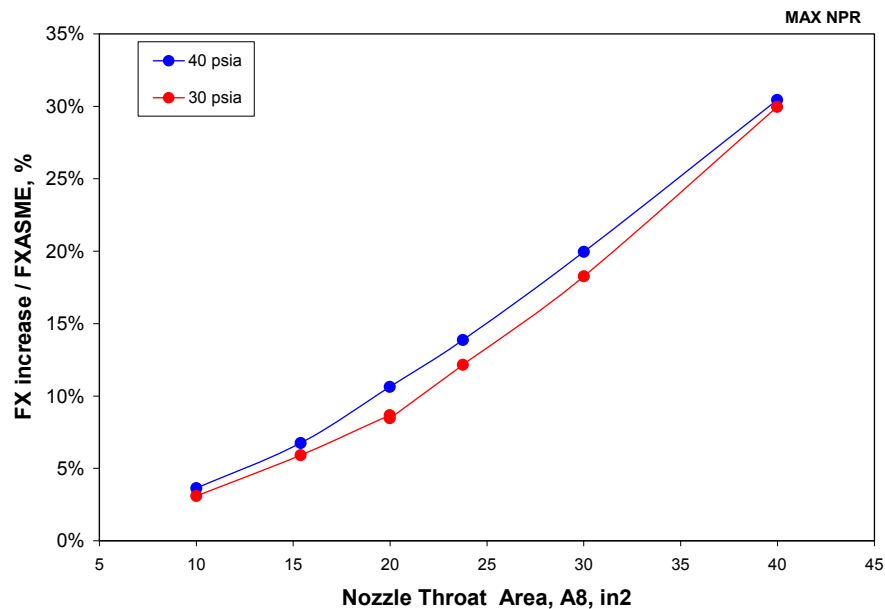
Figure 32.—Axial thrust stand force (FX) increase with ideal area expansion ratio, percent of ASME axial load cell force, 30 and 40 psia.

force measurements are above those for the ASME nozzle calibration. This effect may be small as the axial force increase is only 4.6 percent of full scale load cell range at 40 psia and 3.3 percent at 30 psia. Two 4000-lbf load cells are used. A maximum force of 2693 lbf was measured for the summation of axial load cells at 10 in.[2] and 49 psia; therefore, using 2000-lbf load cells might be considered for use in the future. Area sizing of a research model has to consider the higher ASME nozzle calibration force with larger throat area against the lower load cell force measurements and increases of area expansion effects.

Thrust and Airflow Measurements at 1.5 NPR

Measurements were taken at 1.5 NPR with 20 psia for various ASME nozzles, and the results are presented in Table I using the CDN and CFG coefficients. Comparisons are shown with the choked-flow ASME predictions and with Fluidyne predictions from the aero propulsion industry. Measured CDN at 1.5 NPR is up to 0.5 percent less than the Fluidyne predictions for 1-psid data with nozzle areas of 19.990 in.[2] and larger and for all the data using larger transducers. Measured CFG at 1.5 NPR compares quite well with Fluidyne values having a 0.25-percent agreement except for 1-psid data at 9.9986 in.[2] and 2-psid data at 15.392 in.[2] and 19.990 in.[2]; the respective differences are 0.6, 0.8, and 0.3 percent.

TABLE I.—CDN AND CFG AT 2.0 AND 1.5 NPR

DP25	A8	PT	NPR	CDN	CDN	CDN	CFG	CFG	CFG
				Meas.	ASME choked cal.	ASME Fluidyne pred.	Meas.	ASME choked cal.	ASME Fluidyne pred.
psid	in2	psia							
1	9.9986	20.07	2.07	0.991	0.990	0.992	0.990	0.994	0.996
1	9.9986	20.06	1.58	0.991	---	0.992	0.989	---	0.995
1	15.392	20.09	2.05	0.990	0.990	0.992	0.994	0.994	0.996
1	15.392	20.05	1.51	0.990	---	0.992	0.993	---	0.995
1	19.990	20.07	2.06	0.991	0.990	0.992	0.995	0.994	0.996
1	19.990	20.03	1.58	0.988	---	0.992	0.994	---	0.995
1	23.758	19.94	2.08	0.991	0.991	0.992	0.996	0.994	0.996
1	23.758	20.08	1.56	0.988	---	0.992	0.996	---	0.995
2	15.392	20.02	2.08	0.989	0.990	0.992	0.995	0.994	0.996
2	15.392	20.02	1.48	0.988	---	0.992	0.986	---	0.994
2	19.990	19.98	2.06	0.989	0.990	0.992	0.994	0.994	0.996
2	19.990	20.01	1.60	0.987	---	0.992	0.998	---	0.995
2	23.758	20.09	2.09	0.989	0.991	0.992	0.995	0.994	0.996
2	23.758	20.06	1.56	0.986	---	0.992	0.993	---	0.995
5	23.758	20.09	2.07	0.992	0.991	0.992	0.994	0.994	0.996
5	23.758	20.00	1.58	0.989	---	0.992	0.993	---	0.995

ASME Nozzle Vectoring

The 15.392-in.[2] and the 19.990-in.[2] throat area ASME nozzles were mounted to the facility supply duct with choke plates at the nozzle inlet and wedges for 10° of turning. These were used to check the vectoring measurement system in four directions (left and right yaw, up and down pitch). Pressures of 40, 30, and 20 psia were set in the nozzle; this required station 6 pressures to be approximately 12 percent higher for the 15.392-in.[2] nozzle and 20 percent higher for the 19.990-in.[2] to obtain the same nozzle pressure ratio. Nozzle total pressure was determined from the throat static-pressure taps. The 15.392-in.[2] nozzle used the 1.0-psid DP25 transducers and calibration coefficients while the 19.990-in.[2] nozzle used the 2.0-psid transducers and calibration coefficient averages. Measured axial force included linear interpolations of M5ID and PT5 (instead of PT) for CF5; NPR corrections for CF5 were approximated using PT5/P0 instead of NPR.

Vectoring results are shown in Figures 33 and 34. The negative angles (yaw right and pitch up) are plotted as positive angles for better comparisons. The data comparisons are slightly larger for the smaller nozzle; there is a 0.4-degree spread between the two sets of pitch-up runs. Both figures show non-symmetry for vectoring and a facility bias might be present. The data should be corrected for a zero-angle offset to have symmetry for positive and negative vector angles.
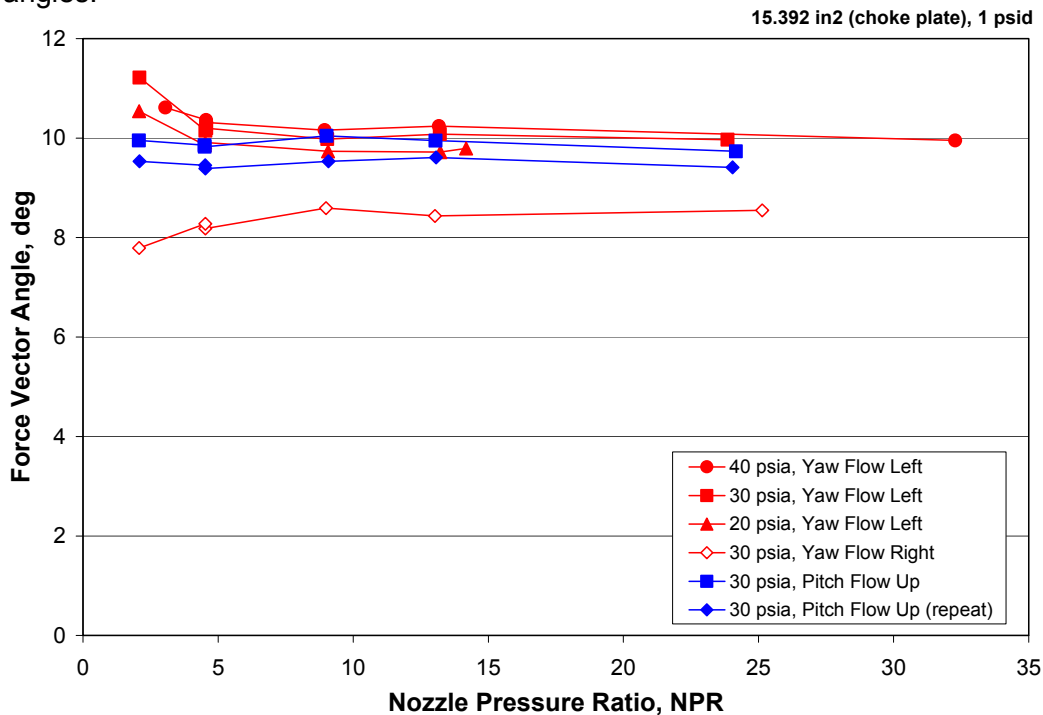

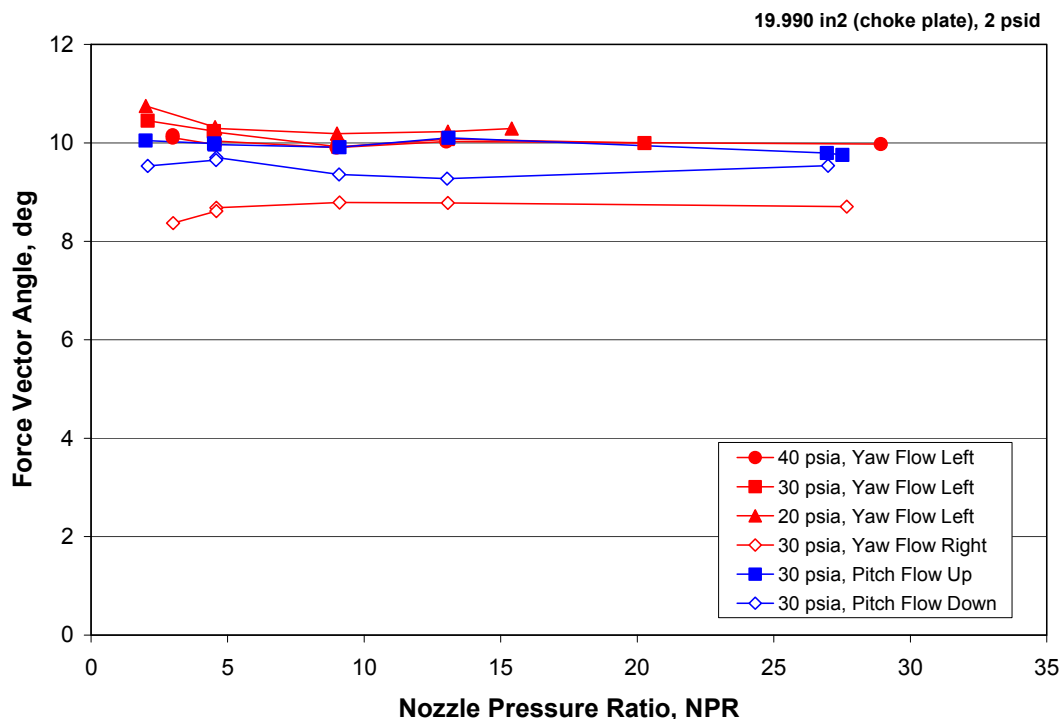Figure 33.—10° vectoring with the 15.392-in.^{2} throat ASME nozzle, 1-psid DP25 transducers.

Figure 34.—10° vectoring with the 19.990-in.^{2} throat ASME nozzle, 2-psid DP25 transducers.

Nozzle Inlet Total-Pressure Profiles

Total pressure profiles are included to show the quality of the nozzle inlet conditions. Figure 35 shows the variation of the station 6 pressure profiles for all the ASME nozzles. As flow at station 6 increases with the increase of throat area, the pressure profile exhibits more distortion. The low pressure at the center is caused by the wake of an upstream temperature measurement rake. The temperature rake crosses the pressure rake at 90° and is also upstream of the flow straightening screen; the total-pressure rake is downstream of the screens.

Figure 36 gives inlet pressure profiles when the temperature measurement rake is out. The pressure is higher in the center when compared to the profile of the previous figure. The three pressure levels have identical profiles.
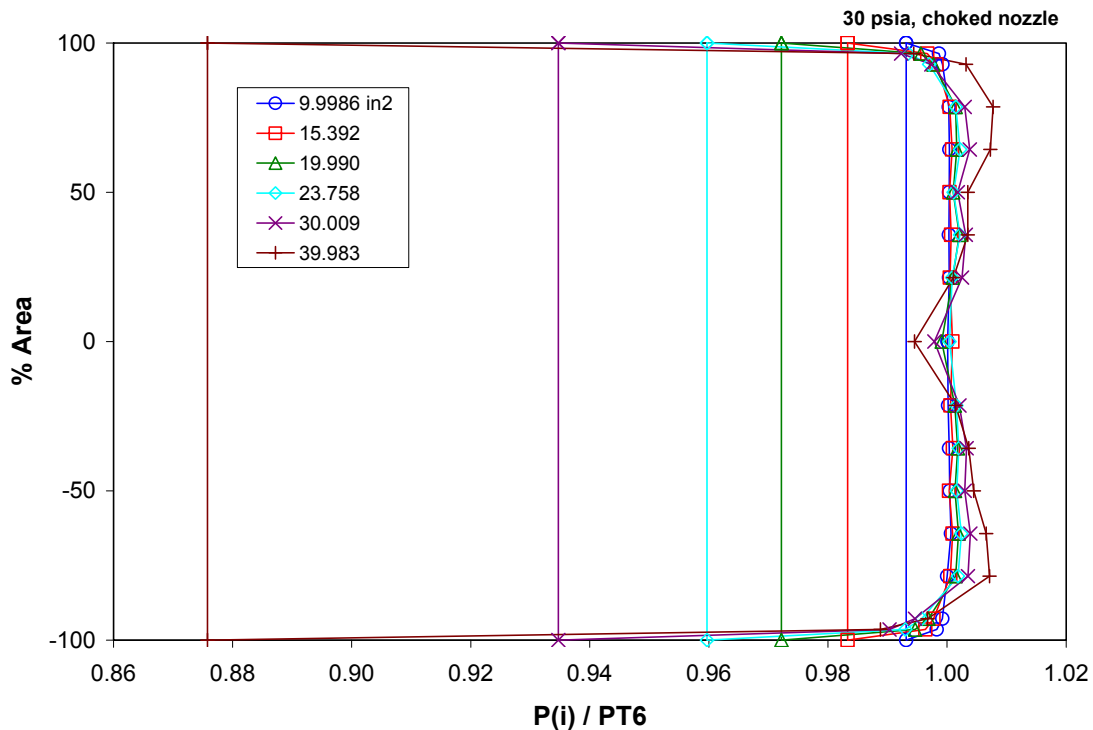

Figure 35.—Inlet total-pressure profiles for all the ASME nozzle throat areas, 30 psia, inlet temperature rake installed.
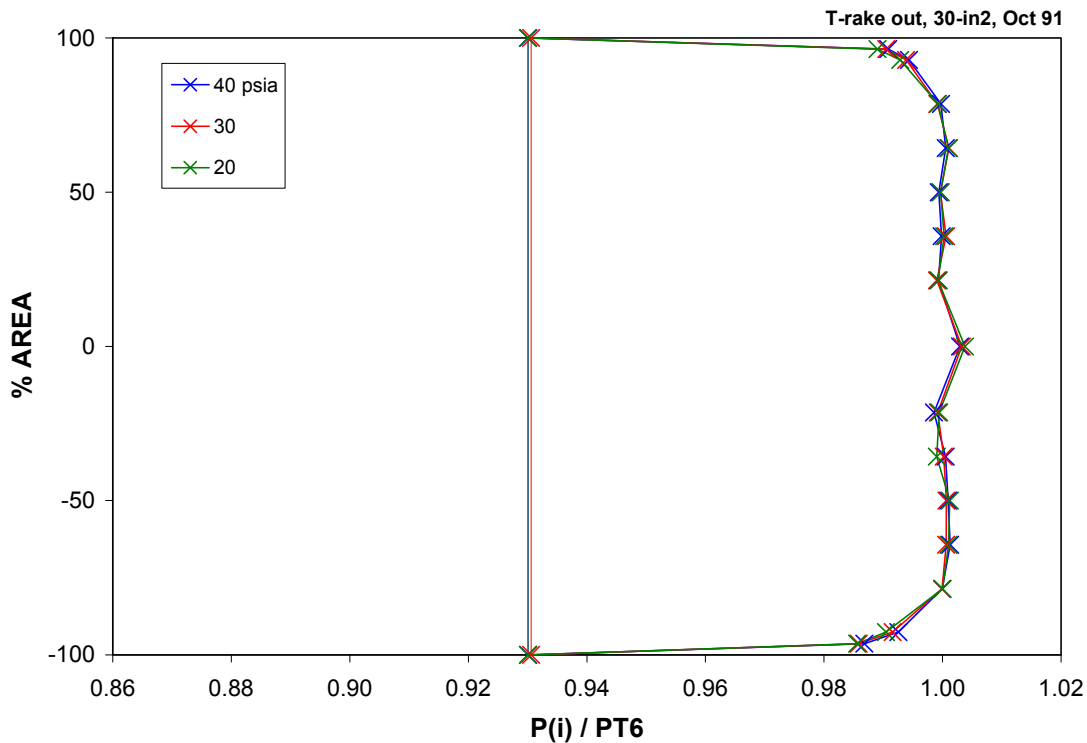
Figure 36.—Inlet total-pressure profiles for three inlet pressures at an ASME nozzle throat area of 30.009-in.^{2}, no inlet temperature rake.

References

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Appendix A.—Abridged and Revised Facility Calculations

Constants:

CONF	= *input*	Configuration number	
NOZZ	= *input*	Nozzle designation	(in CONF)
A8	= *input*	Throat area of ASME nozzle, in2	(in CONF)
A9_A8	= *input*	Nozzle area expansion ratio	(in CONF)
A5	= 56.745	Station 5 flow area, in2	
ALS1	= 14.137	Labyrinth seal face area, in2	
ANGE	= *input*	Nozzle mounting angle (vector calibration), deg	
FXKNOB	= *input*	ADP cal FX Offset (=FXKNOBM at vac tare), lbf	
P0KNOB	= *input*	Value of P0 at time of the most recent KNOB, psia	
SFXP0	= *input*	Slope for P0 effect on FX, in2	
SFYP0	= *input*	Slope for P0 effect on FY, in2	
SFZP0	= *input*	Slope for P0 effect on FZ, in2	
SMXP0	= *input*	Slope for P0 effect on MX, in3	
SMYP0	= *input*	Slope for P0 effect on MY, in3	
SMZP0	= *input*	Slope for P0 effect on MZ, in3	
BETAZ	= *input*	Yaw angle zero correction from vectored ASME, deg	
ALPHAZ	= *input*	Pitch angle zero correction from vectored ASME, deg	

S_{ij}	= *25 inputs, (i=1-5, j=1-5)*	load cell interaction coefficients from in-stand calibration, set equal to SDUM (i, j) in calculations
U_{ij}	= *25 inputs, (i=1-5, j=1-5)*	load cell interaction coefficients from in-stand calibration, set equal to UDUM (i, j) in calculations

PI	= 3.141592654	
RG	= 53.352	ft-lbf / lbm-R
GAM	= 1.4	specific heat ratio
GC	= 32.174	lbm-ft / sec2-lbf
PSTS	= 14.696 / sqrt (518.67)	lbf/in2 / sqrt R

Averages:

DP25	(PS2-PS5) delta-pressure transducers, psid
P0	Altitude-exhaust pressures, psia
PS1	Inlet duct static pressures, psia
PS2	Inlet duct static pressures, psia
PS3	Labyrinth seal inlet static pressures, psia
PS5	Airflow station static pressures, psia
PT5	Airflow station total pressure (average PS1, PS2), psia
PS6	Model inlet static pressures, psia
PT6	Model inlet area weighted total pressure (includes PS6), psia
PS8	Model throat static pressures, psia
PASME	ASME nozzle throat static pressures (PS8), psia
TT6	Model inlet total temperatures, R

Equations:

```
C
C                   A.  FACILITY CALCULATIONS
C
C        F006   NPR
C
          PT   = PT6
C        IF ASME CHOKED-FLOW PLATE USED (VECTORED NOZZLES):
             IF (ANGE.GT.0.) THEN
               PT = 1.8929 * PASME
             ENDIF
            NPR = PT/P0
C
C        F016   Gamma constants (sta. 5)
C
            GP1  = GAM + 1
            GM1 = GAM - 1
            G1   = GM1 / GAM
            G2   = 2 / GP1
            G3   = 2 / GM1
            G4   = GP1 / (2 * GM1)
            G5   = SQRT (GC * GAM / RG)
            G6   = SQRT (2 * RG * GC / G1)
            G7   = 2 / (RG * GC * G1)
            G8   = - 2 / GAM
C
C        F017   Ideal Mach number at sta. 5
C
            PR5F= (PT5 / (PT5 - DP25))**G1
            M5ID= SQRT (G3 * (PR5F - 1))
C
C        F019   Sta. 5 flow coefficient (ASME nozzle choked-flow calibration)
C
            CD5  = curve fits from ASME calibration, fcn (M5ID)
C
C        F020   Mass flow at sta. 5 (primary), lbm/sec
C
            W5ID = G5 * A5 * PT5 * M5ID / (SQRT (TT6) * PR5F**G4)
            WP   = CD5 * W5ID
C
C        F021   Ideal momentum at sta. 5 (metric break), lbf
C
            MOM5ID = GAM * (PT5 - DP25) * A5 * M5ID**2
C
C        F022   Mach number at sta. 5
C
            M5   = CD5 * M5ID
C
C        F023   Corrected mass flow, lbm/sec
```

```
C
         WPCOR = PSTS * WP * SQRT (TT6) / PT
C
C      F027   Differential pressures at lab seal and sta.5, psid
C
       DP30 = PS3 - P0
       DP50 = (PT5 - DP25) - P0
C
C      F028   Force on lab seal, lbf
C
       FLS  = ALS1 * DP30
C
C      F029   Ideal inlet force at sta. 5, lbf
C
       F5ID = MOM5ID + A5 * DP50
C
C      F030   Sta. 5 force coefficient (ASME nozzle choked-flow calibration)
C
       CF5  = curve fits from ASME calibration, fcn (M5ID, PT, NPR, etc.)
C
C      F031   Inlet force at sta. 5, lbf
C
       F5   = CF5 * F5ID
C
C      F032   Effective lab seal area from blank-off plate calibration, in2
C
       PS3QP0 = PS3 / P0
       ALS3 = curve fits from AΔP calibration, fcn (PS3QP0, PT5)
C
C      F033   Pressure tare force, lbf
C
       FTARE = ALS3 * DP30
C
C      F034   NPR for 1D choked flow
C
       NPRC = (1 / G2)**(1/G1)
C
C      F035   Unchoked sta. 8 ideal flow (throat), lbm/sec
C
       D8C  = SQRT (4 * A8 / PI)          !! can use hydraulic mean diameter
C                                         !! (D8C = 4 * A8 / wetted perimeter)
       IF ((PT/PS8) .LE. NPRC) THEN
         M8  = SQRT (G3 * ((PT/PS8)**G1 - 1))
         TS8  = TT6 / (PT/PS8)**G1
         MU8 = 7.3025E-7 * TS8**1.5 / (TS8 + 198.72)
         RN8 = 48 * WP / (PI * D8C * MU8)
         W8ID = G5 * PS8 * A8 / SQRT (TS8) * M8
       ENDIF
C
```

```
C       F036   Choked sta. 8 ideal flow (throat), lbm/sec
C
        IF (NPR .GT. NPRC) THEN
          M8 = 1
          TS8 = TT6 * G2
          MU8 = 7.3025E-7 * TS8**1.5 / (TS8 + 198.72)
          RN8 = 48 * WP / (PI * D8C * MU8)
          W8ID = G5 * PT * G2**(1/G1) * A8 / SQRT (TS8)
        ENDIF
C
C       F037   Ideal velocity at sta. 9 (perfect expansion), ft/sec
C
        VEL9  = G6 * SQRT (TT6 * 1 -  (1/NPR)**G1))
C
C       F038   Nozzle discharge coefficient
C
        CDN =  WP / W8ID
C
C       F039   Ideal thrust at sta. 9, lbf
C
        F9ID = WP * VEL9 / GC
C
C  Force balance, lbf:
C    X-positive forward & Y-positive right (looking upstream), Z-positive down
C    C-calibration forces, positive with X, Y, and Z
C    R-reaction forces, negative with X, Y, and Z (R positive when C negative)
C    tension load cells-positive, compression load cells-negative
C
C       F040   Calibration load cell forces
C
        FCY2  =  CY2
        FCY1  =  CY1
        FCZ1  =  CZ1
        FCZ2  =  CZ2
        FCZ3  =  CZ3
        FCZ4  =  CZ4
        FCX1  =  - CX1
        FCX2  =  CX2
C
C       F041   Reaction load cell forces
C              (Un-vented load cells need to be corrected for P0 zero shift here)
C
        FRY2  =  RY2
        FRY1  =  RY1
        FRZ1  =  - RZ1
        FRZ2  =  RZ2
        FRZ3  =  RZ3
        FRZ4  =  - RZ4
        FRX1  =  - RX1
```

```
         FRX2  =  RX2
C
C        F042    Reaction matrices
C
         R(1)  =  FRX1
         R(2)  =  FRX2
         R(3)  =  FRY1
         R(4)  =  FRY2
         R(5)  =  FRZ1 + FRZ3
         R(6)  =  FRZ2 + FRZ4
C
         Q(1)  =  R(1)
         Q(2)  =  R(2)
         Q(3)  =  R(3)
         Q(4)  =  R(4)
         Q(5)  =  FRZ1 + FRZ2
         Q(6)  =  FRZ3 + FRZ4
C
C        F044    Calibration forces for in-stand static calibration
C
         F(1)  =  FCX1 + FCX2
         F(2)  =  FCY1 + FCY2
         F(3)  =  FCZ1 + FCZ2 + FCZ3 + FCZ4
C
C        F045    Reaction-Calibration force differentials for in-stand static calibration
C
         R1F12 = R (1) - F (1) / 2
         R2F12 = R (2) - F (1) / 2
         R3F22 = R (3) - F (2) / 2
         R4F22 = R (4) - F (2) / 2
         R5F32 = R (5) - F (3) / 2
         R6F32 = R (6) - F (3) / 2
         Q5F32 = Q (5) - F (3) / 2
         Q6F32 = Q (5) - F (3) / 2
         R5F3  = R (5) - F (3)
         R6F3  = R (6) - F (3)
         Q5F3  = Q (5) - F (3)
         Q6F3  = Q (6) - F (3)
         R3F2  = R (3) - F (2)
         R4F2  = R (4) - F (2)
C
C        F046    Research model forces and moments from inverse matrix, lbf and in-lbf
C
         DO I = 1, 5
            FS(I) = SDUM(I,1) * R(1) + SDUM(I,1) * R(2) + SDUM(I,2) * R(3) +
     &              SDUM(I,3) * R(4) + SDUM(I,4) * R(5) + SDUM(I,5) * R(6)
         ENDO
         DO I = 1,5
            FU(I) = UDUM(I,1) * R(1) +  UDUM(I,1) * R(2) + UDUM(I,2) * R(3) +
```

```
&           UDUM(I,3) * R(4) + UDUM(I,4) * R(5) + UDUM(I,5) * R(6)
          ENDO
C
C     F047   Force and moment corrections for P0 and secondary flow,
C              P0 corrections result from tank deflection effects on force balance
C              fcn (P0-P0KNOB), only slopes from calibration are used, linear fit,
C              Pressurized secondary line effects on force balance are calibrated with
C              the model installed and capped lines over a range of secondary
C              pressures, fcn (psec-P0), psec = PS302C, PS303C, PS123C, PS124C
C              and other line pressures
C
       FXP0 = SFXP0 * (P0 - P0KNOB)
       FYP0 = SFYP0 * (P0 - P0KNOB)
       FZP0 = SFZP0 * (P0 - P0KNOB)
       MXP0 = SMXP0 * (P0 - P0KNOB)
       MYP0 = SMYP0 * (P0 - P0KNOB)
       MZP0 = SMZP0 * (P0 - P0KNOB)
C
C              Add secondary-flow pressurized-line curve fits from calibration
C
       FX302 = 0.
       FX303 = 0.
       FY302 = 0.
       FY303 = 0.
       FZ302 = 0.
       FZ303 = 0.
       MX302 = 0.
       MX303 = 0.
       MY302 = 0.
       MY303 = 0.
       MZ302 = 0.
       MZ303 = 0.
C
C     F048   Axial force in x-axis, lbf
C
       FX = - FU (1)
C
C     F049   Side force in y-axis, lbf
C
       FY = FU (2)
C
C     F050   Vertical force in z-axis, lbf
C
       FZ = FU (3)
C
C     F051   Moments, in-lbf
C
       MX = FS (4) - MXP0 - MX302 - MX303
       MY = FU (4) - MYP0 - MY302 - MY303
```

```
                MZ = FU (5) - MZP0 - MZ302 - MZ303
C
C       F052    Axial net force, lbf
C
            FGX = F5 + FLS + FTARE - FX + FXP0 + FX302 + FX303
C
C       F053    Side net force, lbf
C
            FGY = FY - FYP0 - FY302 - FY303
C
C       F054    Vertical net force, lbf
C
            FGZ = FZ - FZP0 - FZ302 - FZ303
C
C       F055    Length for center of vectored force LX to stand x-y centroid, inches
C               Negative aft of centroid, FGX force required to be on x-axis (LYFGX
C               and LZFGX = 0)
C
            LXFZ = - MY / FZ
            LXFY = MZ / FY
C
C       F056    Resultant net force, lbf
C
            FG = SQRT (FGX**2 + FGY**2 + FGZ**2)
C
C       F057.1      Resultant force coefficient
C
            CFG = FG / F9ID
C
C       F057.2      Axial force coefficient
C
            CFGX = FGX / F9ID
C
C       F058    Side force coefficient
C
            CFGY = FGY / F9ID
C
C       F059    Vertical force coefficient
C
            CFGZ = FGZ / F9ID
C
C       F060    Yaw angle, degrees
C
            FGYX = FGY / FGX
            IF (ABS (FGX) .LE. 0.00001)   FGYX = 0.0
            BETA = 57.2958 * ATAN (FGYX)
            BETAC = BETA + BETAZ
            BETAABS = ABS (BETA)
            BETACABS = ABS (BETAC)
```

```
C
C       F061   Pitch angle, degrees
C

         FGZX = FGZ / FGX
         IF (ABS (FGX) .LE. 0.00001)   FGZX = 0.0
         ALPHA = 57.2958 * ATAN (FGZX)
         ALPHAC = ALPHA + ALPHAZ
         ALPHAABS = ABS (ALPHA)
         ALPHCABS = ABS (ALPHAC)
C
C       F062   Roll angle, degrees
C

         FGYZ = FGY / FGZ
         IF (ABS (FGZ) .LE. 0.00001)   FGYZ = 0.0
         PSI = 57.2958 * ATAN (FGYZ)
         PSIABS = ABS (PSI)
C
C       F063   Secondary flow W307 (nozzle) calculation - equations not shown, lbm/sec
C       F064   Secondary flow W302 (venturi) calculation - equations not shown, lbm/sec
C       F065   Secondary flow W303 (venturi) calculation - equations not shown, lbm/sec
C
C       F067   Stream thrust parameter
C

         FSTR = (FG + P0 * A8 * A9_A8) / (PT * A8)
C
C       F068   Stream thrust coefficient
C

         CALL MACHFAR (GAM,-A9_A8, M9ID)
         PRID = (1 + 0.5 * (GM1) * M9ID**2)**(GAM / GM1)
           FSAR = PRID * A9_A8 / CDN * (1 + GAM * M9ID**2)
           FSID = FSAR * PT * A8 * CDN
           CS = (FG + P0 * A8 * A9_A8) / FSID
C
C       F069   Measured tare force, lbf
C

         FXKNOBM = (PT - P0) * (ALSI + A5)        !! FXKNOB param, vac, ADP cal
         FTAREM = FX - FLS - A5 * DP50 + FXKNOB
C
C       F070   Calculated lab-seal area, in2
C
         ALS3M = FTARE / DP30
```

```
C
C      B.  ASME NOZZLE PERFORMANCE FOR CHOKED FLOW CALIBRATION
C                        (DO ONLY IF NOZZ = "ASME")
C
       IF (NOZZ .EQ. 'ASME') THEN
C
C      F071   ASME throat Reynolds number and predicted flow coefficient
C
          RNINIT   = 12 * G2 ** (1/G1) * PT *D8 * G5 / MU8 * TS8 ** 0.5)
          CDPINIT = 1 - 0.184 * RN1 ** (-0.2)
          RNASME = CDPINIT * RNINIT
          CDP = 1 - 0.184 * RNASME ** (-0.2)
C
C      F072   Predicted ASME velocity coefficient (0.109 now recommended, was 0.107)
C
          CVP = 1 - 0.109 * RNASME ** (-0.2)
C
C      F073   Predicted stream thrust parameter
C
          IF (NPR .GE. NPRC) THEN
            FSP = G2 ** (1/G1) * (1 + GAM * CDP * CVP)
          ELSE
            FSP = 1 / NPR * (1 + GAM * CDP * CVP * M8 ** 2)
          ENDIF
C
C      F074   Predicted ASME nozzle force, lbf
C
          FASME = PT * A8 * (FSP - 1/NPR)
C
C      F075   Calculated flow coefficient at station 5
C
          CD5C = CDP * W8ID / W5ID
C
C      F076   Calculated momentum coefficient at station 5
C
          CF5C = (FX + FASME - FLS - FTARE) / F5ID
C
C      F077   Predicted thrust coefficient
C
          CFGP = FASME / (CDP * W8ID * VEL9 / GC)
          CFGXP = CFGP * COS (ANGE * 0.017453293)
          CFGZP = CFGP * SIN (ANGE * 0.017453293)
```

Appendix B.—Data Plots for Thrust Stand Interaction Calibration

These plots show loadcell reactions to forces applied using the in-stand calibration system. There are two sets of loadcells installed on the stand, reaction loadcells and calibration loadcells. There are two axial reaction loadcells (FRX1, FRX2), two lateral reaction loadcells (FRY1, FRY2), and four vertical reaction loadcells (FRZ1 through FRZ4). Calibration loadcells follow the same naming convention. Overall calibration forces (e.g., FCX) are formed by combining calibration loadcell forces in that particular direction. See Appendix A for equations.
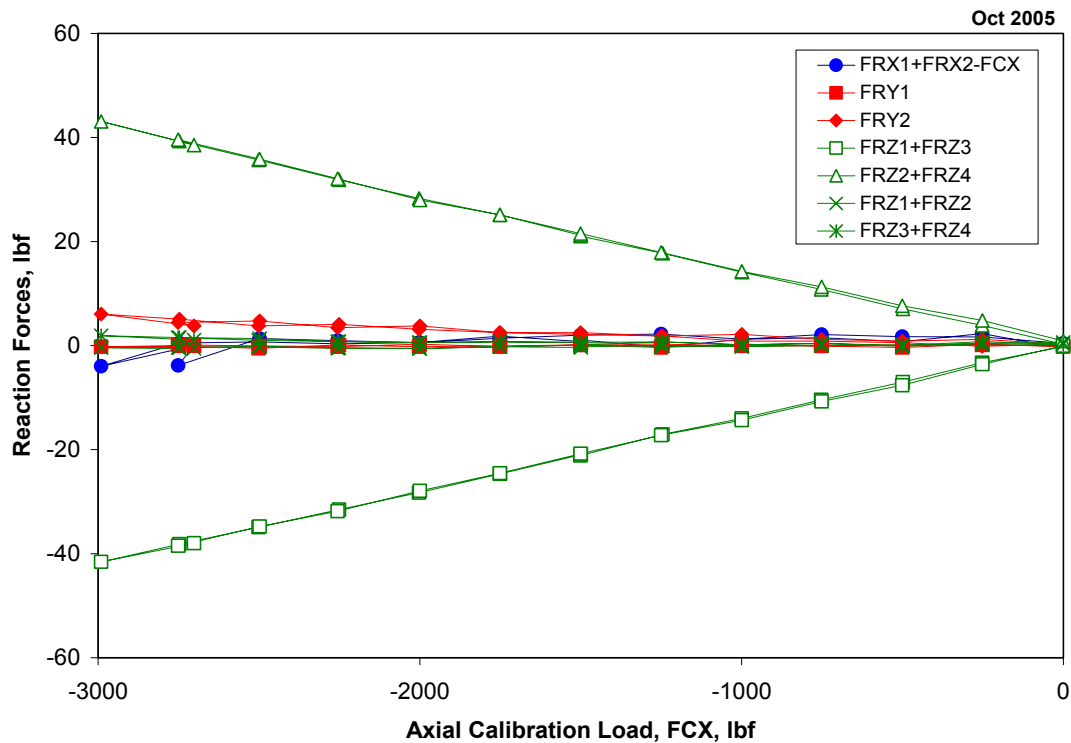
Figure B1.—Reaction load cell calibration with an applied axial force.
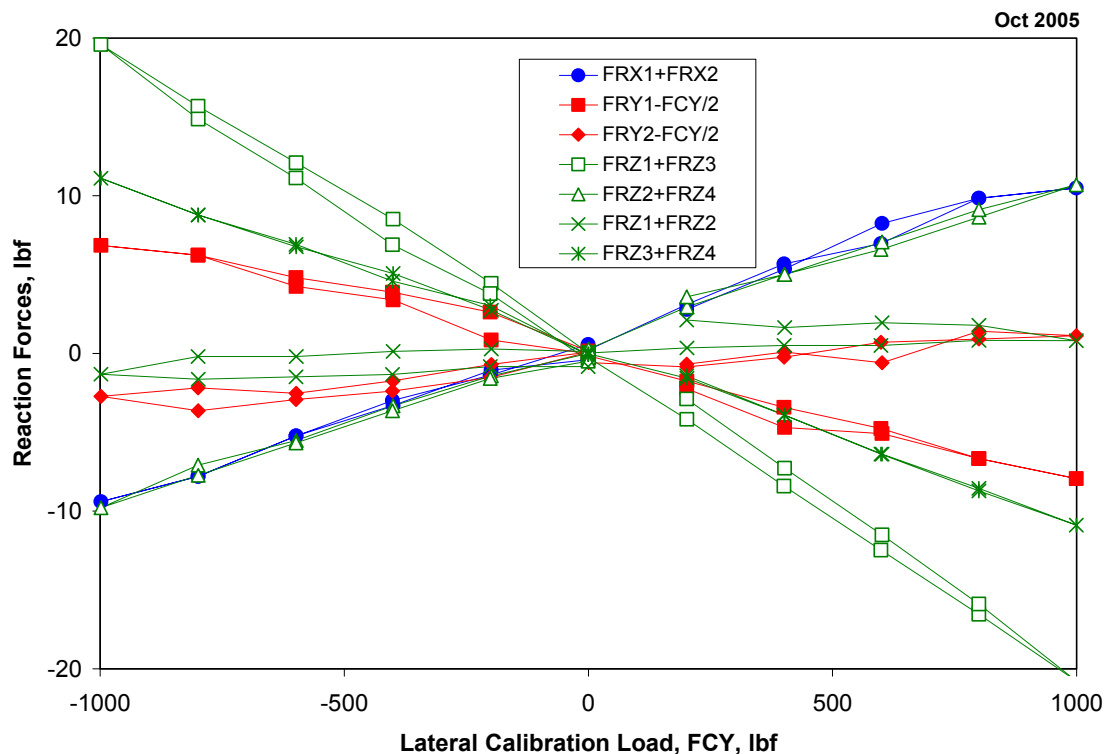
Figure B2.—Reaction load cell calibration with an applied lateral force.
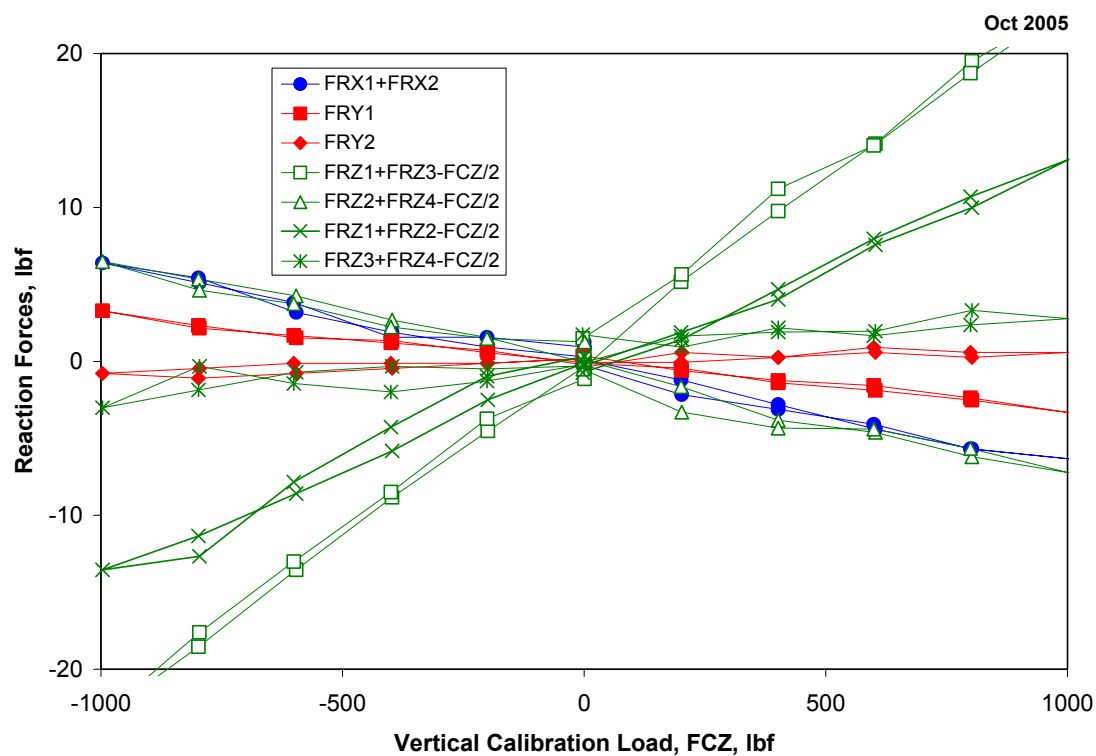
Figure B3.—Reaction load cell calibration with an applied vertical force.
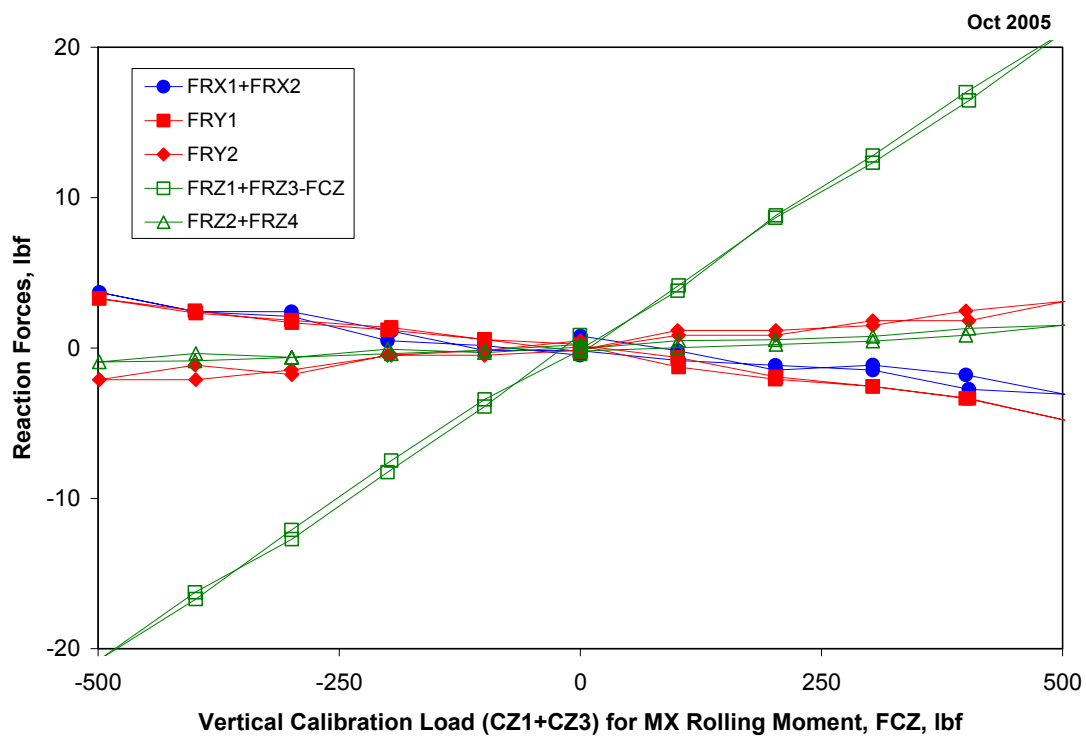
Figure B4.—Reaction load cell calibration with an applied roll moment (left side).
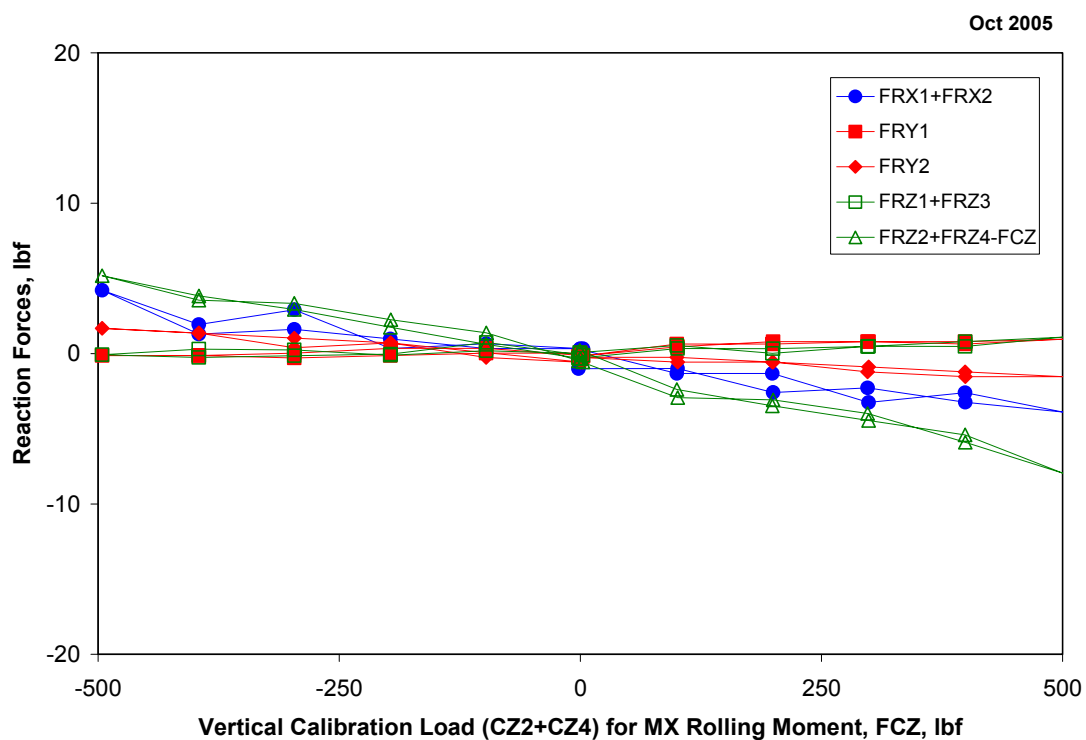
Figure B5.—Reaction load cell calibration with an applied roll moment (right side).
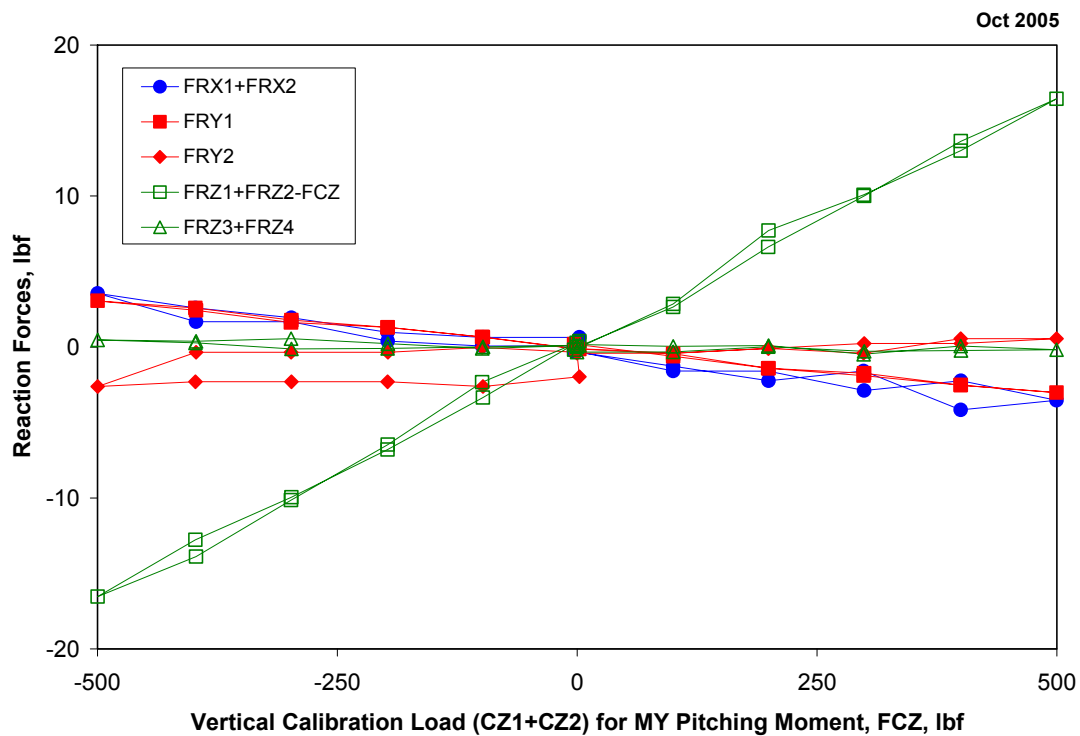
Figure B6.—Reaction load cell calibration with an applied pitch moment (front).
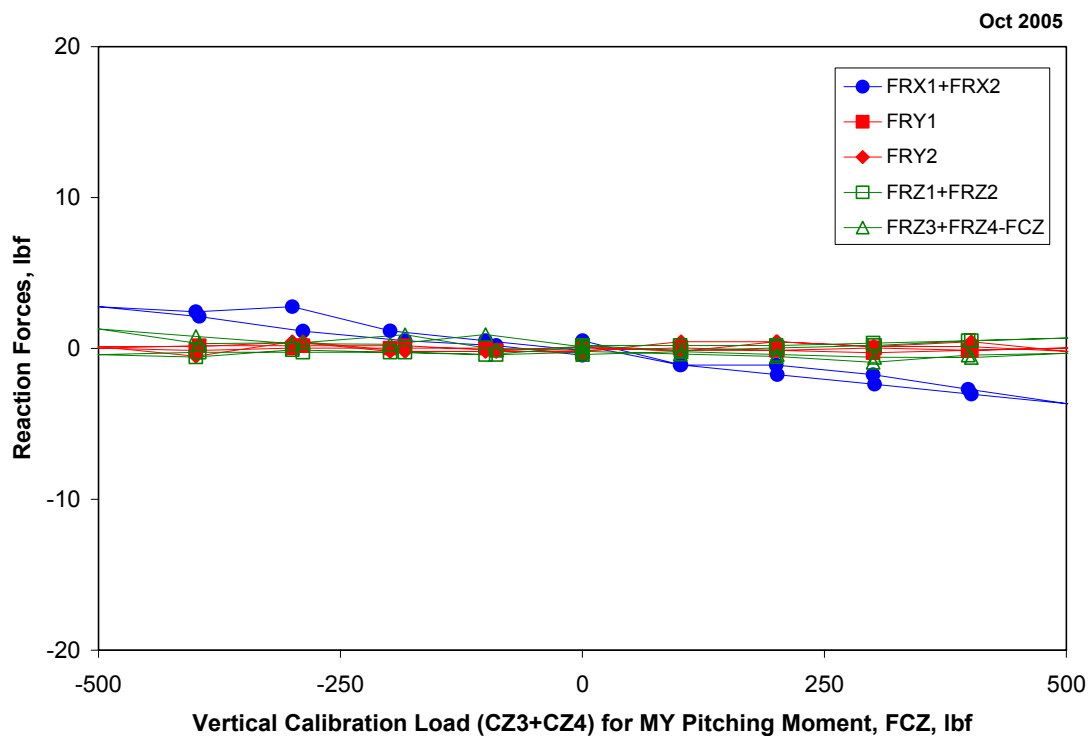
Figure B7.—Reaction load cell calibration with an applied pitch moment (aft).
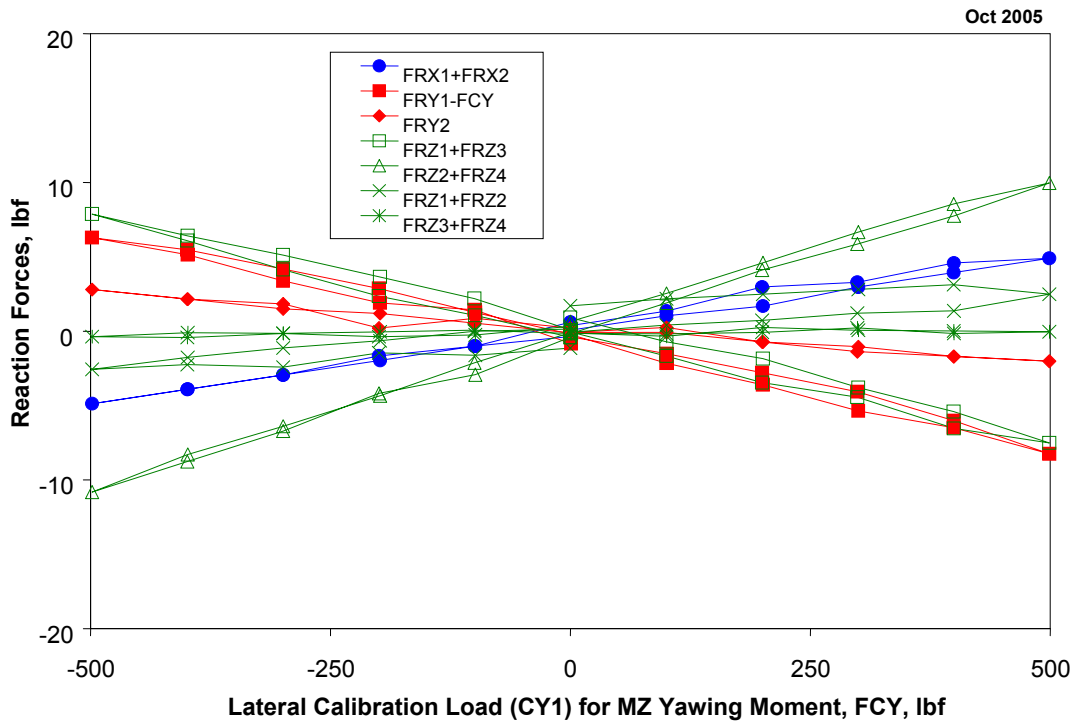
Figure B8.—Reaction load cell calibration with an applied yaw moment (front).
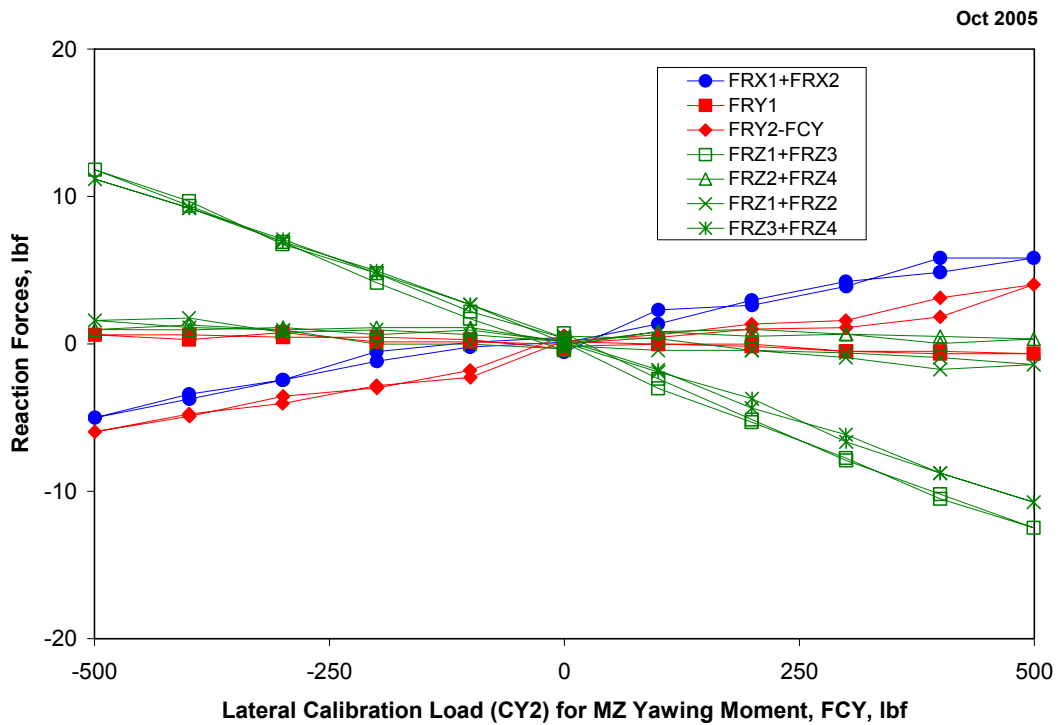
Figure B9.—Reaction load cell calibration with an applied yaw moment (aft).

Appendix C.—Force Interactions for Dead Weight Check
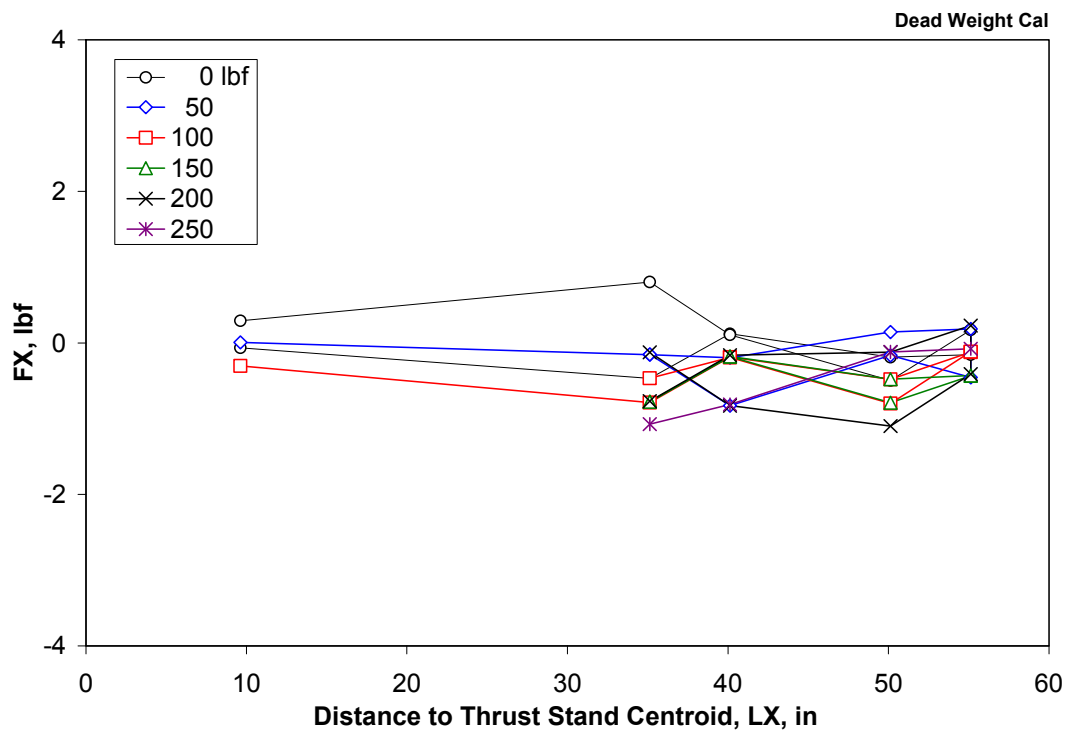
Figure C1.—Axial force FX for dead weight check.
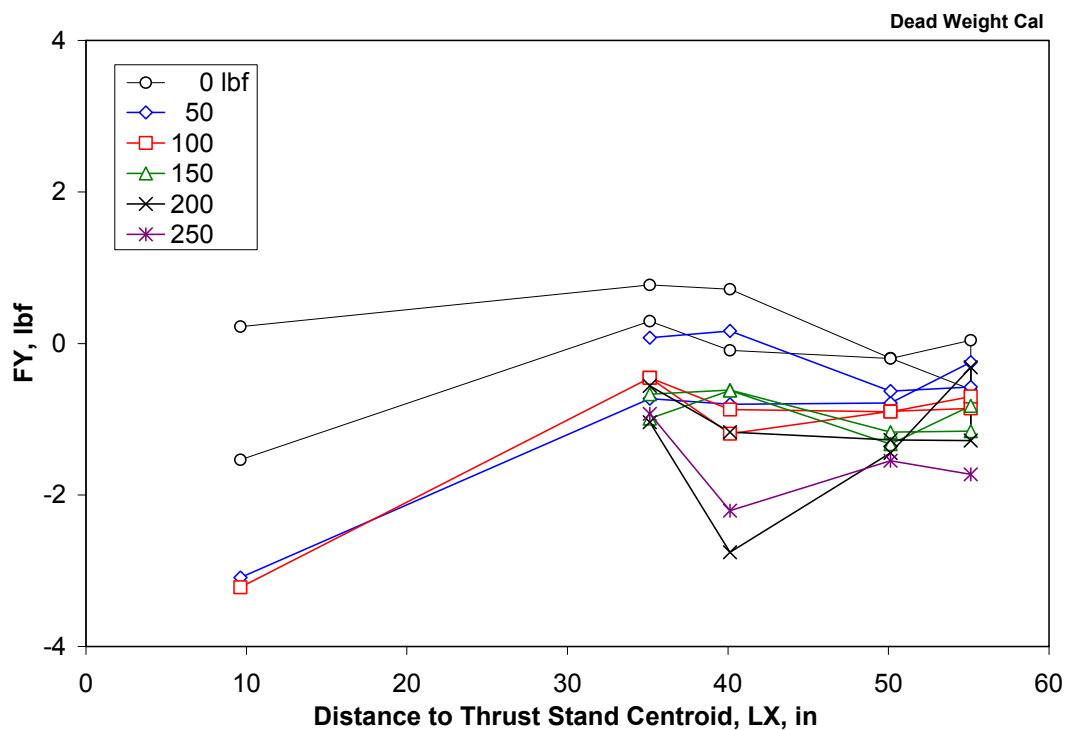
Figure C2.—Lateral force FY for dead weight check.
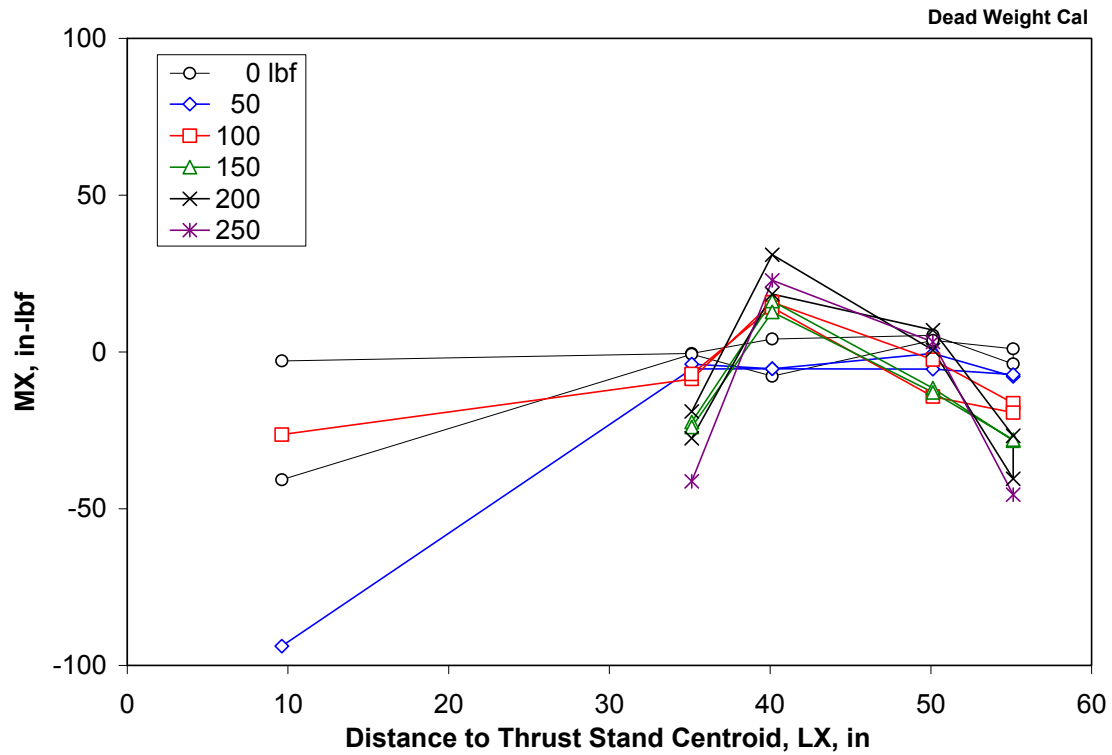
Figure C3.—Roll moment MX for dead weight check.
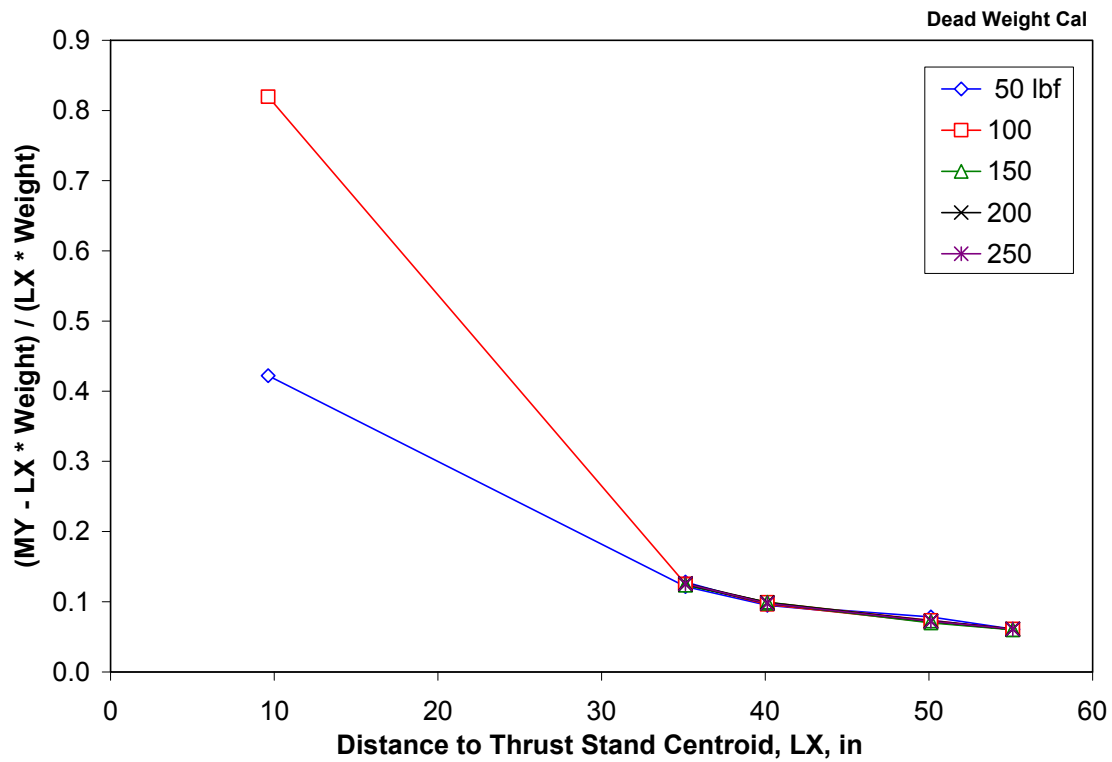
Figure C4.—Pitch moment MY for dead weight check.
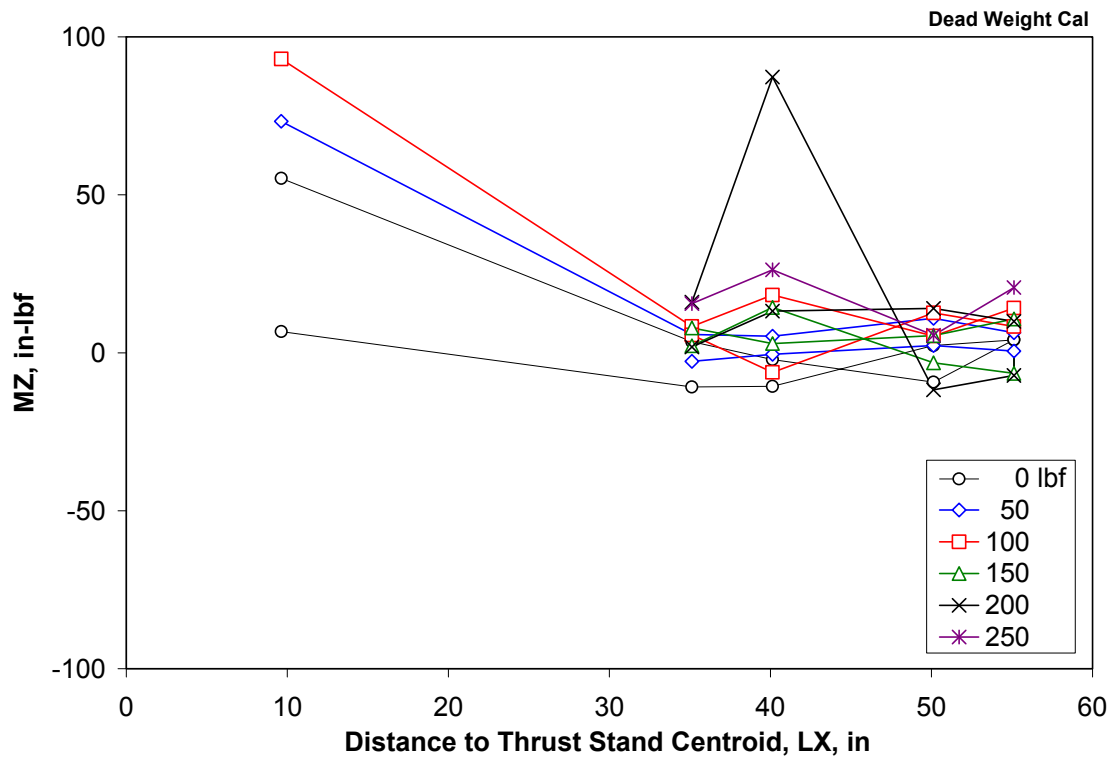
Figure C5.—Yaw moment MZ for dead weight check.

Appendix D.—Nozzle Gross Thrust and Flow Coefficients Using Pre-Calibrations
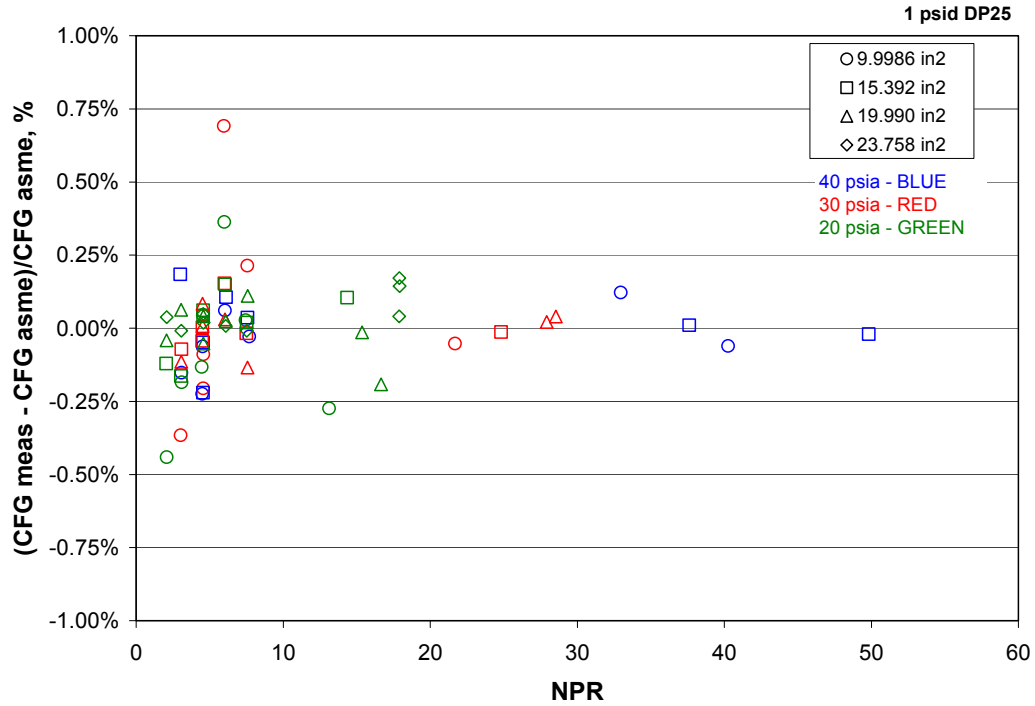
Figure D1.—ASME nozzle gross thrust coefficient CFG from pre-run CF5 calibrations, 1-psid DP25 transducers.
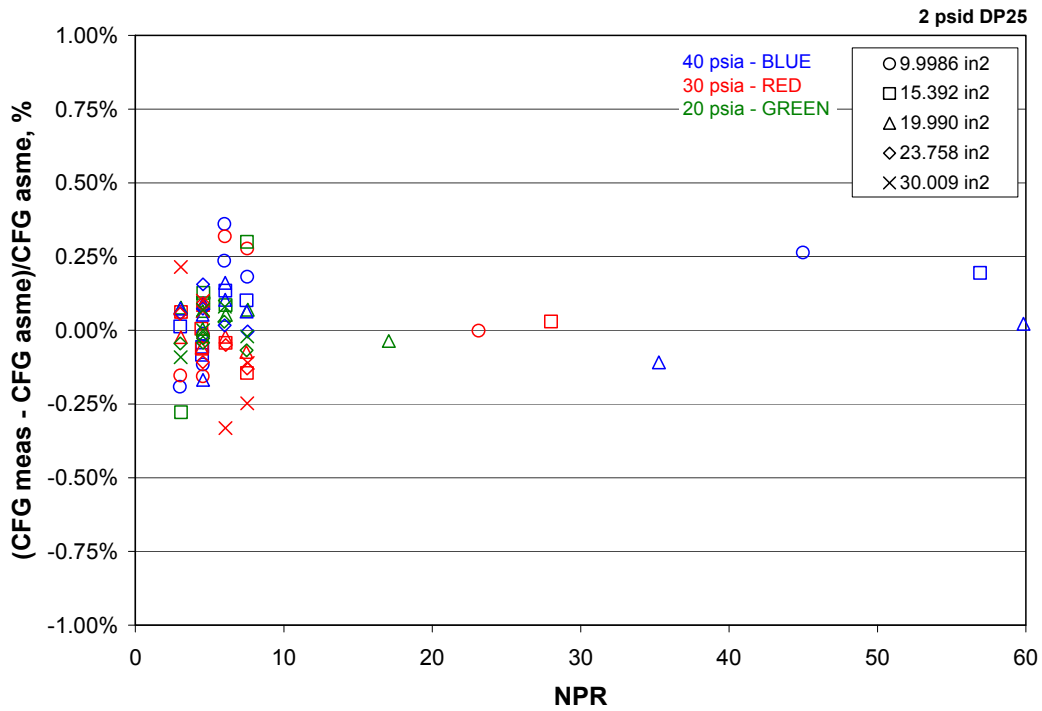
Figure D2.—ASME nozzle gross thrust coefficient CFG from pre-run CF5 calibrations, 2-psid DP25 transducers.
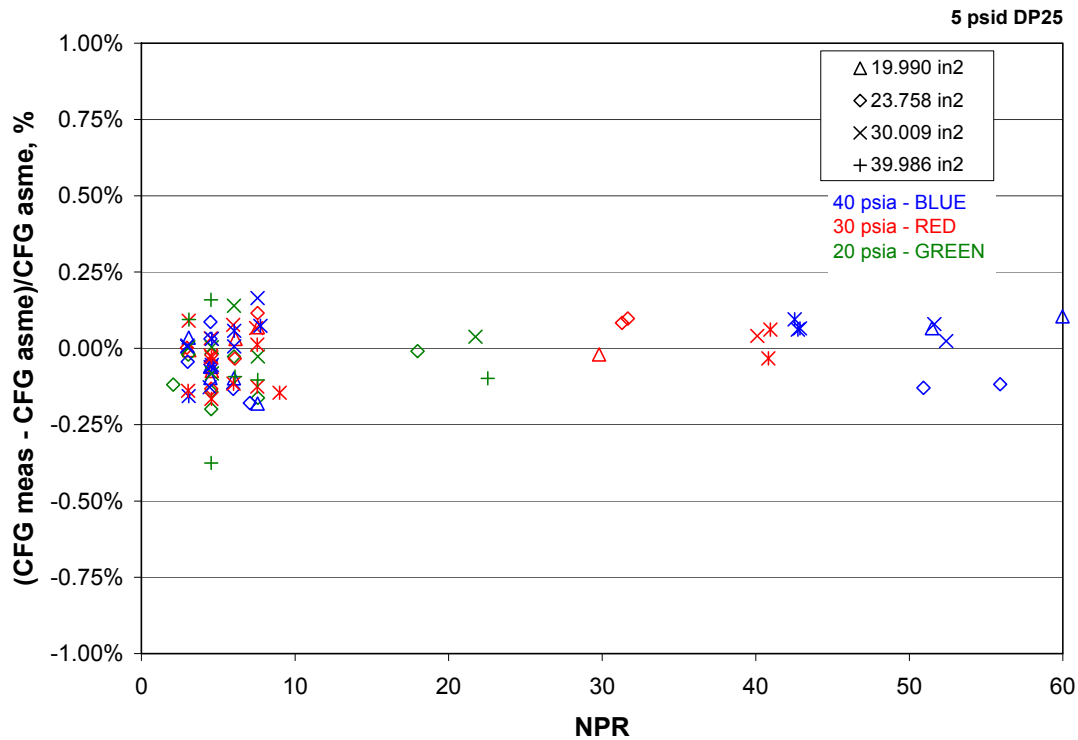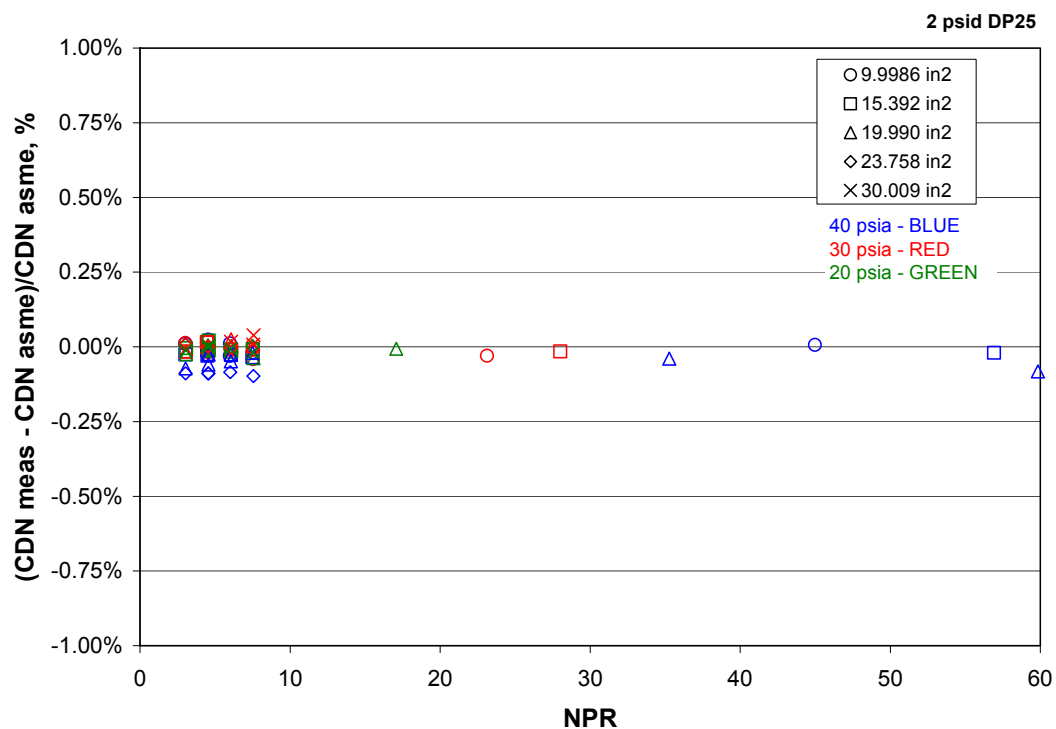
Figure D3.—ASME nozzle gross thrust coefficient CFG from pre-run CF5 calibrations, 5-psid DP25 transducers.
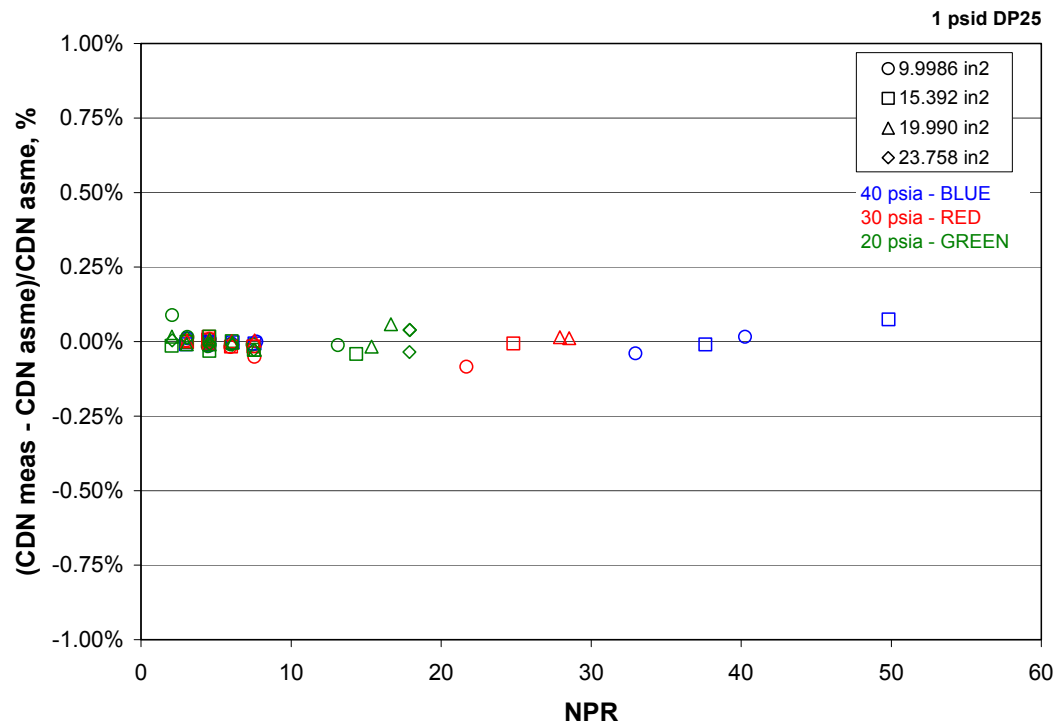
Figure D4.—ASME nozzle flow coefficient CDN from pre-run CD5 calibrations, 1-psid DP25 transducers.

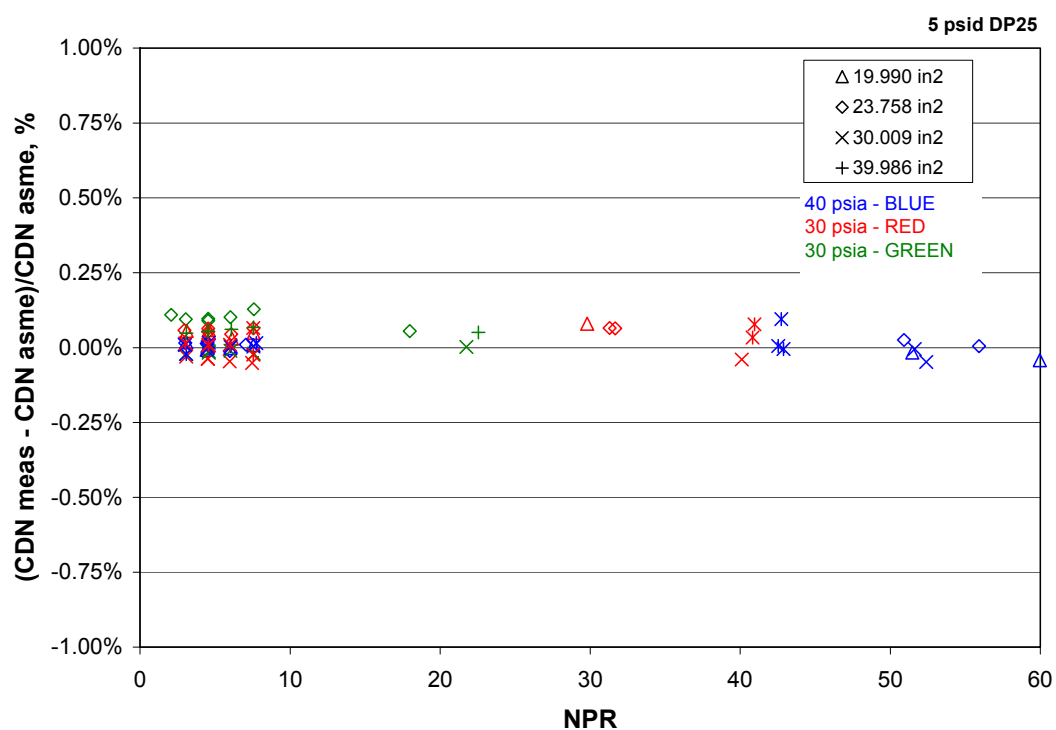Figure D5.—ASME nozzle flow coefficient CDN from pre-run CD5 calibrations, 2-psid DP25 transducers.

Figure D6.—ASME nozzle flow coefficient CDN uncertainty from pre-run CD5 calibrations, 5-psid DP25 transducers.

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13. SUPPLEMENTARY NOTES

14. ABSTRACT
CE-22 facility procedures and measurements for thrust and airflow calibration obtained with choked-flow ASME nozzles are presented. Six calibration nozzles are used at an inlet total pressure from 20 to 48 psia. Throat areas are from 9.9986 to 39.986 in.^{2}. Throat Reynolds number varies from 1.8 to 7.9 million. Nozzle gross thrust coefficient (CFG) uncertainty is 0.25 to 0.75 percent, with smaller uncertainly generally for larger nozzles and higher inlet total pressure. Nozzle discharge coefficient (CDN) uncertainty is 0.15 percent or less for all the data. ASME nozzle calibrations need to be done before and after research model testing to achieve these uncertainties. In addition, facility capability in terms of nozzle pressure ratio (NPR) and nozzle airflow are determined. Nozzle pressure ratio of 50 or more is obtainable at 40 psia for throat areas between 20 and 30 in.^{2}. Also presented are results for two of the ASME nozzles vectored at 10°, a dead-weight check of the vertical (perpendicular to the jet axis) force measurement, a calibration of load cell forces for the effects of facility tank deflection with tank pressure, and the calibration of the metric-break labyrinth seal.

15. SUBJECT TERMS
Test facilities; Test chambers; Calibrating; Nozzle thrust coefficients; Thrust; Nozzle flow; Air flow; Flow coefficients; Loads (forces); Thrust measurement; Data reduction

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