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AEROSPACE PRODUCTS INC.

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High Accuracy Fuel Flowmeter

Final Report - Phase IIC and Phase III
The Mass Flowrate Calibration of
High Accuracy Fuel Flowmeters

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Wilmington, Massachusetts

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16. Abstract

This report describes a facility for the precise calibration of mass fuel flowmeters and turbine flowmeters located at AMETEK Aerospace Products Inc, Wilmington, Massachusetts. This facility is referred to as the Test and Calibration Systems (TACS). It is believed to be the most accurate test facility available for the calibration of jet engine fuel flowmeters over a wide range of operating conditions. The TACS uses a precision device for volumetric flow rate measurement in conjunction with a precision fluid density measurement. The product of (1) the volumetric flow rate measurement and (2) the density measurement results in a true mass flow rate determination.

A dual-turbine flowmeter was designed during this program. The dual-turbine flowmeter was calibrated on the TACS to show the characteristics of this type of flowmeter. An angular momentum flowmeter was also calibrated on the TACS to demonstrate the accuracy of a true mass flowmeter having a "state-of-the art" design accuracy.

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1.0 SUMMARY

This report concludes the Phast IIC and Phase III effort of NASA contract NAS3-24357 to develop a high accuracy fuel flowmeter. The primary objectives of the contract was to develop a fuel flowmeter which was capable of operating in a turbojet engine environment with an accuracy of within 0.25 of one percent of a given flow rate from 0.064 to 3.2 liter/second (approximately 400 to 20,000 lb_m/hr) over a temperature range from -55°C to + 130°C. A review of various flowmeter designs during Phase I led to experimental development of two candidate flowmeters during Phase II namely (1) an angular momentum flowmeter with a constant speed motor drive and (2) a dual-turbine flowmeter with an integral densi-viscometer.

Phase IIC was an extension of Phase II to further the development of the dual-turbine and angular momentum flowmeters. Phase IIC was later modified to abandon further development of the densi-viscometer due to technical difficulties in achieving a desired accuracy of within 0.1 of one percent.

A study was made during Phase I to determine the best method of verifying the accuracy of a flowmeter having the potential for an accuracy of within 0.25 of one percent. This study concluded that the most accurate method would be to use a precision device for volumetric flowrate measurement coupled with a precision method of measuring density to determine mass flowrate. The Phase III effort was directed towards the design and development of the proposed fuel flowrate calibration facility now referred to as the Test and Calibration system (TACS). Phase IIC was finally modified to demonstrate the performance of the dual-turbine flowmeter and an angular momentum flowmeter using the TACS.

The main turbine flowmeter element of the dual-turbine flowmeter demonstrated the necessary accuracy to meet the accuracy objectives of the program. The sensor (downstream) turbine flowmeter did not demonstrate the repeatability needed but the sensor turbine provides the capability of compensating for installation effects. The dual-turbine flowmeter also requires a precision densi-viscometer to provide fluid density and fluid viscosity at operating conditions to fully interpret the output frequencies of the dual-turbine flowmeter in terms of mass flowrate.

The angular momentum flowmeter with a motor drive which was designed during Phase II has the potential for achieving an accuracy of within 0.25 percent. However, the maximum flowrate that was achieved during the Phase II development was about 1.64 kg/s (13,000 lb_m/hr). Several improvements in the design would have to be carried out to maintain a constant impeller rotational speed up to 2.52 kg/s (20,000 lb_m/hr).

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The current trend in the development of angular momentum flowmeters is towards fluid driven flowmeters having an accuracy of within 0.5 percent in the jet engine cruise range of 0.125 to 0.504 kg/s (1000 lbm/hr to 4000 lbm/hr) from +25°C to +120°C (+77°F to +248°F). A flowmeter of this type was tested using the TACS to demonstrate the capability of accurately calibrating a mass flowrate meter in this facility.

The major effort described herein is the calibration and repeatability testing of the TACS. The TACS demonstrated the ability to calibrate either a volumeteric flowmeter (e.g. a turbine type flowmeter) or a mass flowmeter accurately over a range of 0.05 to 2.52 kg/s (400 lbm/hr to 20,000 lbm/hr from -12°C to +95°C (+10°F to 203°F). The expectations of the accuracy of the TACS in this flowrate and temperature range were exceeded. Further improvements in the TACS facility are needed to extend the temperature range to -55°C to 135°C (-67°F to 275°F).

A provisional accuracy statement was prepared for the TACS which included all of the parameters that are expected to influence the accuracy. The conclusion was that TACS has an accuracy of within 0.042 percent at room temperature and does not exceed 0.1 percent at the extreme operating temperatures.

2.0 INTRODUCTION

Phase I of the NASA High Accuracy Fuel Flowmeter (NASA-HAFF) Program was initiated in 1981 to investigate the potential for the development of a high accuracy fuel flowmeter for aircraft jet engines. The primary goal was to develop a flowmeter having an accuracy of within 0.1 of one percent of reading over a flowrate range of 0.05 to 2.52 kg/s (400 to 20,000 lb_m/hr). An accuracy of within 0.25 of one percent of reading was considered acceptable. Appendix A summarizes the design requirements for this flowmeter. The results of Phase I are reported by Mayer et al (1981).

A literature and patent survey was pursued during Phase I to determine if any new concepts shroud be investigated. Consultants expert in the fields of flow metering, fluid dynamics and ultrasonics were also employed to seek flow metering concepts with merit. This survey resulted in investigation of 49 flowmeter concepts and 13 density metering concepts.

After the initial screening of the various concepts was completed, four flowmetering concepts were selected for more in-depth analysis. The four flow metering concepts which were selected for further study were:

(1) Closed Loop Angular Momentum Flowmeter

(2) Open Loop Angular Momentum Flowmeter

(3) Turbine Flowmeter/Densitometer

(4) Vortex Precession Flowmeter/Densitometer

Nineteen (19) parameters were used to further evaluate the four selected flowmeter concepts. The closed loop, angular momentum flowmeter concept was rejected before the experimental phase began because it was not believed that this concept could meet the time response requirements (see Appendix A, Item 14). The closed loop, angular momentum concept had the lowest merit rating of the four concepts and thus was rejected from further study.

The three remaining concepts were analytically and experimentally investigated in 1982 with the recommendation that prototype versions of the dual-turbine flowmeter and the open loop, angular momentum concepts be designed and developed. The vortex precession flowmeter concept was rejected after a period of experimentation due to the loss of a frequency output signal below a flowrate which was higher than the minimum flowrate required. Initial experimental evaluation of the two concepts was completed in June 1984 and the results for Phase II was reported by Mayer et al (1985).

A study of a suitable system for high accuracy flowmeter calibration system was initiated in May 1982 and a report including recommendations for the development of a Test and Calibration System (TACS) was submitted in October 1984. The fluid system was delivered as a package on a structural frame in March 1985 including the mounting and fluid piping for the Flow-Thru Calibrator.

The most accurate equipment for the calibration of mass flowmeters in the past has been the dynamic weigh stand. An in-depth study was made of the various corrections required for determining the true mass flow rate with a dynamic weigh stand. The study, which was reported by Mayer et al (1985), revealed that the accuracy of a dynamic weigh stand was insufficient to calibrate a flowmeter having a expected accuracy of within 0.25 percent.

The study concluded that the most accurate method of mass flow rate calibration was through the use of a "Flow-Thru Calibrator" having a volumetric proving accuracy of within 0.02 percent and used in combination with a precision density meter having an accuracy of within 0.02 percent. The Flow-Thru Calibrator is a precision piston displacement device which uses electro-optical sensors for accurately determining discrete positions of the piston to within 0.001 percent of the piston stroke. The calibration volume of the Flow-Thru Calibrator is checked periodically by collecting fluid samples under the control of the position sensors. Samples of the calibration fluid are collected in bottles and the volume is determined from the net weight and the measured density of the calibration fluid.

Phase IIC was initiated in September 1986. The primary objectives in this phase were (1) to improve the densi-viscometer by improving the amplifier circuit and (2) to continue the development of the angular momentum flowmeter concept.

Phase IIC was later modified to abandon further development of the densi-viscometer. The densi-viscometer that was initially under development was somewhat sensitive to external vibration. The effect of external vibration on the accuracy of the densi-viscometer was such that the accuracy of the density measurement would not be within 0.1 of one percent. The final objectives of Phase IIC were to test the dual turbine flowmeter and the angular momentum flowmeter on the TACS to demonstrate the capability of the TACS as an accurate method of calibrating fuel flowmeters.

3.0 TEST AND CALIBRATION SYSTEM (TACS)

The TACS consists of (1) a fluid flow calibration loop, (2) a piston type Flow-Thru Calibrator for precisely measuring volumetric flow rate and (3) a density meter for precise measurement of the fluid density in the calibration loop. The TACS also includes means for heating and cooling the calibration fluid as well as an accurate method of controlling the flowrate.

One of the unique features of TACS is the ability to establish steady state conditions of temperature, pressure and flowrate prior to a run. The design of the Flow-Thru Calibrator permits calibration fluid to pass through the Flow-Thru Calibrator and the calibration flow loop for as long a period of time as necessary to establish steady state flow conditions and then the Flow-Thru Calibrator can be actuated to obtain a volumetric flowrate measurement for either a one (1.0) gallon or a five (5.0) gallon volumetric displacement.

The TACS is currently capable of sustaining the following operating conditions:

(1) 0.06 to 7.88 Liters/s (1.0 to 125 gpm)

(2) -18 to 93°C (0 to +200°F)

(3) 14.6 to 36.3 kPa (100 to 250 psig)

With facility improvements, TACS will have a temperature range of -55° to 135°C (-67 to +276°F) and the maximum flowrate can be extended to 15.77 liters/s (250 gpm).

TACS has the capability of using any hydrocarbon calibration fluid including MIL-C-7024 (II), JET-A, JP-4 and JP-5. Initial calibration testing was performed with MIL-C-7024 (II) which is sometimes referred to as Stoddard Solvent. It is expected in the future that JET-A will be predominantly used since JET-A is the most common jet engine fuel used commercially.

A vibrating tube density meter is installed in TACS. This density meter normally calibrated in situ with a vacuum pycnometer (PYC). Additional calibration tests of the density meter will have to be conducted in the future to reach full confidence in the calibration accuracy of this density meter. At the present time, maximum calibration accuracy is obtained by characterizing the variation of density with temperature using the PYC. The PYC is setup to sample calibration fluid which bypasses the density meter.

Some of the leading characteristics of TACS that have made it successful are:

1. The salient features of the Flow-Thru Calibrator, namely:

   (a) The repeatability of the volumetric flowrate measurements.

   (b) The capability of accurately estimating the volumetric displacement over a wide range of temperatures.

   (c) The steady flowrate achieved during a calibration runs.

   (d) Thermal jacketing to provide fluid temperature stability.

2. The accuracy of the vacuum pycnometer (PYC) for precise measurement of fluid density which provides:

   (a) Traceability of TACS to NIST by reason of the well established density of distilled water and precision weight standards.

   (b) Precise volumetric calibration of the Flow-Thru Calibrator by direct measurement of the fluid density of the calibration fluid for use in the conversion gravimetric measurements to volumetric measurements.

   (c) Precise fluid density measurements for <u>in situ</u> density meter calibrations or characterization of calibration fluid density as a function of temperature.

3.1 Flow-Thru Calibrator

3.1.1 Principles of Operation

The embodiment of the Flow-Thru Calibrator is described in a US patent by Francisco (1979). Figure 1 shows a cross-sectional view of a Flow-Thru Calibrator used in TACS. It consists of a calibrator piston enclosed in a precision bored cylinder. The cylinder has a nominal internal diameter of 190.5 mm (7.5 inches). The perimeter of the calibrator piston is sealed with spring loaded TFE (tetrafluoroethylene) seals for leak tight operation within the calibrator cylinder.

A poppet valve is mounted within the calibrator piston to allow fluid to flow from the inlet to the outlet in the standby mode. This permits the calibration flow rate, temperature, and pressure to to be established in the rest of the calibration system prior to a calibration run. An O-ring seal is installed in a groove on the edge of the poppet valve to ensure liquid tight sealing between the calibrator piston and the poppet valve during a calibration run. A pneumatic actuator piston assembly is used to control the closure of the poppet valve and the direction of the travel of the calibrator piston. The shaft of the pneumatic actuator is sealed within the inlet head of the cylinder assembly to prevent leakage of air into the fluid or liquid into the pneumatic actuator.

An optical shaft (circular rod) is attached to the downstream side of the poppet valve and sealed within the outlet head of the cylinder assembly. The end of the optical shaft carries a rigid metal flag. The flag moves through the slots in four electro-optical switches. The electro-optical switches can detect the position of the leading edge of the flag to within 0.005 mm (0.0002 inches). The electro-optical switches are positioned such that (1) a one gallon* displacement occurs when the calibrator piston travels between the first two and the second two switches and (2) a five gallon * displacement occurs when the calibrator piston travels between the last two switches. The above values of displacement are nominal values - the actual values are determined by calibration.

A thermal jacket encloses the calibrator cylinder. Calibration fluid flows in a counter-flow direction through the thermal jacket to maintain a uniform temperature of the fluid within the calibrator cylinder.

A fail safe stop is mounted inside the downstream cylinder head to ensure that the poppet valve opens after the flag passes the last electro-optical switch.

3.1.2 Operational Modes of the Flow-Thru Calibrator

Figure 2 shows the Flow-Thru Calibrator (FTC) in the standby mode. The actuator piston is pressurized such as to hold the poppet valve open and the calibrator piston is positioned at the inlet end of the calibrator cylinder. The calibration fluid can now flow freely through the calibrator to stabilize temperature and flowrate within the flowmeter test section prior to an FTC calibration run.

When the FTC calibration run is initiated, the outer end of the actuator piston is pressurized and the other end is vented. The actuator piston first forces the poppet valve closed and then starts the movement of the calibrator piston downstream as shown in Figure 3. A spring between the poppet valve and the calibrator piston assists in keeping the poppet valve closed during a run. The pressure at the outer end of the actuator piston is adjusted such as to just overcome friction between the calibrator piston and cylinder during a run. The calibrator piston travels at a constant velocity during a run. The velocity of the calibrator piston is controlled by the volumetric flow rate entering the Flow-Thru Calibrator. The volumetric flow rate is established by the positional settings of one or more flow control valves which operate in parallel and control the flow downstream of the flowmeter test section and the FTC.

After the poppet valve closes at the start of a run, the mass of calibrator piston must be accelerated by (1) the force of the actuator piston and (2) a slight differential pressure across the area of the calibrator piston. There can be a slight perturbation in the flow rate before the start of a run due to the acceleration of the calibrator piston but this is minimized by proper adjustment of the air pressure at the outer (operational) end of the actuator piston. When the calibrator piston reaches the electro-optical switch at the start position (as shown in Figure 3 for a 5 gal run), the acceleration is complete and the calibrator piston moves at a constant velocity until the end of the run.

* 1.0 US gallon = 3.7854 Liters

When the flag reaches the last electro-optical switch (EOS) (as shown in Figure 4 for a 5 gal run), the EOS actuates a control valve which controls the end of the pneumatic actuator that is pressurized and the end that is vented. After the differential pressure across actuator piston is reversed, the return end of the pneumatic actuator is pressurized near the FTC inlet head. When the return end of the pneumatic actuator is pressurized, the poppet valve is pulled open allowing fluid to again flow through the calibrator piston. The force and movement of the actuator piston then returns the piston to the standby position for the next run.

3.1.3 Run Time Characteristics

Table 1 shows the run time characteristics for the Flow-Thru Calibrator selected for TACS. This Flow-Thru Calibrator has two run displacement volumes with nominal values of 3.785 liters (1 US gallon) and 18.927 liters (5 US gallons). The smaller displacement volume is used to reduce the run time at the lower flow rates.

3.1.4 Electro Optical Switch Spacing

The position of the electro-optical switches shown in Figure 1 allows the calibrator piston to travel about 13.3 cm (5.2 inches) prior to a 3.785 liter run and about 26.6 cm (10.5 inches) for a 18.927 liter run. This arrangement permits a longer time for acceleration of the calibrator piston with the 18.927 liter displacement which is used at the higher flow rates.

The spacing between the electro-optical switches, which determines the stroke of the two displacement volumes, is maintained by four 6.3 mm (0.25 inch) diameter Invar rods. Two parallel rods control the distance between the electro-optical switches (EOS) for the 3.785 liter displacement and two more parallel rods control the distance between the EOS for the 18.927 liter displacement. The low thermal coefficient of expansion of the Invar rods ensures that the thermal expansion of the structure supporting the electro-optical switches will have a minimum effect on the displacement strokes. The temperature of the Invar rods is measured to compensate for the small change in displacement that results from the difference between the operating temperature and room temperature.

3.1.5 Control Consoles For The Flow-Thru Calibrator

Two identical control consoles are used in conjunction with the operation of the Flow-Thru Calibrator. Each control console is (1) capable of precisely determining the frequency output of a turbine flowmeter and (2) measuring the precise time for calibration run. Either control console can be used alone to control the operation of Flow-Thru Calibrator if only one turbine flowmeter needs to be calibrated.

When two turbine flowmeters are to be calibrated simultaneously, both control consoles are used. One control console is designated as the master console and the other is designated as a slave console. The master control console controls the actual operation of the Flow-Thru Calibrator. The slave control console measures the output frequency of a second turbine flowmeter precisely synchronized with the displacement stroke of the Flow-Thru Calibrator. Both control consoles measure the run time period to produce a redundant check of this measurement. The run time is the time required for the piston the travel the distance between two electro-optical switches. (start and end positions).

3.1.6 Turbine Flowmeter Calibration Using Double Chronometry

Each control console uses a method of synchronizing the turbine frequency measurements with the run period for the Flow-Thru Calibrator called double chronometry. This method was first proposed by Francisco (1966) in US Patent 3,403,544.

When the Flow-Thru Calibrator intercepts the electro-optical switch at the start of a run (see Figure 3), the time interval measurement for the run time begins. The frequency counter for measuring the blade passing frequency of the turbine flowmeter is now armed but the counter does not start until the first blade is intercepted by the pickoff (proximity switch) on the turbine flowmeter. A separate counter now starts measuring the run period for the turbine flowmeter (TFM).

When the Flow-Thru Calibrator intercepts the electro-optical switch at the end of the run (see Figure 4), the time interval measurement for the run time ends. However, the time interval for the run period for the TFM continues until the one more blade is intercepted by the pickoff on the turbine flowmeter.

The result is that the time interval for the calibration run t_C can possibly be slightly different than the time interval t_M for N_B turbine flowmeter blades to pass the TFM pickoff. The customary parameter used for characterizing a turbine flowmeter is called the "K-factor". The K-factor is defined as the pulses (number of blades passing) per unit of volume of flow through the turbine flowmeter.

The following equation gives the true K-factor using the principles of double chronometry:

$$K_M = (t_C / t_M) \bullet (N_B / V_{FTC}) \quad (1)$$

where:

K_M = K-factor for a TFM, pulses/m^3 or pulses/gal

t_C = Flow-Thru calibrator run time, s

t_M = TFM time for N_B pulses, s

N_B = Number of TFM output pulses in t_M (s)

V_{FTC} = Flow-thru calibrator displacement volume, m^3 or gal

Double chronometry ensures synchronization between the calibration period for the Flow-Thru Calibrator and a turbine flowmeter as well as eliminating the possible timing error described above. The use of the master and slave control consoles allows two turbine flowmeters to be calibrated simultaneously using double chronometry. The concept of simultaneous calibration of two turbine flowmeters has an advantage that a determination of the repeatability of the Flow-Thru Calibrator and the repeatability of each turbine flowmeter by quadrature analysis described later in this report.

3.1.7 Thermal Expansion of the Cylinder of the Flow-Thru Calibrator (FTC)

It is important to know the actual thermal expansion characteristics of the material from which the cylinder was made and not rely on handbook information. The accuracy of the linear thermal expansion data from compendium sources for stainless steels is estimated to be within ±5.0 percent where the actual measurements of a metal sample is estimated to be within ±2.0 percent. It will be shown that an accuracy ±2.0 percent for the thermal expansion data has a relatively small effect on the volumetric accuracy when compensating for the area expansion of the cylinder.

During operation of the FTC, the circumferential expansion due to temperature change causes the effective area of the piston to change. The spring loaded TFE piston seals make the effective diameter of the piston conform to the inner diameter of the cylinder throughout the operating temperature range. The volumetric change due to temperature is primarily a function of the change in the effective area of the piston since the length of the stroke is controlled by the essentially constant length of the Invar rods which space the EOSs.

The cylinder of the FTC was made from a Type 304 stainless steel pipe. A sample piece of the pipe for the cylinder was supplied at the time of manufacture. A portion of the Type 304 sample from the cylinder was machined such that a smaller sample was produced which was 6.35 mm (0.25 inches) in diameter and 50.4 mm (2.0 inches) long. The lengthwise dimension of the subsample was machined tangential to the mean circumference of the from the original cylinder. The direction of the sample was taken into consideration in case the grain structure in the cylinder had an effect on the thermal expansion characteristics.

The pipe material as shipped to the manufacturer of the FTC was identified by the manufacturer of the material as Heat M7726. The heat number identification provides traceability of the metallurgical analysis of the material for the cylinder and certifies that the analysis conforms to Type 304 stainless steel. The 50.4 mm sample was submitted to the Thermophysical Properties Research Laboratory (TPRL) at Purdue University for analysis of the thermal expansion characteristics. A dual Push-Rod Dilatometer was used to compare the sample with a sapphire sample originally supplied by the National Institute of Standards and Technology (NIST) as Standard Reference Material (SRM) 732. Hahn (1977) gives the thermal expansion characteristics of SRM 732. The results of the thermal expansion measurements were described by Taylor (1987). A table of the results are given in Table 2.

The original TPRL thermal expansion data had a slight offset of $(\Delta L/L) = -0.00001864$ at 20°C. The TPRL thermal expansion data was adjusted for this offset in order to normalize the data to a reference temperature of 20°C. The TPRL thermal expansion data covered a range of -105.4°C to +201.8°C.

The following polynomial equation was developed by the method of least squares for a data range from -63.2 to +151.8°C (18.76 to 305.24°F):

$$(\Delta L/L_0) = A_1 \bullet (T_C-20)+A_2 \bullet (T_C-20)^2+A_3 \bullet (T_C-20)^3 \tag{2}$$

where:

A_1 = 16.213725E-6 $\qquad$ A_3 = 10.617039E-9 $\qquad$ A_2 = -4.774482E-11

T_C = deg C

A tungsten SRM was previously compared with the same sapphire SRM and same dilatometer at TPRL. The comparison resulted in an agreement of the certified values of the thermal expansion for the SRMs to within ±1.5 percent. On this basis, Taylor (1987) estimates that Equation (2) gives the thermal expansion of the sample material within ±2.0 percent from -100 to +200°C.

Table 2 gives a tabulation of the volumetric correction for the FTC and an estimate of the uncertainty of the volumetric correction. At the temperature extremes for which the TACS was designed, the uncertainty is less than 0.005 of one percent at -60°C (-76°F) and less than 0.008 of one percent at +140°C (284°F).

3.2 Fluid and Pneumatic System (TACS)

Figure 5 shows a schematic diagram of the fluid and pneumatic system for the TACS. Calibration fluid is continuously circulated through the system by means of the circulating pump. The current circulating pump has a capacity of 125 gpm at 125 psi. The TACS has piping provisions for adding a second circulating pump in parallel with the other pump to double the calibration flowrate capability. The main flow path from the circulating pumps is through the filters and the Flow-Thru Calibrator to the flowmeter test section. The flow rate at the outlet of the test section is controlled by three parallel flow control valves. The flow control valves permit the volumetric flowrate for calibration to be preset from 0.016 to 15.77 liters/s (1.0 to 125 US gpm).

The calibration fluid from the outlet of the flow control valves returns to a supply tank through the main heat exchanger. Calibration fluid circulates through the cooling side of the main heat exchanger. This arrangement permits either low temperature or high temperature operation. A coolant pump circulates the cooling fluid either through a low temperature tank or through a water cooled heat exchanger. The void volume above the fluid in the supply tank is pressurized with nitrogen to control the calibration pressure for the system.

A portion of the calibration fluid flows from near the inlet of the Flow-Thru Calibrator back to the inlet of the main heat exchanger through a bypass line. A flow control valve also controls the volumetric flowrate through the bypass line. The fluid entering the bypass line first flows through the thermal jacket of the Flow-Thru Calibrator. When the calibration flow rate is low, the bypass flowrate is set high. This ensures a stable operating temperature within the Flow-Thru Calibrator at low flow rates. This also ensures a high flow rate through the circulating pump for stable pump operation and good thermal conditioning of the calibration fluid when the calibration flow rate is low. The fluid pressure in the thermal jacket is essentially the same as the pressure in the cylinder of the FTC. This feature eliminates the necessity to correct the displacement volume for changes in diameter caused by changes in internal pressure.

A four-way, pilot operated valve is used to control the operating modes of the Flow-Thru Calibrator. A solenoid valve, which is under the control of the master control console, actually operates the pilot operated valve.

3.3 Fluid Density Measurement

Fluid density measurement accuracy is critical to the accuracy of the TACS. The volumetric flowrate as determined by the Flow-Thru Calibrator (FTC) is converted to mass flow rate by the product of volumetric flowrate and the density of the calibration fluid at the FTC outlet.

Figure 5 shows a density meter installed in the bypass line from the outlet of the filter after the circulating pump back to the inlet of the main heat exchanger. The density meter installation also includes a means of closing the inlet of the density meter in the event that the fluid temperature exceeds +130°C (+266°F). The density meter could be damaged by fluid temperature in excess of +130°C. The density meter installation also includes a flow control valve at the outlet to ensure that the flow rate through the density meter is within a satisfactory sampling range of 0.25 to 1.26 liter/s (4 to 20 gpm). The location of the flow control valve also ensures that the fluid pressure within the density meter is approximately the same as the fluid pressure in the flowmeter test section.

The density meter uses the principle of a vibrating tube to measure fluid density. The tube consists of a vertical, one inch (Ni-Span-C) pipe about 76.2 cm (30 inches) long which vibrates at a resonant frequency in the second mode of vibration. An equation using (1) the measured resonant frequency of the tube, (2) the fluid temperature and (3) the fluid pressure is used to calculate the fluid density. The drive circuit for the density meter uses a phase locked look (PLL) circuit to ensure that the tube vibrates at the true resonant condition. The fluid density is primarily a function of the resonant frequency but minor corrections are included in the calibration equation for temperature and pressure. Previous tests of the density meter demonstrated repeatability of within 0.01 percent for a temperature range of +20 to +38°C (+68 to 100°F). Various calibrations on the TACS from 0°C to 140°C did not demonstrate the expected repeatability. The results described in this report relied on characterizing the density of the calibration fluid as a function of temperature using the vacuum pycnometer (PYC) as a standard. The primary purpose of the PYC is to calibrate the density meter and thus provide traceability to NIST. Further calibration work is needed to gain confidence in the density meter for continuous density measurement.

Fluid density measurement accuracy is also critical to the volumetric calibration of the FTC since the most practical and accurate method of determining the displacement volume is to weigh samples of the calibration fluid that have the same mass as the fluid displaced. The details of this method are described later, but it is obvious that the accurate conversion from mass to volumetric units requires a precise measurement of the density of the fluid at the test conditions during the volumetric displacement tests.

3.3.1 Fluid Density Measurement Standard

Figure 6 shows a cross-sectional view of vacuum pycnometer (PYC) which is used as a standard for density measurement. The pycnometer is a spherical, stainless steel pressure vessel having an internal volume of approximately 1.0 liter (1000 cm^3). Two integral sampling valves at the inlet and outlet of the pycnometer permit a high sample flowrate. The internal construction of the pycnometer ensures that trapped gas will be bled from inside during sampling.

The vacuum pycnometer is constructed of two concentric, spherical shells with the space evacuated and hermetically sealed between the inner and outer shells. An advantage of the vacuum pycnometer is that it can be handled safely over a wide temperature range. When a sample is collected in an ordinary pycnometer at a low fluid temperature, a slow increase in temperature will cause a rapid rise in the internal pressure due to thermal expansion of the fluid. Every pycnometer has a burst disk on the inlet valve, but one prefers that the burst disk never rupture. The vacuum insulation of the pycnometer also permits easier handling when the fluid sample is collected at extreme temperatures since the outer shell is at room temperature. The vacuum insulation also eliminates water condensation on the outer shell when the fluid sample is below the dewpoint. The vacuum jacket also ensures that the fluid sample will stabilize at the inlet temperature of the PYC just prior to closing the sampling valves.

The American Petroleum Institute (API) has developed a standard, API Chapt 14.6 (1991), for calibrating a pycnometer using the accepted standard density of distilled water to establish the internal volume by weight measurements. The density of distilled water used for API Chapt. 14.6 was the international standard (PTB) by Wagenbreth et al (1971). The compressibility characteristics of distilled water was from Kell (1975). The volume is determined at five pressures from 345 to 10,342 kPa (50 to 1500 psia) to establish the volumetric pressure coefficient. The well-known thermal expansion coefficient for AISI Type 316 stainless steel is used for temperature correction. The temperature of the distilled water samples are measured to within 0.1 deg C. The volume of the prover is determined within 0.05 cm^3 (0.005 percent of the nominal volume).

The pycnometer is used to determine density by attaching the pycnometer to a fluid sampling system. Fluid flows through the pycnometer until it is fully filled with liquid and the pycnometer is in thermal equilibrium with the fluid sample. The fluid temperature is determined near the inlet of the pycnometer to establish the temperature of the fluid sample. The sampling valves are then closed, the pycnometer is uncoupled from the sampling lines and the pycnometer is precisely weighed to within 0.02 grams after removing excess liquid from the external fittings at the sampling valves. The evacuated (tare) weight is determined as a part of the original volumetric calibration procedure. The tare weight can be periodically checked from time to time by cleaning the pycnometer with various solvents and by nitrogen purging to exclude all of the fluid contents prior to evacuation.

The method of calculating density with the vacuum pycnometer is described in Appendix B.

3.3.2 Thermal Expansion Characteristics of the Vacuum Pycnometer

The volume of the vacuum pycnometer (PYC) is determined at room temperature at various pressures as described in Para 3.3.1. The inner spherical shell has an inside diameter of about 12.4 cm (4.9 inches) and a wall thickness of about 1.5 mm (0.060 inches). The inner and outer spherical shell of the PYC are created by cold forming two hemispherical shells from sheet metal and welding the two shells together. The material is thus thinner in some sections during cold forming. The pressure coefficient of the PYC must be determined experimentally since the thickness of the inner spherical shell and the diameter of the shell cannot be measured with sufficient accuracy to predict the pressure coefficient.

API Chapt. 14.6 (1991) currently relies on handbook information to predict the thermal expansion characteristics of the inner spherical shell. The volume of the inner shell can be estimated from the linear expansion characteristics using the following equation:

$$V_T = V_{20} \bullet [1 + (\Delta L/L_0)]^3 \qquad (3)$$

where: V_{20} = Pycnometer volume at 20°C

Bogaard (1991) has recently reviewed the best available data on the thermal expansion of Type 316 stainless steel in preparation for a publication on the properties of stainless steels and has found that the data published by Furman (1950) is representative of the thermal expansion characteristics of this material. The data from Furman (1950) was used to calculate an equation for the linear thermal expansion characteristics from -62 to 162°C (-80 to 324°F) using the method of least squares. The equation is given as follows:

$$(\Delta L/L_0)=A_1\bullet(T_F-68) + A_2\bullet(T_F -68)^2 + A_3\bullet(T_F -68)^3 \qquad (4)$$

where: T_F= Temperature, °F

A_1= 8.4778427E-6 A_2= 2.4517056E-9 A_3= -1.167338E-12

Bogaard (1991) estimates that the available data is accurate to within 5.0 percent. Equation (4) and the 5.0 percent accuracy limit was used to generate the data in Table 3 which shows the change in volume of the PYC and the uncertainty of the change in volume as a function of temperature.

3.3.3 Weight Measurement

The vacuum pycnometer (PYC) requires a precise method of weighing the PYC to achieve the maximum accuracy for the density measurement. An electronic balance which uses a quartz suspension and a 5000 gram capacity was selected for the standard weighing system for the TACS. This electronic balance has a resolution of 0.01 grams and an accuracy of within 0.015 grams.

A 5 kg Class S weight was purchased with the balance. Class S (ASTM Class 1) weights are the highest accuracy weights available for field use and have an accuracy of within 0.00024 of one percent. The 5 kg weight is certified traceable to NIST to be within 0.012 grams of the actual mass.

Two additional Class S weights were procured during 1990, a one (1.0) kg weight and a three (3.0) kg weight. These weights were used to demonstrate the linearity of the electronic balance. The AAPI metrology laboratory used all three weights to check the accuracy of the electronic balance. After the electronic balance was calibrated with the 5 kg weight, the electronic balance read 2000.00 and 3000.00 exactly with the respective weights demonstrating that the linearity was equivalent to or better than the resolution of the balance.

The 5000 gram electronic balance is ideal for weighing the PYC since the gross weight of the PYC is about 3100 grams. The range of the balance was also ideal for the FTC volumetric calibration since the maximum gross weight of a 4 liter, borosilicate serum bottle containing 1.1 gallon of calibration fluid is about 4700 grams.

3.3.4 Fluid Density Characteristics as a Function of Temperature

The variation in the density of calibration fluid, MIL-C-7024 (II), was determined from vacuum PYC measurements on 3/27/91 from 4°F to 195°F. It has been found at AAPI that fluid density of the calibration fluid is extremely linear from 68°F to 100°F but the data collected over the above temperature interval could not be satisfactorily be expressed by a linear equation. The data was fitted to a non-linear equation which has the same form as an equation used in the Petroleum Measurement Tables published as ASTM D1250 and API 2540. This equation has the following form:

$$\rho_t = \rho_{15} \; EXP \; [A_1 \; (T_C - 15) + A_2 \; (T_C - 15)^2] \tag{5}$$

$$\ln(\rho_t) = \ln(\rho_{15}) + A_1 \; (T_C - 15) + A_2 \; (T_C - 15)^2 \tag{5a}$$

$$\ln(\rho_t) = A_0 + A_1 \; (T_C - 15) + A_2 \; (T_C - 15)^2 \tag{5b}$$

where:

$\ln(X)$ = Natural logarithm of X

ρ_t = Density of the fluid at temperature, kg/m^3

ρ_{15} = Density of the fluid at 15°C (59°F) = EXP (A_0)

EXP [X] = Exponential of bracketed term X

T_C = Temperature of fluid, °C

The coefficients A_0, A_1 and A_2 were determined from a least squares regression analysis of equation (5b) with the following results:

$A_0 = 6.6517166$

$A_1 = - 9.673828E-4$

$A_2 = -9.301524E-7$

$\rho_{15} = EXP\ (A_0) = EXP\ (6.6517166) = 774.1120\ kg/m^3$

Figure 7 shows a typical curve of fluid density versus temperature for MIL-C-7024 (II) calibration fluid using density data from PYC density measurements and Equation (5) using the above coefficients.

The density of the calibration fluid will vary as fluid losses in the TACS are replenished from a storage tank. This is due to batch differences as the storage tank is refilled from time to time. For small changes in density, one can assume that the coefficients A_1 and A_2 remain constant and redetermine the density of the calibration fluid at 15°C. The characteristic density of the fluid can then be determined at room temperature with a PYC and the reference density determined from the following form of Equation (5):

$$\rho_{15} = \rho_t / \text{EXP}\ [A_1 \bullet (T_C - 15) + A_2 \bullet (T_C - 15)^2] \qquad (6)$$

As an example, assume that the calibration fluid density is measured as 763.00 kg/m^3 at 25°C. The reference density at 15°C, ρ_{15}, can then be determined using Equation (6) as follows:

$$\rho_{15} = 763.00/\text{EXP}\ (-0.00976684)$$

$$\rho_{15} = 763.00/0.9902807 = 770.489\ \text{kg/m}^3$$

The above value of ρ_{15} represents a new reference density to be used in Equation (5) to determine the fluid density at any other temperature.

When additional calibration fluid is added to the TACS due to fluid loss, a change is the density of the calibration fluid occurs at a given temperature. Equation (6) can then be used to determine the reference density and Equation (5) is then used to estimate density variation over a wide range of temperature. This approach is used to avoid extensive fluid density measurements over a wide temperature range each time there is a slight change in fluid density at a given temperature.

3.4 Volumetric Calibration of the Flow-Thru Calibrator

Figure 8 shows a schematic diagram of the piping setup for the volumetric calibration of the flow-thru calibrator. The Flow-Thru Calibrator (FTC) is calibrated by first circulating calibration fluid through the system to completely fill the FTC with fluid. Fluid is bled from the top of the cylinder and outlet (flanged) head of the FTC to ensure that there is no trapped air within the cylinder of the FTC. Calibration fluid is also circulated through the outer jacket of the FTC to provide a thermal barrier to heat loss. The calibrated fluid temperature is stabilized as near as possible to the room temperature to minimize temperature changes within the FTC during calibration.

The bypass flow control valve is then closed. The circulating and coolant pumps are then shutdown <u>immediately</u> after the double block valves are closed at the outlet of the FTC (see Figure 5). The supply tank is then pressurized with nitrogen gas to about 50 psig. This pressurizes the cylinder of the FTC to 50 psig. A precision pressure gage (0-100 psig) is connected to the outlet of the FTC for pressure measurement during the volumetric calibration process.

The sample line for the FTC volumetric calibration is connected to a fitting at the low end of the internal cylinder and in the outlet head of the FTC. Three valves are manifolded on the sample line (3/8 inch stainless steel tube). The first and last valves on the manifold line are ball valves and the middle valves is a solenoid valve (NC) which has a 1/16 inch diameter orifice. The ball valves are primarily used during the 5 gallon volumetric calibration and the solenoid valve is the only valve to control the sample collection during a one gallon calibration.

There is a Calibrator Interface Board (CIB) which provides a logical interface between the control consoles and the electro-optical switches (EOS) which sense various discrete positions of the FTC piston (see Figure 1). The CIB also controls the operation of the solenoid valve during volumetric calibration.

A manual switch is located on the lower right corner of each control console - this switch sets the operation of the FTC to operation with either 1 gallon or 5 gallon displacement. With the switches in the 1 gallon position, the solenoid valve closes when the flag on the optical shaft reaches the second EOS corresponding to the start of a one gallon run. When a manual switch which is located on the CIB is actuated, the solenoid valve again opens permitting a fluid sample to be collected in a glass serum bottle (4 liters) at the outlet of the solenoid valve. The collection continues until the flag on the optical shaft intercepts the light path of the third EOS signaling the end of the 1 gallon displacement run. The solenoid valve then quickly closes to stop the sample collection.

The solenoid valve thus closes at the start and stop of a volumetric calibration run. At the start of a volumetric calibration run, the piston is at the standby position. The manual switch on the CIB is actuated to signal the start of a run. The pneumatic actuator is then pressurized to drive the poppet valve (in the piston) closed. As soon as the poppet valve is closed, the force from the pneumatic actuator starts moving the piston and forcing the displaced fluid through the solenoid valve. The fluid is then collected in clean bottle for later return to the system. Somewhat less than one gallon is collected in a bottle prior to the start of the one (1) gallon displacement run. The calibration fluid discharged through the solenoid valve prior to the volumetric calibration run is used to ensure that all of the nitrogen in the sample line is expelled including the nitrogen in tubes which act as spigots at the discharge of each valve. The ball valves are each opened and closed slowly to expel residual air or nitrogen. After the solenoid valve closes at the start of a run, the waste bottle is replaced with a clean, dry sample bottle. The tare weight of the sample bottle was determined just prior to the actual collection period. Each sample bottle was numbered with a permanent marker. Each sample bottle was purged with dry air, stoppered and allowed to stabilize at room temperature prior to the tare weight measurement.

Each stopper was kept with the same bottle during the volumetric calibration period and included in the tare weight of each bottle. The stopper was also used to close each bottle to prevent possible errors due to evaporation of the calibration fluid following each sample collection.

One other innovation to the volumetric calibration was to provide a means of installing the vacuum pycnometer (PYC) in the sample line immediately before the fluid discharged into the valve manifold. This permitted a density sample to be taken at the same pressure and temperature conditions as existed within the FTC during the volumetric sample collection. The fluid density sample was taken immediately following the volumetric sample collection.

Since there were eight (8), (four liter) bottles available, seven (7) consecutive one gallon samples were taken during a series of one gallon volumetric calibration runs. The extra bottle was used for waste collection before and after each sample run. The calibrator was permitted to travel beyond the stop position after the volumetric samples were collected to provide a density sample in the PYC to represent the density of the fluid in the FTC during the run.

The five gallon volumetric calibration required more time and skill than the one gallon calibration. The five gallon calibration required the use of five (four liter) bottles with the start and stop of the total volumetric collection occurring with the use of a single bottle collecting fluid from the spigot attached to the solenoid valve. The start and stop of the five gallon volumetric collection had to be totally under control of the solenoid valve. In between the start and the stop, the other four bottles were filled using the two auxiliary ball valves.

After the gross weight of the fluid samples and bottles was measured, the calibration fluid was returned to the supply tank. The bottles were then thoroughly drained of residual fluid and purged with dry air until no residual odor of calibration fluid was present at the mouth of each bottle. The tare weights of the stoppered bottles were then measured in preparation for the next volumetric calibration run.

The bottles were filled with dry air since compensation has to be made for whatever air or air-vapor mixture is expelled during the fluid collection. The expelled contents of the bottle was included as part of the tare weight. It is more accurate to estimate the weight of the dry air expelled than to estimate the weight of partially humidified or vapor saturated air. One gallon (231 cubic inches) of dry air weighs about 4.5 grams; correction for weight of the displaced air is thus significant. Shop air at 80 psig was used as a source of dry air for purging the bottles. If residual calibration fluid had been allowed to remain in the bottles during the tare weight measurements, it is estimated that there would have been an uncertainty of as much as 0.02 of one percent in the determination of the net mass weight of fluid collected. This uncertainty would have been due to the uncertainty of estimating the mass of the vapor expelled (in addition to the air) while the bottles were filling.

3.5 Repeatability of the Flow-Thru Calibrator

Hayward (1977) recommends that the repeatability of a calibrator be determined by using the calibrator to test two physically identical flowmeters in a series as shown in Figure 5. Three equations can then be written to relate the repeatability between the two turbine flowmeters and the Flow-Thru Calibrator shown in Figure 5:

$$(R_{1C})^2 = (R_1)^2 + (R_C)^2 \tag{7}$$

$$(R_{2C})^2 = (R_2)^2 + (R_C)^2 \tag{8}$$

$$(R_{12})^2 = (R_1)^2 + (R_2)^2 \tag{9}$$

The quantities R_{1C} and R_{2C} in Equations (7) and (8) are determined by direct experimental evaluation of the repeatability of each turbine flowmeter versus the Flow-Thru Calibrator. The repeatabilities of the flowmeters are determined by the repeatabilities of the turbine flowmeter constants K_1 and K_2 in units of pulses/gal. The quantity R_{12} is the repeatability of one turbine flowmeter versus the other turbine flowmeter as determined by the variation of the ratio of the output frequencies of the two turbine flowmeters for a discrete number of runs.

The left hand quantities in Equation (7) through (9) can thus be directly evaluated experimentally and then be solved simultaneously to yield the following equation:

$$(R_C)^2 = [(R_{1C})^2 + (R_{2C})^2 - (R_{12})^2]/2 \tag{10}$$

The derivation of Equation (10) from Equations (7) through (9) is from Hayward (1977). The quantity R_C from Equation (10) can be also substituted into Equations (7) and (8) to determine the repeatabilities of the individual flowmeters, or

$$(R_1)^2=(R_{1C})^2-(R_C)^2 \tag{11}$$

$$(R_2)^2=(R_{2C})^2-(R_C)^2 \tag{12}$$

This method of analyzing the repeatability data works well unless the bracketed quantity in Equation (10) is negative or

$$(R_{12})^2 > [(R_{1C})^2 +(R_{2C})^2] \tag{13}$$

This situation can occur at the lower end of flowrate range for the turbine flowmeters. In this case, one has to assume that repeatability of the FTC is no better than the average of R_{1C} and R_{2C}. The solution to this dilemma is to use a smaller sized turbine flowmeter set to accurately prove the repeatability of the FTC at the lower flowrates.

3.6 Provisional Accuracy Statement for the TACS

Tables 9 and 10 give a provisional accuracy statements for the TACS. Table 9 is based on a mass flow rate of approximately 0.24 kg/s (1925 lb_m/hr) and Table 10 is based on a mass flow rate of 2.43 kg/s (19250 lb_m/hr). The repeatability is better than earlier estimates for the TACS. The following tabulation compares the accuracy based on 2σ (95 percent confidence limit) of Table 8 with earlier predictions by Craft 1986a):

Operating Temperature °C	Table 9	Craft (1986a)
−55	0.057	0.086
+20	0.042	0.058
+130	0.107	0.116

The improvements in the accuracy estimates are primarily a results of improvement in the accuracy of the displaced volume and the repeatability of the FTC. Future improvements in the accuracy of the TACS can be achieved by improvement in the accuracy of the density measurements since the accuracy related to the FTC appear to be adequate. Additional repeatability data is needed to confirm the repeatability at the lowest and highest temperatures.

An accuracy statement such as presented in Table 9 is useful for determining where improvements can be made. Only the larger errors in the tabulation have a significant influence on the standard deviation based on the square root of the sum of the squares of the errors.

4.0 DUAL-TURBINE FLOWMETER

4.1 Description of the Dual-Turbine Flowmeter

A complete description of the dual-turbine flowmeter is given by Mayer et al (1985). Figure 9 from this reference shows an outline drawing of the dual-turbine flowmeter. Figure 10 shows a cross-sectional drawing of the densi-viscometer. The design of the dual turbine flowmeter consisted of the following main elements:

1. Main turbine (upstream)
   - Six (6) blades with a 45° (RH) helix angle

2. Sensor turbine (downstream)
   - Six (6) blades with a 23.5° (LH) helix angle

3. Densi-viscometer

The rotation of the sensor turbine is opposite to the main turbine. The rotational speed of the sensor turbine is approximately 36 percent of that of the main turbine. Two variable reluctance pickups are used to sense the passing frequencies of the blades of each turbine. Variable reluctance pickups were selected to eliminate magnetic drag on the turbines which would be produced by magnetically polarized pickups. The latter type of pickup would reduce the output speed and produce erratic output at low flowrates.

4.2 Turbine Flowmeter Correlation Parameters

A turbine flowmeter (TFM) is basically a volumetric flowrate measuring device. As fluid flows through the free-wheeling turbine, a pickup coil senses each time a turbine blade passes. If one gallon of fluid passes through a 1.0 inch TFM, for example, 1500 pulses would typically be generated. The number of pulses per gallon is customarily referred to as the "K-factor".

If a TFM were a perfect volumetric flowrate device, the K-factor would be constant. The K-factor, however, is governed by fluid dynamic factors as well as mechanical bearing losses (particularly at low flowrate).

K-factor is customarily correlated as a function the ratio of output frequency divided by kinematic viscosity (f/ν) or

$$K = \text{Function } (f/\nu). \qquad (14)$$

The ratio (f/ν) is approximately proportional to Reynolds number. The relationship shown by Equation (14) provides a convenient method for determining the K-factor from a given frequency output for a TFM and a given value of kinematic viscosity. The correlation between K-factor and the ratio=(f/ν) is often referred to as the Universal Viscosity Curve (UVC) for a TFM. The linear values of K-factor are typically plotted as a function of the logarithm of the ratio=(f/ν) to clearly show the rapid changes in the K-factor that occur from the laminar flow range and through the transition range into turbulent flow range. The UVC correlation works well at the higher flowrates but deviations from this correlation occur in the laminar flow range.

Mattingly (1991) has recently shown the relationship between the flowmeter K-factor and the Strouhal number. The Strouhal number is generally used to describe the frequency at which vortices are shed in the fluid flow wake of a bluff body. This principle is used to measure the volumetric flowrate through a vortex shedding flowmeter. The Strouhal number is a dimensionless parameter that is defined by the following equation:

$$St = (fD/U_0) \qquad (15)$$

where: f= characteristic frequency of vortex shedding

D= characteristic dimension of the bluff body in the fluid flow stream

U_0= The mean velocity upstream to the bluff body

Since a TFM is a fluid flow device which has the capability of generating a blade passing frequency approximately proportional to volumetric flowrate, the Strouhal number should also be applicable to this device. The output frequency can be found from the equation which defines K-factor or

$$f = KQ \qquad (16)$$

where: Q= volumetric flowrate

Using the diameter of the pipe (or cylinder) as the characteristic diameter D, the upstream velocity can be calculated as follows from the volumetric flowrate:

$$U_0 = Q/(\pi/4)\bullet D^2 \tag{17}$$

Solving for Q from Equation (17) gives:

$$Q = (\pi/4)\bullet D^2 U_0 \tag{18}$$

and substituting Equation (18) into Equation (16) gives:

$$f = K\bullet(\pi/4)\bullet D^2 U_0 \tag{19}$$

Substituting Equation (19) into Equation (15) gives the Strouhal number as:

$$St = K\bullet(\pi/4)\bullet D^3 \tag{20}$$

Equation (20) shows the relationship between the K-factor and the Strouhal number. This relationship has the advantage that for a given Reynolds number, the Strouhal number is constant. Equation (20) can be used on a simplified basis to estimate the effect of thermal expansion on K-factor. The K-factor will be reduced in proportional to the cube of the increase in diameter of the flowmeter. The Reynolds number can be defined by the following equation:

$$Re = DU_0/\nu \tag{21}$$

The product of Strouhal number and Reynolds number has been referred to by Kohan et al (1973) as the Roshko number. The product of these two dimensionless parameters creates an additional dimensionless parameter that can be legitimately used for correlation with the Strouhal number. The product of Equation (20) and Equation (21) is the Roshko number or

$$Ro = (f/\nu)\bullet D^2 \tag{22}$$

The conventional method of showing the correlation of K-factor versus the parameter (f/ν) is thus equivalent to the correlation of the Strouhal number versus the Roshko number with the characteristic diameter terms removed.

The mass flowrate from two tandem flowmeters is calculated from the following equations:

$$W = 3.7854 \times 10^{-3}(m^3/gal) \cdot \rho \cdot [(f_M+f_S)/K)], (kg/s) \tag{23}$$

$$K = 60(f_M+f_S)/Q \tag{24}$$

where: ρ = fluid density, (kg/m^3)

f = rotor blade passing frequency, (Hz)

K = K-factor, (pulses/gal) or (Hz/gal/s)

Q = Volumetric flowrate, (gal/min)

ν = Kinematic viscosity, (centistokes = mm^2/s)

Subscripts:

M = main turbine (upstream)

S = sensor turbine (downstream)

The advantage of the dual turbine design is that the output frequency is insensitive to inlet swirl. The main turbine increases in rotational speed if the rotation of the inlet swirl is in the same direction as the turbine. The sensor turbine, however, slows down under these conditions. The net result is that the sum of the output frequencies remains essentially constant for a given volumetric flow rate regardless of the inlet swirl angle.

Since a turbine flowmeter is a volumetric flowrate sensing device, a precision densitometer is required to convert the volumetric flowrate to mass flowrate.

4.3 Method of Calibration of the Dual-Turbine Flowmeter with the TACS.

Since the TACS has the capability of testing two turbine flowmeters simultaneously, the calibration of the Dual Turbine Flowmeter could be easily accommodated. Even though the two flowmeters had different frequency outputs, the master control console receives the pulsed output from the main turbine and the slave control console simultaneously receives the pulsed output from the sensor turbine for the same run period for the Flow-Thru Calibrator. This method permits determining a overall K-factor based on the sums of the two frequency outputs as given by Equation (23).

Tables 11-14 show the tabulated results for the calibration at room temperature. Table 11 shows the operating conditions and the frequency ratio of main turbine to the sensor turbine. Tables 12, 13 and 14 show the results for the main turbine, the sensor turbine and the combined main and sensor turbines, respectively.

4.4 Results of the Calibration of the Dual-Turbine Flowmeter

Figures 11, 12 and 13 show the variation of K-Factor with the (frequency/viscosity) ratio for the main, sensor and combined frequencies. The results in Figures 11 through 13 are given at -18°C (0°F), -1°C (+30°F) and +24° C (+75°F). The K-factor was plotted versus the logarithm of the frequency/viscosity ratio.

The correlation shown in Figure 12 for the sensor turbine is not as good as for the main turbine. The correlation shown in Figure 11 for the combined and sensor turbine was not as good as for the main turbine alone. This correlation is acceptable inasmuch as the dual-turbine flowmeter provides some inherent immunity to inlet swirl effects.

5.0 ANGULAR MOMENTUM FLOWMETER

The angular momentum flowmeter with fluid drive that was selected for calibration on the TACS is similar to the one described by Hildebrand et al (1977) and shown in Figure 14. The flowmeter tested represents the current "state of the art" for a true mass flowmeter design using the angular momentum concept.

5.1 Principles of Operation of the Angular Momentum Flowmeter

The angular momentum flowmeter shown in Figure 14 consists of a rotor which is driven by the swirling flow at the entrance to the rotor. The swirl is produced by the entering fluid as it passes through a swirl generator. The swirl generator consists of a stationary swirler ball and a plurality of overlapping flat springs wrapped in cylindrical configuration and attached to the front support. This is shown in Figure 14 as the spring finger assembly. The swirler ball has shallow, angular grooves in the outer surface. The cylindrical spring assembly is preloaded to hold the ends of the springs tightly against the swirler ball at low flowrates. All of the fluid entering the flowmeter is forced through the angular grooves of the swirler ball until the differential pressure produced by the flow of the fluid through the small flow area of the grooves finally causes the ends of the flat springs to deflect radially outward (fan out) away from the swirler ball. As the flowrate increases, the additional increase in differential pressure causes the flat springs to fan out more. The net result is that the rotational speed of the rotor increases linearly with respect to flowrate until the flat springs start to deflect radially outward away from the swirler ball. The angular speed of the rotor remains relatively constant with further increase in flowrate to the maximum flowrate for which the flowmeter was designed.

The rotor and turbine elements are similar in design. Each consists of a cylindrical hub which is supported on miniature, precision ball bearings to permit the rotor and turbine elements to rotate freely on a stationary shaft. A plurality of thin, axial vanes are machined on the perimeter of the hub. A cylindrical shroud ring is shrunk onto the tips of the vanes. The rotor and turbine elements can be described as "rotating annular flow straighteners". The accuracy of the flowmeter is partially dependent on the accuracy to which the axial vanes have been machined on the hubs. The cylindrical shrouds on each rotating element permits balancing and enough thickness to carry permanent magnets and other magnetic elements which are essential to detecting rotation of the rotor and angular deflection of the turbine.

As described previously, the rotor rotates freely on the ball bearing at a constant speed at a given flowrate. The speed of a rotation of the rotor is a function of the swirl produced by the swirl generator. The flow straightening effects of the rotor vanes ensures that the angular momentum of the fluid leaving the rotor is proportional the angular velocity of the rotor.

The rotation of turbine element is constrained by a torsional spring. The angular rotation of the turbine element is proportional to the applied torque. Since the turbine element is constrained by a torsional spring and the turbine element does not rotate under steady state conditions, the angular momentum leaving the turbine is zero due to the flow straightening effects of the axial vanes. Since the change in angular momentum of the fluid flow is equivalent to torque applied to the turbine, the angular rotation of the turbine is proportional to the angular momentum of the fluid at the entrance to the turbine or the same as the angular momentum established at the exit of the "free wheeling" rotor.

The rotor and turbine are machined from nonferrous materials and are therefore non-magnetic. There are two permanent bar magnets mounted flush with the outer surface of the rotor shroud. The first bar magnet is located near the rotor inlet and the second bar magnet is located near the rotor outlet but located at the 180° position (opposite side of the cylindrical shroud). The first bar magnet is positioned opposite a start coil which senses each time the rotor makes a complete revolution. Each time the first bar magnet passes the start coil, a single sinusoidal pulse is generated in the coil. At the center of the sinusoidal pulse the polarity changes rapidly from positive to negative. The zero crossing of the center of the pulses signals the start of a microsecond timing device.

The turbine has one longitudinal slot machined in the outer shroud. A single blade, which is a slender bar of soft iron material, is embedded in the slot. A stop coil is wound around the housing which seals the fluid from the sensing coils. The axial length of the stop coil is essentially the same length as the turbine as well as the signal blade. The signal blade is aligned opposite the second bar magnet at a zero mass flow rate.

For adjustment, zero mass flowrate can be simulated by flowing air through the inlet of the flowmeter. Air flow produces a high enough velocity in the swirl generator to drive the rotor at a normal rotational speed (e.g. 3.0 revolutions/second) but the mass rate air flow does not produce a sufficient amount of angular momentum (or torque) to deflect the turbine. Each time the first bar magnet produces a pulse as the rotor passes the start coil, the second bar magnet is simultaneously aligned with the signal blade imbedded in the shroud of the turbine. As the second bar magnet passes the signal blade in the turbine, a second sinusoidal pulse is generated in the stop coil regardless of the angular position of the turbine.

When air flow is used to simulate zero mass flow rate conditions, the start coil is adjusted circumferentially until the pulsed outputs of the start and stop coils are simultaneous. When there is a sufficient mass flowrate to deflect the turbine, then the pulse from the stop coil occurs later than the pulse from the start coil. It will now be shown that the mass flowrate is proportional to time between the start pulse and the stop pulse.

The torque experienced by the turbine for a given flowrate is equal to the angular momentum leaving the rotor, or

$$T_M = W(r_M)^2 \omega \qquad (25)$$

where T_M = torque produced by the fluid impulse, (N•m)

W = mass flow rate, (kg/s)

r_M = mean radius of fluid flowing through the turbine, (m)

ω = angular speed of the rotor, (rad/s)

$$(r_M)^2 = [(r_O)^2 + (r_I)^2]/2 \qquad (26)$$

r_O = outer radius of flow passage

r_I = Inner radius of flow passage

The mean radius defined by Equation (26) is derived by assuming a uniform velocity profile at the exit of the rotor. A different velocity profile will produce a slightly different value for the mean radius.

The spiral spring permits the turbine to rotate an angle of θ_M relative to the shaft in proportion to torque produced by the fluid impulse or

$$T_M = k_S\theta_M \qquad (27)$$

where k_S = torsional spring constant, (N•m/rad)

θ_M = angular rotation relative to the shaft, (rad)

When there is a significant mass flowrate of liquid through the flowmeter, the magnets on the turbine are deflected relative to the magnets on the rotor by the angle given by Equation (27). These magnets will pass the sensor coils at two different times during a single revolution of the driven rotor shaft. The time from the start pulse to the stop pulse is given by the following equation:

$$\Delta t_M = \Theta_M/\omega$$

$$\text{or} \quad \Theta_M = \omega \Delta t_M \tag{28}$$

where Δt_M = time increment, seconds

Substituting Equation (28) into Equation (27) results in the following equation:

$$T_M = k_S \omega \Delta t_M \tag{29}$$

When Equations (25) and (29) are equated to eliminate torque term then

$$W(r_M)^2 \ \omega = k_S \omega \Delta t_M \tag{30}$$

Equation (30) may be solved for the mass flowrate W or

$$W = [k_S/(r_M)^2] \bullet \Delta t_M \tag{31}$$

Equation (31) shows that the mass flow rate is proportional to the time interval Δt_M and independent of the rotor speed, ω. The terms in brackets in Equation (31) are essentially constant except for (1) thermal effects on the spring constant and (2) variations in the mean radius due to thermal expansion of the impeller and fluid dynamic effects.

5.2 Method of Calibrating the Angular Momentum Flowmeter

The basic process of calibrating an angular momentum of flowmeter (AMF) is to use a turbine flowmeter (TFM) downstream of the AMF as a reference. The reason for this is that the Flow-Thru Calibrator (FTC) run time is fixed for a given flowrate and a selected (one gallon or five gallon) displacement volume. At high flow rate the run time is too short to adequately determine a average output reading for the AMF. The AMF generates a flow rate reading for every revolution of the rotor. The typical rotor speed is 3 to 6 rev/s. The TFM, however, generates a continuous pulsed output which produces a frequency output which is approximately proportional to flowrate, but can be accurately determined over a short time interval.

The process of calibrating an AMF with a TFM is to first calibrate the TFM with the FTC and then use the calibration information for the TFM to subsequently calibrate the AMF for a fixed time interval typically 10 to 30 seconds. This method has the advantage that turbine meter is calibrated in situ at the temperature, viscosity, density and flowrate for the test conditions previously selected for the AMF. This eliminates the need to correct for the above operational conditions to accurately estimate the flowrate from the TFM frequency output. For example, when TFMs are used for calibration at room temperature, the K-Factor is characterized as a function of the frequency/kinematic viscosity ratio. TFMs are frequently used at temperatures other than at the temperature at which they were originally calibrated. In this case, the viscosity is estimated from a standard curve and a temperature coefficient to account for the thermal expansion of the TFM is applied. The temperature coefficient for correction of the K-factor that is frequently quoted is -0.25 percent per 100°F increase in temperature or

$$K_T = K_{RT} \bullet [1-0.0025(T_F-77)] \tag{32}$$

where K_T = K-Factor at temperature

K_{RT} = K-Factor at room temperature

T_F = Temperature, °F

This temperature coefficient is determined from the cubical coefficient of thermal expansion of the TFM housing which is typically 304 stainless steel. However, the TFM rotors are typically made from 400 series stainless steel for the magnetic characteristics of martensitic stainless steel. The 400 series stainless steels, however, have a lower coefficient of thermal expansion than the 300 series stainless steels which means that the blade tip clearance will increase with increase in temperature. The temperature coefficient for the K-Factor calibration should actually be determined by calibration at various temperatures.

The estimated value of the kinematic viscosity is used to calculate the ratio of frequency/viscosity (f/ν). This K-Factor versus (f/ν) curve is generally referred to as the universal viscosity curve for a TFM. This correlating curve is not accurate in the laminar flow (low flow) range. The correlation curve shifts as a function of viscosity at low flow rates.

When the TFM is calibrated at the same conditions as specified for the test point, thermal expansion and viscosity (Reynolds number) effects are no longer a factor or an uncertainty in the calibration process.

The density used for determining the mass flowrate from the volumetric flowrate through the FTC or the TFMs was determined by the density measurements using the vacuum pycnometer (PYC). At the present time, the density meter is a secondary standard. More work is needed to establish confidence in the accuracy of the density meter for flow rate calibration. The PYC was used at each temperature and a linear correction for temperature was used for small deviations in temperature. This method made the accuracy of the density determinations to within 0.02 of one percent for each test condition.

5.3 <u>Results of the Calibration of the Angular Momentum Flowmeter with the TACS</u>

Figure 15 shows the results from the calibration of an angular momentum flowmeter (AMF) using the TACS. The flowmeter was calibrated at +12°C (+10°F), +25°C (77°F) and +95°C (203°F). This AMF had a maximum flowrate of 16.5 kg/s (27000 lb_m/hr). Figure 15 shows that the flowmeter was accurate to within $\pm$0.5 of one percent at +25 to 95°C from 1.8 to 9.2 kg/s (3000 to 15000 lb/hr). The flowmeter was also within $\pm$1.0 percent from 92 to 16.5 kg/s (15000 to 27000 lb_m/hr). The calibration curve at +25°C compared favorably with a calibration curve generated on another calibration test stand but it is believed that the accuracy of the data from the TACS represents a higher absolute accuracy than any other test facility available.

6.0 Conclusions and Recommendations

The following conclusions and recommendations are made relative to Phase IIc and Phase III of the high accuracy fuel flowmeter program:

6.1 Dual-Turbine Flowmeter

The characteristics of the main turbine (first rotor) in the dual turbine flowmeters demonstrated satisfactory repeatability over the temperature range of the testing with the TACS. The sensor turbine (low speed, second rotor) demonstrated satisfactory repeatability at low temperature but the characteristics at room temperature did not correlate well with the low temperature data.

The speed of the sensor turbine is about 25 percent of speed of the main turbine which makes the calibration characteristics of the sensor turbine more sensitive to bearing torque and viscous effects in the low flowrate region. The sensor turbine reduces the sensitivity of the dual-turbine flowmeter to installation effects such as inlet pipe bends as well as providing a method of detecting bearing wear or incipient bearing failure. The calibration results also suggest that the bearing support for the sensor turbine could be improved.

The dual-turbine flowmeter requires an accurate measurement of fluid density and fluid viscosity to interpret the output frequency in terms of mass flowrate. The device also requires a temperature measurement of fluid density and fluid viscosity of interpret the output frequency in terms of mass flowrate. This device also requires a temperature measurement of the fluid to compensate for thermal expansion of the flowmeter. Each dual-turbine flowmeter must be individually calibrated to adequately characterize the K-factor versus frequency/kinematic viscosity (f/ν). The dual turbine flowmeter cannot be manufactured with enough precision nor is there a simple means of adjusting the finished product to agree with a standardized calibration curve for interchangeability.

6.2 Angular Momentum Flowmeter

The angular momentum flowmeter with a constant speed motor drive has the potential for achieving an accuracy of with 0.25 of one percent. The typically slow rate of response to step changes in flowrate of the angular momentum flowmeter were addressed in this program by using a turbine flowmeter upstream to the angular momentum flowmeter. The concept of using a turbine flowmeter upstream to the angular momentum flowmeter permits the turbine flowmeter to be continuously calibrated in units of mass flowrate under steady state flow conditions while providing the ability to respond to step changes in flowrate with a typical time constant of less than 25 milliseconds.

The angular momentum flowmeter with a motor drive has the capability of being adjusted to operate within an accuracy of 0.25 percent at most operating conditions by (1) zero adjustment, (2) spring adjustment and (3) skew vane adjustment. Further improvements in the accuracy at extreme operating conditions can be achieved by characterizing each flowmeter for subtle effects such as (1) the variation in leakage losses through clearances due to a variation in fluid viscosity due to temperature change, (2) non-linear spring characteristics, (3) zero shift due to temperature and (4) change in the spring constant due to temperature. Further development of the angular momentum flowmeter with a motor drive is justified should the need for a high accuracy flowmeter should arise in the future.

6.3 Test and Calibration System (TACS)

The TACS has exceed the original expectations in terms of repeatability and accuracy within the current operating limits of temperature and flowrate. Additional improvements will continue to be made this facility in terms of improving the flow control at low flow rates and extending the operating temperature limits. Additional effort is needed to establish the density meter as an accurate and reliable method of measuring fluid density in order to avoid reliance on periodic fluid density checks with a PYC.

APPENDIX A

High Accuracy Fuel Flowmeter Design Guidelines And Specifications

1. Methods of Mass Measurement- Fuel mass flow (both mass flow and total mass flow accumulated) shall be measured either directly, or by using a composite system of separately measuring volumetric flow and fuel density, or by measuring a combination of quantities from which mass flow can be calculated. For a flowmeter system that measures volumetric flow, the preferred method of measuring density is to use a densitometer rather than a correlation between density and temperature. The reason is that fuels that are within the MIL specifications can still show variations between batches that can produce uncertainties up to $\pm 1/2$ percent in density when determined by a temperature measurement. This uncertainty exceeds the contract goal.

2. Types of Fuels - Fuels of interest are JP-3, JP-4, JP-5, JP-8 (Type A-1) and Type A.

3. Flow Range - Typical ranges of fuel flow between engine full power and idle are between 50:1 to 100:1 depending on whether or not the engine has an afterburner. The absolute value of full scale flowrate varies with engine thrust; but for the purpose of this contract, a flowmeter with a nominal full scale of 3.2 liter/second (20,000 lb_m/hr) and a 50:1 operating range is of primary interest. A full scale range of 0.5 liter/second (3000 lb_m/hr) is also of interest and shall be considered.

4. Pressure - Flowmeters are subjected to high pressures because they are usually located downstream of the fuel pump. Operating pressures up to 7000 kPa (1000 psi) shall be considered. Flowmeter bodies shall be hydrostatic pressure tested to 1.5 times the maximum operating pressure.

5. Pressure Drop - At maximum fuel flow the maximum pressure drop across the flowmeter shall be 68 kPa (10 psi).

6. Fuel Temperature - The flowmeter shall be capable of operating over a fuel temperature span from -55°C to +130°C (-67°F to +266°F)

7. Ambient Temperature - The flowmeter shall be capable of operating over an ambient temperature span from -55°C to +130°C (-67°F to 266°F)

8. Accuracy - The total error band for mass flow measurement shall be no greater than ± 0.25 percent of reading. The project goal of the error band is ± 0.1 percent of reading.

9. Resolution - The maximum value of resolution of fuel flow measurement at 1/50 of full scale shall be 0.25 percent.

10. Ambient Pressure - The flowmeter and signal conditioning electronics are usually located in unpressurized regions of the aircraft. The units shall be capable of satisfactory operation in an external pressure environment between 100 kPa and 7 Pa (15 to 0.001 psi).

11. Vibration Characteristics - The flowmeter shall be capable of satisfactory operation in the following vibration - frequency envelope: $\pm$1.2 mm (5 to 14 Hz), $\pm$1 g (14 to 23 Hz), $\pm$0.45 mm (23 to 90 Hz), and $\pm$15g (90 to 2kHz).

12. Size and Weight - Because of space limitations associated with flight applications, the flowmeter shall fit within the cylindrical envelope outlined by the AN fitting nuts (MS-33656) associated with the nominal fuel line tube size of for the flow range specified in Paragraph 3. A protrusion from the side of the flowmeter is acceptable but shall be no larger than a volume of the following dimensions: 3 fuel line tube diameters long, 2 fuel line tube diameters high, and 3/4 tube diameters wide. The maximum length of the flowmeter including end connections shall be 8 fuel line tube diameters. The maximum size of the signal conditioning, which may be located remotely from the flowmeter, shall be 1000 cm^3. The maximum weight of the flowmeter assembly including any required valves and manifolds (but not including signal conditioning) shall be 5 kg.

13. Material - Wetted parts of the flowmeter shall be compatible with the fuels listed above and at the pressures and temperatures listed above without suffering corrosion, brittleness, seal leakage, or other degrading properties.

14. Response - Time constant of the flowmeter shall not exceed 25 ms.

15. Failure Mode - Because the safety of the aircraft is of paramount importance, any failure of the flowmeter shall not cut off fuel supply or otherwise interfere with proper engine performance.

16. Power - The flowmeter and signal conditioning (if required) shall operate on 28 V dc.

17. Output - The output (or outputs) of the flowmeter including signal conditioning (if required) shall be a voltage or frequency which is a single valued function of fuel mass flow or of quantities from which flow can be computed. The output (or outputs) shall be compatible with digital processing techniques. The date processing of the output signal (or signals) is not considered part of this contract.

18. Pressure Pulsations - The flowmeter performance shall be unaffected by maximum fuel line pressure fluctuations of $\pm$2 percent of the fuel pressure for frequencies of fluctuations above 10 Hz.

19. <u>Mounting and Position Sensitivity</u> - The flowmeter shall have AN Series 37° male flared tube (MS-33656) end connections. Flowmeter performance shall be unaffected by changes in operating attitude.

20. <u>Overrange Capability</u> - The flowmeter performance shall be unaffected after being subjected to a fuel flow of 125 percent of full scale.

21. <u>Calibration</u> - It is likely that <u>in situ</u> calibration of the flowmeter in the aircraft will not be done because of the complexity of such a procedure. However, the flowmeter, including identical flight fuel system upstream and downstream tubing sections, shall be calibrated as an assembly on a flow stand of sufficient precision to determine flowmeter accuracy.

Appendix B

Fluid Density Measurement Using a Vacuum Pycnometer (PYC)

The method of measuring the density of a fluid using a vacuum pycnometer is described in this appendix. The basic method applies to any pycnometer.

The following notation is used in this appendix:

F_B = Force on weight pan of an electronic balance, N

g = Local acceleration of gravity, m/s^2

P_G = Gage pressure (US customary units), psig

T_C = Temperature, °C

T_F = Temperature, °F

V_P = Certified volume of PYC, cm^3

W_P = Gross weight of PYC and liquid contents, gm

W_t = Tare weight of the evacuated PYC, gm

ρ_L = Liquid density, kg/m^3

ρ_W = Density of calibration weight, kg/m^3

ρ_A = Density of air at room conditions, kg/m^3

A 5.0 kg Class S, stainless steel calibration weight is used for calibrating the electronic balance. The density of the stainless steel weight material is actually about 7900 kg/m^3. The density of air a standard room conditions, namely: 101.325 kPa (14.696 psia), 20°C (68°F) and 50 percent relative humidity is equal to ρ_A= 1.20 kg/m^3.

The mass of the 5.0 kg weight is adjusted by the manufacturer to produce the same force on the pan of an electronic balance as if the density of the weight was 8000 kg/m^3 at standard room conditions in accordance with NIST weight standards. The true mass of a standard 5.0 kg stainless steel weight (7900 kg/m^3) is actually 5000.0095 gm in order that it will produce the same force on a balance at a standard air density of 1.2 kg/m^3 as if it were exactly 5.0 kg but had a density of 8000 kg/m^3. The tolerance of a Class S (ASTM Class 1) weight is only ± 0.012 gm so that the mass difference of 0.0095 gm is not particularly significant.

When the calibration weight is placed on the pan of the electronic balance, there is (1) a downward force equal to the product of the mass of the weight times the acceleration of gravity and (2) an upward force due to buoyancy of the displaced air surrounding the weight or

$$F_B = [M_W - \rho_A(M_W/\rho_W)]g \tag{B1}$$

or using the above values of density and rearranging Equation (B1) gives:

$$(F_B/g)=[1-(1.2/8000)] \bullet M_W \tag{B2}$$

$$= 0.99985 \bullet M_W = 0.99985\ (5000.00) = 4999.25 \text{ gm}$$

The electronic balance is customarily calibrated in gram units. If a 5000 gm weight is placed on the pan of the electronic balance, the scale is adjusted to read a 5000.00 gm whereas in reality the force on the scale pan is equivalent to a 4999.25 gm weight on the pan if the weight and electronic scale were in a vacuum. When 2000 gm and 3000 gm stainless steel weights are placed on the scale pan for a linearity check, they read the exact mass since the calibration is adjusted for air buoyancy of stainless steel and the local acceleration of gravity.

When the evacuated PYC is weighed, the tare weight is a pseudo-tare weight which is recorded as a reference. When a fluid sample PYC, the force acting on the scale pan does not produce a change in the buoyancy force surrounding the PYC since the fluid sample is contained within the PYC and buoyancy force is a function of the external volume which is constant.

The actual density of a fluid sample is calculated from the gross weight and tare weight measurements using the following equation:

$$\rho_L = (1-\rho_A/\rho_W) \bullet (W_P-W_t)/V_P, \ (\text{gm/cm}^3) \tag{B3}$$

or using the air density and weight density described above Equation (B3) becomes:

$$\rho_L = (0.99985) \bullet (W_P-W_t)/V_P, \ (\text{gm/cm}^3) \tag{B4}$$

The equation for the certified volume of the PYC (Serial No. 134) is given by the following equation using US customary units:

$$V_P = (975.18 + 0.00136 \bullet P_G) \bullet [1+ (\Delta L/L)]^3, \ (\text{cm}^3) \tag{B5}$$

and using the linear thermal expansion characteristics for AISI 316 stainless steel given by Equation (4) [Para 3.3.2]:

$$(\Delta L/L_0) = A_1\ (T_F-68) + A_2\ (T_F-68)^2 + A_3\ (T_F-68)^3 \tag{4}$$

$A_1 = 8.4778427\text{E-}6$ $A_2 = 2.4517056\text{E-}9$ $A_3 = -1.167338\text{E-}12$

Equation (B5) can be written in the following alternate form:

$$V_P = (975.18 + 0.00136 \bullet P_G)\bullet[1+\alpha_V(T_F-68)] \quad \text{(B6)}$$

where: α_V = mean volumetric thermal expansion coefficient between any temperature T_F and the reference temperature of 68°F.

The constant 975.18 is the calibrated volume of the pycnometer at 20°C (68°F) and 101.325 kPa (14.696 psia). The pressure coefficient (0.00136 cm^3/psig) was determined by calibration of the PYC at pressures from 345 to 11721 kPa (50 to 1700 psia). Values of the mean volumetric thermal expansion coefficient α_V are tabulated in Table 2. Equation (B6) is more convenient for hand calculations due to the small variation in the coefficient α_V with temperature.

After the volumetric calibration of the PYC, the weight of the PYC was measured at room temperature with air filling the void volume. The PYC evacuated weight of the PYC was determined as follows:

Weight of PYC filled with air	= 2332.08 gm
Swagelok adapter fittings and TFE tape	= +48.17 gm
	2380.25
Correction for the mass of air in the PYC	= -1.17 gm
Tare weight of the evacuated PYC, W_t	= 2379.08 gm

An example of a fluid density determination using a PYC is described as follows:

W_P = 3085.29 gm at 181.20°F and 178 psig

$-W_t$ = $-\underline{2379.08}$

(W_P-W_t) = 706.21 gm

Using linear interpolation from Table 3:

$$\alpha_V = 26.21E{-}6 + (0.12E{-}6/18.0)\bullet(181.20-176.0) = 26.24E{-}6$$

and substituting into Equation (B6) gives:

$$V_P = [975.18 + 0.00136(178)]\bullet[1+ 26.24E{-}16\bullet(181.20 -68.0)]$$

$$V_P = (975.422)\bullet(1.002971)= 978.32 \text{ cm}^3$$

After substituting the above quantities in Equation (B4), this equation gives the following value for fluid density:

$$\rho_L = (0.99985)\bullet(706.21/978.32)=0.72175 \text{ gm/cm}^3$$

Method of Calculating the Displacement Volume of The Flow-Thru Calibrator

The most accurate method of experimentally determining the displacement volume of the Flow-Thru Calibrator (FTC) is by collecting the quantity of calibration fluid displaced by the FTC and evaluating the volume of the fluid from weight measurements.

The notation used for the analysis described herein is as follows:

$H=$	Altitude above sea level, ft.
$h=$	Height of the column mercury in a barometer, mm Hg
$K_B=$	Correction factor for buoyancy
$K_T=$	Correction factor for thermal expansion
$P_A=$	Atmospheric pressure, psia
$R=$	Universal gas constant for an ideal gas
$T_C=$	Temperature, °C
$T_F=$	Temperature, °F
$V_{FTC}=$	Displacement volume of FTC, cm^3 (or US gallons)
$W_G=$	Gross weight of collection bottle, calibration fluid and stopper, gm
$W_N=$	Net weight of calibration fluid in a collection bottle
$W_T=$	Tare weight of collection bottle with a stopper and dry air contents, gm
$g=$	Local acceleration of gravity, m/s^2
$g_c=$	9.80665 (standard acceleration of gravity), m/s^2
$m_A=$	Molecular weight of air = 28.966 gm/gm-mole
$\rho_{Hg}=$	Density of mercury, $lb_m/in.^3$
$\rho_A=$	Density of air, kg/m^3
$\rho_L=$	Density of liquid, kg/m^3
$\rho_W=$	Density of calibration weight, kg/m^3
$\Phi=$	North latitude, degrees

A mercury barometer was used to measure the atmospheric pressure. The barometer was located at the same elevation as the weighing equipment -no altitude corrections were thus required.

Benedict [1984] gives the following equation for the density of mercury at standard gravity = 9.80665 m/s^2:

$$\rho_{Hg}\ (lb_m/in.^3) = 0.491154/[1+1.01E{-}4 \bullet (T_F - 32.0)] \qquad (C1)$$

The TACS facility is located at 42° 33'37" (42.56°) north latitude at 87 ft above sea level. Benedict [1984] gives the following equation for the correction of standard gravity to local gravity:

$$(g/g_c) = 1-[2.637E{-}3 \bullet \cos(2\Phi) + 9.6E{-}8 \bullet H + 5E{-}5] \qquad (C2)$$

and substituting the values of latitude and altitude listed above into Equation (C2) gives:

$$(g/g_c) = 0.9997173 \qquad (C3)$$

Using the above correction factor and the density of mercury given by Equation (C1) for an average laboratory temperature of 25°C (77°F) gives:

$$\rho_{Hg} = 0.488932(0.9997173) = 0.488794\ lb_f/in.^3 \qquad (C4)$$

when divided by 25.4 mm/in. gives:

$$(\partial P/\partial h) = 0.0192438\ lb_f/in.^2/mm\ Hg \qquad (C5)$$

The density of air in US customary units is given by the following equation of state:

$$\rho_A = m_A P_A/[R \bullet (T_F + 459.67)],\ lb_m/ft^3 \qquad (C6)$$

where m_A= molecular weight of air = 28.966 gm/gm-mol (or lb_m/lb_m-mol)

The value of the gas constant:

$$R = 10.73142\ ft^3\text{-}(lb_f/in.^2)/(lb_m\text{-mol-}°R)$$

for use in Equation (C6) is equivalent to the value of R below:

R= 8314.34 J/(kg-mol-K) given by Mechtly (1973)

To illustrate the method of evaluating the FTC displacement volume from weight measurement, the following data from a 1.0 gallon displacement run is used:

Atmospheric temperature = 24.27°C (75.68°F)

Barometric pressure = 736.5 mm Hg at 25°C (77°F)

FTC pressure = 53.6 psig

FTC fluid temperature = 24.326°C (75.787°F)

Gross weight of fluid and bottle = 4537.37 gm

Tare weight of the bottle = 1732.70 gm

Net weight of fluid sample = 2814.67 gm

Fluid density at FTC fluid temperature and pressure = 0.765368 gm/cm^3

The density of the air in the laboratory environment is found from Equations (C5) and (C6) as follows:

$$P_A = 0.0192438(736.5)=14.1728 \text{ psia}$$

$$\rho_A = 28.966(14.1728)/[10.73142\bullet(75.68+459.67)]$$

$$\rho_A = 0.071458 \text{ lb}_m/\text{ft}^3$$

ρ_A = 1.1446 kg/m^3 (using a conversion factor of 0.062428 lb$_m$/ft^3/kg/m^3)

The correction for air buoyancy is given by Mayer et al (1985), Appendix A, Equation (A-6) pp289 as

$$K_B= (1-\rho_A/\rho_W)/(1-\rho_A/\rho_L) \qquad \text{(C7)}$$

and substituting the above quantities gives

$$K_B= (1-1.1446/8000)/(1-1.1446/765.368)= 1.0013545$$

The displacement volume of the FTC at the reference temperature of 20°C (68°F) is given by the following equation:

$$V_{FTC}= W_N\bullet K_B/(\rho_L\bullet K_T) \qquad \text{(C8)}$$

where $K_T= (1+\Delta L/L_0)^2$ = 1.000122 is the thermal expansion correction for area from Equation (2) at 24.326°C (see Para 3.1.7 and Table 2).

The displacement volume from Equation (C8) is thus evaluated as:

$$V_{FTC} = 2814.67(1.0013545)/[0.765368\bullet(1.000122)]=3682.07 \text{ cm}^3$$

and using a conversion factor of 3785.412 cm^3/gallon gives V_{FTC}= 0.9727 US gallons. The FTC displacement volume is expressed in units of US gallons since the FTC control consoles are designed to accept only these units.

GLOSSARY of ABBREVIATIONS

AAPI AMETEK Aerospace Products Inc.

AGA American Gas Association

AIME American Institute of Metallurgical Engineers

AISI American Institute of Steel Industries

AMF Angular Momentum Flowmeter

API American Petroleum Institute

ASTM American Society of Testing Materials

CCG Calibration Coordination Group of the DoD

CIB Calibrator Interface Board

CINDAS Center for Information and Numerical Data Analysis and Synthesis (Purdue University for DoD).

DoD Department of Defense

EOS Electro-Optical Switch

FTC Flow-Thru Calibrator

GAL US gallons (3.7854 liters or 3.7854 x 10^{-3} m^3)

NIST National Institute of Standards and Technology (Formerly NBS: National Bureau of Standards)

PYC Vacuum Pycnometer

RTD Resistance Temperature Detector

SI International System for Metric Units

SRM Standard Reference Material (Term used by NIST for standard materials furnished and certified by NIST).

TACS Test and Calibration System

TFM Turbine Flowmeter

TPRL Thermophysical Properties Research Laboratory (Purdue University/ now CINDAS)

UVC Universal Viscosity Curve (Pertaining to the correlation of K-factor to frequency/kinematic viscosity for TFMs).

NOTATION

Roman Symbols

A_0, A_1, A_2 = Coefficient used in various empirical equations

D = Characteristic diameter or dimension, (m or in.)

F_B = Force of the weight pan of an electronic balance, (N)

f = Rotor blade passing frequency of a TFM, (Hz)

f_M = Rotor blade passing frequency of the main turbine of a TFM, (Hz)

f_S = Rotor blade passing frequency of the sensor turbine of a TFM, (Hz)

g = Local acceleration of gravity, m/s^2

g_c = Standard acceleration of gravity = 9.80665 m/s^2

H = Altitude above sea level, (ft)

h = Height of the column in mercury barometer, (mm Hg)

K = K-factor for a TFM (pulses/m^3 or pulse/gal)

K_B = Volumetric correction factor for thermal expansion (dimensionless)

K_{RT} = K-factor at room temperature

K_T = K-factor at operating temperature

K_V = Volumetric correction factor for thermal expansion

k_S = Torsional spring constant, (N•m/rad)

m_A = Molecular weight of air = 28.966 gm/gm-mole or lb_m/lb_m-mole

N_B = Number of TFM output pulses in t_M (s)

P_A = Atmospheric pressure, (psia)

P_G = Gage pressure (US customary units), (psig)

P_S = Gage pressure (SI units), (kPa)

Q = Volumetric flowrate, (m^3/s or gpm)

R = Universal gas constant for an ideal gas

R = 8314.34 J/(kg-mol-K) or 10.73142 ft ^{3}-($lb_f/in.^2$)/(lb_m-mol-°R)

R_C = Repeatability of Flow-Thru Calibrator, (percent)

R_1 = Repeatability for Flowmeter 1, (percent)

R_2 = Repeatability for Flowmeter 2, (percent)

R_{12} = Repeatability of Flowmeter 1 versus Flowmeter 2, (percent)

R_{1C} = Repeatability of Flowmeter 1 Versus the Calibrator, (percent)

R_{2C} = Repeatability of Flowmeter 2 Versus the Calibrator, (percent)

r_I = Inner radius of the annular flow passage of the rotor of an AMF, (m)

r_O = Outer radius of the annular flow passage of the rotor of an AMF, (m)

r_M = Mean radius of the fluid flow at the exit of the rotor or the entrance to the turbine of an AMF, (m)

t_C = Flow-Thru Calibrator run time, (s)

t_M = TFM time for N_B pulses, (s)

T_C = Temperature, °C

T_F = Temperature, °F

T_M = Turbine torque in an AMF, (N•m)

T_R = Temperature, °R

U_O = Mean velocity upstream of a TFM (or a bluff body in vortex shedding), (m/s or ft/s)

V_{FTC} = Flow-Thru Calibrator displacement volume, (m^3 or gal)

V_P = Internal volume of a vacuum pycnometer (cm^3)

V_{20} = Volume at a vacuum pycnometer at 20°C (68°F)

W = Mass flow rate, (kg/s or lb_m/hr)

W_G = Gross weight of a collection bottle, fluid and stopper, (gm)

W_N = (W_G-W_T) = Net weight of fluid in a collection bottle, (gm)

W_P = Gross weight of a vacuum pycnometer and its liquid contents, (gm)

W_T = Tare weight of a collection bottle with a stopper and dry air contents, (gm)

W_t = Tare weight of a vacuum pycnometer with the internal volume evacuated, (gm)

Greek and Special Symbols

α_V = mean volumetric thermal expansion coefficient of a vacuum pycnometer, (in./in./°F)

Δt_M = Incremental time between the start and stop pulses of an AMF, s

$\Delta L/L_0$ = Relative linear thermal expansion of a substance, (cm/cm or in./in.)

ρ_A = Density of air, kg/m^3

ρ_{Hg} = Density of mercury, kg/m^3

ρ_L = Density of liquid, kg/m^3

ρ_W = Density of standard calibration weights, kg/m^3

ρ_{15} = Density of the calibration fluid at 15°C (59°F)

μ = Absolute viscosity, (centipoise = 0.001 N•s/m^2)

ν = Kinematic viscosity, (centistokes = mm^2/s)

θ_M = Angular rotation of the turbine element in an AMF (radians)

Φ = North latitude, (deg)

ω = Rotational or angular speed, (rad/s)

∂ = Partial differential

Dimensionless Parameters

Re = Reynolds number = $\rho DU_0/\mu = DU_0/\nu$

Ro = Roshko number = $(f/\nu)\bullet D^2 = St\bullet Re$

St = Strouhal number = fD/U_0

Abbreviations For Units

cm	= centimeters	kPa	= kiloPascals
ft	= feet	m	= meters
gal	= U.S. gallons	N	= Newtons
gpm	= gallons per minute	Pa	= Pascals
in.	= inches	rad	= radians
kg	= kilograms	s	= seconds

CONVERSION FACTORS

Mechtly (1973) has published a comprehensive table for converting from US customary units to SI (metric) units. The inverse conversion factors and grouping related to flow rate are not given by Mechtly (1973). The following conversion factors have been found useful in fluid flowrate measurement:

Length

25.4*mm = 1.0 inches

0.3048*m = 1.0 ft

30.48*cm = 1.0 ft

Area

6.451 6*cm^2 = 1.0 sq inch

Volume

16.387 064*cm^3	= 1.0 cu inch
231*cu in.	= 1.0 gal
3785.411 8 cm^3	= 1.0 gal
3.785 411 8 liters	= 1.0 gal
1000 liters	= 1.0 m^3

Mass

0.453 592 37*kg	= 1.0 lb_m
2.204 622 62 lb_m	= 1.0 kg

Density

0.062 427 96 lb_m/ft^3	= 1.0 kg/m^3
62.427 96 lb_m/ft^3	= 1.0 gm/cm^3
1.0 gm/cm^3	= 1000.0 kg/m^3

Volumetric Flow Rate

0.063 090 196 Liters/s	= 1.0 gpm
1.0 liter/s	= 15.850 323 gpm

Note: * Indicates an exact number by definition

Mass Flow Rate

1.0 kg/s = 7936.641 439 lb_m/hr

0.000 125 997 88 kg/s = 1.0 lb_m/hr

Pressure

Standard atmosphere	= 1.013 25* bar
	= 101.325* kPa
1.0 bar	= 100* kPa
1.0 bar	= 14.503 774 psi
1.0 psi	= 6.894 757 2 kPa
1000 psi	= 6.894 757 2 MPa

Note: * Indicates an exact number by definition

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TABLE 1

TYPICAL CALIBRATION RUN TIMES
FOR THE FLOW-THRU CALIBRATOR
WITH VARIOUS DISPLACEMENT VOLUMES

[1] VOLUMETRIC FLOW RATE cm^3/s (gpm)		[2] MASS FLOWRATE kg/s (lb_m/hr)		RUN TIME FOR TWO DISPLACEMENT VOLUMES [3] 3 785 cm^3 (1 gal)	[4] 18 927 cm^3 (5 gal) [5]
15.8	(0.25)	0.012	(96)	240.0 s	1200.0 s
63.1	(1.00)	0.048	(385)	60.0 s	300.0 s
126.2	(2)	0.097	(770)	30.0 s	150.0 s
315.5	(5)	0.243	(1 925)	12.0 s	60.0 s
630.9	(10)	0.486	(3 850)	6.0 s	30.0 s
1 261.8	(20)	0.972	(7 700)	3.0 s	15.0 s
3 154.5	(50)	2.249	(19 250)	1.2 s	6.0 s
6 309.0	(100)	4.858	(38 500)		3.0 s
12 618.0	(200	9.716	(77 000)		1.5 s
15 772.5	(250)	12.145	(96 250)		1.2 s

NOTES: [1] (gpm) = (US gallon/minute)

[2] Based on a fluid density = 770.0 kg/m^3

[3] Stroke = 13.28 cm (5.23 inches)

[4] Stroke = 64.4 cm (26.14 inches)

[5] US gallon = 3 785.4 cm^3

TABLE 2

THERMAL EXPANSION CHARACTERISTICS
OF THE FLOW-THRU CALIBRATOR

TEMPERATURE DEG C	DEG F	[1] THERMAL EXPANSION $\Delta L/L$	[2] VOLUMETRIC CORRECTION FACTOR	VOLUMETRIC CORRECTION PERCENT	[3] VOLUMETRIC UNCERTAINTY PERCENT
-60	-76	-.001205	0.997592	-.241	0.0048
-50	-58	-.001067	0.997868	-.213	0.0043
-40	-40	-.000924	0.998152	-.185	0.0037
-30	-22	-.000778	0.998444	-.156	0.0031
-20	-4	-.000629	0.998743	-.126	0.0025
-10	14	-.000476	0.999049	-.095	0.0019
0	32	-.000320	0.999361	-.064	0.0013
10	50	-.000161	0.999678	-.032	0.0006
20	68	0.000000	1.000000	0.000	0.0000
30	86	0.000163	1.000326	0.033	0.0007
40	104	0.000328	1.000656	0.066	0.0013
50	122	0.000495	1.000990	0.099	0.0020
60	140	0.000662	1.001325	0.133	0.0026
70	158	0.000831	1.001663	0.166	0.0033
80	176	0.001001	1.002002	0.200	0.0040
90	194	0.001171	1.002343	0.234	0.0047
100	212	0.001341	1.002683	0.268	0.0054
110	230	0.001510	1.003023	0.302	0.0060
120	248	0.001680	1.003362	0.336	0.0067
130	266	0.001848	1.003700	0.370	0.0074
140	284	0.002016	1.004036	0.404	0.0080
150	302	0.002182	1.004369	0.437	0.0087

NOTES:

[1] Linear thermal expansion data from the Thermophysical Properties Research Laboratory (TPRL) by Taylor (1987) for Type 304 Stainless Steel (Heat No. M7726).

[2] Volumetric correction factor is actually an effective piston area correction factor.

[3] Volumetric uncertainty based on a 2.0 percent uncertainty in the linear expansion data.

TABLE 3

THERMAL EXPANSION CHARACTERISTICS OF THE VACUUM PYCNOMETER

TEMPERATURE DEG C	DEG F	[1] THERMAL EXPANSION $\Delta L/L$	VOLUMETRIC CORRECTION FACTOR	VOLUMETRIC CORRECTION PERCENT	[2] VOLUMETRIC UNCERTAINTY PERCENT	[3] MEAN VOL THERM EXP COEFF
-60	-76	-.001166	0.996505	-.350	0.0175	24.27E-06
-50	-58	-.001027	0.996922	-.308	0.0154	24.43E-06
-40	-40	-.000886	0.997346	-.265	0.0133	24.58E-06
-30	-22	-.000742	0.997775	-.223	0.0111	24.72E-06
-20	-4	-.000597	0.998209	-.179	0.0090	24.87E-06
-10	14	-.000450	0.998649	-.135	0.0068	25.01E-06
0	32	-.000302	0.999094	-.091	0.0045	25.16E-06
10	50	-.000152	0.999545	-.046	0.0023	25.30E-06
20	68	0.000000	1.000000	0.000	0.0000	25.43E-06
30	86	0.000153	1.000460	0.046	0.0023	25.57E-06
40	104	0.000308	1.000925	0.093	0.0046	25.70E-06
50	122	0.000465	1.001395	0.139	0.0070	25.83E-06
60	140	0.000623	1.001869	0.187	0.0093	25.96E-06
70	158	0.000782	1.002348	0.235	0.0117	26.09E-06
80	176	0.000943	1.002831	0.283	0.0141	26.21E-06
90	194	0.001105	1.003318	0.332	0.0166	26.33E-06
100	212	0.001268	1.003809	0.381	0.0190	26.45E-06
110	230	0.001433	1.004305	0.430	0.0215	26.57E-06
120	248	0.001599	1.004804	0.480	0.0239	26.69E-06
130	266	0.001766	1.005306	0.531	0.0264	26.80E-06
140	284	0.001934	1.005813	0.581	0.0290	26.91E-06
150	302	0.002103	1.006323	0.632	0.0315	27.02E-06

NOTES:

[1] Linear thermal expansion data from Furman (1950) for type 316 Stainless Steel

[2] Volumetric uncertainty based on a 5.0 percent uncertainty in the linear expansion data.

[3] The mean volumetric thermal expansion coefficient, α_V, referenced to 20°C (68°F).

TABLE 4 FLOW-THRU CALIBRATOR (FTC) VOLUMETRIC CALIBRATION FOR THE TEST AND CALIBRATION SYSTEM (TACS)

DATE: 2/15/91

FLOW TECHNOLOGY INC (EG&G) CALIBRATOR MODEL NO: 0FT-250C300-8H
SERIAL NO: 0F8311002

NOM CAL VOL: 1 gallon X or 5 gallon ______

Barometric Press: 736.5 mm Hg

FTC PRESS: 53.6 psig   Operate Press: 40 PSIG   Return Press: 40 PSIG

TEMP, deg F		BOTTLE NUMBER	BOTTLE TARE WT grams	BOTTLE GROSS WT grams	FLUID NET WT grams	VOLUME [1] GALLON	DEVIATION FROM MEAN Percent
ROOM	FLUID						
75.191	75.768	1	1706.82	4521.75	2814.93	0.971262	+0.00800
75.767	75.782	2	1855.84	4670.66	2814.82	0.971231	+0.00486
75.680	75.787	3	1732.70	4547.37	2814.67	0.971182	-0.00020
75.507	75.777	4	1795.16	4607.74	2814.68	0.971146	-0.00039
75.680	75.782	5	1870.91	4685.57	2814.66	0.971176	-0.00083
75.896	75.796	6	1825.97	4640.59	2814.62	0.971170	-0.00148
75.992	75.810	7	1803.92	4618.38	2814.46	0.971122	-0.00640
					MEAN	0.971184	
				STANDARD DEVIATION (σ)			0.00495

[1] Volume is in US Gallons = 3.785412 Liters corrected for thermal expansion to 20°C (68°F)

TABLE 5 FLOW-THRU CALIBRATOR (FTC) VOLUMETRIC CALIBRATION FOR THE TEST AND CALIBRATION SYSTEM (TACS)

DATE: 2/19/91

FLOW TECHNOLOGY INC (EG&G) CALIBRATOR MODEL NO: 0FT-250C300-8H
SERIAL NO: 0F8311002

NOM CAL VOL: 1 gallon ________ or 5 gallon X
Barometric Press: 760.5 mm Hg
Operate Press: 40 PSIG
Return Press: 40 PSIG

RUN NO:	BAR PRESS mm Hg	FTC PRESS psig	MEAN TEMP, deg F ROOM	FLUID	FLUID NET WT grams	FLUID DEN kg/m^3 [2]	VOLUME [1] Gallon	DEVIATION FROM MEAN Percent
1	763.0	53.0	75.863	75.733	14208.61	766.585	4.902676	-0.00103
2	762.0	53.0	76.915	75.655	14208.54	766.574	4.902710	-0.00032
3	760.5	54.0	75.438	75.651	14208.77	766.574	4.902793	+0.00135
						MEAN	4.902726	
						Standard Deviation (σ)		0.00122

RUN NO:	FTC PRESS psig	FLUID TEMP °F	VACUUM PYCNOMETER MEASUREMENT SUMMARY TARE WT grams	GROSS WT grams	NET WT grams	FLUID DEN kg/m^3
1	53.0	75.796	2379.08	3126.93	747.85	766.560
2	54.0	75.685	2379.08	3126.93	747.85	766.561
3	56.0	75.685	2379.08	3126.93	747.85	766.560

[1] Volume is in US Gallons = 3.7854 liters corrected for thermal expansion to 20°C (68°F)
[2] Fluid density is corrected 12 for FTC fluid temperature = 0.419 $(kg/m^3)/°F$

TABLE 6

REPEATABILITY TESTS OF
FLOW-THRU CALIBRATOR (FTC) WITH CALIBRATION FLUID [1]
AND TWO PHYSICALLY IDENTICAL TURBINE FLOWMETERS (25.4 mm ANC-16) [2]
AT ROOM TEMPERATURE

				REPEATABILITY, PERCENT					
NUMBER TEST RUNS	MEAN TEMP °C(°F)	NOMINAL [3] CALIBRATOR VOL, $10^{-3}m^3$ (gal)	[4] FLOWRATE $10^{-3}m^3/s$(gpm)	TFM 1 VS FTC R_{1C}	TFM 2 VS FTC R_{2C}	TFM 1 VS TFM 2 R_{12}	FLOW-THRU CALIBRATOR R_C	TFM 1 R_1	TFM 2 R_2
4	23 (74)	3.785 (1)	0.0782 (1.24)	0.0654	0.0794	0.0138	0.0510	0.0410	0.0610
4	23 (74)	3.785 (1)	0.1300 (2.06)	0.0159	0.0138	0.0036	0.0104	0.0120	0.0091
4	23 (74)	3.785 (1)	0.2839 (4.5)	0.0013	0.0400	0.0386	0.0050	0.0013	0.039
6	23 (74)	3.785 (1)	0.3344 (5.3)	0.0108	0.0083	0.0039	0.0066	0.0086	0.0052
6	23 (75)	18.927 (5)	0.3028 (4.8)	0.0032	0.0035	0.0022	0.0021	0.0024	0.0028
4	24 (75)	18.927 (5)	0.3470 (5.5)	0.0032	0.0020	0.0016	0.0017	0.0027	0.0010
10	24 (76)	18.927 (5)	0.5994 (9.5)	0.0066	0.0075	0.0010	0.0050	0.0044	0.0056
10	23 (74)	18.927 (5)	1.236 (19.6)	0.0023	0.0021	0.0016	0.0013	0.0019	0.0016
9	23 (74)	18.927 (5)	3.110 (49.3)	0.0023	0.0022	0.0017	0.0014	0.0019	0.0017

NOTES:

[1] MIL-C-7024 Type II

[2] 2.54 mm = 1.0 inch tubing size

[3] $3.7854 \times 10^{-3}m^3$ = 1.0 US gallons
$18.927 \times 10^{-3}n^3$ = 5.0 US gallons
$10^{-3}m^3$ = One liter

[4] (gpm) = (US gallons/minute)
0.06309 liters/s = 1.0 gpm

TABLE 7

REPEATABILITY TESTS OF
FLOW-THRU CALIBRATOR (FTC) WITH CALIBRATION FLUID [1]
AND TWO PHYSICALLY IDENTICAL TURBINE FLOWMETERS (25.4 mm ANC-16) [2]
AT -4°C (+30°F)

				REPEATABILITY, PERCENT					
NUMBER TEST RUNS	MEAN TEMP °C(°F)	NOMINAL [3] CALIBRATOR VOL, $10^{-3}m^3$ (gal)	[4] FLOWRATE $10^{-3}m^3/s$(gpm)	TFM 1 VS FTC R_{1C}	TFM 2 VS FTC R_{2C}	TFM 1 VS TFM 2 R_{12}	FLOW-THRU CALIBRATOR R_C	TFM 1 R_1	TFM 2 R_2
10	-1 (30)	3.785 (1.0)	0.0631 (1.0)	0.0083	0.1305	0.1368	0.0083 [5]	-	-
10	-1 (30)	3.785 (1.0)	0.1325 (2.1)	0.0097	0.0092	0.0035	0.0064	0.0072	0.0065
10	-1 (30)	3.785 (1.0)	0.3407 (5.4)	0.0036	0.0057	0.0047	0.0024	0.0026	0.0024
10	-1 (30)	18.927 (5.0)	0.3596 (5.7)	0.0340	0.0060	0.0039	0.0028	0.0019	0.0053
10	-1 (30)	18.927 (5.0)	0.6877 (10.9)	0.0026	0.0083	0.0077	0.0020	0.0016	0.0080
10	-1 (30)	18.927 (5.0)	1.255 (19.9)	0.0019	0.0023	0.0019	0.0012	0.0015	0.0020
10	-1 (30)	18.927 (5.0)	3.218 (51.0)	0.0017	0.0022	0.0018	0.0010	0.0013	0.0019

NOTES:

[1] MIL-C-7024 Type II

[2] 2.54 mm = 1.0 inch tubing size

[3] $3.7854 \times 10^{-3}m^3$ = 1.0 US gallons
$18.927 \times 10^{-3}m^3$ = 5.0 US gallons
$10^{-3}m^3$ = One liter

[4] (gpm) = (US gallons/minute)
0.06309 liters/s = 1.0 gpm

[5] $R_C = R_{1C}$ due to a high value of R_{12}

TABLE 8

REPEATABILITY TESTS OF
FLOW-THRU CALIBRATOR (FTC) WITH CALIBRATION FLUID [1]
AND TWO PHYSICALLY IDENTICAL TURBINE FLOWMETERS (25.4 mm ANC-16) [2]
AT + 60°C (+140°F)

				REPEATABILITY, PERCENT					
NUMBER TEST RUNS	MEAN TEMP °C(°F)	NOMINAL [3] CALIBRATOR VOL, $10^{-3}m^3$ (gal)	[4] FLOWRATE $10^{-3}m^3/s$(gpm)	TFM 1 VS FTC R_{1C}	TFM 2 VS FTC R_{2C}	TFM 1 VS TFM 2 R_{12}	FLOW-THRU CALIBRATOR R_C	TFM 1 R_1	TFM 2 R_2
3	60 (141)	3.785 (1)	0.1110 (1.76)	0.0042	0.0026	0.0085	0.0034 [5]	-	-
6	61 (142)	3.785 (1)	0.1628 (2.58)	0.0222	0.0182	0.0099	0.0135	0.0176	0.0123
10	57 (135)	3.785 (1)	0.2915 (4.62)	0.0265	0.0291	0.0062	0.0194	0.0180	0.022
6	61 (142)	18.927 (5)	0.3100 (4.91)	0.0321	0.0515	0.0159	0.0293	0.0132	0.0159
10	60 (141)	18.927 (5)	0.6498 (10.3)	0.0113	0.0110	0.0187	0.0112 [5]	-	-
10	60 (140)	18.927 (5)	1.287 (20.4)	0.0018	0.0015	0.0029	0.0016 [5]	-	-
10	60 (140)	18.927 (5)	3.155 (50.0)	0.0015	0.0016	0.0021	0.0004	0.0015	0.0016

NOTES:

[1] MIL-C-7024 Type II

[2] 2.54 mm = 1.0 inch tubing size

[3] $3.7854 \times 10^{-3}m^3$ = 1.0 US gallons
$18.927 \times 10^{-3}m^3$ = 5.0 US gallons
$10^{-3}m^3$ = One liter

[4] (gpm) = (US gallons/minute)
0.06309 liters/s = 1.0 gpm

[5] $R_C = (R_{1C} + R_{2C})/2$
since Equation (10)
could not be solved

TABLE 9

PROVISIONAL ACCURACY STATEMENT FOR THE TEST AND CALIBRATION SYSTEM (TACS)
FOR MASS RATE OF FLOW MEASUREMENT AT 0.24 kg/s (1925 $lb_m hr$) OR 0.315 LITERS/SEC(5.0 gpm)

DESCRIPTION OF ERROR SOURCE	UNCERTAINTY, PERCENT					
	-55°C -67°F)	0°C (+32°F)	+20°C (+68°F)	+60°C (140°F)	+100°C (+212°F)	+130°C (+266°F)
1. FTC VOLUME (20°C) [1]	0.0012	0.0012	0.0012	0.0012	0.0012	0.0012
2. FTC PISTON AREA [2]	0.0045	0.0013	0	0.0026	0.0054	0.0074
3. PYC VOLUME (20°C)	0.0200	0.0200	0.0200	0.0200	0.0200	0.0200
4. PYC VOLUME [4]	0.0165	0.0045	0	0.0093	0.0190	0.0264
5. TEMPERATURE [5]	0.0032	0.0032	0.0041	0.0062	0.0082	0.0090
6. POSITION ERROR (5.0 GAL) [6]	0.0023	0.0023	0.0023	0.0023	0.0023	0.0023
7. TIMING ERROR [7]	0.0002	0.0002	0.0002	0.0002	0.0002	0.0002
8. FTC REPEATABILITY	0.0100(EST)	0.0028	0.0021	0.0293	0.03 (EST)	0.040(EST)
9. STANDARD DEVIATION, σ [9]	0.0285	0.0211	0.0207	0.0374	0.0420	0.0533
10. ACCURACY (2σ, 95 PERCENT CONFIDENCE)	0.0570	0.0422	0.0414	0.0748	0.0840	0.1066

NOTES:

[1] Repeatability of 5 Gallon Volumetric Calibration at Room Temperature.
[2] Uncertainty Due to 2.0 Percent Uncertainty In Expansion of Cylinder Of FTC.
[4] Uncertainty Due to 5.0 Percent Uncertainty In Thermal Expansion of Type 316 Stainless Steel.
[5] Uncertainty In Fluid Density Due to Uncertainty in Temperature (Two Locations).
[6] Start and End Piston Position Error 0.015 mm For 66.4 cm Stroke (0.0006 in. for 26.14 in.).
[7] Start and End Piston Timing Error: 0.0001 Sec For A 60 Sec Run Time (1925 lb_m/hr).
[9] Square Root of Sum of The Squares (Items 1-8).

TABLE 10

PROVISIONAL ACCURACY STATEMENT FOR THE TEST AND CALIBRATION SYSTEM (TACS)
FOR MASS RATE OF FLOW MEASUREMENT AT kg/s 2.43 (19250 lb_m/hr) OR 3.15 LITERS/SEC(50 gpm)

DESCRIPTION OF ERROR SOURCE	UNCERTAINTY, PERCENT					
	-55°C (-67°F)	0°C (+32°F)	+20°C (+68°F)	+60°C (140°F)	+100°C (+212°F)	+130°C (+266°F)
1. FTC VOLUME (20°C) [1]	0.0012	0.0012	0.0012	0.0012	0.0012	0.0012
2. FTC PISTON AREA [2]	0.0045	0.0013	0	0.0026	0.0054	0.0074
3. PYC VOLUME (20°C)	0.0200	0.0200	0.0200	0.0200	0.0200	0.0200
4. PYC VOLUME [4]	0.0165	0.0045	0	0.0093	0.0190	0.0264
5. TEMPERATURE [5]	0.0032	0.0032	0.0041	0.0062	0.0082	0.0090
6. POSITION ERROR (5.0 GAL) [6]	0.0023	0.0023	0.0023	0.0023	0.0023	0.0023
7. TIMING ERROR [7]	0.0002	0.0002	0.0002	0.0002	0.0002	0.0002
8. FTC REPEATABILITY	0.020 (EST)	0.0010	0.0014	0.0004	0.020 (EST)	0.030(EST)
9. STANDARD DEVIATION, σ [9]	0.0333	0.0210	0.0249	0.0232	0.0355	0.0463
10. ACCURACY (2σ, 95 PERCENT CONFIDENCE)	0.0666	0.0420	0.0497	0.0464	0.0710	0.0925

NOTES:

[1] Repeatability of 5 Gallon Volumetric Calibration at Room Temperature.
[2] Uncertainty Due to 2.0 Percent Uncertainty In Expansion of Cylinder Of FTC.
[4] Uncertainty Due to 5.0 Percent Uncertainty In Thermal Expansion of Type 316 Stainless Steel.
[5] Uncertainty In Fluid Density Due to Uncertainty in Temperature (Two Locations).
[6] Start and End Piston Position Error 0.015 mm For 66.4 cm Stroke (0.0006 in. for 26.14 in.).
[7] Start and End Piston Timing Error: 0.0001 Sec For A 6 Sec Run Time (19250 lb_m/hr).
[9] Square Root of Sum of The Squares (Items 1-8).

TABLE 11 TEST AND CALIBRATION SYSTEM (TACS)
DUAL TURBINE FLOWMETER CALIBRATION TESTS
AT ROOM TEMPERATURE

OPERATING CONDITIONS

RUN NO.	FLW RATE GAL/MIN	_MEAN TEMP,DEG F_ _FLUID_	OPT SWITCH	VISCOSITY CSTK	FTC VOL GAL	FREQ RATIO
1	0.6410	74.609	76.687	1.189	0.97127	2.836374
2	1.8706	74.609	76.687	1.189	0.97127	2.774851
3	2.9739	74.619	76.692	1.189	0.97127	2.753517
4	4.0089	74.655	76.715	1.189	0.97128	2.740406
5	5.2379	74.573	76.637	1.190	4.90321	2.735545
6	6.1159	74.508	76.495	1.190	4.90320	2.731602
7	8.3926	74.168	76.481	1.193	4.90317	2.728007
8	10.6373	73.851	76.481	1.196	4.90314	2.731394
9	12.5813	74.232	76.500	1.193	4.90318	2.735515
10	15.5819	74.269	76.509	1.192	4.90318	2.740907
11	20.6803	74.444	76.509	1.191	4.90319	2.748145
12	25.6144	74.573	76.509	1.190	4.90321	2.753526
13	31.1723	74.476	76.504	1.190	4.90320	2.758249
14	40.0522	74.614	76.468	1.189	4.90321	2.764530
15	50.2529	75.037	76.367	1.185	4.90325	2.768817
16	63.7450	75.239	76.307	1.183	4.90326	2.773301

TABLE 12 TEST AND CALIBRATION SYSTEM (TACS)
DUAL TURBINE FLOWMETER CALIBRATION TESTS
AT ROOM TEMPERATURE

MAIN TURBINE CHARACTERISTICS

RUN NO.	FLW RATE GAL/MIN	FREQ HZ	FREQ/VIS HZ/CSTK	K-FACTOR PULSE/GAL
1	0.6410	16.6345	13.988	1556.993
2	1.8706	48.9917	41.198	1571.396
3	2.9739	77.3460	65.046	1560.514
4	4.0089	103.9759	87.466	1556.157
5	5.2379	135.5838	113.982	1553.096
6	6.1159	158.0652	132.816	1550.696
7	8.3926	216.5362	181.470	1548.048
8	10.6373	274.4827	229.469	1548.232
9	12.5813	324.8950	272.416	1549.421
10	15.5819	402.8655	337.888	1551.278
11	20.6803	535.4315	449.679	1553.451
12	25.6144	663.7446	557.996	1554.777
13	31.1723	808.0770	678.827	1555.373
14	40.0522	1038.5668	873.379	1555.818
15	50.2529	1303.0184	1099.342	1555.755
16	63.7450	1652.7636	1396.588	1555.665

TABLE 13 TEST AND CALIBRATION SYSTEM (TACS)
DUAL TURBINE FLOWMETER CALIBRATION TESTS
AT ROOM TEMPERATURE

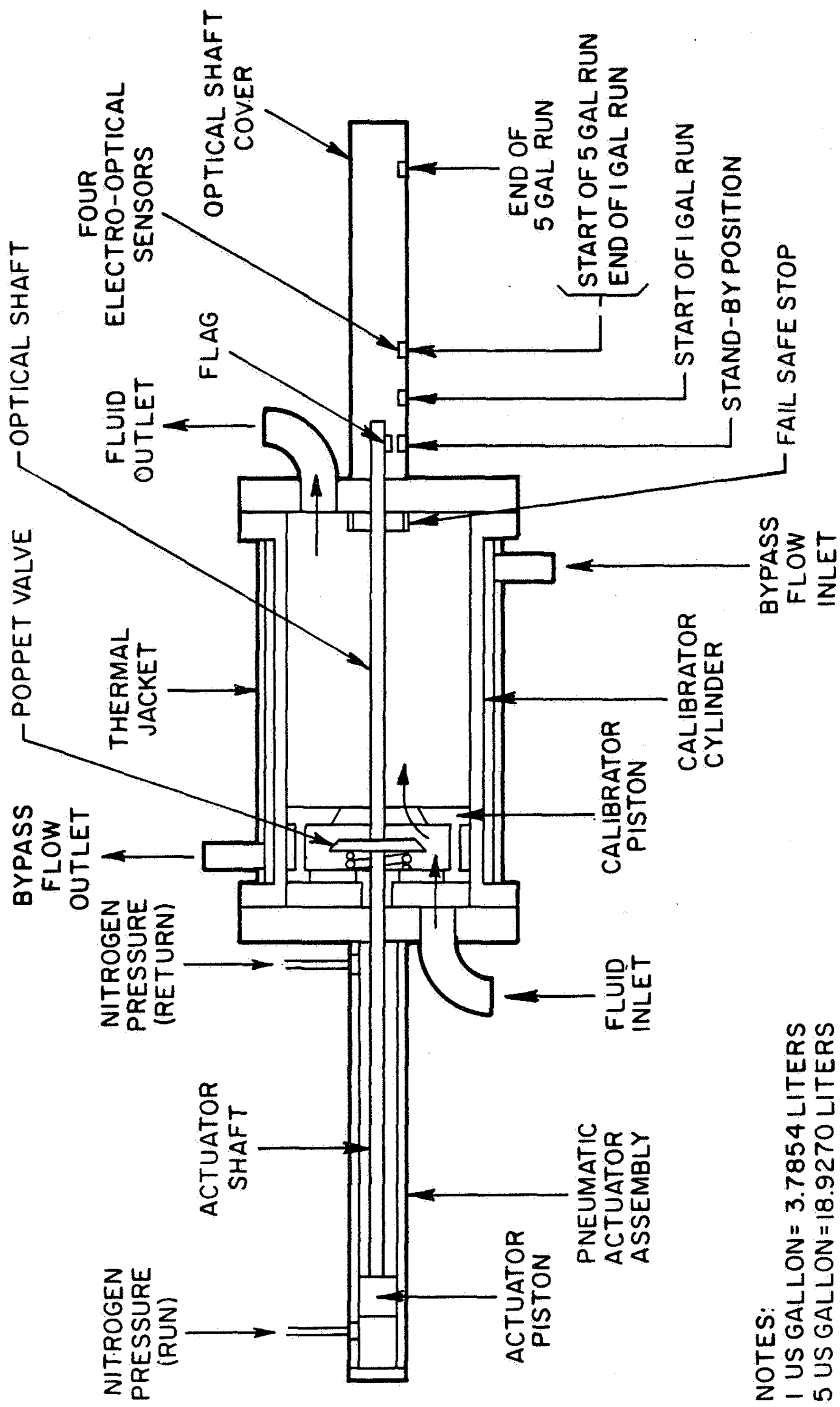
SENSOR TURBINE CHARACTERISTICS

RUN NO.	FLW RATE GAL/MIN	FREQ HZ	FREQ/VIS HZ/CSTK	K-FACTOR PULSE/GAL
1	0.6410	5.8647	4.932	548.932
2	1.8707	17.6556	14.847	566.294
3	2.9739	28.0899	23.623	566.729
4	4.0090	37.9418	31.917	567.851
5	5.2380	49.5637	41.667	567.741
6	6.1160	57.8654	48.622	567.682
7	8.3927	79.3752	66.521	567.459
8	10.6374	100.4918	84.012	566.823
9	12.5814	118.7692	99.585	566.403
10	15.5821	146.9826	123.276	565.967
11	20.6805	194.8338	163.630	565.267
12	25.6147	241.0526	202.648	564.644
13	31.1727	292.9674	246.108	563.893
14	40.0527	375.6757	315.923	562.772
15	50.2534	470.6047	397.044	561.878
16	63.7450	595.9553	503.583	560.943

TABLE 14 TEST AND CALIBRATION SYSTEM (TACS)
DUAL TURBINE FLOWMETER CALIBRATION TESTS
AT ROOM TEMPERATURE

COMBINED MAIN AND SENSOR TURBINE CHARACTERISTICS

RUN NO.	FLW RATE GAL/MIN	FREQ HZ	FREQ/VIS HZ/CSTK	K-FACTOR PULSE/GAL
1	0.6410	22.4992	18.920	2105.926
2	1.8706	66.6473	56.045	2137.689
3	2.9739	105.4359	88.669	2127.243
4	4.0089	141.9177	119.383	2124.008
5	5.2379	185.1475	155.649	2120.837
6	6.1159	215.9305	181.438	2118.378
7	8.3926	295.9114	247.991	2115.507
8	10.6373	374.9745	313.481	2115.055
9	12.5813	443.6642	372.001	2115.824
10	15.5819	549.8481	461.165	2117.245
11	20.6803	730.2653	613.309	2118.718
12	25.6144	904.7971	760.643	2119.421
13	31.1723	1101.0444	924.935	2119.265
14	40.0522	1414.2425	1189.302	2118.590
15	50.2529	1773.6231	1496.386	2117.633
16	63.7450	2248.7189	1900.172	2116.608



NOTES:
1 US GALLON = 3.7854 LITERS
5 US GALLON = 18.9270 LITERS

FIGURE 1. CROSS-SECTIONAL VIEW OF FLOW-THRU CALIBRATOR.

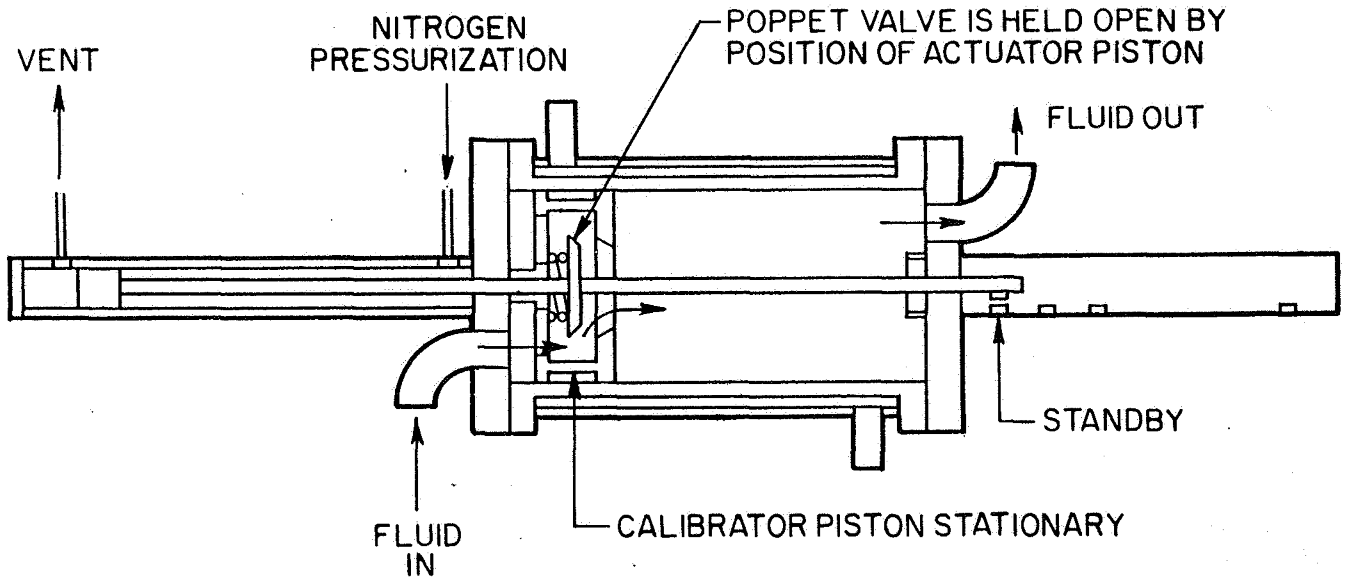


FIGURE 2. FLOW–THRU CALIBRATOR–STANDBY MODE

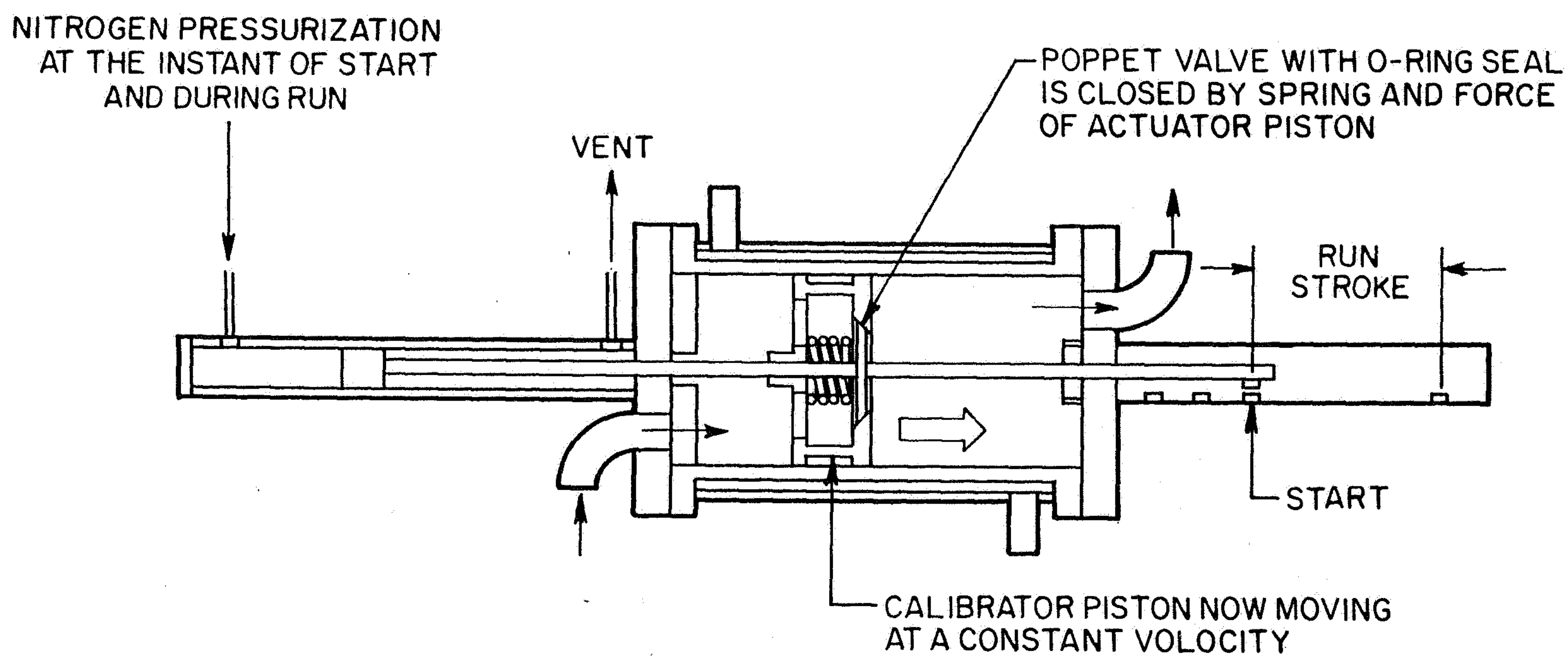


FIGURE 3. FLOW–THRU CALIBRATOR–START OF RUN

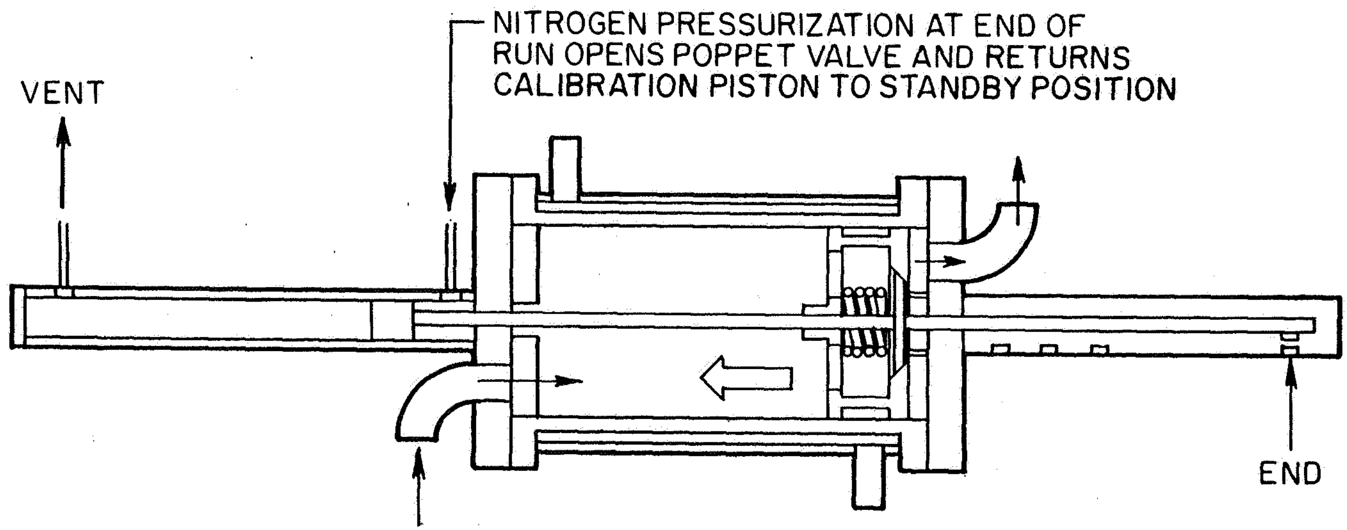


FIGURE 4. FLOW–THRU CALIBRATOR–END OF RUN

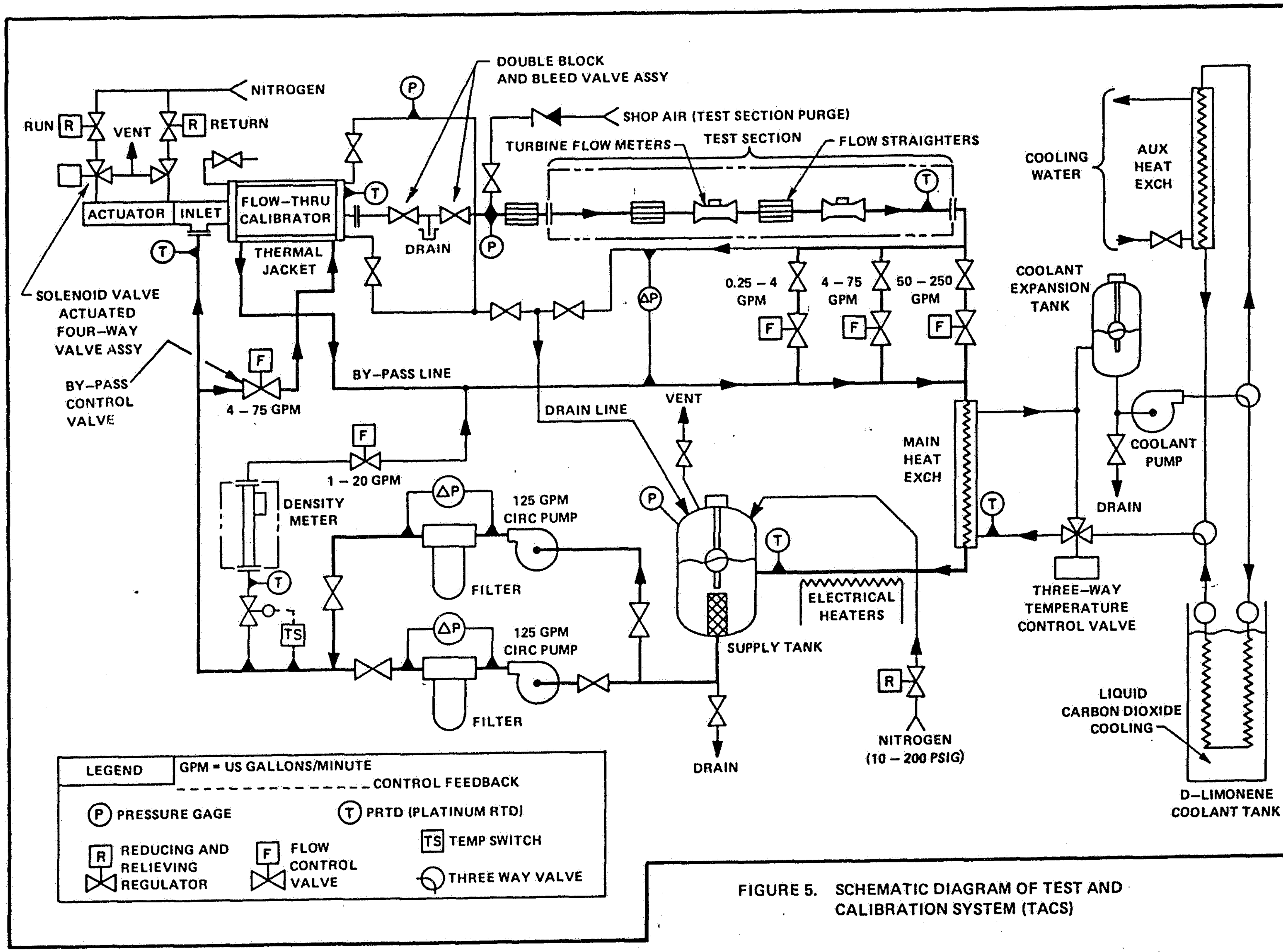


FIGURE 5. SCHEMATIC DIAGRAM OF TEST AND CALIBRATION SYSTEM (TACS)

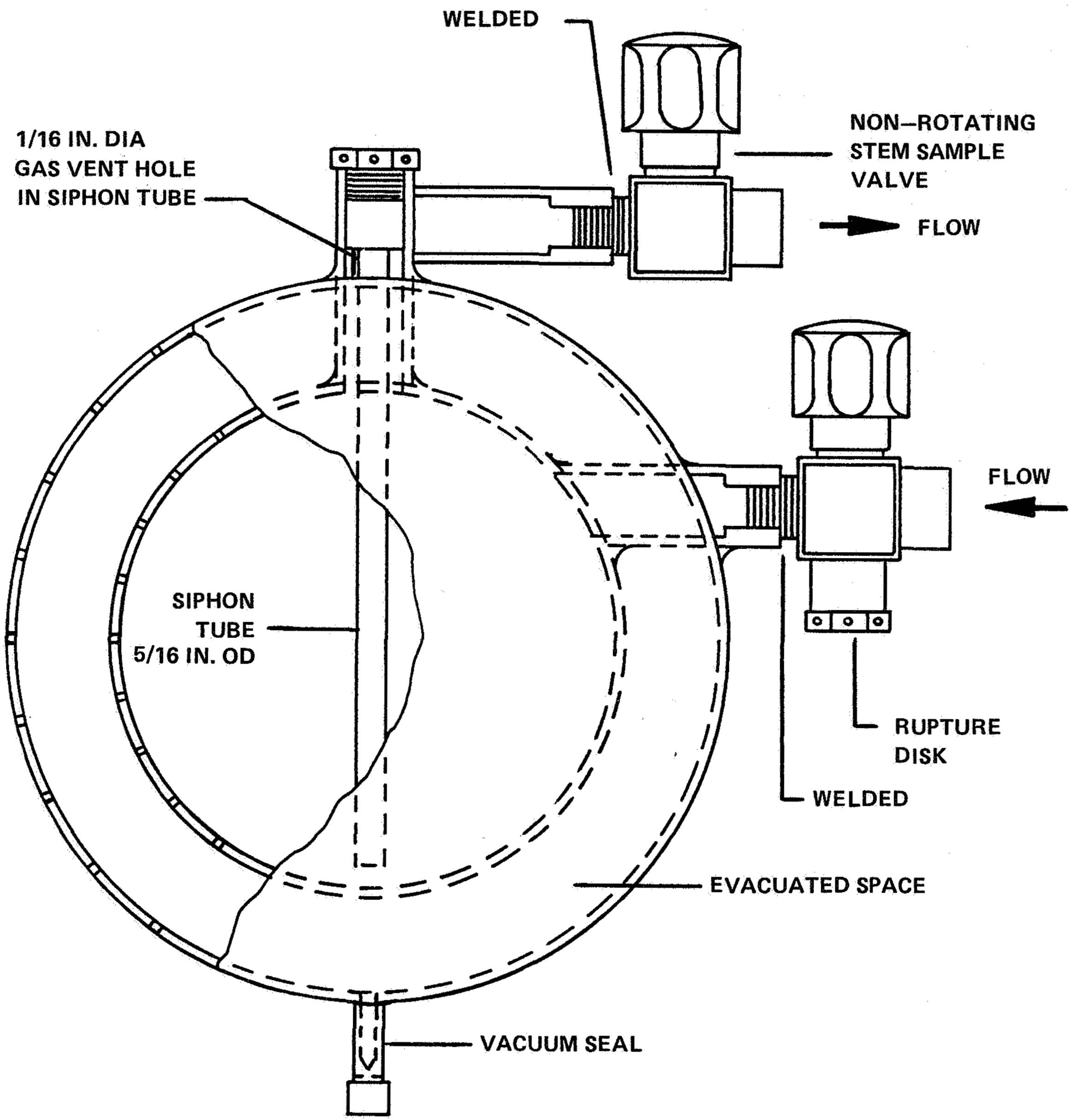


FIGURE 6. CROSS–SECTIONAL DRAWING OF A VACUUM PYCNOMETER

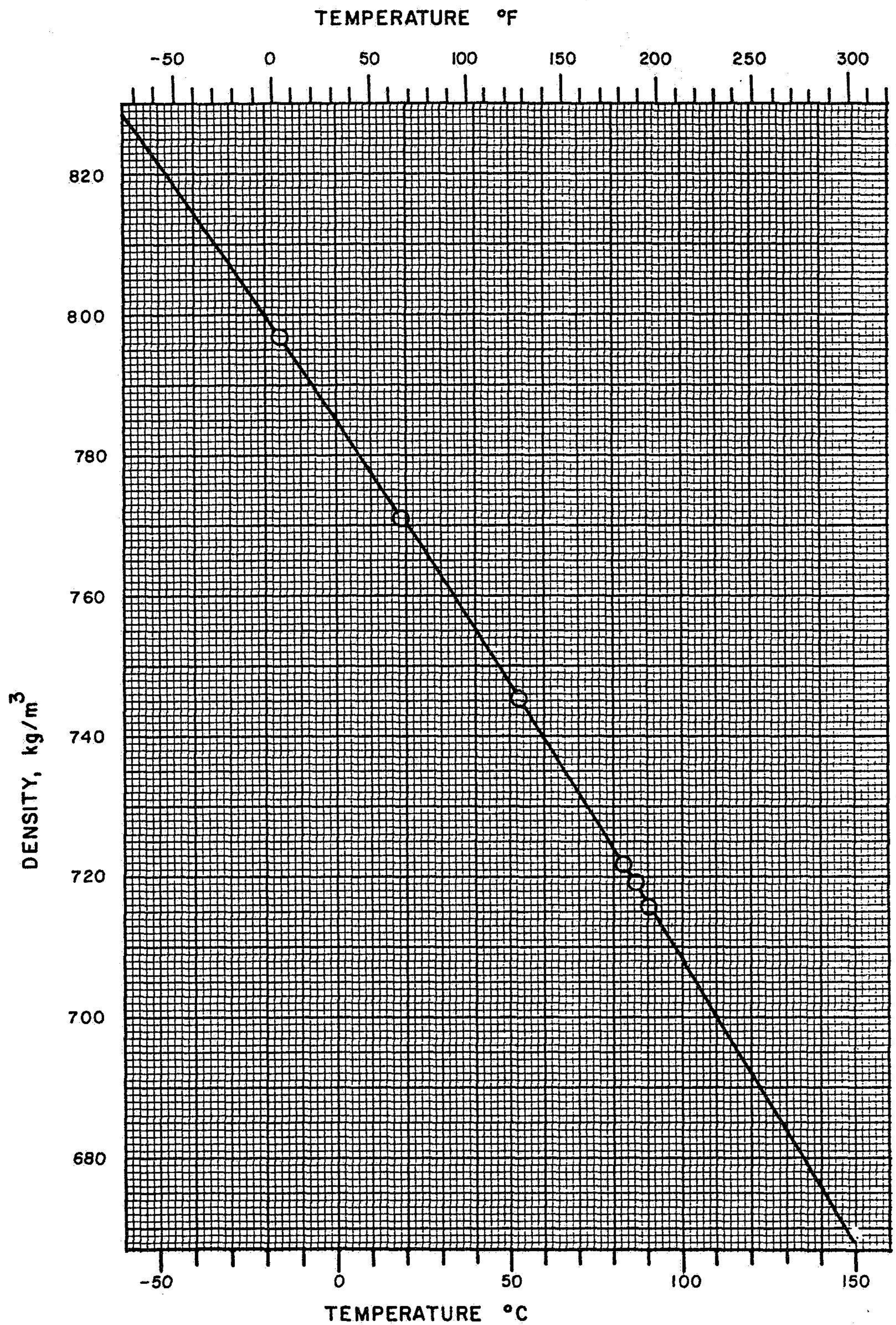


FIGURE 7. TYPICAL DENSITY VERSUS TEMPERATURE CHARACTERISTICS FOR MIL–C–7024 (II) CALIBRATION FLUID

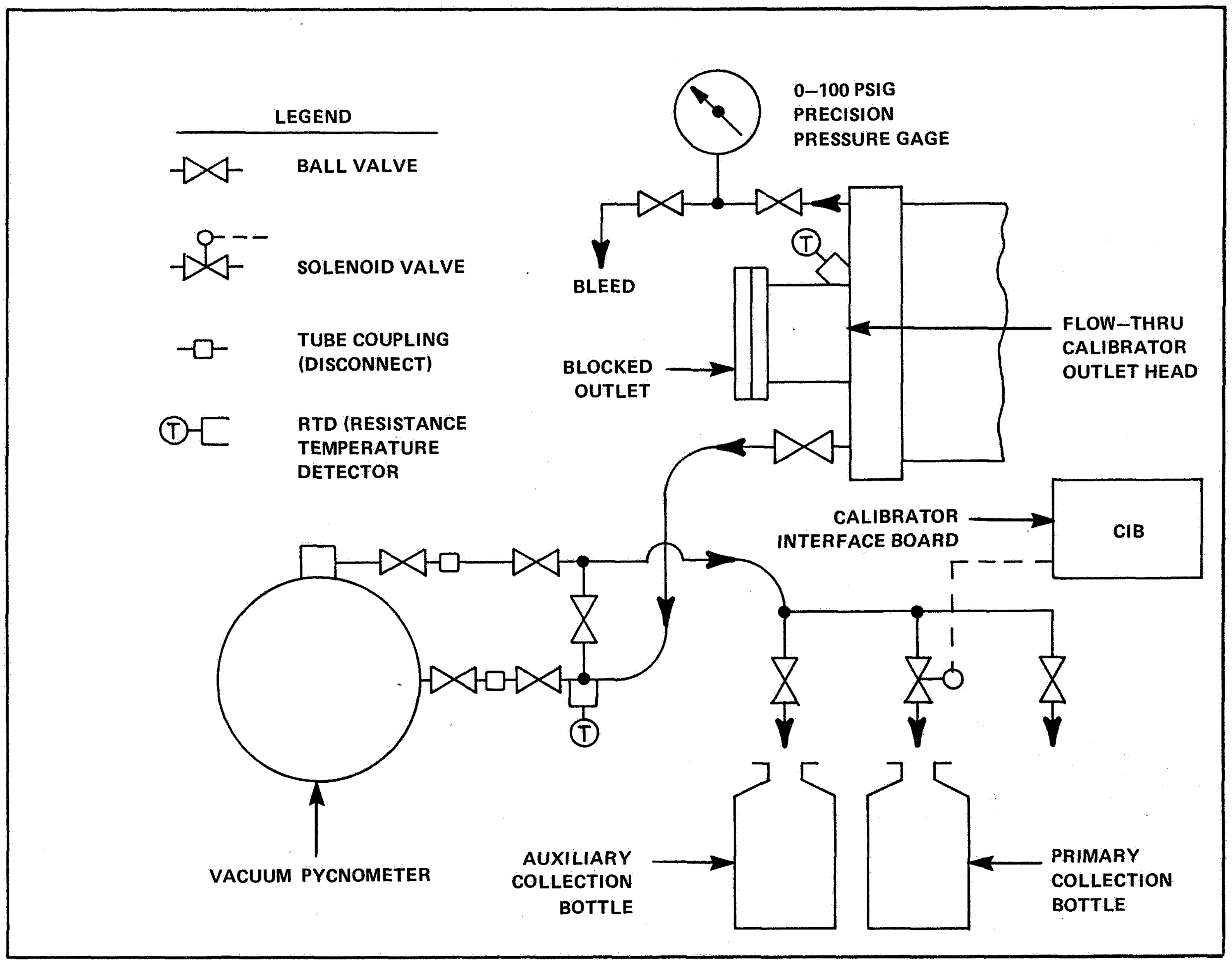


FIGURE 8. SCHEMATIC DIAGRAM OF THE PIPING SETUP FOR THE VOLUMETRIC CALIBRATION OF THE FLOW–THRU CALIBRATOR

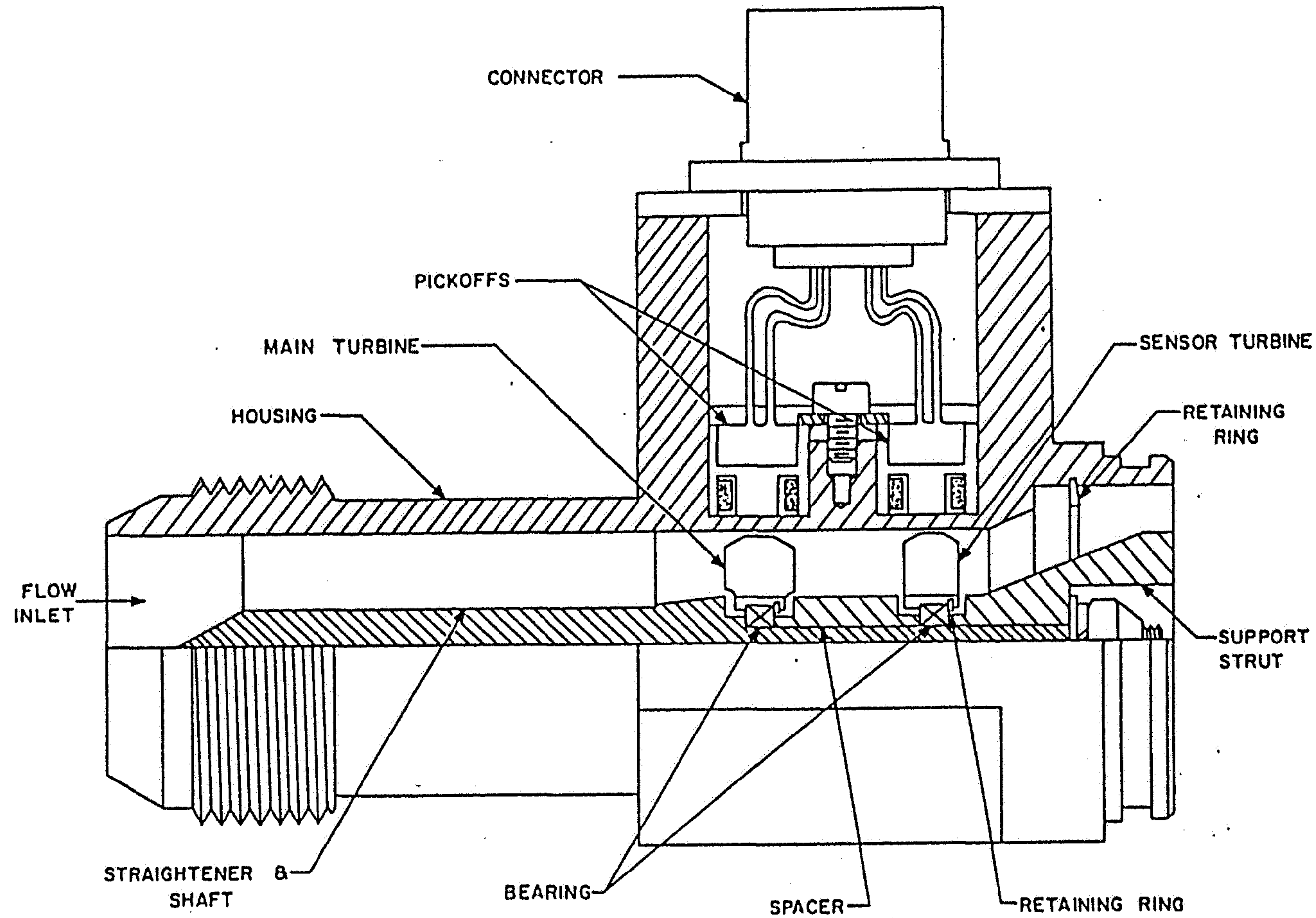


FIGURE 9. CROSS–SECTIONAL DRAWING OF THE DUAL–TURBINE FLOWMETER

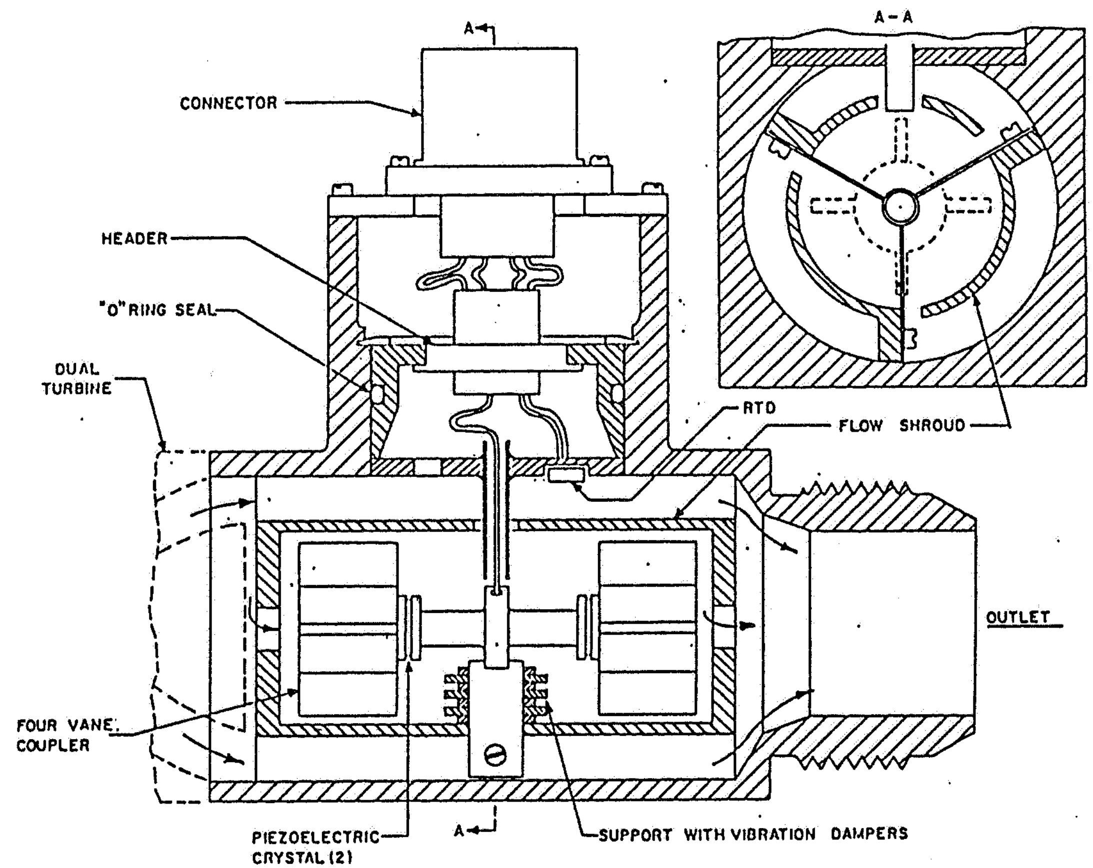


FIGURE 10. CROSS–SECTIONAL DRAWING OF THE DENSI–VISCOMETER FOR THE DUAL–TURBINE FLOWMETER

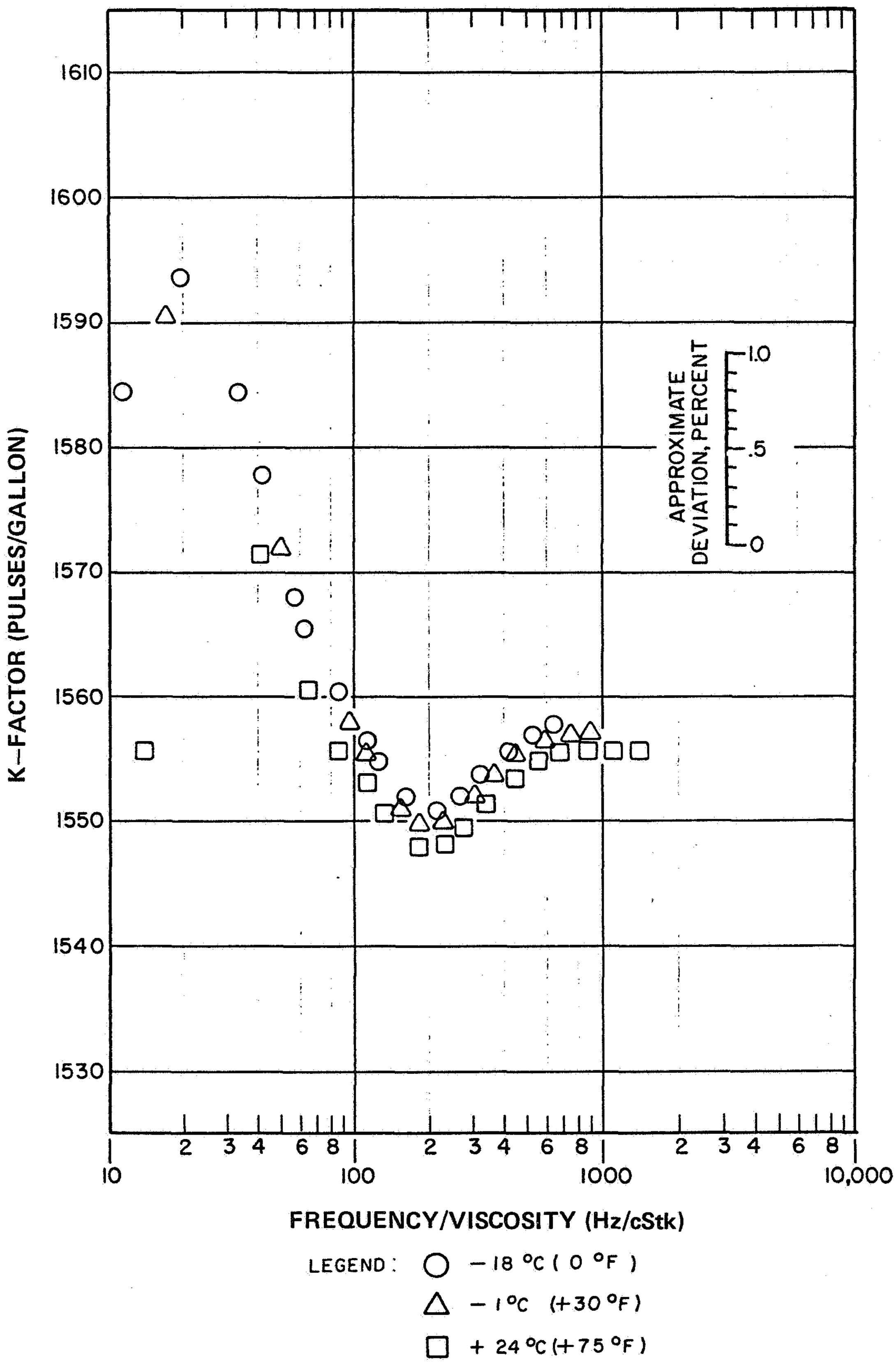
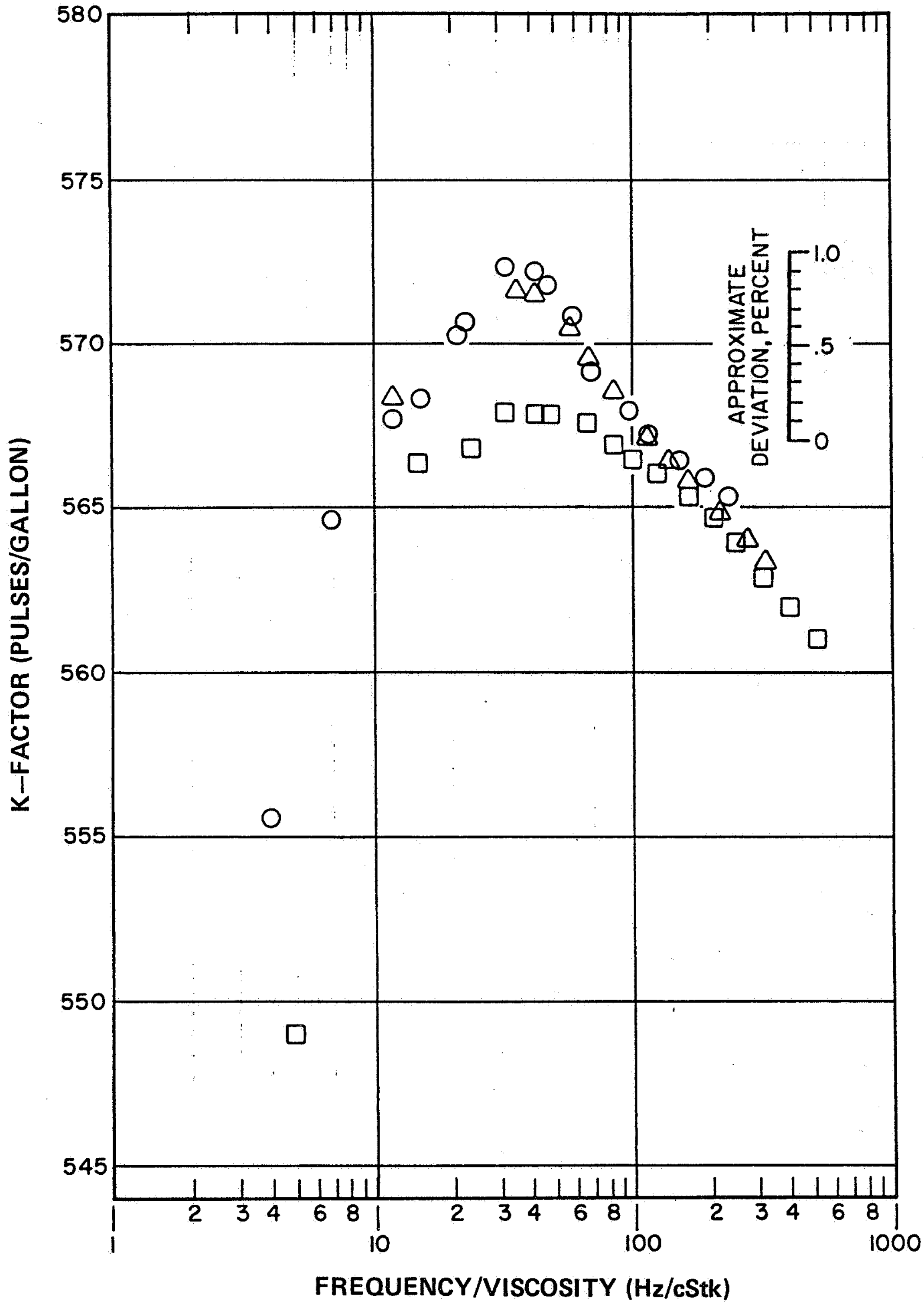


FIGURE 11. CALIBRATION CHARACTERISTICS OF THE MAIN TURBINE OF THE DUAL–TURBINE FLOWMETER



LEGEND: ○ – 18 °C (0 °F)
△ – 1 °C (+30 °F)
□ + 24 °C (+75 °F)

FIGURE 12. CALIBRATION CHARACTERISTICS OF THE SENSOR TURBINE OF THE DUAL–TURBINE FLOWMETER

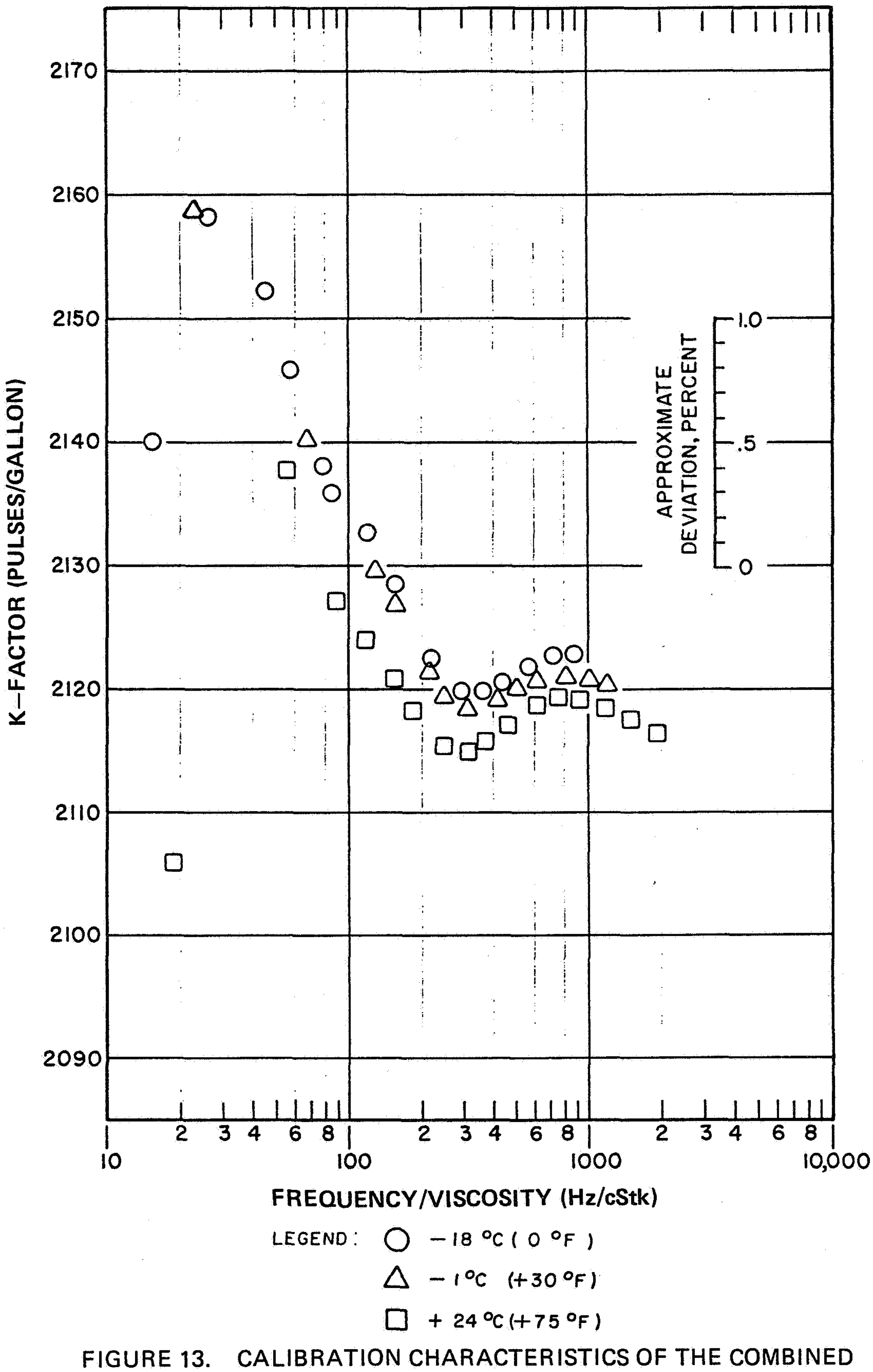


FIGURE 13. CALIBRATION CHARACTERISTICS OF THE COMBINED MAIN AND SENSOR TURBINES OF THE DUAL–TURBINE FLOWMETER

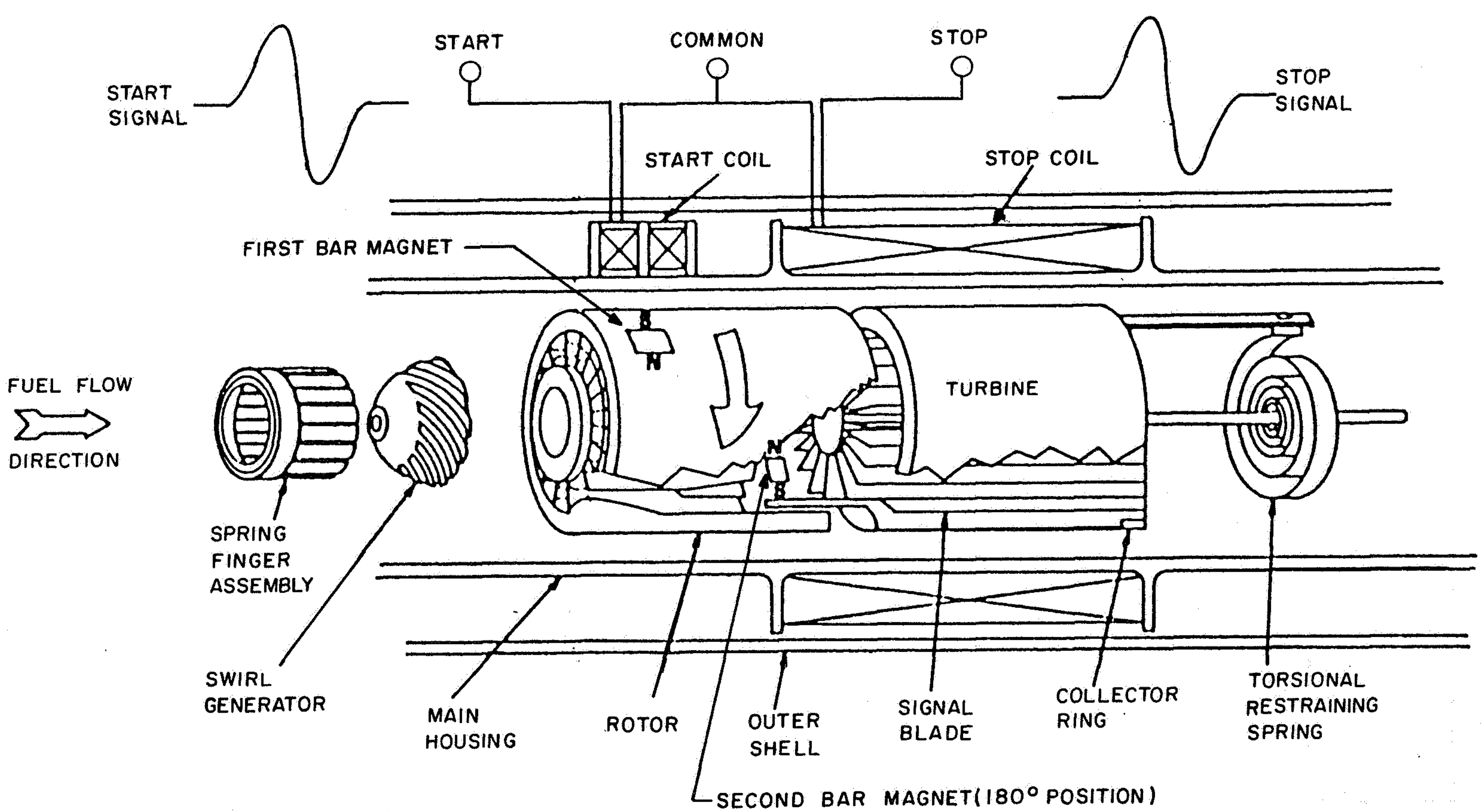


FIGURE 14. ANGULAR MOMENTUM FLOWMETER WITH FLUID DRIVE

NOTE: PARTS UPSTREAM OF ROTOR AND DOWNSTREAM OF TURBINE ARE SHOWN AS EXPLODED ASSEMBLIES

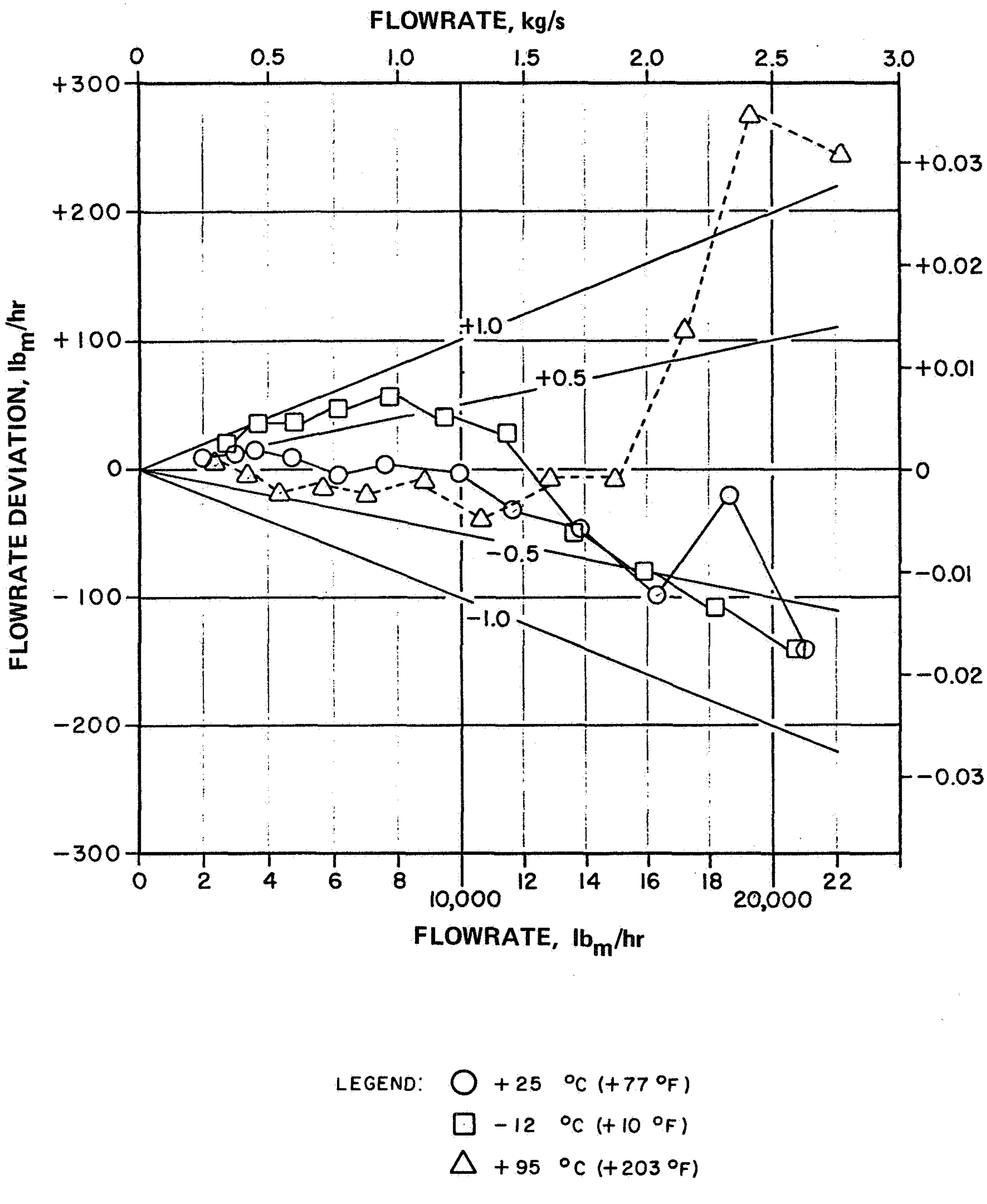


FIGURE 15. CALIBRATION CHARACTERISTICS OF AN ANGULAR MOMENTUM FLOWMETER (NOTE: RADIAL LINES FROM ORIGIN SHOW PERCENT DEVIATION FROM ACTUAL FLOWRATE

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