X-734-67-440

NASA TM X-55967

PRECISION FLOW MEASUREMENT TECHNIQUES FOR LOW THRUST AUXILIARY PROPULSION LIQUID ROCKETS

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AUGUST 1967

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Abstract

This paper is specifically concerned with the techniques required to obtain better precision in the measurement of fuel consumption of small thrusters (monopropellant and bipropellant **0.5** to **5.0** lbf thrust engines) using commercially available impeller wheel meters for steady flow, and an in-house developed photometric device for pulsed flow. By proper use of these devices, propellant flow consumption data accuracies of better than **1%** can be achieved. Flow measurement requirements are considered for both steady and pulsed firing modes, for specific impulses of **150** to **350** lbf-seconds per lbm, and O/F ratios from **1** to **2.**

Frequency standards are used to correlate test stand data with laboratory calibrations of impeller flowmeters. Fluid dynamic simulation is obtained by selecting inert fluids whose kinematic viscosities are approximately those of the propellants. Anomolous behavior demonstrated during calibrations indicate that normal turbine meter frequency-viscosity characterizations are not applicable to impeller wheel units. The design, development, and preliminary testing of a photometric device for pulsed mode flow measurements is discussed. Its accuracy is dependent upon fluid meniscus displacement and can provide **99.7%** probable range accuracy of **-0.423 ± 3 (.999)%** for a displacement of **0.15** inch and **+ .003 ± 3 (.115)%** for a **1.75** inch displacement. The initial models are applicable to a thrust range of **1/2** to **25** lbf. Greater accuracy is feasible with commercially available components of higher precision.

I. Introduction

Spacecraft reaction control systems are selected in the initial planning and preliminary study stages of a program on the basis of mission study tradeoffs of competing systems. Systems considered are those that have performed successfully in previous flights or those for which there is adequate reliable performance data. Data acquisition is not readily accomplished with standard instrumentation and techniques; therefore, an important aspect in the R&D of these systems is to develop the means by which their performances can be assessed in both the steady and pulsed modes of operation. Thrust and propellant consumption measurements are basic to defining engine performance. Accurate steady state measurements are quite difficult to make and the accurate measurement of transient performance is even more difficult because of the low sensitivity of high frequency systems and the low level signals associated with small thrusters.

This paper will deal exclusively with the methods that have evolved for the precise measurement of

a. propellant flow rate using commercial flowmeters for steady state performance data, and

b. propellant consumption using instrumentation developed for pulsed mode operation of ACS thrusters.

The parameter ranges considered include thrust **- 0.5** to **5.0** lbf, specific impulse **- 150** to **350** lbf-seconds per lbm, and O/F ratio from **1** to **2.** Applications of these techniques for lower thrust levels are also indicated.

II. Instrumentation Requirements

Propellant consumption can be obtained for the steady state mode by measuring either volumetric or gravimetric flow rate. Flow rate measurements for the pulsed mode introduce complications because they must be integrated to obtain propellant consumption on a "per pulse" basis to establish the effective specific impulse as a function of the command duty cycle and fluid system dynamics. A second complication of the pulsed mode stems from interaction of the flow measuring device with the propulsion system, causing a change in the propellant feed pressures. In addition, to acquire specific impulse data to better than **2%** accuracy, the propellant consumption data should be better than **1%** and preferably closer to **1/2%.** Therefore, an instrument system that would provide a direct measure of average propellant consumption per pulse, and would be passive relative to the feed system, was considered preferable for the major portion of the contemplated work.

Steadv Flow Reauirements

The requirements for steady flow instrumentation were established by considering the propellant properties, the thrust levels, of O/F ratios, and the specific impulse range for the earth storable monopropellant and bipropellant systems. Propellants considered were hydrogen peroxide **(90%),** nitrogen tetroxide, neat hydrazine, and monomethyl hydrazine. Thrust levels were limited to **0.5** to **5.0** lbf. The O/F range (where applicable) was arbirarily fixed at **1.0** to 2.0. Specific impulse was varied from **100** to **240** lbf-seconds per lbm for the monopropellants, and from **250** to **350** lbf-seconds per lbm for the bipropellants.

Figure **1** is a plot of steady state propellant flow rates, as a function of thrust and specific impulse, for the monopropellants. Figures 2(a) and 2(b) are plots of the steady state flow rates, as functions of thrust and O/F ratios, for the monomethyl hydrazine-nitrogen tetroxide bipropellant systems. The monopropellant flow range runs from **0.015** to **0.36** gallons per minute. The bipropellant systems vary from **0.004** to **0.0824** gpm for MMH and from **0.0036** to **0.067** gpm for NTO, for the complete thrust range.

The overall range for all cases considered is **0.0036** to **0.36** gallons per minute.

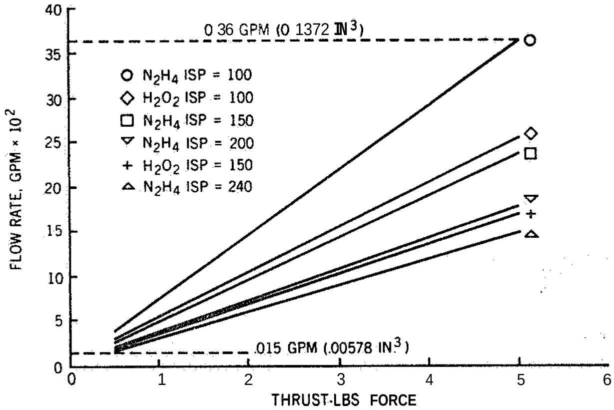

Figure 1. Monopropellant Flow Range.

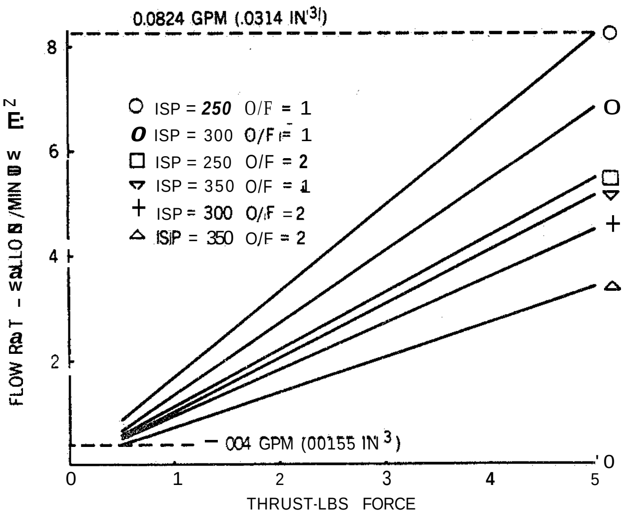

Figure 2a. Bipropellant Flow Ranges—MMH

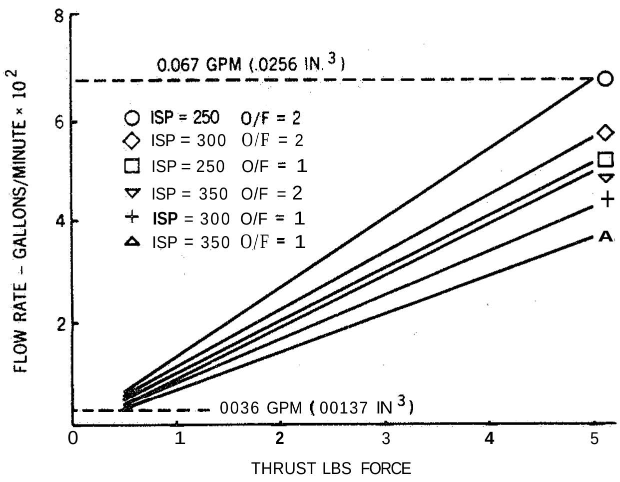

Figure 2b. Bipropellant Flow Ranges—NTO

Single Pulse Propellant Consumption

In establishing the minimum requirement for measuring single-pulse propellant consumption for the same propellants considered for the steady state case, a pulse width of 100 milliseconds was selected as a base line "on" time, since this value is in the range of command pulse widths for the class of ACS systems of particular interest to the Center. Single-pulse volumes (in cubic inches) can be obtained directly from the steady state flow rates for both the monopropellant and bipropellant systems by multiplying the steady flow gallons per minute by 0.385. The upper and lower limits of volume for the 100 millisecond pulse are indicated in parentheses in Figures 1 and 2. The value shown for the steady state I_{sp} has its single pulse equivalent volumetric consumption indicated for an equal value of pulsed mode effective I_{sp}.

For the monopropellants, the lower and upper bounds for the single pulse consumption are 0.00578 cubic inches and 0.1372 cubic inches, respectively. The bipropellant lower and upper bounds for single-pulse consumption are 0.00137 cubic inches and 0.0314 cubic inches, respectively. These values can readily be converted to those required for longer or shorter pulses. For the complete spectrum of indicated applications, an overall range of 0.00137 to 0.137 cubic inches is required.

In both the steady and pulsed applications, the range spread is exactly 100 to 1. It is doubtful that any one instrument will be able to cover the complete range with the desired precision for either firing mode. The normal range spread expected of flow devices is usually 10 to 1. Therefore, it will be necessary to use several instruments or to modify initial requirements such that propellant consumption is averaged over a train of pulses rather than a single pulse.

III. Review of Existing Methods

A survey of commercial instrumentation, custom designs, and devices in use or under development were reviewed. The factors that were considered in their evaluation were:

a. sensitivity or resolution
b. ease of calibration with secondary standards
c. dependence of precision on fluid system dynamics
d. influence of human error
e. limitation of run time on test flexibility
f. linearity of output, where applicable
g. temperature effects on measurement precision.

Steady Flow Measurements

Steady flow rates have been successfully measured by the pressure drops across an orifice plate,[1] the speed of a turbine meter,[2] and by the force on a drag-body flow indicator.[3,4] These devices are all purported to be accurate to within 1% over a useful flow range of 10 to 1. The orifice plate, although accurate, is not particularly convenient to use because of its poor response to fluctuations in the steady flow conditions, and its output is not a linear function of the volumetric flow rate. Turbine meters do have adequate response and linearity characteristics, but are not currently manufactured with sufficiently low flow ranges for the specified applications. Drag-body flowmeters have excellent dynamic response, but are nonlinear and do not cover the required flow range. In addition, their output is dependent on velocity distribution and in some designs upon a complex function of the fluid viscosity. These factors also contribute to the non-linear output, which is inconvenient from an operational point of view.

The only commercially available devices that could be used for the indicated steady flow ranges are impeller wheel devices such as the one shown in Figure 3. These are volumetric type flowmeters which, like the more conventional turbine meter, generate an A.C. millivolt signal whose frequency is proportional to the flow rate. Construction differs from the standard turbine meter in that the rotor is supported by a shaft at right angles to the flow, rather than axially. The flow is directed by an orifice or nozzle perpendicular to the face of the rotor blade. Such devices are available as shelf items in nominal flow ranges as low as .005 to .075 gallons per minute. This would cover all previously discussed low range mono-propellant requirements and all bipropellant requirements down to a thrust level of 0.75 lbs. force if they were usable for their entire range. Unfortunately, we have not been able to obtain a sufficiently stable signal from these units at the lower third of their nominal range to calibrate them to our satisfaction. In addition, a limited number of calibrations performed with de-ionized water and other inert fluids indicates that these devices are probably more sensitive to viscosity than turbine meters,[5] and, as a result, would have a very limited linear range. Therefore, in order to use an inert calibration fluid, Reynolds number or kinematic viscosity would have to be matched to that of the propellant as closely as possible. This will be discussed in detail later in the paper.

The drag body flowmeters previously described in reference (3) are supposed to possess adequate response for the measurement of pulsed flows. Yet, as shown in Figure 4, the device is generally calibrated in terms of total propellant mass per pulse as a function of pulse width. In order to obtain precision in calibration, the average flow for a number of pulses rather than for the single pulse is used. An analog computer is required to integrate the area under the pulse flow trace, and, although the data system gain can be preset, there is no consideration of non-linearities in the calibration process. The calibration curves for a pulse range of 10 to 100 milliseconds duration are not colinear and the spread between curves does not appear to be amenable to an analytical prediction. Repeatibility of integration weight flows per pulse are reported to be within 1%; however, due to the relatively complicated process of calibration, data acquisition, data reduction, and the possibility of additional error due to the non-linearities of a fluid system that is highly dependent upon fluid properties, this device would not satisfy the requirements of a mass flowmeter having adequate dynamic response and accuracy for pulse operation. The manner of calibration indicates that an instrument having high transient response is not actually required. The basic need is for a device which will provide an accurate indication of total integrated flow per pulse for a single pulse, or average total integrated flow for a number of pulses. The chamber pressure and propellant feed pressure traces will generally provide the transient data required to define the dynamics of the propellant systems.

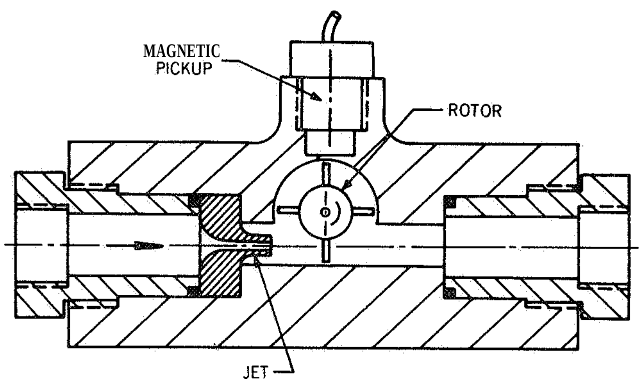

Figure 3. Crossection of a Typical Impeller Wheel Flowmeter

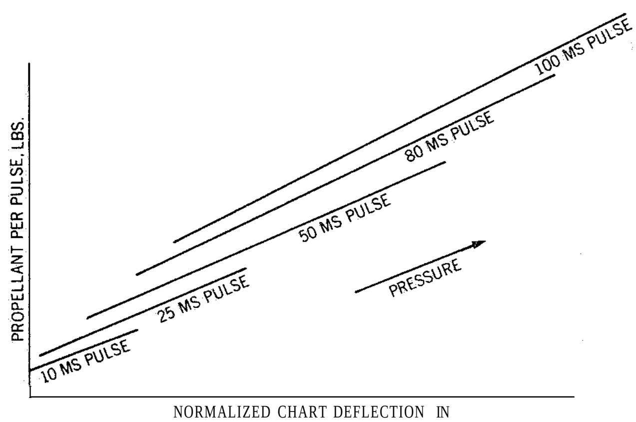

Figure 4. Typical Drag Body Flowmeter Calibration

It has been suggested that flow rates can be obtained by photographing the propellant levels in glass dispensing tubes of a size necessary to provide adequate sensitivity. This method is subject to both displacement and timing errors due to optical distortion and frame rate variation. In addition, the data reduction process is more complicated, and this could introduce an additional source of error.

Pulsed Flow Measurement

A number of approaches have been used for measuring pulsed mode propellant consumption. These were examined to determine whether their performance was desirable for the contemplated applications.

The most commonly used devices are positive expulsion piston units, which appear in a wide variety of forms[6,7,8] but are all designed to measure flow rate during pulse operation. They depend on a direct coupled linear differential transformer, or a linear potentiometer, for a high resolution analog output. The piston is driven by gas pressure, and the seal between the gas and liquid sides is one of the various forms of dynamic piston seals or welded bellows arrangements. The bellows, when properly incorporated, prevent gas leakage and resulting errors that could occur with an O-ring or similar dynamic seal failure. However, the bellows can affect the dynamic response of the unit and the linearity of the volumetric indication. There is also the possibility of a "water hammer" effect in the cutoff transient of the flow rate trace. Therefore the dynamic response of bellows, piston, and transducer to pressure waves during typical duty cycles must be considered in the synthesis of the basic design. Another complicating factor in devices of this type is that, in order to obtain the required resolution, all components must be stringently specified as to their linearity, sensitivity, hysteresis, stability, response, life cycles, line regulation, load regulation, ripple voltage, etc. To achieve the required resolution, run times are necessarily short. Therefore, some arrangement for rapid filling or a multiplicity of units to alternately supply and be supplied with the propellants is required. To minimize the number of active components that must be carefully specified and to reduce the complexity of operation and calibration, a device which can develop the required resolution from common commercial components would be needed. Resolution may also be developed by measuring the propellant consumed by a multiple pulse firing.

The burette arrangement falls into this category of pulsed metering devices. It can be completely passive, involving no transient measurements, and can be tailored to provide a wide range of resolution with standard commercial components.

With these devices, inert gases directly pressurize the fluid contained in precision bore tubes of metal or glass. The difference between the levels in the tube belore and after firing a single pulse, or train of pulses, is a direct volumetric measure of the propellant consumed during the firing. The meniscus level can be monitored wing a linear differential transformer slug float, in the case of the metal tube, or an optical system in glass tube units. Metering units of the first type have obtained long run times by utilizing a multiplicity of coils along the tube axis and switching the electrical outputs as the slug float progresses from one coil to the next. Glass tube burettes have used light diffused through the liquid column and across the meniscus to drive a photoelectric tracking head to indicate position.[9] Cathetometers, transits, or motion pictures have also been used to determine fluid level. A properly used cathetometer can enable the reading of the fluid displacement to within 0.002 inches; however, this is dependent upon the skill of the operator. Tests of operator variability have produced data spreads of a fixed level of 0.020 inches or ten times the accuracy possible with the instrument. Photographic recording is a slow process and is not reducible to the required accuracy or resolution.

An instrument that possesses the inherent simplicity of a burette metering unit, can provide the required resolution. One that can eliminate sources of human error was considered the most suitable for the Center's needs, and was developed[10] in its simplest form. The synthesis, preliminary tests, and application of the unit will be described in detail in Section V.

IV. Steady State Flow Data Acquisition

As was indicated in Section III, there are impeller type flowmeters available that could cover all projected metering requirements for monopropellant thrusters and all bipropellant needs down to the 0.75 lbf thrust level. The products of two suppliers were obtained. Flowmeter "P" had a nominal range of .01 – .08 gpm; flowmeter "B" had a nominal range of .005 – .075 gpm. The supplier's calibrations were conducted with tap water, and, in the case of P, appeared suspiciously linear over the complete flow range. It was deemed necessary to check these calibrations and to consider deviations between water and propellant calibrations. Since the available facilities were not equipped to calibrate directly with propellants, inert simulants those fluid properties closely model the kinematic viscosities, and therefore Reynolds numbers, of the propellants were selected. Fortunately, de-ionized water is an excellent simulant for monomethyl hydrazine. Table 1 lists the properties pertinent to Reynolds number simulation, and additional fluid properties that can be influential in affecting the performance of other flow metering devices.

Table 1 Physical Properties of Propellants and Simulants

FLUID	DENSITY G/CC	DYN VISC CENTIPOISE	KIN VISC CENTISTOKE	REFR IND SODIUM D	SUR TENS DYNES/CM
NITROGEN TETROXIDE	1.434 (25°C)	04130	02880	1.400 (20°C)	2800
METHYLENE CHORIDE	1336	04137	0 3097	14237 (25°C)	2652 (20")
45 7% SODIUM DICHROMATE	1 2378			1.400	
MH	0.874	0781	0.8950	14218	
DEIONIZED WATER	0.9968	08937	0 8987	1 3325	71 97 (25°C)
GLYCEROL SOL (20%)	1671 (21°C)			14218	68 00 (18°C)
N_2H_4	1008	0 97	0 964	1470 (22°C)	66 67 (25°C)
SILICONE BLEND (A)	0818	0 773	0 945	13818	1590
H_2O_2 (90%)	1392 (20°C)	102	0 732	1.399 (22°C)	76 1

As indicated, suitable simulants are available for the hydrazine compounds, with Reynolds numbers being within 1/2 to 2%; but the closest inert simulant for nitrogen tetroxide comes to within only 10% of the kinematic viscosity.

Careful consideration of calibration, data acquisition, and data reduction processes indicated that one possible serious source of error existed: there had to be correlation between data taken at the test stand and data taken in the calibration laboratory in order to use the calibration with a reasonable degree of confidence. The commercial flowmeters each produce an a.c. signal whose frequency depends directly on impeller speed. The a.c. signal is converted to a d.c. output by means of a frequency converter, and this output is recorded to provide an analog record. A secondary check of the analog rates can be made by means of the digital totalizer output and elapsed time indicators.

A simple, direct procedure was established to correlate test stand and laboratory calibrations. At the test stand, a calibration of the frequency converter is performed using an oscillator and an electronic counter to check frequency settings. The output is recorded on a Visicorder, with the amplitude adjusted to provide a 4" deflection at 800 cycles/second for impellers that produce 8 impulses per revolution and the same deflection at 200 cycles/second for impellers that produce 2 impulses per revolution. (For applications where the flow range is in the lower third of the meter's nominal range, the amplification is increased so that greater data reduction precision is possible at very low flows.) A second calibration of the converter is performed in the laboratory using the same or a similar oscillator (checked by an electronic counter) set at the same calibration point as that used at the test stand. This provides the direct correlation between test stand and laboratory instrumentation and should compensate for differences in response and linearity. It is now possible to perform the flow calibration in which the flow in pounds per second is measured against the recorder deflection by the gravimetric collection method. The precision platform balance used for this purpose can be read directly to 0.01 lbs. and estimated to 0.005 lbs., and a megacycle electronic counter provides more than adequate timing precision. The sample is collected until the maximum possible weighing error is 0.1% of the total weight, or until about 5 pounds is collected. The fluid whose properties closely simulate the propellant of interest is used, and its temperature is measured at the flowmeter so that an accurate volumetric flow rate plot can be made. The laboratory volumetric calibration and the test stand analog records of propellant temperature and volumetric flow rate are then used to compute the mass flow rate during engine firings.

Figure 5 is a block diagram of the instrumentation used for this work: 5(a) indicates the test stand frequency calibration equipment, 5(b) indicates the laboratory equipment. The electronic timer in 5(b) is started (in the timing mode) by the fluid interrupting a beam of light in a photoelectric head, and is stopped by the scale pointer reducing the illumination to a second photoelectric head on the scale. The "dribble" volume of the system is minimized by close coupling the control solenoid valve to the "start" head. The scale is rebalanced and read after the counter time interval is recorded. A typical flow calibration record is shown in Figure 6. The broken line indicates how this calibration would be used to reduce test stand data. The volumetric flow rate obtained would have to be converted to a mass flow rate at the temperature of the propellants at the test stand. Figure 7 is a photo of one of the laboratory flow calibration benches showing all equipment and instrumentation.

To demonstrate the importance of considering the fluid properties in selection of the calibration fluid, the volumetric flow rates for de-ionized water and methylene chloride were plotted versus frequency for supplier P's

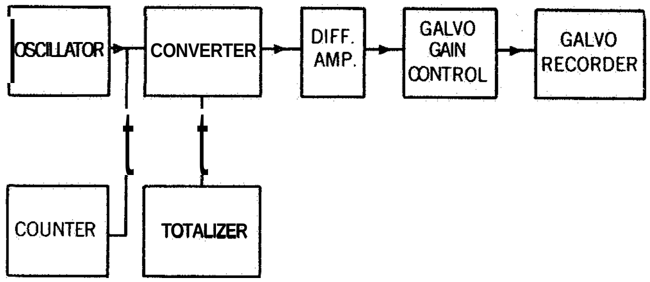

Figure 5(a). Test Stand Frequency Calibration

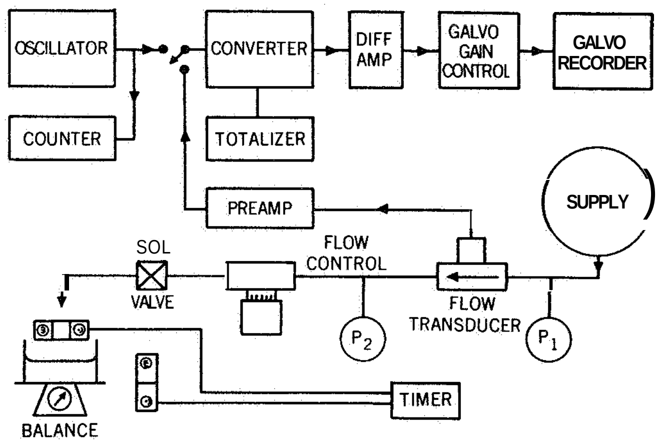

Figure 5(b). Instrumentation for Steady Flow Calibration

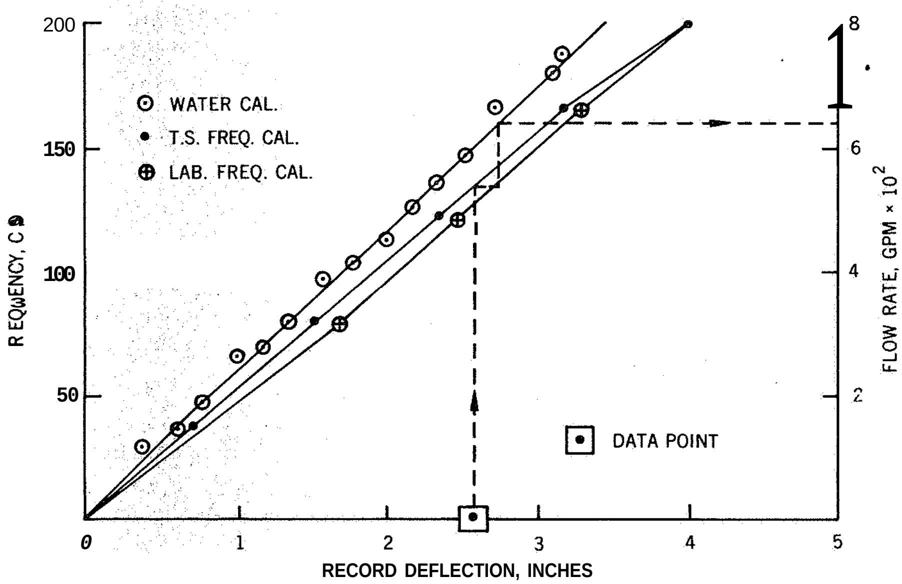

Figure 6. Typical Flowmeter Calibration Record

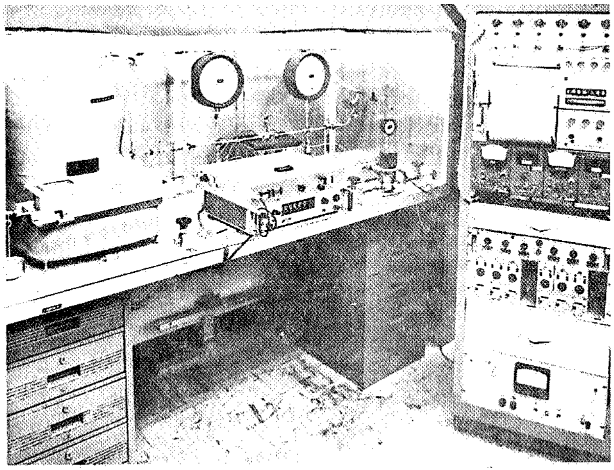

Figure 7. Flow Calibration Bench

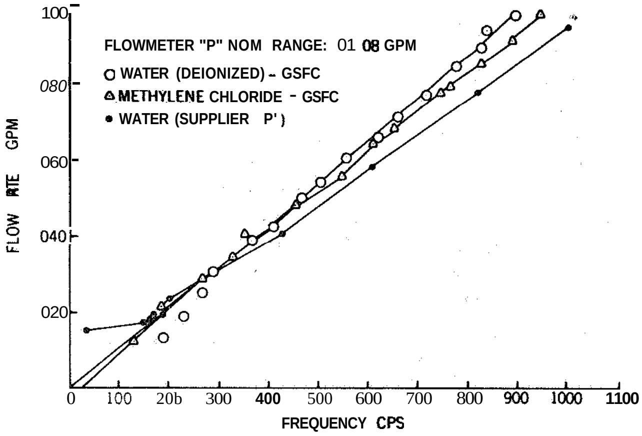

Figure 8. Meter "P" Flow Calibrations

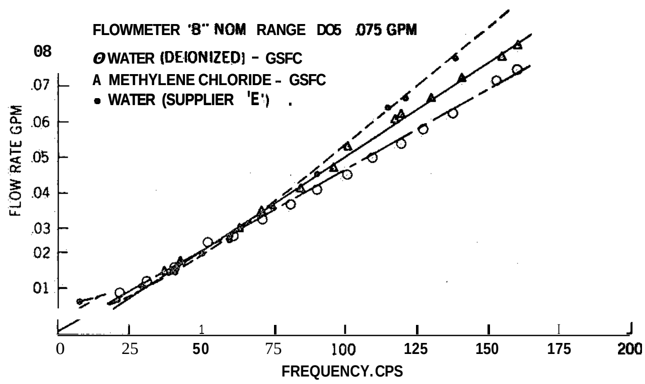

Figure 9, Meter "B" Flow Calibrations

meter, Figure 8, and supplier B's meter, Figure 9. The manufacturer's water calibrations were also plotted on the same graphs.

Examination of Figure 8 indicates a performance paralleling that of the more conventional turbine meters; that is a lower viscosity fluid produces a higher frequency for the same volumetric flow rate. The supplier's water calibration does not bear this out. In fact, at the linear portion, its frequency is 12% higher than that **of** the Center's water calibration. The variation of the water calibration from the methylene chloride is about 4.5% for the same range.

Comparison of the water calibrations for Flowmeter "B" (Figure 9) shows that the frequency output in the linear range is about **25%** lower with the supplier's data. The water calibration has about 20% greater frequency output than the methylene chloride. This is contrary to what is normally expected, since the higher viscosity fluid usually provides a lower frequency output. If water calibration data were used for an MMH run, the volumetric flow rate, theoretically, would be 20% higher than the measured runs producing an equivalent error when computing the specific impulse.

Although the behavior of meter "B" is not that which would normally be expected, repeated calibrations have demonstrated better reproducibility with this device than with meter "P" which possesses more conventional characteristics.

Since these meters are volumetric flow devices, human error factors would be further reduced by devising a

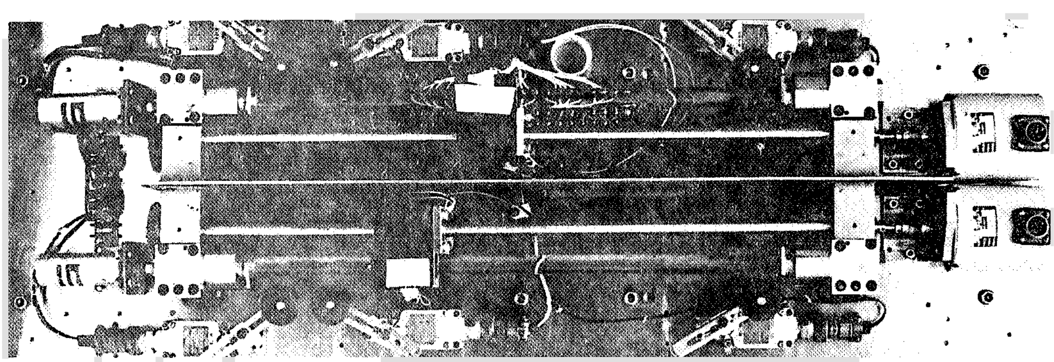

Figure 10. Development Model of Pulsed Mode Flowmeter

means of directly measuring volumetric rather than gravimetric flow. This would be particularly desirable because it would enable correlating calibrations of flowmeters with real propellants while reducing the hazards since the fluids need not be collected to obtain the desired accuracy. They could be dumped into neutralizers or collected cryogenically.

When this correlation data becomes available, it will be possible to demonstrate whether the simulation of a propellant using a fluid with a comparable kinematic viscosity is an entirely valid substitute in these low range flowmeters for the more hazardous propellant calibration. It may also provide some clues to the varying behavior of meters of similar design. To summarize the progress to date in this area, two major points have been demonstrated:

1. the importance of carefully considering the choice and use of simulants as shown by their varying and anomalous performances with different devices, and

2. the need for basic theoretical studies of the behavior of low flow rate impeller wheel meters, to characterize their performance.

V. Pulse Mode Flow Data Acquisition

The following material covers the development, limited testing, and application of a burette metering unit designed to eliminate most human error sources and to provide accuracies (when properly used) on the order of 1% or better for volumetric displacements of approximately 1/2 milliliter.

General Description

The developmental model is a manually operated device for which filling, zeroing, propellant dispensing, and precision readout can be performed from a remote station. The same unit can be modified, if desired, for automatic tracking of the fluid levels to provide a rate signal with comparable accuracy.

The manually operated pulse mode flowmeter consists of two precision-bore glass tubes, sealed to a common pressure manifold at their upper ends and to solenoid valves terminating at a propellant manifold at their lower ends. Each glass tube is encircled by a photohead which is driven along the tube by a ball-screw assembly and motorized lead screw. The photohead contains a point light source and photodiode. The meniscus of the liquid in the tube can be detected by the change of the diode output. Precise resolution of the fluid level is achieved by initially nulling the photodiode outputs, depleting the fluid in one tube while using the other as a reference, and then renulling the diode outputs. The change in fluid level is digitized by means of bidirectional pulse generators directly coupled to the lead screws. The readout of the pulse counter directly indicates meniscus travel in 0.001 inch increments. Figure 10 is a photograph of the burette unit with its steel cover removed. The limit switches shown prevent the optical heads from being driven into the upper and lower manifolds. The intermediate limit switches provide a signal at the control panel to indicate when the heads are one inch from the lower limit switches so that the tubes can be recharged prior to complete rundown. Figure 11 is a photograph of a control panel for a bipropellant system, which incorporates fuel and oxidizer controls. Also shown is the digital indicator and power supplies for motor drives, light sources, and diode bias.

Initial Sizing of the System

In order to simplify the selection of geometric and electrical parameters, a few simple tests of available photo-diodes (1N2175) were performed to obtain some feel for their ability to indicate small liquid level displacements. The first test used a single light source, and the diodes were-wired as two legs in a Wheatstone bridge, with potentiometers in the other two legs. The units were nulled across a galvonometer by longitudinally displacing glass tubes, partially filled with water, clamped into a supporting fixture. Since one of the glass tubes was fixed relative to the base, displacement of the fixture unbalanced the bridge. The galvonometer was used to return the fixture to a null position and the fixture position was read

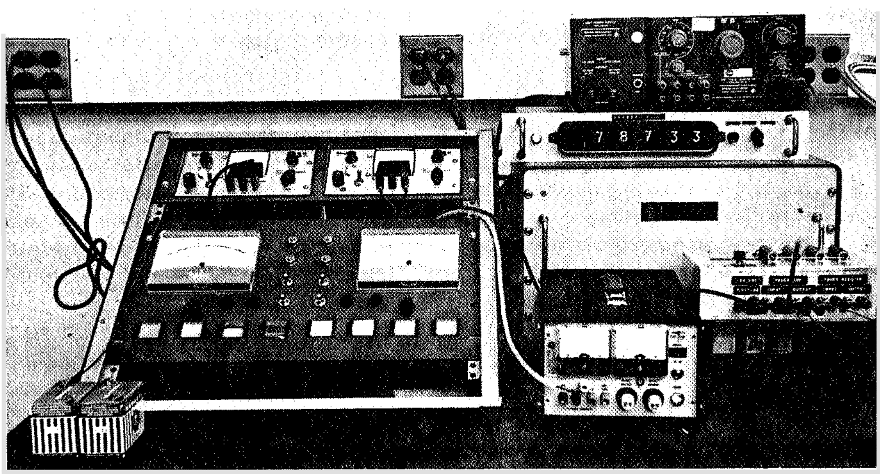

Figure 11. Control Panel for Pulsed Mode Flowmeter

with a dial indicator to **0.0001** inch. Sixty readings were taken and the null position was averaged. The standard deviation computed for the variance about the mean position was **0.0001** inch. To determine the sensitivity for a null arrangement using two separate light sources, an additional 66 readings were taken; the standard deviation Prom the mean position was **0.0002** inch.

Therefore, if a maximum position error of **.001** inch were tolerated, the photodiode bridge would be at least Five times more sensitive than required to sense a displacement within the selected tolerance.

Since initial programs were concerned with **5** lbf. bipropellant systems, the first developmental models were sized for use with these items. Computations were performed to establish maximum overall measuring accuracy assuming that a total equivalent error of 0.001 inch travel could be tolerated. These computations were based on a **100** millisecond pulse width and a **0.500** inch bore tube in the burette. At the **5** lbf thrust level, for an I_{sp} range of **250 - 350,** an O/F range of 1.0 **- 2.0,** and the number of pulses = 5, the theoretical accuracy was **0.28%,** with a fluid column range of **0.352 - 0.808** inch. The same conditions with the number of pulses = **10** provided an accuracy of better than 0.7% for a thrust of 1 lb-force. Using the same geometry, it is theoretically possible to achieve accuracies better than **0.34%** (with a **.001** inch tolerable error) for monopropellants (H_2O_2, N_2H_4) throughtout the **1-5** lbf thrust levels. If the tolerable equivalent linear error is reduced to .0005, the accuracies will improve by a factor of **2.** To use the same geometry for shorter pulse lengths, it would be necessary to increase the number of pulses that are to be fixed before a reading is taken, the increase to be in direct proportion to the ratio of the standard pulse width (**100** ms) to the varied pulse. The usable burette tube length was determined by the mean displacement of oxidizer and fuel for optimum performance of a 5 lbf. engine, or approximately **15** inches for **150** pulses. To make the tubes much longer produces an unwieldy package (becomes excessively heavy) and makes inspection of tube bores difficult.

To use the apparatus for the lower end of the scale (**0.5** lbf. thrust), a second set of precision bore tubes are contemplated. If the crossectional area is one tenth of the first set, then equal theoretical accuracy will be experienced for the same number of pulses as that described above for the **5** lbf level.

On the other end of the spectrum, a **25** lbf engine would meet the measuring accuracies quoted for the **5** lbf engine when only one pulse is fired, and-in each leg the unit would supply sufficient propellant to fire **30** pulses, or a total of 60 pulses of **100** millisecond width before recharging is necessary. Since the possibility of work at this level is not unreasonable, the current equipment, when properly applied, theoretically **has** a capability of **0.25%** accuracy over the thrust range of **0.5 - 25.0** Ib-force, or a range of **1** to 50.

System **Error** Analysis

In order to select standard commercial components capable of achieving the theoretical accuracy when assembled, the effects of tolerance variations of critical components had to be considered. The items of primary concern were variations of bore diameter, lead screw error, pulse generator phasing and counter stability. Other factors that had to be considered were **(1)** varying indices of refraction, **(2)** diode mismatch, **(3)** varying light source intensities, and **(4)** pressurization gas solubility effects on fluid density.

Tube Area and Lead Screw Errors

Assuming a nominal diameter D = **0.500** inch, and errors on the diameter of **0.0001** inch and **0.001** inch, the area errors become **0.04%** and 0.4%, respectively. Lead screws come as standard items with pitch errors of **0.0015** inch in **1.000** inch or **0.0005** in **12** inches. The first is equivalent to **0.15%** (assuming distributed error) and the second is equivalent to a 0.0042% error.

Considering the combination of the most precise bore and the better lead screw, then a volumetric error of **0.044%** is the best that can be expected (assuming temperature variations at laboratory and test stand are kept to within ±2°F). Considering the worst combination of lead screw and tube, then the best accuracy that can be expected is **0.55%** on volume alone. The most precise bore and lesser lead screw produce a volumetric error of **0.19%.**

Pulse Generator and Counter Errors

The errors in the bidirectional pulse generator are due to inaccuracies in phasing the grating slots and to cumulative effects in any sector of the grating. It is not sufficient to obtain **200** counts in **360'** if the lead screw has a .200 pitch. Not only should each count be ideally within **10** minutes of its true phasing, but any accumulated count within **360°** of rotation should be in error by less than **10** minutes. This means that, if on one count the error is +6 minutes, the succeeding counts must not exceed +**4** minutes error or be lower by **-16** minutes. In general, phase errors will accumulate in a random fashion and the cumulative effects should be checked out for 360° in both directions. If a 2000 count generator is used (to obtain better measuring resolution), then the maximum individual and cumulative phase error in either direction should be **1** minute.

Optical System Sensitivity

The optical heads (which in essence form a balanced photometer circuit) consist of a pair **of 1N2175** photodiodes illuminated by individual **253X** miniature high intensity focused beams. Two **4700** ohm potentiometers make up the other side of a Wheatstone bridge that is excited by **45** VDC. The bridge output is sensed by a **5-0-5** micro-ammeter with a series of shunting resistances for sensitivity reduction. An on-off switch in one of the diode legs enables the adjustment of light intensity to produce a fixed photocurrent level in the diode. This is done while the beam is completely in the liquid in order to obtain a fixed output **for** liquids of varying transmissibility. With the diode switch making the circuit, the light source in the opposite head is adjusted to provide a null condition (both heads in fluid). This compensates for deviations both in light sources and diode characteristics. A second, finer nulling procedure at the meniscus readies the instrument for data taking.

The only other effect that might possibly cause deviations in performance is the variation in refractive index of the liquids. A series of tests on the simulants whose optical properties matched those of the propellants was conducted to establish the seriousness of this variable.

Gas Solubility Errors

Since this device does not separate the gas from the liquid interface, it is reasonable, especially at high feed pressures, to expect solution of the nitrogen gas in both the simulants and the actual propellants. Using available experimental data,[11,12] estimates were made of the change in density of the propellants and simulants for a temperature of 68°F and a pressure of *200* psia. The nitrogen tetroxide, under these conditions, dissolves enough gas to increase in density by **5.8%.** Monomethyl hydrazine, under the same conditions, would have less than a **0.2%** change. Water has approximately a **1.1%** density change. Methylene chloride effects were based on carbon tetrachloride data and estimated to have a **5%** density increase due to nitrogen solution.

The effect of gas solution can present a far greater error in measurement than all other factors previously considered. It can also affect the computation of measured performance, unless carefully assessed and taken into account. Fortunately, the density change of the basic bipropellants and their simulants due to nitrogen solubility are within 1%, so the kinematic viscosities will still have a reasonably good match.

In order to overcome these difficulties, in view of a scarcity of data, it will be necessary to experimentally determine all information not available in the literature, and to spot check that which is available.

Laboratory Tests and Evaluations

The testing that has been performed to date was initially aimed at checking the precision of the primary components, and then at checking system performance. Whenever possible, a large number of readings were taken at any set point in order to provide a more acceptable basis for statistical analysis of the data. In these cases, the mean and standard deviations from the mean were computed, and the error spread is presented as the mean plus or minus **3** standard deviations to include all possible data points with a **99.7% probability.**[13] The system tests were conducted with water and with the **45.7%** sodium dichromate solutions having indices of refraction N_D = **1.3325** and **1.400,** respectively. In both cases, nominal fluid column displacements of **0.15, 1.00,** and **1.75** inches were run using a gravimetric measurement of the fluid dispensed to compute volumetric error. The tests were conducted (as shown in Figure *12)* at a 30 psig nitrogen-liquid interface. Samples were collected in glass vials by pulsing a solenoid valve and were weighed with a Right-a-Weigh digital balance that is accurate to **0.1** milligrams and reproducible to better than 0.02 milligrams.

The following material summarizes the results of the initial performance tests on the development model.

Pulse Generator and Counter Accuracy. The pulse generator and counter subsystem were checked for phase error at indicated count and cumulative phase error

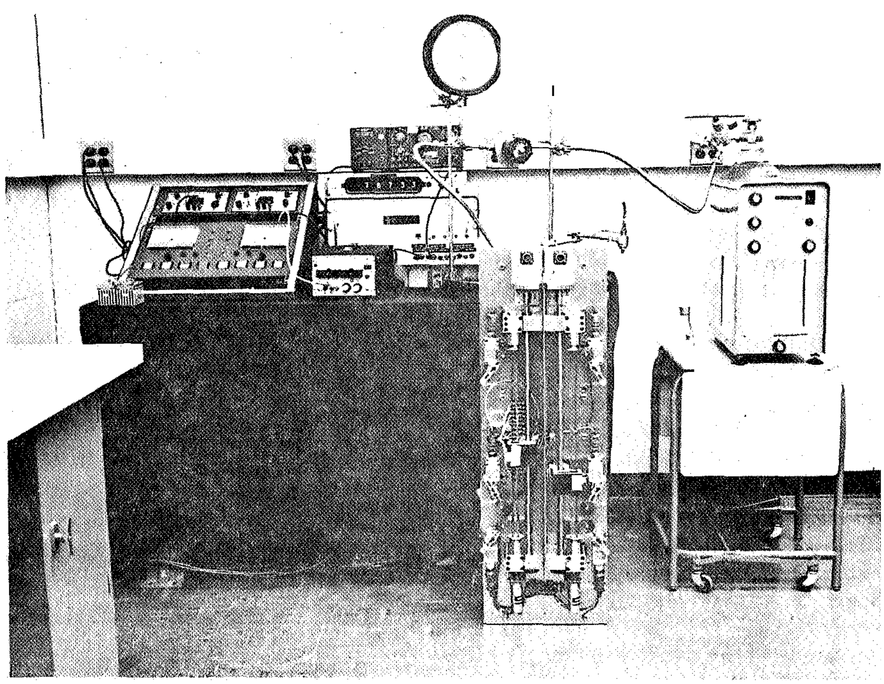

Figure 12. Laboratory Calibration of P.M. Flowmeter

throughout the generator's entire 360° range. This was accomplished using an optical master dividing head with a working accuracy of ±2 seconds of arc. The generator shaft was slowly rotated until a count was indicated on the digital readout. The optical dividing head setting was then noted. For the 200 pulse/360° units, each count is supposed to represent 1.8000 degrees of arc, or a linear travel of 0.0010 inches. The maximum individual deviation on count phase was found to be .039 degrees (2.34 minutes), which is equivalent to a tracking error of 22 microinches. The maximum accumulated deviation occurred 103° away from the maximum individual deviation and was 0.338 degrees (20.2 minutes), which is approximately twice that of an ideal system. However, this represents a tracking error of 0.0002 inch, which is still well within a single count resolution and just about equals the photohead resolution limit. During tests, and for an additional eight hour period in which the counter was left running with the pulse generator stationary, there was no count instability evidenced.

Lead Screw Error. Sixty positions along the 14.25 inch active length of the rolled thread lead screw were checked using a universal measuring machine having 0.0002 inch graduations and a 0.00002 inch vernier. The difference between counter reading and bed position was considered lead screw pitch error at the bed position. Between stations 10.750 and 14.250 the errors were consistently fluctuating above the specified tolerance of 0.0015 inch/inch. Deviations of as much as 0.002 inch in 0.250 inch occurred in the last usable half inch. However, if this last section is avoided, and increments of 1 inch of travel are used, the lead screw error will still be within 0.1%. Final models of the burette system should be made with the precision lead screw (0.0005 inch/12 inches) so that there can be unqualified operation of the device.

Bore Tests. The bore was checked at quarter inch intervals along 7 inches from each end. The mean bore and tolerance was found to be 0.5002 ± .0001 inches, which is well within the limits set for a high quality unit. In addition to the dimensional checks, a pressure test was conducted on these units at 525 psia and they did not fail. The design loading is 300 psia.

The combination of tube, lead screw and digital system (avoiding the last measured half inch of screw) will allow a maximum theoretical volumetric error of 0.20%.

Laboratory Tests with Simulants

The complete system tests were conducted at nominal column heights of 0.15 inch, 1.0 inch, and 1.75 inch, using first de-ionized water and then 45.7% sodium dichromate solution. Both systems were pressurized to only 30 psia in order to reduce the solubility errors to where they could be neglected. Table 2 is a tabulation of the results of these tests based upon gravimetric collection. The mean error is expressed in percent of nominal tracking length along the burette column. The standard deviation is a measure of the variance of the sampled data. The mean error $\pm 3\sigma$ would provide the most pessimistic picture of system capability and would include 99.7% of all probable error due to equipment and personnel. From

FLUID	NO. TRIALS	NOM. AL INCHES	MEAN ERROR $\bar{x}$ - %	STD. DN. σ - %	99.7% PROB. RANGE	
					$\bar{x} + 3\sigma$	$\bar{x} - 3\sigma$
DEIONIZED WATER N_D = 1.3325	50	0.15	-0.423	0.999	+2.574	-3.420
	44	1.00	-0.089	0.212	+0.547	-0725
	25	1.75	+0.003	0.115	+0.348	-0342
45.7% SODIUM DICHROMATE N_D = 1.400	54	0.15	-0.047	0.900	+2.653	-2747
	47	1.00	-0.248	0.239	+0.469	-0.965
	38	1.75	-0.074	0.134	+0.328	-0.476

1 Application

One of the two developmental units was used to obtain the pulsed mode performance of a 0.5 lbf thrust monopropellant hydrazine engine. The total propellant consumptions for trains of 50 pulses were measured with command pulse widths varying from 100 to 500 milliseconds. Additional tests were conducted in which a low range (.005 to .075 gpm) impeller wheel flowmeter was coupled in series but downstream of the photometric unit. This was done to check the validity of data obtained by means of turbine type devices. Figure 13 contains tracings of oscillograph records which demonstrate the mutual effects of the meter and engine dynamics. The top trace is the chamber pressure with the impeller meter just upstream of the engine; the middle trace is the flowmeter analog output; the bottom trace is the chamber pressure with the impeller meter out of the fluid circuit. Several interesting phenomena are indicated in these traces. The peak-to-peak amplitude of the chamber pressure variation is 8% for the lower trace and 15%, or approximately doubled, for the upper trace. In addition, the mean amplitude pressure rise is linear with time for the lower trace,

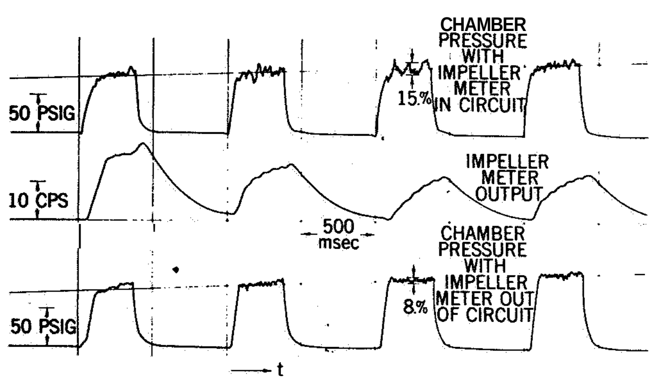

Figure 13. Sea Level Firing - 1/2# M.P. Thrustor (30% Duty Cycle)

while the pulse pressure mean for the upper trace oscillates about a linear rate line. Examination of the flowmeter trace indicates that the response of the meter is definitely inadequate. Steady state flow conditions are not attained during the relatively steady portions of the pressure pulse. The peak values of the flow rate fluctuate and the tail off never achieves a zero value. Figure 14 is a tracing of the meter output for the first, second, third, and seventh pulses for a 50% command duty cycle having a one second period. It is obvious that, even for relatively long pulse operation, the impeller inertia makes this unit unsuitable for this test. The peak frequency of the first pulse overshoots that of a stable pulse (i.e. number 7) by 50%. The tailoff frequency never drops below 20% of the steady state portion of the stable pulse. The record could not be used for normal data reduction. It can be seen that using meters of this type can influence combustion chamber dynamics and using a burette type of device enables the acquisition of propellant consumption data without exerting as much influence on engine performance. This entire area of small engine testing deserves additional attention and will have to be investigated more thoroughly.

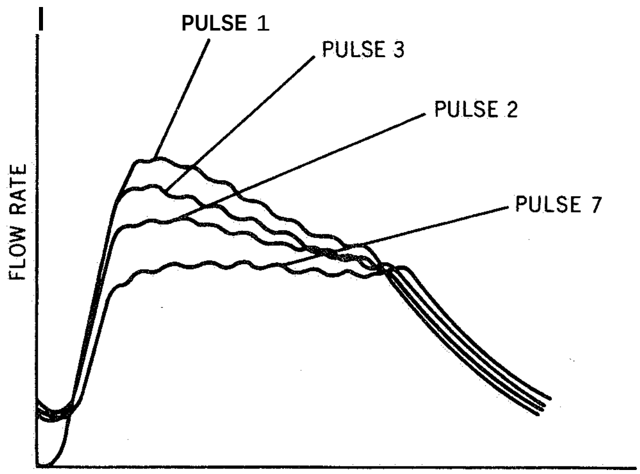

Figure 14. Impeller Flow Meter Output in Pulsed Application

VI. Summary and Additional Work

In summary, although techniques have been developed to enable useful applications of existing steady flow impeller devices, it is felt that their behavior has not been sufficiently studied by either manufacturers or by the Center to justify saying that they really perform either reliably or with high precision. The only alternative at present is to perform frequent calibrations to check reproducibility of performance. A considerable amount of work will have to be done to account for the pressurization gas solubility problems of the fuels at the test stand and the simulants at the calibration laboratory. Care must be taken to match density changes resulting from gas solution at high pressure. To accomplish this, it will probably be necessary to develop precision volumetric flow calibration techniques that maintain the high feed pressures of test stand systems and make use of solubility corrections from data obtained under similar conditions in laboratory tests.

Volumetric calibration devices will also permit direct checkout with propellants and provide the additional data needed to validate the simulant approach. A considerable amount of fundamental work will be required to ascertain the basic behavior of impeller flowmeters to determine why similar devices from different manufacturer's do not respond similarly to viscosity change. Performance will have to be characterized in a general way in terms of viscosity, flow rate, and impeller speed. Criteria for performance should be sought to synthesize more reliable and durable units.

Work to date on the photometric pulsed mode flowmeter has demonstrated with operational units that reasonably good performance can be realized over a fairly wide thrust range (1/2 to 25 lbf) if normal care is exercised and correction factors for density changes due to gas solubility are considered. The device is fairly fool proof and can indicate leakage or other operational difficulties because of its high tracking sensitivity. The current manual model is undergoing redesign to provide a cleaner, lighter unit with an additional digit in the counter so that the accuracy can be doubled by reducing the current ±.001 inch error limit to ±.0005 inch or better. A precision lead screw will be used in place of the current rolled thread screw to provide more precise tracking, and a servo driven unit is being considered for engineering and operational feasibility. It is believed that such a unit could closely approach the tracking precision of a manual device.

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