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Space Shuttle Hypergol Load Determination Using Nonintrusive Ultrasonic Flowmeters

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ABSTRACT

Space Shuttle preflight hypergol oxidizer and fuel loading at John F. Kennedy Space Center (KSC) was monitored using a nonintrusive flow measurement system (NFMS) during the preflight operations. A pair of 4-megahertz ultrasonic transducers measured the flow rate using a transit-time flow measurement technique. Using cellular phone technology, flow-rate data was remotely monitored and recorded. Excellent correlation was observed between the flow profiles measured using the proposed nonintrusive ultrasonic flowmeters (UFM's) and the conventional intrusive turbine flowmeters (TFM's). Based on the preliminary tests, it is concluded that the nonintrusive method of flow measurement has the same or higher accuracy, is simpler to use, and costs less than the existing TFM. Benefits of UFM's include a highly flexible, cost-effective, reliable, hazardfree, and streamlined hypergol operation. Redundant installation of ultrasonic flowmeters was recommended for additional launches prior to the replacement of the existing TFM's.

INTRODUCTION

Space Shuttle hypergol operation (S0024) entails loading of fuel monomethylhydrazine (MMH)] and oxidizer (nitrogen tetroxide) into the orbital maneuvering system (OMS) and reaction control system (RCS) tanks. The filling operation must be precisely controlled to ensure the correct amount of fuel and oxidizer is transferred to the Shuttle for each mission. Accuracy of loading, however, involves measurement of the flow rate through three [two 0 to 10 gallons per minute (gpm) and one 0 to 60 gpm] inline TFM's per system, which must be accurate and functional. Preflight loading is accomplished approximately a week prior to the Space Shuttle launch and involves oxidizer loading on the first day followed by fuel loading. Oxidizer and fuel farms in the launch configuration are shown in figures 1 and 2.

Past experience with TFM's indicates they are prone to failure. Accuracy of measured flow rates is affected by quantization bits, calibration errors, sampling, logic, timing errors, etc. Also, significant direct costs are associated with the removal and replacement of TFM's after each launch. Moreover, mandatory hazardous Self-Contained Atmospheric Protective Ensemble (SCAPE) operations during S0024 alone cost over $38,000 a year. S0024 operations are timeconsuming since some of the loading is accomplished using the two 0-to-10-gpm TFM's and since the 0-to-60-gpm TFM's are inaccurate at low flow rates. Lastly, indirect costs attributable to decontamination, rebuilding, recertification, and handling further add to the overall costs, which potentially may exceed $100,000 annually. These factors strongly justify the need for replacement of the existing TFM's and for the development of newer flow measurement techniques.

NONINTRUSIVE FLOW MEASUREMENT SYSTEM

The purpose of the present effort was to develop a nonintrusive flowmeter system to replace the existing TFM's presently used. Precise measurement and validation of fuel and oxidizer Space Shuttle loads are paramount, especially in light of the amount of fuel expenditure required for Mir docking and other activities involving satellite retrieval and deployment. The goal was to totally eliminate hazardous and costly SCAPE operations and costs attributable to TFM replacement after each launch. Also, reduction in cumbersome Launch Processing System (LPS) post-processing steps was necessary to ensure data integrity while maintaining overall accuracy.

Ultrasonic Flowmeter

A highly versatile, self-contained, portable Panametrics TransPort Model PT868 UFM was adopted for the measurement of hypergol loads during S0024 operations. The proposed nonintrusive flowmeter system is composed of a pair of 4-megahertz transducers that are clamped onto the outside of the pipe and use the transit-time flow measurement technique. The sensor spacing is a function of pipe type, pipe size, and the characteristics of the liquid for which the flow rate will be measured. The two transducers serve as both an ultrasonic signal generator and a receiver and are in acoustic communication with each other. In operation, each transducer functions as a transmitter generating a certain number of acoustic pulses and then as a receiver for an identical number of pulses (see figure 3).

The time interval between transmission and reception of the ultrasonic signals is measured in both directions. When the liquid in the pipe is not flowing, the transit time downstream equals the transit time upstream. When the liquid is flowing, the transit time downstream is less than the transit time upstream. The difference between the downstream and upstream transit times is proportional to the flow rate or velocity of the flowing liquid, and its sign indicates the direction of flow. From the knowledge of flow velocity, other flow-related entities such as volumetric flow and total flow are computed.

The TransPort flowmeter uses built-in digital signal processing (DSP) techniques to display a variety of flow-related parameters. Measurements can be monitored and logged in real time. Increased accuracies are attainable since measurements are made without any pressure drop or pipeline obstruction as in the case of the TFM.

Use of nonintrusive clamp-on transducers means no leaks, corrosion, contamination problems will arise as a result of their use and costly and hazardous SCAPE operation will not be required. Because the UFM has no moving parts to wear or orifices to clog, it does not need regular maintenance. Since UFM's can accurately measure high and low flow rates, S0024 loading duration could possibly be reduced, thereby further minimizing total labor costs.

Pad Installation

The primary purpose of this project was to develop an alternative to the existing TFM's used to make flow measurements during S0024 operations. Therefore, to arrive at a valid comparison of accuracies, both the existing and proposed systems had to be simultaneously installed at the launch pad. Since the actual amount of hypergol loaded into the Space Shuttle tanks must pass through the 0-to-60-gpm TFM, UFM's were instrumented on the 0 to 60 gpm TFM piping. Ultrasonic flowmeters were first implemented on the Rotating Service Structure (RSS) at the 107-foot level (see figures 1 and 2) and on Launch Pad B prior to the commencement of STS-75 S0024 operations. Demonstrations of the proof-of-concept setup were planned for several S0024 propellant loading operations.

Figure 4 illustrates the launch pad installation of nonintrusive, UFM's for the measurement of the hypergol flow rate. Oxidizer pipes and fuel pipes were installed with two sensors located downstream from the 0-to-60-gpm TFM and were oriented vertically. An extra sensor was placed on the horizontal section of the fuel pipe upstream from the 0-to-60-gpm TFM. Redundant sensors provided valuable insight into the disturbed flow pattern induced by the TFM and the influence of the vertical/horizontal UFM orientation.

A unique and innovative way of monitoring and recording flow-rate data was necessary to eliminate any interference with the ongoing S0024 operations. Similar to redundant sensors employed in data acquisition, a redundant method of recording and storing data was essential. Since the SCAPE operation negated the presence of operators, a cellular data acquisition system (COREXCO) was specifically acquired and significantly enhanced to monitor flow parameters, control various recorders, and transfer flow data remotely.

Wireless technology allowed for the processing of flow-rate data and its near real-time display in a remote location. The data acquisition system (DAS) digitized and stored the data to memory and then, at the command of the software running on a remote personal computer, transmitted the data using cellular phone technology. Thus, the transmitted data was recorded locally at the launch pad and at the remote site, while being viewed near real time and compared against TFM data. Data recording was composed of COREXCO memory (1 sample per second) and a

Panametrics log file (1 sample every 5 seconds). Data was downloaded at the end of the loading operations for further processing and comparison with TFM data.

The DAS was powered continuously from a 28-volt-direct-current (V dc) power supply available during S0024 operations. Except for cabling, the DAS and sensors were placed on the launch pad only during the hypergol operations and were removed prior to the Space Shuttle launch for safety reasons. The DAS components are shown in figures 5 and 6.

Launch Pad Measurements

To date, ultrasonic flowmeters have been used to measure hypergol loading during four separate S0024 operations. In each case, both oxidizer and fuel flow were measured using UFM's, and the subsequent results were compared with data normally used by launch pad engineers and technicians performing the actual operations. For brevity, only pertinent data from STS-76 is presented in this report.

Measurements made during S0024 operations prior to the launch of STS-75 were the first successful demonstration of a cellular-phone-based DAS on the Space Shuttle launch pad. Excellent results were obtained in the real-time mode of operation. Approximately 15 points were recorded at the remote site (NASA/KSC Headquarters Building) and subsequently overlayed on the TFM data from the fuel loading. Since the UFM system was battery operated, limited data was obtained. However, the correlation of data from ultrasonics and turbines was excellent.

Significant enhancements to the UFM DAS were necessary to optimize system performance and increase battery life. Prior to the STS-76 loading, the UFM system was interfaced with the launch pad power supply (28 V dc) to charge the batteries to allow for continuous data recording during the entire S0024 operations covering 2 days. The complete data from the oxidizer and fuel loading performed on March 7 and 8, 1996, are included in figures 7 and 8, respectively. In both figures, the top plot represents UFM data and the bottom portion reflects data measured by the 0-to-60-gpm TFM.

The flow profile plots from TFM's and UFM's are nearly identical. This implies that the area under the curves signifies the total amount of fuel loaded in gallons for all four tanks. The left and right OMS tanks were loaded first, followed by the left and right RCS tanks. Typically, it takes about 3 hours to load all four tanks and almost 10 to 12 hours of total time, inclusive of preloading preparation and postloading closeout. This process is repeated for fuel loading on the following day. Oxidizer load data was compared with the ultrasonic data recorded in the Panametrics log file (1 sample every 5 seconds), and the fuel data was obtained from the COREXCO memory buffer (1 sample per second). Despite this fact, the two data acquisitions seemed equally accurate in predicting the flow into the Shuttle. The relative error between the TFM and UFM data is about 2 percent (20 to 25 gallons out of a load of 1200 to 1300 gallons) and does not imply that one system is more accurate than the other. Measurements made by two different UFM DAS's are very similar to the total load data from the TFM. UFM sensors downstream from the TFM indicated a flow disturbance due to the inline TFM.

Laboratory Calibration

Launch pad measurements provided valuable insights into the accuracy of flow data measured using TFM's and UFM's. However, to assess true differences between the UFM's and TFM's under ideal conditions, a closed-loop volumetric liquid flowmeter calibration system (COMTRAK) was used. The COMTRAK system is presently used to calibrate all TFM's. The overall system accuracy of 0.01 to 0.05 percent is possible with calibrations traceable to National Institute of Standards and Technology (NIST) standards. The calibration objectives were:

1. To evaluate "true" variability between the TFM and UFM in a controlled study

2. To accurately simulate oxidizer and fuel launch pad flow geometry

3. To assess horizontal versus vertical launch pad TFM calibration

4. To evaluate the presence of the TFM in the flow path on UFM readings

5. To document the effect of the UFM sensor location along the flow geometry

6 To quantify TFM and UFM errors at low, medium, and high flow rates

7. To calibrate the UFM to NIST standards and compare it with the TFM

Figure 9 shows the setup used in the laboratory calibration. Of significance is the fact that the calibrations were performed using specially fabricated pipe sections to simulate the actual launch pad geometry of oxidizer and fuel skids. The oxidizer section prominently features a flat top as opposed to the fuel section. To closely simulate launch pad flow conditions, the TFM was mounted vertically (typically TFM's have been calibrated horizontally). Lastly, to eliminate turbine-induced flow effects, fuel tests were done with and without an in-line TFM. Calibration tests were made using water instead of hazardous hypergols. Analysis of the data featured a comparison of three separate sets of measurements: TFM, UFM, and the calibrator (test standard) itself.

Table 1 summarizes the results from the calibration effort. It is clear that the traditional way of horizontally calibrating TFM's adds approximately 0.6 percent to the error. The presence of the TFM in the fluid path affects the downstream UFM significantly more than the upstream UFM. The significant error observed between the downstream UFM and the TFM was enhanced by the pipe curvature. Significant error reductions materialized when the TFM was removed. The UFM placed upstream and on the horizontal section of piping yielded the lowest errors (0.3 to 1.1 percent). Comparison of data from the UFM oxidizer and fuel calibrations with the inline TFM yielded 2 to 4 percent errors, partly attributable to the pipe geometry. With the TFM offline, errors were in the range of 0.3 to 1.1 percent, indicating the strong influence of inline TFM's on the flow. Optimal placement of UFM's coupled with the offline TFM resulted in overall loading accuracies in the range of 0.25 to 0.5 percent, which are desired for hypergol operations. Such accuracies may not be possible with the use of the existing TFM's.

RESULTS AND DISCUSSION

The results of the NFMS installed on a noninterference basis clearly demonstrated the relative ease of using the UFM's in the current configuration. Based on the flow profiles, it is evident that the UFM was capable of measuring overall gallons delivered to the Shuttle accurately. In actual use, the overall accuracy of flow measurements using UFM's was as good or better than the TFM. Additionally, true performance of the TFM's in the highly corrosive environment of MMH (Shuttle fuel) and nitrogen tetroxide (Shuttle oxidizer) is unknown. To date, accuracy studies have not been performed, and the calibration has not been done with these fluids. Also, the effect of these fluids on TFM bearing performance is not fully known. These issues are of no consequence since UFM's are nonintrusive in nature and have no moving parts.

NIST-traceable bench calibration is the best method for verifying flowmeter accuracies at KSC. However, the calibration assumes that the actual fluid has the same characteristics as water. Calibrations are performed with the TFM mounted horizontally rather than in the vertical position it assumes at the launch pad, and varying launch pad pipe geometry sections for fuel and oxidizer are not simulated. Results from the NIST-traceable bench calibration performed on the UFM's and TFM's attest to the fact that UFM's are within the same accuracy range as TFM's. Calibration done using the identical medium (water) in a controlled environment and with accurate simulation of the correct launch pad pipe geometry profoundly shows the accuracy and repeatability of UFM's. Although the issue of optimum location (upstream of the TFM on the horizontal pipe section) for mounting UFM's is of importance, such adaptance to the launch pad is trivial.

Establishing total system errors is important so that the total amount of propellant loaded (crucial to the success of each mission) in the Shuttle is documented. This necessitates performing an end-to-end calibration to account for all TFM system components, from the sensor to the Launch Control System where the data is read and interpreted. The importance of ground support equipment totalizers cannot be underestmated since the onboard (vehicle) totalizers do not work about 50 percent of the time on the ground and are not functional in the weightless environment of space. If propellant were to leak out unnoticed while in orbit, the orbiter could literally run out of the propellant for deorbit operations.

An accurate and reliable onboard sensor must be developed. The use of Ultrasonics and advanced data processing techniques is one of the best choices. This method would facilitate the accurate measurement of fluid levels in Earth's gravity and an approximate value in space. This sensor must also be the nonintrusive type, which would enable an economical retrofit. Use of ultrasonic technology will significantly enhance the measurement capability and reliability of onboard sensors.

CONCLUSIONS

The proposed UFM's provide a definite and marked advantage over the existing TFM's. In addition to being totally nonintrusive, they have no moving parts and are not prone to leaks, vibration, or contamination. Ease of installation and quick relocation makes them widely acceptable. The proposed UFM's are extremely economical to operate since they never wear out mechanically and do not require maintenance or calibration after each launch. They can detect empty pipes, semi-filled pipes, and reverse flows. Since UFM's accurately measure low and high flow rates, the S0024 flow-filling duration can be reduced by half. Lastly, UFM's do not require hazardous SCAPE operations.

Based on the present effort of launch pad measurements and laboratory calibration, it is clear that UFM's are as accurate as TFM's. UFM's would help in achieving the desired long-term system loading accuracy in the range of 0.5 to 1 percent, presently not feasible with the TFM. With TFM's, one can expect short-term system accuracies in the range of 0.75 to 2 percent. Long term and short term refer to the length of time the flowmeters are installed in the application lines and exposed to corrosive fuels and the oxidizer. Additional benefits derived from savings in direct and indirect costs and elimination of unneeded operations make UFM's advantageous for application to future S0024 operations and other operations requiring precise flow measurements. The Space Shuttle postflight propellant tank residuals are typically in the range of 5 to 7 percent, which leaves no appreciable margin for flow measurement errors. Additional validation work, however, is essential before implementing UFM's for S0024 operations.

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1. Briefing Note to Mr. Walter Murphy, Director, Engineering Development, NASA Kennedy Space Center, February 26, 1996.

2. Space Shuttle Hypergol Flow Rate Measurements With Ultrasonic Flowmeters During S0024, NASA KSC internal document, unpublished, July 12, 1996.

Table 1. Calibration Results

Comparisons	Percent Error
TFM orientation errors - Horizontal versus vertical calibration	0.6
UFM and TFM (oxidizer setup): TFM inline - Horizontal UFM versus vertical TFM - Vertical UFM versus vertical TFM	0.3 to 1.3 4 to 9
UFM and TFM (fuel setup): TFM inline - Horizontal UFM versus vertical TFM - Vertical UFM versus vertical TFM	2 to 4 6 to 18
UFM and calibrator (fuel setup): TFM offline - Horizontal UFM versus NIST Calibrator - Vertical UFM versus NIST calibrator	0.3 to 1.1 2 to 13

Note: Pad fuel pipe setup had a continuously larger radius bend, which allowed a flow disturbance to propagate further.

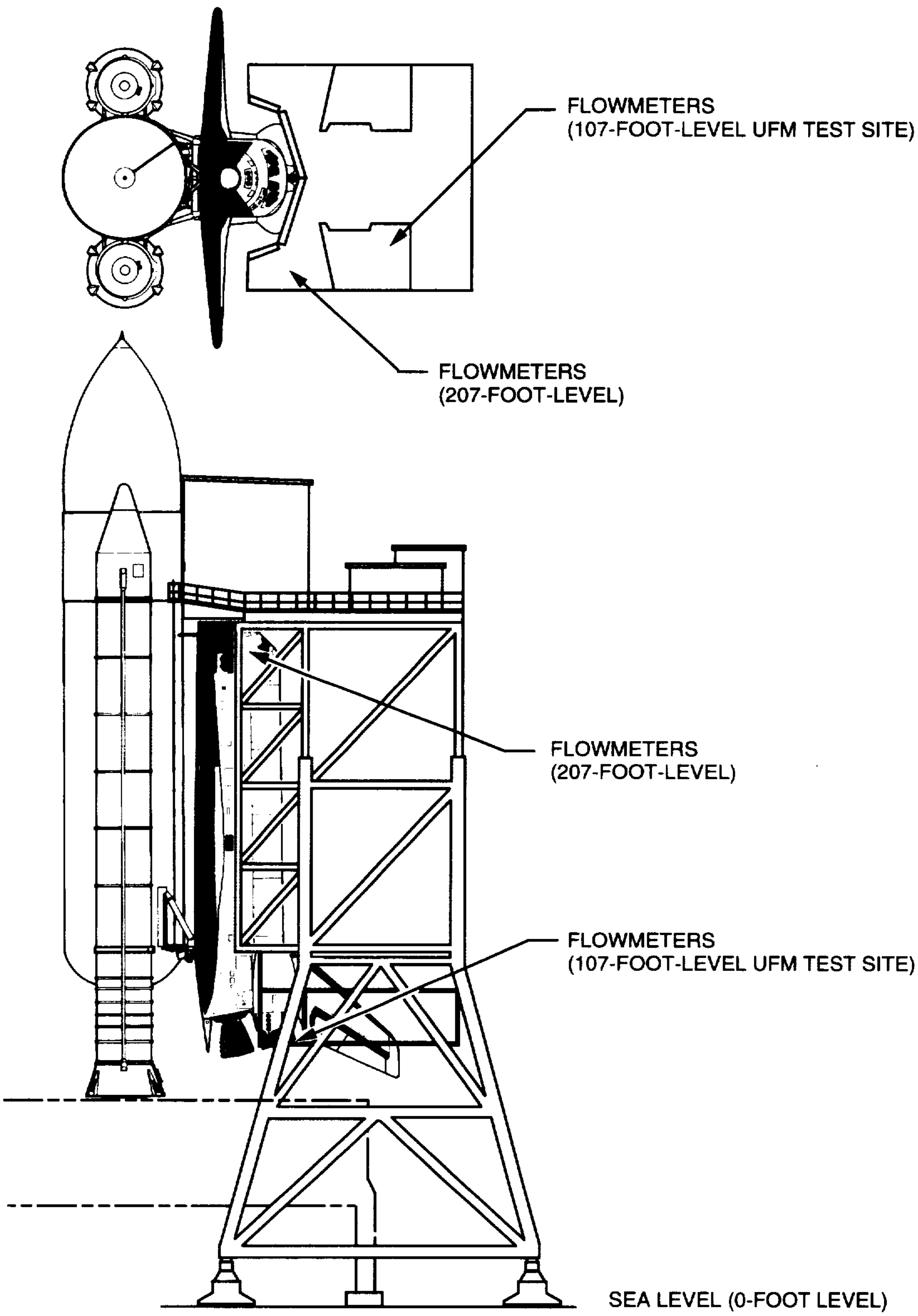


Figure 1. Location of Oxidizer and Fuel Farms of the Hypergol System

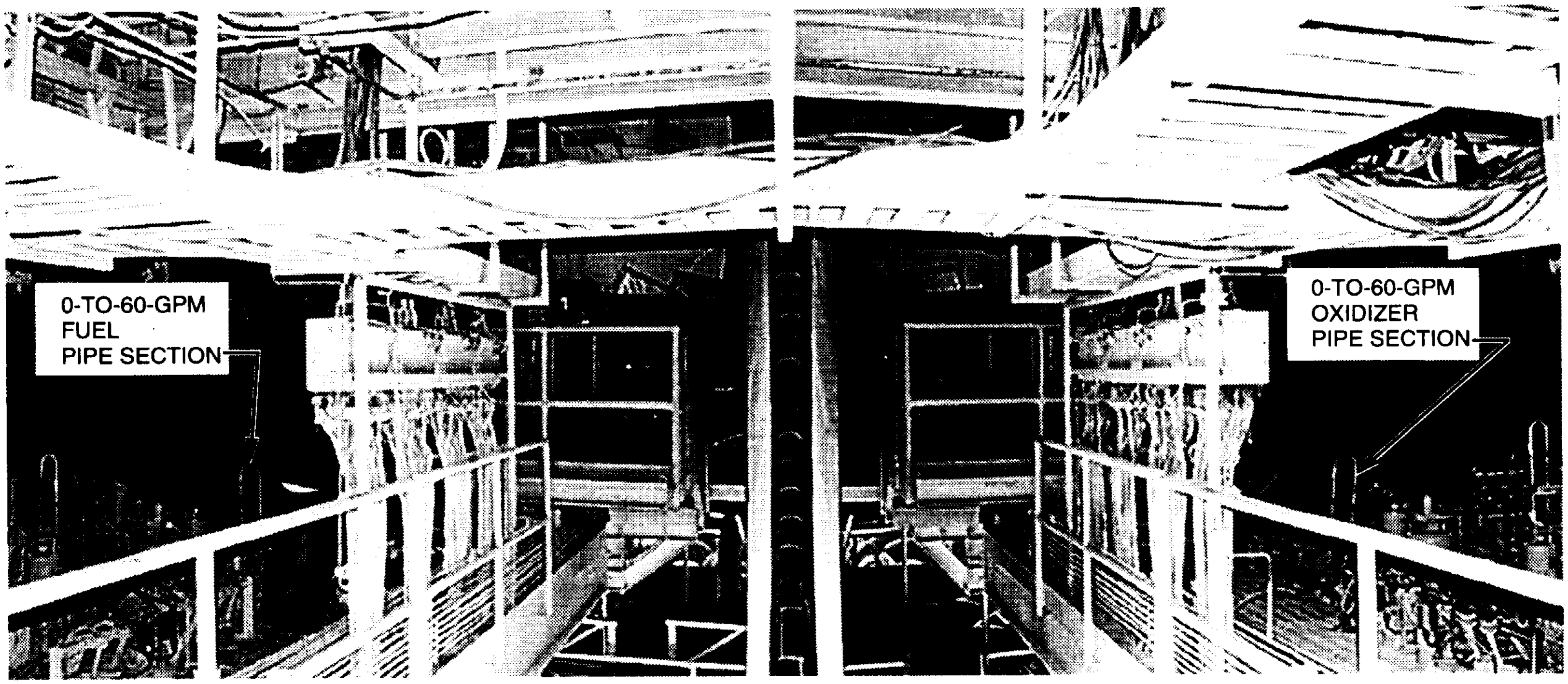


Figure 2. Oxidizer and Fuel Farms at the 107-Foot Level

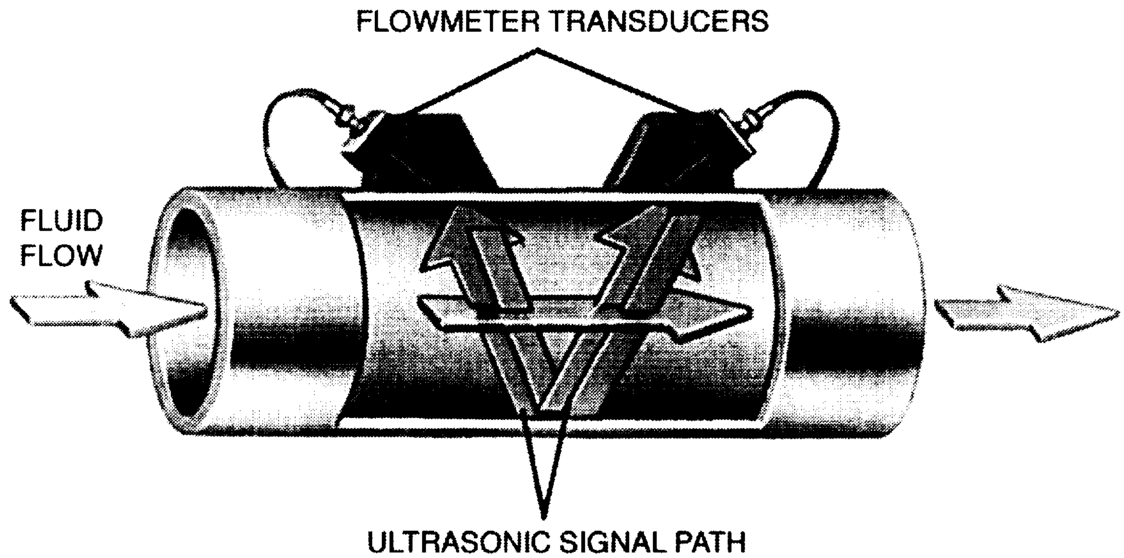


Figure 3. Transit-Time Flow Measurement Technique

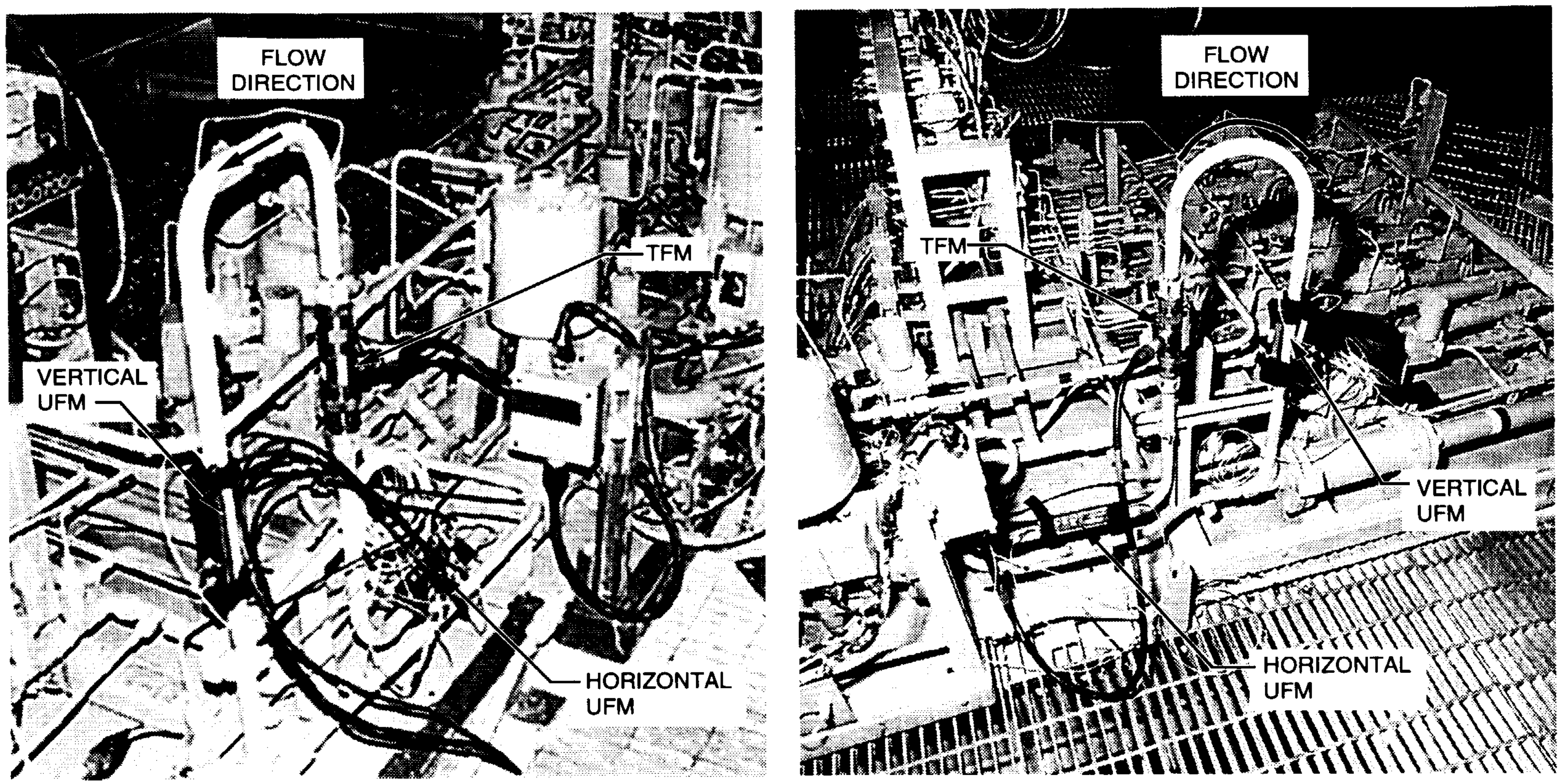
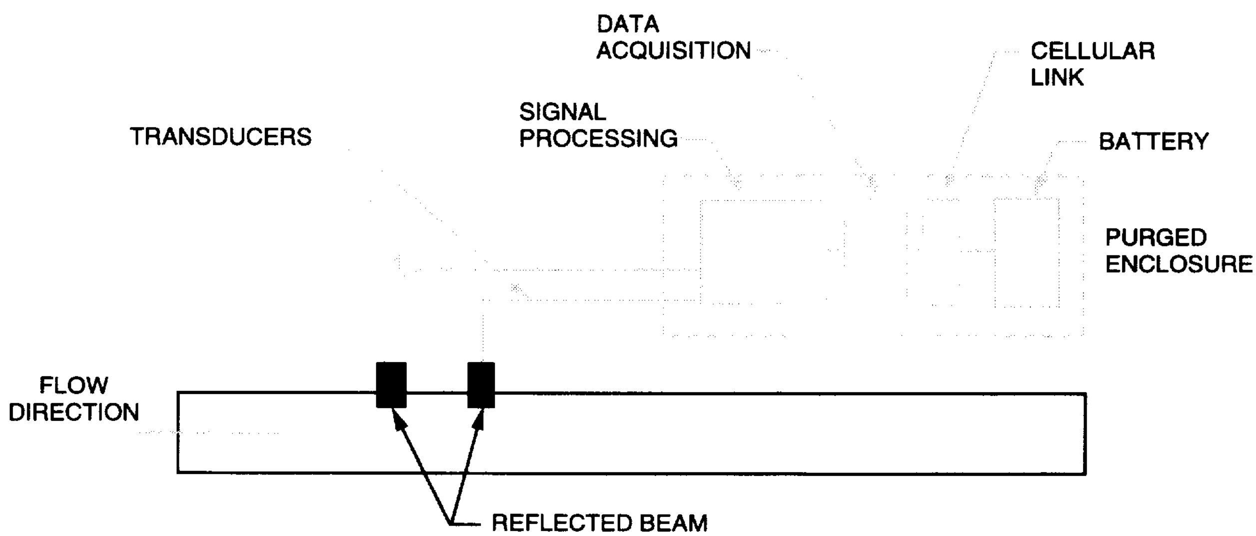


Figure 4. Launch Pad Installation and Measurement Setup



NOTE:

SIGNAL PROCESSING CALCULATES THE DELTA TIME BASED ON THE DIFFERENCE IN TRANSIENT TIME WITH FLOW AGAINST FLOW. THE TRANSDUCERS BOTH SEND AND RECEIVE ULTRASONIC PULSES.

Figure 5. Typical Launch Pad Installation

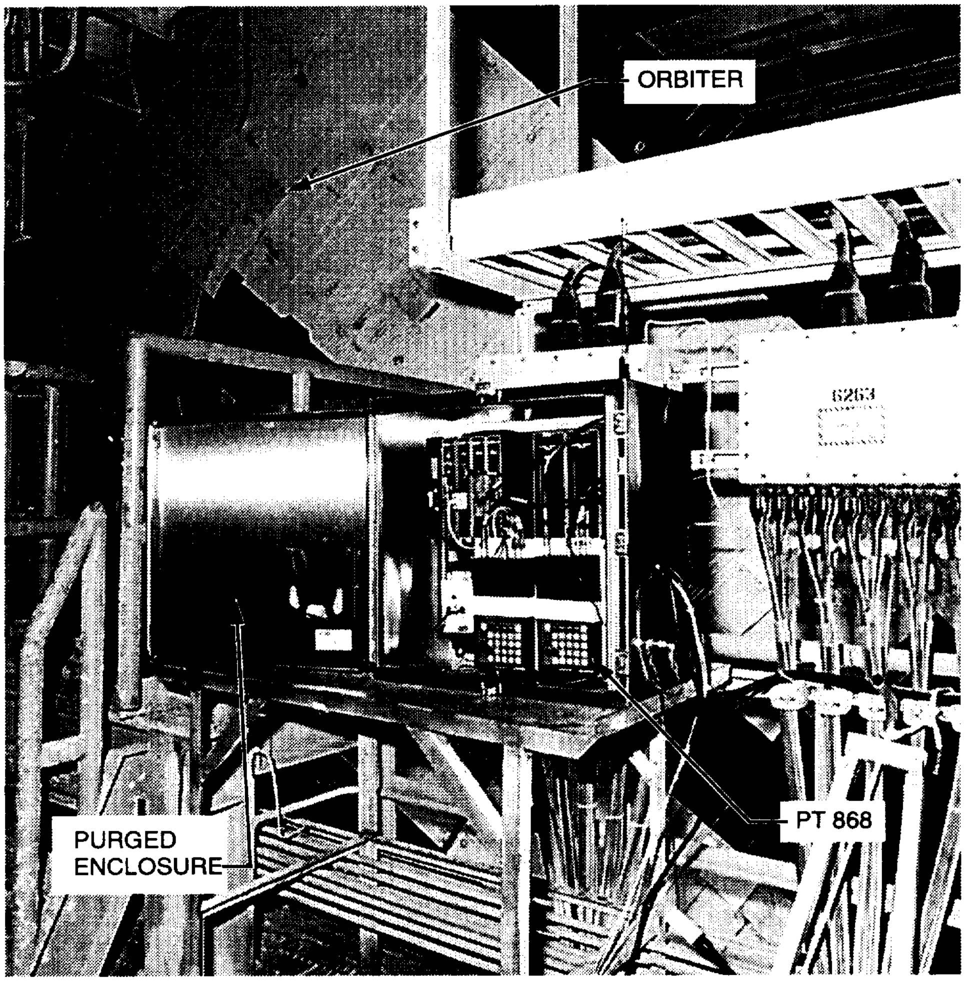


Figure 6. Data Acquisition System Console

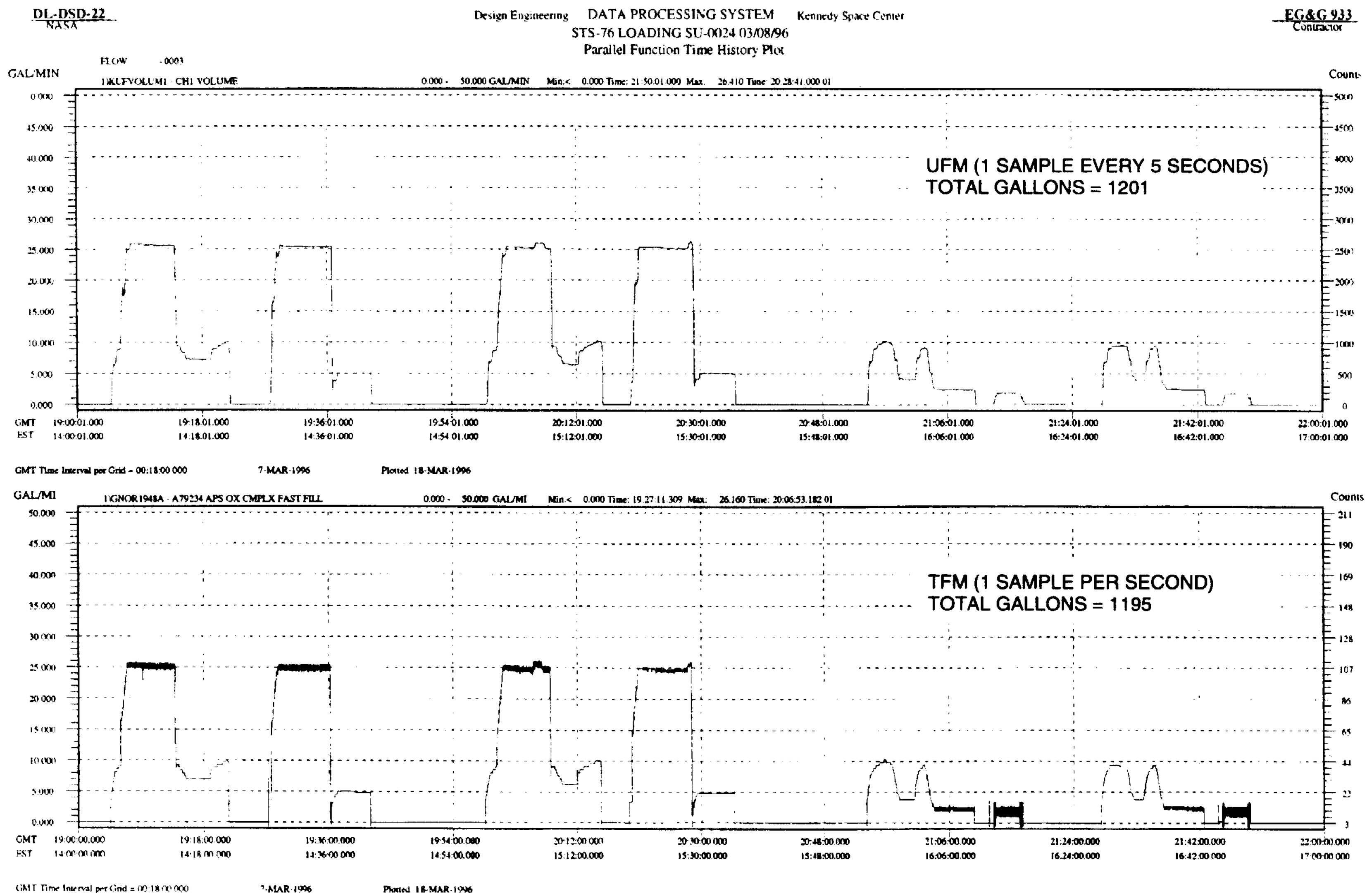


Figure 7. Launch Pad Measurements Comparing TFM Data and UFM Data Measured Using Panametrics PT 868 (1 Sample per 5 Seconds)

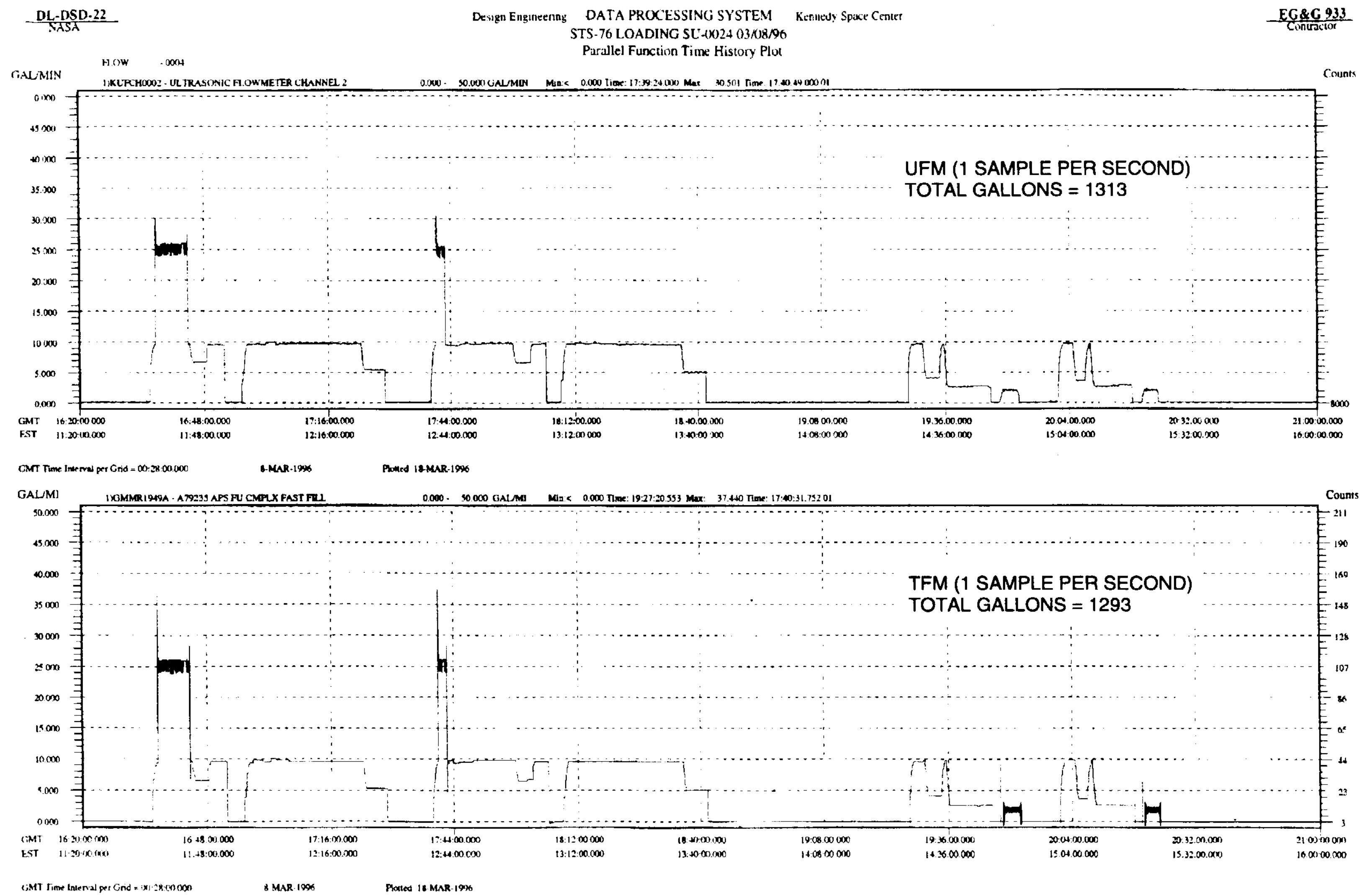


Figure 8. Launch Pad Measurements Comparing TFM and UFM Data Measured Using COREXCO (1 Sample per Second)

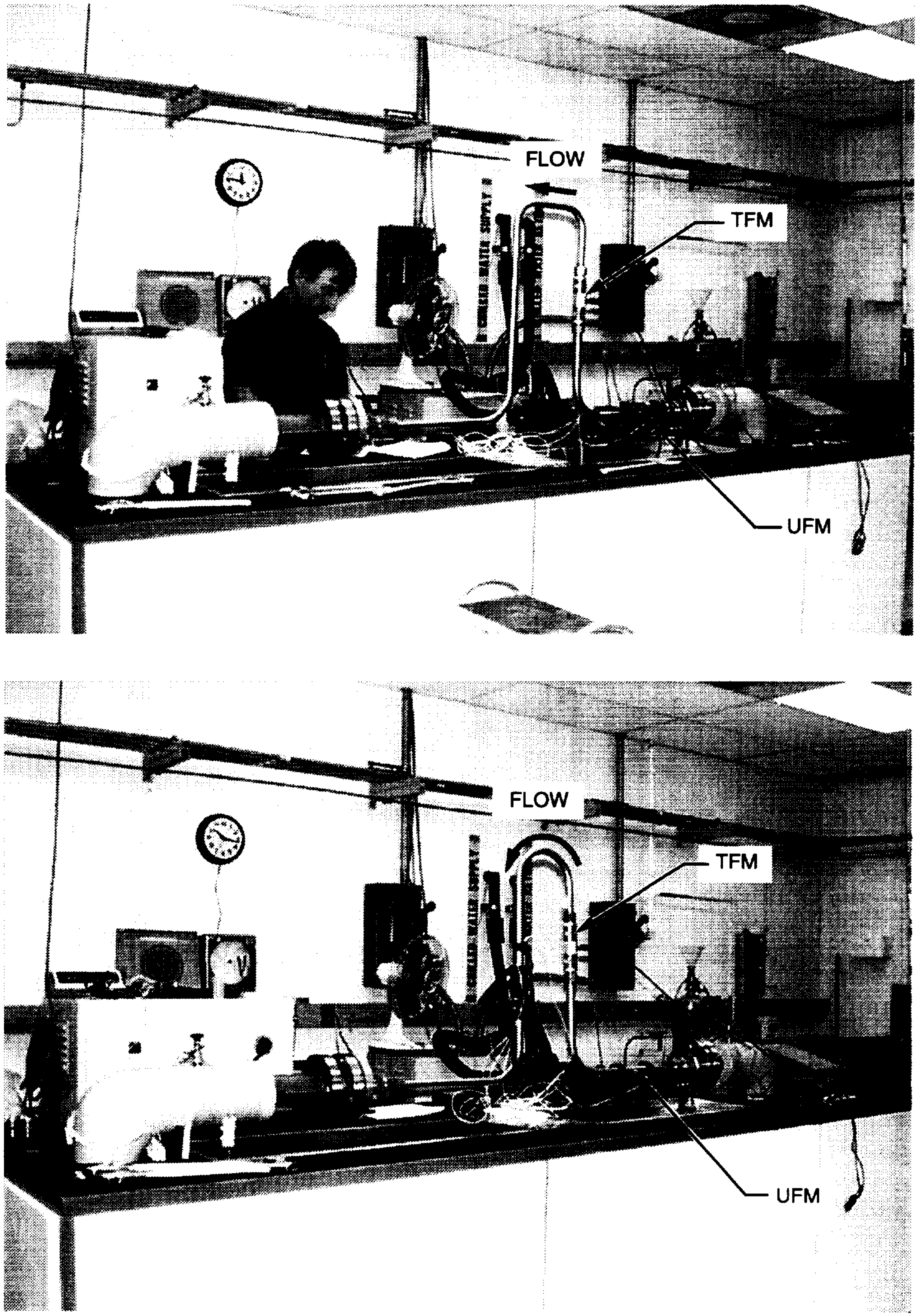


Figure 9. Laboratory Calibration Setup Showing Oxidizer and Fuel Pipe Sections

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13. ABSTRACT *(Maximum 200 words)*

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