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EVALUATION AND DEMONSTRATION OF A PROPELLANT QUANTITY GAGING SYSTEM FOR AUXILLIARY PROPULSION SYSTEMS

By

S.R.Tate and R.J. Hromadka

Final Report

Contract NAS8-21488

Prepared for

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

George C. Marshall Space Flight Center

February 1970

THE MARQUARDT COMPANY

Propulsion Division

Van Nuys, California

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ABSTRACT

A propellant quantity gaging system for auxiliary propulsion systems utilizing earth storable propellants has been investigated. The gaging system utilizes a sensor and associated logic to determine the flow through the engine solenoid valves. A major advantage of this system is that it does not breach the electrical or propellant circuits of the propulsion system in any way. Multiple engines firing simultaneously to identical or different duty cycles may be monitored. The gaging system provides a digital output of the propellant remaining in the propulsion system at any time.

A breadboard and flight weight version of the gaging system were fabricated and used to demonstrate operation to typical space requirements. Analysis of mission errors and gaging system verification tests with a 22 lb thrust bipropellant engine demonstrated that a system accuracy of better than 2% can be obtained.

TABLE OF CONTENTS

LIST OF ILLUSTRATION

LIST OF TABLES

SUMMARY

The Propellant Quantity Gaging System (PQGS) is a device designed to monitor the propellants used by a bipropellant reaction control system and furnishes a digital readout of the system propellant remaining at any time during the mission. The gaging system was designed to operate with an auxiliary propulsion system similar to that planned for the "wet concept" Orbital Workshop.

In operation the gaging system measures the duration of engine firing by detecting the magnetic field generated when the engine solenoid valves are energized. This signal is processed in the sensor module electronics and provides a signal to decrease the count of the display module for each 0.1 pounds of propellant used by the engine. The sensing elements are based on the Hall effect principle and do not breach the propellant or electrical circuits of the propulsion system. The PQGS logic includes a compensation circuit which accounts for the higher initial flow that occurs during starting transients. This provides an accurate means of compensating for the transient flow that is important during short pulse width firings. The system is capable of monitoring engines firing individually or simultaneously to identical or to different duty cycles. The present PQGS uses one sensor per engine which may be used on either the fuel or oxidizer valve. The flight weight PQGS fabricated during the program was built to accommodate a system with three 22 lb thrust engines although the system may be expanded for any number of engines or engine sizes.

The accuracy of the PQGS is primarily dependent on the flow characteristics of the engine and the consistency and repeatability of the characteristics over the mission operating ranges and environments. The analysis of PQGS accuracy has been made for the Marquardt 22 lb thrust (model R-1E) engine operating to the requirements of the wet orbital workshop. Factors considered in the analysis are:

Loading accuracy
Engine to engine repeatability
Engine operating mode - steady state and pulsing
Propellant pressure
Propellant temperature
Engine valve voltage

The characteristics of the R-1E engine have been well documented over the ranges of interest to provide influence coefficients data. These data were used in a Monte Carlo analysis to predict a 3 sigma value for PQGS accuracy during a mission of $\pm$ 1.9%.

The first task in the PQGS program was the fabrication of a breadboard version of the PQGS. This unit was based on a unit developed during previous in-house test programs and used components and techniques contemplated for a flight weight version. The breadboard PQGS was subjected to bench tests at temperature extremes of 20°F and 120°F using a solenoid valve similar to the valve used on the R-1E engine. These tests indicated the need for several circuit modifications. The amplifier for the Hall effect sensor output was replaced with a higher gain amplifier because of excess temperature drift. The low temperature data also pointed out the need for voltage regulation in the voltage supply to the Hall effect sensors.

Operation of the breadboard PQGS was satisfactory in tests made at valve electrical pulse widths from 0.065 seconds to steady state operation and at the temperature extremes. A maximum error of 1.96% was indicated; occurring at the low temperature condition and at the minimum pulse width of 0.065 seconds.

The PQGS circuit modifications generated during the breadboard system tests were incorporated into the flight weight system. General characteristics of the completed flight weight PQGS are:

Weight - 2.4 pounds
Volume of electronic modules - 44 cubic inches
Voltage - 24 to 32 V d-c
Power - 5 watts at 25 V d-c
Maximum propellant indication - 999.9 lb
Minimum resolution - 0.1 lb
Number of sensors - 3

Checkout, calibration and bench test evaluation of the flight weight PQGS were completed satisfactorily.

Evaluation tests of the flight weight PQGS were conducted with a Marquardt model R-1E 22 lb thrust bipropellant engine. The flow and valve characteristics of this engine were used to calibrate the PQGS during bench tests. The engine test was conducted at sea level conditions using two of the Hall effect sensors each being mounted on one of the engine solenoid valves (fuel and oxidizer), thus providing an evaluation of the PQGS simulating two engines firing to the same duty cycle. Tests were conducted over the following conditions:

Pulse width from 0.065 seconds to 10.0 seconds
Pulse frequency up to 12 cps at 0.065 seconds pulse width
Engine valve voltage from 21 to 32 V d-c
Propellant temperatures from 20 to 120°F.

The cumulative error between the measured flow and that indicated by the PQGS did not exceed 1% during the evaluation tests and the final error, after 445 seconds of engine operation and 4,276 engine starts, was 0.4%.

The PQGS demonstrated the ability to accurately measure propellant flow in a bipropellant reaction control system over a range of operating conditions typical of a space mission. Recommendations are made to improve PQGS accuracy and to extend the sensing technique to the detection of solenoid valve malfunction.

INTRODUCTION

In spacecraft utilizing an auxiliary propulsion system for orientation and attitude control, a propellant gaging system is required to provide a continuous monitor of the propellant remaining at any time during the mission. The gaging system used on the attitude propulsion systems of the Apollo service and lunar modules utilized the changes in pressure and temperature of the fixed volume pressurant tanks for this purpose. Other more accurate gaging systems employing radiation or acoustic methods have been demonstrated but have not been fully developed for space vehicles.

Under National Aeronautics and Space Administration (NASA Contract NAS8-21488) The Marquardt Company designed, fabricated and tested a Propellant Quantity Gaging System based on the predictable and repeatable flow characteristics of bipropellant reaction control engines. Work under the contract included the analysis and construction of a breadboard gaging system which was used to evaluate circuit performance at high and low temperatures. A subsequent flight weight system was constructed and evaluated in engine tests under engine operating conditions typical of an Orbital Workshop. The unit was designed to provide an accuracy of $\pm$ 3% during a one year mission when used in an auxiliary propulsion system using the Marquardt model R-1E 22 lb thrust reaction control engines. The gaging system principle is applicable to other solenoid operated flow control devices for which adequate flow-time data is available.

The effort associated with this contract was conducted at The Marquardt Company facility Van Nuys, California during the period April 1969 through December 1969.

DESCRIPTION

Propellant Quantity Gaging System

The propellant quantity gaging system as shown in Figure 1 is composed of three basic elements:

Hall effect sensors
Sensor module
Display module

Information on the state of the engine propellant valves is collected by the engine operation sensors attached to the outside of the propellant valve bodies. These sensors are based on the Hall effect and provide a voltage output whenever magnetic field in the propellant valve is built up.

The outputs of the Hall effect sensors are processed by signal conditioning amplifiers and then used to gate clock pulses into a counter that accumulates a count proportional to the amount of propellant used. Compensation for the flow transient at the start of each pulse firing is provided by gating additional pulses to the counter for a short period at the start of each firing. This is accomplished by one-shot gate generating circuits that are triggered at the beginning of each engine firing.

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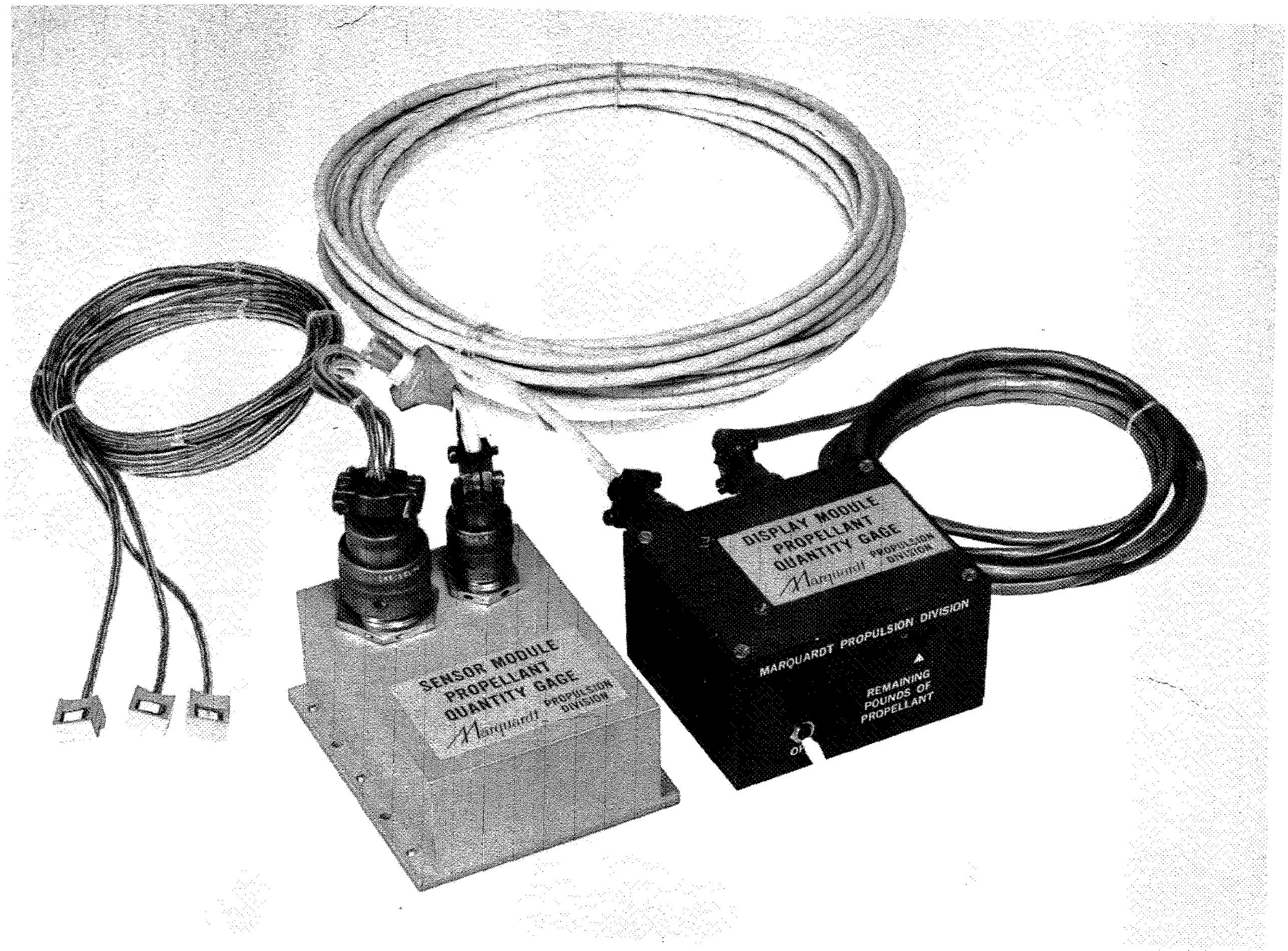


FLIGHTWEIGHT PROPELLANT QUANTITY GAGING SYSTEM

Figure 1

The clock pulses fed to the individual engine operation sensing gates are staggered in time so that the counter can accumulate them independently even in the case of multiple engine firing. This is accomplished by starting with a master clock frequency eight times higher than the frequency of the pulses fed to the individual gates. The train of master clock pulses is then processed by a divided by 8 counter which directs pulses 1, 9 and 17 to the first gate, pulses 2, 10 and 18 to the second gate, etc.

The pulses transmitted through the operation sensing gates and transient compensation gates are fed to an electronic countdown circuit which generates one output pulse each time it reaches a maximum preset count and is reset. Each output pulse decreases the magnetic counter display by one unit representing 0.1 lbs of propellant used.

The detailed operation of the PQGS is illustrated by the block diagram of Figure 2 and by Figure 3 which shows the voltage wave shapes at various points in the circuit during a time when two engines are being fired. Figure 3 shows the propellant valve electrical signals, the engine flow transients, the output of the engine operation sensors and the processes that convert the operation sensor outputs into a change in the indication of the quantity of propellant remaining.

When engine No. 1 is actuated, the magnetic flux from its oxidizer valve is sensed by the Hall effect sensor attached to the outside of the propellant valve body. The output of the Hall effect sensor is amplified and shaped by its signal conditioning amplifier into a square pulse whose duration is equal to the duration of the engine firing. This pulse is transmitted both to the engine operation sensing gate for engine No. 1 and to the differentiating circuit used to sense the beginning of a firing.

The differentiating circuit generates a single pulse at the start of the engine firing when it senses the leading edge of the pulse produced by the signal conditioning amplifier. This pulse is used to trigger the one shot circuit for engine No. 1 which produces a single pulse of fixed duration each time it is triggered by the output of the differentiating circuit. Both the engine operation sensing pulse and the pulse from the one shot (indicating the start of an engine firing) are fed to gating circuits designed to transmit clock pulses to the counter when a gating signal is present at the gate input.

During the period at the beginning of the engine firing, clock pulses are transmitted to the counter from both gates. When the one-shot generated pulse is complete, clock pulses are no longer allowed through the transient compensation gate. Clock pulses continue to flow to the counter through the engine operation sensing gate until the engine firing is terminated. The circuitry for the second engine behaves similarly to the circuitry for engine No. 1, gating pulses to the counter for the duration of the second engine firing with an extra burst of pulses being sent during the beginning of the engine firing to compensate for the transient flow during engine starting.

The pulses that reach the counter from the four gates associated with engines No. 1 and 2 eventually cause the count to reach the preset maximum count of the counter. When this maximum count is reached, the counter is reset to zero and an output pulse is sent to the display. The display is a magnetically actuated counter which indicates the quantity of propellant remaining in the propulsion system tanks. Its indication is decreased by one unit in the least significant

ELECTRICAL BLOCK DIAGRAM P.Q.G.S.

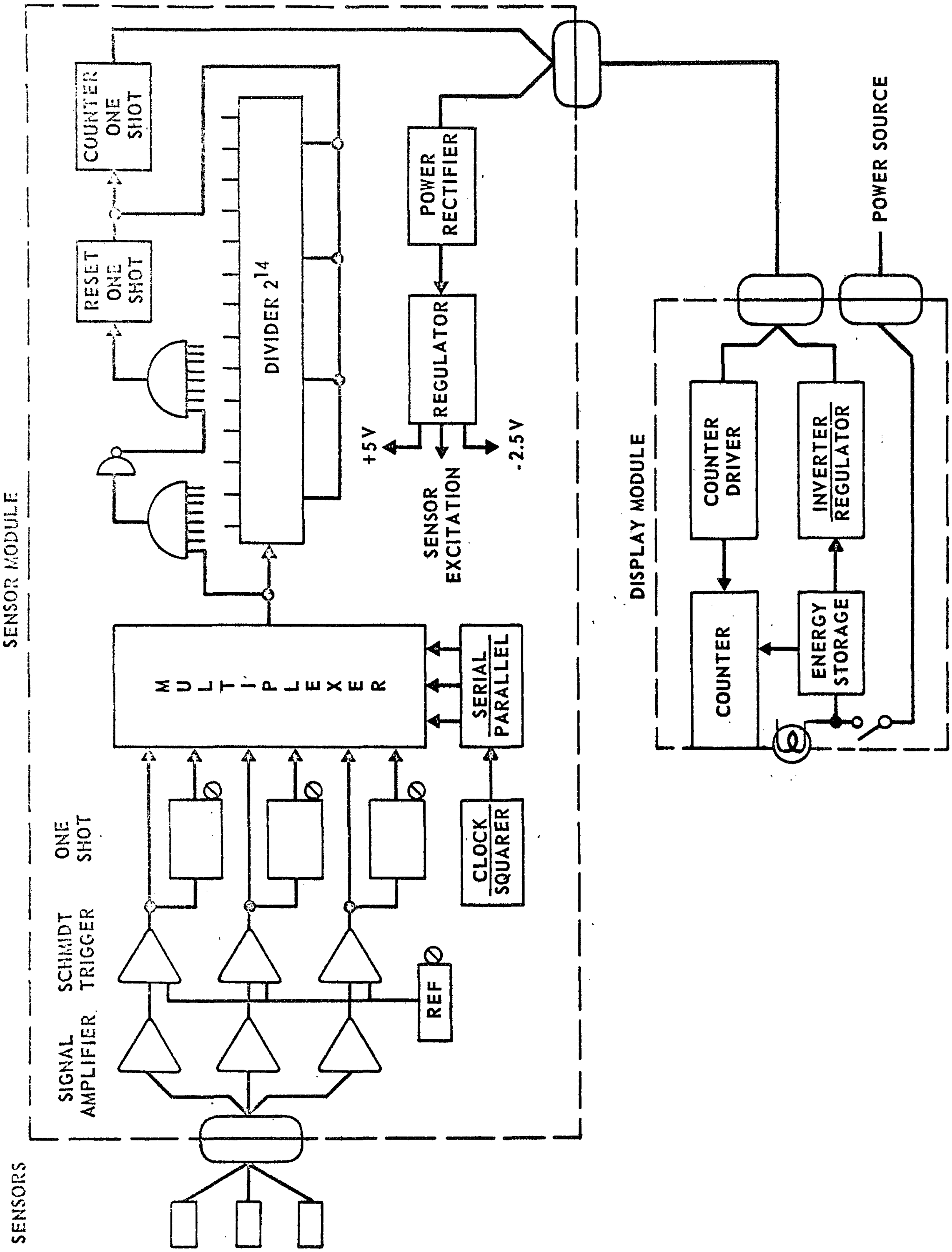
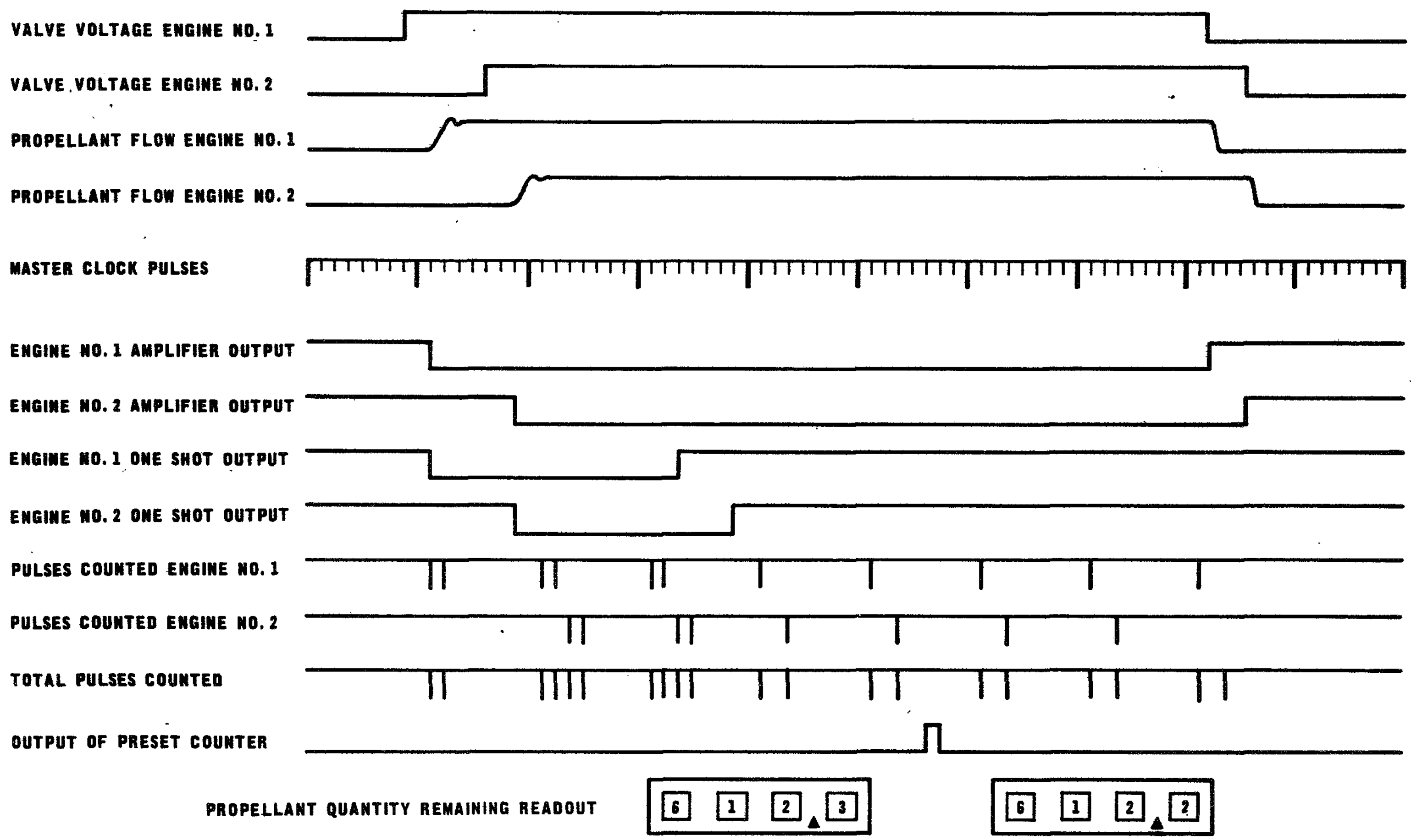


Figure 2

QUANTITY GAGING SYSTEM OPERATION



NOTE: ACCURACY OF CLOCK PULSE DENSITY HAS BEEN TRADED FOR CLARITY OF OPERATION.

Figure 3

bit each time it receives a pulse indicating the electronic counter has counted to its maximum value and has been reset. The system concept has the flexibility of providing telemetry signals or inputs to an on-board computer without major changes.

Engine

The analysis and calibration of the PQGS has been based on its use in a system with Marquardt's model R-1E engine. This engine is a radiation cooled bipropellant engine rated at 22 pounds of thrust. Basically the engine consists of a stainless steel injector head with a single doublet injector, two coaxial solenoid injector valves and a molybdenum combustion chamber and nozzle.

Extensive development and qualification of the engine have been completed on the MOL program and the performance and characteristics of the engine are well documented over a wide range of operation and environmental conditions. The R-1E engine was in the process of a design iteration for use on the Orbital Workshop, Figure 4, when the engine program was terminated due to the change from "wet" to "dry" concept for the workshop.

Error Analysis

The accuracy with which the propellant gaging system predicts the propellant remaining in an auxiliary propulsion system is dependent upon the flow characteristics of the engines in the system. Factors considered in predicting the over all mission accuracy are:

- Engine to engine repeatability
- Engine duty cycle
  - Engine pulse width
  - Engine off time (pulse frequency)
- Engine operating ranges
  - Engine solenoid valve voltages
  - Propellant temperatures
  - Propellant inlet pressures
- Propellant system dynamics
  - System configuration and location of components
  - Multiple engine operation
- Propellant quantity gaging system accuracy
  - Operating voltage sensitivity
  - Operating temperature sensitivity

ORBITAL WORKSHOP AUXILIARY PROPULSION ENGINE

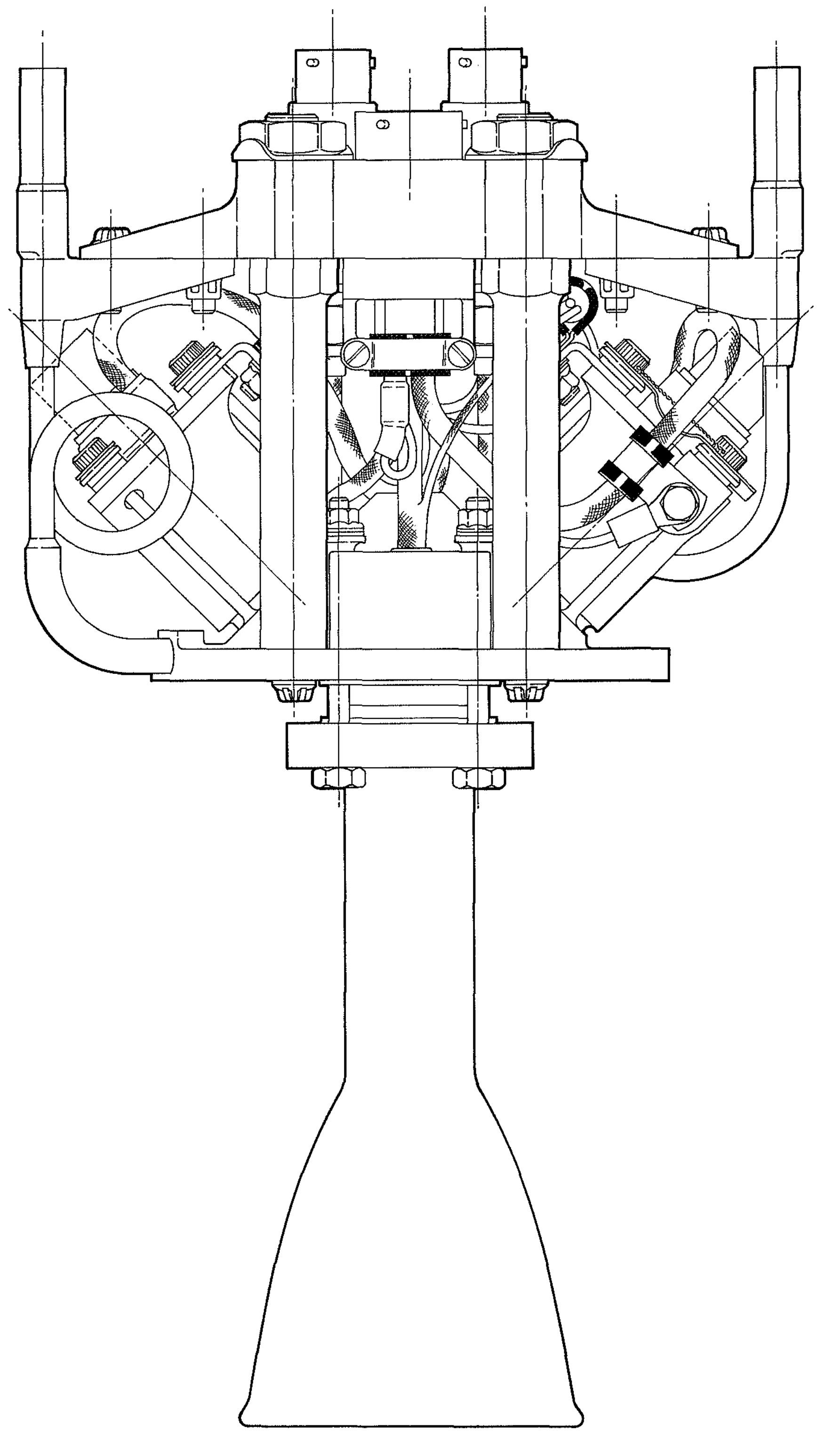


Figure 4

Engine to Engine Repeatability

An important consideration in engine to engine repeatability is the calibration conducted during engine acceptance tests. These calibrations establish the ultimate thrust level and mixture ratio (O/F) of the engine at nominal conditions of inlet pressure, propellant temperature and solenoid valve voltage. Since the R-1E engine has not been produced in large quantities, no large data sample is available for the engine. However, results of production tests of Marquardt's 100 lb thrust bipropellant R-4D engine indicates that engine to engine propellant flow rate repeatability of $\pm$ 1.2% (3 sigma) can be achieved. This data has been used in predicting the mission accuracy.

Flow Variations at Standard Operating Conditions

At a specific set of operating conditions of propellant inlet pressure, propellant temperature and solenoid valve voltage, the valve opening time, valve closing time and the variations in propellant valve ΔP as chamber pressure is being established become more significant as the pulse width is decreased. A plot of effective flow rate versus pulse width is shown in Figure 5. Effective flow rate is defined as the quantity of propellant used per pulse divided by the pulse electrical on time. This parameter emphasizes the effect on propellant consumption of conducting a mission at a particular pulse width. The decrease in effective flow rate at short pulse widths is the result of two conditions. First, the flow rate during the engine start is higher than the normal steady state flow rate due to the larger pressure drop ΔP that exists across the valve prior to the establishment of the combustion chamber pressure. The second more predominant effect is that the valve opening time, at nominal voltage, is longer than the valve closing time thus the total time the valve is open is shorter than the electrical pulse width. The effects of pulse width is adequately compensated for in the PQGS by the sensing of solenoid valve magnetic field buildup, and by the one shot feature that compensates for the start up transient.

Another factor contributing to the quantity of propellant used at short pulse widths is the duty cycle. As the off time between pulses becomes short the succeeding pulses are influenced by the pulse tail off characteristics and the system dynamic propellant pressures. The effects of off time between pulses is shown for the R-1E engine in Figure 6 for a pulse of sixteen milliseconds on time. In the duty cycle considered for the Orbital Workshop (minimum pulse on time 0.065 sec, maximum pulse rate 10 cps; i.e., minimum off time = 0.035 seconds) the effects on effective flow rate due to duty cycle are smaller than indicated on Figure 6.

Solenoid Valve Characteristics

The engine solenoid valve characteristics that influence propellant flow are primarily the changes in valve open and valve closing time due to changes in solenoid valve voltage, valve temperature and valve inlet pressure. Propellant temperature and inlet pressure also influence flow directly because of changes in propellant density and pressure drop.

R1E ENGINE

EFFECTIVE FLOW RATE vs. ELECTRICAL PULSE WIDTH

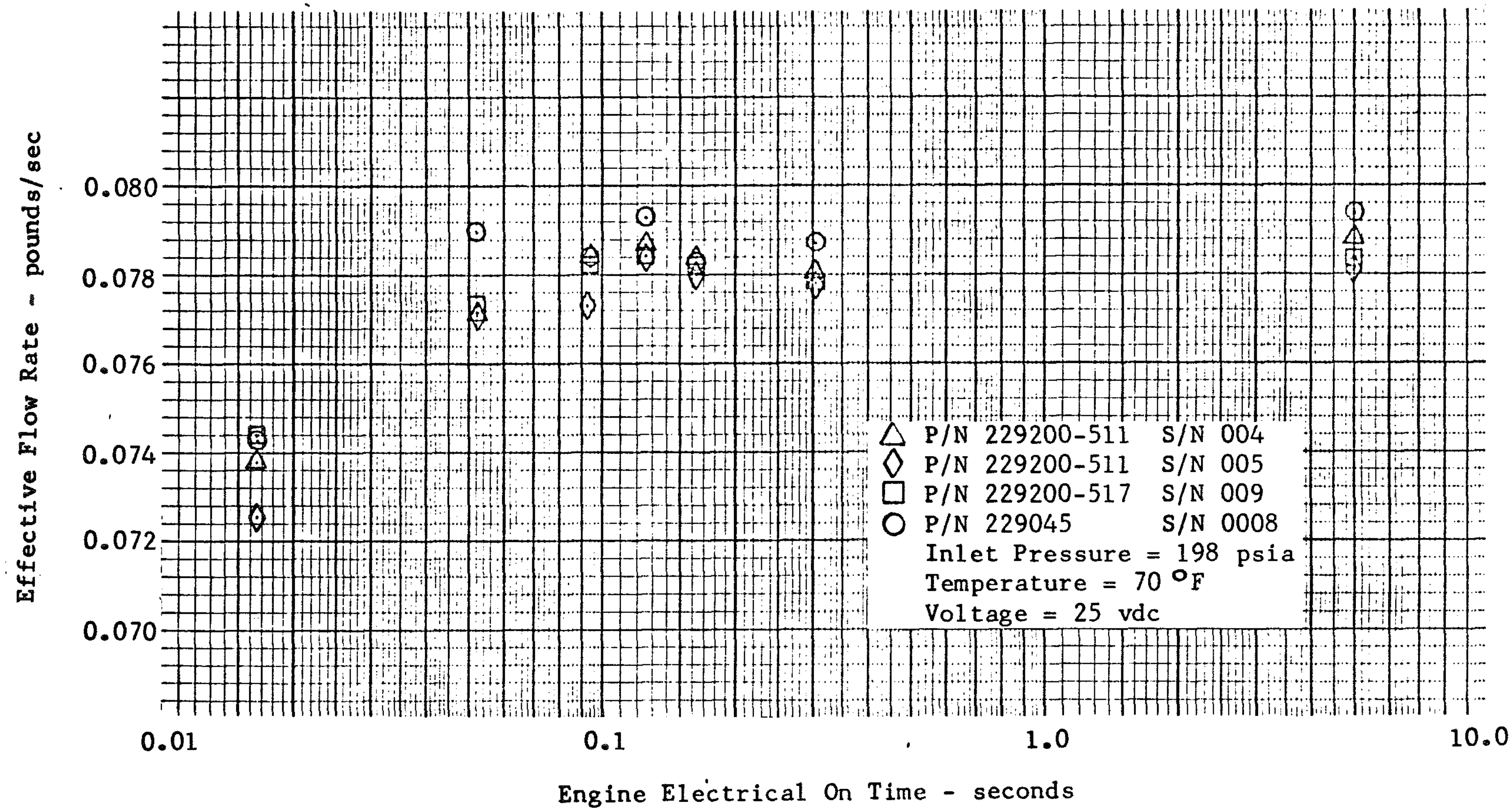


Figure 5.

R1E ENGINE

EFFECTIVE FLOW RATE vs. OFF TIME BETWEEN PULSES

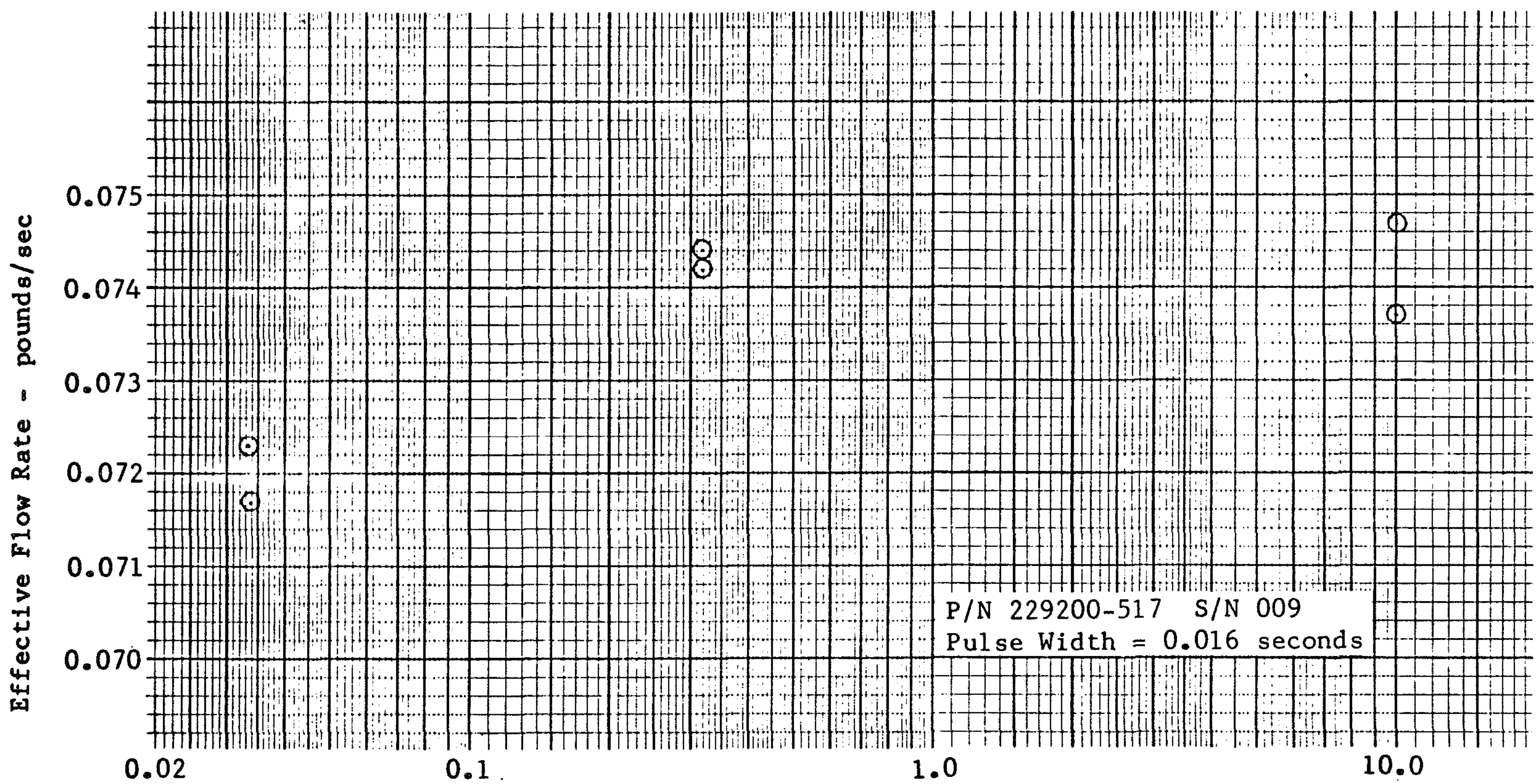


Figure 6

The effect of valve voltage on valve open time is readily seen from Figure 7 which shows solenoid valve current as a function of extremes in temperature and voltage. The time at which the valve starts to open is indicated at the initial inflection point in the curve and the time at which the valve is full open is the point at which the current starts to rise again. Table I shows the effective decrease in pulse width (difference between the electrical pulse width and time the valve is full open) as a function of solenoid valve voltage.

TABLE I

EFFECTIVE PULSE WIDTH DECREASE

VOLTAGE	OPENING TIME (MILLISEC)	CLOSING TIME (MILLISEC)	EFFECTIVE DECREASE (MILLISEC)
21	10.0	4.9	-5.1
25	8.1	5.1	-3.0
29	6.8	5.2	-1.6

Since the Hall effect sensor in the PQGS recognizes the buildup of magnetic flux when the valve is energized, the PQGS receives a signal proportional to the time the valve is actually open. Thus, the PQGS compensates for the changes in valve open time that occur because of the changes in solenoid valve voltage. Figure 8 shows influence coefficient data for the R-1E engine flow during a 16.5 millisecond pulse over a range of operating voltages. An estimate of the effects of minimum and maximum valve voltage on effective flow rate is shown in Figure 9 as a function of engine electrical on time. It can be seen that valve voltages have little effect on the effective flow rate for pulse widths longer than 0.500 seconds.

Flow Variations Due to Changes in Inlet Pressure

A variation in engine flow with inlet pressure is expected due to the change in the ΔP across the solenoid valve. Presently, the PQGS does not sense or recognize changes in propellant pressure. During R-1E engine tests on other engine programs the influence coefficients for independent changes in fuel and oxidizer pressure were determined. These are shown in Figures 10 and 11. The results of these data have been considered in the over all mission accuracy analysis.

Variations in Flow Due to Changes in Propellant Temperature

Changes in flow with propellant temperature have been well documented for the R-1E engine. These are shown in the influence coefficient data shown in Figures 12 and 13 for steady state operation. The anticipated influence of an increase in propellant temperature is for flow rate to decrease because of the decrease in propellant density. For the R-1E engine, engine flow rate is also influenced by the decrease in engine performance at high propellant temperatures (increase at low temperatures). This change in combustion chamber pressure results in a significant change in the pressure drop across the engine solenoid valves. Variation in flow per pulse due to temperature in the operating range is shown in Figures 14 and 15. The variations in the propellant temperatures were considered independently in the influence coefficient test program in order to account for possible differences in propellant tank temperatures.

TYPICAL R1E ENGINE SOLENOID VALVE OPENING RESPONSE

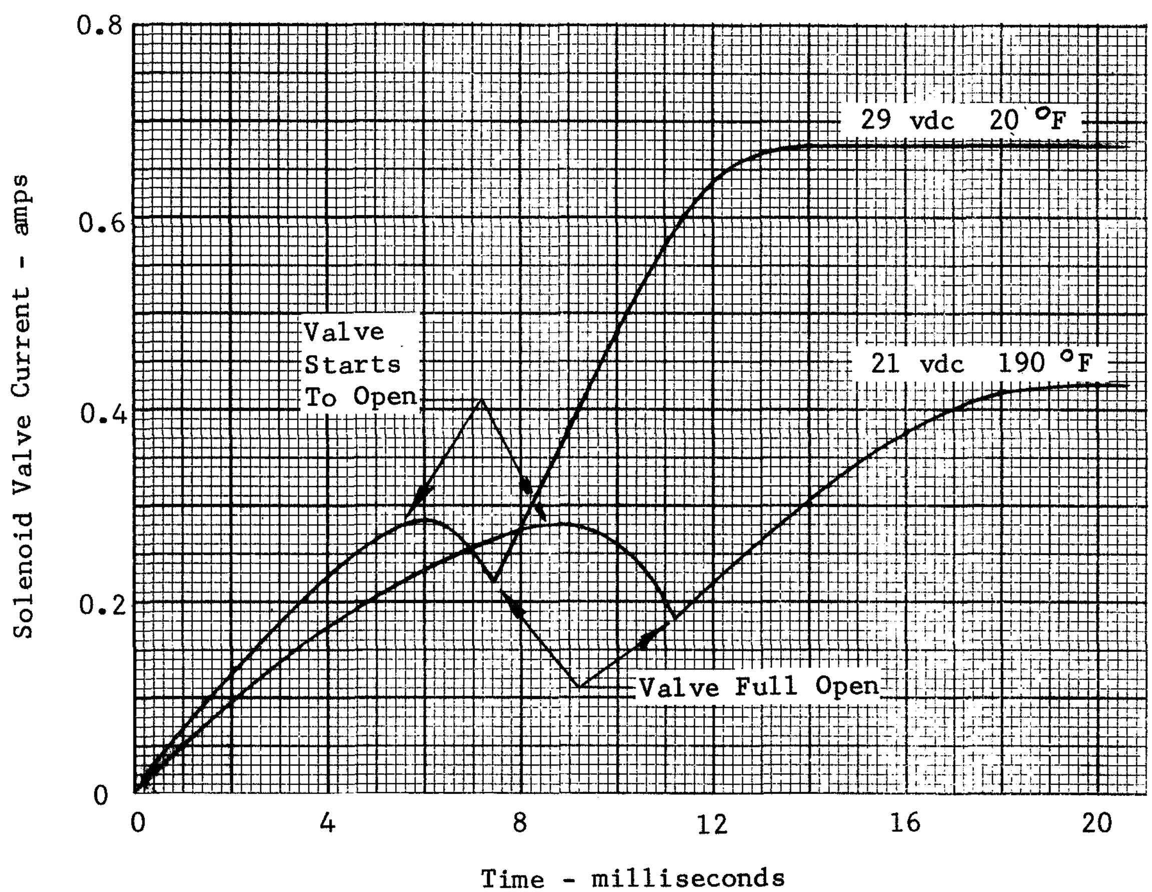


Figure 7

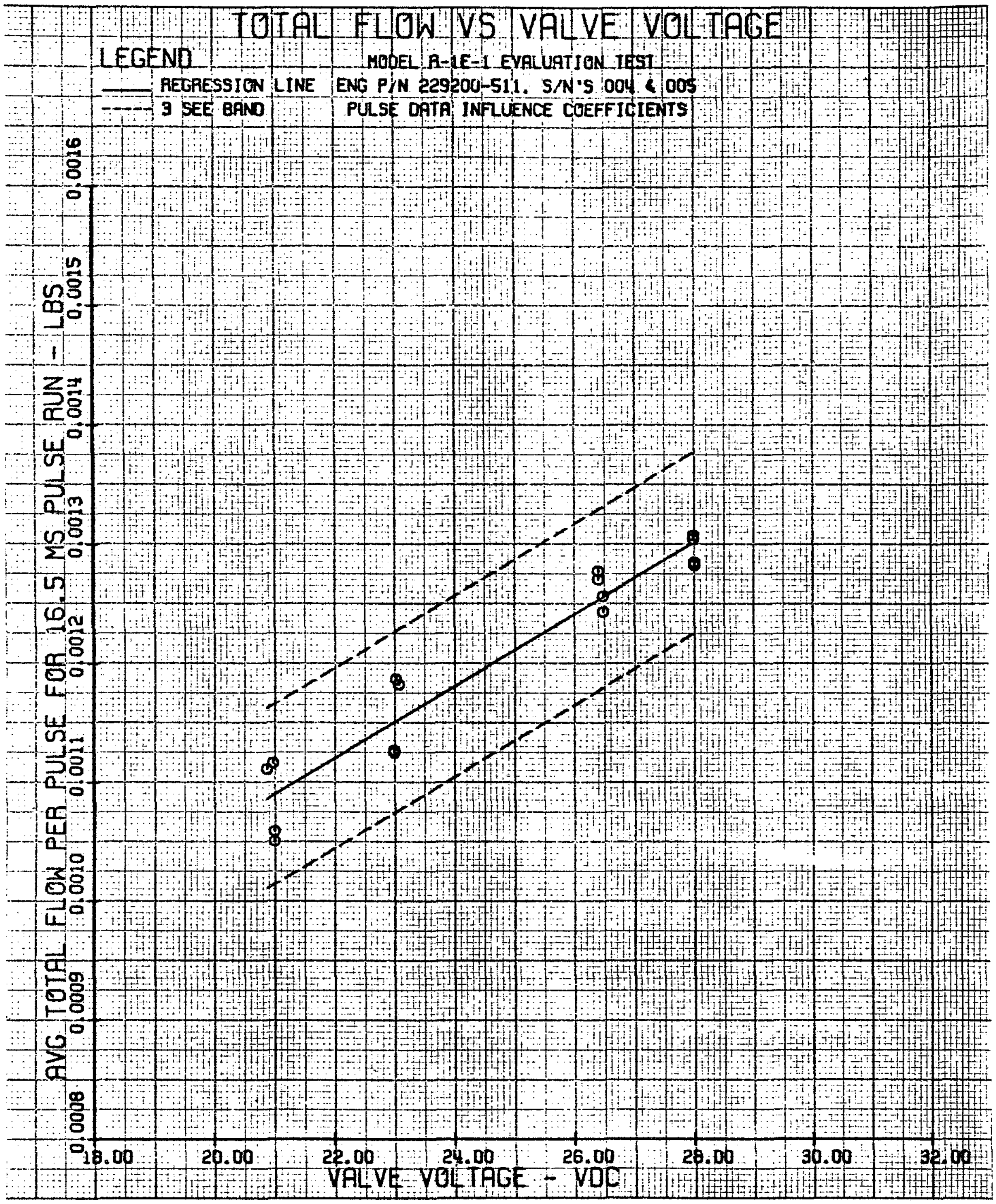

TOTAL FLOW VS VALVE VOLTAGE
LEGEND
MODEL R-1E-1 EVALUATION TEST
REGRESSION LINE
ENG P/N 229200-511, S/N'S 004 & 005
3 SEE BAND
PULSE DATA INFLUENCE COEFFICIENTS
AVG TOTAL FLOW PER PULSE FOR 16.5 MS PULSE RUN - LBS
0.0008
0.0009
0.0010
0.0011
0.0012
0.0013
0.0014
0.0015
0.0016
18.00
20.00
22.00
24.00
26.00
28.00
30.00
32.00
VALVE VOLTAGE - VDC

Figure 8

R1E ENGINE

EFFECTIVE FLOW RATE vs. ELECTRICAL PULSE WIDTH

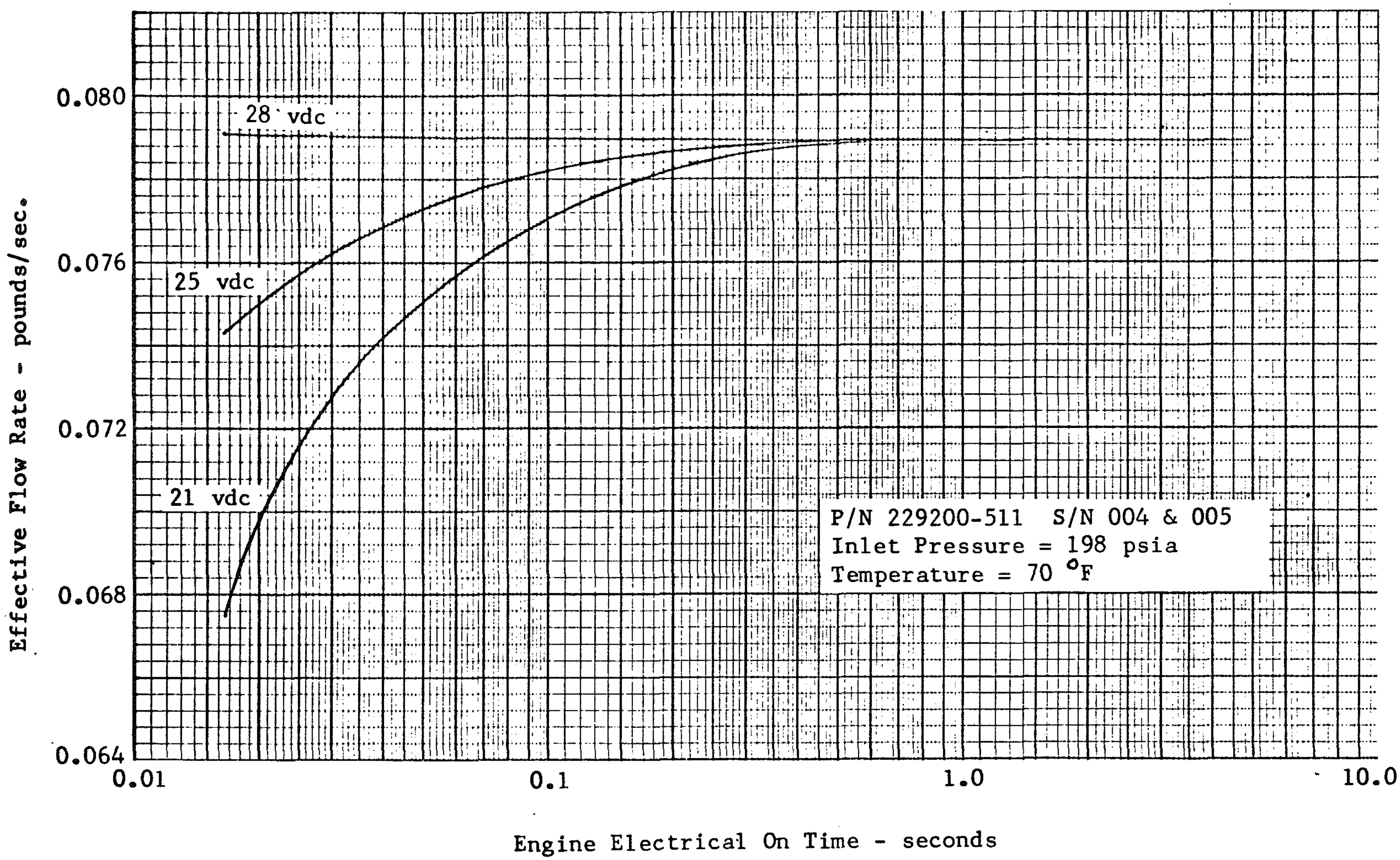


Figure 9

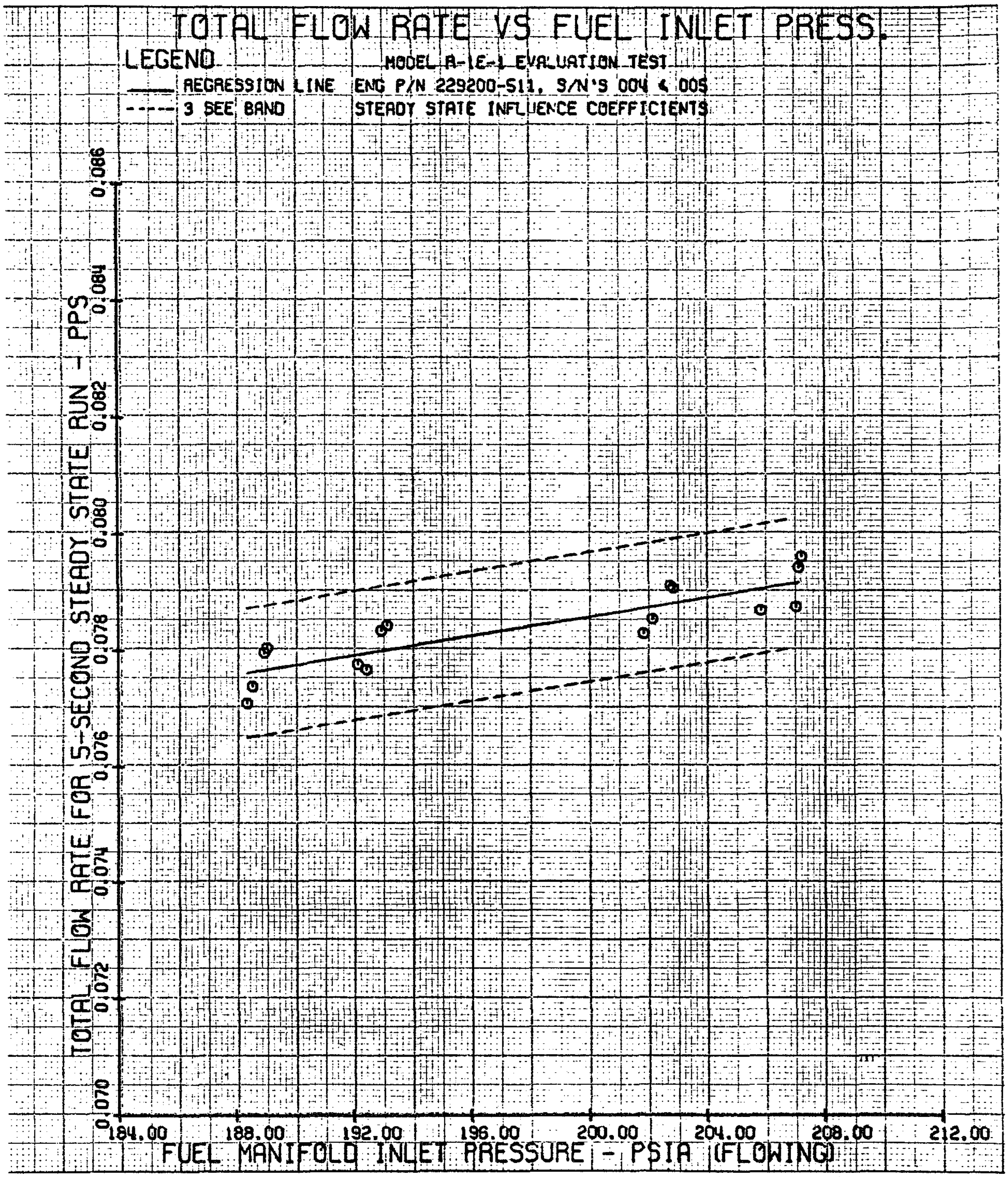
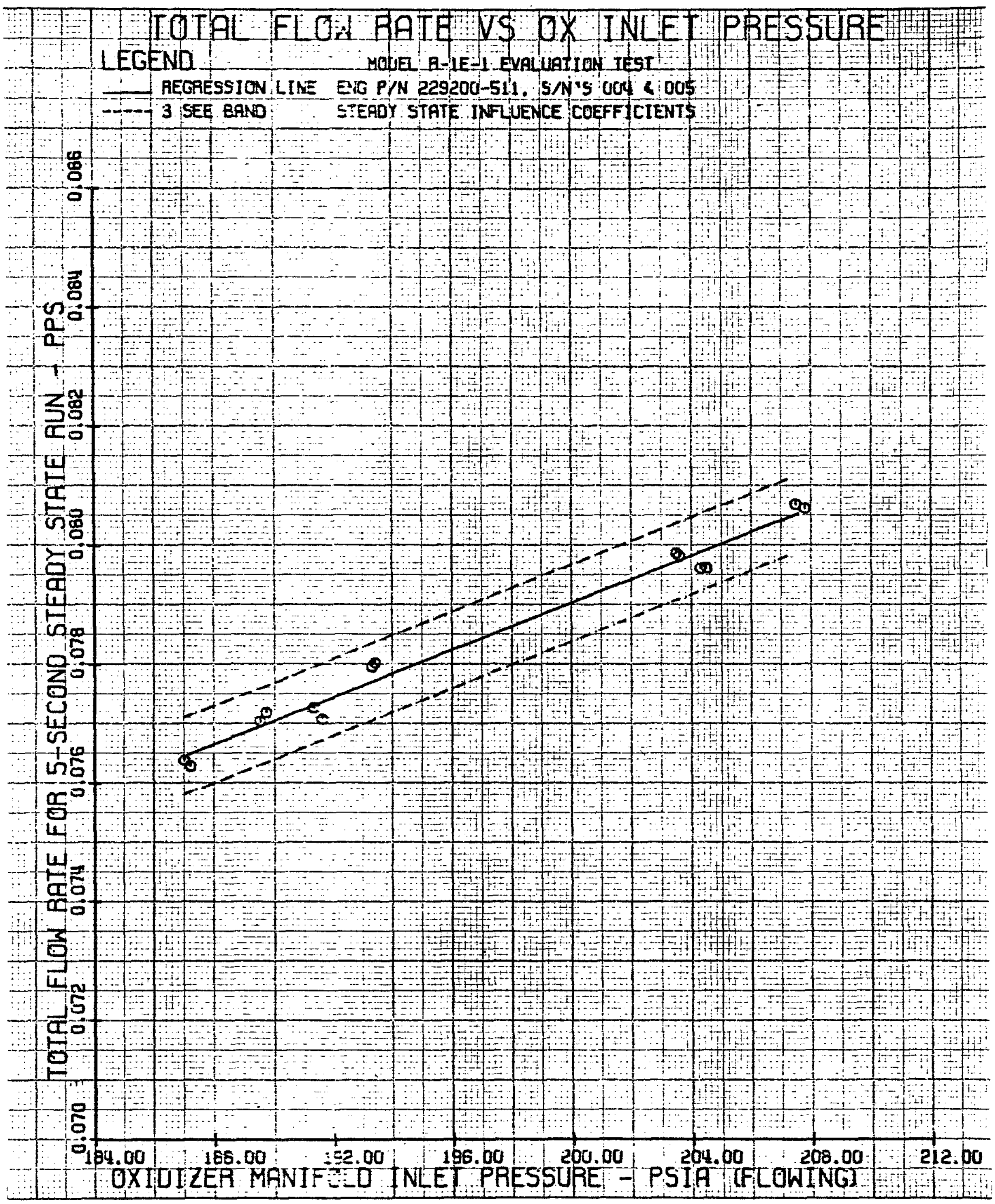

TOTAL FLOW RATE VS FUEL INLET PRESS.
LEGEND
MODEL A-1E-1 EVALUATION TEST
REGRESSION LINE
ENG P/N 229200-S11, S/N'S 004 & 005
3 SEE BAND
STEADY STATE INFLUENCE COEFFICIENTS
TOTAL FLOW RATE FOR 5-SECOND STEADY STATE RUN - PPS
0.070
0.072
0.074
0.076
0.078
0.080
0.082
0.084
0.086
184.00
188.00
192.00
196.00
200.00
204.00
208.00
212.00
FUEL MANIFOLD INLET PRESSURE - PSIA (FLOWING)

Figure 10


TOTAL FLOW RATE VS OX INLET PRESSURE
LEGEND
MODEL R-1E-1 EVALUATION TEST
REGRESSION LINE
ENG P/N 229200-511, S/N'S 004 & 005
3 SEE BAND
STEADY STATE INFLUENCE COEFFICIENTS
TOTAL FLOW RATE FOR 5-SECOND STEADY STATE RUN - PPS
0.070
0.072
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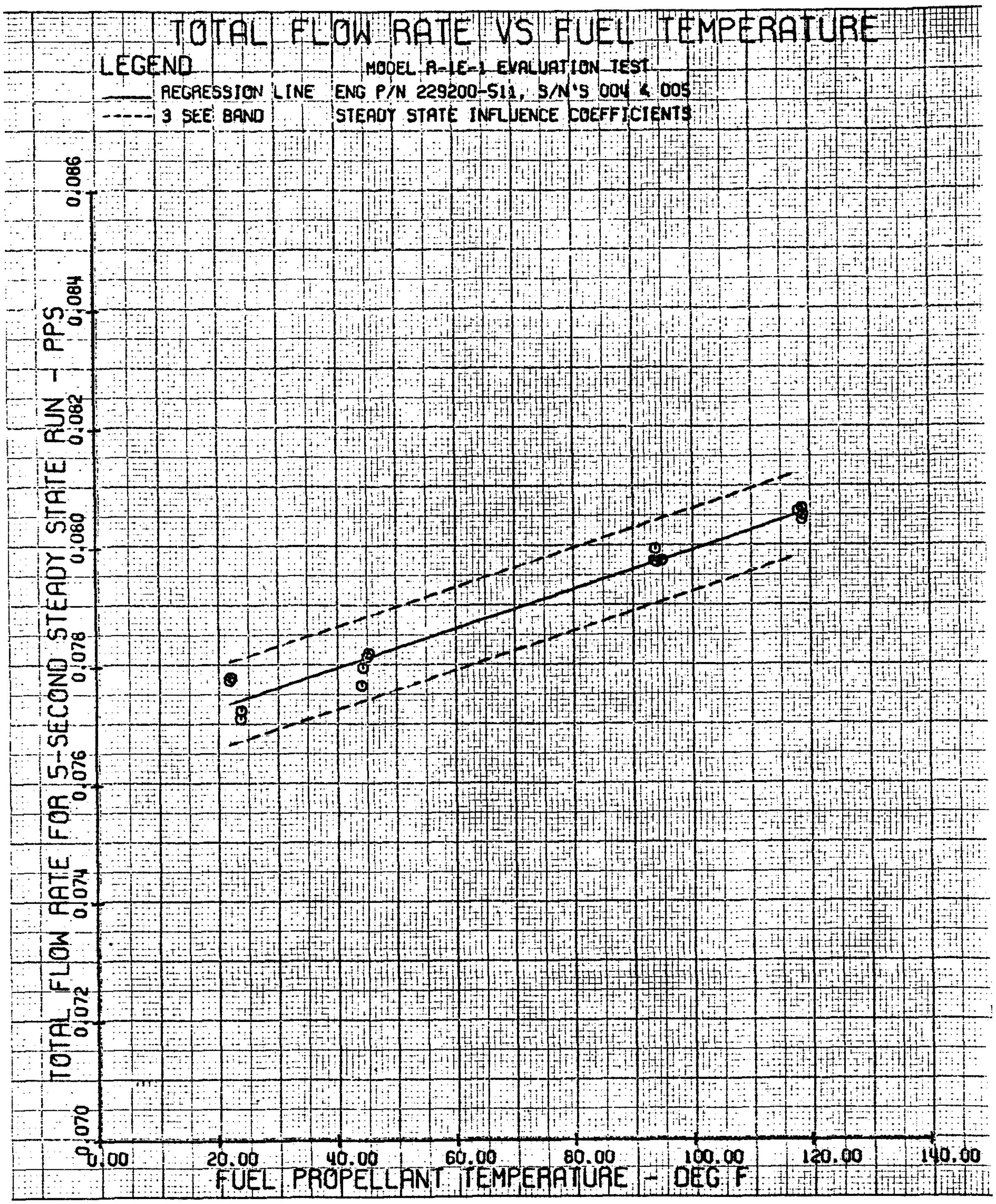
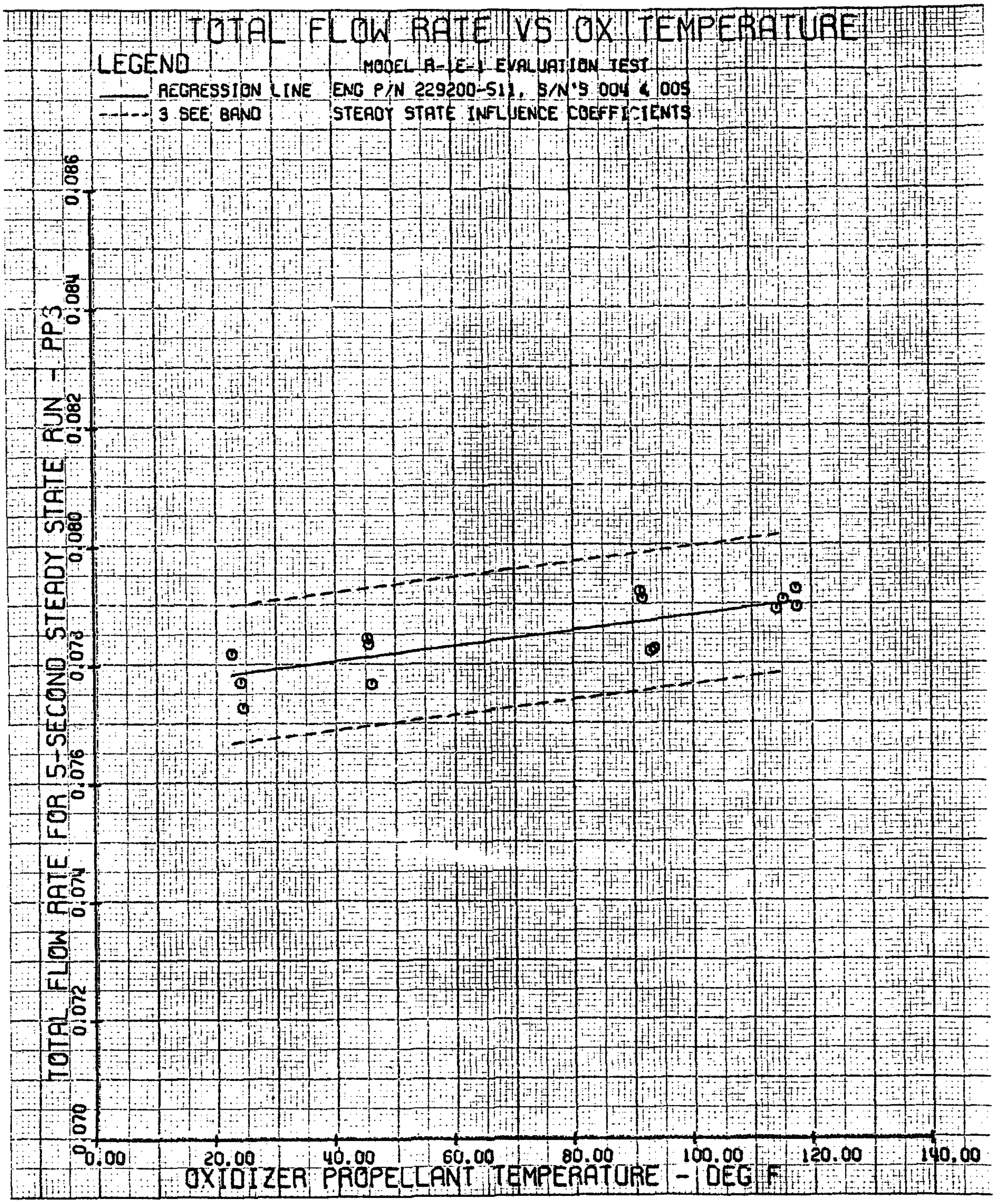
0.076
0.078
0.080
0.082
0.084
0.086
184.00
188.00
192.00
196.00
200.00
204.00
208.00
212.00
OXIDIZER MANIFOLD INLET PRESSURE - PSIA (FLOWING)

Figure 11



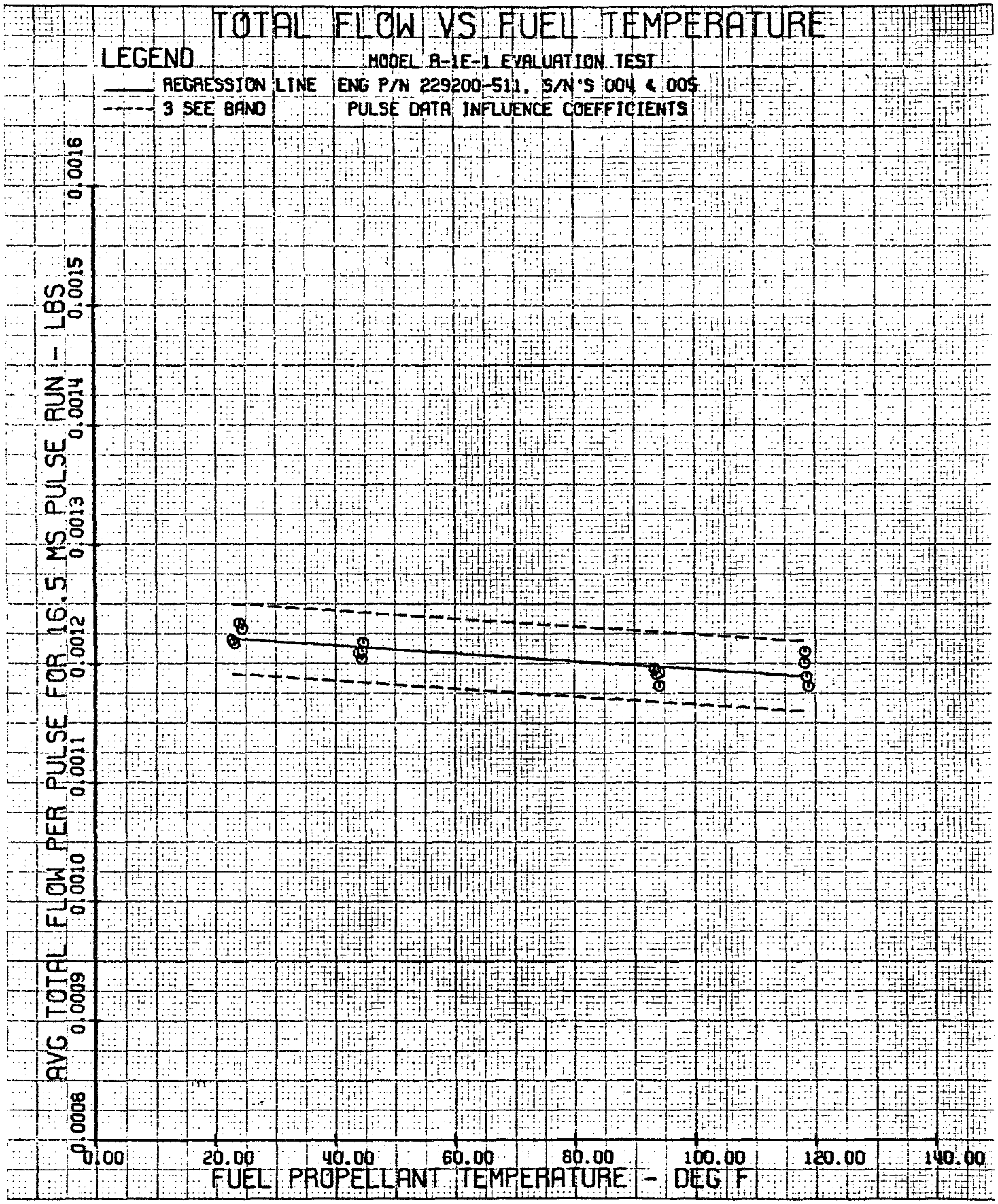
TOTAL FLOW RATE VS FUEL TEMPERATURE
LEGEND
MODEL A-1E-1 EVALUATION TEST
REGRESSION LINE
ENG P/N 229200-S11, S/N'S 004 & 005
3 SEE BAND
STEADY STATE INFLUENCE COEFFICIENTS
TOTAL FLOW RATE FOR 5-SECOND STEADY STATE RUN - PPS
0.070
0.072
0.074
0.076
0.078
0.080
0.082
0.084
0.086
0.00
20.00
40.00
60.00
80.00
100.00
120.00
140.00
FUEL PROPELLANT TEMPERATURE - DEG F

Figure 12



TOTAL FLOW RATE VS OX TEMPERATURE
LEGEND
REGRESSION LINE
3 SEE BAND
MODEL A-1E-1 EVALUATION TEST
ENG P/N 229200-511, S/N'S 004 & 005
STEADY STATE INFLUENCE COEFFICIENTS
TOTAL FLOW RATE FOR 5-SECOND STEADY STATE RUN - PPS
0.070
0.072
0.074
0.076
0.078
0.080
0.082
0.084
0.086
0.00
20.00
40.00
60.00
80.00
100.00
120.00
140.00
OXIDIZER PROPELLANT TEMPERATURE - DEG F

Figure 13


TOTAL FLOW VS FUEL TEMPERATURE
LEGEND
REGRESSION LINE
3 SEE BAND
MODEL A-1E-1 EVALUATION TEST
ENG P/N 229200-511, S/N'S 004 & 005
PULSE DATA INFLUENCE COEFFICIENTS
AVG TOTAL FLOW PER PULSE FOR 16.5 MS PULSE RUN - LBS
0.0008
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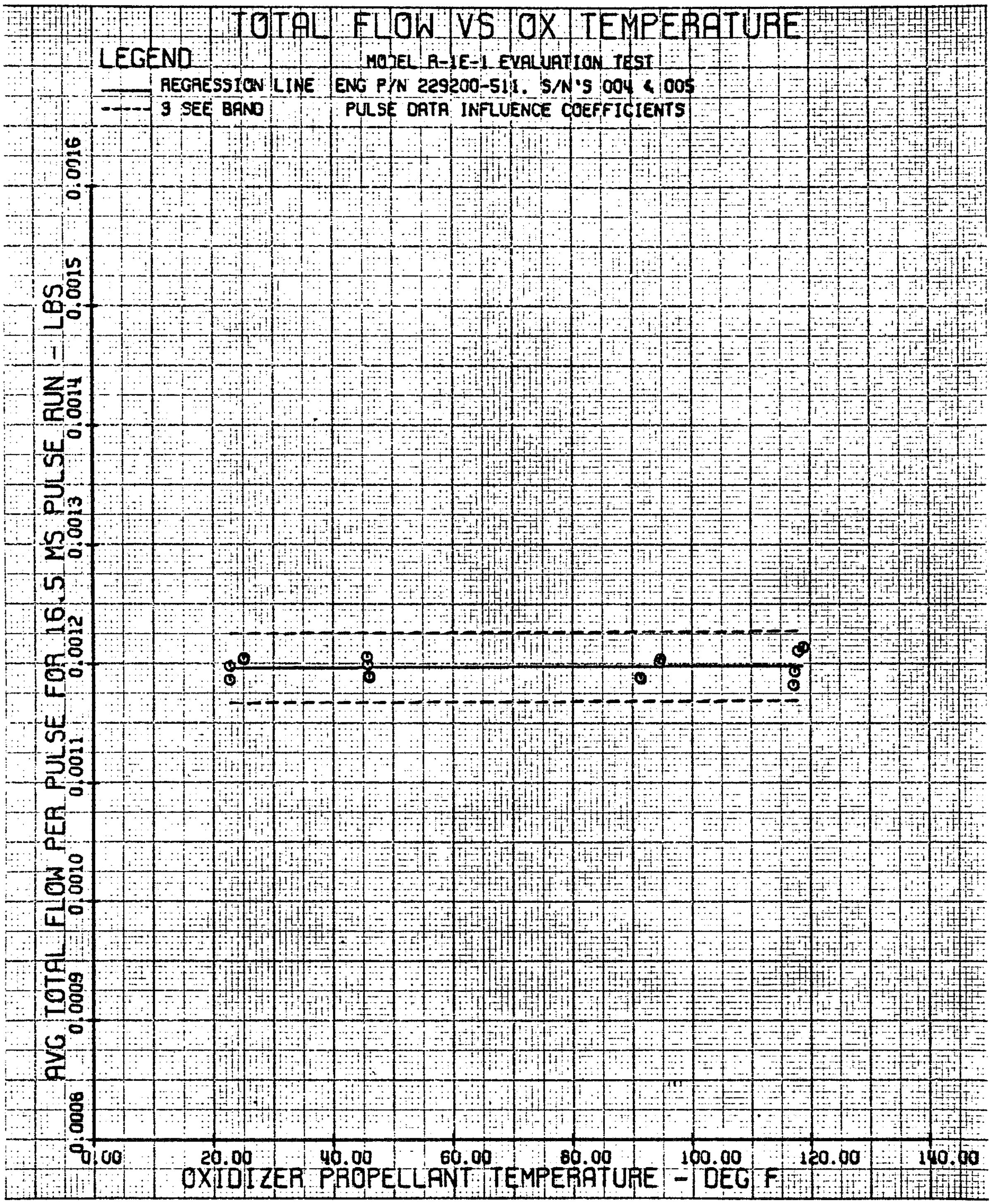
0.0010
0.0011
0.0012
0.0013
0.0014
0.0015
0.0016
0.00
20.00
40.00
60.00
80.00
100.00
120.00
140.00
FUEL PROPELLANT TEMPERATURE - DEG F

Figure 14



TOTAL FLOW VS OX TEMPERATURE
LEGEND
REGRESSION LINE
3 SEE BAND
MODEL R-1E-1 EVALUATION TEST
ENG P/N 229200-511. S/N'S 004 & 005
PULSE DATA INFLUENCE COEFFICIENTS
AVG TOTAL FLOW PER PULSE FOR 16.5 MS PULSE RUN - LBS
0.0008
0.0009
0.0010
0.0011
0.0012
0.0013
0.0014
0.0015
0.0016
0.00
20.00
40.00
60.00
80.00
100.00
120.00
140.00
OXIDIZER PROPELLANT TEMPERATURE - DEG F

Figure 15

Variation in Mixture Ratio

During the course of a mission, variations in propellant mixture ratio will occur due to:

Engine duty cycle
Variations in propellant pressure
Variation in system temperature

The variation in mixture ratio for the R-1E engine due to changes in engine on time is shown in Figure 16. A knowledge of the mission in terms of per cent to be performed at various pulse widths permits a calculation of the over all mission mixture ratio and allows the tankage to be loaded to the optimum mission mixture ratio.

PQGS Error Sources

The digital circuitry used to build the PQGS is designed to minimize its contribution to system error. The two error sources which have been analyzed were the effects of PQGS temperature on the counting rate and on the gating thresholds of the valve operation detectors. The PQGS counting rate is determined by a 100 KHz crystal oscillator. The crystal used in this oscillator has a temperature coefficient of 0.0003% per °F so that for a range of temperature of ± 50°F the PQGS calibration should be within ± 0.002% of its nominal value. Variations in temperature of the Hall effect sensors used to detect propellant valve operation can cause a shift in the valve operation detection flux level of 0.11% per °F. The valve temperatures can vary over the range from 20 to 125°F corresponding to a shift in the threshold flux of ± 12%. Since the flux buildup time is in the order of 8 milliseconds the temperature effect corresponds to approximately one millisecond in counting time. For the minimum pulse width of 65 milliseconds this is equivalent to 1.5%.

System Errors

The results of the error analysis are presented in Table II, which shows the environmental range considered and the resulting variations in system accuracy associated with these variations. In general, the PQGS is calibrated to provide no systematic errors at either the 65 millisecond pulse width or for steady state operation. Because of uncertainties associated with this calibration on a given mission, a systematic error as large as 1.2% may exist because of instrumentation errors and uncertainty about the average performance of the thrustors being used. In addition to this systematic error the PQGS output may differ from the true amount of propellant consumed by an amount which depends on the pressures, temperatures, and valve supply voltages encountered during the mission.

R1E ENGINE

MIXTURE RATIO vs. ELECTRICAL ON TIME

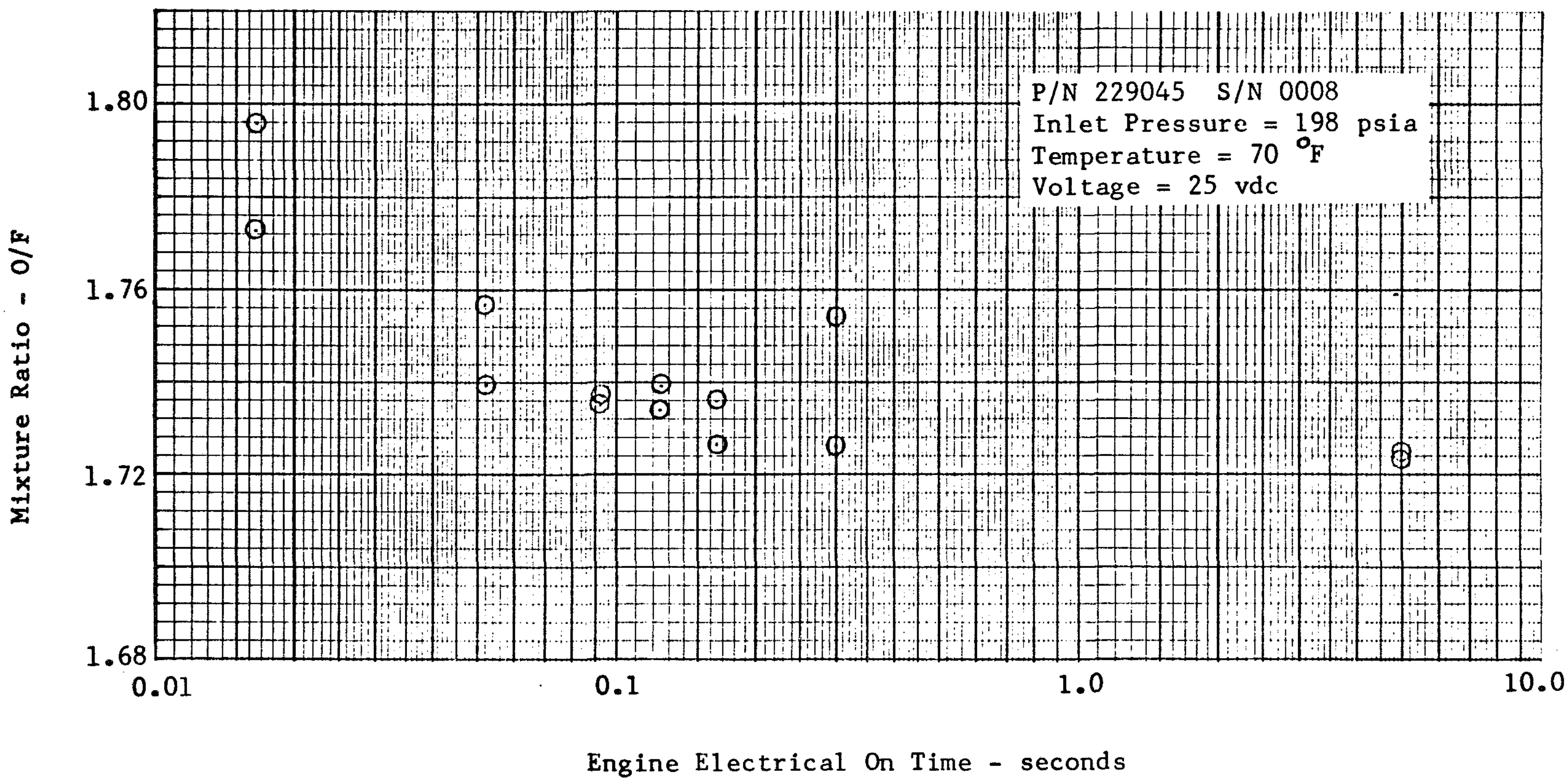


Figure 16

TABLE II

ERROR SOURCES

Source	3σ Error Contribution
Loading Accuracy	±0.5%
Engine-to-Engine Repeatability	±2.0%
Steady State	
Oxidizer Supply Temperature 20-125°F	+0.72%/-0.96%
Fuel Supply Temperature 20-125°F	+1.89%/-2.52%
Oxidizer Supply Pressure 210-218 psia	±1.01%
Fuel Supply Pressure 210-218 psia	±0.42%
Pulsing (65 ms EPW)	
Oxidizer Supply Temperature	+.09%/-.12%
Fuel Supply Temperature	+1.62%/-1.22%
Oxidizer Supply Pressure	±.58%
Fuel Supply Pressure	±0.54%
Valve Voltage 20-30 VDC	+2.54%/-3.80% (1)

Simulated Mission Analysis

A Monte Carlo analysis was used to determine the actual 3 sigma limits of the system accuracy. The analysis was accomplished using the IBM 360/50 computer and the 360/50 system subroutine RANDU which computes uniformly distributed random real numbers between 0 and 1. The method of computation of the random numbers is the power residue method.

Each variable in the analysis was assumed to follow a normal distribution. A series of missions was simulated to determine the distribution of the quantity gaging system accuracy.

The effect of pressure, temperature and valve voltage on engine propellant consumption were reduced from data taken during Influence Coefficient testing of the Marquardt Model R-1E engine.

Table III below summarizes the effect of pressure, temperature and valve voltage on propellant consumption during pulsing and steady state operation. The variability of 65 millisecond consumption was estimated from 0.0165 millisecond pulse width influence coefficient data by adjusting for the longer pulse width.

(1) The error contribution due to voltage as determined from influence coefficient data provides a conservative mission error analysis. The PQGS counting time is also influenced by voltage of the engine solenoid valve in a compensating manner.

TABLE III

INFLUENCE COEFFICIENTS

PARAMETER	$\frac{\% \Delta W_{tot}}{\Delta \text{parameter}}$
STEADY STATE	
Oxidizer Supply Temperature	**.016%/°F**
Fuel Supply Temperature	**.042%/°F**
Oxidizer Supply Pressure	**.252%/psi**
Fuel Supply Pressure	**.105%/psi**
PULSING (65 ms pulse)	
Oxidizer Supply Temperature	**.002%/°F**
Fuel Supply Temperature	**-.027%/°F**
Oxidizer Supply Pressure	**.146%/psi**
Fuel Supply Pressure	**.134%/psi**
Valve Voltage	**.634%/VDC** (1)

The results of the Monte Carlo analysis are shown in Table IV below, which gives 60 of the 100 values of PQGS accuracy at a point near the end of the simulated mission.

TABLE IV

PROPELLANT QUANTITY GAGING SYSTEM MISSION ACCURACY ANALYSIS - 100 MISSIONS (%)

-0.24575	0.19516	0.07334	-1.67281	-1.06332	-0.62123
-0.17517	-0.44299	0.10887	-0.30509	1.07849	-0.24182
0.19463	-0.03456	-0.62505	-0.77564	-0.05210	1.38696
-0.33940	0.40721	-0.52135	0.75836	-0.86134	-0.59051
0.07266	0.42983	-0.06498	-0.02203	0.24305	-1.18523
0.37067	0.07618	0.38636	0.20837	0.03749	0.21111
0.08386	-0.13894	0.65675	0.15129	0.60741	-0.02131
0.06829	0.99186	-0.59324	0.57741	-1.03772	-0.66150
0.36664	-0.37399	-0.19626	-0.82838	0.36427	-0.39860
0.30318	-1.10664	0.64062	0.41198	0.04214	0.16926

A sample calculation for an individual run is shown in Figure 17 below.

(1) The error contribution due to voltage as determined from influence coefficient data provides a conservative mission error analysis. The PQGS counting time is also influenced by voltage of the engine solenoid valve in a compensating manner.

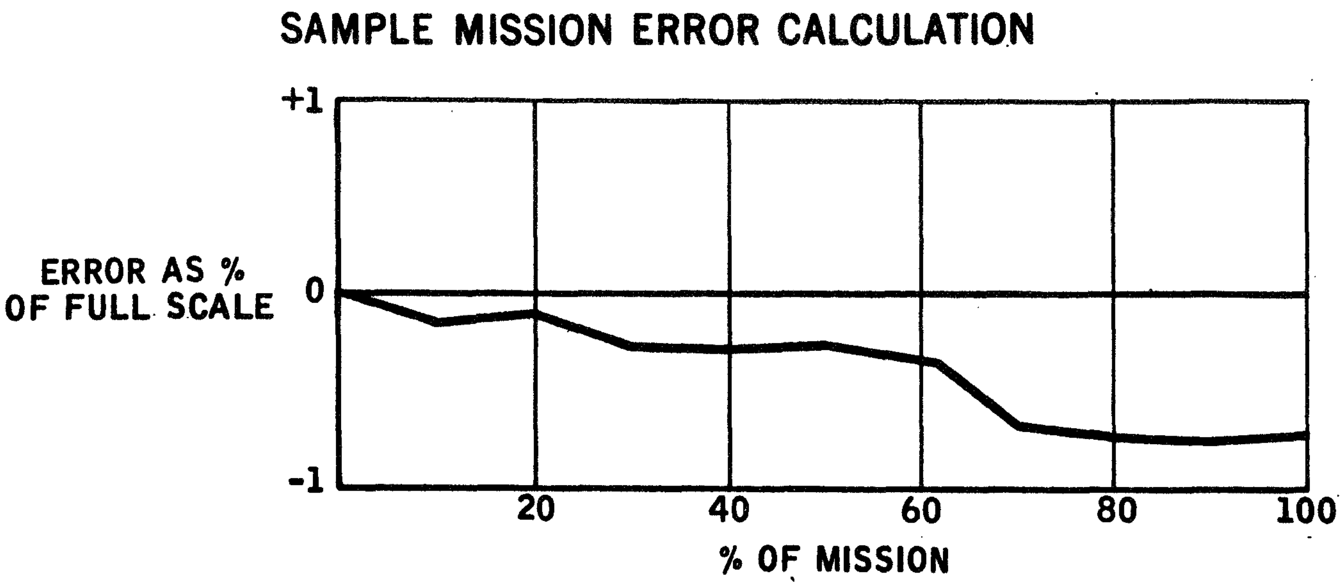


Figure 17

The system errors from the Monte Carlo analysis were plotted on probability paper in Figure 18, and the 3 sigma limits were determined based on a normal distribution. The 3 sigma value for the PQGS accuracy is $\pm$ 1.9%.

PROPELLANT QUANTITY GAGING SYSTEM BREADBOARD

The breadboard version of the PQGS was designed to bridge the gap between the work conducted on an in-house development program and the prototype flight weight PQGS system. This unit incorporated major changes from the conceptual stage to insure reproducibility and reliable performance. The breadboard PQGS also used features and techniques contemplated for the flight weight system and was used to establish calibration procedures, verify accuracies and evaluate the performance of individual circuit components. Except for purchased components and the printed circuit cards all fabrication and assembly of the PQGS was conducted at Marquardt.

Circuit Design Considerations

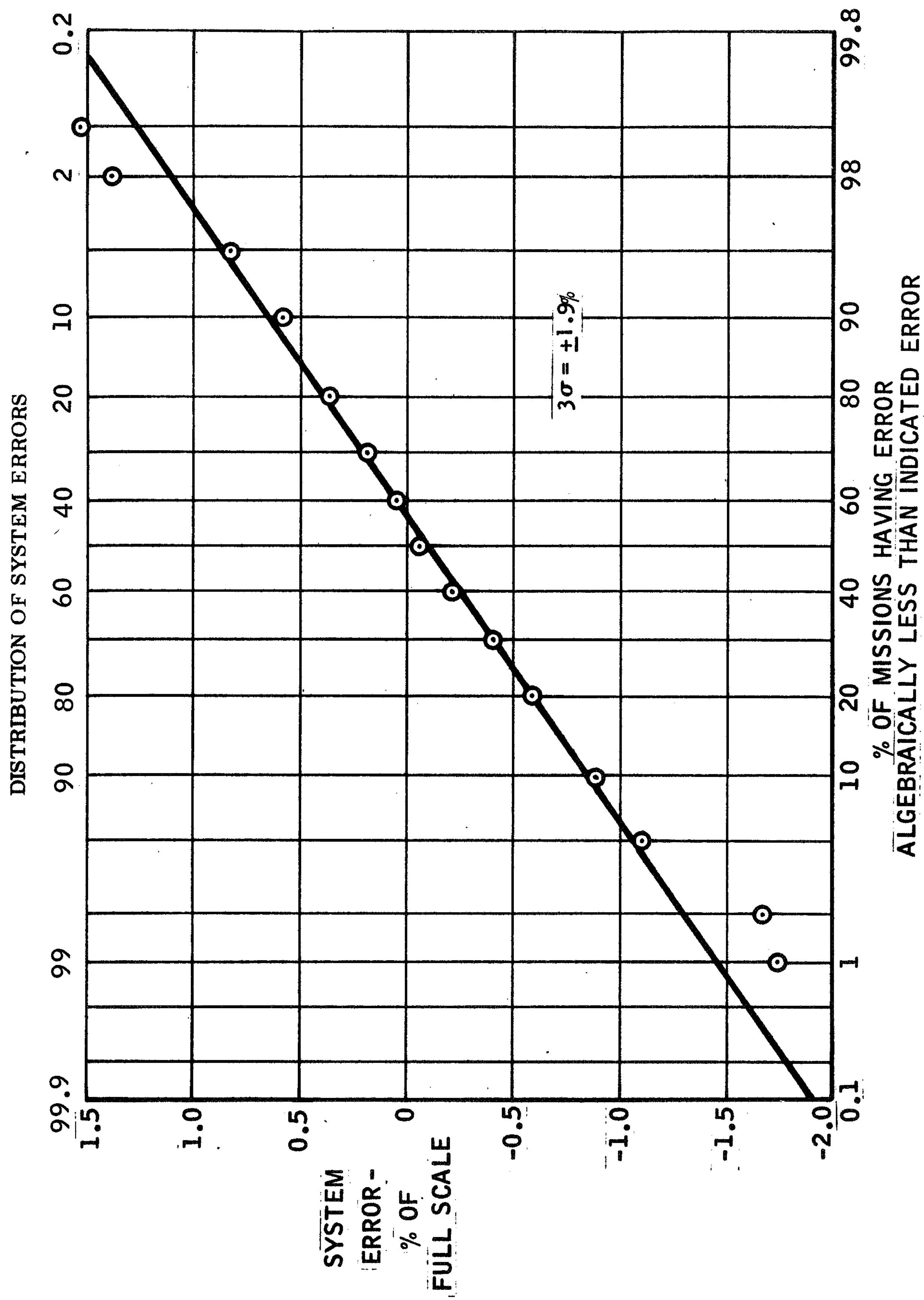
Preliminary design criteria were generated to describe specific requirements of each circuit and of each component in the circuits in order to assure their satisfactory performance to the design requirements.

The major areas studied were:

Hall effect excitation current versus amplifier gain

Hall effect offset, amplifier offset and thermal drift

Transformer, rectifier, regulator and voltage levels required



DISTRIBUTION OF SYSTEM ERRORS
99.9
99
90
80
60
40
20
10
2
0.2
0.1
1
10
20
40
60
80
90
98
99.8
% OF MISSIONS HAVING ERROR
ALGEBRAICALLY LESS THAN INDICATED ERROR
1.5
1.0
0.5
0
-0.5
-1.0
-1.5
-2.0
SYSTEM
ERROR -
% OF
FULL SCALE
$3\sigma = \pm 1.9\%$

Figure 18

Inverter frequency and waveform

Component ratings, reliability, availability

Temperature coefficients and thermal management

Clock frequency, divider capability

Printed circuit card layout, assembly and interfacing

Construction of sensors to interface with Orbital Workshop engine

Layout and construction of sensor and display modules

Selection of memory and display

Breadboard Components

The PQGS is divided into three sections: the sensors to be mounted on an engine, the sensor module to be mounted in a central location in an engine cluster and the display module to be mounted in the spacecraft cockpit. The sensor and display modules of the breadboard system were not packaged in order to permit easy access during checkout and testing. The sensors contain no electronics other than the Hall Effect Device because of a possibility of a severe engine environment and the necessity of having an extremely small package to mount on an engine valve.

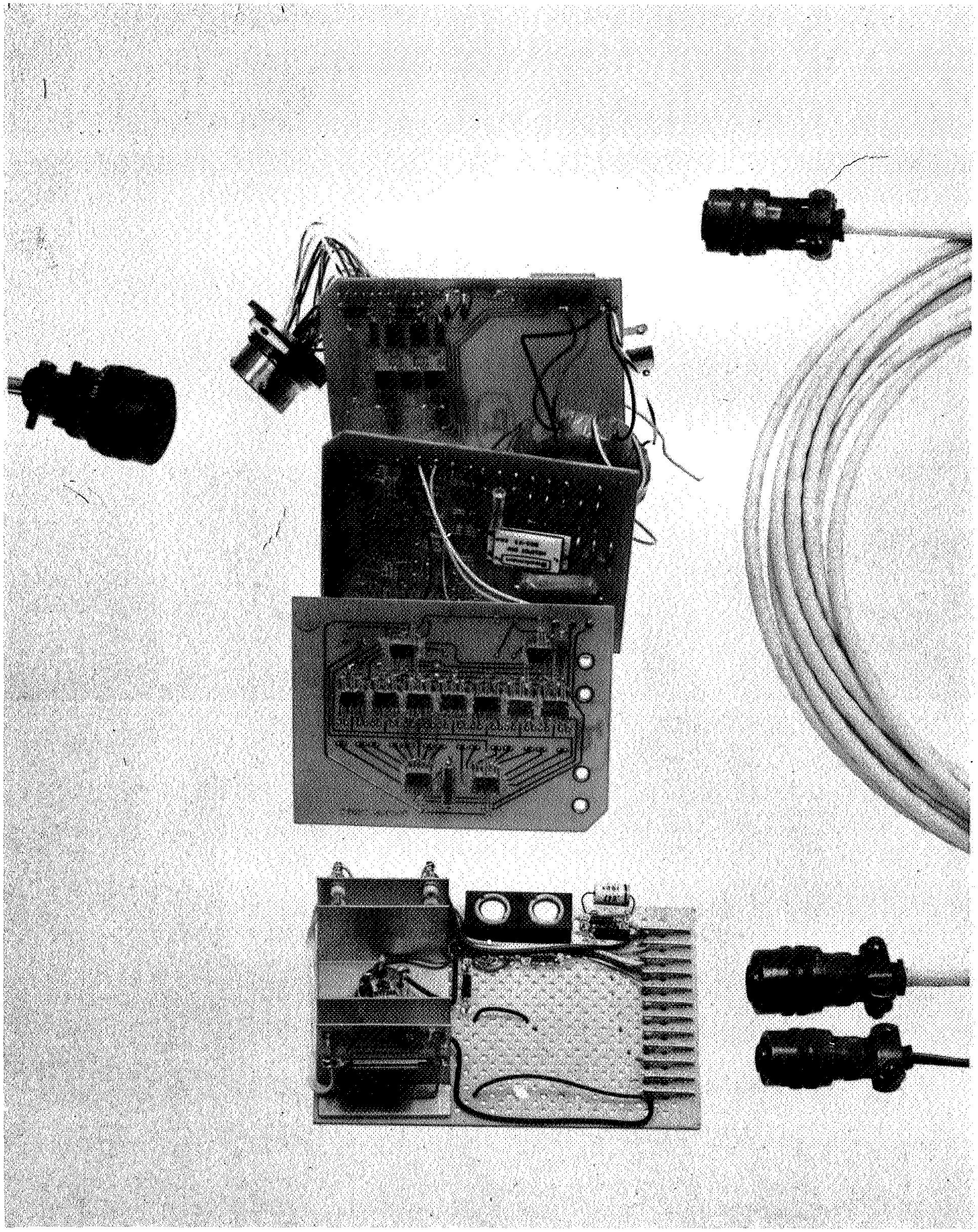
The majority of electronics are contained in the sensor module and serve to convert the low level sensor signals to higher level signals and to convert and compute the signals to a digital form suitable to drive the display. The sensor module contains three circuit cards and a power distribution transformer. One circuit card amplifies the sensor output signal, converts the amplified signal to a digital format and supplies the sensors with a filtered constant current. The other two cards provide the digital functions (clock, channel multiplexing, dynamic compensation, static flow conversion) and voltage regulation. The transformer is required in order to conserve power by distributing power to three low power busses that vary in voltage and current requirements. The sensor module of the breadboard system is shown in Figure 19.

The display module accepts signals in a serial format from the sensor module, and provides the readout and memory functions while also supplying the regulated a-c voltages needed to drive multi-level power circuits in the sensor module.

The display module contains an electromagnetic counter to perform both functions of a display readout and a non-volatile, non-destructive memory. In addition, a display readout driver, regulated inverter line transient surge suppressor and input voltage polarity protector are included.

Breadboard Checkout Tests

One of the modifications made to the breadboard circuits, from the circuits of the original PQGS concept, was a change in the integrated circuits from the dual in-line pin type to the flat pack type. This approach appeared advantageous from the standpoint of component availability and lower power consumption in the digital circuitry. The power supply buss existed for the digital integrated



NEG. 9613-1

PROPELLANT QUANTITY GAGING SYSTEM BREADBOARD

Figure 19

circuits so a type 518 linear integrated circuit was chosen to simplify power requirements. It appeared that the type 518 would have sufficient gain and was preferable to the higher voltage type 709 linear integrated circuit. This proved to be a poor choice since there was insufficient amplification to perform the combination amplifier - Schmidt trigger function with one integrated circuit. As a result the amplifier - Schmidt trigger functions were separated and an additional stage of the type 518 linear integrated circuit was added. This change resulted in an excellent operating circuit but requires more power than if the circuits had been changed to use the type 709 integrated circuit.

A second modification was made to the breadboard PQGS when the verification of circuit voltages, during checkout tests, indicated that the voltage drop of the diodes in the excitation supply was higher than estimated. This required additional turns to be added to the supply transformer winding.

Breadboard Bench Tests

The tests to evaluate performance of the breadboard PQGS were conducted with the three sensors mounted on a propellant solenoid valve similar to that used on the Marquardt 22 lb thrust bipropellant engine. These tests were conducted with the entire breadboard and valve placed in a Missimer test chamber as shown in Figure 20. The test chamber permitted variations in temperature from 20° to 130°F. To simulate spacecraft power supplies the supply voltage to the propellant quantity gaging system was varied independently of the solenoid valve voltage. The voltage to the PQGS was varied between 24 and 32 V d-c and the valve voltage was varied between 21 and 28 V d-c. Valve electrical pulse widths between 65 milliseconds and steady state conditions were investigated.

The initial thermal bench tests indicated an error at the low temperature, 20°F, condition. Analysis of the data and PQGS circuits indicated that the error was due to the unregulated voltage supplied to the Hall effect sensors. A regulator was added in the module before the inverter to hold the sensor excitation constant.

Bench tests of the PQGS were designed to investigate the voltage, temperature and pulse width ranges expected for an engine solenoid valve operating on an engine. Since flow transients that occur in engine operation are difficult to simulate in bench testing the following technique was used to verify the PQGS accuracy.

An average PQGS count per second was obtained from the steady state operation of the solenoid valve at high and low voltages and at each of the temperature conditions. As seen from Table V there was no significant deviation from this average for steady state operation at any of the temperature or voltage conditions.

At short pulse widths the time during which the PQGS counts is a function of the amplified Hall effect sensor output characteristic and the level of the Schmidt trigger, Figure 21. In addition, the one shot generator augments the counting time by its predetermined setting.

SET-UP - PQGS BREADBOARD THERMAL TESTS

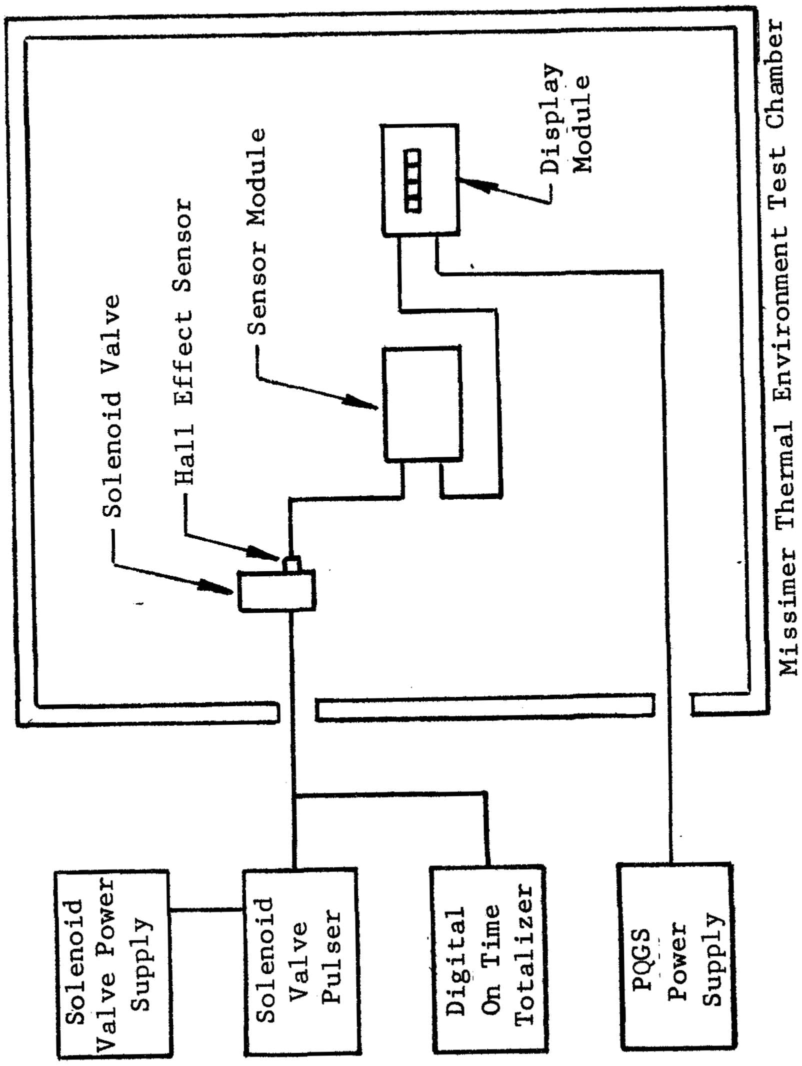


Figure 20

TABLE V

TEMPERATURE TEST DATA-BREADBOARD PROPELLANT QUANTITY GAGING SYSTEM

Run #	Pulse Width ms	Temp °F	Valve Voltage V d-c	Digital Counter Net(sec)	Total Number Pulses	PQGS Counter Net	Per** Pulse ms Correction	Corrected Digital On Time	PQGS Counts Per Sec	% Error* to SS Avg Read	Remarks
1	SS	75	29	99.624	1	254	---	99.624	2.550	-0.04	
2	SS	75	21	99.890	1	255	---	99.890	2.553	+0.08	
3	100	75	21	99.863	1005	233	9.0	90.818	2.567	_0.64	
4	100	75	29	99.550	1002	241	5.0	94.540	2.550	-0.04	
5	65	75	29	64.114	1005	151	5.0	59.091	2.555	+0.16	
6	65	75	21	64.513	1006	160	9.0	55.477	2.890	---	Data Error
7	SS	20	29	99.986	1	255	---	99.986	2.550	+0.04	
8	SS	20	21	100.035	1	255	---	100.035	2.549	-0.08	
9	100	20	29	98.559	1002	236	5.0	93.549	2.523	-1.12	
10	100	20	21	98.924	1005	225	9.0	89.879	2.507	-1.76	
11	65	20	29	63.994	1005	148	5.0	58.969	2.512	-1.56	
12	65	20	21	64.649	1007	139	9.0	55.586	2.502	-1.96	
13	SS	130	29	100.254	1	256	---	100.254	2.554	+0.12	
14	SS	130	21	100.774	1	257	---	100.774	2.550	-0.04	
15	100	130	29	101.312	1001	245	5.0	96.307	2.548	-0.12	
16	100	130	21	101.293	1003	234	9.0	92.266	2.539	-0.48	
17	65	130	29	66.012	1002	156	5.0	61.002	2.556	+0.20	
18	65	130	21	66.369	1005	146	9.0	57.324	2.550	-0.04	

*Average steady state reading 2.551 counts/second (from runs 1, 2, 7, 8, 13 and 14)

**As determined from Figure 21. Includes 1 ms/pulse correction for the dynamic compensation circuit.

SENSOR AMPLIFIER OUTPUT vs. TIME

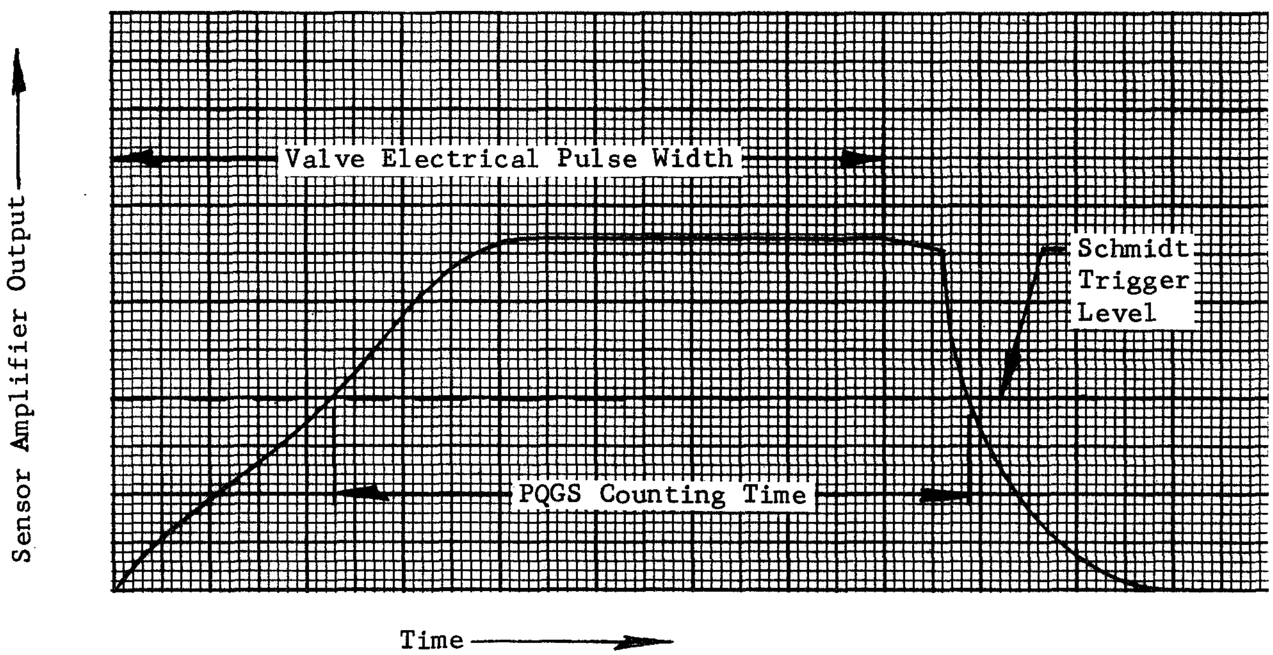


Figure 21

As seen previously in Table I, the solenoid valve on time is shorter than the electrical pulse width because of the difference in opening and closing times and this difference is a function of valve voltage.

For the valve tested, the counting time at 21 volts was 10 milliseconds less than the electrical on time. With one millisecond obtained from the one shot generator, the PQGS counting time differed from the valve electrical off time by 9 milliseconds. Similarly, at 29 volts this difference was 5 milliseconds.

These time differences were subtracted, for each pulse in the series, from the digital counter net time, in Table V to obtain the counts per second for each pulse run comparable to the average steady state value.

Although not truly representative of the errors to be expected in engine operation because of flow dynamics when chamber pressure is being established, the test showed that the compensation for valve start and stop dynamic remains essentially constant over the temperature ranges. Compensation for the engine flow dynamics is made by adjustment of the one shot generator.

FLIGHT WEIGHT PROPELLANT QUANTITY GAGING SYSTEM

The electronic sections of the flight weight propellant gaging system are the same as the final configuration generated during the breadboard system evaluation tests. Minor modifications made were the inclusion of internal noise suppression to the sensor module and resizing of the Hall effect sensor to better fit the engine solenoid valve. A block diagram and electrical schematic of the flight weight system are shown in Figures 22 and 23.

Fabrication

Packaging of the circuit boards and components of the flight weight system presented no major difficulties and resulted in the system as shown in Figure 1. Photos of the individual circuit board and internal views of the sensor and display modules are shown in Figure 24 through 28.

Some difficulty was encountered in potting the sensors without damage to the Hall effect crystal (white rectangular area on the face of the sensor as shown in Figure 1). A four step potting procedure was devised that required additional curing time but resulted in an excellent sensor that has shown to be extremely durable.

Checkout and Calibration

A checkout test was conducted on the assembled unit to determine correctness and operation of each of the individual circuits and to calibrate the PQGS to the characteristics of the engine to be used in the engine firing evaluation test. The Schmidt trigger of the PQGS was set so that the unit would start counting when the output of the sensor amplifier reached 450 millivolts. The one shot generators for the three sensor channels were each set to five milliseconds. This time was derived from the test engine valve opening and closing times, the time from valve electrical on until the Schmidt trigger started the PQGS count,

ELECTRICAL BLOCK DIAGRAM P.Q.G.S.

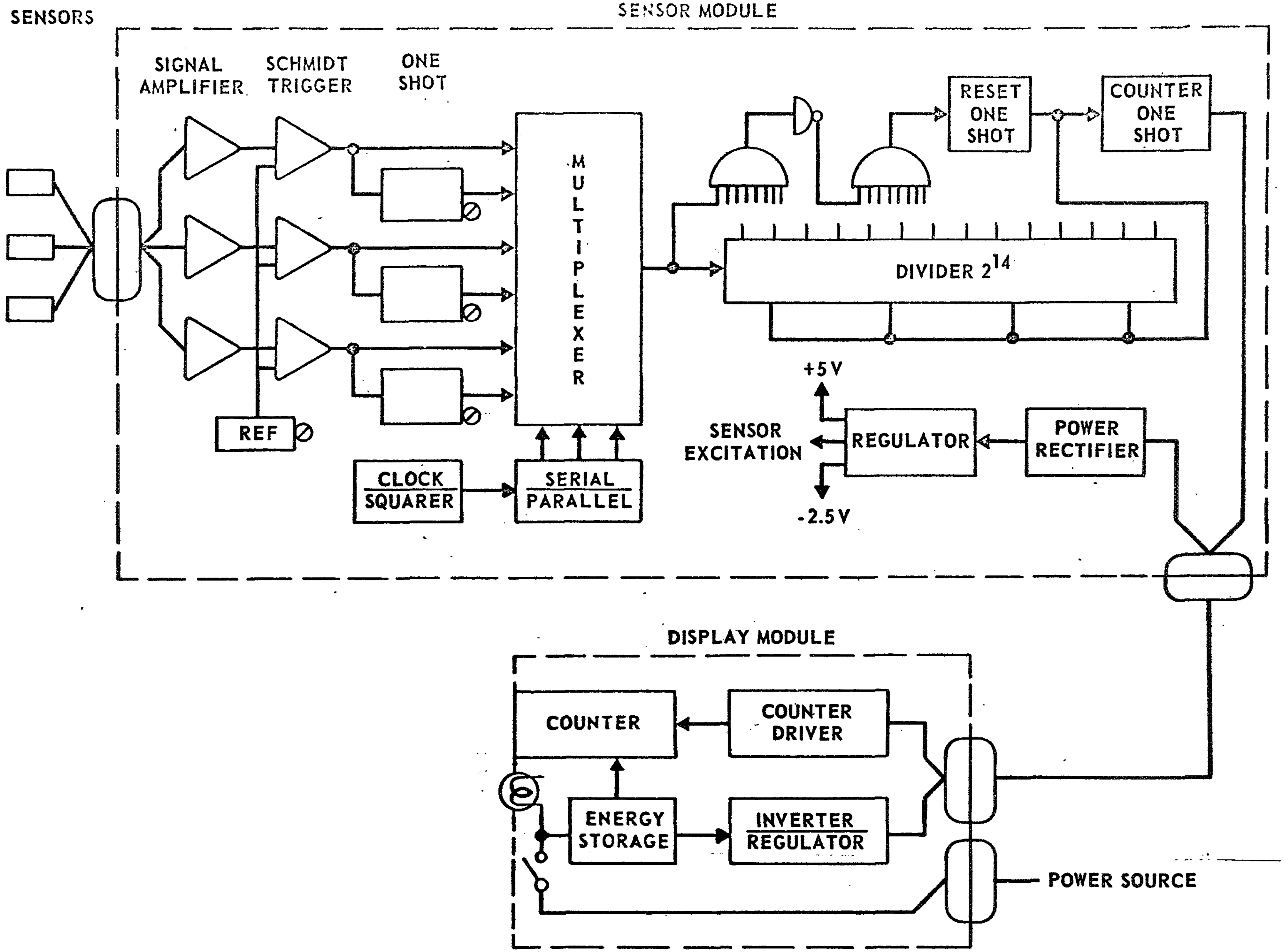
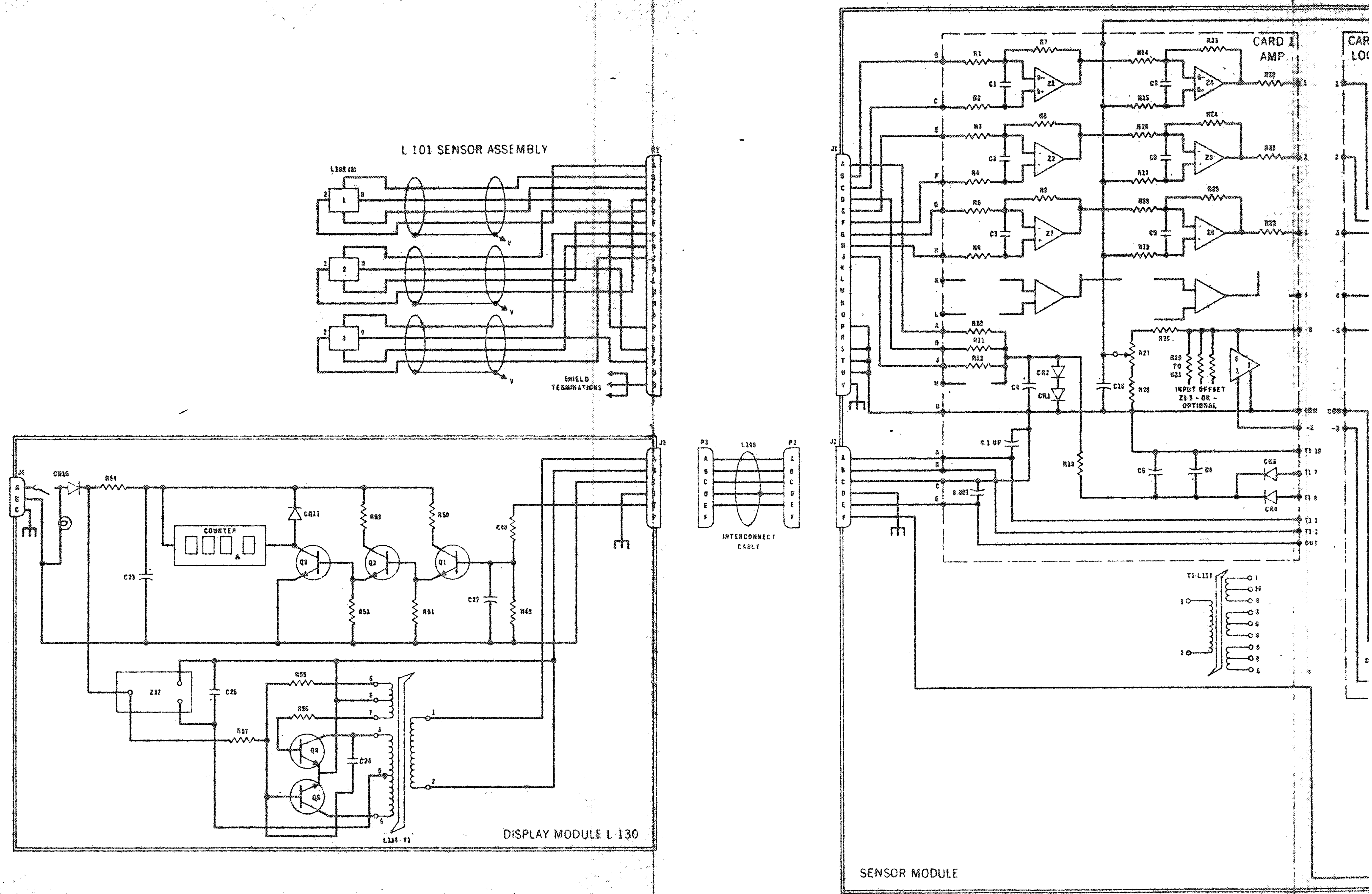
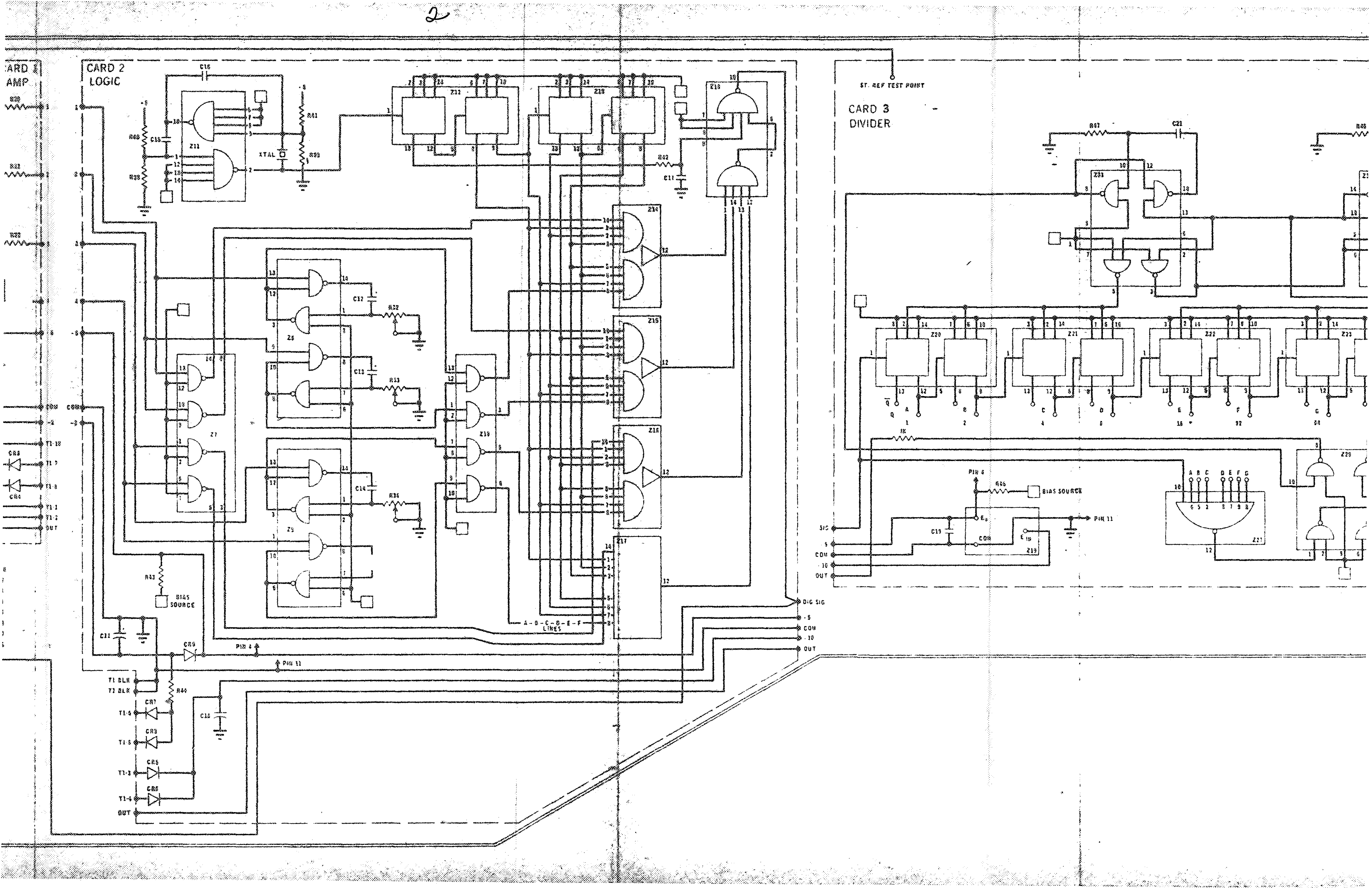
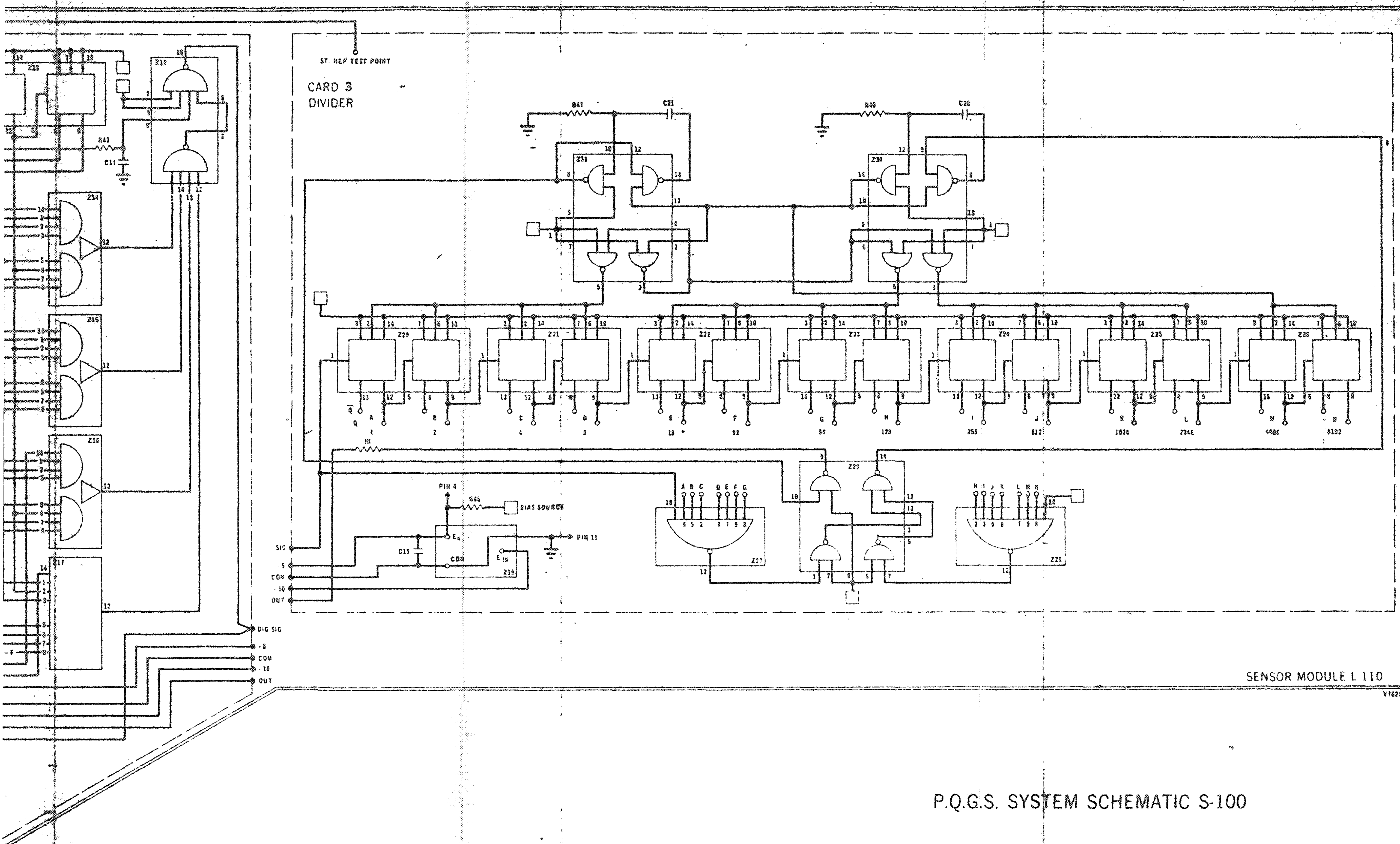


Figure 22

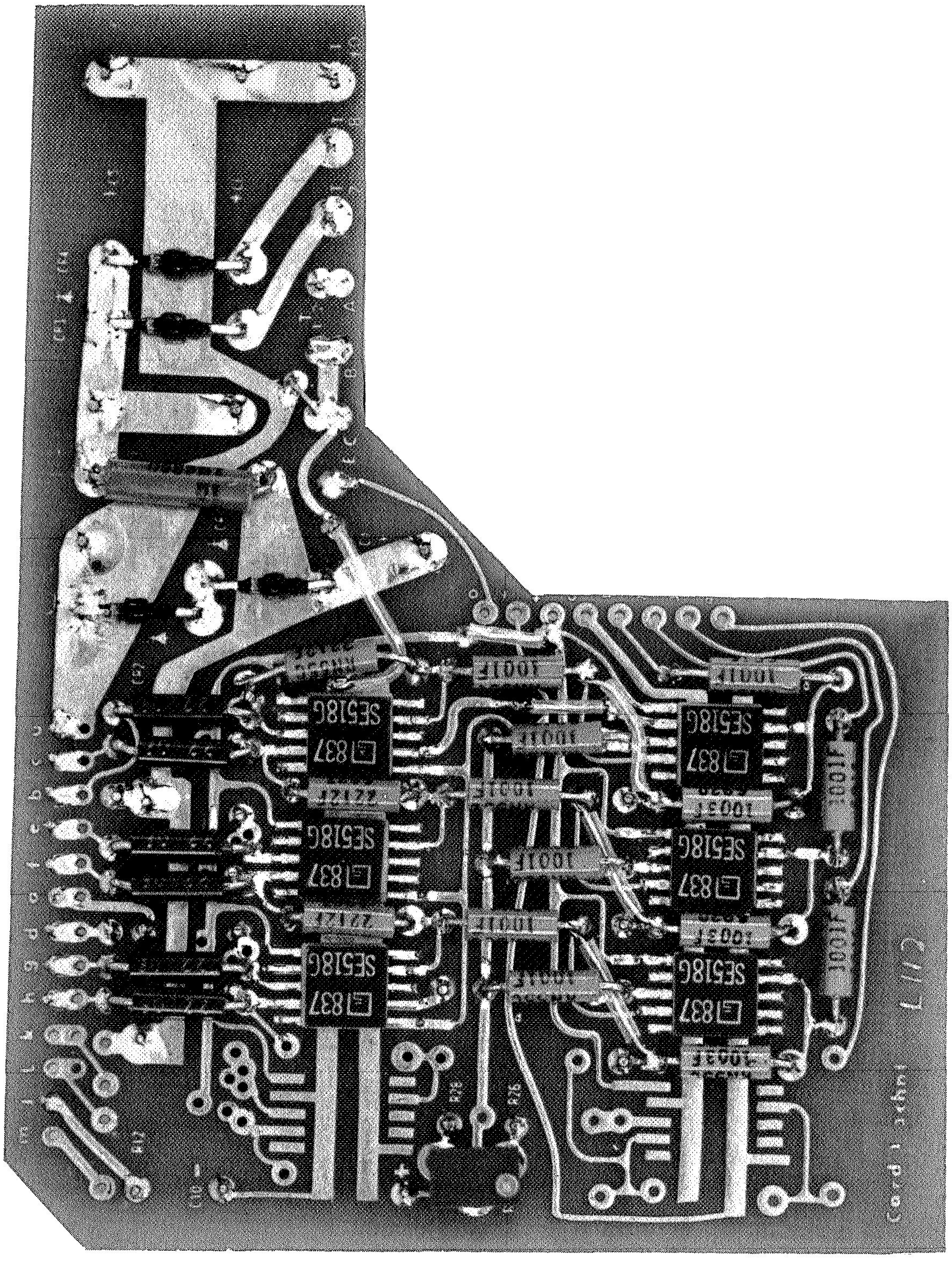

L 101 SENSOR ASSEMBLY
SHIELD TERMINATIONS
COUNTER
DISPLAY MODULE L 130
INTERCONNECT CABLE
CARD & AMP
INPUT OFFSET
Z1-3 - OR - OPTIONAL
0.1 UF
SENSOR MODULE


2
CARD 2
LOGIC
CARD 3
DIVIDER
ST. REF TEST POINT
XTAL
BIAS SOURCE
A - B - C - D - E - F
LINES
DIG SIG
PIN 4
PIN 11
T1 BLK
T2 BLK
OUT
COM



P.Q.G.S. SYSTEM SCHEMATIC S-100

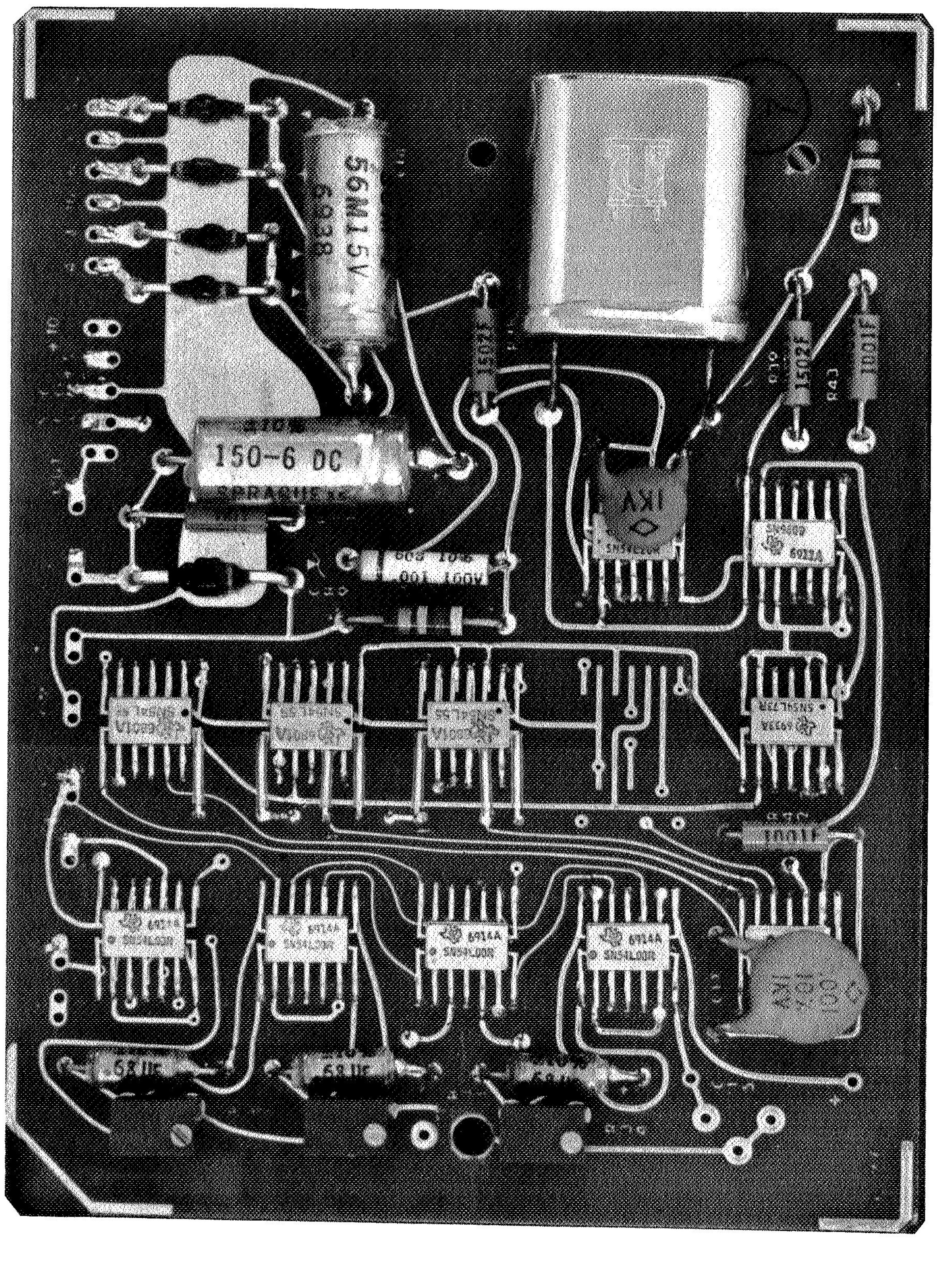
FIGURE 23



CIRCUIT CARD NO. 1

NEG. 9705-3

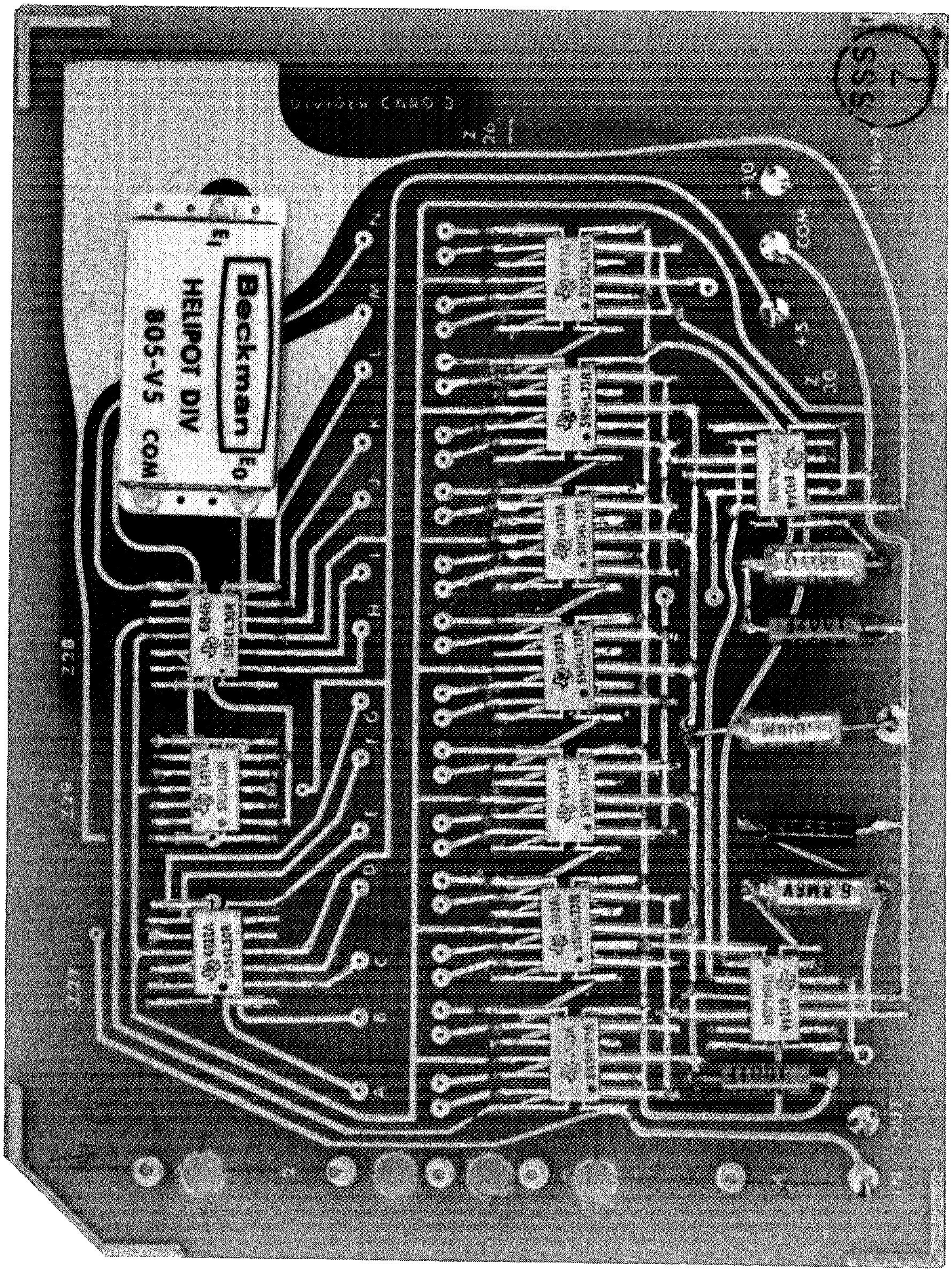
Figure 24



CIRCUIT CARD NO. 2

NEG. 9705-4

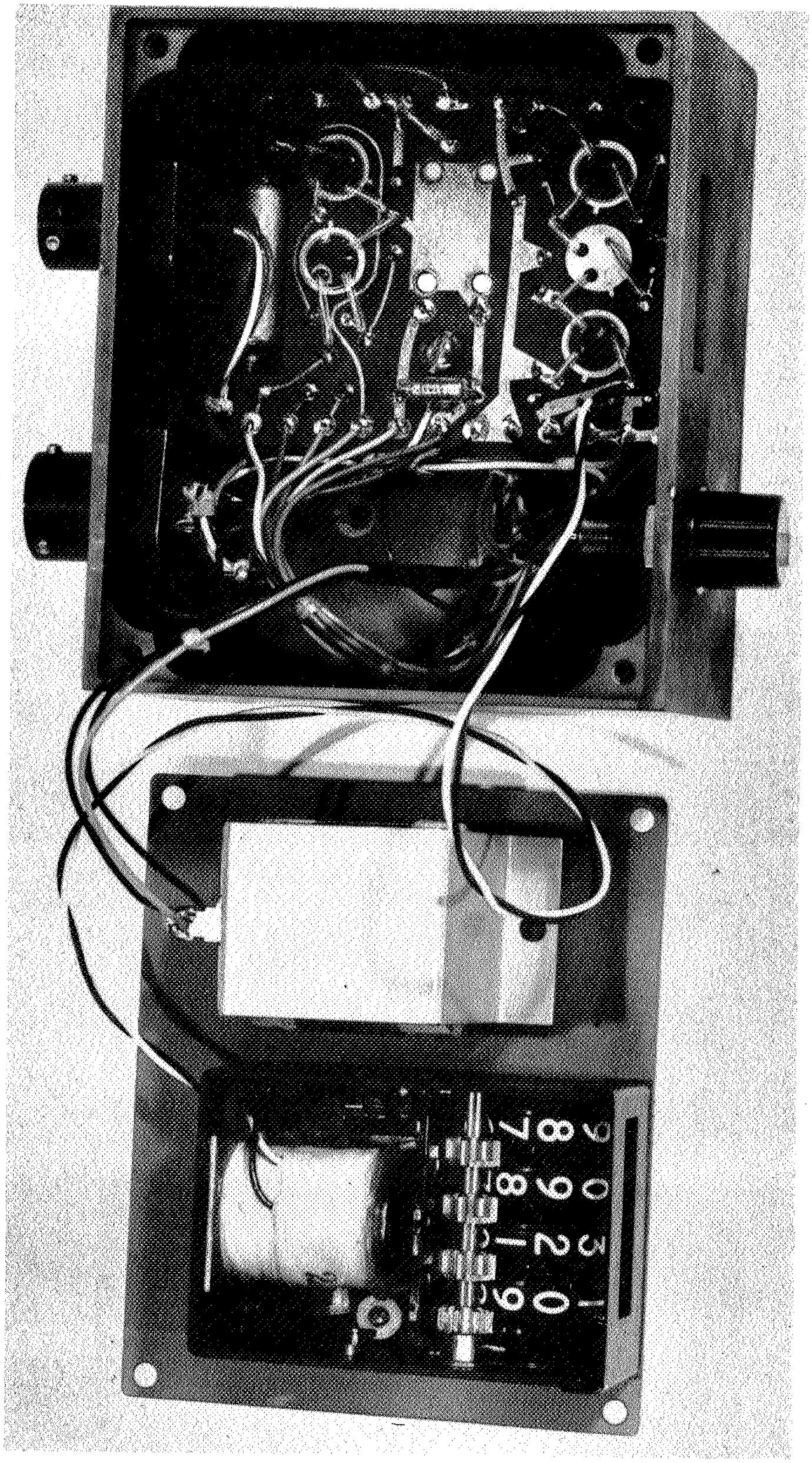
Figure 25



CIRCUIT CARD NO. 3

NEG. 9705—5

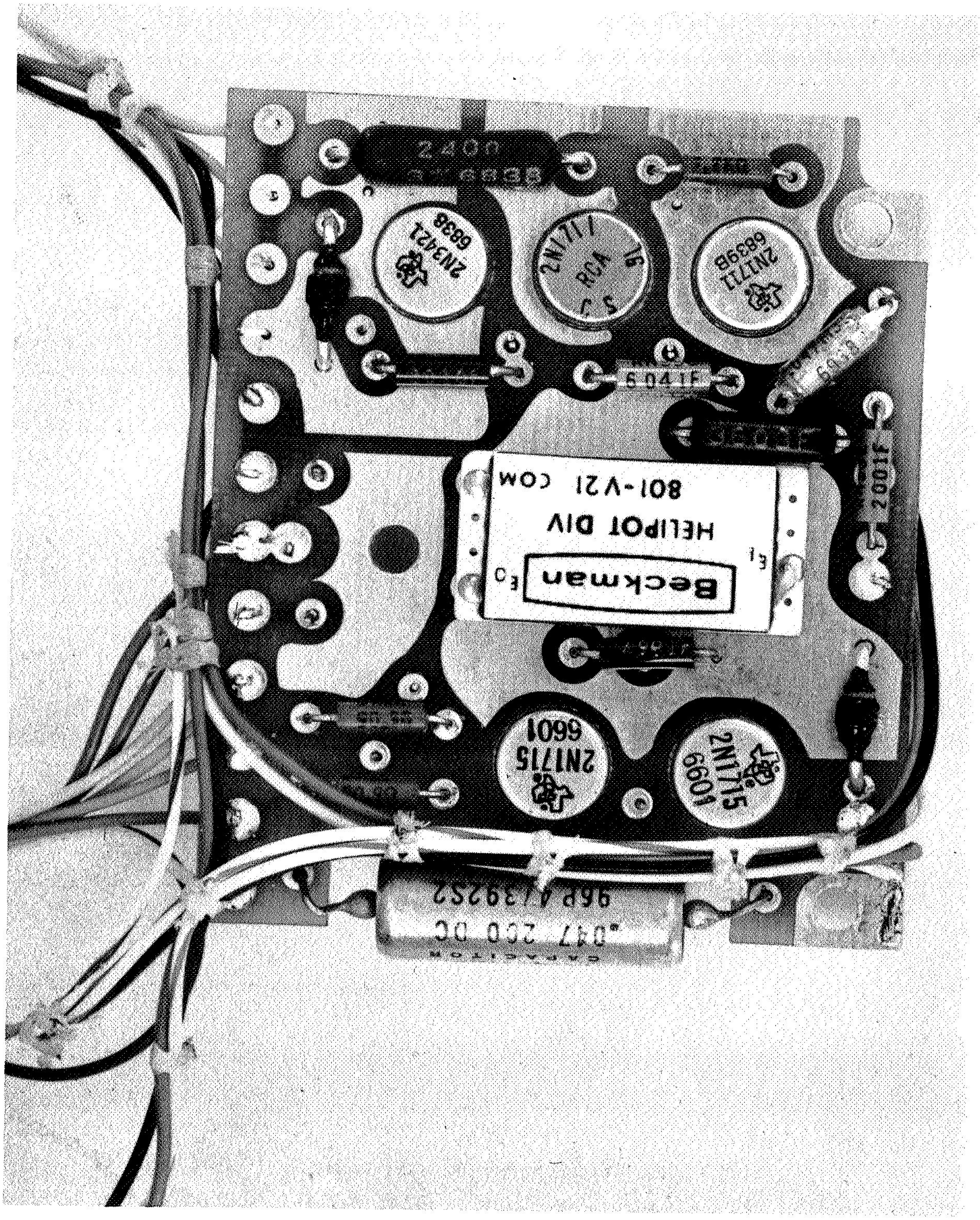
Figure 26



DISPLAY MODULE LAYOUT

NEG. 9705-7

Figure 27



NEG. 9705-8

CIRCUIT CARD NO. 4 - REAR VIEW

the time from when the valve was de-energized until the PQGS stopped counting and an estimated correction factor to account for the higher engine flow experienced during the engine starting transients. The counting rate for the PQGS was established from the engine steady state flow rate of 0.0791 pounds per seconds at nominal operating conditions. This flow was used to set the PQGS divider so that the display was reduced by 0.1 pound for each 1.26 seconds of engine operation.

The flight weight propellant system has the following characteristics:

Characteristics

General.--

Maximum propellant reading	999.9 pounds of propellant
Minimum resolution	0.1 pound of propellant
Thrustors to be measured	3 - 22 lb thrust Model R-1E thrustors

The propellant quantity gaging system has been calibrated for a Marquardt 22 lb thrust R-1E engine (P/N 229045, S/N 0008) having the following characteristics at a nominal inlet pressure of 198 psia.

Vacuum Thrust	21.5 pounds
Specific Impulse	272 seconds
Steady State Flow Rate	0.0791 pounds/seconds
Steady State Mixture Ratio (O/F)	1.72

Electrical.--

Input voltage	24 to 32 volts d-c reverse polarity protected Pin A +, Pin B -, Pin C case ground
Standby current	250 ma.
Peak current	550 ma.
Input power	200 ma, 25 V d-c, 5 watts (without lamp)
Lamp No. 327	

The electrical supply is floating relative to the case ground. The sensor and display modules are electrically interlocked to protect the inverter from non-loaded conditions.

Interconnect cable voltages	Power: 55 volts peak to peak at 5 KHz
	Signal: 4 volts positive going 45 ms duration
	Shield: Common with cases only

Mechanical.--

		Dimensions Excluding Connectors			
	Weight	Width	Length	Height	Vol.
Sensors and Plug	0.3 #		3 ft		1.6 in^3
Sensor Module	1.1 #	3.5"	4.0"	1.7"	23.8 in^3
Display Module	1.0 #	3.5"	3.0"	2.0"	21.0 in^3

ENGINE TEST EVALUATION

The engine test evaluation of the flight weight propellant quantity gaging system was conducted in the Marquardt precision rocket laboratory, Figure 29, to evaluate the performance of the PQGS. Conditions evaluated during the testing included:

Effects of engine on time from pulse widths of 0.065 seconds to steady state runs of 10 seconds duration.

Effects of engine off time up to a pulse frequency of 12 cycles per second at the minimum pulse width of 0.065 sec.

Effects of engine solenoid valve voltage from 21 V d-c to 32 V d-c

Effects of engine propellant temperature from 20 to 125°F.

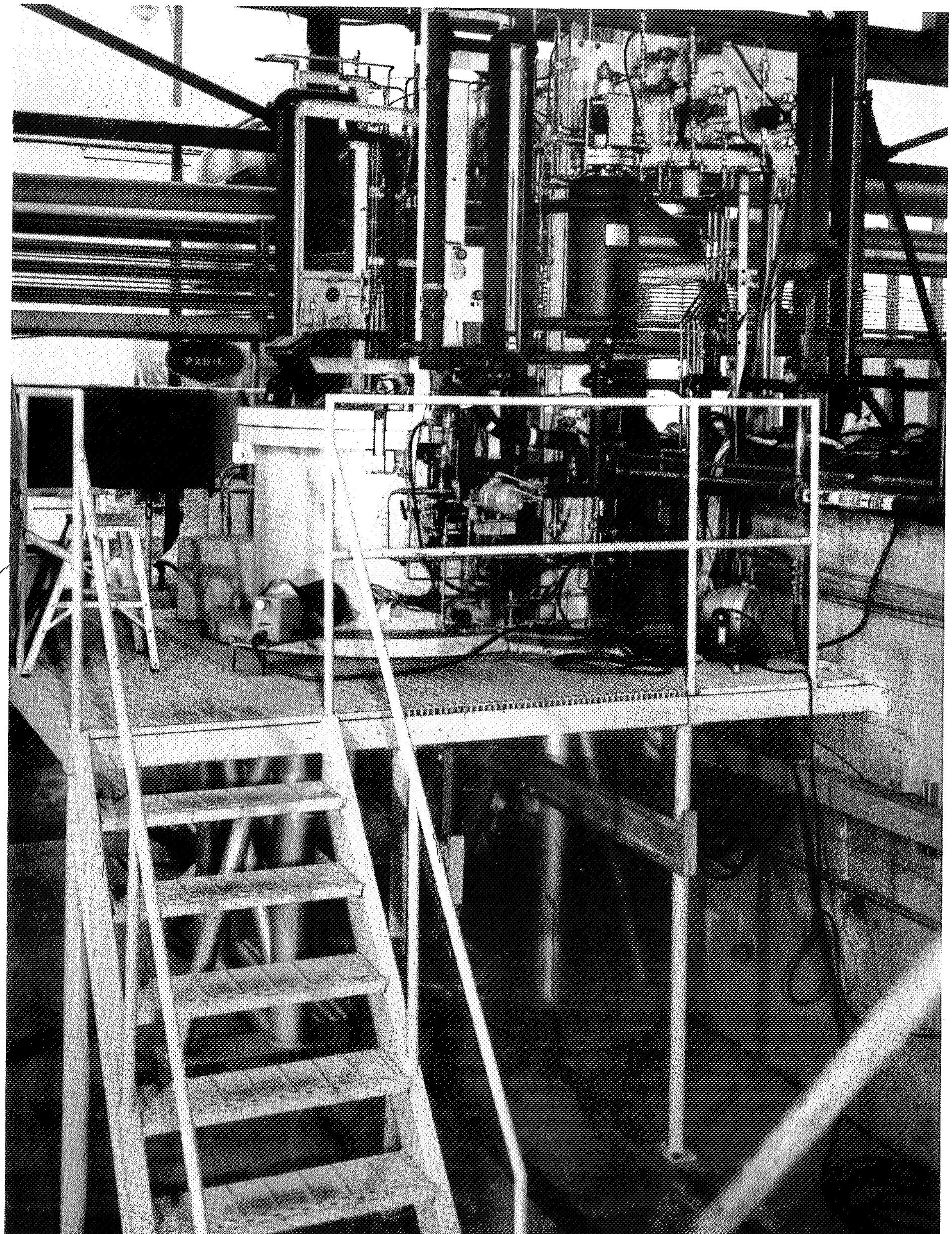
Test Engine

The engine used in the PQGS evaluation tests was a 22 lb thrust model R-1E engine P/N 229045, S/N 0008. This engine is the final configuration developed during the Manned Orbiting Laboratory (MOL) program at Marquardt and had been subjected to MOL qualification tests. The engine had been calibrated during acceptance tests to the following requirements.

TABLE VI

TEST DATA PARAMETERS

PARAMETER	TEST SPECIFICATION REQUIREMENT	ACCEPTANCE TEST DATA
Steady State Thrust (vac)	21.0 to 22.0 lb	21.50 lb
I_{sp}	$\geq$ 245 sec	274.6 sec
O/F Ratio	1.65 - 1.75	1.723
Pulsing (Pulse Width 0.0165 sec)		
Average Total Impulse	0.237 - 0.309 lb sec	0.275 lb sec
I_{sp}	$\geq$ 201 sec	221.3 sec
O/F Ratio	1.43 - 1.82	1.817



PRECISION ROCKET LABORATORY-PAD E - TEST AREA
ALTITUDE CHAMBER AND PROPELLANT SYSTEM

NEG. 8933-2

Figure 29

Test Facility

The engine tests were conducted with the engine installed in Pad E of Marquardt's precision rocket laboratory. Propellants used were monomethylhydrazine and nitrogen tetroxide pressurized with helium to the nominal engine operating pressures of 198 psia. Manifolds supplying propellants to the engine were temperature conditioned so that temperature of the propellants could be maintained up to the engine solenoid inlets. A schematic of the test plumbing used to supply propellants to the engine is shown in Figure 30. The engine was oriented to fire vertically down. Pad E has been used extensively in the development, acceptance and qualification testing of the 22 lb thrust R-1E engine.

Instrumentation

The primary instrumentation during the PQGS evaluation tests was measurement of engine flow. To obtain an accurate measure of pulse flow, Pad E utilizes a sight tube system that records the level of propellant in a vertical tube before and after a pulse run. Calibrations of the sight tube system have demonstrated a 3 sigma accuracy of 0.7% for the MMH section and 1.4% for the nitrogen tetroxide section.

The fixed capacity of the sight tube system limited each run to approximately 10 seconds of total run time. Runs in the test matrix were based on this propellant capacity and extended pulse series were obtained by reloading the sight tube system and conducting additional runs. Propellant inlet pressures were established at the nominal operating pressure for the engine, 198 psia, and maintained during the entire test.

One Hall effect sensing element of the PQGS was mounted on each of the engine solenoid valves as shown in Figure 31. Although only one sensor per engine is required in normal PQGS operation the use of two sensors permitted the evaluation of two of the PQGS channels during the test. This operation simulated two engines firing to the same duty cycle. The calibration of the PQGS had been conducted during bench testing and was based on the engine flow rate documentation obtained during the engine acceptance tests.

Test Results

A resume of the conditions tested and of the propellant used is shown in Table VII. Since there are two sensors mounted on the engine, the quantity of propellant used as indicated by the PQGS was twice as much as actually used by the engine. The PQGS flow indication was divided by two in order to compare to the actual flow and determine the system errors.

The least count of the PQGS is 0.1 lb of propellant. For the 22 lb thrust engine this corresponds to approximately 1.2 seconds of steady state engine operation. The engine run time was limited by the range of the flow meter so that to get a representative sample of operation at each condition, a total of four runs

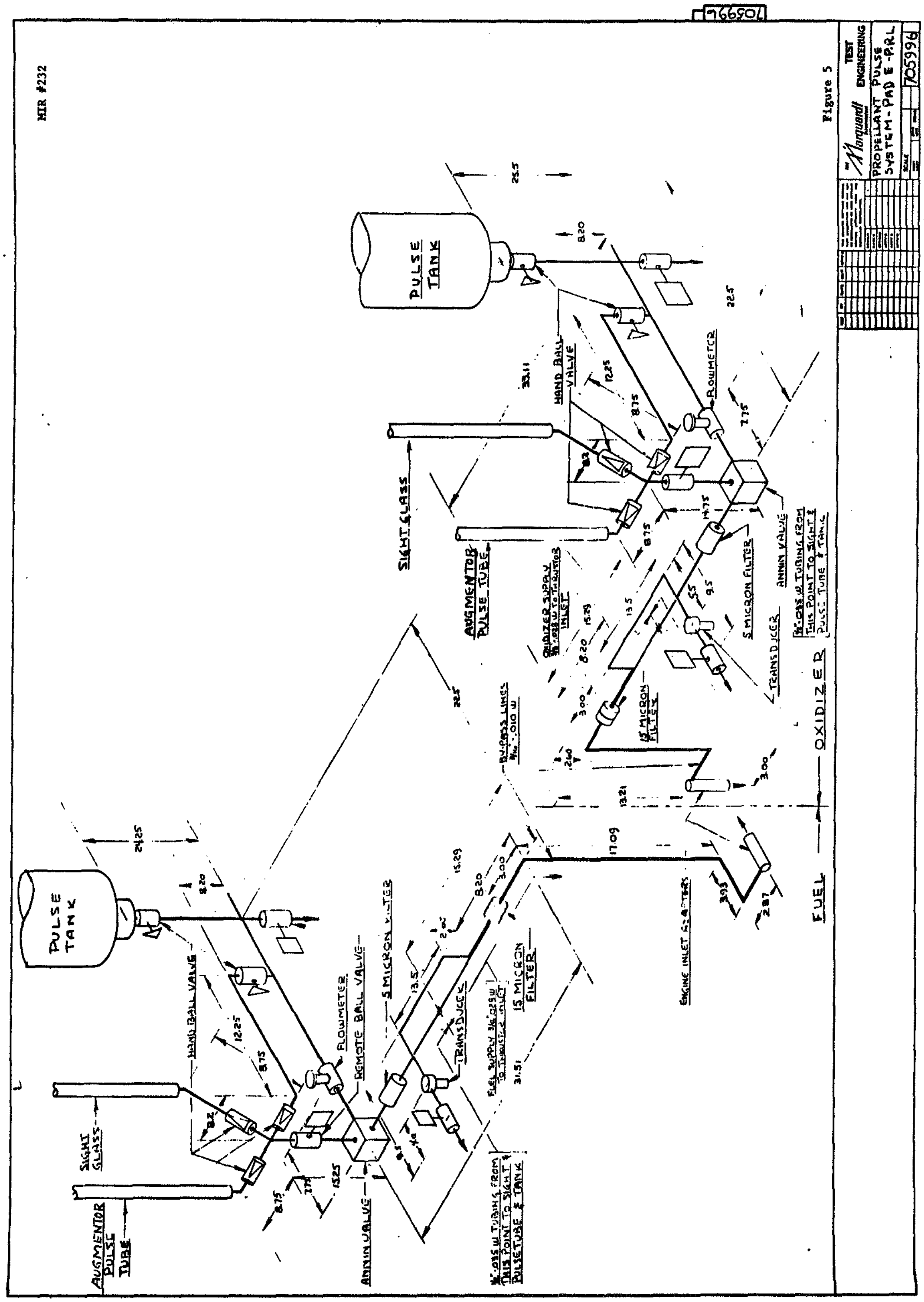
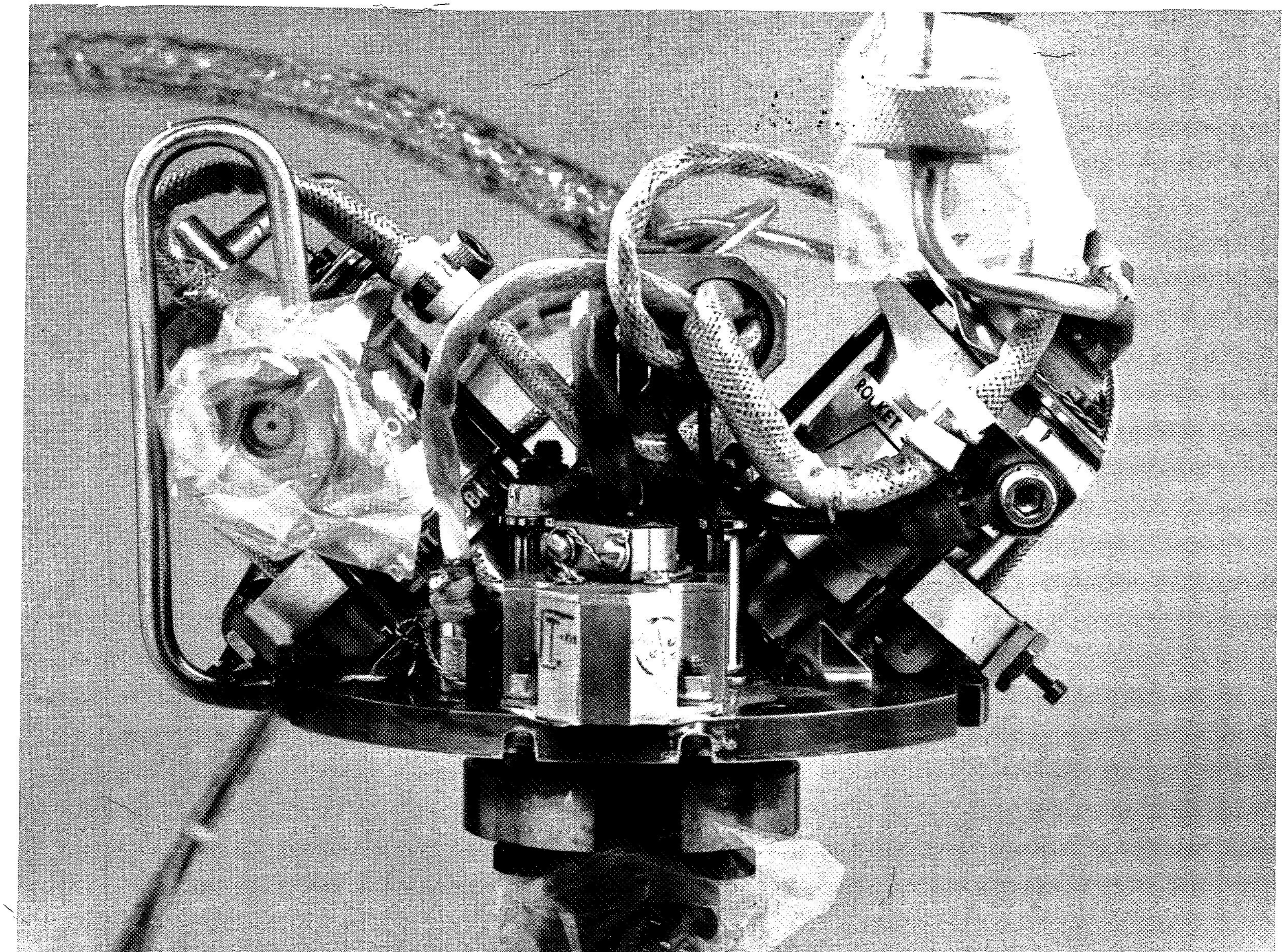

MIR #232
Figure 5
PULSE TANK
PULSE TANK
SIGHT GLASS
AUGMENTOR PULSE TUBE
HAND BALL VALVE
FLOWMETER
REMOTE BALL VALVE
5 MICRON FILTER
15 MICRON FILTER
TRANSDUCER
ANNIN VALVE
ENGINE INLET ADAPTERS
FUEL
OXIDIZER
Marquardt TEST ENGINEERING
PROPELLANT PULSE SYSTEM - PAD E - P.R.L
705996

Figure 30

NEG. 9741-1



ENGINE MOUNTED P.Q.G.S. SENSOR DETAIL

Figure 31

TABLE VII

PQGS EVALUATION - ENGINE FIRING TEST SUMMARY

ENGINE OPERATING CONDITION	ENGINE PROPELLANT USED (LB)	ENGINE ELECTRICAL ON TIME (SEC)	CONDITION AVERAGE FLOW RATE (LB/SEC)	CONDITION AVERAGE O/F RATIO	PQGS FLOW INDICATION 2 SENSORS (LB)	CUMULATIVE PROPELLANT USAGE (LB)	CUMULATIVE PQGS INDICATION (LB)	CUMULATIVE FLOW ERROR (LB)	CUMULATIVE % ERROR	CONDITION FLOW ERROR (LB)
4 Runs 10 Sec S.S. Each T = 80°F	3.282	41.379	.0793	1.700	6.5	3.28	3.25	-.03	-.91	-.03
560 Pulses .065 Sec on, 1.00 Sec off 26 V d-c, T = 75°F	2.876	36.554	.0787	1.732	5.7	6.16	6.10	-.06	-.97	-.03
264 Pulses .100 Sec on, 1.00 Sec off 26 V d-c, T = 75°F	2.098	26.505	.0791	1.728	4.2	8.26	8.20	-.06	-.73	.00
80 Pulses .500 Sec on, 1.00 Sec off 26 V d-c, T = 76°F	3.180	40.000	.0795	1.707	6.3	11.44	11.35	-.09	-.78	-.03
560 Pulses .065 Sec on, .100 Sec off 26 V d-c, T = 77°F	2.828	36.400	.0777	1.710	5.7	14.26	14.20	-.06	-.42	+.02
560 Pulses .065 Sec on, .020 Sec off 26 V d-c, T = 78°F	2.807	36.400	.0771	1.693	5.8	17.07	17.10	-.03	+.18	+.09
560 Pulses .065 Sec on, 1.00 Sec off 21 V d-c, T = 77°F	2.752	36.400	.0756	1.712	5.5	19.82	19.85	+.03	+.15	.00
560 Pulses .065 Sec on, 1.00 Sec off 32 V d-c, T = 77°F	2.943	36.400	.0808	1.724	6.0	22.77	22.85	+.08	+.35	+.06
4 Run 10 Sec S.S. Each 26 V d-c, T= 130°F	3.295	41.177	.0800	1.599	6.5	26.06	26.10	+.04	+.15	-.04

TABLE VII (Continued)

PQGS EVALUATION - ENGINE FIRING TEST SUMMARY

ENGINE OPERATING CONDITION	ENGINE PROPELLANT USED (LB)	ENGINE ELECTRICAL ON TIME (SEC)	CONDITION AVERAGE FLOW RATE (LB/SEC)	CONDITION AVERAGE O/F RATIO	PQGS FLOW INDICATION 2 SENSORS (LB)	CUMULATIVE PROPELLANT USAGE (LB)	CUMULATIVE PQGS INDICATION (LB)	CUMULATIVE FLOW ERROR (LB)	CUMULATIVE % ERROR	CONDITION FLOW ERROR (LB)
560 Pulses .065 Sec on, 1.00 Sec off 26 V d-c, T=130°F	2.874	36.456	.0788	1.641	5.7	28.94	28.95	+.01	+.03	-.02
4 Runs 10 Sec S.S. Each 26 V d-c, T = 28°F	3.173	40.638	.0780	1.731	6.4	32.11	32.15	+.04	+.12	+.03
560 Pulses .065 Sec on, 1.00 Sec off 26 V d-c, T = 28°F	2.799	36.400	.0769	1.756	5.8	34.91	35.05	-.14	+.40	+.10
TOTAL 4276 ENGINE STARTS	TOTAL 34.907	TOTAL 444.709	AVERAGE .0785	AVERAGE 1.701	TOTAL 70.1					

were made at each condition. The individual runs are tabulated on Table VIII. Two runs were aborted during the test. Run number 3066 was terminated with only 0.123 seconds of engine operation and no change was observed in the PQGS reading The engine on time corresponds to approximately 0.01 lb of propellant flow and no correction was made to the data in eliminating this run. During run 3071 the run was completed; however, because of procedural error the actual engine flow was not obtained. This run was eliminated from the data by subtracting the delta recorded on the PQGS during the run.

The two conditions that appear to produce the largest error are:

Minimum pulse width with short (0.020 seconds) off time between pulses (runs 3083 through 3086)

Minimum pulse width at low propellant temperature (runs 3107 - 3110)

For both of these conditions the PQGS indicated flow approximately 3% higher than the actual flow. Additional tests at these conditions should be made to substantiate the actual magnitude of the error since the least count of the PQGS is significant in determining the error.

Figure 32 shows the cumulative results of running a mission composed of the twelve conditions of the test matrix. The propellant used as indicated by the PQGS is within 1% of the actual at any time during the mission and for the entire testing the PQGS is within 0.4% of the measured flow.

CONCLUSIONS AND RECOMMENDATIONS

Conclusions

1. Engine propellant consumption can be measured without breaching the propellant or electrical circuits of a propulsion system by sensing the magnetic flux generated when the engine solenoid valves are energized.

2. Within the operating ranges considered, the R-1E bipropellant rocket engine flow characteristics are predictable and repeatable for use in gaging propellant consumption of an auxiliary propulsion system.

3. Accuracy of the gaging system has been demonstrated to be within the design goal of 3% for operation over engine valve voltage, environmental temperature and duty cycle operating conditions typical of an Orbital Workshop mission.

TABLE VIII

PQGS EVALUATION - ENGINE TEST DATA

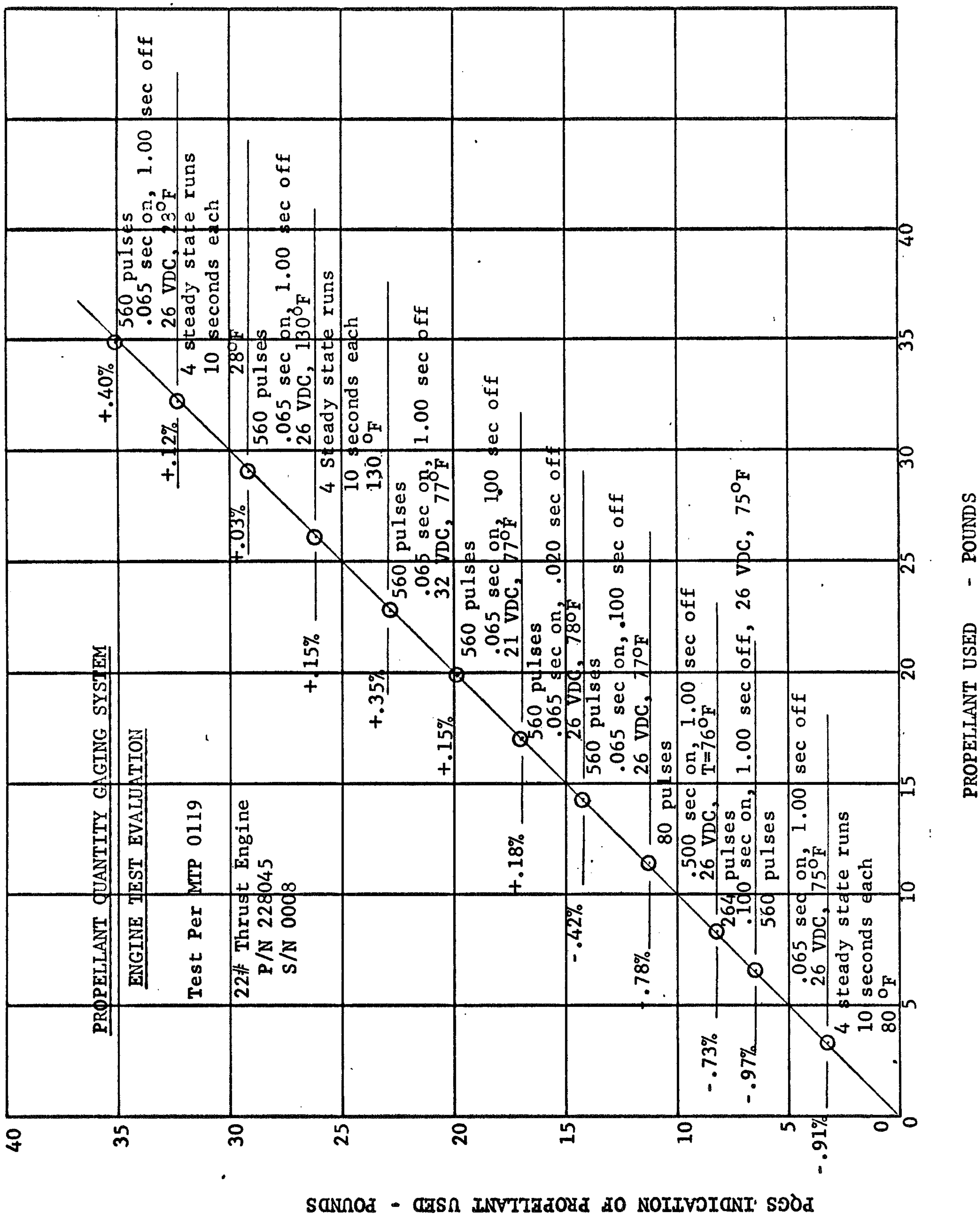
RUN NUMBER	PULSE ON TIME (SEC)	PULSE OFF TIME (SEC)	NUMBER OF PULSES	ENGINE ON TIME (SEC)	FUEL USED (LB)	OXIDIZER USED (LB)	PROPELLANT USED (LB)	PQGS READING (LB)
3062	S.S	-	-	10.383	.3057	.5184	.8241	184.5*
3063	S.S	-	-	10.394	.3083	.5215	.8298	182.8
3064	S.S	-	-	10.400	.3098	.5213	.8311	181.2
3065	S.S	-	-	10.197	.2918	.5056	.7974	179.6
3066	.065	1.000	-	.123	Run Not Completed			179.6
3067	.065		140	9.128	.2639	.4525	.7164	178.2
3068	.065		140	9.142	.2623	.4559	.7182	176.7
3069	.065		140	9.142	.2643	.4590	.7233	175.3
3070	.065		140	9.142	.2619	.4562	.7181	173.9
3071	.100		88	8.835	No Flow Data Obtained			172.5
3072	.100		88	8.835	.2551	.4410	.6961	171.1
3073	.100		88	8.835	.2575	.4453	.7028	169.7
3074	.100		88	8.835	.2565	.4428	.6993	168.3
3075	.500		20	10.000	.2927	.5035	.7962	166.7
3076	.500		20	10.000	.2938	.4998	.7936	165.1
3077	.500		20	10.000	.2938	.5020	.7958	163.6
3078	.500	1.000	20	10.000	.2945	.5001	.7946	162.0
3079	.065	.100	140	9.100	.2629	.4478	.7107	160.6
3080		.100			.2624	.4475	.7099	159.1
3081		.100			.2587	.4443	.7030	157.7
3082		.100			.2597	.4447	.7044	156.3
3083		.020			.2597	.4400	.6997	154.8
3084		.020			.2610	.4409	.7019	153.4
3085		.020			.2606	.4424	.7030	151.9
3086		.020			.2612	.4415	.7027	150.5
3087		1.000			.2531	.4298	.6829	149.1
3088		1.000			.2541	.4359	.6900	147.8
3089		1.000			.2537	.4359	.6896	146.4
3090	.065	1.000	140	9.100	.2539	.4359	.6898	145.0

* Initial PQGS Reading - 186.1

TABLE VIII (Continued)

PQGS EVALUATION - ENGINE TEST DATA

RUN NUMBER	PULSE ON TIME (SEC)	PULSE OFF TIME (SEC)	NUMBER OF PULSES	ENGINE ON TIME (SEC)	FUEL USED (LB)	OXIDIZER USED (LB)	PROPELLANT USED (LB)	PQGS READING (LB)
3091	.065	1.00	140	9.100	.2699	.4638	.7337	143.5
3092					.2715	.4660	.7375	142.0
3093					.2693	.4629	.7322	140.5
3094	.065	1.00	140	9.100	.2695	.4700	.7395	139.0
3095	S.S	-	-	10.289	.3166	.5034	.8200	137.4
3096	S.S	-	-	10.294	.3162	.5070	.8232	135.8
3097	S.S	-	-	10.295	.3173	.5000	.8173	134.2
3098	S.S	-	-	10.299	.3176	.5077	.8253	132.5
3099	.065	1.000	140	9.114	.2716	.4468	.7184	131.1
3100					.2718	.4469	.7187	129.7
3101					.2729	.4472	.7201	128.2
3102	.065	1.000	140	9.114	.2720	.4451	.7171	126.8
3103	S.S	-	-	10.137	.2894	.5027	.7921	125.2
3104	S.S	-	-	10.155	.2905	.5025	.7930	123.6
3105	S.S	-	-	10.164	.2907	.5012	.7919	122.0
3106	S.S	-	-	10.182	.2911	.5050	.7961	120.4
3107	.065	1.000	140	9.100	.2541	.4446	.6987	118.9
3108					.2530	.4466	.6996	117.5
3109					.2534	.4462	.6996	116.0
3110	.065	1.000	140	9.100	.2547	.4459	.7006	114.6



PROPELLANT QUANTITY GAGING SYSTEM
ENGINE TEST EVALUATION
Test Per MTP 0119
22# Thrust Engine
P/N 228045
S/N 0008
560 pulses .065 sec on, 1.00 sec off 26 VDC, 23°F
4 steady state runs 10 seconds each 28°F
560 pulses .065 sec on, 1.00 sec off 26 VDC, 130°F
4 Steady state runs 10 seconds each 130°F
560 pulses .065 sec on, 1.00 sec off 32 VDC, 77°F
560 pulses .065 sec on, .100 sec off 21 VDC, 77°F
560 pulses .065 sec on, .020 sec off 26 VDC, 78°F
560 pulses .065 sec on, .100 sec off 26 VDC, 77°F
80 pulses .500 sec on, 1.00 sec off 26 VDC, T=76°F
264 pulses .100 sec on, 1.00 sec off, 26 VDC, 75°F
560 pulses .065 sec on, 1.00 sec off 26 VDC, 75°F
4 steady state runs 10 seconds each 80°F
+.40%
+.12%
+.03%
+.15%
+.35%
+.15%
+.18%
-.42%
-.78%
-.73%
-.97%
-.91%
PROPELLANT USED - POUNDS
PQGS INDICATION OF PROPELLANT USED - POUNDS

Figure 32

Recommendations

Several areas of technical expansion are possible for the PQGS. The accuracy demonstrated during the program is well within the goal established, even though no specific compensation exists for variations in engine propellant temperature or pressure. The engine test program at high and low temperatures indicates systematic errors that may be significant if the majority of a mission were to be conducted at a temperature extreme. Compensation for propellant temperature can be accomplished in the PQGS circuitry using sensing devices that do not breach the propellant system. Since the propellant flow characteristics of the engine are influenced by the variations in engine performance with temperature as well as changes in propellant density the temperature compensation feature must be related to the particular engine used with the PQGS.

The accuracy of the PQGS has been analyzed based on propellant pressures within the operating range of 210 to 218 psia. The accuracy of the system could be further improved by providing compensation for changes in propellant pressure. This would also provide accurate propellant usage data for engine operation beyond the operating range and for off design operation.

The Hall effect sensor in the PQGS has the inherent potential for recognizing several types of system malfunction including:

Failure of the engine valve to open when supplied with an electrical signal

Failure of the engine valve to close when electrical signal is terminated.

The buildup of the magnetic field is dependent on whether the valve armature does or does not move. This feature could be utilized to indicate the two modes of malfunction indicated above.

In summary the following areas appear worthy of further investigation:

1. Development of the PQGS to improve accuracy by investigating the techniques for propellant temperature and pressure compensation.

2. The detection of solenoid valve malfunction via the use of the Hall sensor be investigated to provide a reliable method of detecting the position and malfunction modes of solenoid devices.

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