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TWO PRIMARY METHODS OF PROVING GAS FLOW METERS

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COLORADO ENGINEERING EXPERIMENT STATION INC.

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NASA Lewis Research Center
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FINAL REPORT

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COLORADO ENGINEERING EXPERIMENT STATION INC.
P.O. Box 344
Boulder, Colorado 80302

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NASA Lewis Research Center
Cleveland, Ohio
Robert C. Johnson, Project Manager
Instrument & Computing Division

FOREWARD

The work described herein was done at the Colorado Engineering Experiment Station, Inc. The report was originally issued as a paper which was presented at the Symposium on Flow: It's Measurement and Control in Science and Industry, May 10-14, 1971, Pittsburgh, Pa., Paper No. 3-8-216.

ABSTRACT

This report presents two primary methods for determining the mass flow rates of gases for use in calibrating gas flowmeters up to 9 kg/sec (20 lb/sec). The rate of flow is determined from the time interval for a measured change of mass in a storage vessel. In one of the two methods the change of mass is determined by weighing the storage vessel on an analytical balance before and after the test (the mass-time method). In the other method the mass is determined from the calibrated volume of the storage vessel, and the pressure and temperature measurements made before and after the test. This is called the pressure-volume-temperature-time (PVTt) method. The estimated uncertainty in a mass flow rate measurement on the mass-time facility is $\pm$0.02 percent; and $\pm$0.08 percent on the PVTt facility.

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SUMMARY

This report presents two primary methods for determining the mass flow rates of gases for use in proving the calibrations of gas flowmeters up to 9 kg/sec (20 lb/sec). The rate of flow is determined from the time interval for a measured change of mass in a storage vessel. In one of the two methods the change of mass is determined by weighing the storage vessel on an analytical balance before and after the test (the mass-time method). In the other method the mass is determined from the calibrated volume of the storage vessel, and pressure and temperature measurements made before and after the test. This is called the pressure-volume-temperature-time (PVTt) method. The estimated uncertainty in a mass flow rate measurement on the mass-time facility is $\pm$0.02 percent (95% confidence level); and $\pm$0.08 percent on the PVTt facility. Intercomparison tests between the mass-time and PVTt methods indicated a standard deviation of $\pm$0.02 percent from the mean, which reflects the sum of the random errors from all sources in the two methods. This precision will permit the high systematic accuracy of the mass-time method to be transferred to the PVTt method.

INTRODUCTION

Two primary methods for measuring the mass flow rate of gases are presented in this report. The methods cover overlapping flow ranges so that intercomparison tests may be conducted. The intercomparison tests permit the PVTt method to be calibrated using the mass-time method, thereby obtaining high systematic accuracies. The methods are designed to provide the high accuracy required for calibration of transfer standards, and are too time consuming to be practiced for the routine calibration of flowmeters. The flow ranges of the two methods are complementary, such that flow rates from 5×10^{-4} to 9 kg/sec (1×10^{-3} to 20 lb/sec) are feasible.

BACKGROUND

The quantities, mass, length, and time, are measured by comparison against their fundamentally defined units of measure, usually by means of a succession of intermediate standards. Most other quantities are defined in terms of these fundamental quantities such that primary methods are required for their measurement. The most direct primary method for measuring mass flow rate is to determine the mass discharged in a measured time interval, i.e. the mass-time primary method. This technique has been used by Reference 1 for small flow rates.

Another traditional primary method utilizes a storage vessel with a calibrated volume. Pressure and temperature measurements are made before and after a timed interval of discharge to or from the vessel. The change of mass in the storage vessel is then determined by the equation of state. This is called the pressure-volume-temperature-time (PVTt) primary method. An example of this method for flow rates up to 1 1/2 kg/sec (3 lb/sec) is given in Reference 2. This method has an economic advantage at high flow rates where the facilities must be large in size. But this method, by itself, has the disadvantage of a greater uncertainty due to the several sources of bias error. To overcome this disadvantage it is desirable to calibrate the volume of the system using weighed gas, thereby obtaining a systematic accuracy equivalent to the mass-time method.

PRINCIPLES THE TWO METHODS HAVE IN COMMON

Both primary methods determine the average flow rate over the period of the test. It is desirable to maintain steady state flow during the test so the flowmeter being calibrated will be operating at a single state. The flow systems are shown schematically in Figure 1. Prior to the start of the test, steady state flow is established through the test section, with diversion of the flow from the storage vessel marking the start of the test. Actuation of the diverter starts the time-interval measurement, which is stopped at the end of the test. Sufficient data must be obtained from the flowmeter during the test to permit average values of the flowmeter parameters to be determined to the accuracy required. Both methods require determination of the mass of gas in the storage vessel before and after the test. The means used for the mass determinations are the basic difference between the two methods.

Both methods could be operated with the storage vessel located either upstream or downstream of the test meter. (References 1 and 2 used the downstream location.) The two facilities presented in this paper have the storage vessel located upstream of the test section to permit higher flow rates to be obtained from the sizes of storage vessels used. The upstream storage vessel thus serves as the gas supply during the test, and compensation must be provided for the decreasing pressure and temperature during the "blow down" in order to achieve steady state conditions in the test section. The temperature is held nearly constant by heat exchangers, and the pressure is manually regulated by control valves. Any variation from steady state is accounted for by obtaining frequent measurements during the test of the pressure, temperature and flowmeter readings. By maintaining close control and obtaining sufficient data during the test the desired accuracy can be obtained with the storage vessel at the upstream location. Offsetting the additional effort this entails during a test is the convenience of being able to use a much smaller storage vessel than would be required if the storage vessel were located downstream of the test section. The convenience in the case of a mass-time facility results from a smaller analytical balance, and ease of handling the storage vessel. In the PVTt method there is no advantage of an operational nature, but the problem of measuring average temperatures becomes less difficult as the size of the vessel is decreased.

MASS DETERMINATION FOR THE MASS-TIME METHOD

The ratio of tare weight to weight of gas stored in the storage vessel should be kept low for maximum accuracy in weighing. Woven steel spheres are used for storage vessels because their high strength-weight ratio results in a relatively low tare weight, as follows:

Storage Vessel	Tare Weight kg (lb)	Stored Air kg (lb)	Tare/Air Ratio
1	40.9 (90)	6.91 (15.2)	5.9
2	77.4 (170)	13.8 (30.4)	5.6

The storage vessels are weighed on an analytical balance with a 2.4 meter (8 ft.) arm. Two weighings are performed for each mass determination with the storage vessel and weights interchanged between weighings. This is called transposition weighing which eliminates any bias error due to the arms of the balance not being exactly equal in length. Corrections are made for the difference in boyancy between the weights and the storage vessel. It should be noted that any minor source of bias error that has not been detected and corrected would cancel out if it was constant between the initial and final weighings. The only known bias error is the accuracy of the standard weights, which are certified to 0.001 percent.

The precision with which the mass of air discharged from the storage vessel could be measured by weighing was determined experimentally. Weighings were made of the storage vessel with and without additional standard weights to simulate gas discharged. The standard deviation was $\pm$0.0057 percent, or $\pm$0.014 percent based on 95 percent confidence level.

MASS DETERMINATION FOR THE PVTt METHOD

This method requires that the volume, V, of the storage vessel be determined by calibration. This was initially performed by the traditional method of weighing water into and out of the storage vessel. However, this calibration was replaced by a weighed-air calibration for reasons that will be discussed later.

The mass of gas discharged is obtained using the equation of state as follows:

$$(M_1 - M_2) = \frac{V}{R}\left[\left(\frac{P}{ZT}\right)_1 - \left(\frac{P}{ZT}\right)_2\right] \quad (1)$$

M is mass, R is the gas constant, and Z is the compressibility factor. The percentage sensitivity of the result to the P/ZT term is greater than one, with the actual sensitivity being dependent on the difference between the initial and final pressures. If P_2 is one-half P_1, then the percentage error in the calculated mass $(M_1 - M_2)$ would be twice the percentage error in the P_1 measurement. Since the pressure measurement is most significant it should be made by the best possible means. A dead-weight gage was used with a certified accuracy of 0.01 percent of measurement.

The temperature measurement must provide the average temperature of the gas contained in the storage vessel. The temperature is measured by three platinum resistance elements, each being enclosed in a copper sheath which spirals along the entire length of the vessel. These temperature probes, along with the necessary readout instruments, were calibrated against a certified platinum resistance thermometer. The effect of ambient pressure on these probes was investigated up to 200×10^5 N/m^2 (200 atm), and no error was found. The bias error in the gas temperature measurement is estimated to be less than 0.01 K (0.02F) (0.005 percent at 294 K (530R)).

During a test the temperature of the air in the storage vessel decreases as the pressure decreases, which causes a substantial difference in temperature between the air and the walls of the storage vessel. At least an hour is allowed for thermal equilibrium to be established before pressure and temperature measurements are made. The measurements are repeated 30 minutes later. Agreement of the mass determinations from the readings obtained at the different times indicates that sufficient time had been allowed for thermal equilibrium, and also provides a check on the leak tightness of the system. An average of the two mass determinations are used to reduce the random error in the result. Heating blankets on the storage vessel are used to return the vessel to ambient temperature after high flow rate runs.

The compressibility factor, Z, was obtained from published data [3]. The gas constant, R, is consistent with the values of compressibility factor so that it does not contribute any additional error. The accuracy of the compressibility factor is estimated to be 0.02 percent, with better confidence at lower pressures.

A systematic error analysis of the bias error sources indicates the mass determination from equation (1) can be made to within 0.08 percent. The PVTt facility was later recalibrated by weighed air. This permitted all bias errors to be removed, except the bias error of the mass determination by weighing (0.001 percent). The results of the recalibration will be discussed under "Intercomparison Tests".

TIME MEASUREMENT

The PVTt and the mass-time facilities use the same timing system. The timing system is shown in schematic form in Figure 2 and consists of two digital counters, two low frequency standards, one oscilloscope, and one shortwave receiver. The two counters and two frequency standards provide redundancy, such that an average value can be obtained, and a test need not be discarded in the event that one of the electronic components malfunctions.

A set of contacts on the three-way valve supplies 28 volts DC to a pair of reed relays which gate the electronic counters. These relays have a closing time of 1.0 millisecond and an opening time of 0.5 millisecond. The counters are supplied with the 1000 Hz output of the low frequency standards providing a resolution of one millisecond. The counters have a possible error of ±1 count, or ±1 millisecond. The three-way valve has a response time of 0.015 second. A linear sum of all timing errors would include the following: twice the response time of the three-way valve, the sum of the response time of the two reed relays, and the one millisecond error of the counters, resulting in a maximum timing error of 0.033 second. If a run time of 330 seconds is established as a minimum value, the possible 33 millisecond timing error would cause a maximum error in the time measurement of 0.01 percent.

The only other known source of inaccuracy in the time measurement system would be the error in the 1000 Hz signal of the low frequency standards which was held to an insignificant value by the following procedure. The low frequency standards have outputs in decades from 10 to 10^5 Hz, all of which are supplied by the same crystal. These standards are compared periodically against National Bureau of Standards radio station WWV. The WWV signal is received by the shortwave receiver, and the one-second time pulses of this signal triggers the horizontal sweep of the oscilloscope. If the 10^4 Hz signal from the standards are observed on the oscilloscope at a sweep rate of ten microseconds per centimeter and the drift of the 10^4 Hz signal is less than one centimeter in 100 seconds, an accuracy of better than one part in ten million (0.0001 percent) is achieved. This error is one hundred times smaller than the errors in the timing system.

INTERCOMPARISON TESTS

Two types of intercomparison tests between the mass-time and PVTt facilities could be considered. A transfer standard, such as a critical (sonic) flow nozzle, could be calibrated on both facilities and a comparison made of the results. This type of intercomparison has the advantage of checking the total performance of both facilities, including the mass determinations and the timing system. This type of intercomparison has two disadvantages however. The comparison assumes the transfer standard is not biased by any systematic differences between the two installations. It would be desirable to run this type of check but an intercomparison of the facilities should preferably avoid this variable. The second disadvantage is that the random errors associated with the transfer standard are included in the data along with the random errors of the primary facilities. This additional random error in the data makes it necessary to obtain a larger amount of data before sufficiently accurate mean values are obtained. Because of the long period of time required for primary measurements (1 to 2 points per day on the PVTt facility, and 3 to 5 points per day on the mass-time facility) the need for a large amount of data should be avoided.

The second type of intercomparison is limited to the mass determination of the two facilities. Since the same timing system is used on both facilities this is not considered to be a serious limitation. The comparison is made by weighing the storage vessel on the analytical balance and discharging it into the storage vessel of the PVTt facility. The procedures used on both facilities to determine the change of mass are identical to those used before and after test runs. The results of 5 intercomparison tests indicated an average difference of 0.079 percent between the mass measurements of the two facilities. If all of this discrepancy were attributed to the PVTt facility, and the timing error was added linearly, a total bias error of 0.09 percent would result. This would be within the original objective of 0.1 percent for the PVTt primary method.

Because the systematic error analysis indicates a much higher accuracy for the mass determination by weighing (0.001 percent) than by the PVTt method (0.08 percent) it is desirable to calibrate the PVTt facility using weighed air. The constant bias errors in volume, pressure, temperature, and compressibility factor would then be corrected through the use of an effective volume for the PVTt facility. This procedure is valid providing the same instrumentation and reference tables are used during the use of the facility as during the calibration.

The standard deviation of the five intercomparison tests was 0.021 percent, indicating the mean correction for the PVTt facility had an uncertainty of 0.026 percent based on a 95 percent confidence level. To reduce the uncertainty in the PVTt facility calibration to 0.01 percent with a 99 percent confidence level will require an additional 25 calibration points.

SUMMARY OF ACCURACY AND RANGE OF THE TWO PRIMARY METHODS

The maximum bias error in the time measurement, as obtained by linear summation of the absolute values of the estimated component errors is ±0.010 percent.

The uncertainty in the mass flow rate as determined by the mass-time method is summarized as follows: The random error in weighing was found experimentally to be ±0.014 percent based on a 95 percent confidence level. The only known bias error is from the standard weights, which are certified to 0.001 percent. The estimated maximum bias error in the flow rate is therefore ±0.011 percent. The estimated uncertainty in a mass flow rate measurement on the mass-time facility is ±0.025 percent with a 95 percent confidence level, using linear addition of the random and bias error estimates. These estimates are based on test runs exceeding 330 seconds, and a minimum of 1 1/2 kg (3 lb) of gas discharged from the storage vessel. The maximum flow rate of the mass-time facility is presently 0.05 kg/sec (0.1 lb/sec) and may be increased to 0.2 kg/sec (0.5 lb/sec).

The uncertainty in the mass flow rate as determined by the PVTt facility is summarized as follows: The random error in mass determination was found experimentally to be ±0.057 percent with a 95 percent confidence level. After a 30 point calibration by weighed air the bias error will be reduced to ±0.01 percent. The estimated maximum bias error in the flow rate measurement is ±0.02 percent. The estimated uncertainty in a flow rate measurement is ±0.077 percent with a 95 percent confidence, using linear addition of the random and bias error estimates. These estimates are based on maximum flow rates of 3 kg/sec (6 lb/sec), with flow rates of 9 kg/sec (20 lb/sec) obtainable at lower accuracy.

CONCLUSION

The facilities presented have the present capability of providing gas flow calibrations with estimated systematic accuracies of 0.011 percent at flow rates up to 0.05 kg/sec (0.1 lb/sec) and 0.02 percent at flow rates up to 3 kg/sec (6 lb/sec), with extensions to flow rates of 9 kg/sec (20 lb/sec) being feasible. These facilities permit transfer and secondary standard flowmeters to be calibrated with estimated uncertainties of 0.025 to 0.077 percent with a 95 percent confidence level.

REFERENCES

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3. Joseph Hilsenrath, et.al., "Tables of Thermal Properties of Gases," NBS Circular 564, November 1, 1955.

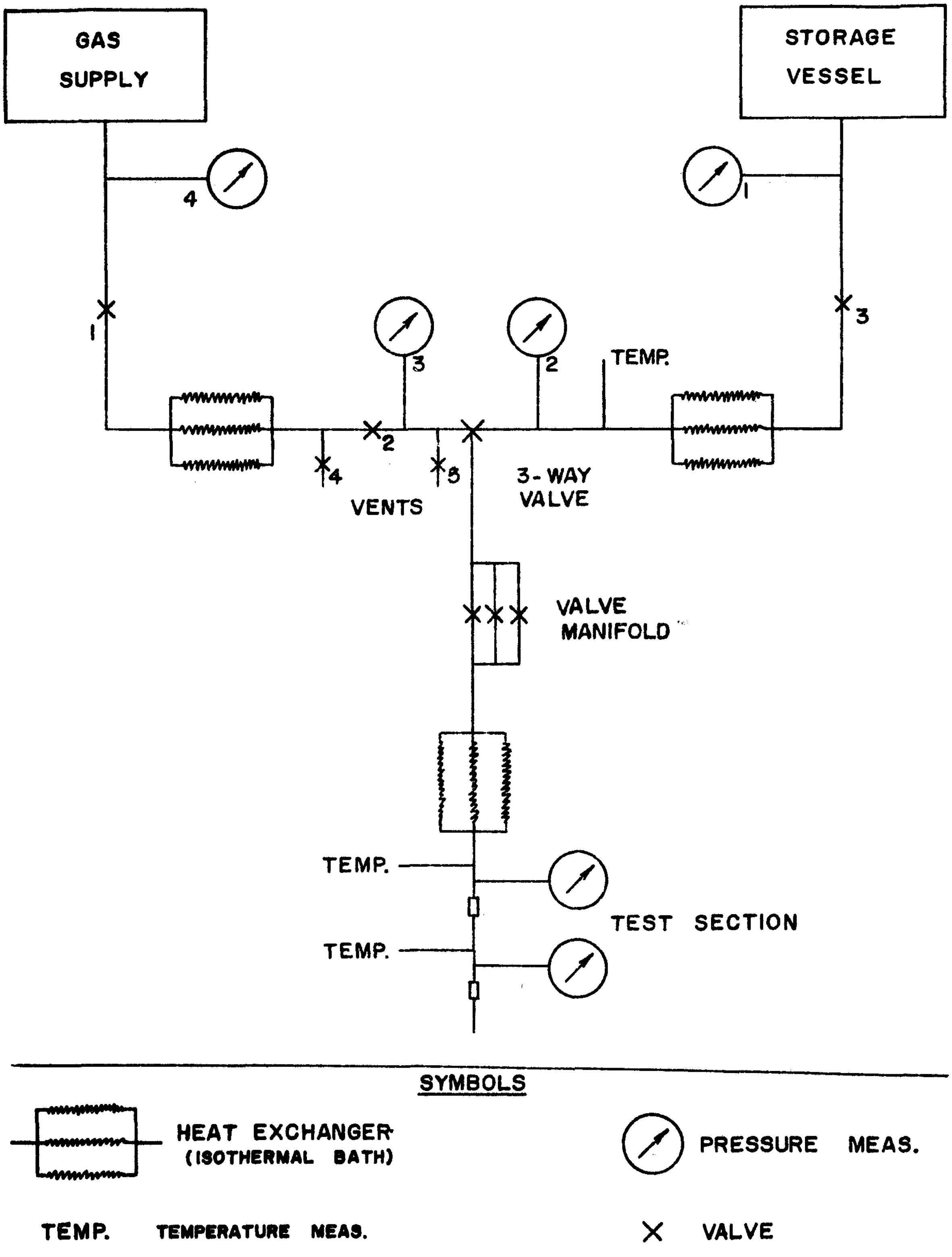

Figure 1

SCHEMATIC FLOW DIAGRAM OF THE PVTt AND MASS-TIME PRIMARY FLOW MEASUREMENT FACILITIES

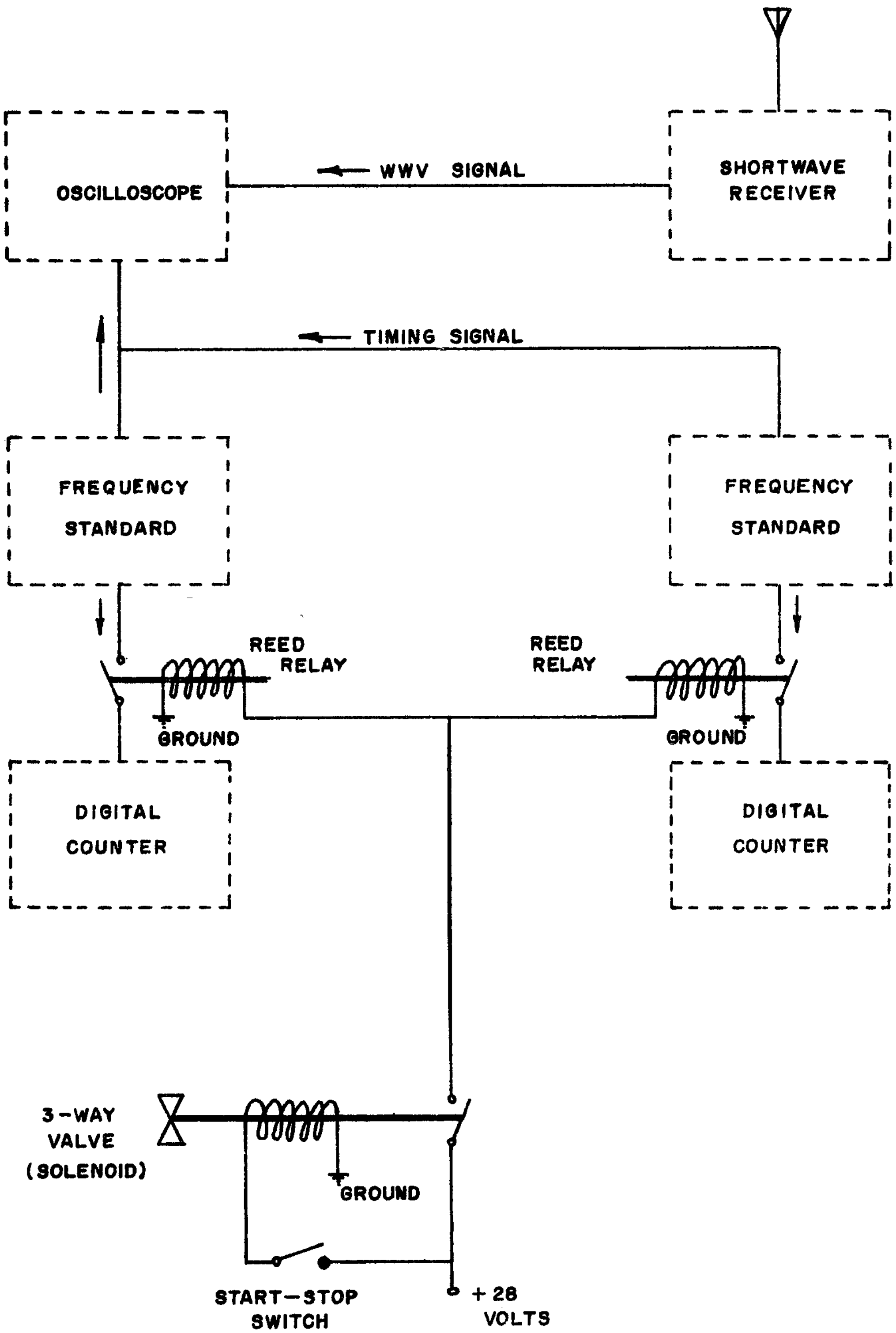

FIGURE 2

TIMING SCHEMATIC

NASA Mailing List

NASA Lewis Research Center (1)
21000 Brookpark Road
Cleveland, Ohio 44135
Attn: James Bolander
Mail Stop 500-312

NASA Lewis Research Center (1)
21000 Brookpark Road
Cleveland, Ohio 44135
Attn: Norman T. Musial

NASA Scientific and Technical (10)
Information Facility
Box 33
College Park, Maryland 20740
Attn: Nasa Representative

NASA Lewis Research Center (2)
21000 Brookpark Road
Cleveland, Ohio 44135
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NASA Headquarters
Program Office R. A.

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Space Administration
Washington, D. C. 20546
Attn: N. F. Rekos
NASA Headquarters
Program Office R.A.P.

NASA Lewis Research Center (1)
21000 Brookpark Road
Cleveland, Ohio 44135
Attn: Office of Reliability
& Quality Assurance

NASA Ames Research Center (1)
Moffett Field, California 94035
Attn: Library

NASA Flight Research Center (1)
P.O. Box 273
Edwards, California 93523
Attn: Library

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Pasadena, California 91103
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Langley Station
Hampton, Virginia 23365
Attn: Library

NASA Manned Spacecraft Center (1)
Houston, Texas 77001
Attn: Library

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Huntsville, Alabama 35812
Attn: Library

NASA Lewis Research Center (20)
21000 Brookpark Road
Cleveland, Ohio 44135
Attn: Robert C. Johnson