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LARGE SIZE CRYOGENIC TURBINE TYPE FLOWMETER TECHNOLOGY

By

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Prepared for

National Aeronautics and Space Administration

Contract NAS 3-2555

AEROJET-GENERAL CORPORATION

SACRAMENTO, CALIFORNIA

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TECHNOLOGY REPORT

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ABSTRACT

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The procurement, calibration, facility installation, and use of turbine flowmeters for the very large liquid oxygen/liquid hydrogen components of the M-1 Rocket Engine are described. Also, construction details of one turbine flowmeter and limited calibration data for several turbine flowmeters are given. The relative capabilities of the nation's major testing organizations are presented along with facility recommendations.

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I. SUMMARY

The M-1 Engine Development Program was initiated at the Sacramento Plant of the Aerojet-General Corporation under NASA Contract NAS 3-2555 in 1962. Full-scale testing of the turbopump assemblies and thrust chamber assembly as well as other components was accomplished prior to the program termination.

In this report, the term "large" when used in context with the flowmeters implies their relationship to the available facilities as well as to the scaling factors.

The procurement, calibration, facility installation, and use of turbine flowmeters for the very large liquid oxygen/liquid hydrogen M-1 rocket components are discussed in this report.

Emphasis is placed upon design features that minimize repair time as well as cost. Calibration facility needs are also presented along with the construction details of one type of turbine flowmeter. Limited calibration data for several cryogenic turbine flowmeters are given as well as data that shows the relative capabilities of the nation's major testing organizations. Facility recommendations are also provided.

II. INTRODUCTION

The term "large flowmeter" as used in this report implies a flowmeter of a size, for which there are inadequate facilities for one or more of the following functions: manufacturing; testing and calibrating; repairing; and handling. It also implies that the elements for scaling upward from current technology cannot be satisfactorily verified using existing facilities. Within the context of the M-1 Program, wherein liquid oxygen and liquid hydrogen were used, all meters with a minimum diameter of eight-inches were considered large. Although this was the case in the M-1 Program, it should be noted that the oil industry has used 30-in. and 36-in. non-cryogenic turbine flowmeters for some time, having developed calibrating and handling techniques.

The primary unknowns in flowmeter scaling appear to be related to the use of cryogenics. These unknowns are the predictability of the calibration factor shift from water to the cryogenic fluid and the unpredictable line loads resulting from differential contractions during system chilldowns. A number of other scaling factors must also be considered by the designer. These include fluid slip caused by the large spacing between the blades, the relative influence upon the slip of selecting flat blades as opposed to the helical blade, the fabrication techniques for flow straighteners, and the time constant. Of these considerations, only the selection between helical and flat blades will not be discussed because the author has no experience with the helical blades. All of the M-1 meters were supplied with flat blades on the rotors.

The design of the M-1 liquid oxygen and liquid hydrogen turbine flowmeters involved consideration of the effects of chilldown, dynamic loading, materials, bearings, sub-component testing, cleaning, handling, and calibration. These designs were predicted upon the anticipated excessive cost and lost time of having to remove these devices from the flow lines for repair and/or calibration.

Certain aspects of the designs increased the costs relative to other more standard meters in the field. The use of straightening vanes within the meter, pre-loaded ball bearings, multiple sensing coils, and special sensing coil and rotor tests are representative of these special details.

The most difficult problem in connection with the use of the "large" flowmeter is that of calibration. Most of the M-1 flowmeters for the thrust chamber and pump development test stands could not be calibrated in water to full range at any existing facility and could not be calibrated in liquid hydrogen at all.

Most development programs require a steady-access to calibration facilities; however, the cost of such facilities when considered in relationship to the lead-time required in using a centralized national facility poses a question that remains to be resolved.

III. TECHNICAL DISCUSSION

A. UNIQUE LARGE METER APPLICATION FEATURES

The use of large meters presents the normal flow measurement problems along with unique ones. As encountered in this project, the unique problems were calibration, handling, and cleaning.

However, there are certain advantages in using the large meter, such as:

1. The capability for incorporating flow straighteners of almost any desired design.

2. The capability for utilizing pressure, temperature, and multiple pickup coil taps without any serious design compromise.

3. The capability for using large, rugged bearing designs, that are easy to replace.

4. The high probability for being able to disassemble, replace bearings, and reassemble them without seriously affecting K factor.

Each of the above factors, along with the others presented in this report, resolve themselves into one prime consideration; their affects upon costs and schedules. Because the replacement of a flowmeter that is possibly six feet long (Figures No. 1 through No. 4), weighing over 2000 lb and having foam insulation, is very expensive, it is necessary to take special precautions in the design to minimize any need for repairs.

B. CALIBRATION

Regardless of flowmeter size, operational problems arise which require testing to determine performance, design deficiencies, corrective action, and general flow measurement problem analysis. The use of cryogenic propellants requires calibration in the cryogenic liquid rather than using a water calibration factor. This is well documented in the literature(1).

With one type and size of turbine flowmeter used in the Titan I propulsion system development programs, it was demonstrated by repeated calibrations that the water-to-liquid oxygen K factor shift for any one meter was repeatable to ± 0.54% 3σ, which necessitated that only one calibration be performed in cryogenics, after which water could be used(2). While this did not apply when a new rotor was installed, it did apply to bearing and miscellaneous component replacements. Thus, if acceptable repeatability of K factor shift with large meters could be demonstrated, the cost and lead time for successive cryogenic calibrations would be eliminated.

As late as 1964, the capability to calibrate some of the M-1 flowmeters to full-scale in water did not exist. The specific water calibration results are given below.

Size	Approximate Rated Q (GPM)	Approximated ΔP In Propellant	Achieved Acqual Q
14-in. (LO_2)	20,000	28	15,500
14-in. (LH_2)	60,000	12	21,000
18-in. (LH_2)	60,000	4	42,000
20-in. (LH_2)	60,000	3	43,500

In general, cavitation resulted when attempting to exceed these values. The meters were well into the linear region of performance, although some doubt may always exist if rated flow cannot be reached.

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(1) National Bureau of Standards Report 7692, Recommendations to the NASA Covering a Cryogenic Fluid Flowmeter Calibration Facility, USDC, NBS, Boulder Laboratories, Boulder, Colorado, May 15, 1963

(2) Deppe, G. R. and Dow, R. H., The Design, Construction, and Operation of a Cryogenic Flow Calibration Facility, Aerojet-General Technical Memorandum No. TM-149, 17 January 1962

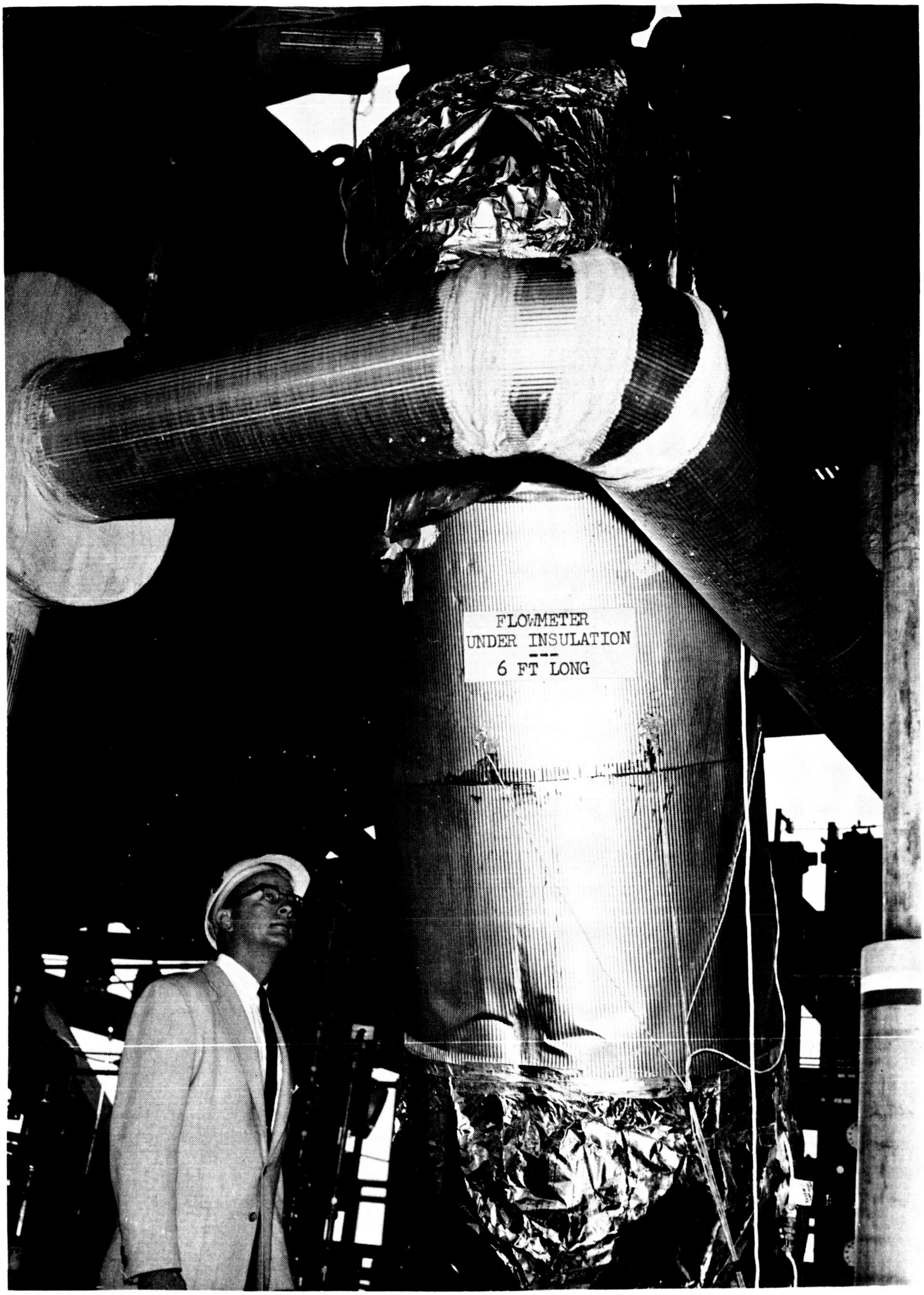

Figure 1

Test Stand E-1 LH_2 Insulated 18-in. Meter Installation

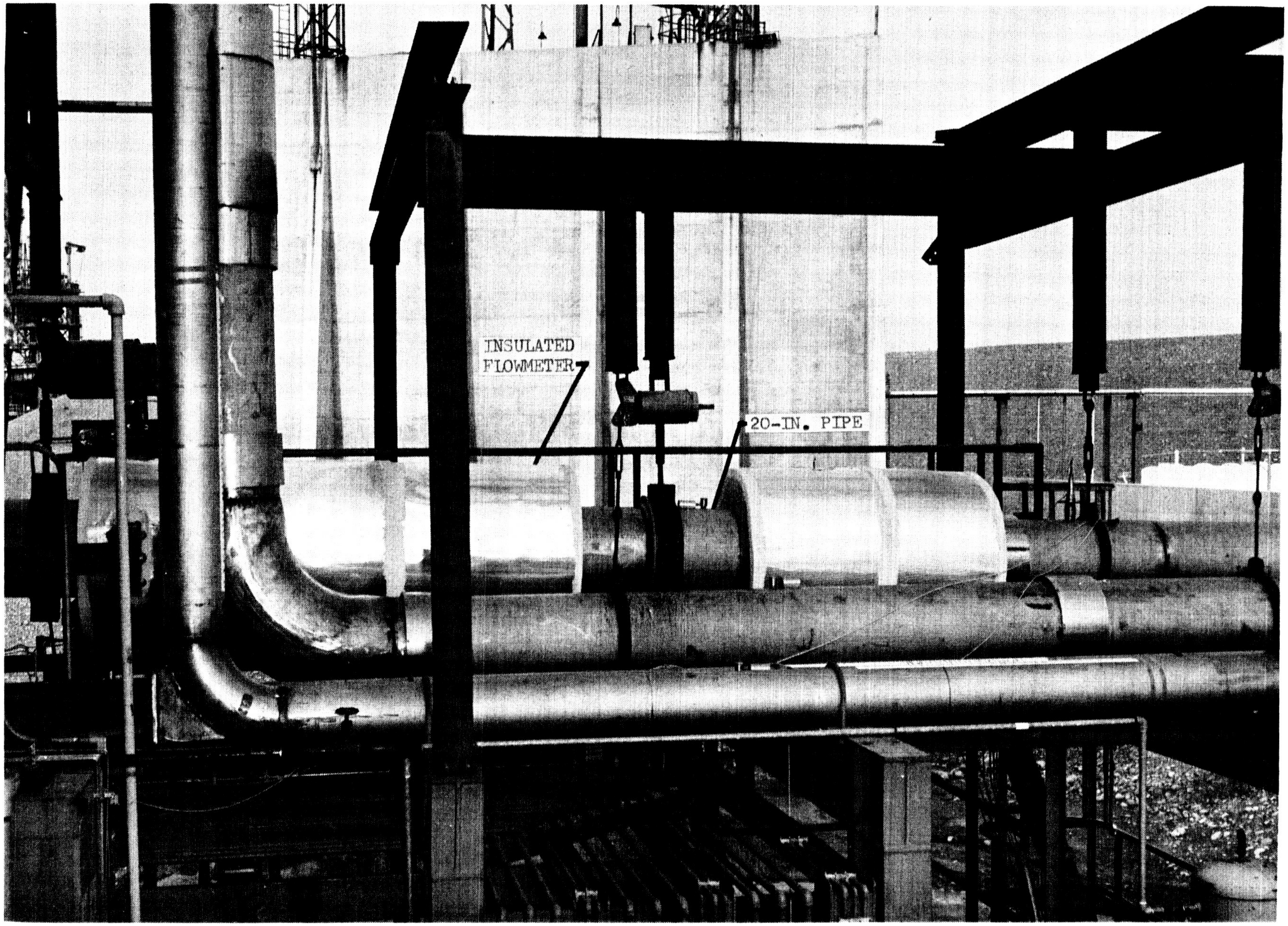

Figure 2

Test Stand E-1 LH_2 20-in. Meter Installation Pump Discharge Line

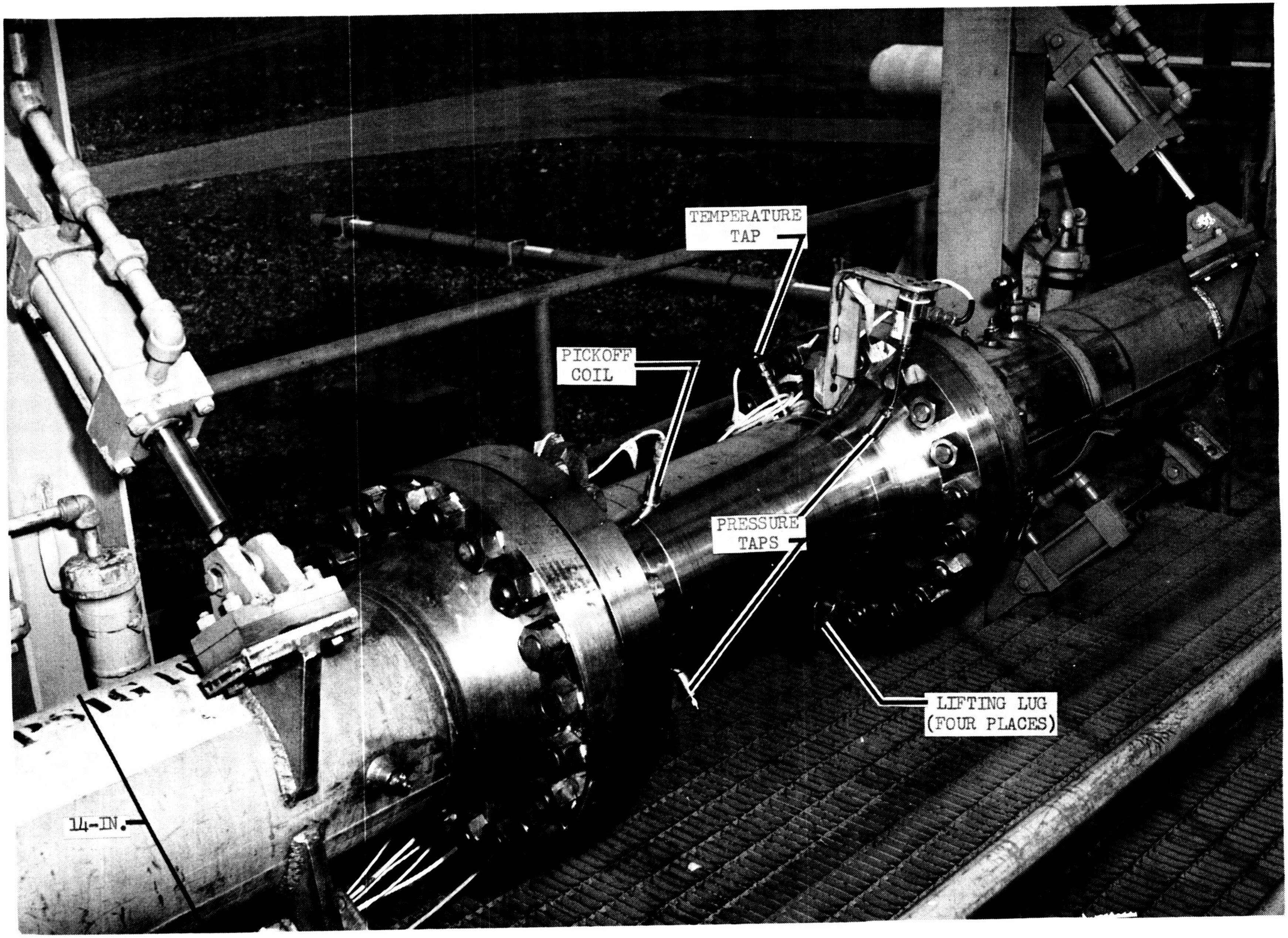

Figure 3

Test Stand H-8 14-in. LO_2 Meter Installation

Figure 4

Test Stand H-8 20-in. lH_2 Meter Installation

Compounded with the above limitation, no flow facility is known to exist that can reach 60,000 gpm of liquid hydrogen, and no facility exists at Aerojet-General Corporation for highly accurate liquid oxygen calibration in excess of 4,000 gpm.

In the absence of a cryogenic calibration for large meters, the Aerojet-General Corporation uses rationalized correction factors to water calibration constants. These are (K in cycles per gallon):

Water to LO_2	+ 0.6%
Water to LH_2	+ 0.8%

These numbers are a combination of experience with liquid oxygen and the predicted contraction of the stainless steel with temperature. The variability from meter to meter, for all types, is unknown, but for a certain type (3) in liquid oxygen, the shift varied from + 0.2% to approximately + 2.0%.

A small amount of data exists for the M-1 flowmeters and several NERVA eight-inch meters. These data tend to indicate that the same bandwidth of K factor shifts applies to the M-1 meter design.

Figure No. 5 presents water and hydrogen data for an eight inch liquid hydrogen meter that was calibrated in water at Alden Laboratories, Worcester Polytechnic Institute, Worcester, Massachusetts using a gravimetric system, that is accurate to approximately ± 0.3% (statistical analysis was not submitted). This meter was then calibrated in liquid hydrogen at Los Alamos Scientific Laboratory (LASL) Cryogenic Facility, Jackass Flats, Nevada (see Appendix A). The latter data was derived from an in-line venturi and a tank liquid level system that was estimated by LASL to be accurate to between one and two percent. These data indicate an average shift from water to liquid hydrogen of approximately + 1.1%. The sharp decline at the low end can be expected if the data is valid. Mortenson and Wheelock (4) reported data for an eight inch turbine meter which was linear over a 10:1 range in water, but showed a sharp drop in calibration constant in LH_2 at approximately 25% of the upper calibration point. It is emphasized that the LASL data were preliminary, but they did indicate a trend.

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(3) Deppe, G. R. and Dow, R. H., Design, Construction, and Activation of a Cryogenic Flow Facility, Vol. 8, Advances in Cryogenic Engineering, Plenum Press, August 1962, page 371

(4) Mortenson, L. N. and Wheelock, H. R., Liquid Hydrogen Flow Measurement, Tenth Annual Institute of Environmental Sciences Meeting, Philadelphia, Pa., April 13-15, 1964

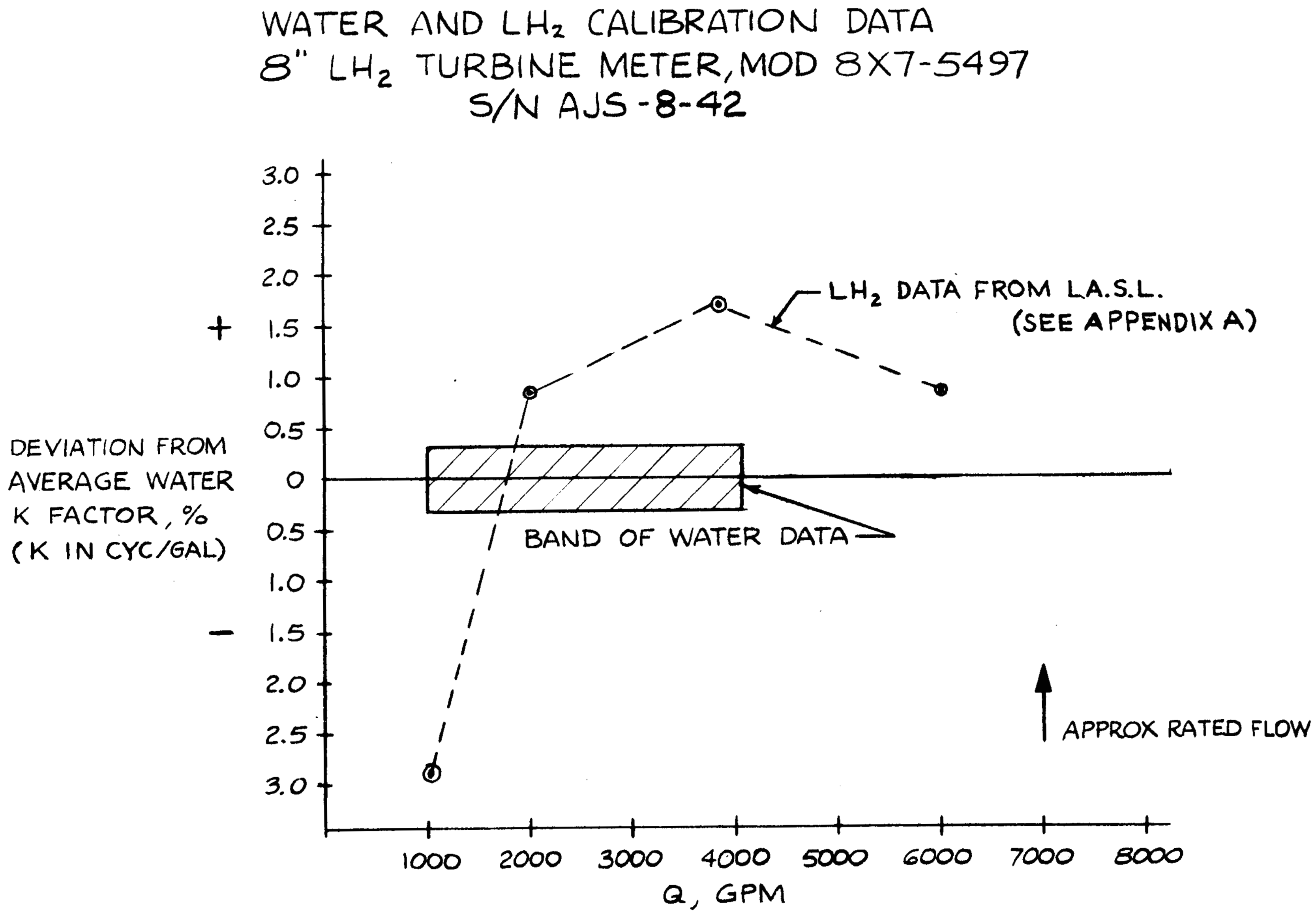

Figure 5

Water and LH_2 Calibration Data, 8-in. LH_2 Turbine Meter,

Model No. 8x7-5497, S/N AJS-8-42

Figure No. 6 presents water and liquid nitrogen data for an 18-in. meter used for pump testing. The water data was obtained from Wyle Laboratories, El Segundo, California. The liquid nitrogen data is compiled from an on-stand liquid level system used during pump testing. Two level sensing systems were used for data reduction. A "hot wire" point system was used as a scale factor reference for a continuous capecitance probe, which, in turn, was used for the data reduction. The system was used approximately 15 times because of the limited oxidizer pump test schedule. Consequently, the factors affecting accuracy and precision were never fully analyzed or understood. However, in a few of the tests, wherein approximately 50% of the tank volume was discharged, it is observed that the K factor in liquid nitrogen is within the assumed band described above. In tests which discharged 25% or less of the tank volume, level sensing errors produced a scatter of some 15%.

A 14-in. liquid oxygen flowmeter was calibrated in an F-1 turbopump test stand in liquid oxygen at the Marshall Space Flight Center, Huntsville, Alabama. The meter had been previously calibrated in water to 75% of full-scale.

The water calibration performed at Wyle Laboratories, Norco, California, revealed a K factor which was linear within ± 0.25% of the mean. The liquid oxygen calibration at MSFC, Huntsville, Alabama, used a time-volume technique. The volume reference is a water-calibrated tank, point liquid level sensors, and a calibrated contraction of the tank to liquid oxygen temperatures. A complete error analysis of the system has not been presented by MSFC. However, an analysis given by Mr. J. Norris of the NASA Lewis Research Center, Cleveland, Ohio, based upon data supplied by MSFC, indicates a 3γ error of approximately 0.3%, excluding the affects of nitrogen condensation. One report indicates that this affect may be between 0.5% and 1.0%.(5) A best estimate of the 3γ calibration error lies between ± 0.5% and ± 1.0%. The tank system uses optical point level sensors along with capacitance point level; however, MSFC personnel advised that the capacitance probe data should be used as the prime data source.

A plot of the results, using the average water K factor as the reference, is provided as Figure No. 7. Numerical results are provided as Appendix B. Of the 12 flow tests performed, the capacitance probe data were not recorded in two tests and three of the flow tests were accompanied by cavitation. In the remaining seven flow tests, two points stand out as possibly incurring cavitation. Analysis of pressure drop data in relationship to vapor pressure produced no valid reason for rejection; therefore, the value of + 1.06% is being used. If there were a valid reason for

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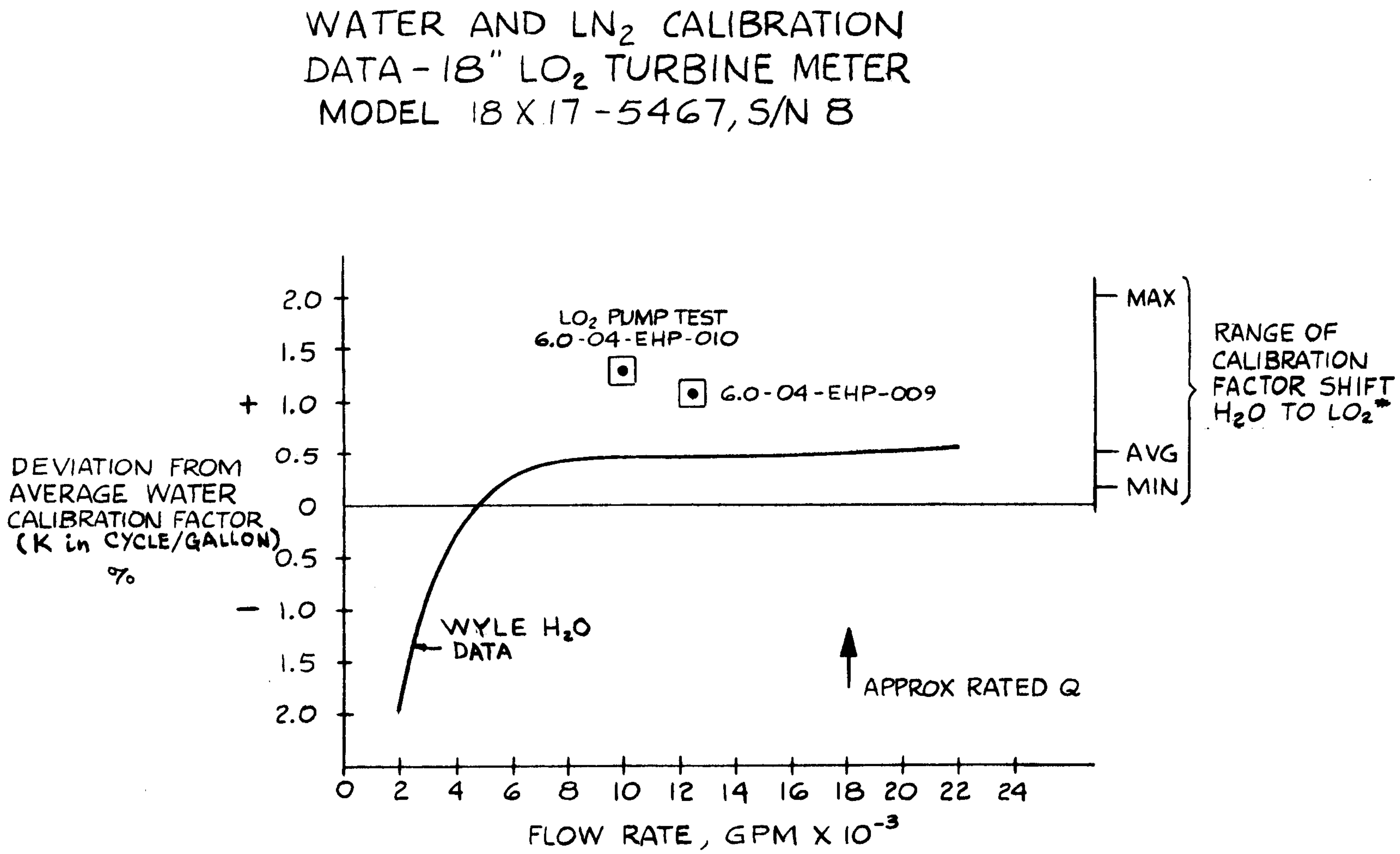
(5) Bucknell, Lawler, and Street, Cryogenic Flow Measurement, ISA 19th Annual Conference and Exhibit, October 12-15, 1964, Pre-Print No. 12.2-1-64



* From: Deppe, G.R. and Dow, R.H., <u>Design, Construction, and Activation of a Cryogenic Flow Facility</u>, Vol. 8, Advances in Cryogenic Engineering, Plenum Press, August 1962, page 371

Figure 6

Water and LH_2 Calibration Data, 18-in. LO_2 Turbine Meter,

Model No. 18x17-5487, S/N 8

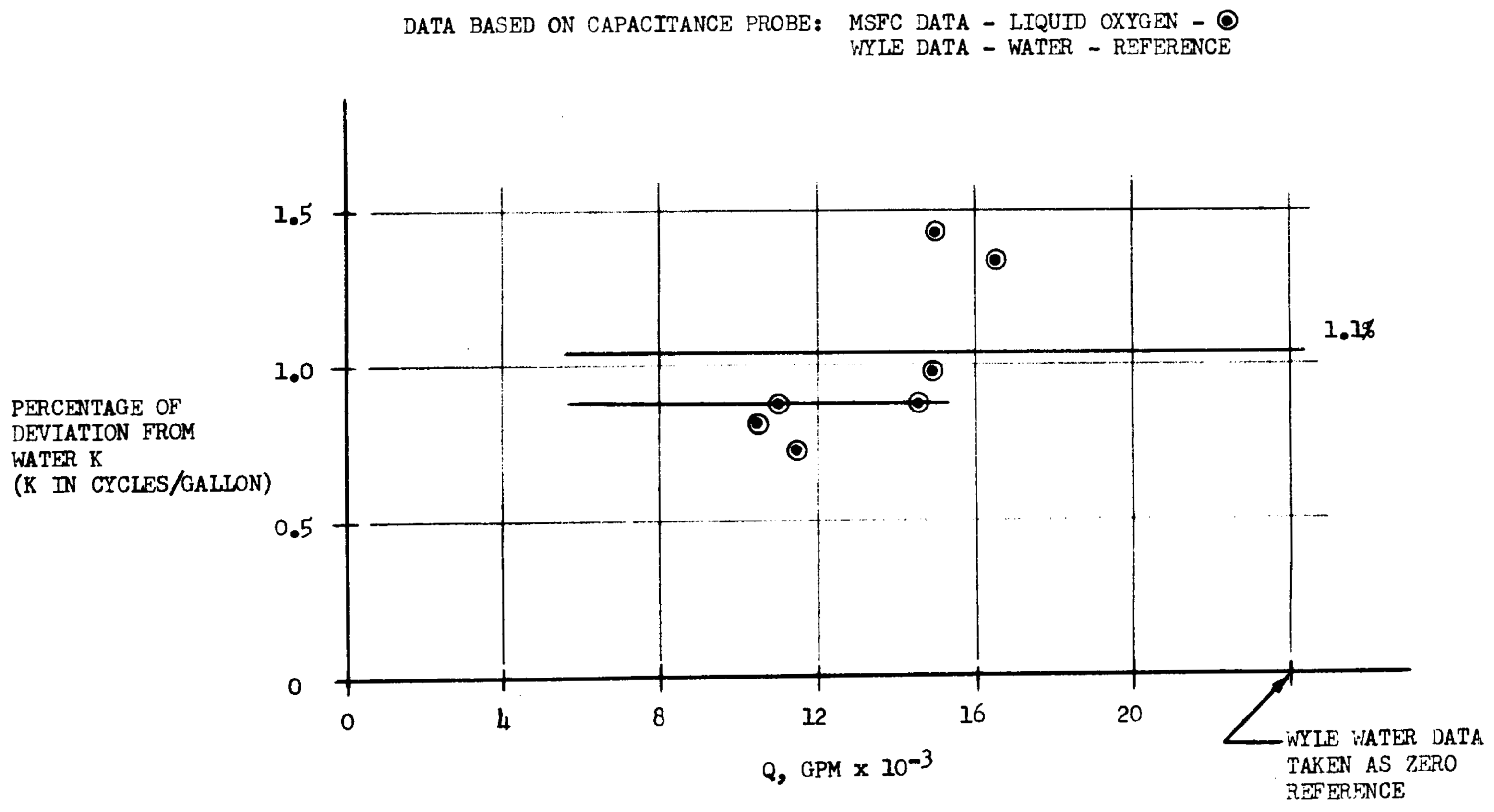


Figure 7

LO_2 Calibration Data, 14-in. Turbine Meter, 14x12-5498, S/N AJ-512-5 rejecting the two high values, the average shift is approximately + 0.9%. Both values lie within the limits previously published(6). The following is a summary of the calibrations:

K (seven test average) Liquid Oxygen = 0.6309 cycles/gallon
3σ Variance = ± 0.93%
Flow Range + 10,500 gpm to 16,500 gpm
Average Shift From Water = + 1.1%

The calibration constant derived from each of the flow tests represents an average of from six to 45 individual increments of volume. The seven test K factor shown above is an average of the increment averages. The variance of data within each flow test is ± 3.3%, 3σ, which is representative of the difficulty encountered in measuring flow with relatively small increments of volume.

An 18-in. flowmeter, installed in the Test Stand E-1 suction line, was used during the liquid hydrogen pump development program. The meter was water calibrated to approximately 70% of rated flow at Wyle Laboratories. It was then checked in liquid hydrogen against a dual liquid level system in the on-stand tanks during pump tests. The systems are identical to those used in the liquid oxygen pump development program. Figure No. 8 shows the comparative water and liquid hydrogen data. This specific problem emphasizes the need for an accurate quantity gage during tests as well as a calibration facility "off-line." No explanation has been found as yet for the extreme deviation of the data from the expected value. Pre-rotation and/or velocity profile affects have not been known to produce more than a 5% shift of the calibration factor. The average correction factor to the meter K is -17.3%, which is derived from these data and based upon the information detailed in Appendix D. The spread of data is 14.5% to 21.6%, which incorporates the turbine meter and level sensing variability.

Another set of calibration data for liquid hydrogen meters was obtained in the NERVA Program. In this effort, a tank weighing system was installed for the purpose of providing an on-line calibration device during pump, nozzle, and reactor simulator tests. A schematic of this system is shown in Figure No. 9.

The system evidenced an approximate 2% spread of data when discharging approximately 5% of the tank. However, recently, some long duration tests, in which 30,000 gallons (30% of the tank) were discharged at the rate of approximately 5,000 gpm, indicated that the assumed + 0.8% calibration factor shift from water to liquid hydrogen is correct for that type of meter, within ± 1.0%, 3σ. (see Appendix D). Thus, the 16% to 20% reduction of calibration factor for the M-1 18-in. flowmeter is not considered normal and most probably the cause could have been ascertained had the program continued.

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(6) Deppe, G. R. and Dow, R. H., Vol. 8, Advances in Cryogenic Engineering, op. cit.

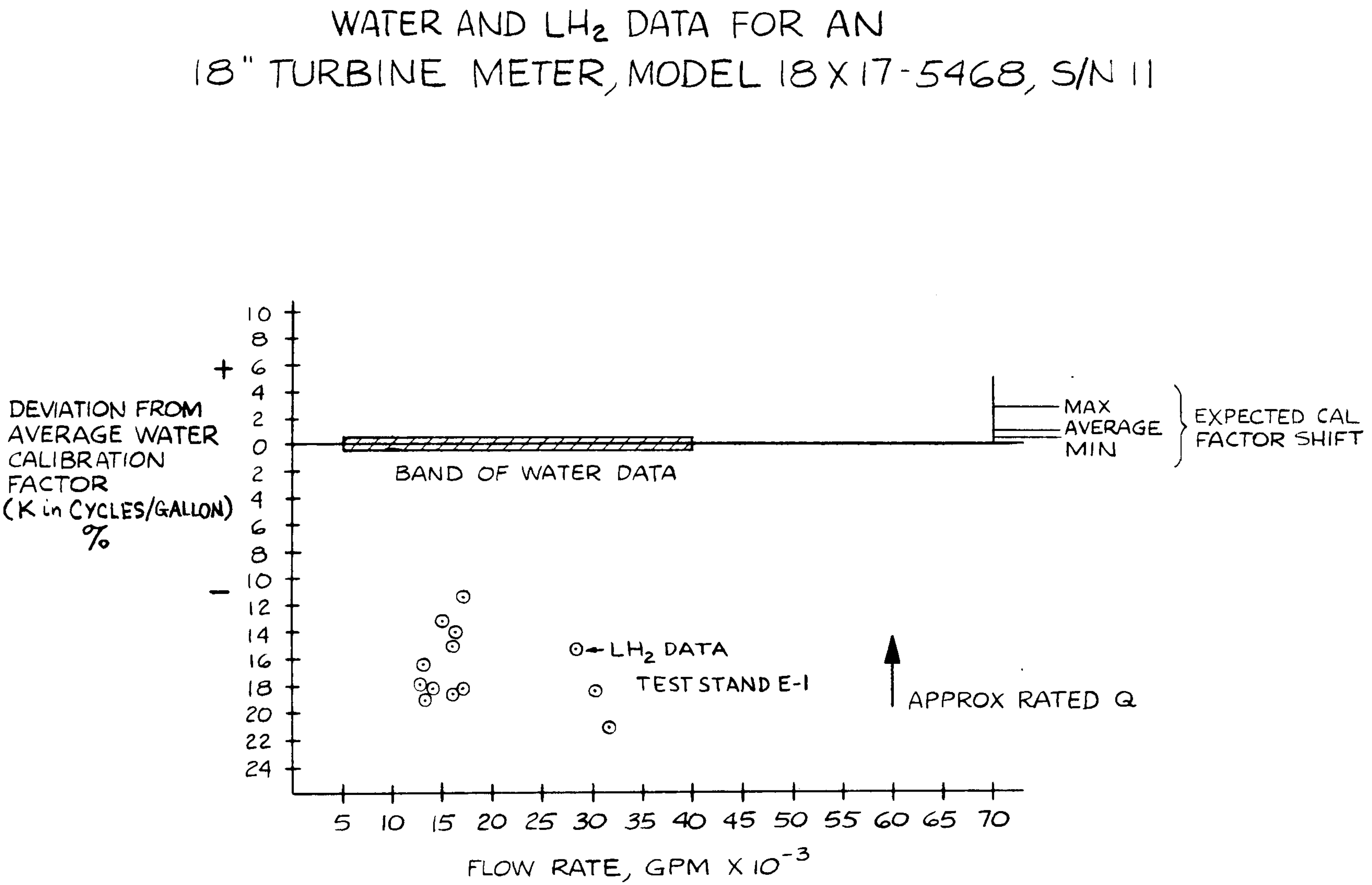

Figure 8

Water and LH_2 Data for an 18-in. Turbine Meter,

Model 18x17-5468, S/N 11

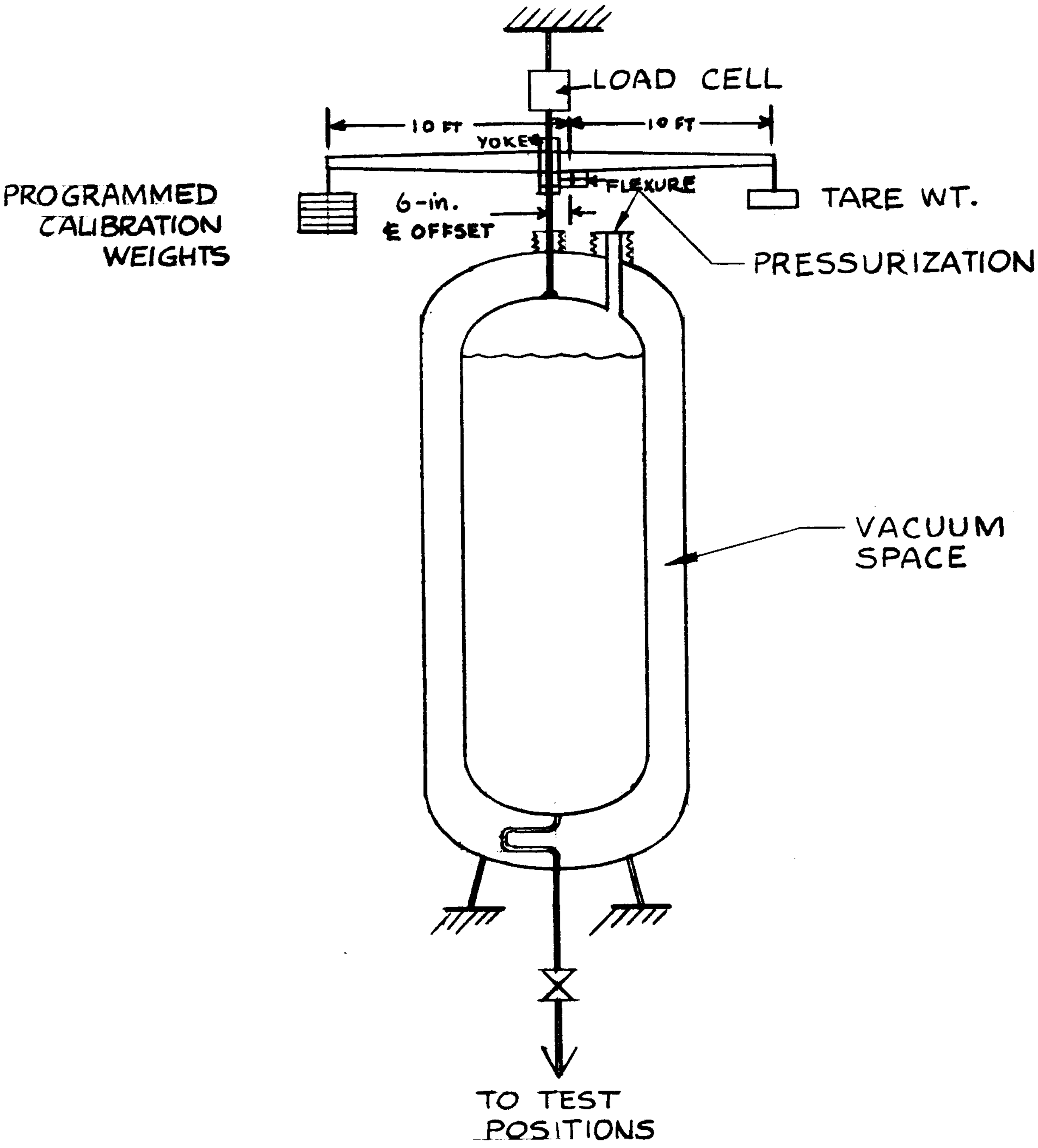

Figure 9

NERVA Flow Calibration Facility, Test Zone H

It is pertinent at this point to examine the relative merits of "on-line" versus "off-line" calibration facilities. The obvious advantages of the "on-line" calibration are that propellants and manpower can be conserved. Also, meters are calibrated in the hardware environment (in the propellants or fluids relating to the hardware).

The disadvantages are well summarized by the problems associated with resolving the 18-in. liquid hydrogen meter data previously described. The cost of removal, inspection, and reinstallation (see Figure No. 1) exceeded $3,000 in addition to a schedule impact of five to six days delay. The availability of an "off-line" facility would probably have permitted detection of the problem before installation in the test position. The cost of performing five liquid hydrogen tests, outflowing approximately 12,000 gallons each test, was estimated to be approximately $44,000, without a pump installed. The cost of a single pump test can be the same. Thus, the tradeoffs between on-line and off-line calibration must consider the practical schedule as well as the cost problems encountered. New flowmeters (and any new transducers) will experience development problems. An off-line facility appears to best meet the needs for overcoming the problems presented.

Actually, a combination of a good on-line calibrator and a single off-line facility appears to be the most optimum solution. Generally, the on-line device will not produce the accurate data to be procured from a system designed specifically for calibration. A possible exception is the in-line prover system being developed by Flow Technology, Inc. for MSFC. According to reported information, this unit is 4-in. in diameter and designed for ambient use; however, it should be able to operate in cryogenics. No further information is currently available. This system is based upon the industry-tested "ball-prover" system. The cost of such a system for cryogenic meters of the size being discussed is estimated to be in excess of $1,000,000; therefore, only one such system per test complex appears feasible. This cost appears to be an argument in favor of an off-line system, available to the industry in general, backed up by less accurate and far less expensive on-line systems.

The Aerojet-General Corporation approach of using two liquid level systems for "on-line" calibrations is similar to that used by the Marshall Space Flight Center. These systems provide a capability for acquiring data with an error of approximately one to two percent. The Rocketdyne approach, which is reported to be a float and a series of switches, is probably capable of better than 1% data because of surface averaging, and should be relatively inexpensive. However, it must be noted that these approaches cause test stands to be used for testing flowmeters rather than development hardware when meter troubles arise . This has an adverse effect upon test schedules. The difficulty currently encountered in getting the 14-in. liquid oxygen meter calibrated at Marshall Space Flight Center is a prime example of this type of interference. The calibrations are approximately four months behind schedule because of problems directly related to conflict with test stand pump testing schedules.

The discussion of an "off-line", or centralized calibration facility is an extremely complex one as related to these "large" meters. An over-all philosophy rather than a specific method will be presented briefly.

At the one extreme, it would seem advantageous to install calibration systems for each development program. This minimizes time delays in the solution of metering problems. However, the cost for such a facility to handle liquid hydrogen on a volumetric calibration basis, up to 600 lb/sec is in excess of $5,000,000, including all design, construction, and activation. The last report for the National Bureau of Standards oxygen and hydrogen facility (gravimetric) was that it would cost in excess of $8,000.000(7). Thus, to install independent capabilities at Aerojet-General, Rocketdyne, and the Marshall Space Flight Center, could cost approximately $20,000,000.

At the other end of the spectrum, the construction of a centralized national facility reduces facility costs, but involves several trade-offs. The system should be operated as a service to the respective Government contractors. Means for absorbing propellant and manpower costs must be established. The individual contractors must, in general, increase their spare flowmeter inventory because of potential delays in obtaining services. Entire line sections with the flowmeter must be accommodated, as piping effects are major contributors to calibration factor deviations.

The individual programs would have to estimate the number of extended trips to the central facility that would be required to solve problems which are unknown at the time of proposal preparation. The significant point to note is that calibration costs per meter are in excess of one order of magnitude higher than for meters in the four inch to six inch diameter category, and significant program dollars must be allocated for such effort. The cost of improving a flow measurement and perhaps specific impulse by one percent is at least an order of magnitude less than an injector improvement program would cost to meet contractual requirements. The pioneering work done by Aerojet-General Corporation with water to liquid oxygen calibration factor shifts(8) is estimated to have saved $5,000,000 in injector development. The calibration stand and the corresponding calibration costs totaled approximately $600,000.

A compilation of the major water and cryogenic fluid calibration facilities is given in Tables I, II, and III. The column entitled "Approximate Maximum Flow, gpm" is somewhat misleading because of the need for pressure

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(7) Deppe, G.R. and Dow, R.H., Vol.8, <u>Advances in Cryogenic Engineering</u>, op. cit.

(8) Deppe, G. R. and Dow, R. E., Vol. 8, <u>Advances in Cryogenic Engineering</u>, op. cit.

TABLE I

MAJOR WATER FLOW CALIBRATION FACILITIES

PLACE	APPROXIMATE MAXIMUM FLOW (gpm)	MAXIMUM SYSTEM PRESSURE (psig)	TYPE OF CALIBRATION	ESTIMATED ACCURACY (3σ)
Wyle Labs	60,000	140	Volumetric	0.32%
Alden	20,000	35	Gravity	0.3%
Cornell	30,000	35	Venturi	1.0%
Aerojet	4,000	550	Volumetric	0.2%
Edwards AFB	10,000	50-100	Volumetric Prover	0.1%

TABLE II

MAJOR CRYOGENIC FLOW FACILITIES, LIQUID HYDROGEN

PLACE	APPROXIMATE MAXIMUM FLOW (gpm)	MAXIMUM SYSTEM PRESSURE (psig)	TYPE OF CALIBRATION	ESTIMATED ACCURACY (3σ)
Wyle Labs	1,200	100	Gravity	0.23%
Rocketdyne (J-2 Test Stand)	*	•	Volumetric	1.0%
Pratt-Whitney	1,200	•	Gravity	0.36%
Aerojet (NERVA)	3,000	100	Gravity	0.5%
Aerojet (M-1 Pump Stand)	30,000	100	Volumetric	2-3%

* Unknown

TABLE III

MAJOR CRYOGENIC FLOW FACILITIES, LIQUID OXYGEN

PLACE	APPROXIMATE MAXIMUM FLOW (gpm)	MAXIMUM SYSTEM PRESSURE (psig)	TYPE OF CALIBRATION	ESTIMATED ACCURACY (3σ)
Wyle Labs	4,000	100	Gravity	0.3%
Rocketdyne (F-1)	18,000	*	Volumetric	*
MSFC (F-1)	15,000	100	Volumetric	1.0%
Aerojet	4,000	550	Volumetric	0.3%
Aerojet (Pump Stand)	6,000	110	Volumetric	2.0 to 3.0%

* Unknown

drop considerations both within the meter and some device downstream of the meter to prevent cavitation. Thus, it is seen that the Wyle system was unable to achieve full flow with some of the M-1 meters, even though the system can deliver 60,000 gpm through an unrestricted line. Because some of the data pertaining to Rocketdyne and Pratt-Whitney systems are unavailable, verbal contacts and literature surveys have been relied upon for system performance(9).

The NASA Lewis Research Laboratory and Aerojet-General have jointly studied the details related to performing meter calibrations in the M-1 Pump test facility located at Aerojet-General, Sacramento. The results of this study were reported in a NASA Lewis Research Center memorandum.(10) Table II does not include the performance of a modified E Zone system. By incorporating extensive level sensing and gas measurements, along with major line modifications, the calibration errors may be reduced to less than ± 1.0%, 3γ .

C. FLOWMETER COST ESTIMATES AND LEAD TIMES

This section discusses some of the specific information relating to costs of cryogenic meters up to 20-in. diameter, incorporating flow straighteners and multiple sensing coils, temperature and pressure taps, and other described details.

Figure No. 10 is a composite of vendor information for catalog meters as well as procurement data for meters supplied to Aerojet-General. The 900 lb flange meter data is from the procurement files and covers meters which incorporate the following:

1. Water calibration
2. Flow straighteners (tube bundle)
3. Cryogenic tests of sensing coils
4. Rotor balancing
5 Secondary protective bearings
6. Ball bearings
7. Rotor assembly immersion in liquid nitrogen
8. X-ray weld inspection
9. Lifting lugs
10. All stainless steel construction
11. Industrial level cleaning
12. Packaging

The shipping costs were not included in the data.

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(9) Advances in Cryogenic Engineering, Volumes 8, 9, and 10, Plenum Press

(10) NASA LeRC Memorandum L. T. Weise to Record, dated 1 April 1965, subject: Large Size Flow Meter Calibration System, E Area

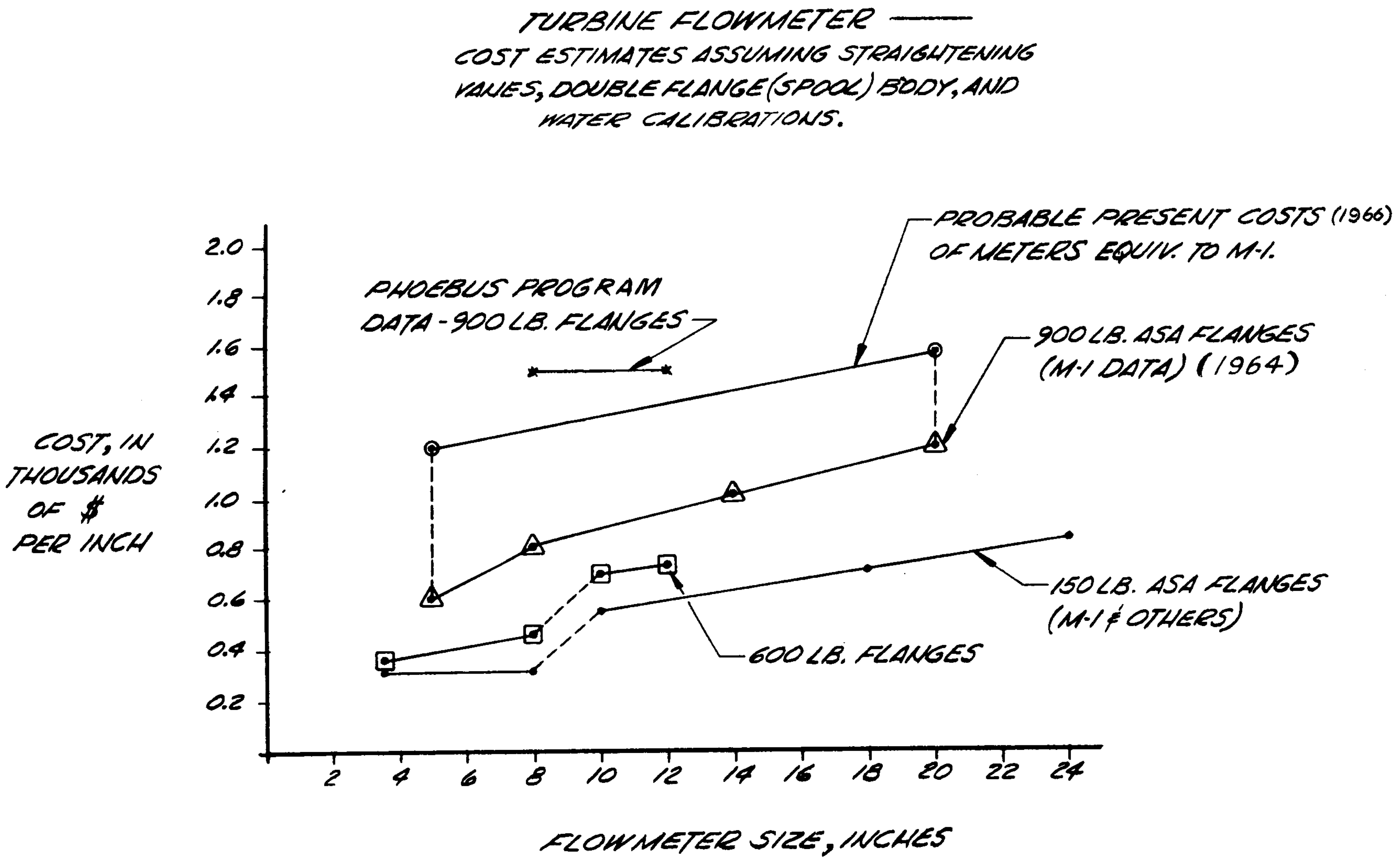

Figure 10

Flowmeter Cost as a Function of Size

A high pressure, 20-in. liquid hydrogen meter (see Figure No. 4) can cost in excess of $30,000, exclusive of cryogenic calibration and shipping costs. If four instead of two meters were purchased for each propellant to support a thrust chamber development test program, based upon the foregoing arguments related to a centralized national facility, approximately $100,000 added costs would be necessary for one test stand.

The observed lead times for large meters ranges from six months to one year. Generally, the major lead time factors are: the flanges; the tubing (in heavy schedules); the flow straighteners; calibration; and X-rays and reviews of the negatives.

The fabrication facilities of the major producers seem adequate for the sizes now used. Studies have been made of rocket boosters in the 20 to 100 million pound thrust category, requiring flowmeters (assuming flow is measured) up to 60-in. in diameter. One vendor estimated their costs to run approximately $3,000 per inch, or $180,000 per meter.

D. FACTORS IN DESIGN MINIMIZING REPAIR AND CALIBRATION COSTS

It was briefly mentioned at the beginning of this report that the removal, handling, checking, and reinstallation of a large meter represents significant cost and lead time elements. Further, recalibration costs and lead times are significant. Design features that can be incorporated into large meters but not necessarily into smaller (6-in. and less) meters, which should minimize the need for removal are:

1. Testing of the entire meter, or if not practical, at least the rotor/bearing assembly should be tested in a fluid near the operating temperature prior to installation into a line.

2. Designing the flow straighteners and other shaft/rotor support fixtures for absolute position and part indexing to assure that the calibration constant is affected to less than 0.1% by complete disassembly, bearing replacement, and reassembly.

3. Selecting materials that retain the highest possible impact strength at the operating temperatures.

4. X-raying of all welds which lend themselves to the technique. Also performing a double verification of the results before proceeding with the next assembly.

5. Dynamically balancing the rotors to as high a degree as practical.

6. Using ball bearings where the possibility of over-spinning exists.

The bearings should incorporate flow passages. Angular contact ball bearings, pre-loaded, should be used in tandem to permit flow in either direction. (This is not to suggest that the meters perform equally well in either direction, but rather that the maximum bearing stress be taken out in either direction.)

7. The final design should incorporate stress analyses relating to temperature differentials (during childown) and reactions to fluid shock forces where it is possible to estimate them.

8. A flow straightener should be incorporated within the meter.

9. The design should be extremely rugged.

Design features that can minimize flow analysis time include multiple sensing coils pre-tested in cryogenics (or at the temperature to be used), as well as temperature and pressure taps within the body of the flowmeter.

A feature which can minimize system problems should a bearing fail catastrophically, is a "secondary" hub or bearing, lined with Armalon, Rulon, or other plastic, spaced to prevent the rotor blades from hitting the inside wall of the flowmeter. A disadvantage of this method is that in the event the plastic is not properly installed, it could cause a drag on the rotor hub with a consequent error in the K factor. Incorporating a minimum of four handling lugs on the outside of the meter minimizes handling problems and hence costs and lead times.

The selection of the type of flow straighteners and their location deserves some special attention. The M-1 meters were considered both for radial vanes and cylindrical tubes, with the selection being made in favor of the latter. This selection was based upon the premise that the tube bundle resolved the flow elements into smaller units, increasing the probability of removing pre-rotation. No comparative data is known to exist to provide a clear choice between one or the other. The ability to clean the vane type is superior than with the tube type. However, regardless of type, it has been observed that the best correlation of calibration data exists when a straightening section is used with a meter. This leads to the conclusion that straighteners within the meter are desirable. The best straighteners appear to be a series of flat plates with many holes drilled through them which eliminates both the rotation and velocity profile problems. However, it increases system pressure drops to the point where the costs will undoubtedly increase significantly for the piping, tanks, and pressurization systems. A thorough study of these trade-offs has not been made.

E. TIME CONSTANT

The M-1 flowmeters were procured to a specification which required a time constant of less than 25 milliseconds, as calculated by the method used by Professor Grey(11). The equation developed by him is:

$$\tau = \frac{1}{A \cos \alpha} \qquad \text{Equation (1)}$$

where τ is the time required for the rotor to reach a value $1 - \frac{1}{\varepsilon}$ of the imposed step function, A is a factor involving the number of blades, blade tip and root radii, and an inverse function of the moment of inertia, and α is the pitch angle of the blade relative to the flow axis of the meter. Thus, Equation (1) can be written

$$\tau = \frac{I}{N} \cdot \frac{1}{A' \cos \alpha} \qquad \text{Equation (2)}$$

extracting the factors N (number of turbine blades) and I. The scaling question previously posed related to time constant is one involving rotor mass, blade angle, and number of blades. Using the Grey calculation technique, all of the meters fell within the specified 25 milliseconds. Proving the design is another matter and only examination of the records during testing shows if adequate response is obtained. Figure No. 11 presents data from one fuel turbopump test. The first plateau on Figure 11 is the cold gas drive portion, and the second plateau is the hot gas generator driven region(12). The test was aborted because of an overspeed condition, and the rapid series of events displayed by the flow trace indicates response to changing conditions within the time resolution of the data sampling system (approximately 25 milliseconds). The rotor in this meter was approximately 17½-in. in diameter.

F. FABRICATION PROBLEMS

Probably the two most prevalent problems related to these meters were the welding and the tube bundle fabrication. All of the other aspects were standard machining operations.

The welding problems were related to the requirement for meeting ASME codes for Unfired Pressure Vessels, as they apply to inclusions and gas pockets. The interpretation of the X-ray photographs between the vendor's inspection service and the buyer's experts resulted in some delays because of differences in opinion as regards reading the photographs and subsequent rework of welds. Also, the use of a weld rod (349 SS) in joining 304 stainless parts resulted in totally unacceptable magnetic joints. The 349 rod was selected for ease of welding, but the post-weld magnetic properties were overlooked.

The tubular flow straightener sections (Figures No. 12 and No. 13)

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(11) Grey, Jerry, Transient Response of the Turbine Flowmeter, Daniel and Florence Guggenheim Jet Propulsion Center, Princeton, New Jersey, February 1956

(12) Ritter, J. A., Summary of Observed Results When Chilling the M-1 Fuel Turbopump to Liquid Hydrogen Temperature, NASA CR-54828, 3 June 1966

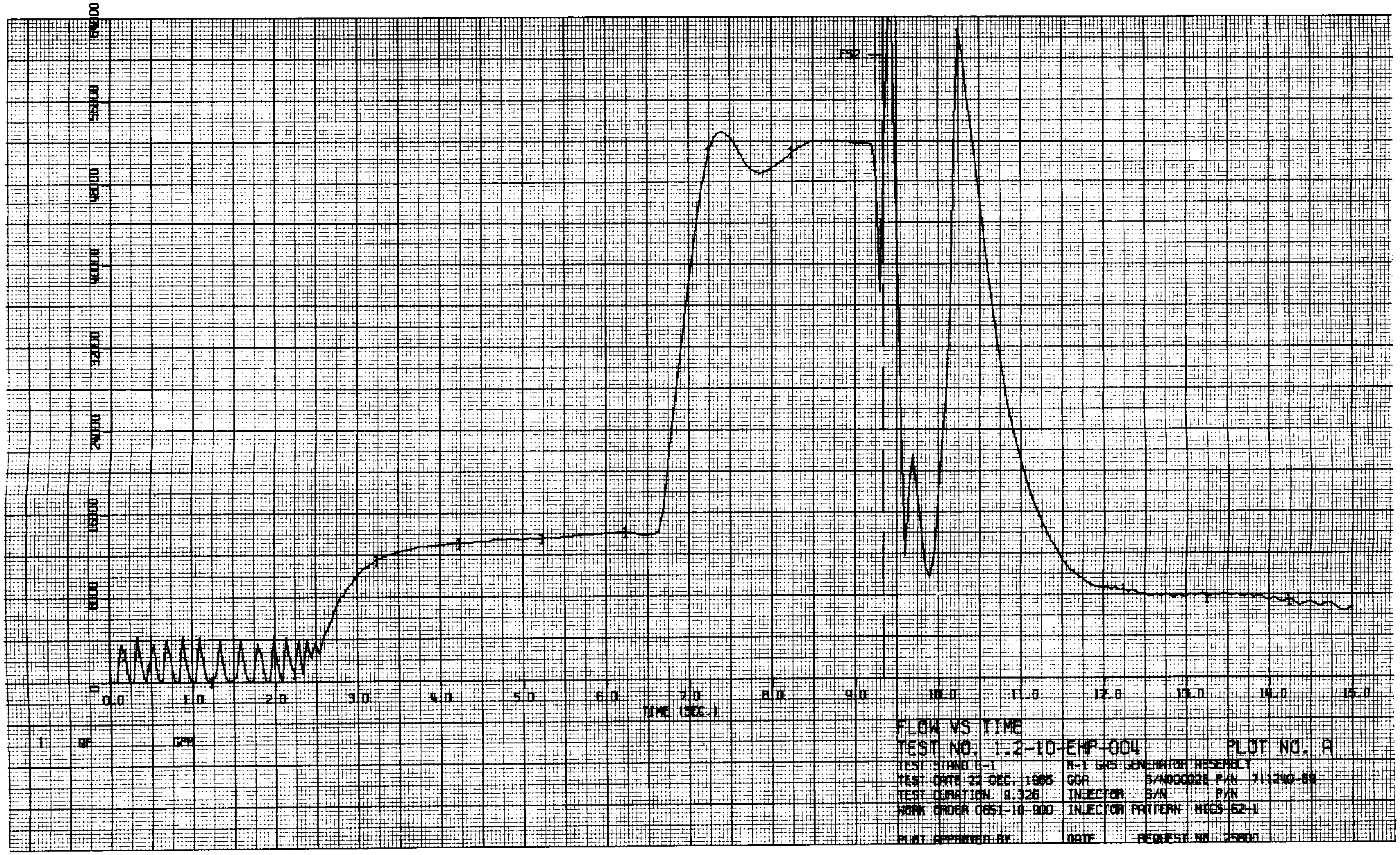

Figure 11

Turbine Flowmeter Data, M-1 Turbopump Test 1.2-10-EHP-004

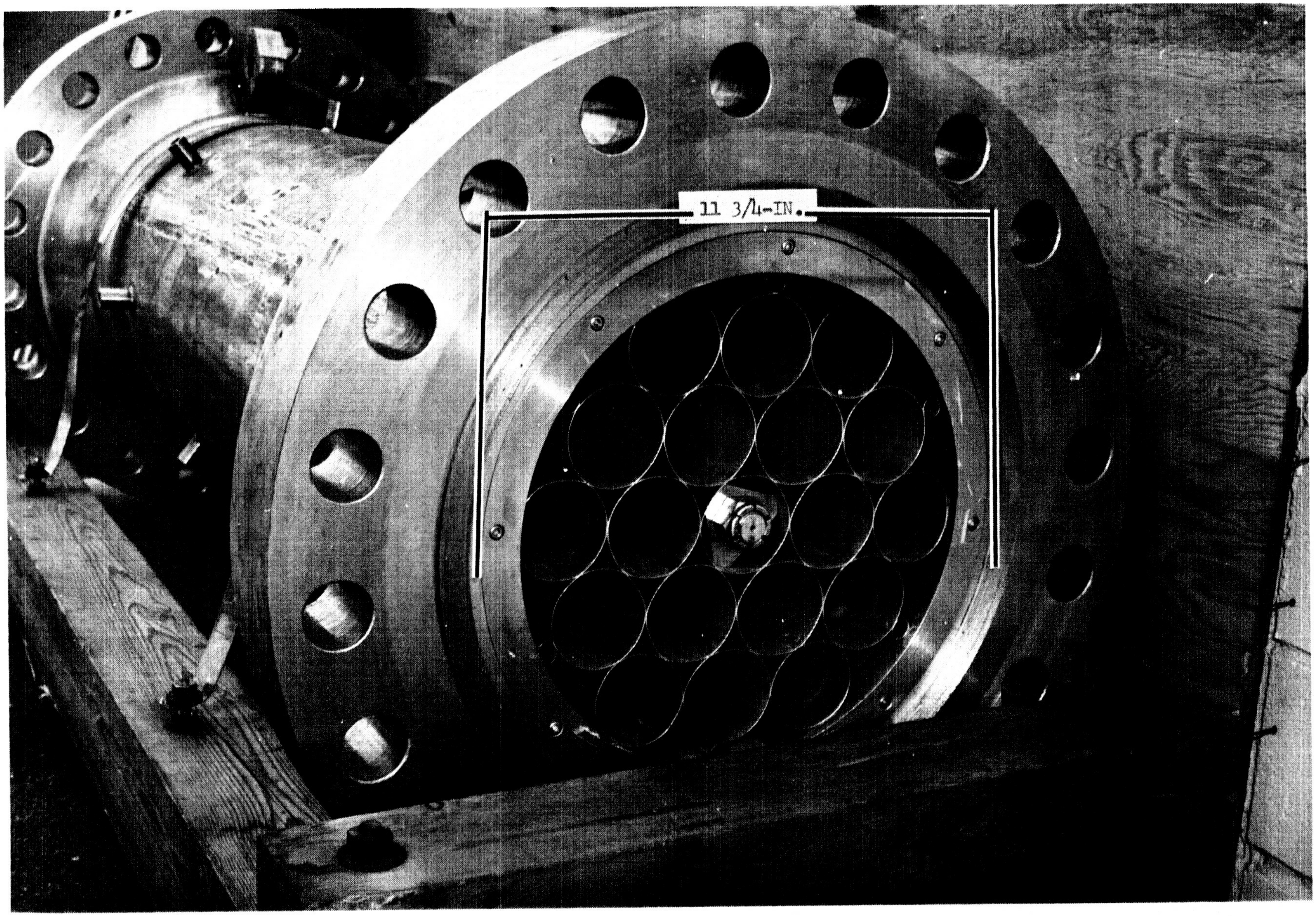

Figure 12

End View, 20-in. LH_2 Meter

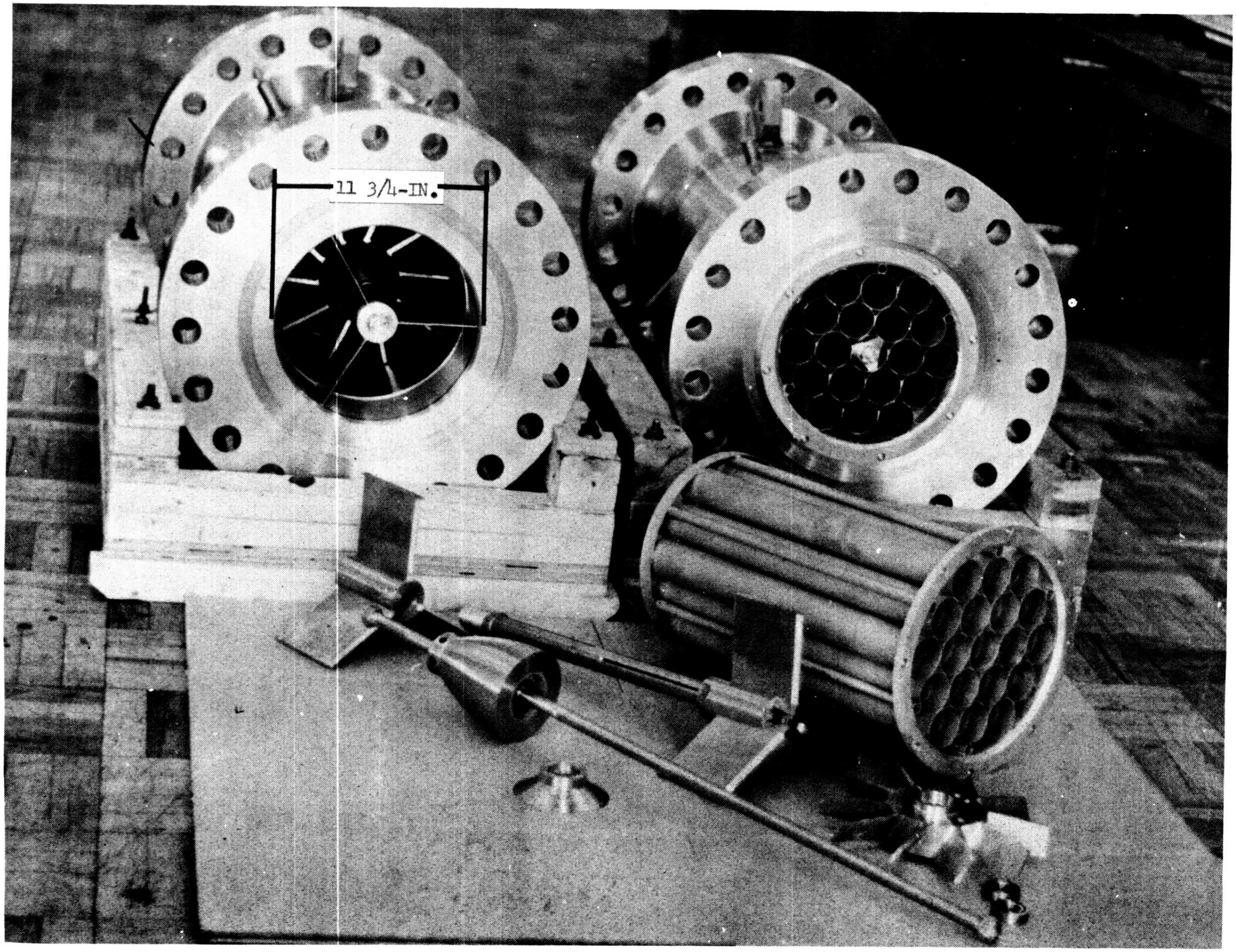

Figure 13

14-in. LO_2 Meter Disassembled

presented a series of fabrication problems which resulted in the development of a liquid oxygen-cleanable, rugged flow straightener of unique design. The individual tubes are upset or expanded at both ends, allowing approximately .030-in. between all tubes except for the last 1-in. to 1-1/2-in. at both ends. The tubes were spot-welded and subsequently nicrobrazed in a controlled atmosphere brazing furnace. Silver brazing individual tubes resulted in deformation resulting from temperature differentials. Also, use of a stainless steel which showed evidence of stress corrosion cracking in the silver brazing process had to be changed to the low carbon stainless steel.

Figure No. 14 shows the surface characterized by the so-called stress corrosion cracking. Photomicrography of cross-sections revealed that the cracks extended to as much as 50% of the thickness of the material(13).

G. CLEANING AND HANDLING

The use of large test components implies correspondingly large test hardware and it would appear that the available cleaning and handling equipment would be adequate. However, the length of the meter housing required when using flow straighteners within the meter may exceed the existing facilities. While other specific cleaning problems have arisen, the clean room facilities, including the use of clean tools specially designed for the flowmeter, should be reviewed.

The handling problems observed during the M-1 Program were limited to the clean room facility hoists, as well as the methods and machinery required for meter installation in the vertical test stand (see Figure No. 1). The horizontal test stand with an overhead traveling crane (Figures No. 3 and No. 4) presented no problems.

It is at the point of installation and removal of a meter such as shown in Figure No. 1, that cleaning and handling requirements merge. The ability to maintain system cleanliness on a rainy day after a series of cryogenic flows is a test of ingenuity. Multi-point lifting devices are needed to maneuver the meter in and out of its position. Plastic sheeting located above the work area is effective as a seal against moisture. The system must be designed with adequate flexibility to adapt to the clearance required to remove and install a meter.

H. INSULATION

No comparative data was developed for vacuum jacketed versus foam insulation of liquid hydrogen lines. However, the hydrogen pump tests

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(13) Aerojet-General Failure Analysis Report FA 64-416, K. Gustafson to G. R. Deppe, dated 4 September 1964, subject: <u>M-1 Damage to Type 302 SS Flow Straightening Vane Caused by Flux</u>

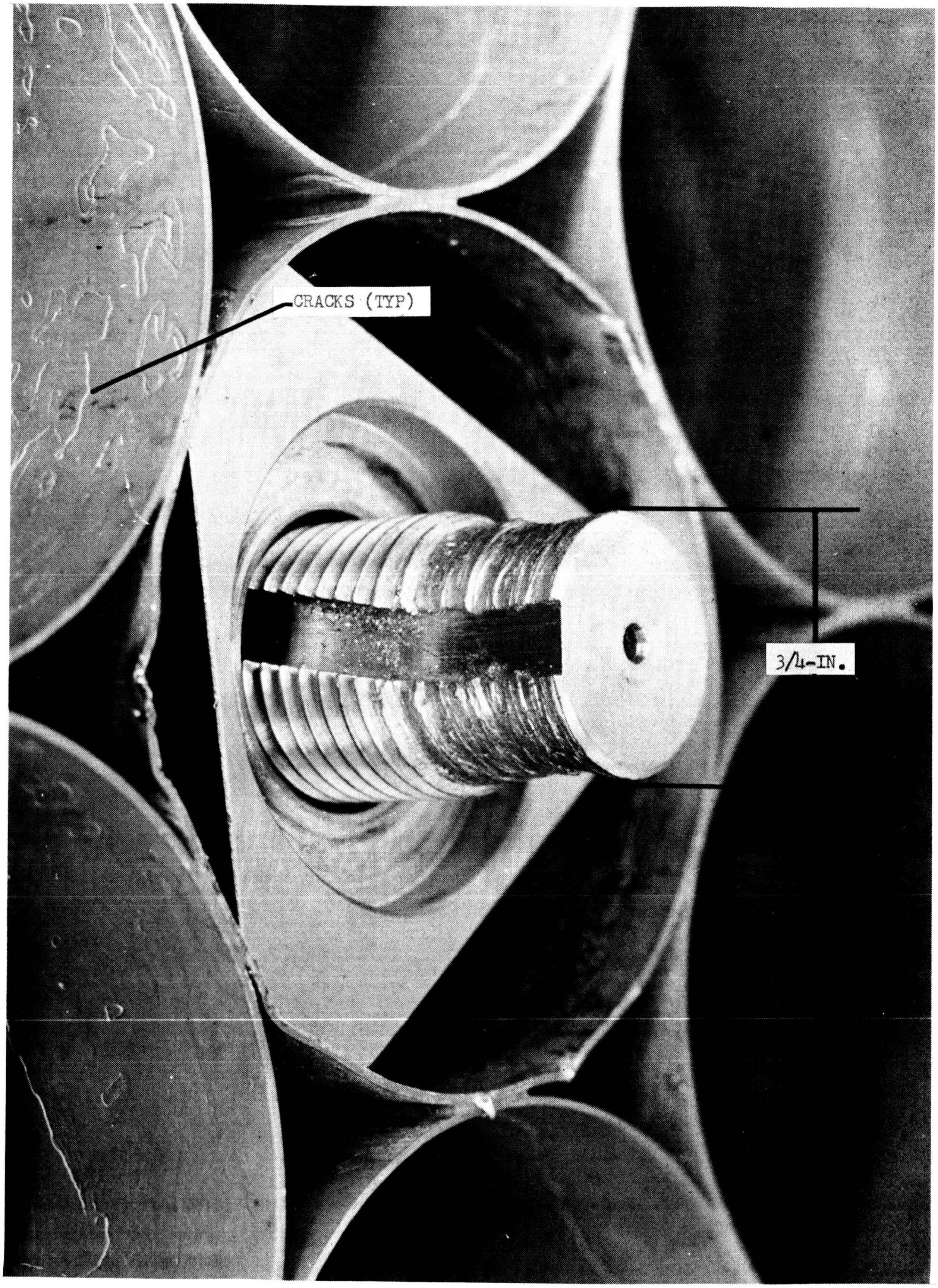

Figure 14

Stress Corrosion Cracking of Tubular Flow Straightener were run with approximately 30 ft of foam insulated pump suction line (Figure No. 1), extending vertically downward from an 18,000 gallon dewar(14). The temperature data observed indicated an average value of -419°F for the tests, and a shift during any one test of less than 0.5°F. The material used for the insulation in Polyurethane foam (i.e., Upjohn Company, CPR 314-2).

Use of vacuum jacketed flowmeters is probably warranted in some circumstances. However, the joints or flanges must either be vacuum jacketed or foam insulated after installation of the meter. The cost of applying foam insulation on a meter such as shown in Figure No. 1 is estimated to be $1,000. The outside protective layer is aluminum, adding a radiant heat transfer barrier. The estimated cost of adding a vacuum jacket to the 18-in. meter is $3,000 to $5,000. For simplicity and effectiveness, it would seem that foam insulation is the best approach for this type of service.

IV. CONCLUSIONS

The limited use of the M-1 meters makes it impossible to provide any large measure of data from which to draw conclusions. The principal areas in which experience was gained are calibrations, bearings, handling , and insulation.

A. CALIBRATIONS

No commercial or Government facility is known to exist which can provide water and cryogenic calibrations to full-scale for some of the M-1 size meters. Existing facilities that can approach the required flow rates in water have adequate accuracies. Existing facilities that can approach M-1 flow rates in cryogenics are built into rocket test stands and are not readily available(15). The accuracies are not as good as those provided for the previous generation of rocket flowmeters by a factor of approximately 5. The costs for calibrations (in water) of meters in the 14-in. to 20-in. range can be as much as ten times the cost for meters of six inches or less. Cryogenic calibration cost comparisons are not meaningful as yet because of the limited data for the large meters.

On-stand calibration devices, such as liquid level systems, are useful in resolving flowmetering problems.

The assumed range of + 0.2% to + 2.0% for the shift of calibration constants from water to liquid oxygen appears valid for some 8-in. and 18-in. meters. (Units of calibration factor are cycles/gallon.)

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(14) Schwartz, M. H. and Commander, J. C., Cooldown of Large Diameter Liquid Hydrogen and Liquid Oxygen Lines, NASA CR-54809, 20 April 1966

(15) NASA LeRC Memorandum, L. T. Weise to Record, op. cit.

B. BEARINGS

The use of 440-C ball bearings requires protection against moisture because they will corrode. There is insufficient data to draw any conclusions regarding the effect of this upon performance. Several cases of overspinning the M-1 flowmeter to twice maximum meter ratings resulted in no apparent problems. The meters have not been examined subsequent to the over-spinning, but no change in test data occurred. The incidents occurred in the gas generator and thrust chamber test programs.

C. HANDLING

The external lifting lugs are an absolute requirement for these large meters. The test stand facilities require chain hoist attachments for meter installation and removal.

D. INSULATION

The polyurethane foam insulation plus a light gage aluminum reflective exterior appears satisfactory for large (18-in.) liquid hydrogen line insulation, relative to flow measurements in a temperature regime of -420°F.

V. RECOMMENDATIONS

The following specific recommendations are made in the areas of calibration and applications.

A. CALIBRATION FACILITIES

1. All large test facilities should incorporate "on-line" calibration devices. In addition, a single accurate, off-line facility should be provided to handle development problems and highly accurate calibration requirements. Thrust chamber development test stands should incorporate redundant flowmeters, despite the added costs. This is independent of the tank metering device. The costs related to removal, repair and/or recalibration of a large meter are significant without considering the costs of repeating a test because of lost flow data.

2. National facilities for calibration in both water and cryogenic propellants should be reviewed for support requirements to existing and future large rocket programs.

B. APPLICATION

1. Redundant sensing coils, pressure and temperature ports, and flow straighteners should be incorporated into large meters.

2. Test stand facilities should include a perforated plate flow straightener upstream of the flowmeter. This involves added system pressure drop.

3. Cryogenic testing of sub-components prior to assembly is advisable. Coils typically develop open circuits when subjected to temperature cycling. No difficulties have been experienced as yet in the M-1 Program. Rotor assemblies for liquid oxygen meters should be immersed in liquid nitrogen and those for liquid hydrogen meters should be immersed in liquid nitrogen or liquid hydrogen.

4. If tubular flow straighteners are used in a facility or meter requiring cleaning to liquid oxygen levels, the upset end feature should be used to provide sensible gaps that can be cleaned. Circumferential hoops plus a flange at one end for attachment and indexing are essential.

5. In the absence of a cryogenic calibration, water values should be adjusted by + 0.6% for liquid oxygen and + 0.8% for liquid hydrogen (calibration factor expressed in cycles per gallon).

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9. National Bureau of Standards Report 7692, Recommendations to the NASA Covering a Cryogenic Fluid Flowmeter Calibration Facility, USDC, NBS, Boulder Laboratories, Boulder, Colorado, May 15, 1963

10. Aerojet-General Failure Analysis Report FA 64-416, K. Gustafson to G. R. Deppe, dated 4 September 1964, subject: M-1 Damage to Type 302 SS Flow Straightening Vane Caused by Flux

11. NASA LeRC Memorandum, L. T. Weise to Record, dated 1 April 1965, subject: Large Size Flow Meter Calibration System, E Area

APPENDICES

APPENDIX A

FLOW DATA FOR 8-IN. TURBINE FLOWMETER

Appendix A

UNIVERSITY OF CALIFORNIA
LOS ALAMOS SCIENTIFIC LABORATORY
(CONTRACT W-7405-ENG-36)
P. O. Box 1663
LOS ALAMOS, NEW MEXICO
87544

IN REPLY REFER TO: CMF-9-1645E

February 4, 1966

G. R. Deppe
Aerojet General Corporation
Bldg. 4610, Dept. 0830
Sacramento, California

Dear Gordon:

Flow data on the eight inch turbine flowmeter is tabulated below.

Flowrate GPM	Calibration Factor PPG	Pressure PSIA	Uncertainty Percent 3σ
1105	3.35	33.2	± 3.5
2129	3.48	118	± 2.2
4078	3.51	333	± 1.6
6043	3.48	663	± 1.4

We would have liked to run another test to determine the reproducibility of these points, however, the schedule is such that it is doubtful that we could run again for several months. There is a possibility that two more points, one each at 6000 and 7000 GPM, may be retrieved after a closer look at the data.

I hope you will find this data useful.

Very truly yours,

RWStokes

R. W. Stokes

RWS:hp

cc: M&R - 2
CMF-9 File

APPENDIX B

WATER AND LIQUID OXYGEN CALIBRATION DATA

TURBINE FLOWMETER 14 x 12 - 5498 S/N AJ 12-5

WATER AND LIQUID OXYGEN CALIBRATION DATA

TURBINE FLOWMETER 14 x 12 - 5498 S/N AJ 12-5

I. WATER DATA - WYLE LABORATORIES, MARCH 1965

Flow Rate (GPM)	K (PUL/GAL)
3488	0.6230
4404	0.6228
5929	0.6240
7236	0.6240
9205	0.6239
10276	0.6243
11782	0.6245
15069	0.6247
15447	0.6249

II. LIQUID OXYGEN DATA - MARSHALL SPACE FLIGHT CENTER

DECEMBER, JANUARY 1965

Flow Rate (GPM)	K (PUL/GAL)
10,500	0.6293
11,100	0.6297
11,500	0.6289
14,400	0.6301
14,700	0.6309
14,800	0.6337
16,500	0.6337

APPENDIX C

LH_2 FLOW DATA COMPARISON FROM TESTS ON TEST STAND H-6, SERIES 1.2-21-NNP-XXX, 1965-1966

LH_2 FLOW DATA COMPARISON FROM TESTS ON STAND H-6, SERIES 1.2-21-NNP-XXX, 1965-1966

(Turbine Meter Data Contains a + 0.8% K Factor Shift)

RUN	W_fT	W_fS	ε_1,%	W_fD	ε_2,%
002	76.27	78.84	-0.56	75.98	-0.38
003	77.97	77.66	-0.39	77.90	-0.09
004	78.48	77.98	-0.6	78.21	-0.34
005	77.38	77.00	-0.49	77.30	-0.11
006	78.21	78.28	+0.07	77.83	+0.48
007	77.73	78.14	+0.5	77.83	+0.13
008	78.16	78.01	-0.18	77.85	-0.39
009	78.50	78.34	-0.20	78.91	+0.52
010	77.74	77.67	-0.09	77.80	+0.08
011	77.52	77.73	+0.27	77.59	+0.09
012	78.11	78.09	-0.02	77.94	-0.21
013	78.77	78.40	-0.50	78.37	-0.54
			$\bar{x}$ = - .1825		$\bar{x}$ = - .0633
			1σ = .347		1σ = .337

NOMENCLATURE:

W_fS = Suction Flow, Pottermeter Model 8-5370, S/N AJS-8-24

W_fD = Discharge Flow, Pottermeter Model 8-5369, S/N AJS-22

W_fT = Flow Calculated From Tank VH-11

$$\varepsilon_1 = \frac{W_fS - W_fT}{W_fT} \times 100 \quad (\%)$$

$$\varepsilon_2 = \frac{W_fD - W_fT}{W_fT} \times 100 \quad (\%)$$

APPENDIX D

FLOW RATE COMPARISON, TEST STAND E-1, FUEL PUMP PROGRAM

FLOW DATA COMPARISON, TEST STAND E-1

FUEL PUMP PROGRAM

TEST SERIES 1.2-06-EHP, 1965

Test No.	Q_{FM}^{*} GPM	Q_{LL}^{*} GPM	$\frac{Q_{LL} - Q_F}{Q_F}^{*}$ X 100
003	14,500	16,610	14.6%
004	13,400	15,820	18.1%
007	13,900	15,900	14.5%
008	11,150	13,200	17.9%
009	26,700	32,500	21.6%
010	25,700	30,500	18.7%

TEST SERIES 1.2-10-EHP

001	25,000	28,950	15.8%
			$\bar{\bar{X}}$ = 17.3%

* A wide variance exists in data, depending upon when within each test a flow rate sample is taken. Where available, steady-state numbers were taken. The duration of steady-state is a matter of 10 sec to 20 sec in most cases. The variance is also a function of the total quantity of liquid discharged, as the percent of variability increases with decreasing discharged volume.