NASA TECHNICAL NOTE

N73-25278
NASA TN D-7323

NASA TN D-7323

LIFE TESTS OF SMALL TURBINE-TYPE FLOWMETERS IN LIQUID HYDROGEN

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NATIONAL AERONAUTICS AND SPACE ADMINISTRATION • WASHINGTON, D. C. • JUNE 1973

1. Report No.	2. Government Accession No.	3. Recipient's Catalog No.
NASA TN D-7323		

4. Title and Subtitle	5. Report Date
LIFE TESTS OF SMALL TURBINE-TYPE FLOWMETERS IN LIQUID HYDROGEN	June 1973
	6. Performing Organization Code
7. Author(s) Howard F. Hobart, Herbert L. Minkin, and Isidore Warshawsky	8. Performing Organization Report No. E-7371
	10. Work Unit No. 502-24
9. Performing Organization Name and Address Lewis Research Center National Aeronautics and Space Administration Cleveland, Ohio 44135	11. Contract or Grant No.
	13. Type of Report and Period Covered Technical Note
12. Sponsoring Agency Name and Address National Aeronautics and Space Administration Washington, D.C. 20546	14. Sponsoring Agency Code

15. Supplementary Notes

16. Abstract

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17. Key Words (Suggested by Author(s))	18. Distribution Statement
Flow measurement; Liquid hydrogen; Flowmeters; Cryogenic instrumentation; Turbine-type flowmeter; Instrumentation; Ball-bearings; Flowmeter calibration	Unclassified - unlimited

19. Security Classif. (of this report)	20. Security Classif. (of this page)	21. No. of Pages	22. Price*
Unclassified	Unclassified	16	$3.00

* For sale by the National Technical Information Service, Springfield, Virginia 22151

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SUMMARY

A total of 14 turbine-type flowmeters of 2.5 and 4-centimeter nominal size were operated for 100 or more hours at an average fluid speed in the unobstructed, upstream pipe of 20 meters per second for the smaller meters and 9 meters per second for the larger meters. Calibration shifts over a 6:1 range of calibration flow rates varied from 0.5 percent to 1 percent after 50 hours of operation. It is concluded that use of ball bearings with glass-filled Teflon retainers is most likely to produce minimal calibration shift with protracted use. Bearing replacement after 50 to 100 hours is recommended, depending on accuracy requirements, for flowmeters used at the fluid speeds of the tests.

INTRODUCTION

The axial-flow, turbine-type flowmeter is the most popular flowmeter for liquid hydrogen service in aerospace applications. Characteristics of this type of meter in sizes from 2- to 4-centimeter nominal size have been presented in previous reports (refs. 1 and 2), which give data on the reproducibility and linearity of meter calibrations. Reference 2 compared the performance of meters with various types of bearings, but the presentation was incomplete because of the absence of data on bearing life. The work reported here is intended to provide this missing information. This report, therefore, together with references 1 and 2, embodies the present state of statistical knowledge of the performance of small turbine flowmeters with liquid hydrogen. However, this knowledge is limited by the fact that the life-test data were obtained only on meters that had many common design features.

The life tests consisted of running 14 previously calibrated meters continuously at some average fluid speed, interrupting the operation at 50, 100, and 150 hours to perform a precision calibration in the facility described in references 3 and 4. The life-test facility was a separate one. (See section Arrangement of Life Test Facility.) One half of the test time involved running the flowmeters in the forward direction and one-half of the test time was consumed in reverse flow.

The effects of bearing replacement and of approach-hub shape on the calibration curve were also investigated briefly.

Background bibliographic information and the discussion of performance parameters other than bearing life are contained in reference 2.

APPARATUS

Arrangement of Life-Test Facility

Principal elements of the life-test facility are shown in figure 1. Two 20 000-liter hydrogen dewars were joined by a test section in which the flowmeters were installed.

The 5-centimeter-diameter transfer lines consisted of vacuum jacketed flexible hoses. All valves were vacuum jacketed and remotely operated. Each dewar had its own heat exchanger for self-pressurization. The heat exchanger was convectively cooled by the ambient air. An auxiliary pressurized helium gas line was connected to the top of the dewar to augment the pressurization.

Operating pressures were generally in the range of 2 to 3.5 bar. These pressures produced average fluid speeds (in the unobstructed pipe) of 20 meters per second for the 2.5-centimeter meters and 9 meters per second for the 4-centimeter meters.

Test Section

The test section was interchangeable with the test section used in the calibration facility (refs. 3 and 4) except that it accommodated four flowmeters in series and the elaborate flow-straightening apparatus described in reference 2 was replaced by simple screens. Figure 2 shows details of the test section.

Meters Tested

The following types of meters were tested (the notation matches that used in reference 2):

(1) Type E-F (two tested). Nominal 2.5-centimeter size, three blades, with full-complement ball bearings and with conical hubs (fig. 3)

(2) Type E-R (two tested). Same as E-F except with shielded ball bearings using glass-filled Teflon retainers

(3) Type F-R (six tested). Nominal 2.5-centimeter size, six blades, with shielded ball bearings using glass-filled Teflon retainers and with hemispherical hubs (fig. 4)

(4) Type Bd-R (four tested). Nominal 4-centimeter size, six blades, with ball bearings using glass-filled Teflon retainers and with conical hubs (fig. 3). These meters had originally been designed for water service rather than liquid hydrogen service.

TEST PROCEDURE

Method of Operation

To produce flow through the test meters, one dewar was vented while the other was pressurized by use of the heat exchanger and auxiliary helium pressurization system. When the liquid in one dewar was almost depleted and the other dewar was correspondingly almost filled, the valves were manipulated to reverse the flow. Gradual depletion of the hydrogen supply (through venting) was compensated for by occasionally refilling one of the dewars with fresh liquid.

A limitation on available helium flow rate and the varying efficiency of the heat exchanger caused a slight monotonic decrease in fluid speed from beginning to end of run. The maximum deviation from average speed was about 10 percent. The average speed was 20 meters per second for the 2.5-centimeter meters and 9 meters per second for the 4-centimeter meters; the 9-meter-per-second value was enforced by the limited volumetric flow obtainable with the facility. The duration of uninterrupted flow was about 30 minutes.

Pulse frequency and wave shape were monitored continuously to detect possible blade breakage during the life test.

Preliminary Tests

It was originally intended to run the flowmeters for 100 hours in the life test facility and then to remove them for calibration in the precision calibration facility (refs. 3 and 4). However, about 70 hours after initiation of the life tests, some blades broke off of three meter rotors. All breaks occurred at the blade root. Fluorescent dye and microscopic examination of the remaining blades showed several cracks at the blade roots. All of the blade roots lacked fillets. It was also found that, at about the same time as the breakage, there was a possibility that the pressurizing helium gas had become contaminated with nitrogen. Although the cause of blade breakage is not certain, the most probable reconstruction of events is that an upstream flowmeter rotor was hit by frozen nitrogen and that the broken blade in turn collided with downstream rotors, breaking blades on these rotors. The remedial action taken, other than prevention of helium contamination, was (a) to install 50-mesh (0.5-mm pitch) screens in front of each flowmeter, (b) to manufacture new replacement rotors of pure nickel rather than the 400-series stainless steel previously used, in order to improve impact resistance, and (c) to inspect the new rotors for sound blade-root construction before installation. Rotor replacement was made on five meters out of the 14 meters tested. No further blade breakage was encountered after these precautions.

Principal Tests

Calibration procedure. - After the blade-breakage incident, the procedure generally adopted was to calibrate the flowmeters initially in the precision calibration facility, to run them for 50 hours, remove them and recalibrate them, then reinstall them in the life test facility for another 50 hours, and then recalibrate them. Funding limitations prevented running more than 100 hours, except for four meters, which were run for 150 hours.

Calibration time, averaging 6 hours per meter, was neglected in measuring accumulated time. Some of the meters also had been used before the life test; this usage (except in one case) averaged 17 hours and also was ignored in the totalization. Thus the lifetimes reported err on the conservative side.

Bearing installation and replacement. - All meters tested used the type of construction shown in figures 3 and 4. Bearing alinement was achieved through use of three springy sheet-metal cylinders that also acted as flow straighteners. Whenever bearings were changed, all portions of the assembly (with the exception of factory-cleaned shielded bearings) and all handling tools were ultrasonically cleaned with clean acetone, dried with clean air, and assembled using only clean, metallic tools and polyethylene gloves; no internal part was touched with the fingers.

Hub shape test. - The only difference in construction between type E (three blades, conical hub) and type F (six blades, hemispherical hub) meters, other than the number of rotor blades, is in the shape of the rotor support hubs. In order to determine what effect, if any, this difference had on the shape of the calibration curve, identical six-bladed rotors were installed in a type E and a type F meter. New shielded bearings were used in each case, and similar cleaning and assembly techniques were followed. Rotor diameter, casing diameter, and blade tip clearance were identical in both cases to within 0.05 millimeter. Axial play was identical to within 0.1 millimeter.

RESULTS

Method of Presentation of Results

Results of the calibration tests are conveniently represented by the change in calibration factor C (pulses per unit volume), expressed as a percentage of the asymptotic calibration factor C_m (the asymptote of the original calibration curve at high fluid speeds). The calibration factor after n hours is represented by C_n. The original calibration factor is represented by C_0. The abscissa for the deviation curves is taken as fluid speed in the unobstructed pipe, for reasons of practicality and convenience discussed in reference 2.

Each calibration curve represents the mean of at least two separate calibrations (generally three). Each mean curve has a probable error of 0.06 percent at the upper end of the calibration range and of 0.1 percent at the lower end of the calibration range.

Type E-F Meters

One of these meters stopped running after 130 hours. Disassembly revealed that the bearings were badly spalled. A photograph of this bearing is shown in figure 5; the ball diameter is 0.8 millimeter. The curves of calibration deviation for this meter (fig. 6(a)) suggest that this meter had always been of poor quality, since even the 50-hour curve shows nearly a 4-percent deviation at full scale.

The second type E-F meter showed (1) less than 1/2-percent deviation at the maximum flow of 30 meters per second, after 150 hours of operation, and (2) less than 1-percent deviation above 5 meters per second, after 50 hours of operation. Deviation curves for this meter are shown in figure 6(b). The behavior is anomalous to the extent that deviations after 100 hours exceeded those after 150 hours.

Type E-R Meters

Deviation curves for these meters are shown in figure 7. Although deviations at full scale (30 m/s) were less than 2 percent over a 150-hour period, only the 50-hour calibration curves show acceptably small deviations (less than 1.3 percent) over the full range (4 to 30 m/s) of calibration.

Type F-R Meters

Figure 8 summarizes results on the six meters. These meters showed deviations considerably smaller than those of type E-R meters. Four meters showed deviations of less than 0.5 percent after 100 hours over the full range (2 to 25 m/s) over which they were calibrated; the deviation of the average meter did not exceed 0.2 percent. A fifth meter showed a deviation of not over 0.5 percent after 50 hours and not over 1 percent after 100 hours; these are the uppermost curves in figure 8. A sixth meter showed deviations of up to 0.9 percent after 50 hours, but this limit was not exceeded after 100 hours. The 100-hour curve is the lowermost curve in figure 8.

Type Bd-R Meters

Figure 9 shows deviations after 100 hours of operation in the life test facility. The performance of meter Bd-R1 is considered anomalous; this meter had shown superior performance over a period of several years. Its calibration reproducibility was far superior to that of the average meter, and comparable with that of the calibration facility itself. In fact, this meter, uniquely, had received about 100 hours of usage before the present life test. The other three meters showed deviations up to 4 percent over the range of 2 to 12 meters per second.

Summary of Life Test Results

Table I summarizes the principal results of the life tests. Type E meters maintained their calibrations within 1 percent, over the range 5 to 30 meters per second, after 50 hours of operation at an average fluid speed of 20 meters per second (12 000 rpm rotor speed). Four out of six type F meters maintained their calibration within 1/2 percent, over the range 2 to 25 meters per second, after 100 hours of operation at an average fluid speed of 20 meters per second (12 000 rpm rotor speed); maximum deviation among all six meters did not exceed one percent. The type Bd 4-centimeter meters, after 100 hours at an average speed of 9 meters per second (6000 rpm rotor speed), showed negligible shift at the nominal full scale speed of 12 meters per second, but the shift increased progressively as speed dropped, averaging 3 percent at 2 meters per second for three of the meters. The fourth meter, whose performance was anomalous, was the best of all flowmeters tested, showing not over 0.3-percent deviation over the range 1.5 to 12 meters per second, after 100 hours in the life test facility and another 100 hours in calibrations performed over the last 4 years.

Effect of Bearing Replacement

Dashed curves in figures 7 and 9 show deviations when new bearings were installed after the conclusion of the life tests. Two of the three curves suggest that bearing wear had been the cause of calibration shift with time, but the curve in figure 9 does not confirm such a correlation. However, firm conclusions from the bearing-replacement test are obscured by the fact that experience over the past 5 years indicates a 25-percent probability that the act of flowmeter disassembly and reassembly will produce as much as a 1-percent shift in C_m.

Observation of Bearing Wear

Examination, at ×80 magnification, of the surfaces of the balls in a few of the bearings showed progressive deterioration of surface quality with time. Deterioration of surface finish was barely perceptible after 12 hours of operation of a type E-R meter. After 150 hours, a few pits of about 10-micrometer diameter were evident and the ball surface appeared mottled, with an average pit diameter of about 4 micrometers. The balls of a full-complement bearing (type E-F meter) showed greater wear than the balls of the type E-R meter bearing with glass-filled Teflon retainers.

Effect of Hub Shape

The results of the comparison of hub shapes are shown in figure 10. The dashed curve is the calibration curve of a meter with a six-bladed rotor and conical hubs. The upper and lower curves represent the envelope of calibration curves of five six-bladed (type F-R) meters with hemispherical hubs. The results suggest that approach-hub shape has negligible effect on calibration-curve shape.

DISCUSSION AND CONCLUDING REMARKS

In the absence of additional statistical information, the life-test information presented under Summary of Life Test Results represent the probable performance to be expected from the types of flowmeters tested.

The calibration shifts reported are significantly larger than the random deviations to be expected (as reported in ref. 2) but are acceptably small for many applications.

Although the numerical results might be somewhat different if the flow were always in the same direction, the conclusions concerning the comparative performance of the different types of flowmeters would remain valid for unidirectional flow.

The results obtained suggest that flowmeters should be built so that bearings may readily be removed and replaced at periodic intervals, say 50 to 100 hours. For highest probability that the calibration will not be altered by the process of bearing replacement, the mechanical design should be such that all axial and radial clearances and all angular alinements are accurately reproduced after the act of bearing replacement; this criterion was not fully met in the flowmeters reported on here, as is indicated by occasional shifts in the value of asymptotic calibration factor after disassembly and reassembly.

Flowmeters used for long periods of time in tankage-transfer operations may, therefore, require bearing replacement, and/or calibration after 50 hours of use.

On the other hand, it should be noted that rocket-testing applications may involve a total flowmeter usage of less than 10 hours. The additional time spent in calibrating a flowmeter four times, as recommended in reference 2, may itself amount to a similar period of time. In this application, bearing replacement may be unnecessary.

Bearings with glass-filled Teflon retainers appear to be preferable to those of the full-complement type, because of reduced bearing wear with protracted use. However, the bearings with retainers usually are shielded, so that cleaning is impossible; hence, great care must be taken that these bearings are not exposed to dust or dirt during handling.

Reference 2 should be consulted for background bibliographic information and for the discussion of performance parameters other than bearing life.

Lewis Research Center,
National Aeronautics and Space Administration,
Cleveland, Ohio, April 3, 1973,
502-24.

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TABLE I. - SUMMARY OF LIFE TEST DATA

Type of flowmeter	Nominal size, cm	Number of meters tested	Number of rotor blades	Approach-hub shape	Average fluid speed in life test, m/s	Maximum fluid speed in calibration, m/s	Maximum rotor speed in calibration, rpm	Deviation data, fig. no.	Deviation from original calibration after n hr of life test[a]
E-F	2.5	2	3	Conical	20	30	18 000	6	One meter defective. One meter: <1% above 5 m/s after 50 hr, <0.5% at 30 m/s after 150 hr
E-R	2.5	2	3	Conical	20	30	18 000	7	All meters: <1.3% above 4 m/s after 50 hr, <2% at 30 m/s after 150 hr
F-R	2.5	6	6	Hemispherical	20	30	18 000	8	Four meters: <0.5% above 2 m/s after 100 hr All meters: <1% above 2 m/s after 100 hr
Bd-R	4	4	6	Conical	9	-12	8 000	9	All meters: <4% above 2 m/s after 100 hr

[a]Principal results.

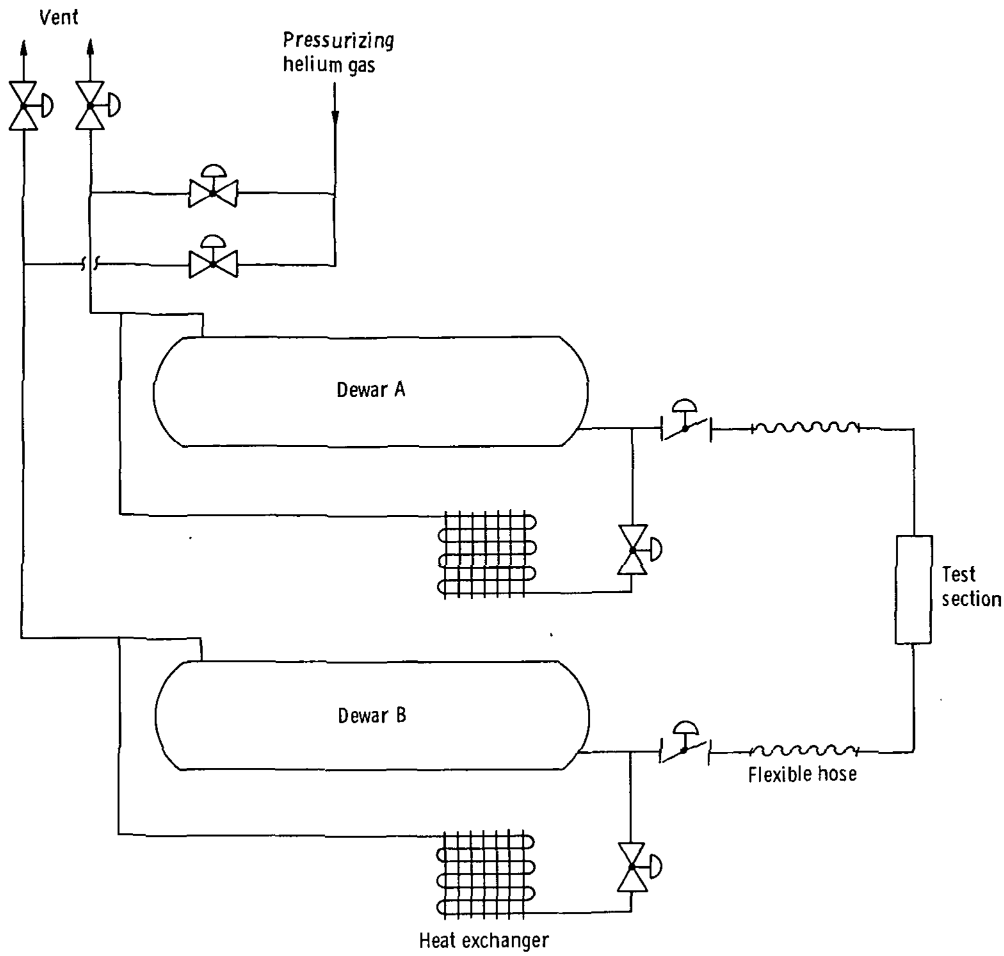


Figure 1. - Flowmeter life test facility.

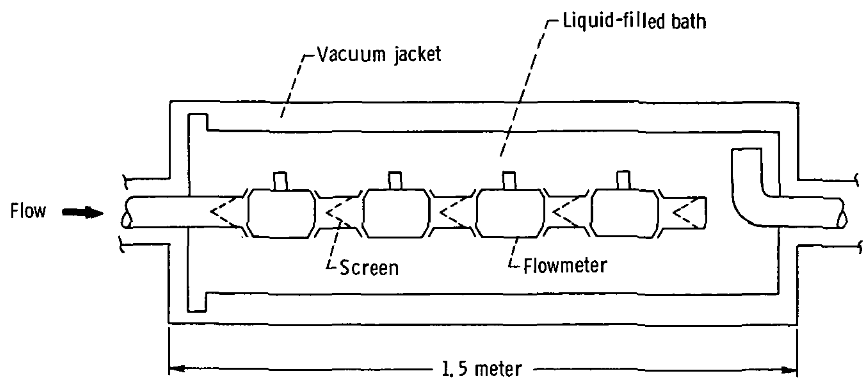


Figure 2. - Simplified outline of test section. (Transverse scale is exaggerated for clarity.)

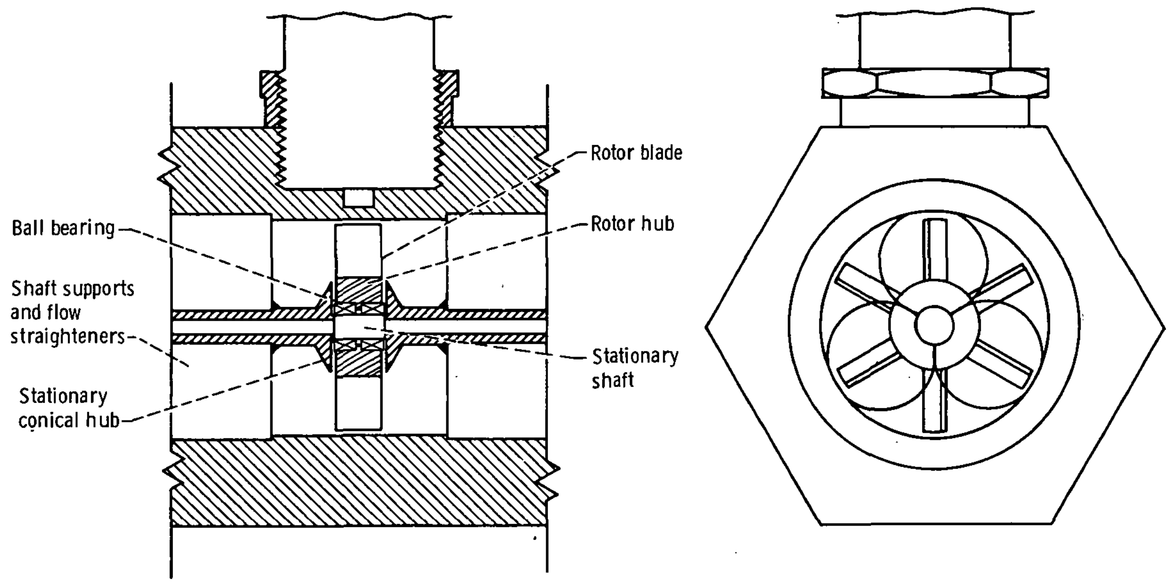


Figure 3. - Conical hub flowmeter, types E (three blades) and Bd (six blades).

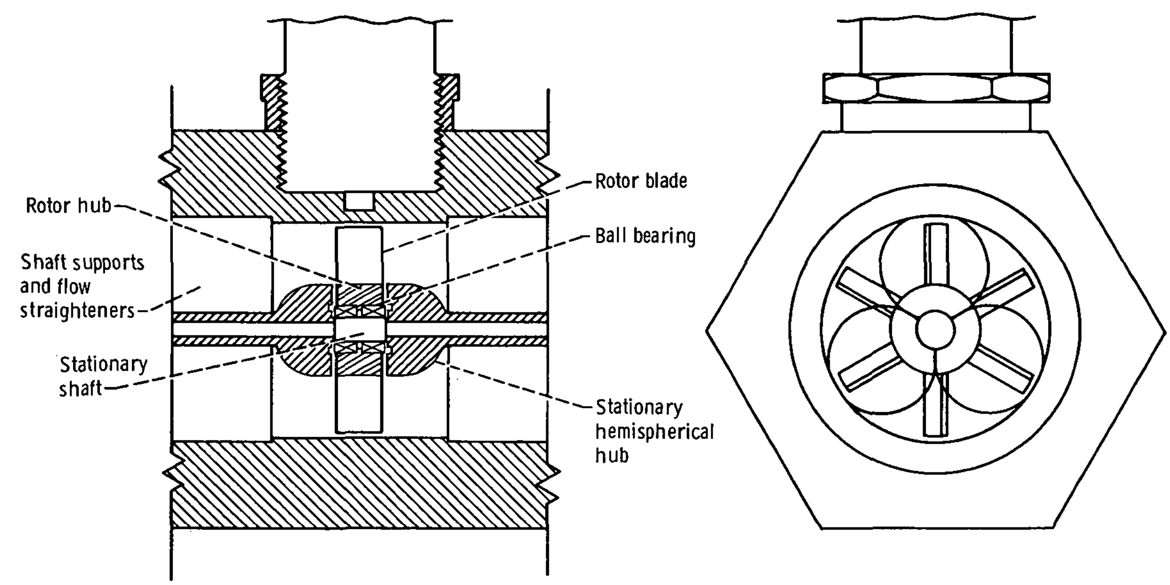


Figure 4. - Hemispherical hub flowmeter, type F.

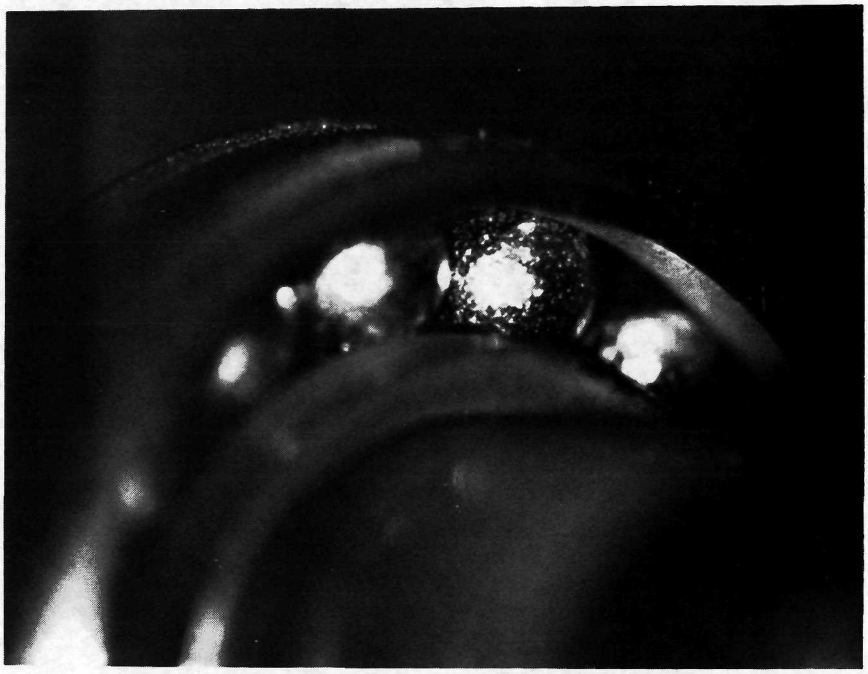
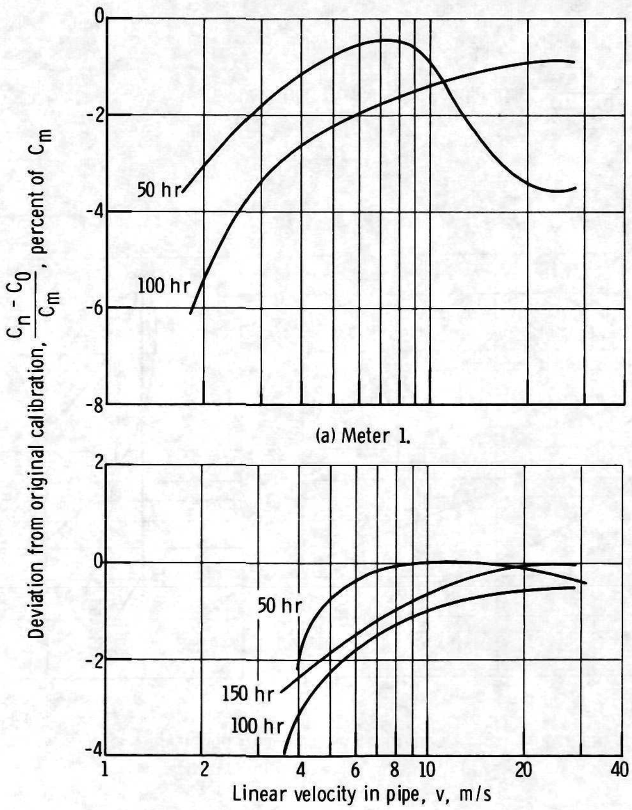
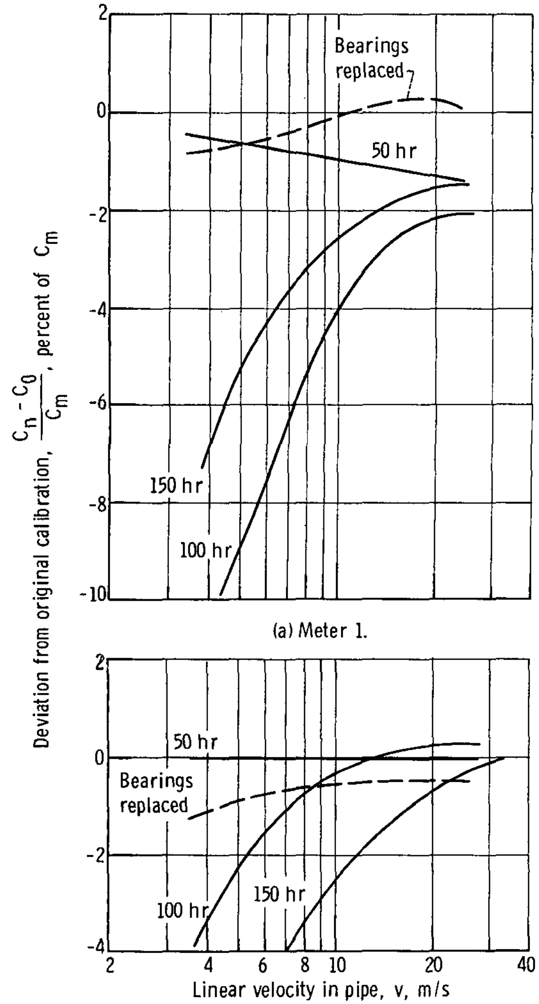


Figure 5. - Spalled ball bearing from type E-F meter; ball diameter, 0.8 millimeter.



(b) Meter 2.

Figure 6. - Effect of run time on calibration of type E-F meters.



(a) Meter 1.

(b) Meter 2.

Figure 7. - Effect of run time on calibration of type E-R meters.

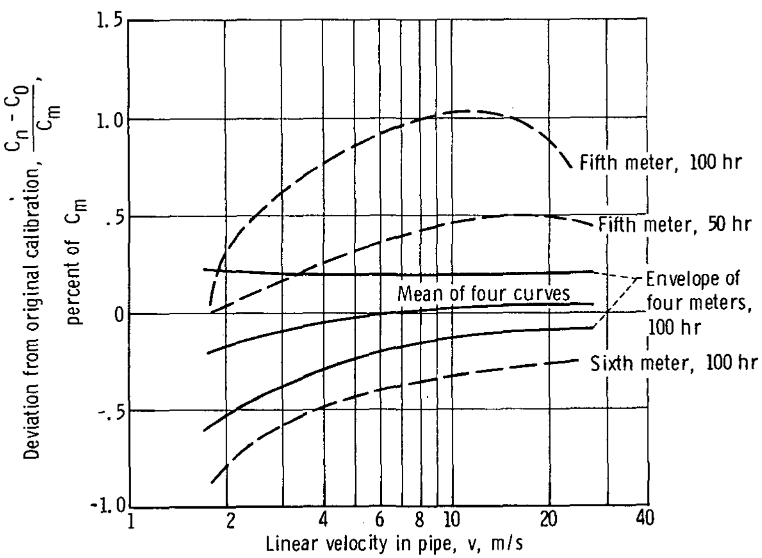


Figure 8. - Effect of run time on calibrations of six type F-R meters.

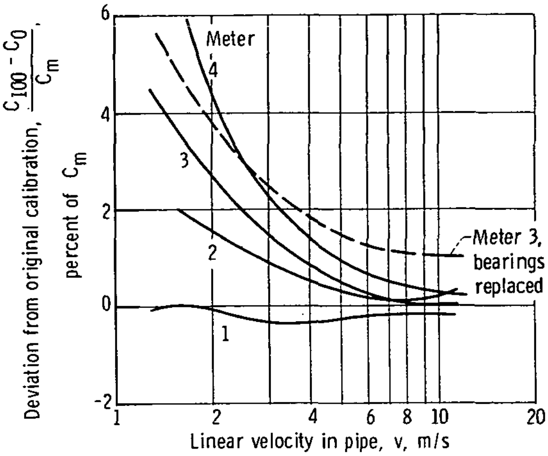


Figure 9. - Effect of 100-hour run time on calibrations of four type Bd meters.

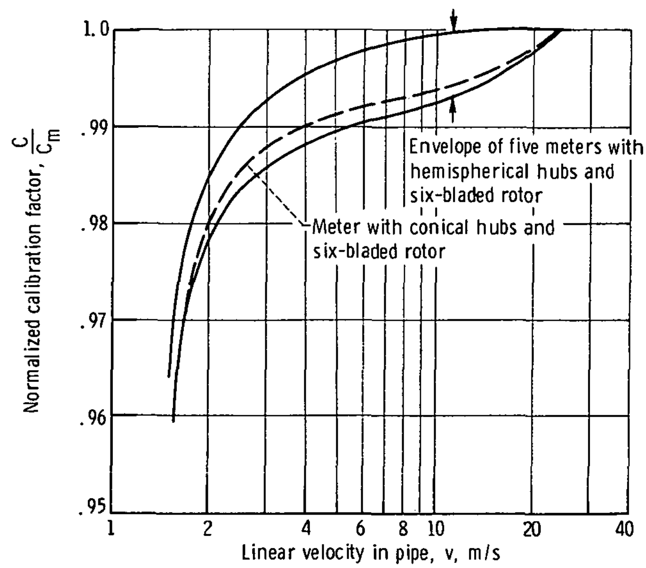


Figure 10. - Effect of hub shape on calibration curve.

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