Received by OSTI

JAN 21 1987

K/OA-6038
(ISPO-259)

MARTIN MARIETTA

**Investigation of Technology for the
Monitoring of UF_6 Mass Flow in UF_6
Streams Diluted with H_2**

O. J. Baker
J. N. Cooley
W. A. Hewgley
B. W. Moran
D. W. Swindle, Jr.

UNITED STATES PROGRAM FOR TECHNICAL ASSISTANCE TO IAEA SAFEGUARDS

POTAS

DEPARTMENT OF STATE
DEPARTMENT OF ENERGY
ARMS CONTROL AND DISARMAMENT AGENCY
NUCLEAR REGULATORY COMMISSION

OPERATED BY
MARTIN MARIETTA ENERGY SYSTEMS, INC.
FOR THE UNITED STATES
DEPARTMENT OF ENERGY

DISTRIBUTION OF THIS DOCUMENT IS UNLIMITED

DISCLAIMER

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise, does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

POTAS DISCLAIMER

This report was prepared as an account of work sponsored by an Agency of the United States Government. Neither the United States nor the United States Department of Energy, nor any of their employees, nor any of their contractors, subcontractors, or their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Further, neither the subject matter nor the content of this report reflects any policy, express or implied, by the United States Government.

December 1986

K/OA--6038

DE87 004145

INVESTIGATION OF TECHNOLOGY FOR THE MONITORING OF UF_6 MASS FLOW IN UF_6 STREAMS DILUTED WITH H_2

O. J. Baker^a
J. N. Cooley^b
W. A. Hewgley^a
B. W. Moran^b
D. W. Swindle, Jr.^b

DISCLAIMER

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

UNITED STATES PROGRAM FOR TECHNICAL ASSISTANCE TO IAEA SAFEGUARDS

This work was supported by the
U.S. Program for Technical Assistance
to IAEA Safeguards (POTAS) under
Task A-146, " UF_6 Mass Flow Monitoring"

Prepared by the
OAK RIDGE GASEOUS DIFFUSION PLANT
operated by
MARTIN MARIETTA ENERGY SYSTEMS, INC.
for the
U.S. DEPARTMENT OF ENERGY
under Contract No. DE-AC05-84OR21400

^aInstrument and Control Engineering, Engineering Division.

^bInternational Technology Programs.

MASTER

DISTRIBUTION OF THIS DOCUMENT IS UNLIMITED

CONTENTS

	<u>Page</u>
EXECUTIVE SUMMARY	xi
PART I. SURVEY OF METERS FOR UF ₆ GAS FLOW MONITORING	
I. INTRODUCTION	3
A. Objective	3
B. Scope	3
II. APPROACH	4
A. Literature Review	4
B. Operating Experience	4
III. RESULTS	4
A. Mass Flow Meters	4
1. General Description	4
2. Applications	5
3. Conclusions and Recommendations	5
a. Conclusions	5
b. Recommendations	5
B. Orifice Meters	5
1. General	5
2. Theory and Description	6
3. UF ₆ Applications at Martin Marietta Energy Systems, Inc.	8
a. Gas Centrifuge Plant Control Valve	8
4. Features, Cost and Availability	11
C. Pitot Tube Meters	11
1. General	11
2. Theory and Description	11
3. UF ₆ Applications at Martin Marietta Energy Systems, Inc.	13
a. Diffusion Plant Interstage Flow Meter	13
4. Features, Cost and Availability	13
D. Thermal Meters	16
1. General	16
2. Theory and Description	16
3. UF ₆ Applications at Martin Marietta Energy Systems, Inc.	18
4. Features, Cost and Availability	18
E. Vortex Shedding Meters	18
1. General	18
2. Theory and Description	18
3. UF ₆ Applications at Martin Marietta Energy Systems, Inc.	22
a. Vortex Shedding Flow Meters for Use in the WMCO, Fernald, Ohio, UF ₆ to UF ₄ Reduction Facility	22
4. Features, Cost and Availability	23

	<u>Page</u>
F. Vortex Precession (Swirl) Meters	23
1. General	23
2. Theory and Description	23
3. UF ₆ Applications at Martin Marietta Energy Systems, Inc.	26
a. Feed Rate Testing of 10- and 14-Ton UF ₆ Cylinders	26
4. Features, Cost and Availability	26
G. Selection of the Two Most Promising Meters	26
1. Criteria for Selection	26
2. Selection 1 - Orifice Meter	30
3. Selection 2 - Pitot Tube Meter	30
4. Less Promising Flow Meters - Thermal, Vortex Shedding and Vortex Precession	33
5. Plan for Evaluating the Two Most Promising Flow Meters	33
IV. CONCLUSIONS AND RECOMMENDATIONS	36
A. Conclusions	36
B. Recommendations	36
ACKNOWLEDGEMENTS	37
LIST OF REFERENCES	39
BIBLIOGRAPHY	41
Appendix A. FLOW METER CHECKLIST (REFERENCE 2)	43

PART 2. SURVEY OF INSTRUMENTS FOR GAS ANALYSIS

I. INTRODUCTION	47
II. ANALYTICAL INSTRUMENTATION	47
A. Laser Fluorimeter	47
1. General Description	47
2. Considerations	47
B. Atomic Absorption Spectroscopy	47
1. General Description	47
2. Considerations	48
C. Gas Mass Spectrometry	48
1. General Description	48
2. Considerations	49

	<u>Page</u>
D. Infrared-Ultraviolet-Visible Spectrophotometry	49
1. General Description	49
2. Considerations	50
E. Gas Chromatography	50
1. General Description	50
2. Considerations	50
F. Acoustic Gas Analysis	51
1. General Description	51
2. Considerations	51
III. RECOMMENDATIONS	52

LIST OF FIGURES

<u>Figure</u>		<u>Page</u>
1	Concentric Orifice Plate	7
2	Flow Pattern With Orifice Plate	9
3	Pressure Profile With Orifice Plate	10
4	Schematic of a Pitot Tube Installation	14
5	Heat Transfer Flow Meter	17
6	Hot Wire Flow Sensing Probe	19
7	Vortex Shedding From a Bluff Body	21
8	Construction of a Typical Vortex Precession (Swirl) Meter	25
9	Orifice Meter Schematic Diagram	31
10	Instrument Application Diagram for Orifice Flow Meter	32
11	Pitot Tube Meter Schematic Diagram	34
12	Instrument Application Diagram for Pitot Tube Meter	35

LIST OF TABLES

<u>Table</u>		<u>Page</u>
1	Requirements for Proposed Applications	3
2	Orifice Meter Data	12
3	Pitot Tube Meter Data	15
4	Thermal Flow Meter Data	20
5	Vortex Shedding Meter Data	24
6	Vortex Precession (Swirl) Meter Data	27
7	UF ₆ Gas Flow Meters: Comparison Between User Requirements and Prospective Meters	28

EXECUTIVE SUMMARY

To assist the International Atomic Energy Agency (IAEA) in the development of an effective safeguards approach for an aerodynamic uranium enrichment plant, the applicability of gas flow meters, in-line enrichment monitors, and instruments for measuring uranium or UF_6 concentrations in process streams as a means for verifying declared plant throughput have been investigated. Evaluations were conducted to identify and to assess available instruments applicable to measurements of UF_6 - H_2 gas streams.

The process gas in an aerodynamic enrichment plant is a mixture of UF_6 and H_2 , the greater volumetric percentage of which is hydrogen. To quantify the amount of uranium being fed into and withdrawn from the cascades for nuclear materials accountability verification, a mass flow measurement in conjunction with a measurement of the uranium (or UF_6) concentration in the process gas is required. Prior to this assessment, a safeguards strategy was conceived that would use gas flow meters for determining mass flows and in-line enrichment monitors for measuring uranium concentrations. This initial evaluation concluded that in-line enrichment monitors (e.g., the U.S.-developed, germanium detector-based, gas phase enrichment monitor) were only applicable to pure UF_6 streams. To accomplish the measurement of uranium concentrations in a mixed process stream, the study was broadened to include an evaluation of known instruments that may be applicable to the measurement of uranium or UF_6 concentration in a UF_6 - H_2 gas stream.

The gas flow monitor survey was conducted assuming a range of operating conditions representative of aerodynamic enrichment plant operating parameters. Three gas stream compositions were considered: (1) a pure UF_6 gas stream, (2) a gas stream comprised of 95% H_2 and 5% UF_6 , and (3) a gas stream comprised of 99.7% H_2 and 0.3% UF_6 . The assumed gas temperature range for all three streams was 27 to 49°C (80 to 120°F). The pure UF_6 stream was assumed to be contained in a small diameter process pipe (i.e., < 25 cm) at a pressure ranging from 3 to 150 torr. The UF_6 - H_2 process streams were assumed to be contained in a large diameter process pipe (i.e., 25 to 71 cm) at a pressure ranging from 3 to 6 atm. These data were then expanded to determine the corresponding gas flow velocities and mass flow rates. The features of the flow meters selected for evaluation were compared to these operating criteria to determine the most applicable meter(s). The gas analysis instrument survey was conducted assuming a UF_6 - H_2 process stream. The design and operating features of the gas analyzers chosen for evaluation were compared to select the best instrument for the proposed application.

The mass flow technology investigation is presented as two detailed instrument surveys. Part 1 assesses the applicability, availability, and effectiveness of gas flow meters as a means for verifying the mass flows of pure UF_6 streams and UF_6 streams diluted with an H_2 carrier gas. Part 2 evaluates known instruments applicable to measurement of uranium or UF_6 concentrations in a UF_6 - H_2 process stream. Included with each

survey are recommendations of specific instruments for safeguards application and suggestions for additional analyses.

Based on criteria that bound expected operating conditions at locations where gas flow monitoring might be feasible in an aerodynamic enrichment plant, five flow meters were evaluated in the gas flow monitoring study (Pt. 1). The survey identified the orifice, pitot tube, thermal, vortex shedding, and vortex precession (swirl) meters as promising for the intended use. Subsequent assessments of these flow meters revealed that the orifice meter and the pitot tube meter are the best choices for the proposed applications. The orifice meter is simple, reliable, relatively inexpensive, and provides a high sustained accuracy. Its main limitations are a high unrecoverable pressure drop and a flow rangeability of 3 to 1 suggesting its application in low velocity gas streams of small diameter piping (i.e., 2 to 20 cm). The pitot tube meter is relatively inexpensive and can be applied in high velocity gas streams without incurring excessive pressure drops. Its limitations are relatively low accuracies, a tendency to become plugged under extended use, and a flow rangeability of 3 to 1. These advantages and limitations suggest that pitot tube meters be adopted for application in high velocity gas streams of large diameter piping systems (i.e., 20 to 76 cm). Prior to using the orifice meter and pitot tube meter in plant applications, an evaluation program is necessary to confirm the suitability of these meters under conditions simulating those expected in service. The specific information required to simulate operating conditions includes gas composition, process conditions (i.e., gas temperature and pressure), and installation conditions (i.e., pipe type, pipe size, ambient conditions, and flow state).

The gas analysis instrument survey (Pt. 2) evaluates known instruments that may be used to measure uranium or UF_6 concentration in a UF_6 - H_2 process stream at an aerodynamic enrichment plant. Of the six procedures evaluated, four have been used for process monitoring in a UF_6 environment: gas mass spectrometry, infrared-ultraviolet-visible spectrophotometry, gas chromatography, and acoustic gas analysis. The remaining two procedures, laser fluorimetry and atomic absorption spectroscopy, would require significant development work before they could be used for process monitoring. Based on cost, availability, operating range, accuracy, analysis time, and installation requirements, ultraviolet-visible spectrophotometry is felt to be the best procedure currently available to perform the required measurement. This technique is a standard laboratory analytical measurement procedure that has been adapted for process measurements in situ, in slip streams, and in hot cells. The procedure is simple, rapid, and accurate. Commercial process instruments with years of application experience are readily available. These analyzers are affordable, highly reliable, and require low maintenance. The chief limitation of the instrument is degradation of the optical windows with time; however, because of the corrosive gas environment, every intrusive gas analysis system would be affected by the harsh operating conditions. Selection of a specific spectrophotometric analyzer is dependent on whether it will be used in situ or in a slip stream.

In conclusion, evaluation of gas flow meters that have been used successfully in UF_6 gas flow measurement indicate that two — the orifice meter and the pitot tube meter — are the best choices for the applications investigated. Based on an analysis of known instruments that may be applicable to the measurement of uranium or UF_6 concentrations in a $\text{UF}_6\text{-H}_2$ process stream, ultraviolet-visible spectrophotometry is considered to be the best instrumental procedure currently available. Final selection of a gas flow meter for possible future IAEA application in safeguarding an aerodynamic uranium enrichment plant is dependent on facility-specific design and process data (i.e., pipe size, pipe type, gas flow conditions, gas composition, temperature, and pressure). The choice of a spectrophotometric analyzer is dependent on the interface requirement (i.e., in situ vs slip stream). Commercial process instruments with years of application experience are readily available for both applications. Final selection of a flow meter and a spectrophotometric analyzer cannot be made until additional plant application information becomes available. Even then, final selection should be made only after test loop evaluations have been conducted in which the proposed instruments have been subjected to conditions representative of those expected in service. The instruments being recommended for safeguards application that satisfy the set boundary conditions are intrusive (i.e., they require in-line installation as opposed to on-line).

Part 1

Survey of Meters for UF_6 Gas Flow Monitoring

O. J. Baker
W. A. Hewgley
Instrument and Control Engineering
Engineering Division

This study assesses the applicability, availability, and effectiveness of gas flow meters as a means for verifying the mass flows of pure UF_6 streams diluted with a carrier gas. The initial survey identified the orifice, pitot tube, thermal, vortex shedding, and vortex precession (swirl) meters as promising for the intended use. Subsequent assessments of these flow meters revealed that two — the orifice meter and the pitot tube meter — are the best choices for the proposed applications: the first is recommended for low velocity gas, small diameter piping; the latter, for high velocity gas, large diameter piping. Final selection of the gas flow meters should be based on test loop evaluations in which the proposed meters are subjected to gas flows, temperatures, and pressures representative of those expected in service.

I. INTRODUCTION

A. OBJECTIVE

The objective of this study was to assess the applicability, availability and effectiveness of gas flow meters as a means for verifying the mass flows of pure UF₆ streams and UF₆ streams diluted with a H₂ carrier gas. The requirements for the flow meters are provided in Table 1.

TABLE 1. Requirements for Proposed Applications

	Pure UF ₆ gas stream	95% H ₂ and 5% UF ₆ gas stream	99.7% H ₂ and 0.3% UF ₆ gas stream
1. Pressure range, atmospheres	0.004 - 0.20	3-6	3-6
2. Temperature range, degrees F	80-120	80-120	80-120
3. Gas stream velocities, ft/s (T = 105 degrees F)	56.1	239.5	604.7
4. Gas stream mass flow rates lb/h (Note 1)	18,572	1,048,420	413,971
5. Process pipe size, in.	up to 10	up to 28	up to 28

NOTE 1: Assumes 10" diameter pipe for the pure UF₆ gas stream and a pressure of 150 Torr. For the UF₆-H₂ gas streams, assumes 28" diameter pipe and a pressure of 6 atmospheres.

B. SCOPE

To meet the aforementioned objective, the following activities were performed:

1. Available gas mass flow monitoring equipment was identified.
2. The capabilities and costs associated with each system were characterized.
3. The strengths and weaknesses of each system for the proposed applications were assessed.
4. The two most promising systems were identified and further assessments made.
5. Findings were reviewed internally and incorporated in this final report.

II. APPROACH

The approach taken to identify and evaluate promising UF₆ gas flow meters consisted of (1) reviewing the literature, and (2) reviewing the experience gained over the years by Martin Marietta Energy Systems, Inc. personnel who were engaged in applying these meters in various uranium enrichment facilities. A brief discussion of this effort is provided in the following paragraphs.

A. LITERATURE REVIEW

The primary information sources reviewed were instrument engineering handbooks, technical articles and papers, instrument data sheets, and manufacturers'/vendors' data. Where additional information was required in particular areas, phone conversations were held with knowledgeable people. Results of the literature review were then incorporated in the body of this report.

B. OPERATING EXPERIENCE

As a long-time operator of major uranium enrichment facilities for the Department of Energy, Martin Marietta Energy Systems, Inc. has acquired considerable experience in applying various sizes and types of UF₆ gas flow meters. Applications have ranged from monitoring flows inside test loop piping to monitoring flows inside large gaseous diffusion and gas centrifuge cascade piping. Interviews were held with instrument engineers and operators who had direct experience in applying UF₆ gas flow meters; the resulting information gleaned was then assessed and incorporated in the body section of this report.

To assure a balanced assessment of study results, independent technical staff members of Martin Marietta Energy Systems, Inc., reviewed the report and suggested changes where deemed appropriate.

III. RESULTS

A. MASS FLOW METERS

1. General Description

Recently, a family of mass flow meters has been developed which enable direct measurement of the mass of the process stream. Such a method of determining mass flow is more accurate and reliable than the more common method of extrapolating mass flow measurements from volumetric flow. This is true because the latter method must take into consideration pressure, temperature and the specific gravity of the process stream. Unfortunately, available mass flow meters are designed for relatively small flow rates, which limitation prevents them from being considered for this study.

2. Applications

All mass flow meters operate from the principle of Newton's second law of angular motion. Such flow meters require first imparting of angular momentum to the fluid stream and then measuring the resulting torque produced by the angular momentum and the stream's angular velocity.

Seven types of mass flow meters have been identified by Lipták and Venczel 1/ as being available for low process stream flow rate applications. They are:

- (a) Impeller-Turbine
- (b) Constant-Torque-Hysteresis Clutch
- (c) Twin-Turbine
- (d) Coriolis
- (e) Gyroscopic
- (f) Coriolis/Gyroscopic
- (g) Linear

Pending development of larger capacity mass flow meters, applications for monitoring relatively high flow rate process streams must rely primarily on the volumetric method of measurement.

3. Conclusions and Recommendations

a. Conclusions

Although providing the potential for increased accuracy and reliability, mass flow meters as currently developed are inadequate in flow rate capacity to be of interest for the proposed applications. Therefore, no detailed evaluation of this type meter was made in this study.

b. Recommendations

Users should keep abreast of developments in the mass flow meter area and at such time as large flow rate meters appear practical, should reconsider them for possible use as UF6 mass flow meters.

B. ORIFICE METERS

1. General

Orifice meters fall under the broad classification of head-type meters, which includes in addition to orifice meters, venturi tubes, weirs, flumes, pitot tubes and flow nozzles. Orifice meters and pitot tubes are the most promising of these meters for the proposed UF6 gas flow applications, mainly because of

their relatively low cost. However, venturi tubes and flow nozzles are alternatives for UF₆ gas flow applications which should be considered if the orifice meters or pitot tubes present a problem in a specific application. Weirs and flumes are not practical for UF₆ gas flow applications.

The first applications of orifice meters are believed to date back to the Romans who used orifices to meter water distributed to homes. Application of orifice plates for gas flow measurements was started by Weymouth in the United States in 1903.^{1/} Today, orifice meters are extensively applied in a wide range of applications, which reflects the many advantages (simple, reliable, relatively inexpensive and high sustained accuracy) this type of flow meter offers the user.

2. Theory and Description

The principle from which orifice plate operation is derived is Bernoulli's Theorem. This theorem, an expression for the conservation of energy in fluid flow, states that the sum of the ratio of the pressure to the mass density, the product of the gravitational constant and the vertical height, and the square of the velocity divided by 2, are constant. This principle is applied in flow measurement by deliberately changing the velocity of the flow stream by passing it through a reduced cross-sectional area. An example of this is the orifice plate which, when installed inside a pipe in which fluid is flowing, will alter the flow of the fluid in a controlled way. Measurements of pressure on each side of the orifice plate together with other information such as the orifice geometry and density of the fluid, make it possible to determine the volume flow rate and the mass flow rate of the fluid. The basic equations are:

$$V = k \sqrt{\frac{h}{\rho}}$$

$$Q = kA \sqrt{\frac{h}{\rho}}$$

$$W = kA \sqrt{h\rho}$$

where V is fluid velocity, Q is the volume flow rate, W is the mass flow rate, A is the cross-sectional area of the pipe, h is the differential pressure between the points of measurement, ρ is the density of the fluid, and k is a constant that includes the ratio of the cross-sectional area of the pipe to the cross-sectional area of the restriction, units of measurement, correction factors, etc.

The standard orifice plate is a circular metal disc, usually ranging from 1/8 to 1/2 inch thick, with an orifice in the center and a protruding tab. Figure 1 is an illustration of a concentric orifice plate. When used as a restriction in the pipe, the

Figure 1 Concentric Orifice Plate (Reprinted with permission of Chilton Book Company - Reference 1)

orifice plate changes the flow pattern of the fluid stream, as shown in Figure 2. The resulting pressure profile of the fluid is shown in Figure 3. The fluid increases in velocity and decreases in pressure after passing through the orifice. The maximum velocity and minimum pressure of the fluid occurs at a point called the vena contracta. This location typically will be from 0.35 to 0.85 pipe diameters downstream from the orifice plate.

The orifice plate is machined to exacting dimensions and usually is mounted between a pair of flanges. Taps are drilled in the flanges to provide a means for measuring pressure differential. Additional measurements of temperature and pressure upstream of the orifice are necessary in order to determine the density of the fluid. The above outputs are connected to suitable instrumentation, which in turn provides output mass flow rate readings for the gas stream.

For more details on orifice meters, refer to References 1 and 2.

3. UF6 Applications at Martin Marietta Energy Systems, Inc.

a. Gas Centrifuge Plant Control Valve

Recently, Martin Marietta Energy Systems, Inc. designed a key control valve used in the process stream of the gas centrifuge cascade so that it would serve both as an orifice type UF6 mass flow meter and a back pressure control valve. By combining these two functions, significant cost savings were achieved. The design was accomplished by incorporating a linear variable differential transformer (LVDT) inside the valve. The LVDT provides a linear output signal that is proportional to the valve's bellows head movement. The bellows head movement, in turn, is proportional to the valve seat port area. Through this arrangement, the UF6 gas flow rate through the valve is directly proportional to the LVDT output voltage. This combination orifice meter/control valve proved to be a reliable and accurate UF6 flow meter during extensive use in the gas centrifuge demonstration plant.

In two related applications, the test facility used to calibrate and certify the above mentioned UF6 control valve/flow meter utilized a calibrated flow orifice and a Hastings Raydist mass flow meter to measure test loop gas flow rates. These flow meters performed satisfactorily during numerous tests in which either pure air or pure UF6 was used as a flow stream. Also, a Hastings flow meter and a calibrated flow orifice were successfully applied in a gas centrifuge UF6 test setup referred to as the Header Conditioning Feed Unit. Since UF6 flow rates in these tests were low (about 5 lbs/hour), this application is only mentioned to illustrate the wide range of flow rates that have been measured with UF6 gas flow meters.

Figure 2 Flow Pattern with Orifice Plate (Reprinted with permission of Chilton Book Company-Reference 1)

Figure 3 Pressure Profile with Orifice Plate (Reprinted with permission of Chilton Book Company - Reference 1)

4. Features, Cost and Availability

Table 2 summarizes features, pricing and availability data on the orifice meter method of measuring mass flow rates.

C. PITOT TUBE METERS

1. General

Like orifice meters, pitot tube meters fall under the classification of head-type meters. The pitot tube was conceived in 1732 by Henri de Pitot, a French physicist, and is used as a means of measuring fluid velocity. Fluid velocity is determined by measuring the differential pressure between the tip (dynamic) and side (static) openings of the pitot tube. Although pitot tubes are relatively cheap and can be applied successfully in high flow rate installations, their low accuracy and tendency to plug up limit somewhat their use.

2. Theory and Description

The theory of pitot tubes is explained in detail by Lipták and Venczel ^{1/} and no attempt will be made here to repeat this derivation. It is sufficient to discuss their final equation for a compressible perfect gas to illustrate the principle from which pitot tubes operate from. This equation is:

$$P_t - P = P_v = \frac{(\gamma-1)}{\gamma} \frac{\rho(V_p^2)}{2gc}$$

where P_t is the total pressure that can be sensed by a fixed probe providing the fluid stagnates at the sensing point in an isentropic manner, P is the static pressure of the fluid whether in motion or at rest, P_v is the dynamic pressure equivalent to the kinetic energy of the fluid considered as a continuum, γ is the ratio of specific heats, ρ is the fluid density, V_p is the approach velocity at the probe location, and gc is a constant. The equation assumes a perfect gas for which $\frac{P}{\rho\gamma}$ remains constant during an isentropic change.

To explain this equation in terms of application of a pitot tube in a gas stream, the pitot tube will measure P_t and P . The difference (differential) in these two measurements provides P_v or the dynamic pressure of the fluid. Knowledge of the fluid's specific heat and density then make it possible to determine V_p , the fluid's approach velocity.

TABLE 2 - Orifice Meter DataA. Features

1. Pressure Range, Atmospheres	Only limited by readout devices.
2. Temperature Range, Degrees F	Function of associated readout device only.
3. Gas Stream Mass Flow Rates, Lbs/Hour	Limited only by pipe size.
4. Flow Rangeability	3 to 1
5. Accuracy	+0.25 to +2% full scale (Does not consider errors in bore diameter calculation or inaccuracies of readout device.)
6. Process Pipe Size, Inches	No limit
7. Process Connection	Orifice plate inside process pipe; pressure taps drilled in flanges located on each side of orifice; separate pressure taps and temperature connectors for density estimation.
8. Body Material	Stainless steel, Monel, or other metals
9. Signal Output and Indicator	Analog (square root), ΔP transmitter
10. Limitations	Orifice causes high unrecoverable pressure drop. For mass flow measurements, must also provide upstream pressure and temperature measurement capability.
11. Advantages	Simple, reliable, relatively inexpensive and provides high sustained accuracy.

B. Relative Purchase Price

Low

C. Availability

Readily available from numerous suppliers.

In practice, P_t and P are measured by mounting a pitot tube inside the pipe so that the flow stream impacts the tube's opening as shown in Figure 4. The pitot tube external connections are connected to appropriate instrumentation, which provide measurements of pressure and differential pressure. These data combined with other data that are derived from measurements of fluid temperature enable volume and mass flow rate values to be determined.

Additional information on pitot tubes is provided in References 1, 2 and 4.

3. UF6 Applications at Martin Marietta Energy Systems, Inc.

a. Diffusion Plant Interstage Flow Meter

The Martin Marietta Energy Systems, Inc., Portsmouth Gaseous Diffusion Plant required a means for measuring UF6 process stream interstage flows with an accuracy of $\pm 5\%$. The flow meters selected had to exhibit minimum pressure loss and be suitable for use in several different piping configurations, none of which provided an ideal straight pipe approach for the UF6 gas to be measured. The pitot tube was thought to meet the low pressure loss requirement but not the accuracy requirement unless the low pressure differential measured in this particular application was amplified. The pitot-venturi flow meter, on the other hand, would provide both the low pressure loss characteristic and the high differential pressure output suitable to give a $\pm 5\%$ accuracy. Pitot-venturi flow meters manufactured by the Taylor Instrument Company were subsequently procured for evaluation.

The Taylor pitot-venturi flow meters were tested in several different process stream configurations over the range of process temperatures and pressures anticipated in service. The UF6 mass flow rates used during the tests ranged from 1500 lbs/hour to 55,000 lbs/hour. Results revealed that the pitot-venturi flow meters met the accuracy and pressure loss requirements established for them. Subsequent application of these flow meters in the actual cascade was deemed satisfactory.

4. Features, Cost and Availability

Pertinent data relating to features, pricing and availability of pitot tube meters are summarized in Table 3.

Figure 4 Schematic of a Pitot Tube Installation (Reprinted with permission of Chilton Book Company - Reference 1)

TABLE 3 - Pitot Tube Meter DataA. Features

1. Pressure Range, Atmospheres	Up to .08
2. Temperature Range, Degrees F	Limited only by sensor elements
3. Gas Stream Mass Flow Rates, Lbs/Hour	Limited only by pipe size
4. Flow Rangeability	3 to 1
5. Accuracy	+0.5 to 5% full scale
6. Process Pipe Size, Inches	No limit
7. Process Connection	Through-wall connections from pitot tube and pressure and temperature sensors to external equipment.
8. Body Material	Stainless steel and other metals.
9. Signal Output and Indicator	Analog signals and processing equipment.
10. Limitations	Pitot tubes have low accuracies and tend to foul up under extended use. For mass flow measurement, must also provide upstream pressure and temperature capability.
11. Advantages	Relatively inexpensive and can be applied in high mass flow rate measurement applications.

B. Relative Purchase Price

Low

C. Availability

Readily available from numerous suppliers.

D. THERMAL METERS

1. General

Thermal flow meters consist of two types: (1) Those that measure the rise in temperature of the fluid after a known quantity of heat has been added to it, and (2) those that measure the effect of the fluid on a hot body. Although this type of flow meter is not classified by Lipták and Venczel ^{1/} as a mass flow meter type (see Section III-A), it is in reality a mass flow meter that may be used for both gas and liquid service. The authors have decided to leave thermal meters outside of the mass flow meter category, hence this meter is treated in this section of the report.

2. Theory and Description

The first of the two types of thermal flow meters referred to above is based upon the following well known heat transfer equation:

$$W = \frac{Q}{C_p(T_2 - T_1)}$$

where W is the mass flow rate of fluid (lbm/hour), Q is the heat transferred (Btu/hour), C_p is the specific heat of the fluid (Btu/lbm degrees F), T₂ is the temperature (degrees F) of the fluid after heat has been transferred to it, and T₁ is the temperature (degrees F) of the fluid before heat is transferred to it. A thermal flow meter works like this: Heat is added to the fluid through use of an electric immersion heater. The input power to this heater is Q, which is measured by a wattmeter. Thermocouples or other temperature sensors strategically located inside the fluid provide measurements of T₁ and T₂. Therefore, using the measured values for Q, T₁ and T₂ and substituting in the value of specific heat (known because the fluid is known), the mass flow rate of the fluid, W, can be calculated. A simple illustration of this scheme is shown in Figure 5.

A major disadvantage of this type of thermal flow meter is that the heater element and temperature sensors inside the pipe are subject to corrosion and erosion. Attempts have been made to locate the heater and temperature sensors outside the pipe, but the inherent problems with these devices suggest that they should not be considered by users in the proposed applications.

The second of the two types of thermal flow meters referred to above are often called hot wire probes. Two thermocouples located inside the pipe and connected in series to form a thermopile are heated by passing an alternating current through it. A third thermocouple, also located inside the pipe, is connected in the

Figure 5 Heat Transfer Flow Meter (Reprinted with permission of Chilton Book Company - Reference 1)

direct current output circuit of the thermopile, so that it is not heated by the alternating current. The fluid passing through the pipe cools the heated thermopile by convection. Since the alternating current power to the thermopile is held constant, the thermopile will reach an equilibrium temperature and thus produce an emf that is a function of the temperature of the fluid, the velocity of the fluid, and the fluid's density, specific heat and thermal conductivity. The third temperature sensor, which is not heated, detects the ambient temperature of the fluid and produces an emf that is proportional to the fluid temperature. This emf cancels the effect of the ambient fluid temperature on the output signals of the heated thermopile. Figure 6 shows a schematic for this type thermal flow meter.

For more details on the thermal flow meter, refer to References 1 and 3.

3. UF6 Applications at Martin Marietta Energy Systems, Inc.

Martin Marietta Energy Systems, Inc., has evaluated and used numerous thermal type flow meters over the years. Unfortunately, this type UF6 flow meter seems to only be useful in applications where low gas flow rate and short term operational conditions exist. Where attempts have been made to operate these type meters over long periods of time, deposit and flake buildup on the sensors have caused meter accuracy reductions.

4. Features, Cost and Availability

Table 4 summarizes information relating to the features, pricing and availability of thermal flow meters.

E. VORTEX SHEDDING METERS

1. General

Vortex shedding meters operate on the principle that as fluid flowing in a pipe hits a bluff body, the fluid rolls into vortices behind the body. These vortices are shed from each side of the body at a frequency directly proportional to the fluid velocity. The detection of this frequency through use of sensors forms the basis for determining the flow rate of the fluid. Vortex shedding meters are simple, have a relatively low pressure drop and maintain their calibrations adequately over extended periods. However, their use is limited to a pipe size of about eight inches.

2. Theory and Description

Referring to Figure 7, when the fluid flowing in the pipe hits the bluff body, the fluid is separated into vortices behind the body. The vortices are shed first from one side of the body and then the other. As this takes place, there is a fluid velocity and

Figure 6 Hot Wire Flow Sensing Probe (Reprinted with permission of Chilton Book Company - Reference 1)

TABLE 4 - Thermal Flow Meter DataA. Features

1. Pressure Range, Atmospheres	Up to 82
2. Temperature Range, Degrees F	Up to 450
3. Gas Stream Mass Flow Rates, Lbs/Hour	Up to 40,000
4. Flow Rangeability	Not known
5. Accuracy	<u>+2%</u> full scale
6. Process Pipe Size, Inches	Normally applied in small diameter pipes.
7. Process Connection	Through-wall connections from immersion heater and temperature sensors to the external equipment.
8. Body Material	Stainless steel, glass, Teflon, etc.
9. Signal Output and Indicator	Analog signals.
10. Limitations	Subject to corrosion and erosion of heater and sensors located inside the pipe; limited to relatively small mass flow rates.
11. Advantages	Relatively good accuracy and repeatability characteristics
<u>B. Relative Purchase Price</u>	Medium
<u>C. Availability</u>	Readily available from numerous suppliers.

Figure 7 Vortex Shedding from a Bluff Body (Reprinted with permission of Chilton Book Company - Reference 1)

pressure distribution change adjacent to the bluff body. This change occurs at the same frequency as the vortex shedding frequency. The detection and electronic processing of this frequency make it possible to measure the velocity of the fluid flowing in the pipe.

Lipták and Venczel ^{1/} state that various detectors can be used to measure one of the following:

- (1) The oscillating flow produced at the face of the bluff body.
- (2) The oscillating differential pressure produced across the sides of the bluff body.
- (3) The flow produced through a hole drilled through the bluff body.
- (4) The oscillating flow or pressure produced at the backside of the bluff body.
- (5) The presence of free vortices produced downstream from the bluff body.

Regardless of which of the above is used, the fundamental meter output is a frequency signal which is fed to appropriate electronic equipment for processing, etc. The vortex shedding meter provides a linear digital (or analog) output signal without use of transmitters or converters, thus simplifying the equipment installation. In order to provide readouts in terms of mass flow rates, pressure and temperature measurements of the process fluid must also be obtained.

For more information on vortex shedding meters, refer to Reference 1.

3. UF6 Applications at Martin Marietta Energy Systems, Inc.

a. Vortex Shedding Flow Meters for Use in the WMC0, Fernald, Ohio, UF6 to UF4 Reduction Facility

- 1) Martin Marietta Energy Systems, Inc., evaluated two 1-inch Model Y-102-M-NNN-B-1-S-3S3-C Yewflo vortex shedding flow meters for the Westinghouse Company, Fernald, Ohio, plant. The objective of the tests was to determine if this flow meter was suitable for measuring UF6 gas flows in the reducers of the UF6 to UF4 Reduction Facility under the following conditions:

Pressure	-	10 to 15 psig
Temperature	-	200 to 230 degrees F
Flow Rate	-	800 to 1200 lbs/hour UF6

The flow meters were subjected to a series of tests in the ORGDP Cascade Pilot Plant Test Loop during which measurements of temperature, pressure and flow were taken and recorded, using a computer data acquisition system. Results showed that the 1-inch Yewflo vortex shedding meter was reliable, accurate, and a good choice for use in the WMC0 UF6 to UF4 Reduction Facility.

4. Features, Cost and Availability

Information relating to the features, pricing and availability of vortex shedding meters is provided in Table 5.

F. VORTEX PRECESSION (SWIRL) METERS

1. General

In the vortex precession meter, the incident fluid stream is first given a swirling motion, then is accelerated, and finally is changed from a straight path to a helical path. The resulting spiraling vortex is known as vortex precession. The frequency of precession is proportional to the velocity of the fluid stream, which forms the basis for this type meter.

2. Theory and Description

As shown in Figure 8, the fluid stream enters the vortex precession meter through swirl guide vanes. The resulting swirl enters a reduced bore section of the meter, thereby causing the fluid to accelerate. The swirling fluid then enters an enlarged bore section of the meter housing which then causes the fluid swirl to change from a straight to a helical path. The fluid velocity in the vortex is higher than that of the rest of the fluid. As each vortex passes the sensor, there is a change in the local fluid velocity. The frequency at which this velocity changes is proportional to volumetric flow rate. This frequency, in turn, can be detected by either thermistor or piezoelectric sensors.

Assuming the use of a thermistor as a sensor, the following action occurs. The thermistor is heated by a constant electric current. The amount of heat removed by the passing fluid is dependent upon the fluid velocity. As each "high velocity" vortex passes the sensor, its resistance changes. Since a constant current is applied to the thermistor sensor, these resistance changes are detected as voltage changes. The resulting voltage wave is amplified and filtered, producing a square wave output that is linear with fluid flow rate.

Sizing of a vortex precession meter must be based upon the various operating conditions. Also, pressure and temperature measurements must be provided in order to give readout in mass flow rates.

TABLE 5' - Vortex Shedding Meter DataA. Features

1. Pressure Range, Atmospheres	Up to 102
2. Temperature Range, Degrees F	-40 to +300
3. Gas Stream Mass Flow Rates, Lbs/Hour	Limited by expandability
4. Flow Rangeability	Varies with the fluid viscosity, density and vapor pressure, and the application's flow rate and line pressure.
5. Accuracy	<u>+0.75%</u> of Rate
6. Process Pipe Size, Inches	8
7. Process Connection	Through-wall electrical and pressure connections
8. Body Material	Stainless steel, carbon steel and other metals.
9. Signal Output and Indicator	Linear digital (or analog) signal fed into digital electronic units.
10. Limitations	① Limited to pipe sizes ranging from 1 to 8 inches; flow range for this meter depends upon the operating fluid viscosity, density and vapor pressure, and the application's flow rate and line pressure; will not function near or greater than sonic velocity.
11. Advantages	Simple, reliable, has relatively low pressure drop; maintains its calibration over extended periods, and low installed cost.

B. Relative Purchase Price

Medium

C. Availability

Readily available from various suppliers.

Figure 8 Construction of a Typical Vortex Precession (Swirl) Meter (Reprinted with permission of Chilton Book Company - Reference 1)

Additional details on vortex precession meters are provided in References 1 and 3.

3. UF6 Applications at Martin Marietta Energy Systems, Inc.

a. Feed Rate Testing of 10- and 14-Ton UF6 Cylinders

The objective of these tests, which were conducted by Martin Marietta Energy Systems, Inc. at the Paducah Gaseous Diffusion Plant for the Gas Centrifuge Enrichment Plant, was to determine the maximum sustainable discharge rates for both 10-ton and 14-ton UF6 cylinders under conditions anticipated for the future gas centrifuge UF6 feed system. To determine the UF6 gas mass flow rates, a 3-inch Fischer-Porter Swirlmeter, Model 10S2000, was installed in the cylinder output line. The Swirlmeter output readings, together with the separate internal pipeline temperature and pressure readings, were fed to a computer which calculated the UF6 mass flow rates. Flow rates obtained during the tests were in the range of 0 to 4,000 lbs/hour, and no problems with the Swirlmeter were noted during the test series.

4. Features, Cost and Availability

Table 6 provides information relating to the features, pricing and availability of vortex precession meters.

G. SELECTION OF THE TWO MOST PROMISING METERS

1. Criteria for Selection

The following UF6 gas stream compositions and operating parameters were considered in this survey:

Gas Composition	-	1. Pure UF6 gas stream
		2. Gas stream with mixture of 95% H2 and 5% UF6
		3. Gas stream with mixture of 99.7% H2 and 0.3% UF6
Pressure	-	1. Pure UF6 gas stream (3-150 Torr)
		2. UF6-H2 gas streams (3-6 Atmospheres)
Temperature	-	80 degrees - 120 degrees F

These data were expanded to include gas flow velocities and mass flow rates and a tabulation then made to compare the requirements with the features of the five types of flow meters initially selected for evaluation. The results are provided in Table 7.

TABLE 6 - Vortex Precession (Swirl) Meter DataA. Features

1. Pressure Range, Atmospheres	Up to 102
2. Temperature Range, Degrees F.	Up to 250
3. Gas Stream Mass Flow Rate, Lbs/Hour	Depends upon the type sensor and the gas density
4. Flow Rangeability	10 to 1 (Can be obtained providing the flow does not exceed sonic velocity.)
5. Accuracy	<u>+1.25%</u> of Rate
6. Process Pipe Size, Inches	6
7. Process Connection	Pressure taps and sensor lead connections brought through piping wall
8. Body Material	Stainless steel
9. Signal Output and Indicator	Linear digital signal
10. Limitations	Limited to pipe size of 6 inches; requires calibration; has a high pressure drop.
11. Advantages	Simple, reliable, good flow range capability, and long term stable calibration.

B. Relative Purchase Price

Medium

C. Availability

Limited number of suppliers.

Table 7. UF_6 gas flow meters: comparison between user requirements and prospective meters

	User Requirements			Prospective Meters				
	Pure UF_6 gas stream	95% H_2 and 5% UF_6 gas stream	99.7% H_2 and 0.3% UF_6 gas stream	Orifice meter	Pitot tube meter	Thermal meter	Vortex shedding meter	Vortex precession (swirl) meter
1. Pressure range, atmospheres	0.004 - 0.20	3-6	3-6	Only limited by readout devices	Up to 408	Up to 82	Up to 102	Up to 102
2. Temperature range, °F	80-170	80-120	80-120	Function of associated readout device only	Limited only by sensor elements	Up to 450	-40 to +300	Up to 250
3a. Gas stream velocities, meters/s ($T = 105^\circ\text{F}$)	17.1	73.0	184.3	Limited only by pipe size	Limited only by pipe size	----	Limited by expandability	Depends on the type sensor and the gas density
ft/s ($T = 105^\circ\text{F}$)	56.1	239.5	604.7	----	----	----	----	----
3b. Gas stream mass flow rates kg/s (Note 1)	2.34	132.1	52.16	Limited only by pipe size	Limited only by pipe size	5.0	----	----
lb/h (Note 1)	18,572	1,048,420	413,971	----	----	Up to 40,000	----	----
4. Flow rangeability	Not specified	Not specified	Not specified	3 to 1	3 to 1	Not known	Varies with the fluid velocity, density, and vapor pressure and the applications flow rate and line pressure.	10 to 1 (if flow is less than sonic velocity)
5. Accuracy	Not specified	Not specified	Not specified	± 0.25 to $\pm 2\%$ full scale (does not consider errors in bore diameter calculation or inaccuracies of readout device)	± 0.5 to 5% full scale	$\pm 2\%$ full scale	$\pm 0.75\%$ of rate	$\pm 1.25\%$ of rate
6. Process pipe size, in.	Up to 10	Up to 28	Up to 28	No limit	No limit	Normally used 8 in small- diameter pipes		6
7. Process connection	Prefer externally mounted hardware	Prefer externally mounted hardware	Prefer externally mounted hardware	Orifice plate inside process pipe; pressure taps drilled in flanges located on each side of orifice; separate pressure taps and temperature connectors for density estimation	Through-wall connections from Pitot tube and pressure and temperature sensors to external equipment	Through-wall connections from immersion heater and temperature sensors to the external equipment	Through-wall electrical and pressure connections	Pressure taps and sensor lead connections brought through piping wall

Table 7. UF_6 gas flow meters: comparison between user requirements and prospective meters (continued)

	User Requirements			Prospective Meters				
	Pure UF_6 gas stream	95% H_2 and 5% UF_6 gas stream	99.7% H_2 and 0.3% UF_6 gas stream	Orifice meter	Pitot tube meter	Thermal meter	Vortex shedding meter	Vortex precession (swirl) meter
8. Body material	Not specified	Not specified	Not specified	Stainless steel, Monel, or other metals	Stainless steel and other metals	Stainless steel, glass, Teflon, etc.	Stainless steel, carbon steel, and other metals	Stainless steel
9. Signal output and indicator	Not specified	Not specified	Not specified	Analog (square root), ΔP transmitter	Analog signals and processing equipment	Analog signals	Linear digital (or analog) signal fed into digital electronic units	Linear digital
10. Limitations	Not specified	Not specified	Not specified	Orifice causes high unrecoverable pressure drop. For mass flow measurements, must also provide upstream pressure and temperature measurement capability	Pitot tubes have low accuracies and tend to foul up under extended use. For mass flow measure- ments, must also provide upstream pressure and temperature measurement capability	Subject to corrosion and erosion of heater and sensors located inside the pipe; limited to relatively small mass flow rates	Limited to pipe sizes ranging from 1 in. to 8 in.; flow range for this meter depends upon the operating fluid velocity, density, and vapor pressure, and the applications flow rate and line pressure; will not function near or greater than sonic velocity	Limited to pipe size of 6 in.; requires calibration; has a high pressure drop
11. Advantages	Not specified	Not specified	Not specified	Simple, reliable, relatively inexpensive, and provides high sustained accuracy	Relatively inexpensive and can be applied in high mass flow rate measurement applications	Relatively good accuracy and repeat- ability characteris- tics	Simple; reliable; has relatively low pressure drop; maintains its calibration over extended periods; and medium installed cost	Simple, reliable, good flow range capability, and long-term stable calibration
12. Relative purchase price	Not specified	Not specified	Not specified	Low	Low	Medium	Medium	Medium
13. Availability	Not specified	Not specified	Not specified	Readily available from numerous suppliers	Readily available from numerous suppliers	Readily available from numerous suppliers	Readily available from numerous suppliers	Limited number of suppliers

Note 1: Assumes 10-in.-diam pipe for the pure UF_6 gas stream and a pressure of 150 Torr. For the UF_6 - H_2 streams, assumes 28-in.-diam pipe and a pressure of 6 atmospheres.

As noted in Table 7, there are several gaps in the requirements; this is to be expected at this early stage of defining users needs. These data gaps will be filled as further discussions between users and flow meter designers are completed. The checklist in Appendix A, which was taken from Reference 2, lists the key questions which the user and flow meter designer must ultimately answer before selecting a flow meter.

An assessment of the data in Table 7, together with other information, suggests that the most promising flow meters for the proposed applications are (1) the orifice meter and (2) the pitot tube meter. These selections are discussed in the following sections.

2. Selection 1 - Orifice Meter

The best selection for the proposed applications is the orifice meter. This meter is simple, reliable, relatively inexpensive and provides a high sustained accuracy. Its main limitations are (1) a high unrecoverable pressure drop and (2) a flow rangeability of 3 to 1. This suggests that this type meter should be utilized in applications where these two limitations are not overriding. It is suggested that the orifice meter be considered for low velocity gas stream applications typical of those used in product and withdrawal lines of continuous UF6 and UF6/H2 gas process cascades. The pipe diameters for this application might range from about 1 inch to about 8 inches.

Figure 9 is a diagram showing how the orifice meter might be applied in a low velocity UF6 or UF6/H2 gas process stream. The corresponding instrumentation application diagram is shown in Figure 10. As shown in Figure 9, the pressure differential across the orifice plate, which is located inside the pipe, is measured and the resulting signal transmitted to a flow computer. Separate temperature and pressure measurements upstream from the orifice plate are also made and fed to the computer to enable the gas density effects to be determined. The computer is programmed to calculate the mass flow rate, using internal stored data (such as on pipe geometry, gas stream composition, and relationships between gas density and temperature and pressure) and measurements taken from the process stream.

3. Selection 2 - Pitot Tube Meter

The next best selection is the pitot tube meter because (1) it is relatively inexpensive and (2) it can be applied in high velocity gas streams without incurring excessive pressure drops. The limitations of the pitot tube meter are (1) relatively low accuracies, (2) their tendency to foul up under extended use and (3) a flow rangeability of 3 to 1. The above advantages and limitations suggest that pitot tube meters

Figure 9 Orifice Meter Schematic Diagram

Figure 10 Instrument Application Diagram for Orifice Meter

should be adopted for applications where high velocity gas streams exist. An example of this would be applications inside large diameter piping systems in which high velocity UF₆ and UF₆/H₂ gas streams are flowing. Pipe diameters here might be in the range of about 8-inches to about 30-inches.

Figure 11 is a diagram showing how the pitot tube flow meter might be applied in high velocity process gas streams. The applicable instrument diagram is shown in Figure 12. As noted in Figure 11, the pitot tube sensor is installed inside the process pipe and it supplies both a static, or low pressure, measurement and an impact, or high pressure, measurement to the differential pressure transmitter. The output signal from the differential pressure transmitter, in turn, is fed to the flow computer, as are the separate temperature and pressure measurements taken upstream from the pitot tube sensor. The computer calculates the mass flow rate, using data maintained in storage inside the computer (e.g. on pipe geometry, gas stream composition, and relationships between gas density and pressure and temperature) and the gas stream data taken during the measurement run.

In previous discussions, the single pitot tube was presented in the generic sense. In practice, the single pitot tube is rarely used because of its tendency to vibrate and the need to make a velocity traverse in order to obtain an accurate measurement. Instead, multiple port pitot tube assemblies such as the Annubar (manufactured by Dieterich Standard Corporation) are usually used.

4. Less Promising Flow Meters - Thermal, Vortex Shedding, and Vortex Precession

Although the thermal, vortex shedding and vortex precession meters are practical for many industrial gas flow applications, they do not appear promising for the proposed applications. The main drawbacks are their inability to be applied in large diameter pipes (say greater than 8 inches) and to operate satisfactorily at relatively high mass gas flow rates. However, it would be prudent for users to continue monitoring new developments in these categories of flow meters so that they can be reconsidered at such time as the above limitations are eliminated.

5. Plan for Evaluating the Two Most Promising Flow Meters

Prior to using the orifice meter and pitot tube meter in plant applications, an evaluation program is necessary to confirm the suitability of these meters under conditions simulating those expected in service. An outline of this evaluation program is provided below.

DWG. NO. K/G-86-2232
(U)

Figure 11 Pitot Tube Meter Schematic Diagram

DWG. NO. K/G-86-2235
(U)

Figure 12 Instrument Application Diagram for Pitot Tube Meter

- a. Review of Process Stream Design and Operational Data
 - (1) Piping design data
 - (2) Gas stream flow data
 - (3) Operational data
- b. Design of Testing Program
 - (1) Selection of test loops
 - (2) Procurement of materials and equipment
 - (3) Preparation of test procedures
- c. Conduct of Tests in Test Loops
 - (1) Install equipment and modify existing test loops
 - (2) Conduct calibration tests
 - (a) Orifice flow meter
 - (b) Pitot tube flow meter
 - (3) Conduct endurance tests to confirm long-term measurement reliability
- d. Final Report
 - (1) Test description
 - (2) Test results
 - (3) Conclusions and recommendations
 - (4) Appendices

Such an evaluation program could be performed by Martin Marietta Energy Systems, Inc., or other contractor having experience in applying these type flow meters in UF₆ or UF₆/H₂ gas streams.

IV. CONCLUSIONS AND RECOMMENDATIONS

A. CONCLUSIONS

It was concluded that there are five types of flow meters that have been used successfully in UF₆ gas flow measurement applications. Two of these--the orifice meter and the pitot tube meter--are promising for the proposed applications. The first is promising for low velocity gas, small diameter piping, applications while the second is promising for high velocity gas, large diameter piping, applications. The final flow meter selections must await more definitive evaluations, such as described in Section III-G-5 above.

B. RECOMMENDATIONS

It is recommended that users consider use of the orifice meter and the pitot tube meter in applications involved in monitoring UF₆ and UF₆/H₂ gas streams. Final selection of the flow meters should be based on results of an evaluation program (see Section III-G-5), in which the selected flow meters are subjected to the gas flows, pressures and temperatures representative of those expected in service.

ACKNOWLEDGEMENTS

The authors gratefully acknowledge the assistance provided by Mr. D. W. Swindle and Ms. J. N. Cooley, of Martin Marietta Energy Systems, Inc. (MMES), who administered this project. Also, our thanks go to Messrs. John T. Patton, John E. Cleaves, and B. W. Moran, all of MMES, who supplied engineering data on various types of UF₆ mass flow meters and served as technical reviewers.

REFERENCES

1. Béla G. Lipták and Kriszta Venczel, Instrument Engineers' Handbook, Chilton Book Company, Radnor, Pennsylvania, 1982 (Revised Edition).
2. R. W. Miller, Flow Measurement Engineering Handbook, The Foxboro Company, Foxboro, Massachusetts, 1983.
3. Howard S. Bean, ed., Fluid Meters: Their Theory and Application, Report of ASME Research Committee on Fluid Meters, The American Society of Mechanical Engineers, New York, New York, 1971 (Sixth Edition).
4. R. G. Folson, "Review of the Pitot Tube", Contributed by the Research Committee on Fluid Meters and Presented at the Diamond Jubilee Annual Meeting, Chicago, Illinois, November 13-18, 1955; Published in Transactions of the American Society of Mechanical Engineers, October 1956, Pages 1447-1460.

BIBLIOGRAPHY

1. Robert P. Benedict, *Fundamentals of Temperature, Pressure, and Flow Measurements*, John Wiley and Sons, Inc., New York, New York, 1969.
2. Anon.; Interim Supplement 19.5 on Instruments and Apparatus; Application: Part II of Fluid Meters; Report of American Society of Mechanical Engineers Research Committee on Fluid Meters; ASME; New York, New York, 1972.
3. Yao Tzu Li and Shih-Ying Lee, "A Fast-Response True-Mass-Rate Flowmeter," *American Society of Mechanical Engineers Transactions* July 1953, Pages 835-840.
4. K. O. Plache, "Coriolis/Gyroscopic Flow Meter", *Mechanical Engineering*, March 1979, Pages 36-41.
5. Dan B. LeMay, "A Practical Guide to Gas Flow Control", *Instruments and Control Systems*, September 1977, Page 73-77.
6. D. J. Lomas, "Selecting the Right Flowmeter: Part I: The Six Favorites", *Instrumentation Technology*, May 1977, Pages 55-62.
7. D. J. Lomas, "Selecting the Right Flowmeter: Part II: Comparing Candidates", *Instrumentation Technology*, June 1977, Pages 71-77.
8. G. A. Watson, "Flowmeter Types and Their Usage", *CME*, February 1978, Pages 27-32.
9. B. T. Arnberg, "Review of Critical Flowmeters for Critical Gas Flow Measurements", *Journal of Basic Engineering*, December 1962, Pages 447-457.
10. W. J. King, "Measurement of High Temperatures in High-Velocity Gas Streams", *American Society of Mechanical Engineers Transactions*, July 1943, pages 421-431.
11. Anon.: "Orifice Metering of Natural Gas: Gas Measurement Committee Report No. 3", *American Gas Association*, April 1955.

Appendix A

FLOWMETER CHECKLIST (Ref. 2)

In selecting a flow meter, the user and flow meter designer should answer the following questions:

1. What type of fluid is to be handled?
 - o Is the fluid a liquid, gas or vapor?
 - o Is the fluid clean, dirty, or slurry?
 - o Is the fluid corrosive?
2. What are the process conditions? The temperature and pressure limits?
3. What are the installation conditions?
 - o Is an open-channel or closed-conduit measurement planned?
 - o What is the line size?
 - o What is the operating pipe Reynolds number?
 - o Is adequate upstream length available?
 - o Can flow conditioners be used?
 - o Is there excessive pipe vibration?
 - o Will the flow be steady or pulsating?
 - o What are the ambient or room conditions of temperature and humidity?
4. What are the performance and general flow measurement requirements?
 - o What overall accuracy is required, and over what range?
 - o Is the flow meter normally used at a specific flow rate or over a range of flows?
 - o Is the flow meter to be used for control only, and what frequency of response is necessary (0.1 s is usually required for small-line-size control)?
 - o What is the range of flow rates to be measured, and what rates will occasionally be experienced?
5. What are the economics of installation and operation? Economic considerations include:
 - o Initial cost of the primary and secondary devices and auxiliary equipment
 - o Installation cost, including labor and piping
 - o Energy cost to operate the flow meter and pumping cost to compensate for the overall pressure loss
 - o Reliability versus maintenance cost
 - o Availability of parts and service facilities
 - o Possible uses in future applications
 - o The risks in trying a new flow meter type

Part 2

Survey of Instruments for Gas Analysis

J. N. Cooley
B. W. Moran
D. W. Swindle, Jr.
International Technology Programs

This study evaluates known instruments that may be applicable to the measurement of uranium or UF_6 concentration in a UF_6 - H_2 process stream at an aerodynamic enrichment plant. Of the six procedures evaluated, four have been used for process monitoring in a UF_6 environment: gas mass spectrometry, infrared-ultraviolet-visible spectrophotometry, gas chromatography, and acoustic gas analysis. The remaining two procedures, laser fluorimetry and atomic absorption spectroscopy, would require significant development work before they could be used for process monitoring. Infrared-ultraviolet-visible spectrophotometry is judged to be the best procedure currently available to perform the required measurement.

I. INTRODUCTION

Continued improvement in the effectiveness of nuclear safeguards procedures applied by the International Atomic Energy Agency (IAEA) to uranium enrichment facilities (i.e., verification that the facilities are being operated in accordance with operators' declarations) is a steadfast goal of the Technology Verification and Safeguards Department staff. Continuous monitoring of the UF_6 mass flow into and out from the process cascades by the IAEA is proposed to augment the current enrichment plant safeguards procedures. Studies of enrichment monitors and gas mass flow monitors have been reported previously. This study evaluates known instruments that may be applicable to the measurement of uranium or UF_6 concentration in a UF_6 - H_2 process stream at an aerodynamic enrichment plant. The information necessary to perform the evaluation was obtained through discussions with instrument manufacturer technical representatives and with technical personnel at the Oak Ridge Gaseous Diffusion Plant who have used the instruments for process or laboratory applications. Technical reports, technical textbooks, and vendor specification brochures were used to obtain general information on each procedure.

II. ANALYTICAL INSTRUMENTATION

A. LASER FLUORIMETER

1. General Description

In fluorimetry, atoms are selectively excited by a tuned wavelength of ultraviolet light, and the reemitted light of a different frequency is measured. This procedure has been in routine use in the analytical laboratories for the measurement of uranium content of solids and solutions. To the best of our knowledge, the procedure has not been applied to gases, and no development work for this application is in process. Development of an on-line laser fluorimeter for uranium solutions is in its early stages.

2. Considerations

Although laser fluorimetry may be applicable to process gas analysis, no development work has been, or is being, performed on this application. Therefore, no further evaluation of this analytical technique was made for this study.

B. ATOMIC ABSORPTION SPECTROSCOPY

1. General Description

In atomic absorption spectroscopy the sample is burned, and the absorption of specific wavelengths of light passing through the flame is measured. The procedure is based on the fact that metal atoms absorb strongly at discrete

characteristic wavelengths that coincide with the emission spectra lines of the particular metal. The procedure has been in routine use in analytical laboratories for the measurement of impurity content of different materials. In general usage, a solution of the sample would be atomized and mixed with a combustible gas; for an aerodynamic enrichment process, the combustible gas (hydrogen) is the carrier gas of the process.

2. Considerations

Cost	Approximately \$20,000
Availability	Available from several instrument manufacturers
Gas pressure range	Greater than one atmosphere and as required to maintain the design flame size.
Gas temperature	No limit
Accuracy	1 to 2%
Analysis time	Less than 5 min
Process connection	Bleeder line from process pipe to supply sample to be burned
Limitations	Procedure requires an open flame in a hydrogen process environment. Sample materials are nonrecoverable. Hood required to remove waste gases (containing uranium) from the operating environment. Atomic absorption spectrometers are currently designed only for laboratory applications and have not been evaluated for on-line process control usage. Development of the procedure would be required.
Advantages	Measurement is specific for the atom of interest. Rapid and accurate measurement method

C. ¹¹ GAS MASS SPECTROMETRY

1. General Description

In gas mass spectrometry sample molecules are ionized, accelerated, and collimated to form a beam. The beam is bent through a magnetic field. The amount of bending of the beam depends on the mass and charge on each ion. Ions of different elements and isotopes of the same element are thereby separated so that the quantity of each type of ion may be measured. On-line gas mass spectrometers have been utilized by the uranium enrichment industry for the measurement of the enrichment of process UF_6 gas and for the determination of the identity and concentration of contaminants in the UF_6 gas flow. Although these measurements

have been routinely performed separately by different instruments, both measurements are capable of being made with a high degree of accuracy by a single instrument. Measurements can be made by scanning the range of ion masses of interest or by measuring at only the peaks of those ion masses of importance.

2. Considerations

Cost	Greater than \$100,000
Availability	Finnigan Mat and other mass spectrometer manufacturers
Gas pressure range	0.05 to 200 millibar
Gas temperature	18 to 30°C
Accuracy	Better than $\pm 0.5\%$
Analysis time	Approximately 15 min per sample
Process connection	Installation according to instrument specifications on a slip stream from the process line
Limitations	High maintenance and calibration requirements (requires at least monthly realignment and calibration). High cost of instrument. Gas mass spectrometers are designed for laboratory applications
Advantages	High accuracy and precision. Measurement is specific for compounds of interest

D. INFRARED-ULTRAVIOLET-VISIBLE SPECTROPHOTOMETRY

1. General Description

In infrared-ultraviolet-visible spectrophotometry the transmission or absorbance of light of a specific wavelength through a cell is measured. The wavelength of the light is selected for the energy of vibration or rotation of a molecular bond within the compound of interest. The greater the concentration of the compound of interest, the greater the absorbance of that frequency of light. This technique is a standard analytical laboratory measurement procedure for many compounds in both liquid and gas solutions. The technique has been adapted for process measurements in situ, in slip streams, and in hot cells. Different development groups have produced variations of the technique. For in situ and hot cell applications fiber optic cables have been employed to carry source and withdrawal light to and from a measurement probe or a sample cell. Slip stream applications have been developed where the slip stream is passed through the sample cell. Infrared-ultraviolet-visible spectrophotometry has replaced gas chromatography and acoustic gas analysis for process

monitoring of UF₆ gas purity at the U.S. uranium enrichment plants.

2. Considerations

Cost	Approximately \$20,000
Availability	DuPont and other process instrument manufacturers
Gas pressure range	Atmospheric pressure is generally recommended sample cells amenable to 69 bars pressure are available
Gas temperature	Up to 538°C
Accuracy	1 to 2%
Analysis time	Less than 5 min
Process connection	Varies with application and design of instrument. In-situ and slip stream from the process line applications have been developed
Limitations	Degradation of optical windows with time
Advantages	Rapid and acceptably accurate measurement method. Measurement is specific for compounds of interest. Instruments have been proven in use as process monitors

E. GAS CHROMATOGRAPHY

1. General Description

In gas chromatography a sample gas or volatile solution is injected into a flowing carrier gas. The gas flows through a chromatographic column that has been packed with a material that will differentially detain the flow of different compounds through the column. Different compounds are thereby separated in passage through the column, and the quantity of each compound can be measured. This procedure is routinely used in analytical laboratories and has been used for process monitoring in the uranium enrichment industry. For use at an aerodynamic enrichment plant, hydrogen could be used as the gas chromatographic carrier gas.

2. Considerations

Cost	Approximately \$10,000
Availability	Available from several instrument manufacturers
Gas pressure range	Not stated
Gas temperature	Not stated
Accuracy	1 to 2%
Analysis time	Generally approximately 15 min

Process connection	Installation of sampling valves on a slip stream from the process line
Limitations	Commercial systems generally not designed for corrosive gases. This results in shortened column, detector, and sampling valve life expectancies. Carrier gas must be supplied to system
Advantages	Fast and accurate measurement method

F. ACOUSTIC GAS ANALYSIS

1. General Description

In acoustic gas analysis, sound is transmitted through a resonant cell containing the sample gas. The wavelength of the sound is dependent on the specific heat, the temperature, the pressure, and the molecular weight of the gas. The frequency of the sound is tuned such that the length of the sample cell is equal to one wavelength. As the mole fractions of the sample gas change, the resonant frequency of the cell changes proportionately. For a two-gas system the concentration (mole fraction) of each gas can be determined from a calibration curve. Acoustic gas analysis has been used for the measurement of UF_6 concentration in process streams at uranium enrichment plants.

2. Considerations

Cost	Approximately \$5000
Availability	System for UF_6 in N_2 carrier was made by Los Alamos
Gas pressure range	Not stated
Gas temperature	Not stated
Accuracy	Better than 5%
Analysis time	Less than 5 min
Process connection	Installation of resonant cell on a slip stream from the process line
Limitations	Highly dependent on gas temperature and pressure. Not specific for UF_6 . Highly dependent on the purity of the gas stream. Instrument for corrosive gases not commercially available. Development work required to optimize measurement for UF_6 - H_2 gas mixture. Resonant chamber must be kept clean for good accuracy and precision. Microphones degraded by corrosive gases
Advantages	Fast and acceptably accurate measurement method for two component gas streams

III. RECOMMENDATIONS

Based on the results of this study and the recommendations of process personnel who have used some of the instruments, ultraviolet-visible spectrophotometry is the best instrumental procedure currently available to measure UF_6 concentration in a $\text{UF}_6\text{-H}_2$ process stream. Use of sapphire optical windows on the sample cell should retard degradation of the window; use of a split-beam photometer will extend the useful life of a window once it begins to cloud. For measurements to be performed on a slip stream from the process line, the DuPont 400 Split-beam Photometric Analyzer has been recommended by process personnel because of its ruggedness and reliability (an explosion proof model is also available). For in situ applications a spectrophotometer sample cell probe has been developed at the Oak Ridge National Laboratory that can be inserted directly into the process stream. For this application a process line pipe elbow is replaced with a pipe "T." The probe is inserted into one arm of the "T" and connected to the spectrophotometer by fiber optic cables. This technology could permit the use of several probes with one spectrophotometer and would be amenable to the application of tamper resistant techniques.

Ultraviolet-visible spectrophotometry was selected over the other five techniques for the following reasons: (1) cost, (2) readily available commercial process instruments with years of application experience, (3) low maintenance and high reliability, (4) simplicity of the procedure, (5) acceptable accuracy, (6) fast analysis times, and (7) specificity for measurement of UF_6 .

DISTRIBUTION

Martin Marietta Energy Systems, Inc.

O. J. Baker
J. A. Carter
J. N. Cooley
W. A. Hewgley
J. R. Merriman
A. S. Quist (2 for OSTI)
J. E. Rushton
D. W. Swindle, Jr.
Enrichment Technology Library
Plant Records (RC)

Arms Control and Disarmament Agency

K. E. Sanders, NWS/NST

International Atomic Energy Agency

D. R. Terrey (5)
A. von Baeckmann (5)

International Safeguards Project Office

L. Green
A. Waligura (75)

U.S. Department of State

J. C. Kessler, OES/NTS
J. H. Menzel, NP
T. S. Wilkinson, OES/NTS

U.S. Department of Energy

G. A. Hammond, OSS
O. B. Johnson, OSS
W. C. Bartels, OSS