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Semiconductor Measurement Technology:

Workshop on Mass Flow Measurement and Control for the Semiconductor Industry

Robert F. Berg, David S. Green, and George E. Mattingly

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[1] At Boulder, CO 80303.

[2] Some elements at Boulder, CO.

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Chemical Science and Technology Laboratory
Process Measurements Division
National Institute of Standards and Technology
Gaithersburg, MD 20899-8360

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Executive summary

On 15-16 May 2000 at NIST, 45 scientists and engineers met to identify research and standards that will benefit users and manufacturers of mass flow controllers (MFCs) and related equipment. Most attendees represented companies closely associated with the semiconductor industry, including manufacturers of MFCs, of process tools, and of semiconductor devices. They were asked to:

1. Identify the technical problems limiting the productivity of the U.S. semiconductor manufacturing industry.
2. Prioritize the ways these problems can be resolved using NIST's assistance.

Brief presentations were given and lengthy discussions were held on the following topics:

1. Flow meter performance.
2. Standards and calibration.
3. Gas properties.
4. Alternatives to thermal mass flow controllers.

The attendees proposed 21 tasks directed at the identified problems. A subsequent vote identified the seven strongly recommended tasks listed below.

	Strongly recommended task	Institution
1	Devise a technique to verify MFC performance that is independent of the process chamber.	none specified
2	Characterize the performance of each new MFC with nitrogen as well as with its nameplate gas.	MFC manufacturers
3	Increase the range of transfer standards for conducting round-robin tests (0.01 sccm to 1000 slm).	NIST
4	Improve the primary (0.025%) and transfer (0.1%) standards for gas flow.	NIST
5	Expand and reprioritize the list of gases to be studied. Schedule and conduct property measurements.	NIST
6	Establish and maintain a public, Web-based database of gas properties.	NIST
7	Develop metrology to characterize liquid flow controllers.	NIST

These recommendations will help NIST guide its research on gas properties, flow standards, and flow measurement techniques.

Introduction

Flow measurements are central to the manufacture of semiconductor devices, especially in chemical vapor deposition and plasma etch processes. A mass flow controller's performance affects production costs in at least two ways. Irreproducibility of the MFC increases the product's defect rate, and inaccuracy of the MFC increases the time required to copy a process recipe from one process tool to another. As shown in the table below, five of the technology working groups for the 1999 International Technology Roadmap for Semiconductors raised issues related to MFC performance.

Working group	Issues related to mass flow control
Design	• Uncertainty due to manufacturing variability
Front end processes	• Control boron penetration • Achievement of lateral and depth abruptness • Etch CD control and selectivity • Sidewall etch control
Interconnect	• Combinations of materials… • Low plasma damage… • As features shrink, etching and filling high aspect ratio structures will be challenging…
Factory integration	• Control production equipment and factory processes to reduce parametric variation • Minimize waste and scrap and reduce the number of nonproduct wafers
Defect reduction	• Advanced modeling (chemistry/contamination), materials technology, software and sensors are required to provide robust, defect-free process tools …

All MFCs require both a *model* and a *calibration*. The model, which depends on the MFC's design, relates the raw output, which might be in volts, to the final output, which is in units of flow. The model cannot account for differences between MFCs caused by manufacturing variations. The calibration, which is done for every MFC, accounts for these differences.

The great variety of fluids used in semiconductor processing challenges the model. More than 30 gases are in routine use, and the continual introduction of new processes is adding liquids as well as gases to this list. Not only must the model be sufficiently general to accommodate different fluids, but also it must have accurate thermodynamic and transport property data for each fluid.

The variety of fluids challenges the calibration also. Calibrations frequently use a benign surrogate gas instead of the hazardous process gas for which the MFC is intended. With the use of a surrogate gas, an error in the MFC model or in the process gas's properties leads to an error in the calibration.

In addition to accurate property data, good models and calibrations require accurate flow standards. An MFC model can be tested only to the accuracy of the standard, and a calibration requires a flow standard whose accuracy exceeds that required of the MFC.

NIST has a long history of providing accurate, unbiased measurement standards and property data. In response to the semiconductor industry, NIST recently established programs to measure the properties of semiconductor gases and to extend gas flow standards to lower flow rates. The workshop's recommendations will help NIST guide its research on gas properties, flow standards, and flow measurement techniques.

Acknowledgements

Gil Yetter of International Sematech introduced us to engineers concerned with flow measurement in Austin, provided a large list of other contacts, and gave us constant encouragement. We thank him also for the encouragement he gave to the workshop attendees. We thank Lori Phillips Buckland of the NIST Public and Business Affairs Division for handling many essential administrative tasks. Planning for the workshop began under the direction of the recently retired chief of the Process Measurements Division, Greg Rosasco. We thank him and the present division chief, James Whetstone, for their support. Most of all, we thank the speakers, the session leaders, and the other participants, for the time, expense, and effort they generously gave.

Funding for the workshop's planning came from the Process Measurements Division (PMD) and the National Semiconductor Metrology Program (NSMP). The PMD develops and provides measurement standards and services, measurement techniques, recommended practices, sensing technology, instrumentation, and mathematical models required for analysis, control, and optimization of industrial processes. Work supporting flow measurements takes place in the PMD's Fluid Flow, Fluid Science, and Pressure & Vacuum Groups. The NSMP is a NIST-wide effort designed to meet the highest priority measurement needs of the semiconductor manufacturing industry and its supporting industries. The National Semiconductor Metrology Program supports a broad portfolio comprising 40 semiconductor metrology development projects at NIST.

Further information

National Institute of Standards and Technology	http://www.nist.gov
Process Measurements Division	http://www.cstl.nist.gov/div836/
National Semiconductor Metrology Program	http://www.eeel.nist.gov/omp

Technical contacts

Robert F. Berg
100 Bureau Drive
NIST
Gaithersburg, MD 20899-8364

robert.berg@nist.gov 301-975-2466

George E. Mattingly
100 Bureau Drive
NIST
Gaithersburg, MD 20899-8360

george.mattingly@nist.gov 301-975-5939

Workshop objective and format

The objective of this two-day workshop was to identify research and standards that will benefit users and manufacturers of mass flow controllers and related equipment The attendees were asked to:

1. Identify the technical problems limiting the productivity of the U.S. semiconductor manufacturing industry.
2. Prioritize the ways these problems can be resolved using NIST's assistance.

As shown in the table below, most of the workshop attendees represented companies closely associated with the semiconductor industry. The NIST attendees were from the Process Measurements Division or the Office of Microelectronic Programs. Appendix E lists the names and addresses of the attendees.

Type of institution	Attendees
MFC manufacturers	13
semiconductor tool manufacturers	3
MFC users in semiconductor industry	4
MFC users in other industries	2
other semiconductor flow measurement companies	8
semiconductor consortia (International Sematech)	2
independent consultants	4
NIST	7
other federal laboratories (Oak Ridge National Lab)	2
TOTAL	45

Appendix D gives the workshop schedule. On the morning of the first day, brief talks set the context for the workshop's four topics:

1. Flow meter performance.
2. Standards and calibration.
3. Gas properties.
4. Alternatives to thermal mass flow controllers.

That afternoon, the attendees divided into four groups corresponding to these topics. In each group, the attendees addressed the following questions:

- What are the present requirements and how well are they realized?
- How will the requirements change over the next ten years?
- How can national laboratories such as NIST best assist industry?

On the morning of the second day, the attendees met to discuss the results from each group. They then divided for a second, brief breakout session. That afternoon, each breakout group presented up to six proposed tasks. Proposals presented by more than one group were combined. The attendees then voted on the importance of the tasks.

Presentation abstracts

Mass flow controller performance and characterization

Gary Allen
Applied Materials

The presentation focuses on the characteristics, requirements, gases, and types of mass flow controllers utilized currently in the semiconductor industry. The importance of flow control in semiconductor equipment processes is paramount to the capability, repeatability, and manufacturing of integrated circuits. MFCs (mass flow controllers) are controlled by both analog and digital connections, some digital MFCs via a standard protocol.

The transient characteristics of gas flow into sub-atmospheric pressure chambers are important in the overall understanding of semiconductor processes. Some of these characteristics are dead time, step response time, settling (control) time, overshoot, repeatability and valve leak by. Other characteristics of accuracy, linearity, reproducibility, and zero offset are also necessary in understanding the behavior of MFCs.

In today's semiconductor industry different types of MFCs are becoming prevalent. The most common variety in the industry are thermal-based MFCs. Pressure-based MFCs are finding applications in semiconductor processes. Two types of flow sensors which are utilized in other industries are Coriolis and MEMS-based sensors. Although not fully developed, these types of sensors may find semiconductor applications in the future.

Since performance requirements had not been developed for the MFCs in the semiconductor industry, Applied Materials set forth a commodity specification to define and test to those requirements. Utilizing a rate of rise measurement system Applied was the first organization to characterize the transient behavior of MFC flow into a sub-atmospheric pressure chamber. This technique best replicates the behavior of gas entering into a wafer process chamber.

Calibration gases, referred to as surrogate gas(s) are utilized to best replicate the nameplate gas. The nameplate gas is the actual process gas which the MFC is calibrated for. The relationship of surrogate to name plate gas is paramount in understanding how to calibrate an MFC. Knowing that these relationships are non-linear, polynomial equations can be generated to best fit the function of this relationship. Additionally the relationships back to nitrogen, for all gases, are important so that testing of MFCs integrated into semiconductor equipment can be tested, prior to shipment and installation in the fab.

Performance evaluation is a necessary evil for understanding which MFCs are best for a specific semiconductor process. The testing requirements allow for ranking of suppliers, and for interactive development of MFCs with the manufacturers of these instruments. Additionally, comparative analysis, such as: the analog vs. digital; along with thermal vs. pressure based and the like can be reviewed.

The improvements in calibrations, diagnostics, and digital communication protocols have enhanced the capabilities of MFCs and allow for statistical process control methods to be applied. This should allow for process repeatability improvements, necessary in the development of semiconductor processes.

Issues which need to be overcome are: Cross-talk, pressure regulator interaction, and gas bursting; these phenomenon and behaviors are evident in the issues which semiconductor manufacturers face on a daily basis. Also the behavior of various types of MFCs need to be studied and understood. Are various types of MFCs affected by the same phenomenon? Liquid and subatmospheric delivery regimes also require testing, understanding, and evaluation in order to develop and improve semiconductor processes.

I hope that this presentation stirs interest in the terminology, issues, behavior, performance and understanding of how MFCs are manufactured and applied in today's semiconductor industry.

Gas flow standards and calibration

John D. Wright
National Institute of Standards and Technology

The Fluid Flow Group at the National Institute of Standards and Technology in Gaithersburg, Maryland offers calibration services for flow meters used in gas, water, and liquid hydrocarbon. Gas flow meters are calibrated with piston provers, bell provers, or PVTt systems for flows between 0.04 L/min and 78000 L/min. Further details of these calibration services are documented, including the principle of operation and measurement uncertainties. The definition of traceability (direct and indirect) and the importance of proficiency tests that include inter-laboratory comparisons are discussed.

Consistent ±3 sigma calibration

Bill Valentine
Kinetics Fluid Systems

MFC manufacturers have been claiming an accuracy of ±1% FS since the invention of the MFC. Several years ago, Unit Instruments set out to create a metrology system capable of delivering product such that 99.7% (±3 sigma) of all product shipped would meet an accuracy of ±1% FS. Unit Instruments' strategy consisted of a three-tier attack.

First step was to understand our capabilities in metrology. We developed a system called CrossCheck, where we compare various primary standards against each other. The primary calibration techniques utilized in our system are constant volume (bell prover), constant pressure (rate-of-rise) and gravimetric. These calibration methods do not share common modes of error. Consequently, comparing primaries against each other is the most effective method to determine if one of your calibration techniques has degraded. In addition to comparing primaries internally, we participate in round robin comparisons with NIST. Critical flow nozzles are used to check metrology between service centers and our main metrology center, and laminar flow elements are used to transfer metrology to the production floor.

Next, we set out to determine if we had a capable process. 1092 MFCs were screened over a period of 14 months. The MFCs were selected to cover a wide range of gases and ranges. Calibration was verified on two different calibration stations. The measurements statistically demonstrated our process was capable to ± three sigma limits.

Finally, we needed to show our solid metrology and production process would translate into superior on tool performance. Accuracy on nitrogen does not insure a MFC will perform on tool with the process gas. Using our onsite gravimetric facility and a gravimetric facility at Oak National Laboratory, we validated our product was linear and thus its surrogate gas calibration would not be compromised by the application of conversion factors. Several tests were performed on traditional problem gases. Results presented include Cl2, BCl3, HBr, and WF6.

The impact of various gas properties on the operation of an MFC

Dan Mudd
Mass Flow Associates of Texas

Gas properties directly influence the operation of an MFC. Specific MFC components are influenced by specific gas properties and determine if the component is operating within its linear region. Problems can arise with the use of surrogate gases as substitutes for "nasty" nameplate gases if any MFC component is operated outside its linear region when flowing either a surrogate calibration gas, the nameplate gas or a surrogate transient-response gas. An evaluation of the gas properties and foot printing of the individual components can suggest surrogate calibration practices and procedures to avoid miscalibrations seen in the industry associated with the use of surrogate gases by MFC manufacturers. A review of the key gas properties affecting an MFC and their effect on the individual MFC components is made.

NIST's program to measure the thermophysical properties of semiconductor process gases

John J. Hurly and Michael R. Moldover
Process Measurements Division, National Institute of Standards and Technology

NIST has developed a facility to safely study the toxic, corrosive, and hazardous gases that are used in the processing of semiconductors. We have completed measurements of the speed of sound in the process gases Cl_2, HBr, BCl_3, WF_6, and $(CH_2)_2O$, and in the surrogate gases SF_6, CF_4, and C_2F_6. The data span the temperature range from 200 K to 475 K and the pressure range from 25 kPa to the lesser of 1500 kPa or 80% of the sample's vapor pressure. The measurements are made along isotherms. Each isotherm is individually analyzed, and from the zero-pressure intercept the ideal-gas heat capacities $C_P(T)$ are obtained with uncertainties of $0.001\times C_P(T)$. The slope and curvature of each isotherm provides information about the gas's virial equation of state. The density virial coefficients are obtained by simultaneously fitting all the sound speed measurements to model pair and three-body intermolecular potentials. From the potentials, we can estimate the viscosity $\eta(T)$ and the thermal conductivity $\lambda(T)$. The calculations extrapolate well and extend to temperatures in excess of 800 K, well above the range of the measurements. For gases where other data exist, we find the uncertainties in the calculated properties are less than $0.001\times\rho$, $0.1\times\eta$, and $0.1\times\lambda$. We plan to measure $\eta(T)$ and $\lambda(T)$, thereby reducing their uncertainties under 1 %. We plan to measure the properties of the other gases that the semiconductor processing community identifies as having the highest priority. We have posted a trial version of a user-friendly database to disseminate the properties of process gases and carrier gases. This database can be found at **http://properties.nist.gov/SemiProp/**. Please send comments concerning this database to john.hurly@nist.gov.

Requirements for the next generation gas mass flow controllers

Kaveh Zarkar
Millipore Corporation

Continued advancement and improvements in the era of 0.25 μm and finer feature sizes in semiconductor chip manufacturing have seen the advent of newer, faster and smaller fluid handling components. Also, shifts in the industry trend from batch process to single wafers has impacted the traditional gas system components. Future semiconductor process capabilities, particularly the emerging demand for CVD and plasma etch, eventually will affect the gas delivery systems and components, specifically the mass flow controllers, which are important gas delivery components directly affecting the film integrity and quality. Industry will require new and continuously improving generations of MFCs that are superior in performance, more versatile in handling multiple gases, as well more reliable with reduced cost of ownership. To achieve the best results, gas delivery component selection is going to play a vital role in achieving the tighter and more demanding process requirements. This paper examines the specifics of each critical process as it relates to the MFC selection and functionality.

Participants in breakout sessions

Performance of flow meters

Gary Allen (leader)	Applied Materials
Jeff Anastas	MKS Instruments
Robert Berg	NIST
Daniel Coffman	Applied Materials
Joel Derk	Lucent
France D'Spain	SW Research Institute
Ed Francis	National Semiconductor
Tim Kipley	Aera Corporation
Thomas Maginnis	University of Massachusetts at Lowell
George Mattingly	NIST
Mike Munson	Dominion Semiconductor
Thomas Naughton	Dresser Equipment Group
Jeff Rose (assistant)	Motorola
Greg Secord	DH Instruments
William White	W3

Standards and calibration

Michael Bair	DH Instruments
Trace Beck	International SEMATECH
Brian Dickson	Lucas Labs
Gary Frank	Unit Instruments
Bill Johnson	Eastman Kodak
William Kosh	Dresser Equipment Group
James Long	Aera Corporation
Balarabe Mohammed	Applied Materials
Daniel Mudd	Mass Flow Associates of Texas
George Porter	Porter Instrument Co.
William Valentine (leader)	Unit Instruments
Bob Williams	Coastal Instruments
John Wright (assistant)	NIST

Gas properties

William Alvesteffer	Teledyne Hastings
Wang Chiun	Unit Instruments
James Hardy (assistant)	Oak Ridge National Laboratory
John Hurly (leader)	NIST
Jim Hylton	Bechtel Jacobs Company LLC
Max Klein	Scitefair International, Inc.
Jack Martinez	NIST
Gil Yetter	International SEMATECH

Alternatives to thermal mass flow controllers

Chris Davis	FuGasity
Joe Dille	Brooks Instrument
David Green	NIST
Bin Han	MKS Instruments
Albert Henning	Redwood Microsystems
Michael Moldover (assistant)	NIST
Maceo Ward	Millipore Corporation
Kaveh Zarkar (leader)	Millipore Corporation
Jay Zemel	Scitefair International, Inc.

Discussions in the full workshop

The next four subsections summarize the discussions held in the full workshop. The context for these discussions consisted of six presentations, whose slides are reproduced in Appendix F, and the discussions in the breakout groups. Many discussions led to the proposal of a specific task. The list of tasks in Appendix A gives a summary of these topics. This section explains why some of the tasks were proposed, and it provides brief accounts of discussions that did not lead to proposed tasks.

Performance of flow meters

The breakout group used a recent article to estimate future MFC requirements (Kaveh Zarkar, "Requirements for next-generation gas-flow components", Solid State Technology, March 2000, pp. 27-32). Table 1 of this article listed improvement factors expected for MFC requirements by 2004. The table below applies Zarkar's improvement factors to Applied Materials' present MFC requirements. Four of the requirements in 2000 are listed on slide 10 of Gary Allen's presentation (Appendix F). The other rows (turndown ratio, overshoot, and settling time) were written down after discussions in the breakout group.

Characteristic	Requirement in 2000	Requirement in 2004
accuracy	1% of full scale	0.5% of full scale
repeatability	0.25% of full scale	0.13% of full scale
valve leak	1% of full scale	0.3% of full scale
turndown ratio	20	80
overshoot	10% of set point	2% of set point
step response	1.5 s	0.3 s
settling time	2 s	1 s

The attendees generally agreed with this table. However, one representative of an MFC manufacturer asked if the desired requirements were driven more by measurement feasibility than by the needs of the manufacturing processes. Several examples of process needs were given in response, one of which was tungsten deposition requiring a 1-second step response with no overshoot. One participant made the general point that improved MFCs will enable new processes.

The attendees characterized the most important MFC requirement as *interchangeability*, which means that replacing one MFC with another MFC designed for the same flow rate has negligible effect on the manufactured product. Interchangeability comprises the requirements of accuracy, linearity, and reproducibility. Several participants emphasized that the MFCs must be interchangeable for transient as well as for steady flows. One participant pointed out that the interchangeability of MFCs from the same manufacturer is easier to achieve than interchangeability of MFCs from different manufacturers. Due to differences in design and calibration, the interchangeability of two MFCs from different manufacturers seems unlikely unless both MFCs have accuracies better than the required interchangeability.

One representative of an MFC manufacturer stated that there is little demand for MFCs that operate at low flow rates. Others disagreed, saying that demand is increasing, or saying that demand would be greater if the MFCs were more reliable at low flow rates. Problems common at low flow rates, such as long gas delivery lines and poorly controlled valve sequencing, make it difficult to verify such reliability. Several participants stated that standards at low flow rates would be helpful here. Another comment was that accurate flow control is needed for recipes requiring stochiometry ratios exceeding 100:1.

A benign surrogate gas, such as SF_6, is frequently used to calibrate an MFC intended for a difficult process gas, such as WF_6. Different MFC manufacturers use different sets of surrogate gases, which can complicate the comparison of MFCs from different manufacturers. Many participants advocated that every MFC manufacturer characterize each MFC's performance with nitrogen, even if nitrogen was not the calibration gas. This would allow a simple verification that the MFC was working properly, both at the tool manufacturer as well as at the semiconductor fabrication plant, even if the MFC was not intended for use with nitrogen. The cost of such characterization was not clear.

Other issues considered included the following.

- Better techniques to measure gas flows at subatmospheric pressures are needed.
- Characterization of an MFC for the process gas is best done by a function of flow rate instead of by a flow-independent "gas correction factor".
- Frustration exists with MFC zeros that are set either incorrectly or inconsistently.

Standards and calibration

The breakout group called for the following new or improved tests and standards.

- Transient flows and crosstalk due to pressure variations.
- An "*in situ*" standard for process gases accurate to 1 % between 0.01 sccm and 1000 sccm.
- Liquid flows below 15 ml/minute.
- Transfer standards between 0.01 sccm and 1000 slm for "round robin" (interlaboratory) tests.

The group also called for clarification in two areas.

- The phrase "NIST traceable" needs to be made more meaningful. This was motivated by John Wright's distinction between *direct* and *indirect traceability*. Several participants pointed out that "NIST traceable" is widely abused.
- Documents are needed on the "best practice" for various primary standards, similar to those produced by the National Conference of Standards Laboratories. The existence of SEMI standards for MFC testing needs to be publicized better.

Many participants emphasized the desirability of calibrating an MFC with the intended process gas instead of a benign surrogate gas. While more expensive, such "live gas" calibration improves the MFC's accuracy, thereby reducing the cost of "tweaking in" a new process on the semiconductor manufacturing tool. The participants identified only four facilities for live gas testing. The first, at a government laboratory (Oak Ridge National Laboratory), has been little used in recent years. The others are at a commercial testing laboratory (W3 Corporation) and at two MFC manufacturers (Kinetics and Millipore). One process engineer suggested approaching end users such as himself for help. A widely accepted cost-benefit analysis of live gas calibration does not exist.

Gas properties

The thermophysical properties of process gases have a direct effect on the design, calibration, and operation of MFCs. The large uncertainties associated with the gas properties of many process gases make the improvement of MFC models more difficult. The accuracy required of a property depends on how the MFC's performance is affected by that property. For example, for a thermal MFC the most important property is the heat capacity at constant pressure, but for a sonic nozzle MFC it is the speed of sound. Three improvements were discussed.

- Direct experimental measurements of properties. The Fluid Science Group at NIST is characterizing four to ten semiconductor process gases per year with accuracies sufficient for thermal MFCs (for example, 0.1% in heat capacity and 0.5% in viscosity).
- Development and application of techniques to estimate properties. This will provide property values much faster than the measurements at the cost of worse accuracy. The associated uncertainties are expected to be approximately 20 times larger than for direct measurements, and the techniques require at least a few measurements for their validation and improvement.
- Compilation of existing property values, both measured and estimated, in an easily accessible database.

The importance of mixture properties was unclear. MFCs that prepare a mixture by controlling the flow of pure gases do not require the properties of the mixture created downstream. MFCs that control the flow of a dilute mixture (for example, a small amount of O_2 in He) may require the mixture's properties, but they are easily estimated from the properties of the pure components because the mixture is dilute. NIST is not aware of any process that requires the flow control of a concentrated mixture. The identification of such processes would be extremely valuable.

The breakout group recommended development of a generic MFC model, starting with components such as the flow divider. This recommendation, which was discussed twice earlier in the contexts of gas correction factors and of surrogate gases, was controversial. Attendees representing MFC manufacturers noted that MFC designs are proprietary.

Alternatives to thermal mass flow controllers

The breakout group used a matrix approach to think about competing flow measurement techniques. One side of the matrix listed measurement techniques, including thermal MFCs. The other side listed manufacturing processes, examples of which can be found in Kaveh Zarkar's presentation (Appendix F). In principle, each cell of the matrix could be filled with an assessment of the suitability of a particular technique for a particular process. In practice, this could not be done during the workshop because it would have required detailed knowledge of the processes and their fluids as well as the techniques. Examples of such details include the following.

- process
  - operating pressure
  - flow requirements
  - flow dynamics
  - step time requirement
- fluid
  - precursor phase (solid, liquid, gas, vapor)
  - chemical compatibility
  - density
  - specific heat
  - vapor pressure

Predicting the future suitability of the techniques was even more difficult. Alternatives to thermal MFCs have capabilities that are still being developed, and new manufacturing processes continue to immerge. The panel recommended that SEMI, NIST, and the semiconductor industry work together to characterize the new processes and fluids.

The breakout group concluded that NIST can help the development of new flow measurement techniques in the following ways.

- Provide flow standards suitable for new techniques.
- Provide property data for new process gases.
- Use scientific understanding to improve existing techniques. A recent example is the identification of molecular relaxation effects in sonic nozzles.
- Develop new techniques.

Final recommendations

Of the 21 proposed tasks listed in the Appendix A, seven received a vote from at least 40 % of the non-NIST attendees. These strongly recommended tasks are listed in the table on the next page. Each of the other 14 tasks received a vote from less than 25% of the attendees.

Five of the seven strongly recommended tasks require action by NIST. As part of NIST's Chemical Science and Technology Laboratory (CSTL), the Process Measurements Division uses six guiding criteria to set program priorities. The workshop's recommendations are discussed below in relation to these criteria.

1. **The magnitude and immediacy of the industrial need.**

The industrial interest in this workshop showed that the industrial need for gas property values and flow standards is immediate and at least moderate. The rapid introduction of new processes by the semiconductor industry may make the need more urgent.

2. **The degree of correspondence between a particular industrial need and CSTL's mission.**

The degree of correspondence is high. Providing reference standards for flow and property values for pure, industrially important fluids will fulfill CSTL's mission by enhancing the productivity of U.S. industry.

3. **The opportunity for CSTL participation to make a major difference.**

CSTL's participation will make a major difference for two reasons. First, CSTL is the premier source for the thermophysical properties of gases. Second, NIST's reputation as an unbiased, reliable provider of reference standards for flow and other quantities makes it likely that the proposed flow standards will be used by industry.

4. **The nature and size of the anticipated impact resulting from CSTL's participation.**

CSTL has the capability to match most of the industrial needs. See criteria 1 and 2.

5. **CSTL's capability to respond in a timely fashion with a high-quality solution.**

CSTL's capability to respond is large because many of the needs match existing programs or expertise in CSTL. Tasks 4, 5, and 6 correspond to programs in the Process Measurements Division. Tasks 1 and 3 correspond to recent work done in the Division.

6. **The nature of opportunities afforded by recent advances in science and technology.**

The opportunities are significant and numerous. The gas property measurements rely on acoustic techniques recently developed and under constant improvement at NIST. The existing transfer standard for low flow rates of gases relies on recent advances at NIST in modeling laminar flow elements.

Tasks strongly recommended by the workshop

	Task	Institution	Relation of task to work at NIST
1	Devise a technique to verify MFC performance that is independent of the process chamber.	none specified	NIST's Process Measurements has a history of solving fluid measurement problems. An example is the acoustic flow meter recently developed in NIST's Fluid Science and Pressure & Vacuum groups.
2	Characterize the performance of each new MFC with nitrogen as well as with its nameplate gas.	MFC manufacturers	Not applicable.
3	Increase the range of transfer standards for conducting round-robin tests (0.01 sccm to 1000 slm).	NIST	NIST's Pressure and Vacuum has developed a laminar flow meter that is suitable as a transfer standard for flows between 1 and 1000 sccm. NIST's Fluid Flow Group has expertise with sonic nozzles, which are suitable for flows up to 1000 slm. In 1993, the Fluid Flow Group built and coordinated round-robin tests with a sonic nozzle artifact for flows at 300 sccm and 800 sccm. These efforts could be extended to the recommended range of flow rates.
4	Improve the primary (0.025%) and transfer (0.1%) standards for gas flow.	NIST	NIST's Pressure and Vacuum Group recently demonstrated the operation of a new primary standard with 0.1% uncertainty. In the near future, an improvement to 0.05% is expected. The existing transfer standard was modeled with 0.2% uncertainty, and improvement in the near future to 0.1% is expected.
5	Expand and reprioritize the list of gases to be studied. Schedule and conduct property measurements.	NIST	Workshop attendees are being queried about gas priorities. Gas property measurements are under way in the Fluid Science Group.
6	Establish and maintain a public, Web-based database of gas properties.	NIST	NIST's Fluid Science Group has posted a trial Web database of gas properties.
7	Develop metrology to characterize liquid flow controllers.	NIST	NIST's Fluid Flow group has expertise in developing liquid flow standards.

Appendices

A. Prioritization of the proposed tasks

The following tables show the tasks proposed by the breakout groups and their prioritization by the attendees. Most proposals also specify the institution that would accomplish the task. The tasks are reworded here to improve the descriptions written on flipcharts during the workshop.

Each attendee was allowed to vote for six tasks without voting more than once per task. *The votes of NIST attendees are excluded from the tables.*

We emphasize that all of the tasks were proposed only after discussion in the full workshop as well as in the breakout groups. Thus, even those tasks with few votes deserve serious consideration.

Performance of flow meters

Task	Institution	Votes
Write standard on procedure for adjusting MFC zero.	SEMI	6
Devise a technique to verify MFC performance that is independent of the process chamber.	none specified	14
Characterize the performance of each new MFC with nitrogen as well as with its nameplate gas.	MFC manufacturers	23
Develop techniques to characterize delivery of gas below atmospheric pressure.	NIST	4

Standards and calibration

Write document on best practices for primary standards.	NIST	6
Develop a facility and methods for testing transient performance.	NIST	3
Increase the range of transfer standards for conducting round-robin tests (0.01 sccm to 1000 slm).	NIST	24
Improve the primary (0.025%) and transfer (0.1%) standards for gas flow.	NIST	27
Develop a test facility for corrosive and toxic gases.	none specified	4
Develop primary standards for liquid flows below 15 ml/min. (TEOS, TMB, etc.)	NIST	8

Gas properties

Task	Institution	Votes
Expand and reprioritize the list of gases to be studied. Schedule and conduct property measurements.	NIST	20
Supplement experimental measurements by estimating, with uncertainties, the properties of pure gases.	NIST	6
Establish and maintain a public, Web-based database of gas properties.	NIST	20
Create an industry advisory board to guide NIST.	MFC manufacturers, tool manufacturers, MFC users	5
Develop a generic MFC model. Suggested first submodels: sensor, flow restrictor, transient response.	MFC manufacturers, NIST	6
Identify important gas mixtures. Estimate, with uncertainties, their properties. (Industry survey, literature search, measurements.)	NIST	5

Alternatives to thermal mass flow controllers

Identify processes likely to be important.	SEMI	2
Identify chemical precursors likely to be important.	SEMI	1
Create a database of precursor properties.	NIST	1
Identify the flow ranges likely to be important.	SEMI	0
Develop metrology to characterize liquid flow controllers	NIST	19

B. Suggested topics for breakout sessions

1. **Flow meter performance**
   - 1.1. Industries
     - 1.1.1. semiconductor device manufacturing
     - 1.1.2. others: air pollution, pharmaceuticals, leak testing, …
   - 1.2. Process conditions
     - 1.2.1. flow rate
     - 1.2.2. fluid composition
     - 1.2.3. pressure (including transients)
     - 1.2.4. temperature
     - 1.2.5. corrosion
   - 1.3. Requirements
     - 1.3.1. accuracy
     - 1.3.2. stability (repeatability)
     - 1.3.3. dynamic range
     - 1.3.4. interchangeability
   - 1.4. Challenges from new processes
     - 1.4.1. lower flow rates
     - 1.4.2. pressures below one atmosphere
     - 1.4.3. new fluids (gas mixtures, high temperature vapors, liquids)

2. **Standards and calibration**
   - 2.1. Requirements
     - 2.1.1. flow rate
     - 2.1.2. uncertainty
     - 2.1.3. traceability
     - 2.1.4. relation of surrogate gas to process gas
     - 2.1.5. location (standards lab, MFC manufacturer, process tool)
   - 2.2. Primary flow standards
     - 2.2.1. gravimetric (weighing)
     - 2.2.2. constant volume (pressure rate-of-rise)
     - 2.2.3. constant pressure (piston prover)
   - 2.3. Transfer flow standards
     - 2.3.1. pressure drop across a laminar flow impedance
     - 2.3.2. thermal MFC
   - 2.4. Research at national laboratories
     - 2.4.1. improved flow standards
     - 2.4.2. new standards (transient flow, mixtures)
     - 2.4.3. validation of MFC models by comparison of process and surrogate gases
     - 2.4.4. MFC corrosion and reliability testing
   - 2.5. SEMI guidelines and test methods
     - 2.5.1. practical implementation
     - 2.5.2. validation

3. **Gas properties**
   3.1. Influence of properties on MFC models
   3.2. Property measurements
      3.2.1. thermodynamic (heat capacity, compressibility, virial coefficients)
      3.2.2. transport (viscosity, thermal conductivity)
      3.2.3. other (speed of sound, Prandtl number)
   3.3. Property models
      3.3.1. prediction from molecular structure
      3.3.2. mixture properties
      3.3.3. sources of reliable data and correlations
   3.4. Generic modeling of dynamics
      3.4.1. hydrodynamics
      3.4.2. slip
      3.4.3. thermal diffusion
      3.4.4. molecular relaxation rates

4. **Alternatives to thermal mass flow controllers**
   4.1. Micro-electrical-mechanical systems (MEMS)
   4.2. Pressure drop across a laminar flow impedance
   4.3. Sonic nozzle
   4.4. Coriolis effect
   4.5. Acoustic

C. Abbreviations and jargon

CD	critical dimension
CSTL	Chemical Science and Technology Laboratory
MFC	mass flow controller
nameplate gas	The process gas named on the body of the MFC.
NIST	National Institute of Standards and Technology
round robin	A scheme to compare laboratory measurement capabilities in which a test artifact is circulated among the laboratories.
sccm	standard cubic centimeter per minute ($\approx$ 1.34 µmol/s)
SEMI	Semiconductor Equipment and Materials International
semiconductor tool	Work station for deposition on and etching of semiconductor wafers, including a process chamber and a gas handling system.
slm	standard cubic liter per minute (1000 sccm)

D. Workshop schedule

Monday, May 15

8:30 Introductions

9:00 **Talks to outline the issues**

- *Performance of flow meters*
  Gary Allen, Applied Materials
- *Standards and calibration*
  John Wright, NIST
  Bill Valentine, Kinetics

10:15 Coffee

- *Gas properties*
  Dan Mudd, Mass Flow Associates of Texas
  John Hurly, NIST
- *Alternatives to thermal mass flow controllers*
  Kaveh Zarkar, Millipore

12:00 **Guidelines for breakout sessions**

12:15 Lunch

1:15 **Breakout sessions**
3:00 Coffee
5:00 Adjournment
6:00 Social hour
7:00 Dinner

Tuesday, May 16

8:30 **Reports from breakout sessions**
10:15 Coffee
11:00 **Final breakout sessions**

12:15 Lunch

1:15 **Prioritization of recommendations**
3:00 Adjournment
3:30 Tours of NIST flow facilities

E. Participant addresses

Gary Allen
Applied Materials
2901 Patrick Henry Dr.
MS 5509
Santa Clara, CA 95054 USA
Telephone: 408/986-3436
Fax: 408/563-6114
gary_allen@amat.com

William Alvesteffer
TET Hastings Instruments
P.O. Box 1436
Hampton, VA 23661 USA
Telephone: 757/723-6531
Fax: 757/723-3925
walveste@teledyne.com

Jeffrey Anastas
MKS Instruments
651 Lowell St.
Methuen, MA 01844 USA
Telephone: 978/682-4567
Fax: 978/682-4956
jvanastas@yahoo.com

Mike Bair
DH Instruments, Inc.
1905 West 3rd St.
Tempe, AZ 85281 USA
Telephone: 480/967-1555
Fax: 480/968-3574
dhi@dhinstruments.com

Trace Beck
Int'l. SEMATECH
2706 Montopolis Dr.
Austin, TX 78741 USA
Telephone: 512/356-7609
Fax: 512/356-7008
trace.beck@sematech.org

Bobby Berg
NIST
100 Bureau Drive
Mail Stop 8364
Gaithersburg, MD
20899-8364 USA
Telephone: 301/975-2466
robert.berg@nist.gov

Daniel Coffman
Applied Materials
9700 U.S. Hwy.
2900 East MS/3100-183
Austin, TX 78724 USA
Telephone: 512/272-2979
Fax: 512/272-3060
dan_j_coffman@amat.com

France D'Spain
SW Research Institute
6220 Culebra Rd.
San Antonio, TX 78238 USA
Telephone: 210/522-2979
Fax: 210/522-3658
fdspain@swri.org

Christopher Davis
FuGasity
616 Huntington Lane
Allen, TX 75002 USA
Telephone: 214/679-5380
Fax: 775/358-0434
fugasity@aol.com

Joel Derk
Lucent Technologies
555 Union Blvd.
Allentown, PA 18103 USA
Telephone: 610/712-7550
Fax: 610/712-7513
jlderk@lucent.com

Brian Dickson
Lucas Labs
393-J Tomkins Court
Gilroy, CA 95020 USA
Telephone: 408/846-1402
Fax: 408/848-3352
lucaslabsl@aol.com

Joe Dille
Brooks Instrument
407 W. Vine St.
Hatfield, PA 19440 USA
Telephone: 215/362-3523
Fax: 215/362-3745
joe.dille@frco.com

Ed Francis
Nat'l. Semiconductor Corp.
1111 West Bardin Rd.
Arlington, TX 76017 USA
Telephone: 817/468-6522
Fax: 817/557-7644
ed.francis@nsc.com

Gary Frank
Unit Instruments/Kinetics
Fluid Sys.
22600 Savi Ranch Pkwy.
Yorba Linda, CA 92887 USA
Telephone: 714/921-2640
Fax: 714/921-0985
gfrank@kineticsgroup.com

David Green
NIST
100 Bureau Drive
Gaithersburg, MD 20899-
8364 USA
Telephone: 301/975-4869
david.green @nist.gov

Bin Han
MKS Instruments, Inc.
651 Lowell St.
Methuen, MA 01844 USA
Telephone: 978/682-6066
Fax: 978/691-1170
bin_han@mksinst.com

J.E. Hardy
ORNL
P.O. Box 2008
Oak Ridge, TN 37831 USA
Telephone: 865/576-8670
Fax: 865/574-1249
hardyje@ornl.gov

Albert Henning
Redwood Microsystems, Inc.
959 Hamilton Ave.
Menlo Park, CA 94025 USA
Telephone: 650/617-0854
Fax: 650/326-9217
henning@redwoodmicro.com

John Hurly
NIST
100 Bureau Drive
Mail Stop 8360
Gaithersburg, MD
20899-8360 USA
Telephone: 301/975-2476
Fax: 301/869-4020
john.hurly@nist.gov

James Hylton
Oak Ridge Nat'l. Lab
P.O. Box 4699
MS 6437
Oak Ridge, TN 37831 USA
Telephone: 865/574-0349
865/241-4668

William Johnson
Eastman Kodak Co.
Kodak Park
Bldg. 23, Rm. 443
Rochester, NY 14652 USA
Telephone: 716/477-0925
Fax: 716/477-0569
william.a.johnson@
kodak.com

Tim Kipley
Aera Corporation
8601 Cross Park
Ste. 100
Austin, TX 78754 USA
Telephone: 512/339-7100
Fax: 512/339-8889
tkipley@aeramfc.com

Max Klein
Scitefair International, Inc.
900 24th Street, NW
Unit G
Washington, DC 20037 USA
Telephone: 202/785-0416
Fax: 202/857-0697
kleinmax@aol.com

William Kosh
Dresser Equipment Group,
Inc.
38 Wellington Rd.
Milford, CT 06460 USA
Telephone: 203/783-6603
Fax: 203/783-6660
bkosh@dresser.com

James Long
Aera Corporation
8601 Cross Park
Ste. 100
Austin, TX 78754 USA
Telephone: 512/339-7100
Fax: 512/339-8889
jlong@aeramfc.com

Thomas Maginnis
UMASS Lowell
95-18 Tennis Plaza Rd.
Dracut, MA 01826 USA
Telephone: 978/957-1052
scholar@netway.com

Jack Martinez
NIST
100 Bureau Drive
Mail Stop 8101
Gaithersburg, MD
20899-8101 USA
Telephone: 301/975-8125
jack.martinez@nist.gov

George Mattingly
NIST
100 Bureau Drive
Mail Stop 8360
Gaithersburg, MD
20899-8360 USA
Telephone: 301/975-5939
Fax: 301/975-8288
george.mattingly@nist.gov

Balarabe Mohammed
Applied Materials, Inc.
2901 Patrick Henry Dr.
Santa Clara, CA 95054 USA
Telephone: 408/563-1495
Fax: 408/563-6114
bala_mohammed@amat.com

Michael Moldover
NIST
100 Bureau Drive
Gaithersburg, MD 20899-
8360 USA
Telephone: 301/975-2459
michael.moldover@nist.gov

Daniel Mudd
Mass Flow Associates of
Texas
5988 Mid Rivers Mall Dr.
Saint Charles, MO 63304
USA
Telephone: 636/922-3670
Fax: 636/441-6881
dtm@mfc1.com

Michael Munson
Dominion Semiconductor
9600 Godwin Drive
Manassas, VA 20110 USA
Telephone: 703/396-1743
Fax: 703/396-1700
mmunson@dominionsc.com

Tom Naughton
Halliburton
250 East Main Street
Stratford, CT 06614 USA
Telephone: 203/385-0475
Fax: 203/385-0408
tnaughto@dresser.com

George Porter
Porter Instrument Co., Inc.
245 Township Line Rd.
Hatfield, PA 19440 USA
Telephone: 215/723-4000
Fax: 215/723-2199
georgeporter@
porterinstrument.com

Jeff Rose
Motorola
3501 Ed Bluestein Blvd.
MD-K10
Austin, TX 78741 USA
Telephone: 512/933-5599
Fax: 512/933-5262
rtla30@email.sps.mot.com

Greg Secord
DH Instruments, Inc.
1905 West 3rd St.
Tempe, AZ 85281 USA
Telephone: 480/967-1555
Fax: 480/968-3574
dhi@dhinstruments.com

Bill Valentine
Kinetics Fluid Systems
22600 Savi Ranch Pkwy.
Yorba Linda, CA 92887 USA
Telephone: 714/921-2640
Fax: 714/921-1749
bvalentine@
kineticsgroup.com

Chiun Wang
Unit Instruments/Kinetics
Fluid Sys.
22600 Savi Ranch Pkwy.
Yorba Linda, CA 92887 USA
Telephone: 714/921-2640
Fax: 714/921-0985
cwang@kineticsgroup.com

Maceo Ward
Millipore
915 Enterprise Blvd.
Allen, TX 75013 USA
Telephone: 972/359-4502
Fax: 972/359-4106
maceo_ward@millipore.com

William White
W3 Corporation
605 Spice Island Dr.
Ste. 5
Sparks, NV 89431 USA
Telephone: 775/358-2332
Fax: 775/358-0434
bill@w3corp.sparks.nv.us

Bob Williams
Coastal Instruments, Inc.
P.O. Box 577
Burgaw, NC 28425 USA
Telephone: 910/259-4485
Fax: 910/259-3375
bobw@mfchelp.com

John Wright
NIST
100 Bureau Drive
Gaithersburg, MD 20899 USA
Telephone: 301/975-5937
john.wright@nist.gov

Gil Yetter
Int'l. SEMATECH
2706 Montopolis Dr.
Austin, TX 78741 USA
Telephone: 512/356-3227
Fax: 512/356-7008
gil.yetter@sematech.org

Kaveh Zarkar
Millipore Corp.
915 Enterprise Blvd.
Allen, TX 75013 USA
Telephone: 972/359-4000
Fax: 972/359-4107
kaveh_zarkar@millipore.com

Jay Zemel
Scitefair International, Inc.
3508 Market St.
Ste. 35
Philadelphia, PA 19104 USA
Telephone: 215/382-5690
Fax: 215/382-5691
zemel@ee.upenn.edu

F. Presentation viewgraphs

Mass flow controller performance and characterization
Gary Allen, Applied Materials

Gas flow standards and calibration
John Wright, NIST

Consistent ±3 sigma calibration
Bill Valentine, Kinetics Fluid Systems

The impact of various gas properties on the operation of an MFC
Dan Mudd, Mass Flow Associates of Texas

NIST's program to measure the thermophysical properties of semiconductor process gases
John Hurly, NIST

Flow controller for semiconductor industry
Kaveh Zarkar, Millipore

NIST Workshop - Mass flow measurement & control for the semiconductor industry

MFC Characteristics and Behavior

May 15th, 2000

Gary Allen
Applied Materials
Technology Engineer
Fluid Systems Development

Topics

1) Definitions & Flow Terminology
2) MFC Types & Internal Components
3) AMAT Testing & Requirements
4) Gases and Surrogate gases
5) Comparative Performance Data
   - Analog MFC vs D/A MFC vs DeviceNet MFC
6) Issues and Concerns
7) New MFC Capabilities
8) Conclusions
9) Discussion / Questions

MFC Definitions & Terminology

Analog MFC
Digital / Analog MFC
DeviceNet digital MFC
Transient characteristics
Dead time
Step response time
Control (settling) time
Overshoot
Accuracy (% FS)
Linearity
Valve leak by
Sensor offset
Sensor drift
Repeatability
Reproducibility
Cross talk
Thermal Based
Pressure Based
Coriolis Based

APPLIED MATERIALS

MFC Types and Internal Components

- MFC types
  - Thermal based
  - Pressure based
  - Coriolis
  - MEMS
- Internal Components
  - sensor
  - valves
  - bypass
  - control logic

APPLIED MATERIALS

Testing Requirements

- AMAT MFC Commodity Specification
  - P/N 0251-00345 ; defines the minimum set of requirements for MFC configuration, performance and reliability.
- Applied Materials tests performance of MFC types and models via RoR system.
  - creates a common test method for comparative analysis
  - measures transient flow characteristics of MFCs
  - limited to 3 SLM

APPLIED MATERIALS®

AMAT Performance Characterization

- Tests specific performance characteristics for compliance to AMAT MFC Commodity Specification (p/n 0251-00345)
- Test for nine different characteristics
  - dead time, step response time, control time, overshoot, accuracy, valve leak-by
  - calculate - linearity, repeatability, reproducibility
- Nine different set points (2% to 100%) repeated three times
- Four different test gases are utilized (N2, He, CF4, SF6)
  - Typical inlet pressure 30 psia
  - Initial chamber pressure 35 mTorr
- Tests each MFC independently.
- Sample rate 25 mSec.

APPLIED MATERIALS®

Gases & Surrogate Gases

- The Semiconductor industry utilizes approximately 170 different gases, in which the list grows every year.
- SEMI published list E52-95 "Practice for Referencing Gases used in Digital Mass Flow Controllers.
- Gases run the gamut of inert, toxic, corrosive, flammable, vapor from liquids, liquids, and solids
- MFCs are not calibrated with the the name plate gas.
- Typically a GCF gas correction factor is applied linearly for the surrogate to name plate gas.

APPLIED MATERIALS®

Gases & Surrogate Gases

<u>Issues with surrogate gases</u>

- Correlations between name pate gases and surrogate gases are not linear, therefore GCFs can cause inaccuracies.
- Applied has found multiple cases of GCFs being inaccurate. In some cases these have been as high as 8%FS.
- Different manufacturers utilize different surrogate gas for calibration.

APPLIED MATERIALS®

Gases & Surrogate Gases

- Digital MFCs are utilizing gas correction functions to eliminate linearity issues of gas correction factors.
- Some gas correction functions are theoretical, while others are derived from empirical testing.
- Live gas testing allows for these gas correction functions to be developed, and appear to generate the best correlations.
- We recommend that MFC manufacturers develop these non-linear relationships to only one surrogate gas - Nitrogen.

APPLIED MATERIALS®

Performance Comparison

Characteristic	Spec Requirement	Analog MFC*	D/A MFC #	DeviceNet MFC #	1.13 DNet MFC #
Dead Time	N/R sec	0.35 sec	0.31 sec	0.18 sec	0.2 sec
Step Resp Time	1.5 Sec	0.72 sec	0.91 sec	1.01 sec	0.71 sec
Settling Time	2.0 Sec	1.30 sec	1.18 sec	1.92 sec	1.55 sec
Overshoot	10% Set Point	7.95%	5.08%	4.60%	3.43%
Valve Leak-by	1% FS	0.08%	0.32%	0.18%	0.11%
Accuracy	1% FS	0.38%	0.75%	0.78%	0.45%
Linearity	1% FS	0.39%	0.81%	0.52%	0.49%
Repeatability	.25% FS	no data available	0.22%	0.09%	0.05%
Reproducibility	N/R 1% FS	1.74%	1.40%	0.70%	0.62%

* Single gas MFC
# Multi-gas MFC

APPLIED MATERIALS®

New MFC capabilities

- Improved calibrations
  - through the use of gas correction **functions** derived through live gas empirical data, Polynomial equations determine calibration curves rather than a single point linear relation between surrogate gas and name plate gas.
- Multiple gas calibrations
  - can be stored in a single MFC, which allows for capability of reduced inventories.
- Common communication protocols
  - allow for enhanced diagnostics
  - easier integration

APPLIED MATERIALS®

Issues and Concerns

<u>Cross-talk</u> - a pressure fluctuation in a SLD manifold which causes MFC flow output to vary.

<u>Regulator interaction</u> - improperly functioning mechanical pressure regulators can affect transient behavior of MFC.

<u>Gas Bursting</u> - uncontrolled amounts of gas, caused by various MFC interaction with semiconductor tools.

<u>In situ flow verification</u> - a means to verify gas flow on the semiconductor tools, independent to the process chamber.

APPLIED MATERIALS®

Issues and Concerns

Pressure based MFC

- potential" down stream" Crosstalk?
- continuous sonic velocity concern?
- inlet pressure concern?

Liquid Delivery Measurement

- measure in liquid or vapor phase?
- transient characteristics?

SDS Delivery Systems

- experimental methods limited
- dealing with low differential pressures

APPLIED MATERIALS

Conclusions

- Digital MFCs have improved performance and capability over existing analog MFCs.
- Comparative performance evaluations and interactive feedback have improved the capabilities of MFCs in the past three years.
- Gas correction functions should be verified by some level of live gas testing.
- More work has to be completed to understand the interaction of inlet & outlet pressure, relative to transient characteristics & accuracy.
- Transient measurement techniques must be developed for liquid and SDS MFCs.

APPLIED MATERIALS

Gas Flow Standards and Calibration

John D. Wright

Project Leader

Fluid Flow Group
National Institute of Standards and Technology
Gaithersburg, MD, USA

www.nist.gov/fluid_flow

outline

Outline

- Mission
- Flow standards
- Traceability and Proficiency
- Inter-lab comparisons

www.nist.gov/fluid_flow

gas standards

Mission

- Support industry by maintaining and disseminating measurement standards
- Improve uncertainty of primary flow standards as needed by industry
- Conduct calibrations, inter-lab comparisons (international and domestic)
- Flowmeter research for transfer standards

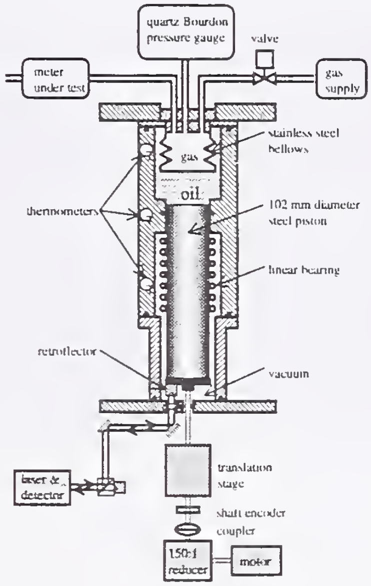
www.nist.gov/fluid_flow

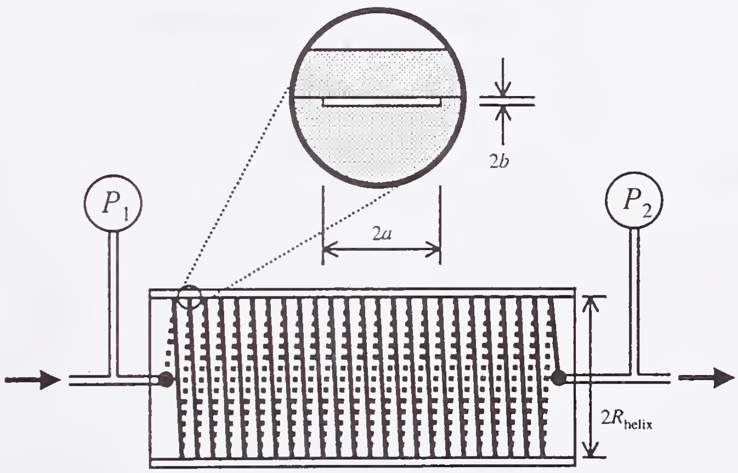
NIST Pressure and Vacuum Group

Improved gas flow calibrations from 0.01 to 1000 sccm

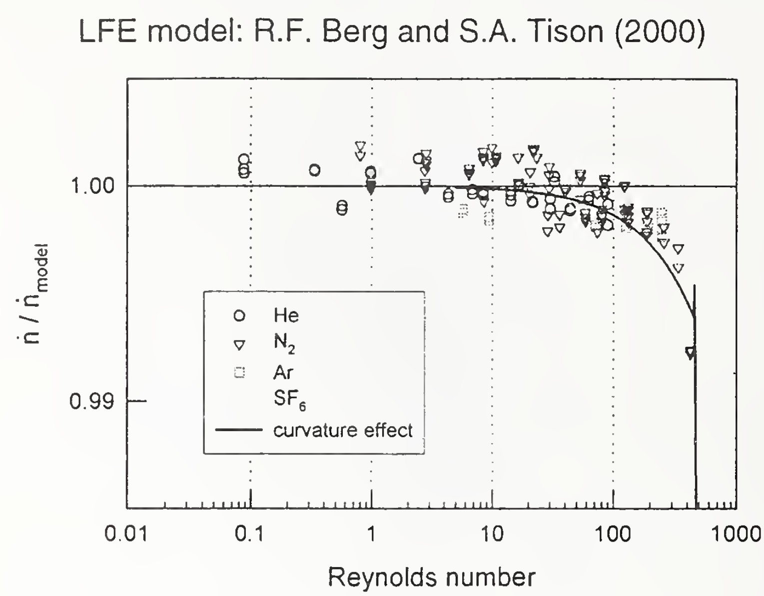
- Primary standards
  - first-generation
    - constant volume; pressure rate-of-rise
    - 0.1% in practice
  - second-generation
    - constant pressure; volume displacement measured by laser interferometer
    - approximately 0.05% expected
- Transfer standards based on a laminar flow impedance
  - first-generation (rectangular cross-section)
    - good reproducibility (short-term is 0.005%, long-term is at least 0.1%)
    - new model has minimal empiricism (only free parameter is duct diameter)
  - second-generation (circular cross-section) completed
- New directions
  - Workshop on mass flow control
  - Investigation of acoustic flow meter as a measurement standard

Constant-pressure piston flow meter





Laminar flow meter with rectangular cross section
S.A. Tison and L. Berndt (1997)



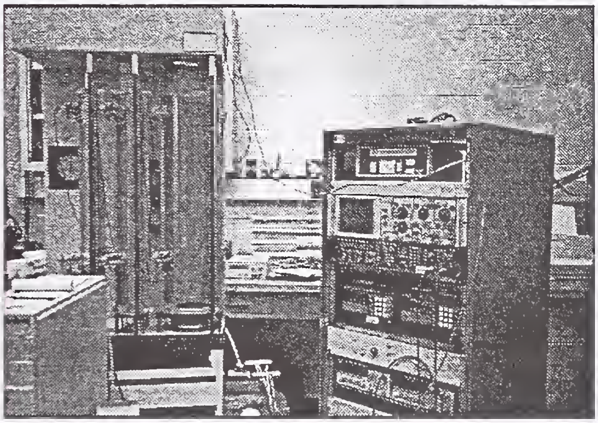
NIST Fluid Flow Group
Gas Flow Standards

Facility	Min. Flow [slm]	Max. Flow [slm]	U (k=2) [%]	Fluid
Small Piston	3.72e-2	5.22e-1	0.19	Non-Corrosive Non-Toxic Gases
Medium Piston	2.03e-1	2.84e+0	0.16	
Large Piston	2.12e+0	2.97e+1	0.18	
GVC	*1.00e+0*	*1.00e+3*	*0.05*	*Non-Corrosive Non-Toxic Gases*
Small Bell	1.61e+1	2.26e+2		Non-Corrosive Non-Toxic Gases
Medium Bell	3.05e+1	4.55e+2	0.17	
Large Bell	1.03e+2	1.44e+3		
PVTt	8.62e+2	7.76e+4	0.20	Dry-Air

www.nist.gov/fluid_flow

pistons

Piston Provers



Min. Flow [slm]	Max. Flow [slm]	U (k=2) [%]	Fluid
3.72e-2	5.22e-1	0.19	Non-Corrosive Non-Toxic Gases
2.03e-1	2.84e+0	0.16	
2.12e+0	2.97e+1	0.18	

www.nist.gov/fluid_flow

GVC

bells

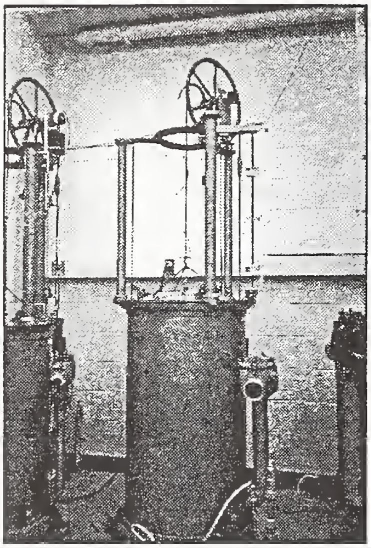
Gravimetric-Volumetric Calibrator (GVC)

Min. Flow [slm]	Max. Flow [slm]	U (k=2) [%]	Fluid
1.00e+0	*1.60e+3*	*0.050*	*Non-Corrosive Non-Toxic Gases*

www.nist.gov/fluid_flow

www.nist.gov/fluid_flow

Bell Provers

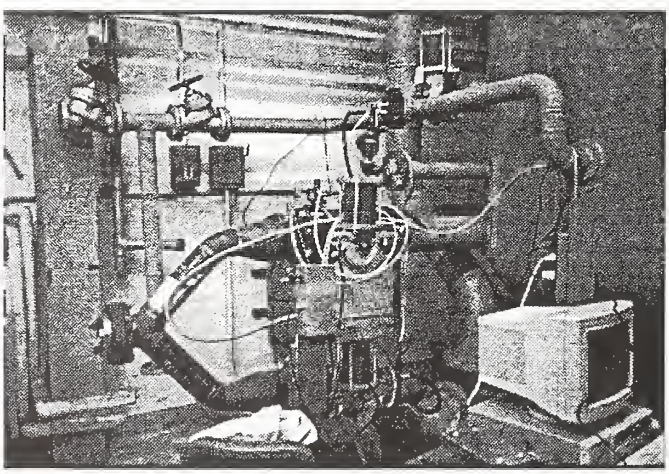


Min. Flow [slm]	Max. Flow [slm]	U (k=2) [%]	Fluid
1.61e+1	2.26e+2		
3.05e+1	4.55e+2	0.17	Non-Corrosive Non-Toxic Gases
1.03e+2	1.44e+3		

PVTt

EMCF

Pressure-Volume-Temperature-time (PVTt)



Min. Flow [slm]	Max. Flow [slm]	U (k=2) [%]	Fluid
8.62e+2	7.76e+4	0.20	Dry-Air

www.nist.gov/fluid_flow

Traceability

- A measurement or sensor is said to be *traceable* if it can be connected to a stated reference, usually a national standard, through an unbroken chain of documented calibrations with stated uncertainties.
- May be indirect or direct.

International Vocabulary of Basic and General Terms in Metrology, 2nd edition, International Organization for Standardization, 1993.

www.nist.gov/fluid_flow

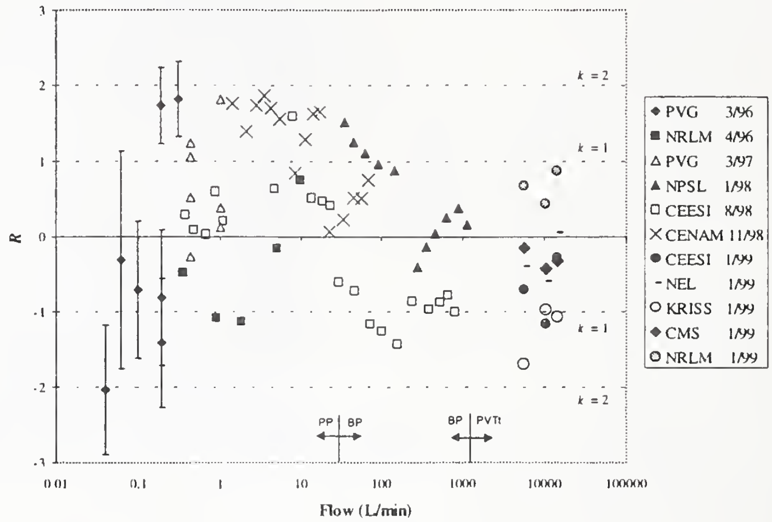
Proficiency

- A laboratory proves *proficiency* by having well founded and performed calibration procedures and by demonstrating agreement with other laboratories via comparisons.

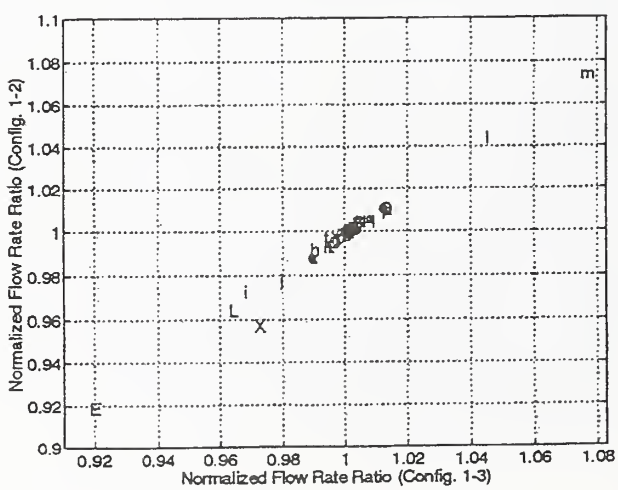
Calibration Laboratories Technical Guide,
C. D. Faison, editor, NIST Handbook 150-2, 1997.

www.nist.gov/fluid_flow

Fluid Flow Group Inter-lab Comparisons

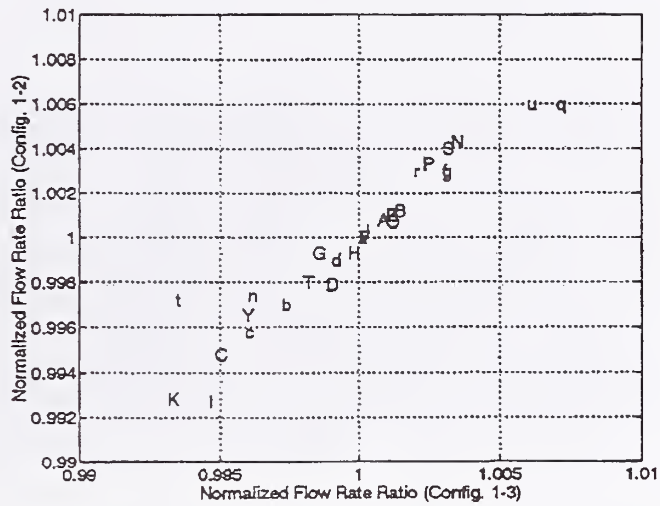


Sematech Round Robin, 1993



www.nist.gov/fluid_flow

Sematech Round Robin, 1993



www.nist.gov/fluid_flow

Summary

- primary gas flow standards are being improved
- both traceability and proficiency are important
- comparisons ensure quality, check entire calibration process

www.nist.gov/fluid_flow

end

Kinetics Fluid Systems

Consistent +/- 3 Sigma Calibration
Bill Valentine, Director of Engineering

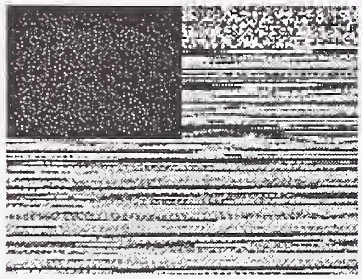
KINETICS

1% FS Accuracy?

- Claimed since the beginning of the MFC
- Past: 70% of product met an accuracy of 1% FS on surrogate gas. (1 sigma process)
- Goal: 99.7% of product would meet an accuracy of 1% FS on surrogate gas AND process gas
- Now shipping product with % SP accuracy

KINETICS

Do you understand your capabilities and limitations, or do you just feel lucky?



KINETICS

3 Tier Attack

- Metrology
  - Do we have a solid foundation?
- Process Capability
  - Are we under control?
- On Tool Performance
  - Can we translate solid metrology and process capability into on tool performance?

KINETICS

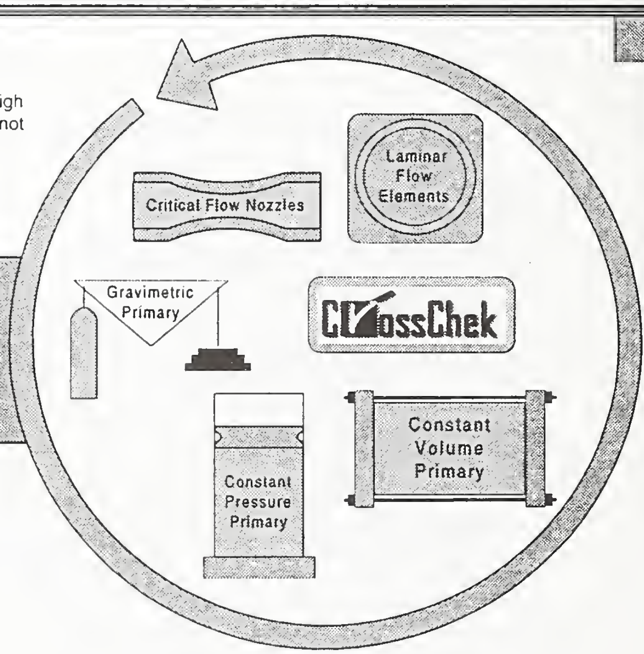
METROLOGY

- He who has one flow standard always knows the flow rate.
- He who has two flow standards, never knows the flow rate.

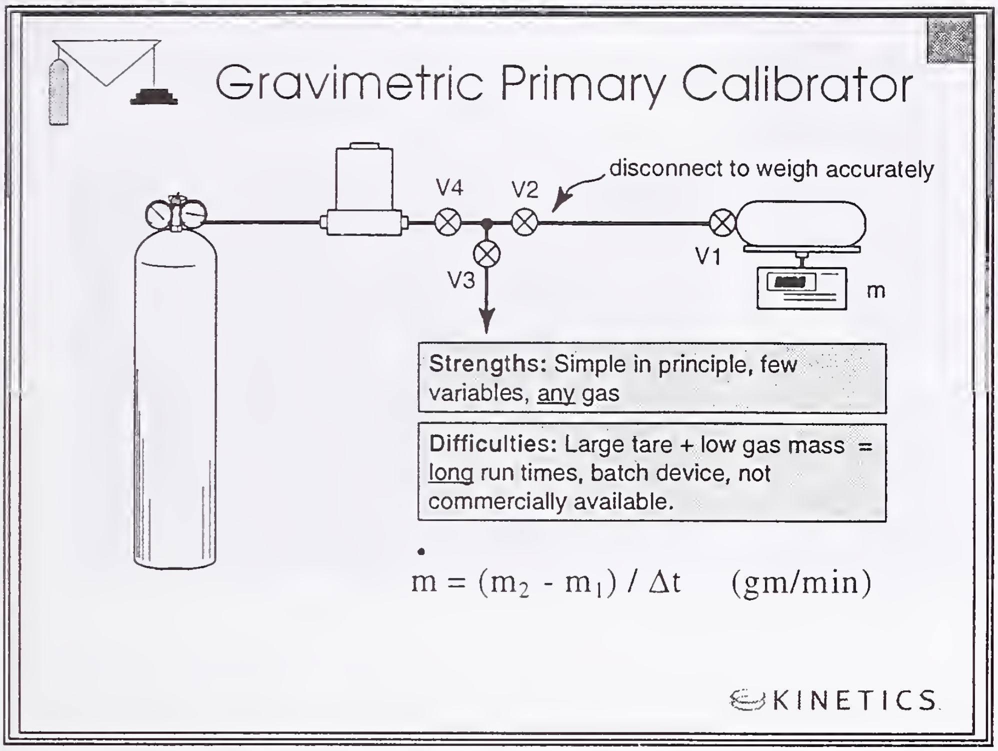
KINETICS

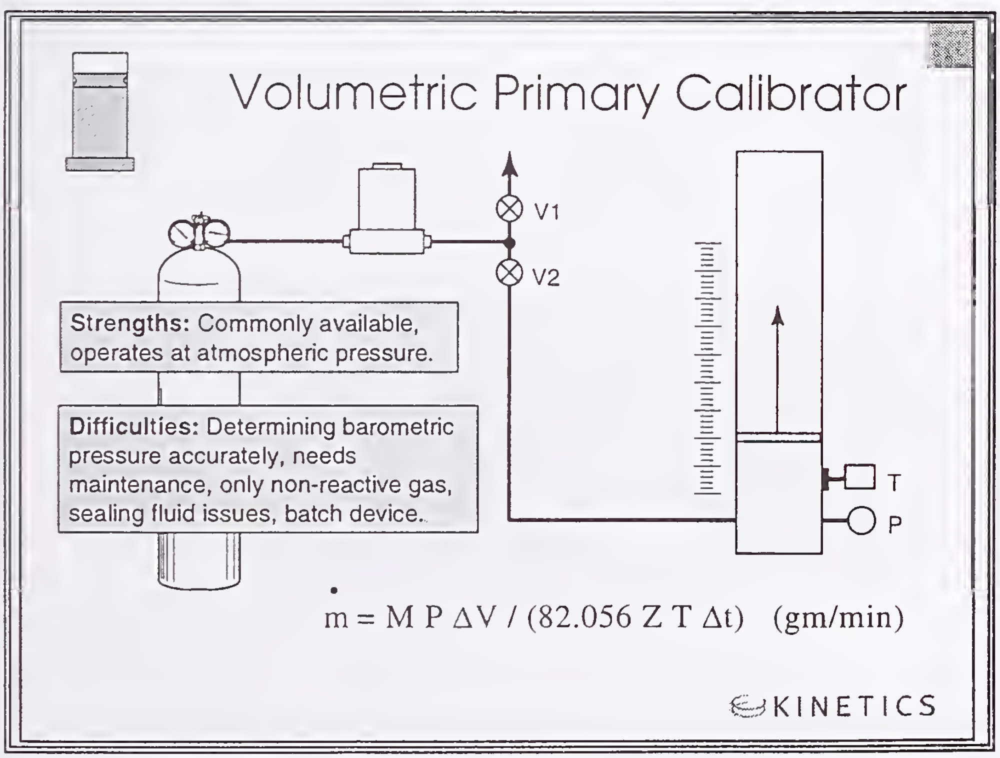
Without cross-checking different primary calibrators which do not share the same error sources, high confidence in flow accuracy cannot be maintained

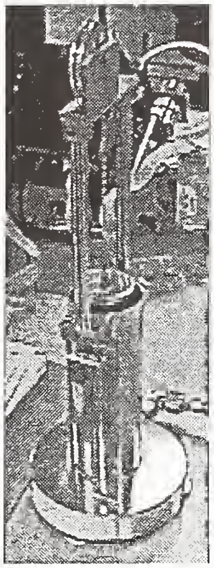
Using All the Tools



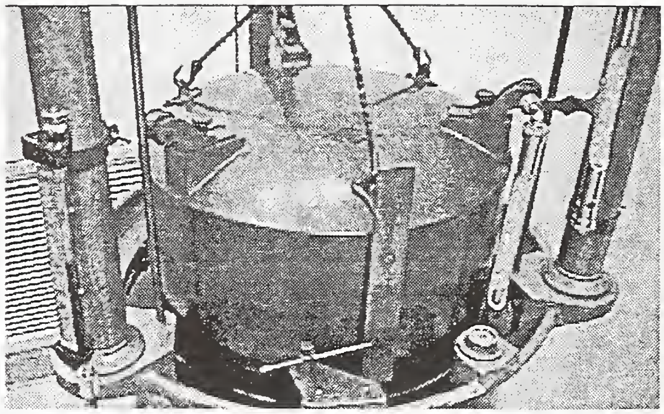
KINETICS


Gravimetric Primary Calibrator
disconnect to weigh accurately
V4
V2
V3
V1
m
Strengths: Simple in principle, few variables, any gas
Difficulties: Large tare + low gas mass = long run times, batch device, not commercially available.
$\dot{m} = (m_2 - m_1) / \Delta t$ (gm/min)
KINETICS


Volumetric Primary Calibrator
V1
V2
T
P
Strengths: Commonly available, operates at atmospheric pressure.
Difficulties: Determining barometric pressure accurately, needs maintenance, only non-reactive gas, sealing fluid issues, batch device.
$\dot{m} = M\ P\ \Delta V / (82.056\ Z\ T\ \Delta t)$ (gm/min)
KINETICS

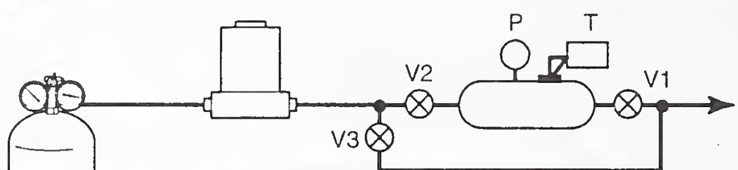


Bell Provers



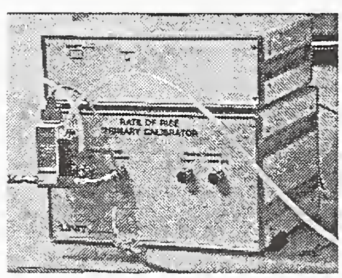
KINETICS

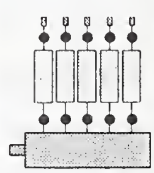
Rate-of-Rise Primary Calibrator



Strengths: Rugged, moveable, use with any gas.

Difficulties: Determining volume, pressure, gas temperature, configuration induced uncertainties, batch device.





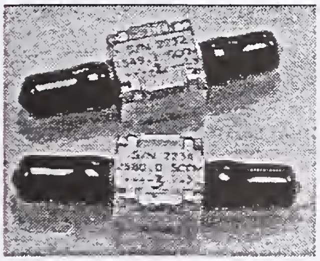
$$\dot{m} = M\ V\ \Delta P\ /\ (82.056\ Z\ T\ \Delta t) \quad \text{(gm/min)}$$

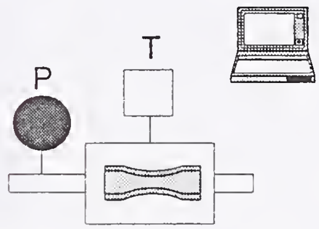
KINETICS

Critical Flow Nozzles

Strengths: Very small, very stable, robust, excellent at intermediate flows, continuous reading.

Difficulties: Initial characterization, data reduction, limited gases and ranges, pressure drop.





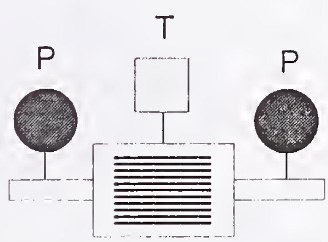
$$\dot{m} = C_d C^* A_t P_o / \sqrt{(RT)} \quad \text{(gm/min)}$$

KINETICS

Laminar Flow Elements

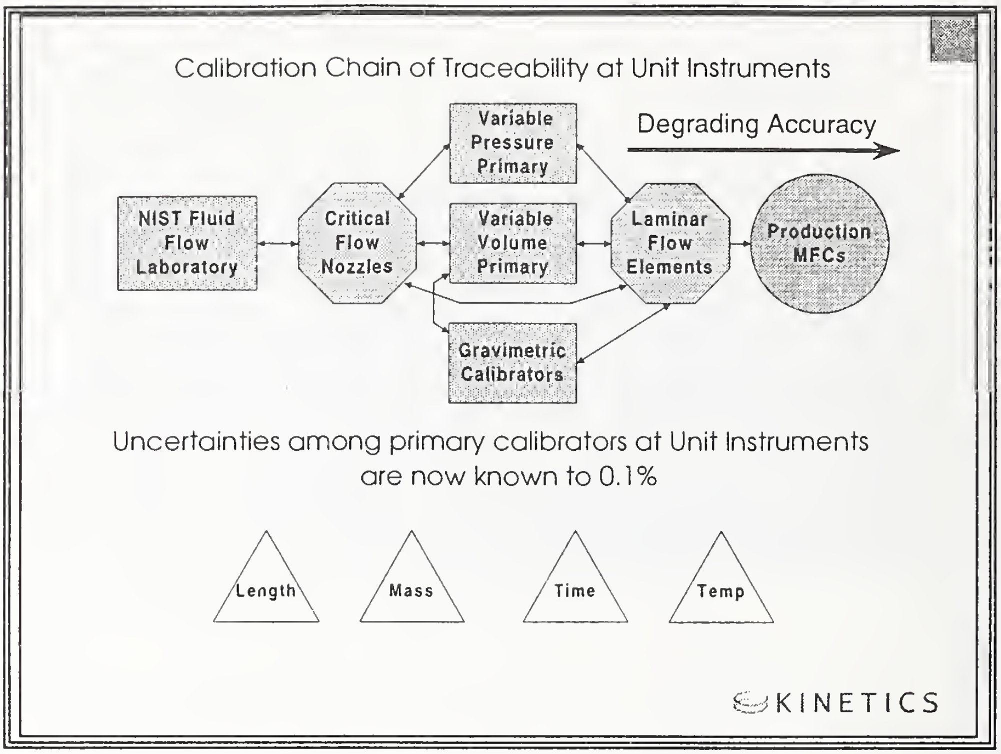
Strengths: Very stable if handled well, continuous reading, linear, excellent at all semi industry flows.

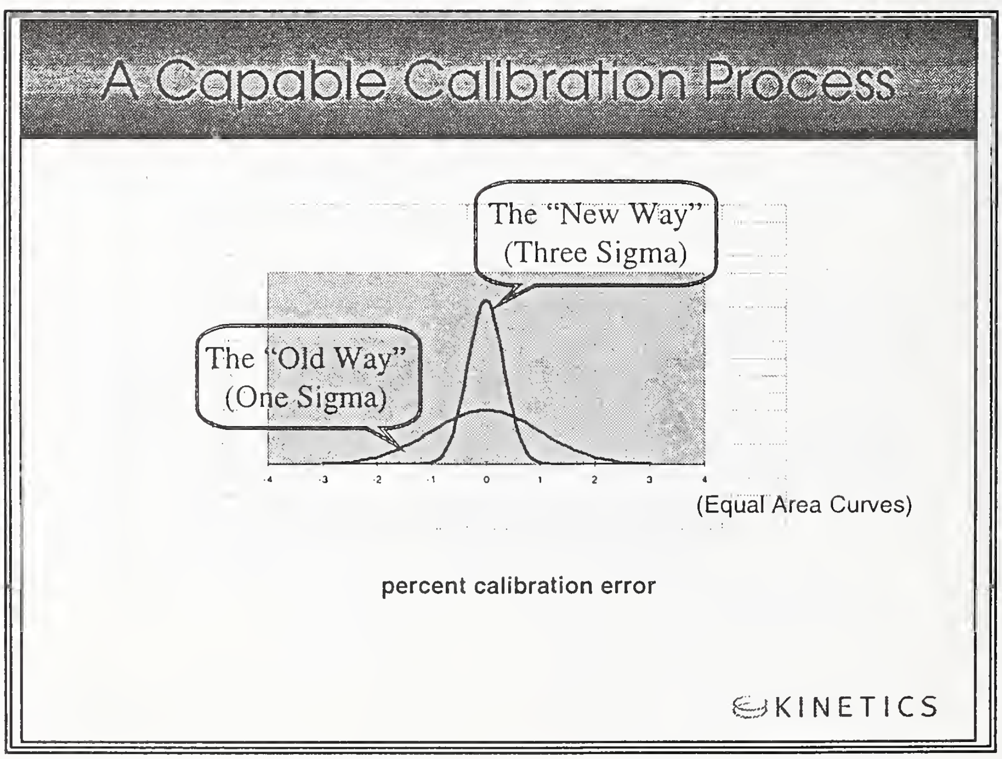
Difficulties: Initial characterization, temperature effects, pressure drop.

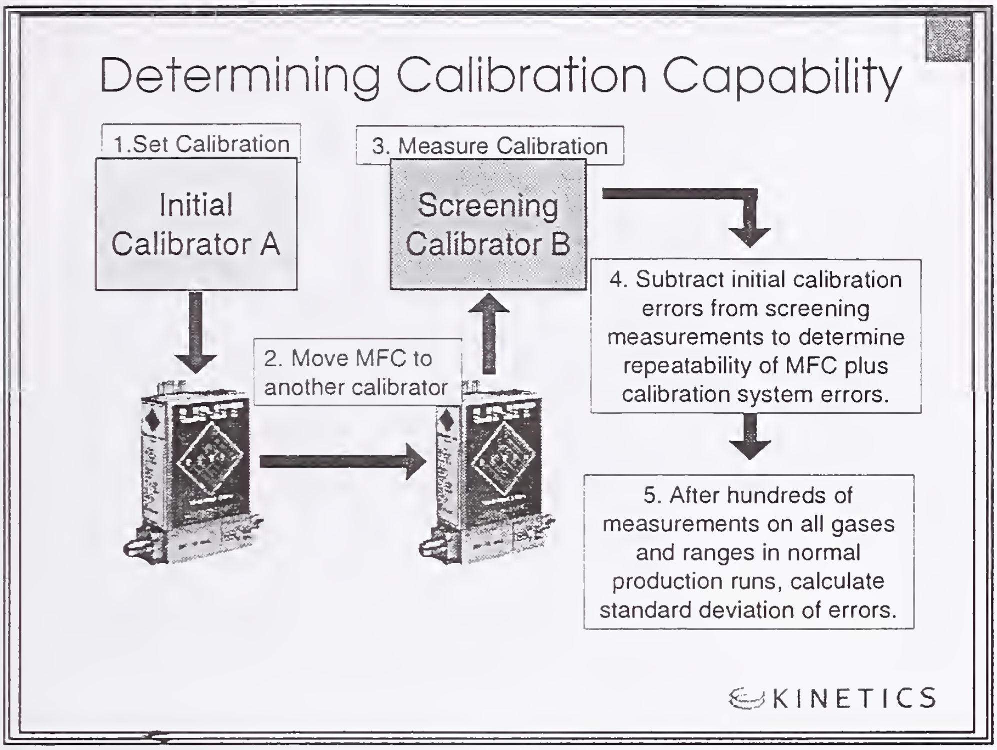


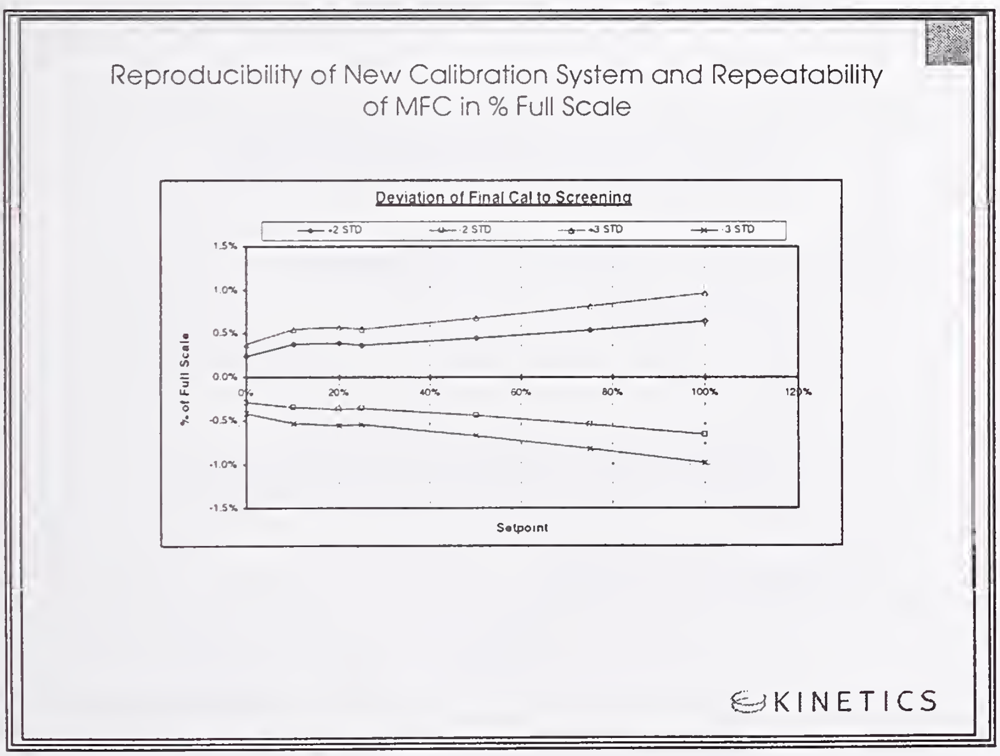
$$Qs = C\ P\ \Delta P\ D^4 / (\mu\ L\ T\ Z) \quad \text{(sccm)}$$

KINETICS

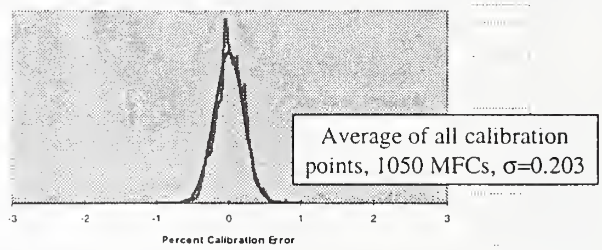

Calibration Chain of Traceability at Unit Instruments
Degrading Accuracy
NIST Fluid Flow Laboratory
Critical Flow Nozzles
Variable Pressure Primary
Variable Volume Primary
Gravimetric Calibrators
Laminar Flow Elements
Production MFCs
Uncertainties among primary calibrators at Unit Instruments are now known to 0.1%
Length
Mass
Time
Temp
KINETICS


A Capable Calibration Process
The "New Way" (Three Sigma)
The "Old Way" (One Sigma)
-4 -3 -2 -1 0 1 2 3 4
(Equal Area Curves)
percent calibration error
KINETICS


Determining Calibration Capability
1.Set Calibration
Initial Calibrator A
3. Measure Calibration
Screening Calibrator B
2. Move MFC to another calibrator
4. Subtract initial calibration errors from screening measurements to determine repeatability of MFC plus calibration system errors.
5. After hundreds of measurements on all gases and ranges in normal production runs, calculate standard deviation of errors.
KINETICS


Reproducibility of New Calibration System and Repeatability of MFC in % Full Scale
Deviation of Final Cal to Screening
+2 STD
-2 STD
+3 STD
-3 STD
1.5%
1.0%
0.5%
0.0%
-0.5%
-1.0%
-1.5%
0%
20%
40%
60%
80%
100%
120%
% of Full Scale
Setpoint
KINETICS

Actual Calibration Data vs. the Normal Distribution

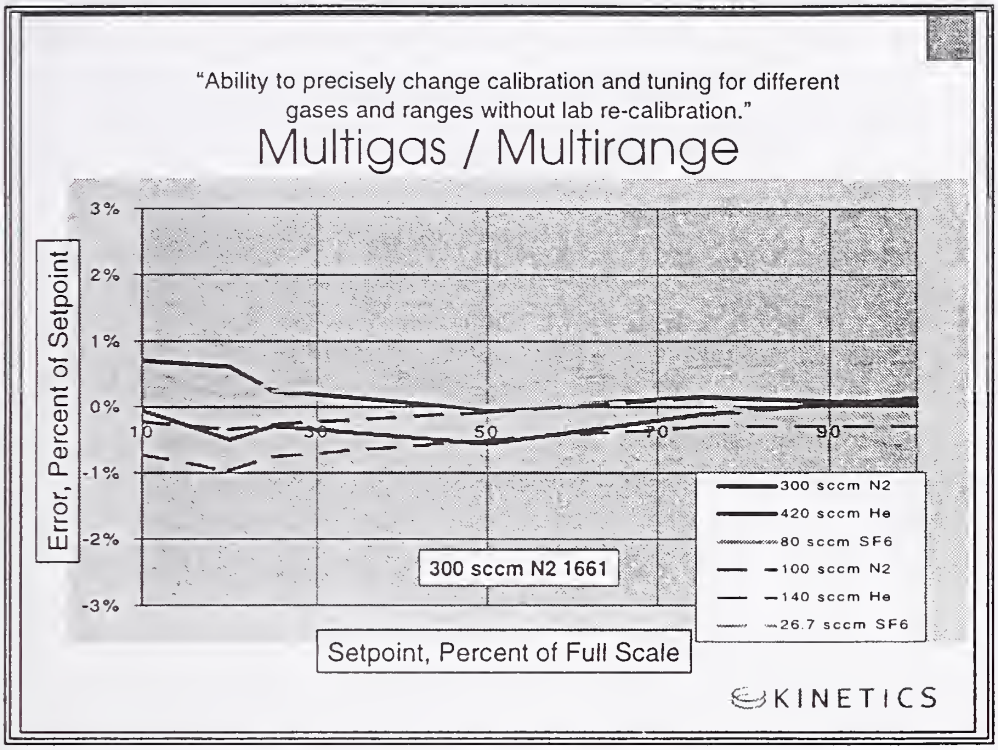


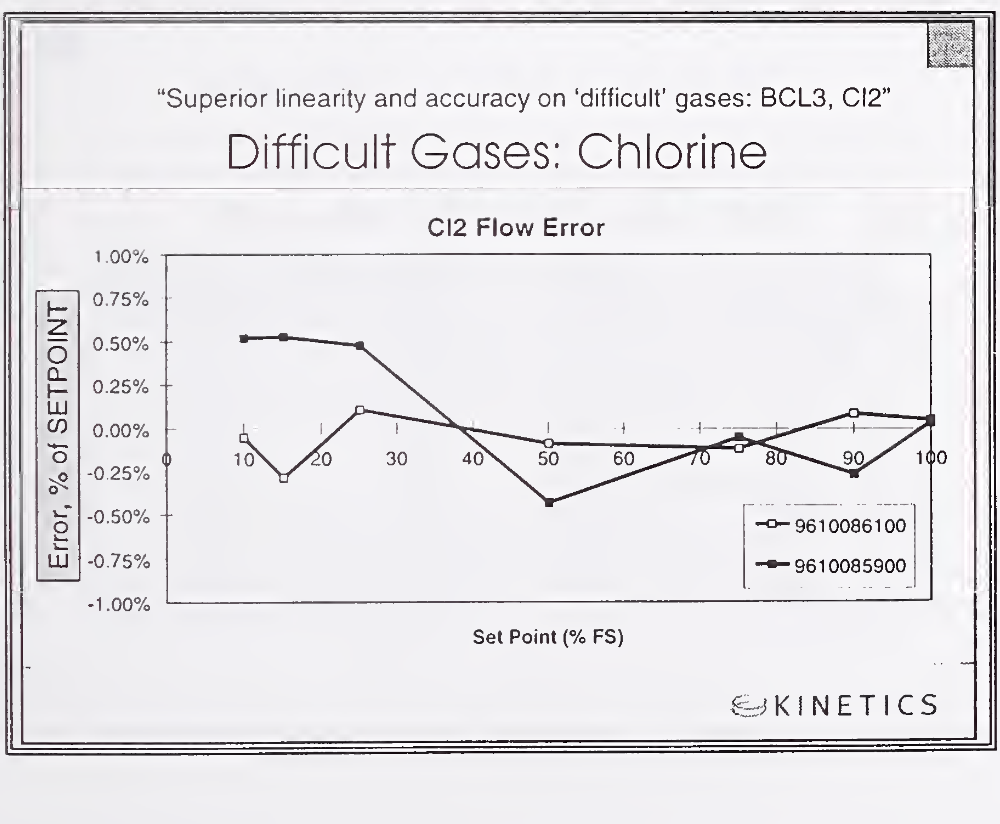
KINETICS

ON TOOL PERFORMANCE

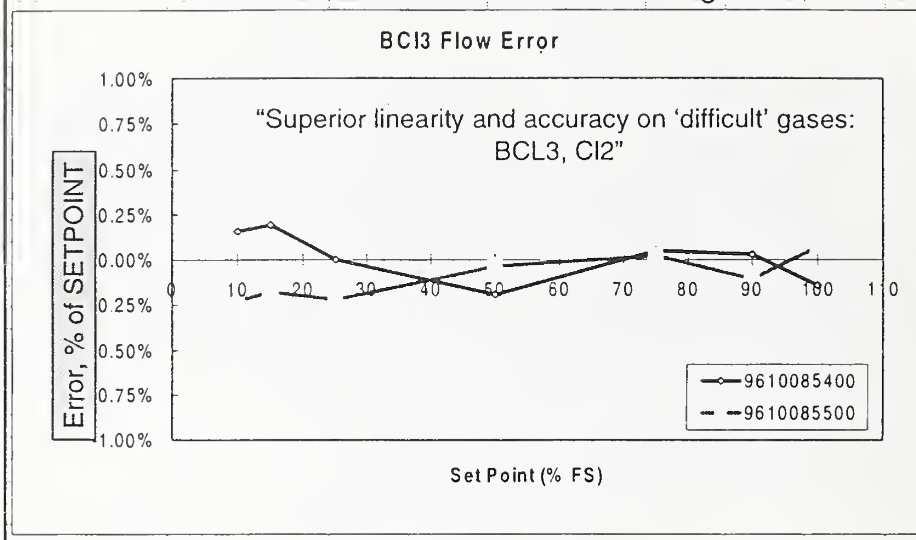
- Process gas calibration is not feasible
- Conversion factors
  - Must understand your device and it must be linear
- Gravimetric
  - Characterization, not to generate a function
- Proof
  - BCl3, Cl2, WF6, HBr

KINETICS


"Ability to precisely change calibration and tuning for different gases and ranges without lab re-calibration."
Multigas / Multirange
3%
2%
1%
0%
-1%
-2%
-3%
Error, Percent of Setpoint
10
30
50
70
90
300 sccm N2
420 sccm He
80 sccm SF6
100 sccm N2
140 sccm He
26.7 sccm SF6
300 sccm N2 1661
Setpoint, Percent of Full Scale
KINETICS


"Superior linearity and accuracy on 'difficult' gases: BCL3, Cl2"
Difficult Gases: Chlorine
Cl2 Flow Error
1.00%
0.75%
0.50%
0.25%
0.00%
-0.25%
-0.50%
-0.75%
-1.00%
Error, % of SETPOINT
0
10
20
30
40
50
60
70
80
90
100
9610086100
9610085900
Set Point (% FS)
KINETICS

Difficult Gases: BCl_3



KINETICS

Multi-Gas MFCs: a Reality

Metrology Report, UFC-1661, 200 sccm WF6			
Primary Calibrator:	Bell Prover #109	Bell Prover #109	Gravimetric
Setpoint	SF6 Error, % of Setpoint	N2 Error, % of Setpoint	WF6 Error, % of Setpoint
7%	0.21%	0.28%	0.37%
13%	0.00%	0.30%	0.50%
33%	-0.30%	0.02%	-0.24%
67%	-0.19%	-0.10%	-0.68%
100%	-0.09%	-0.65%	-0.26%

KINETICS

The Good News

- Achieving accuracy is not magic
- Discipline, Hard Work, and Persistence

The Bad News

- Once you get your act together, can you change the character of your product?
- What do you do when you still can´t agree?
- Future processes are demanding greater range
- Current technology is at limited to 1% SP
- Still Confusion

KINETICS

The Impact of Various Gas Properties on The Operation of an MFC

By Dan Mudd, 5/15/2000

MASS FLOW ASSOCIATES of TEXAS
5988 Mid Rivers Mall Drive, Suite #117 • St. Charles, MO 63304
PHONE: 636-922-3670 • e-mail: dtm@mfc1.com • FAX: 636-441-6881

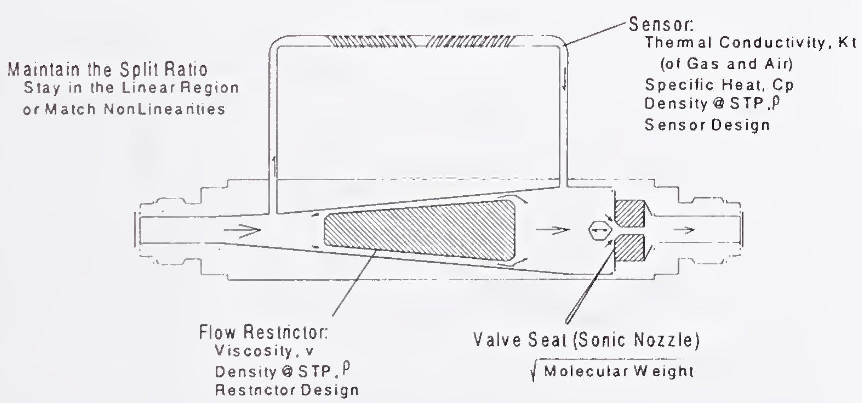
Presentation Outline

- Why Gas Properties Are of Interest
- Components of a Simple MFC and the Role of the Various Gas Properties
- Second Tier Influences

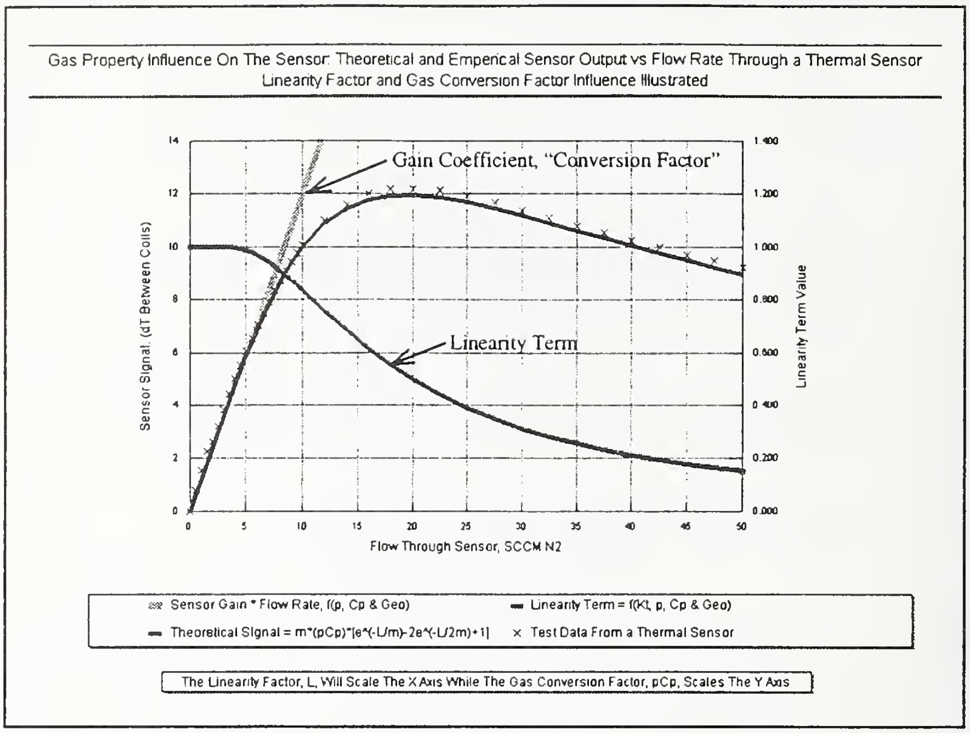
Why Are The Gas Properties of Interest?

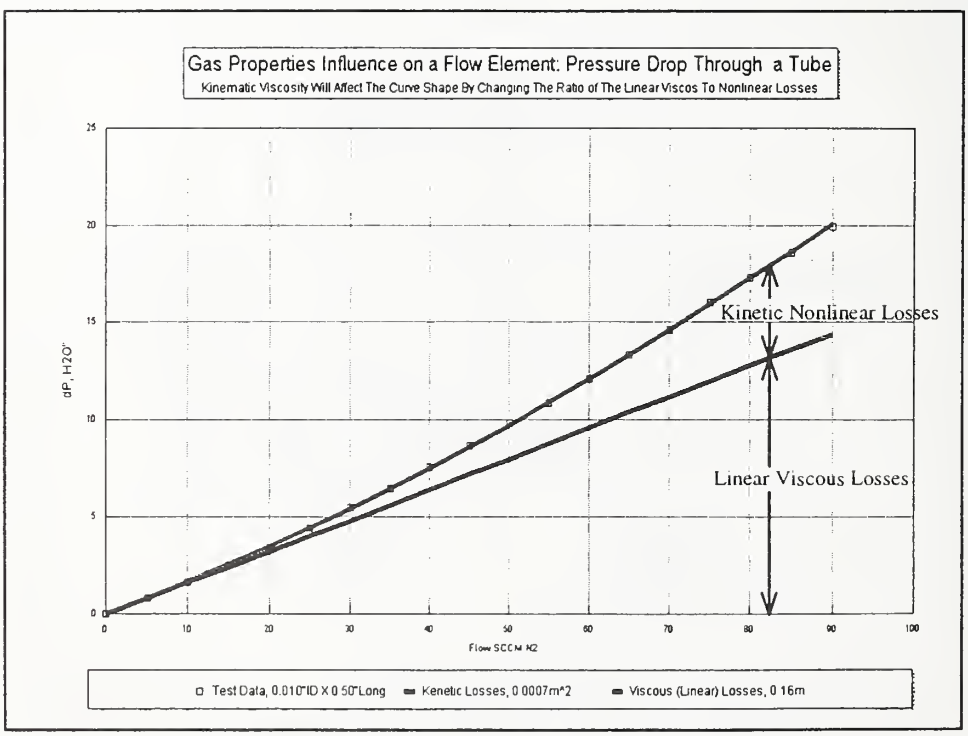
- They Suggest That the Configuration of the MFC Should Change With The Nameplate Gas.
- Sheds Light on Surrogate Gas Calibration Procedures and Limitations.
- Indirectly Affects MFC to MFC Variability.

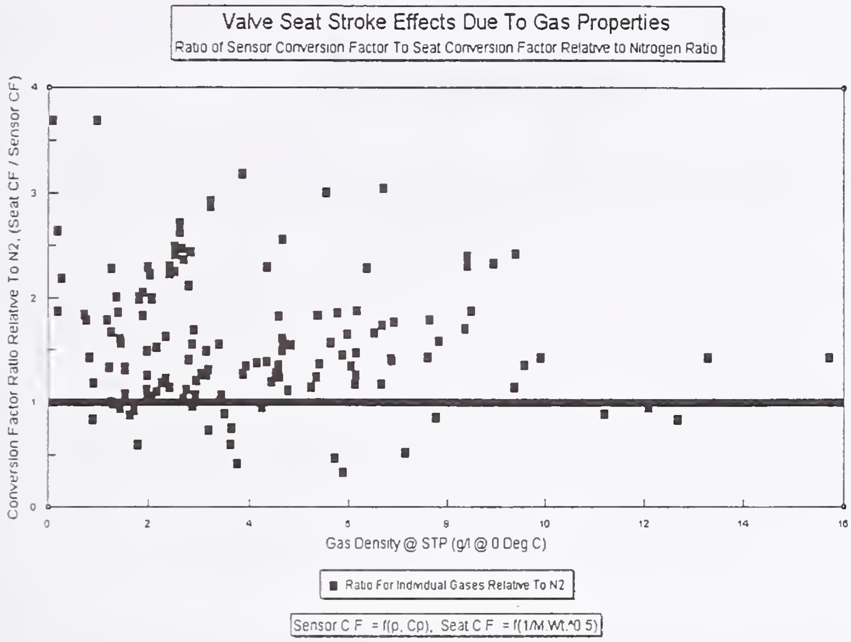
Components of a Simple MFC and the Role of Various Gas Properties



Mass Flow Associates of Texas
www.mfc1.com


Gas Property Influence On The Sensor: Theoretical and Emperical Sensor Output vs Flow Rate Through a Thermal Sensor
Linearity Factor and Gas Conversion Factor Influence Illustrated
Gain Coefficient, "Conversion Factor"
Linearity Term
Sensor Signal, (dT Between Coils)
Linearity Term Value
Flow Through Sensor, SCCM N2
Sensor Gain * Flow Rate, f(ρ, Cp & Geo)
Linearity Term = f(Kt, ρ, Cp & Geo)
Theoretical Signal = m*(ρCp)*[e^(-L/m)-2e^(-L/2m)+1]
Test Data From a Thermal Sensor
The Linearity Factor, L, Will Scale The X Axis While The Gas Conversion Factor, ρCp, Scales The Y Axis


Gas Properties Influence on a Flow Element: Pressure Drop Through a Tube
Kinematic Viscosity Will Affect The Curve Shape By Changing The Ratio of The Linear Viscos To Nonlinear Losses
Kinetic Nonlinear Losses
Linear Viscous Losses
dP, H2O"
Flow SCCM N2
Test Data, 0.010"ID X 0.50"Long
Kenetic Losses, 0.0007m^2
Viscous (Linear) Losses, 0.16m



Gas Properties: Second Tier Influences

- Non Ideal Gas Behavior
  - Compressibility Factor
  - Virial Coefficients
- Properties of Newer Gases are Less Accurate or Not Available
- Temp and Pressure Influence Can Influence MFC in Specific Cases

Summary

- Thermal Conductivity, Specific Heat, Viscosity, Density and Molecular Weight are The Primary Properties Influencing MFCs.
- The Gas Properties Suggest That the Configuration of the MFC Should Change With The Nameplate Gas.
- The Gas Properties Shed Light on the Surrogate Gas Calibration Procedures and Limitations.
- Gas Properties Indirectly Affects MFC to MFC Variability

NIST's Program to Measure The Thermophysical Properties of Semiconductor Process Gases

John J. Hurly and Michael R. Moldover
Physical and Chemical Properties Division,
National Institute of Standards and Technology,
Gaithersburg, MD 20899-8380

NIST

John J. Hurly and Michael R. Moldover

Which Gases Studied?

Table 1. Experimental *T* and *P* ranges.

	T Range (K)	*P* Range (MPa)	No. Points
CF_4	$300 \leq T \leq 475$	$0.10 \leq P \leq 1.5$	114
C_2F_6	$175 \leq T \leq 475$	$0.10 \leq P \leq 1.5$	181
SF_6	$230 \leq T \leq 460$	$0.10 \leq P \leq 1.5$	280
BCl_3	$300 \leq T \leq 460$	$0.05 \leq P \leq 0.15$	119
HBr	$230 \leq T \leq 440$	$0.05 \leq P \leq 1.5$	232
Cl_2	$260 \leq T \leq 440$	$0.10 \leq P \leq 1.5$	326
WF_6	$290 \leq T \leq 420$	$0.05 \leq P \leq 0.3$	146
$(CH_2)_2O$	$285 \leq T \leq 420$	$0.05 \leq P \leq 1.0$	339

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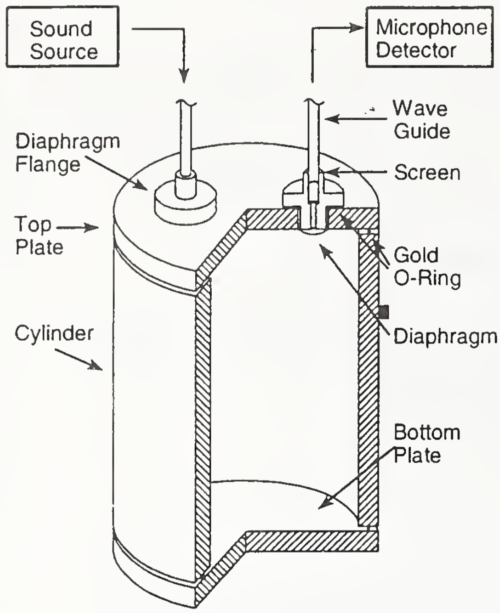

Cylindrical Resonator

Sound Speed.

Ideal-Gas Heat-Capacity, $C_P^0(T)$.

$P(T,V)$, Equation of State.

Thermal and viscous losses at the boundaries.

Duct effects

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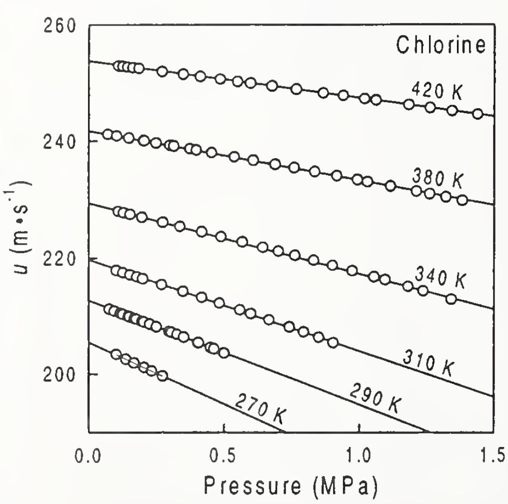
Analysis of Sound Speeds.



Acoustic Virial Equation Of State:

$$u^2 = \frac{\gamma^o RT}{m}\left(1 + \frac{\beta_a p}{RT} + \frac{\gamma_a p^2}{RT} + \frac{\delta_a p^3}{RT} + \ldots\right)$$

- Zero-Pressure intercept - $C_P^0(T)$

$$\frac{C_P^0(T)}{R} = \frac{\gamma_0(T)/M}{\gamma_0(T)/M - 1}$$

- Slope - $P(T,V)$

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Ideal-Gas Heat-Capacities

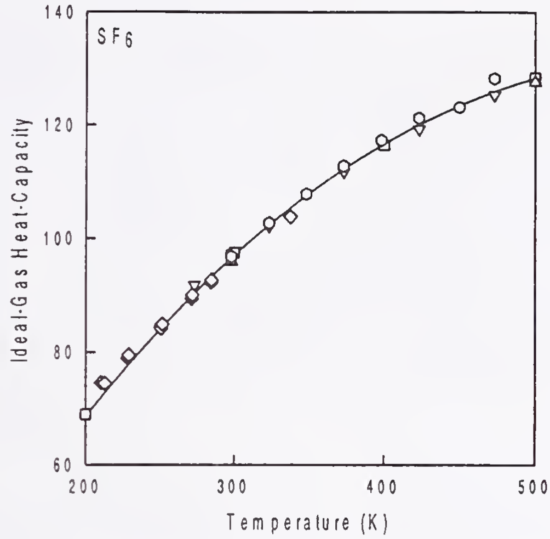

Figure 3. Measured Ideal-Gas Heat-Capacities for SF_6 compared to various calculated values from spectroscopy.

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Virial Equation of State

$$P = RT\rho\left[1 + B(T)\rho + C(T)\rho^2 + \cdots\right]$$

- Exact Thermodynamic Relations Relating Acoustic to Density Virial Equation of State.
- Algebraic expressions for $B(T)$, $C(T)$ ....
- Able to Fit $u(P,T)$ Surface.

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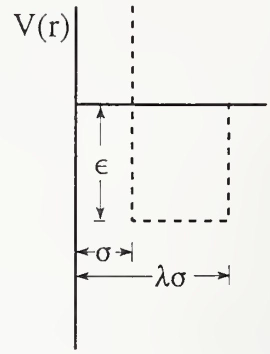
Hard-Core Square-Well Model

$$B(T) = b_o \left[1 - \left(\lambda^3 - 1 \right) \Delta \right]$$

$$C(T) = \frac{1}{8} b_o^2 \left(5 - c_1 \Delta - c_2 \Delta^2 - c_3 \Delta^3 \right)$$

$$c_1 = \lambda^6 - 18\lambda^4 + 32\lambda^3 - 15$$
$$c_2 = 2\lambda^6 - 36\lambda^4 + 32\lambda^3 + 18\lambda^2 - 16$$
$$c_3 = 6\lambda^6 - 18\lambda^4 + 18\lambda^2 - 6$$



where $\Delta = \exp(\epsilon/k_B T) - 1$,
ϵ is the well depth,
λ is the ratio of the attractive diameter to σ hard diameter,
$b_0 = ⅔\pi N_A \sigma^3$ is the molar volume of the hard core.

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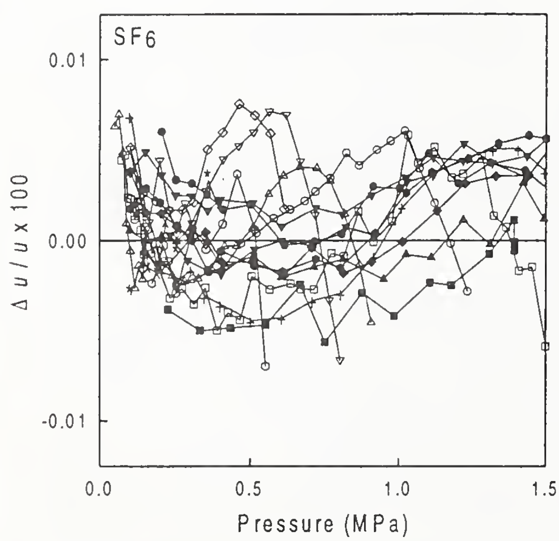
Fitted SF_6 Sound Speeds



Deviations of SF_6 speed-of-sound data from fitted equations,
$[(u_{exp} - u_{eos}) / u_{eos}] \times 100$.
Key: ■ 460K; ● 440K; ▲ 420K; ▼ 400K; ◆ 380K; ⬢ 360K; ✚ 340K; □ 320K; ○ 300K; Δ 280K; ∇ 270K; ◇ 260K; ⬡ 250K; ✳ 240K; ✖ 230K.

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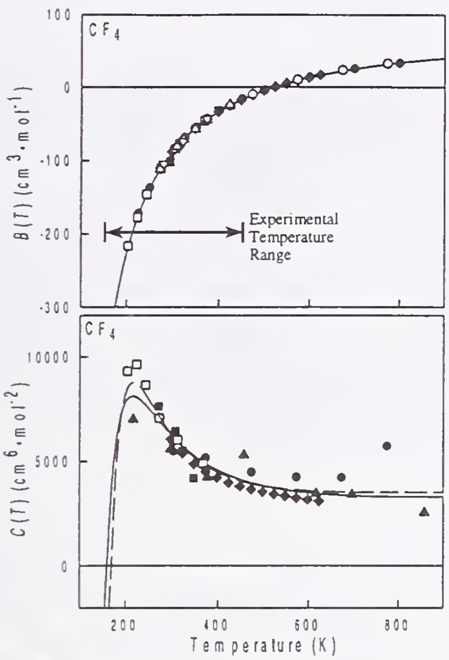
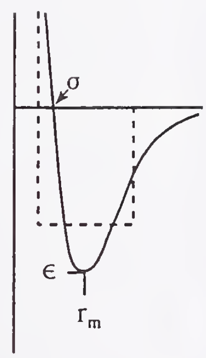
Virial Coefficients of CF_4



Virial Coefficients of CF_4.
Key: —— fit to the HCSW
- --- -) fit to the HCLJ.
Data: ● Ref. [11];
■ Ref. [12]; ▲ Ref. [13];
▼ Ref. [14]; ◆ Ref. [15];
○ Ref. [16]; □ Ref. [17];
Δ Ref. [18]; ∇ Ref. [19].

Advanced Modeling



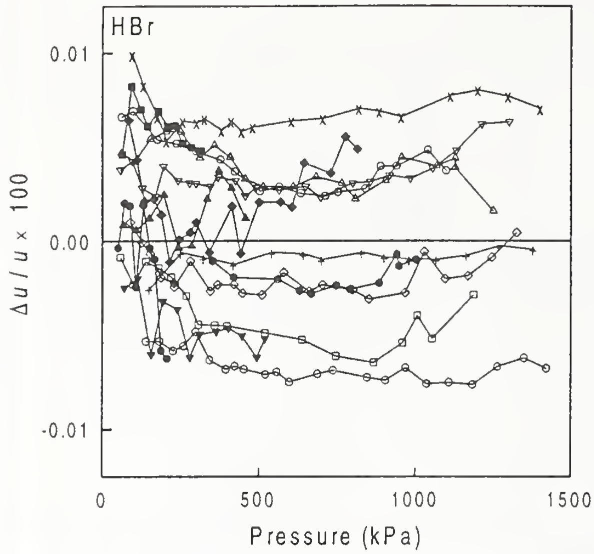
- Hard-Core Lennard-Jones 12-6 Potential.

$$\varphi(r_{ij}) = 4\,\varepsilon \left\{ \left(\frac{\sigma - 2a}{r_{ij} - 2a} \right)^{12} - \left(\frac{\sigma - 2a}{r_{ij} - 2a} \right)^{6} \right\}$$

- Axilrod-Teller triple-dipole term

$$\varphi(r_{123}) = \frac{\nu_{123}\left(1 + \cos\theta_1 \cos\theta_2 \cos\theta_3 \right)}{\left(r_{12}^3\, r_{13}^3\, r_{23}^3 \right)}$$

Fitted HBr Sound Speeds



Deviations of measured sound speeds in HBr from fitted equations, $[(u_{exp} - u_{eos}) / u_{eos}] \times 100$. Key: ● 230 K; ■ 240 K; ▲ 250 K; ▼ 260 K; ◆ 280 K; ○ 300 K; □ 320 K; Δ 340 K: ∇ 360 K; ◇ 380 K; ⬢ 400 K; ✖ 420 K; ✚ 440K.

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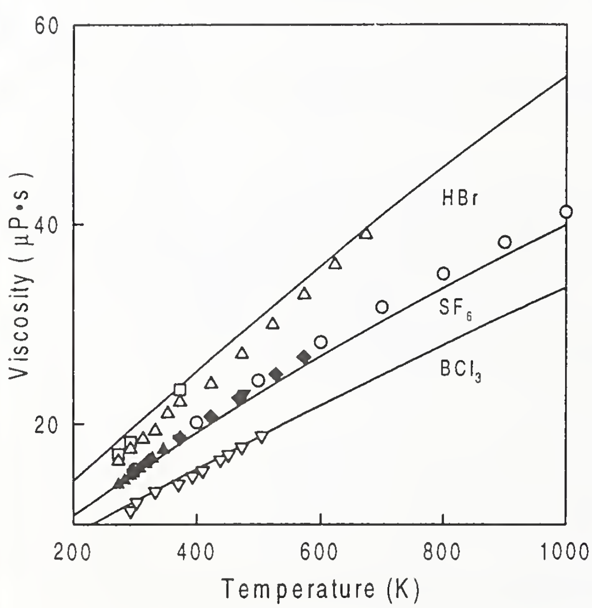
Estimated Viscosities



Gas viscosities. Curves and Open symbols are estimates; Solid Symbols are measurements. Key: —— present estimate; HBr: □ Ref. [25]; Δ Ref. [26]; BCl_3: ∇ Ref [30]; SF_6: ○ Ref. [27]; ◆ Ref. [28]; ▲ Ref. [29]; ▼ Ref. [30].

- Eucken Approximation.

$$[\lambda]_{Eucken} = \frac{15}{4}\frac{R}{M}\eta\left(\frac{4}{15}\frac{C_v}{R} + \frac{3}{5}\right).$$

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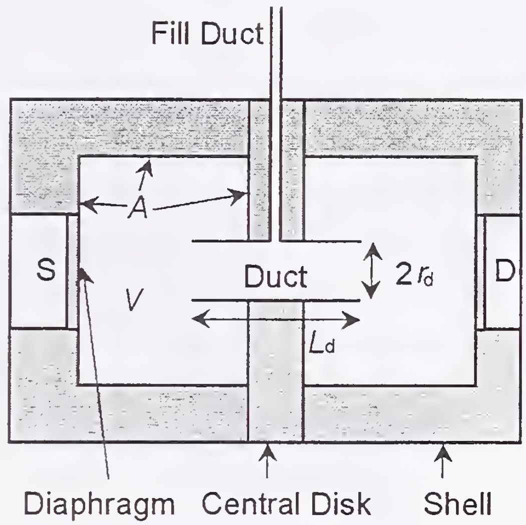

Greenspan Viscometer

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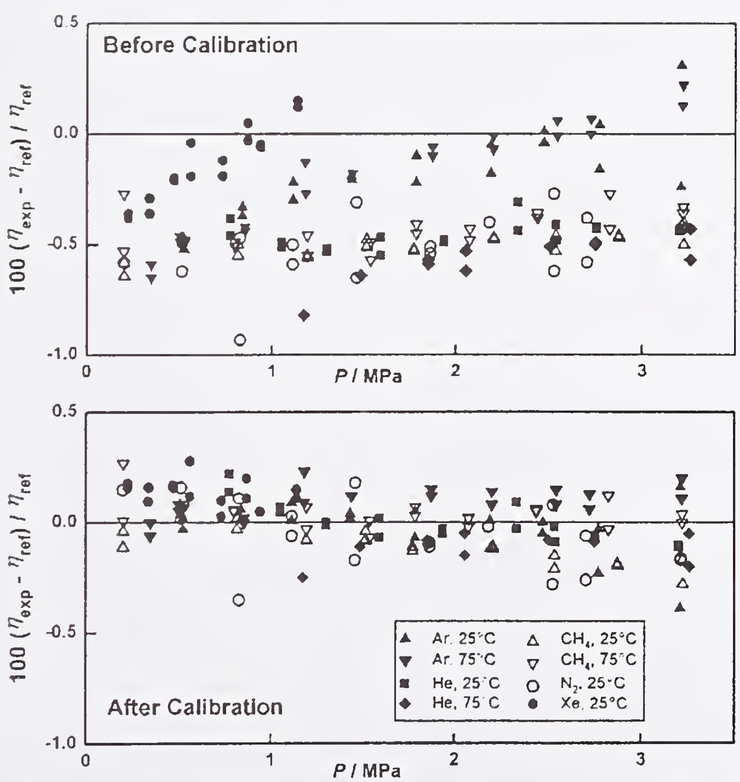

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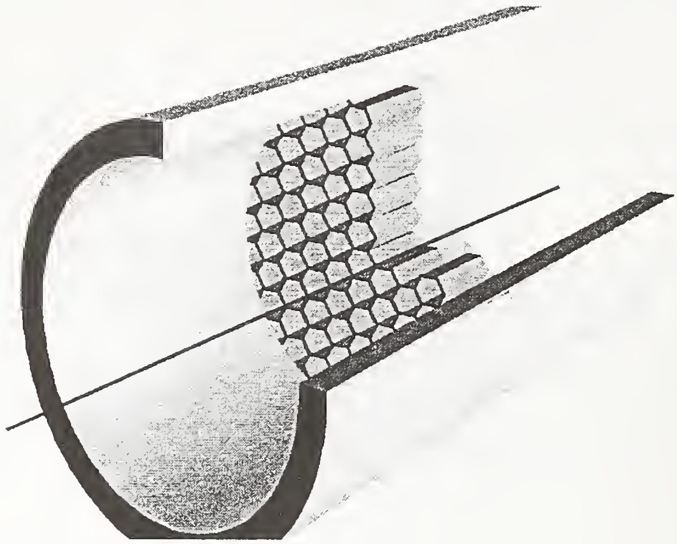

Prandtl Number Device

$(Pr \equiv \eta C_p/\lambda)$

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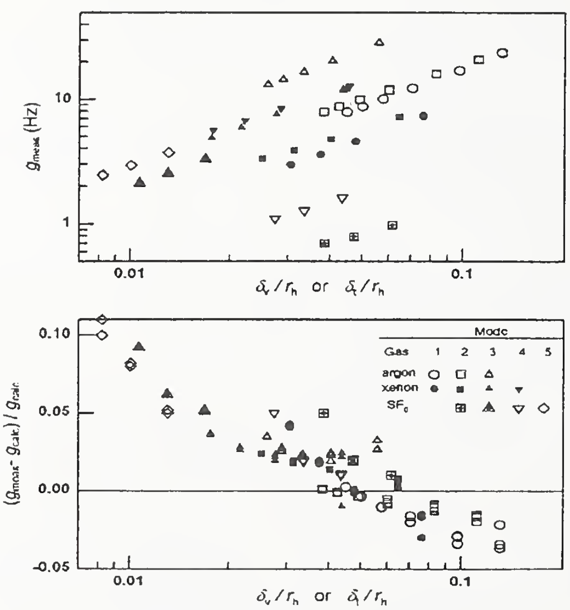

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Tungsten Hexafluoride	M.W. [1] 297.84	N.B.P. [2] 290.25 K	T.P. [2] 275.0 K
WF_6	P_c [3] 4.57 MPa	T_c [3] 452.7 K	V_c [3] 0.1 m^3/kmol

T K	$C_p^o(T)/R$	Vapor Pressure MPa	$B(T)$ $cm^3 \cdot mol^{-1}$	$dB/dT \cdot T$ $cm^3 \cdot mol^{-1}$	$C(T)$ $cm^6 \cdot mol^{-2}$	$dC/dT \cdot T$ $cm^6 \cdot mol^{-2}$	κ mW/(m·K)	η μPa·s
Estimated Uncertainty	1.0/0.1%	1%	Gas densities are calculated to better than 0.1% over the temperature and pressure ranges of the reference.				10%	10%
Reference	[4]/[5]	[6]	[5]	[5]	[5]	[5]	[5]	[5]
255	13.49	15.47	-1097.3	2819.0	-505611	5435305	6.5	16.05
260	13.60	21.22	-1044.2	2654.8	-409306	4512569	6.6	16.28
265	13.71	28.66	-995.0	2505.4	-330733	3760214	6.8	16.51
270	13.82	38.15	-949.5	2369.0	-266380	3143590	6.9	16.75
275	13.92	50.09	-907.2	2244.1	-213492	2635750	7.1	16.98
280	14.03	64.94	-867.8	2129.6	-169892	2215594	7.3	17.21
285	14.13	83.21	-831.1	2024.3	-133851	1866498	7.4	17.44
290	14.23	105.45	-796.7	1927.2	-103990	1575285	7.6	17.67
295	14.33	-	-764.5	1837.5	-79201	1331447	7.7	17.91
300	14.42	-	-734.4	1754.5	-58589	1126565	7.9	18.14

References:
1. IUPAC; "Atomic Weights of the Elements 1993"; *J. Phys. Chem. Ref. Data* 1995, 24, 1561.
2. E. F. Westrum, *Pure and Appl Chem.*, 1964, 8, 187.
3. V. V. Malyshev, *Teplofizika Vysokikh Temperatur*. 1973, 11, 1010.
4. M. W. Chase, "NIST-JANAF Themochemical Tables, Fourth Edition", *J. Phys. Chem. Ref. Data*, Monograph 9, 1998, 1-1951.
5. J. J. Hurly, "Thermophysical Properties of Gaseous Tungsten Hexafluoride from Speed-of-Sound Measurements", *Int. J. Thermophys.*, In Press.
6. D. R. Stull, "Vapor Pressure of Pure Substances", *Ind. Eng. Chem.* 1947, 39, 517.

Figure 9. Example Web Page for the On-Line Semiconductor Process Gas Properties Database.

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Index of Semiconductor Process Gases

Argon	Ar	Nitrogen Trifluoride	NF_3
Allene	C_3H_4	Nitrogen	N_2
Arsenic Trifluoride	AsF_3	Phosgene	$COCl_2$
Arsine	AsH_3	Phosphourous Trifluoride	PF_3
Trimethyl Arsine	$As(CH_3)_3$	Phosphorous Pentafluoride	PF_5
Diborane	B_2H	Phosphine	PH_3
Pentaborane	B_5H_9	Sulfur Dioxide	SO_2
Boron Trichloride	BF_3	Stibine	SbH_3
Bromine	Br	Silane	SiH_4
Carbon Monoxide	CO	Disilane	Si_2H_6
Carbon Tetrafluoride	CF_4	Silicon Tetrachloride	$SiCl_4$
Chlorine	Cl_2	Silicon Teterafluoride	SiF_4
Chlorine Trifluoride	ClF_3	Sulfur Hexafluoride	SF_6
Ethylene Oxide	C_2H_4O	Titanium Tetrachlofirde	$TiCl_4$
Helium	He	Tungsten Hexafluoride	WF_6
Hexafluroethane	C_2F_6	Uranium Hexafluoride	UF_6
Hydrogen Bromide	HBr	Vinyl Bromide	C_2H_3Br
Hydrogen Chloride	HCl	Vinyl Fluoride	C_2H_3F
Hydrogen Fluoride	HF	Vinyl Chloride	C_2H_3Cl
Hydrogen Sulfide	H_2S	Trimethyl Gallium	$Ga(CH_3)_3$
Molybdenum Hexafluooride	MoF_6	Triethyl Gallium	$Ga(C_2H_5)_3$
Nitric Oxide	NO	Trimethyl Indium	$In(C_2H_5)_3$
Nitrous Oxide	NO_2		

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Conclusions

- We can measure sound speeds $u_r < 0.01\%$ in process and surrogate gases spanning the ranges $0.05 \leq P \leq 1.5$ MPa and $200 \leq T \leq 475$ K.
- From Sound Speeds we deduce the ideal-gas heat-capacity, and the virial equation of state which is valid outside our experimental temperature range. $u_r < 0.1\%$
- Through advanced modeling, we can estimate transport properties over a wide temperature range. $u_r < 10\%$
- We are developing advanced acoustical techniques for measuring viscosity and thermal conductivity.
- We will make the results available in a user friendly format, via web or PC program.

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Flow Controller for Semiconductor Industry

Kaveh Zarkar Ph.D.

Manager, Advanced Technology

NIST

May 15- 16- 00

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SIA ROADMAP (NTRS)

- "…reductions in feature size and increases in wafer diameter are not sufficient to keep the industry on its historic 25-30% manufacturing cost learning curve."
- "…improvements in developing, purchasing and operating equipment are required…OEE."

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Contents

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- Semiconductor Key Industry trends.
- Key Processes.
- Dynamics.
- Technology development trends.
- Technical Trend for Mass Flow Control.

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[illegible] SIA Roadmap (NTRS)

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- National Technology Roadmap for Semiconductors

	1999	2000-2002		2003
TREND CATEGORY:	TREND	TREND	IMPLICATION	TREND
Min Feature Size	250nm	180 - 150 nm	New materials are needed.	130 nm
DRAM Level	65 Mb	256 Mb- 1G	Material QC	4G
Number of metal levels (Logic)	6	6-7		7
Interconnect Metal	A1-Cu	A1-Cu		Cu
IMD	$Si0_2$	$Si0_2$, Si0F		Si0F, Aerogels, etc.
Gate Oxide	40-45A	35-40A		20-30A
Contact / via CD	0.28	0.2		N/A
Contact via aspect ratio (Logic) (DRAM)	5.5:1	6.3:1		Amorphous Carbon for Ultra Low K.

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[illegible] Key Industry Trend

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- Shift in the Industry trend from Batch Process to Single Wafer would impact the traditional Gas System Components.
  - **Low Flow Rates for some processes <1 sccm, etch CVD processes**
  - Higher flow rates for RTP, EPI (100- 300 slm)
  - Low Pressure Drops
  - ESC Adoption for Vacuum Processes
  - Heat Transfer and Pressure Control of Wafer on the Chuck. (Backside Wafer Cooling/Heating)
  - Integration of analytical tools with equipment

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Equipment Manufacturer's Major Challenge in 2000's

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- Improve OEE (MTBF,MTTR), under new performance requirement.
- Automation/uniform communication protocol.
- New Materials handling/process.
- Real Time Process Control.
- Tool Cost/Footprint Reduction.
- Safety/Environmental.
- Process Integration.
- Lower Consumable cost per die.

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Semi Equipment Selection Criteria

Source: SEMI

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Decade	1960s	1970s	1980s	1990s
COO and Price	10	20	30	45
Performance	90	70	30	25
Global Support	0	10	30	25
Continuing Improvement	0	0	0	5

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Technology Development Trends

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- Migration to Lower Process Pressure HDCVD
- Migration to Liquid Source Pre-cursors (SACVD)
- Low and High K Dielectric material advancement
- Higher Process Temperature recipes.
- In-Chamber Gas Monitoring and Delivery Control
- Direct Liquid Injection, Vaporizer systems
- Backside Wafer Cooling/Heating

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Technology development Trends

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- SACVD (TEOS / O3), will be the main technology focus for encapsulation of SOD and capping layers for the next few generations
  - TEOS is the material of the choice for FEOL processes
  - Liquid/ bulk precursors are emerging applications
  - DLI, Challenges for Liquid Source delivery
- Requirement:
  - Liquid MFCs for DLI
  - Vaporizer systems
  - Robust Platform technology for liquid/vapor delivery

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Technology development Trends

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- Low and High K materials are advancing.

Material	K Value	Deposition Method
SiN	7	CVD
SiO_2	4	CVD
SiOF	3.3	CVD
Polyamide	3-3.5	Spin-on
Hydrogen Silsesquioxane HSQ	3	Spin-on
Fluorinated Polyamides	2.8	Spin-on
Methyl Silsesquioxane MSQ	2.7	Spin-on
Organic Polymers	2.3-2.7	Spin-on
Polyarylene Ethers	2.6	Spin-on
Parylene F	2.3	CVD
Fluorinated Amorphous Carbon	2.2	CVD
Teflon	2.1	CVD, Spin-on
Silica Aerogels	1.1-2.0	Spin-on
Air Bridges	1.0	Subtractive

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Technology Development Trends

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- Dielectric continued..........
  - Most near future schemes involve vaporized liquids
  - Most liquids are air reactive- Carrier gas purity control and better delivery systems are needed.
- Requirement
  - Bulk HCL purification for chamber clean is ideal. High capacity purifiers are needed.
  - High Flow controllers for HCL & NH3. Small capillary MFCs are not suited. Large Capillary and P-based should be considered
  - Low inlet pressure MFCs for SSD* application.

*SSD = Solid Source Delivery

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- Direct Liquid Injection, Vaporizer Systems.
  - Material properties dictate product technology development.
- Chemical categories:
  - Chemicals used in the future Technology Trends for Metal CVD, Dielectric CVD, Barrier CVD, EPI and Clean are often difficult to handle, due to their properties.
    - Liquid Stability
    - Vapor Stability
    - Viscosity
    - Toxicity

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[illegible] Chemical Categories

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Category	Flow R	Vapor P	Stable	Gas
A	Low	High	Yes	TEOS,TMP TiCl4,TDMAT
B	Low	Low	Yes	Ta2O5,TDEAT TEASAT
C	Med	High	No	Cu(I),TaN
D	Low	High	Yes (Pyro)	DMAH
E	High	High	Yes(Corr)	HSiCl3,TiCl4, H2SiCl2
F	Low	Low	No (solid)	BST,PLZT, SBT,
G	Low	Low	Yes (Toxic)	PH3,AsH3,BF3

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[illegible] In-Chamber Monitoring

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- Requirement:
  - In-Chamber Gas Constituency Monitoring systems
  - DeviceNet as Sensor Bus prime mover.
  - Network ready Gas Panel components.
  - Self diagnostic capability (Interactive Sensors) is Key.
  - Multifunctional components (Filters/Purifiers, MFCs) is required for the cost and "footprint" reduction.

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[illegible] Typical Process Tool

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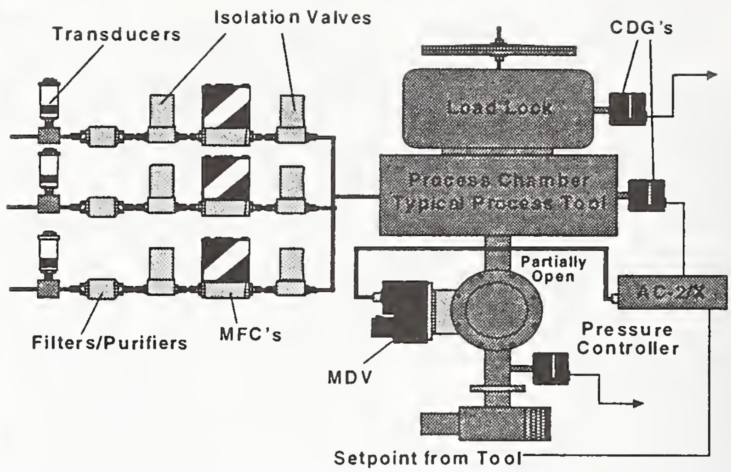

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Technical Advances in Mass Flow Control

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- Mass Flow Controller Technology.
  - Thermal Mass Flow Controllers
  - P-Based Mass Flow Controllers
  - Sonic Nozzle Mass Flow Controllers
  - MEMS based Mass Flow Controllers
  - Coriolis based Mass Flow Controllers
  - Acoustic Flow Controllers
- Future MFC Performance. (Key Attributes)
  - Mechanical Design (Valve, Flow Sensors)
  - Electronic Design (Analog, Digital)
  - Serviceability/Reliability (Self Diagnostics)
  - Communications (Sensor Bus motivation)

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- All Mass Flow Controllers, have in common, three functional elements:
  - "Sensor" to measure the Mass Flow Rate.
  - "Valve" to regulate the flow of gas.
  - "Electronics" to translate input commands to achieve the desired flow rate output.

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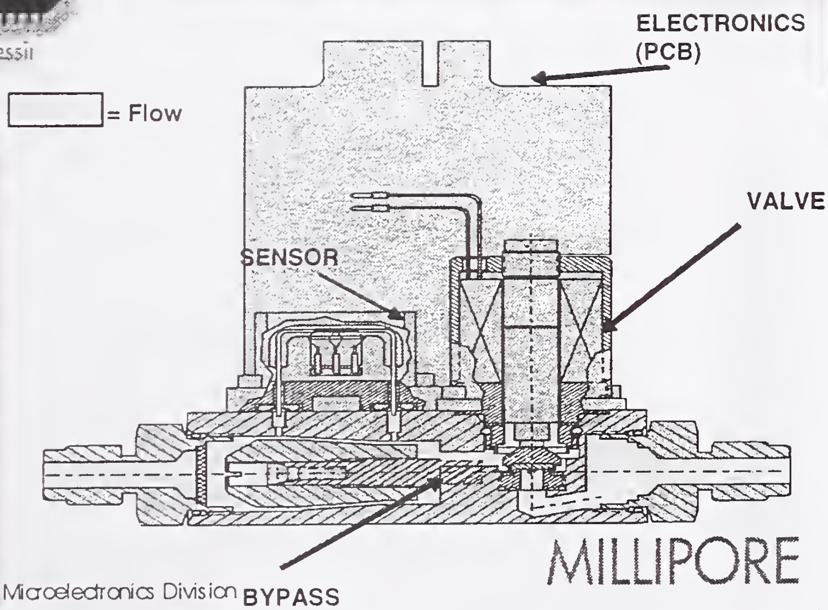

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Thermal Mass Flow Control

- Flow Splitter
- Flow Sensor
- Control Valve
- Electronics

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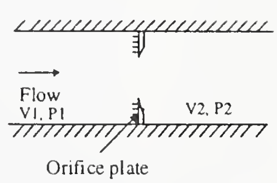
Pressure-based Mass Flow Control

- **Based on Flow through an Orifice**

ΔP across orifice is proportional to the volumetric flow rate through the orifice.

Flow is considered choked when the velocity is sonic. This is considered critical flow and is the maximum velocity for a given inlet pressure.

For critical flow conditions:



$q = .01749 * (P1_{(psia)}/29.7) * \sqrt{MW_{air}/MW_{gas}} * d_o^2\ (\mu m)$ or

$q = C * 13.63 * P1_{(psia)} * \sqrt{1/T_{(R)} * S_g}$

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Pressure Based Mass Flow Control

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- Flow Orifice Plate.
- Upstream Pressure Transducer
- Downstream Pressure Transducer
- Control Valve
- Electronics

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Sonic Nozzle Mass Flow Control

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- Based on measuring Flow through an orifice under "Choked Condition".
  - Sonic Nozzle Orifice
  - "Upstream" Pressure Transducer
  - Control Valve
  - Electronics

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MEMS P-based Mass Flow Control

- Based on measuring Flow through an orifice, using "MEMS" sensors.

  - Micromachined Silicon Orifice
  - Micromachined Pressure Sensor
  - Micromachined Control Valve
  - Electronics

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MFC's Key Attributes

- Accuracy
- Linearity
- Repeatability
- Reproducibility
- Transient Characteristics
- Leak Integrity
- Particle Generation
- Pressure Coefficient
- Temperature Coefficient
- Attitude Sensitivity
- Long Term Stability
- Valve Leak Through
- Reliability
- Serviceability

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Digital Mass Flow Controller advantage

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- **Increased Functionality**
  - Improved Accuracy (Digital valve control)
  - Increased Dynamic Range. > 100 :1
  - Increased Controllability.
  - Elimination of mechanical/manual adjustment
  - Multiple Gas curve storage.
  - Embedded "Drag & Drop" multigas Calibration database.
  - Elimination of Overshoot/undershoot for fast TTS.
  - Self-Diagnostics to reduce Tool downtime.
    - Raw sensor monitor
    - Control Valve Current or voltage
    - Flow Oscillation
    - Gas line Pressure measurement.
    - Gas Line Temperature measurement

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[illegible]

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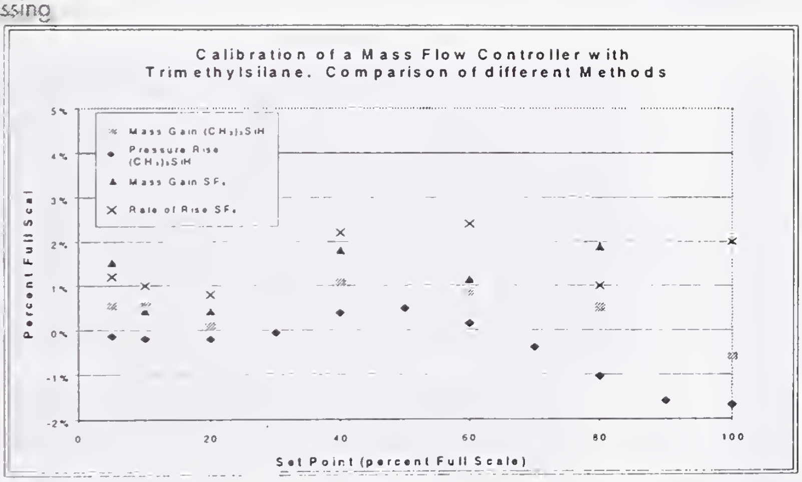

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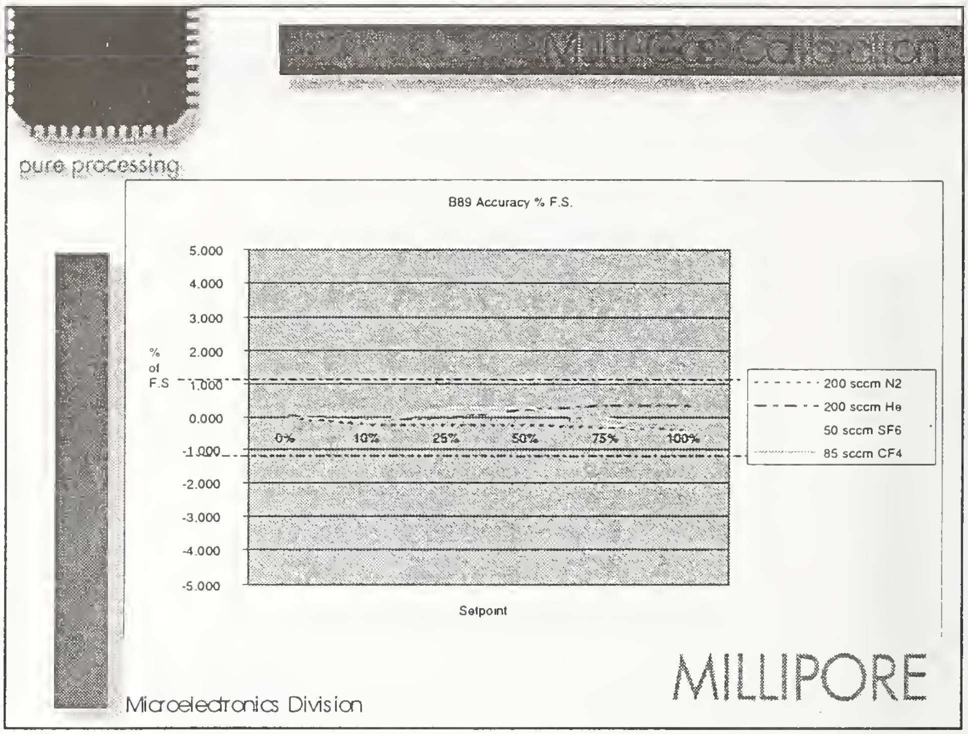
Multi-Gas Calibration
pure processing
B89 Accuracy % F.S.
5.000
4.000
3.000
2.000
1.000
0.000
-1.000
-2.000
-3.000
-4.000
-5.000
% of F.S
0%
10%
25%
50%
75%
100%
Setpoint
200 sccm N2
200 sccm He
50 sccm SF6
85 sccm CF4
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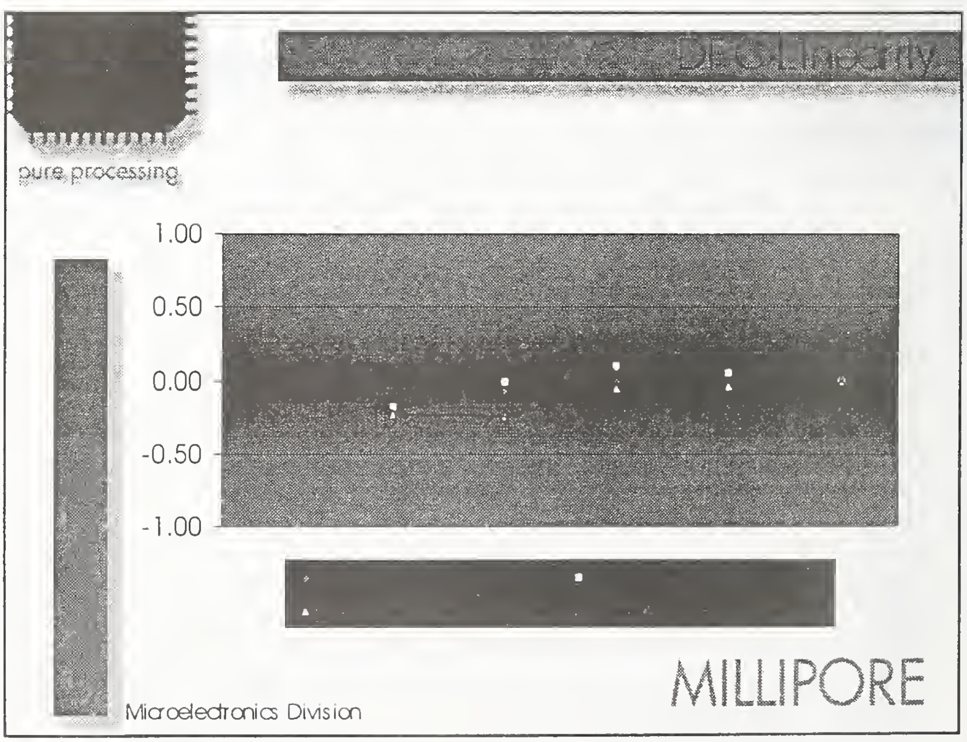
Linearity
pure processing
1.00
0.50
0.00
-0.50
-1.00
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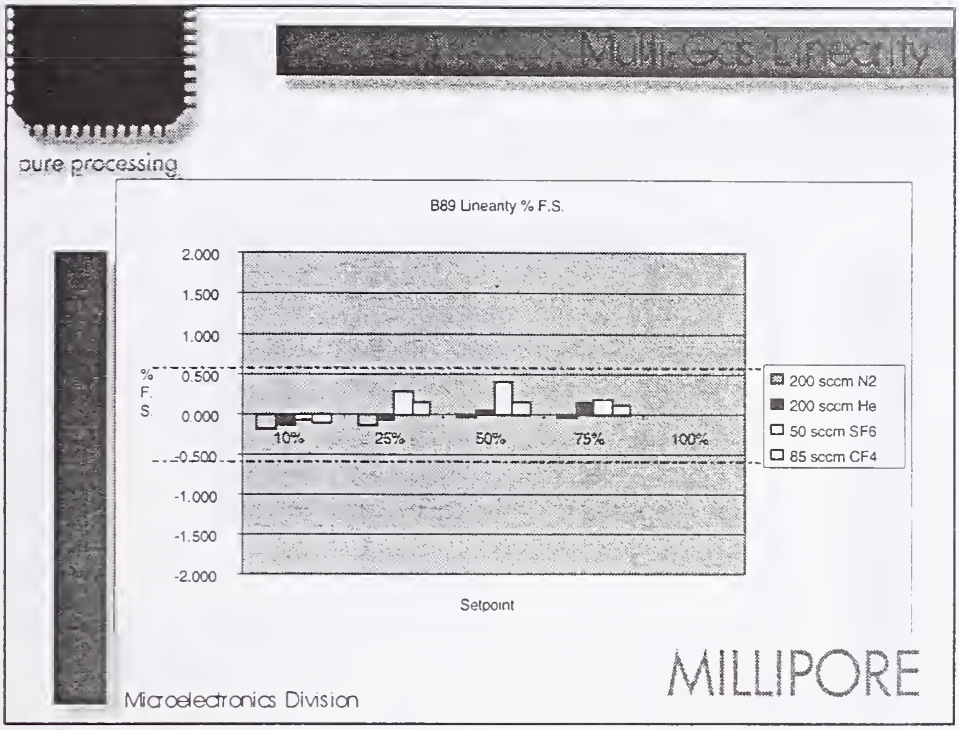
Multi-Gas Linearity
pure processing
B89 Linearity % F.S.
2.000
1.500
1.000
0.500
0.000
-0.500
-1.000
-1.500
-2.000
% F. S.
10%
25%
50%
75%
100%
200 sccm N2
200 sccm He
50 sccm SF6
85 sccm CF4
Setpoint
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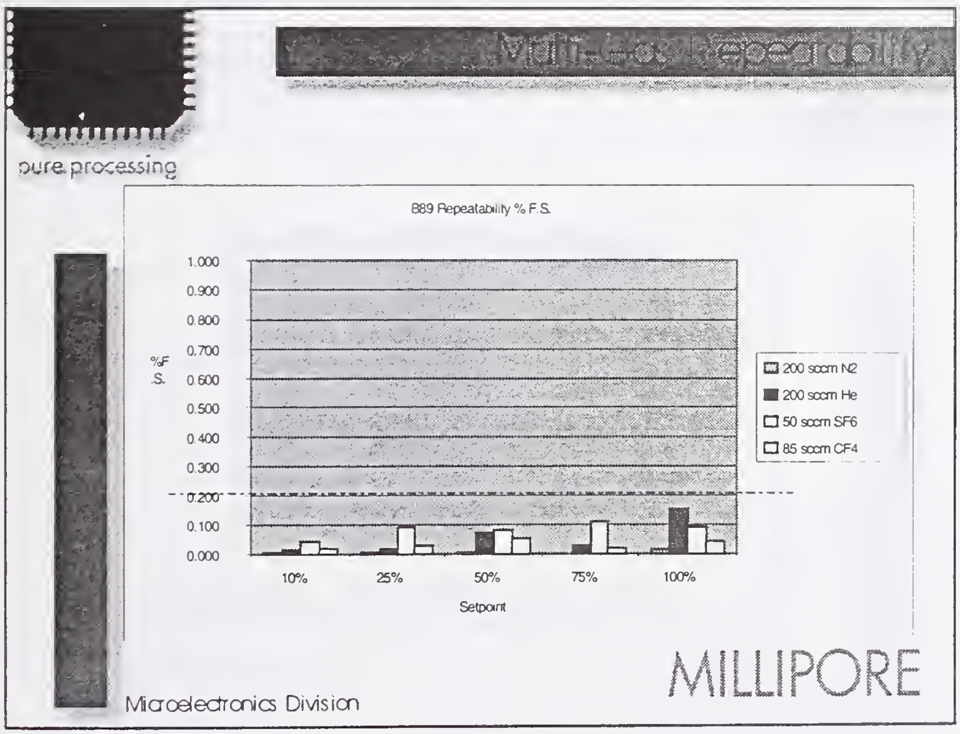
Multi-Gas Repeatability
pure processing
B89 Repeatability % F.S.
1.000
0.900
0.800
0.700
0.600
0.500
0.400
0.300
0.200
0.100
0.000
%F .S.
200 sccm N2
200 sccm He
50 sccm SF6
85 sccm CF4
10%
25%
50%
75%
100%
Setpoint
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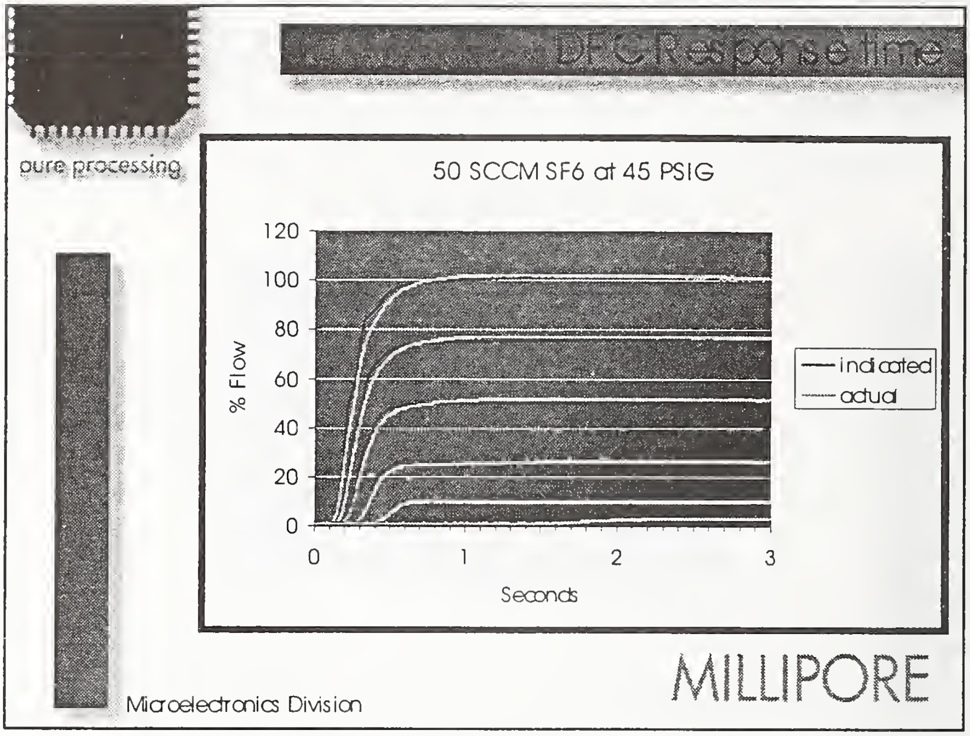

DFC Response time
pure processing
50 SCCM SF6 at 45 PSIG
120
100
80
60
40
20
0
% Flow
0
1
2
3
Seconds
indicated
actual
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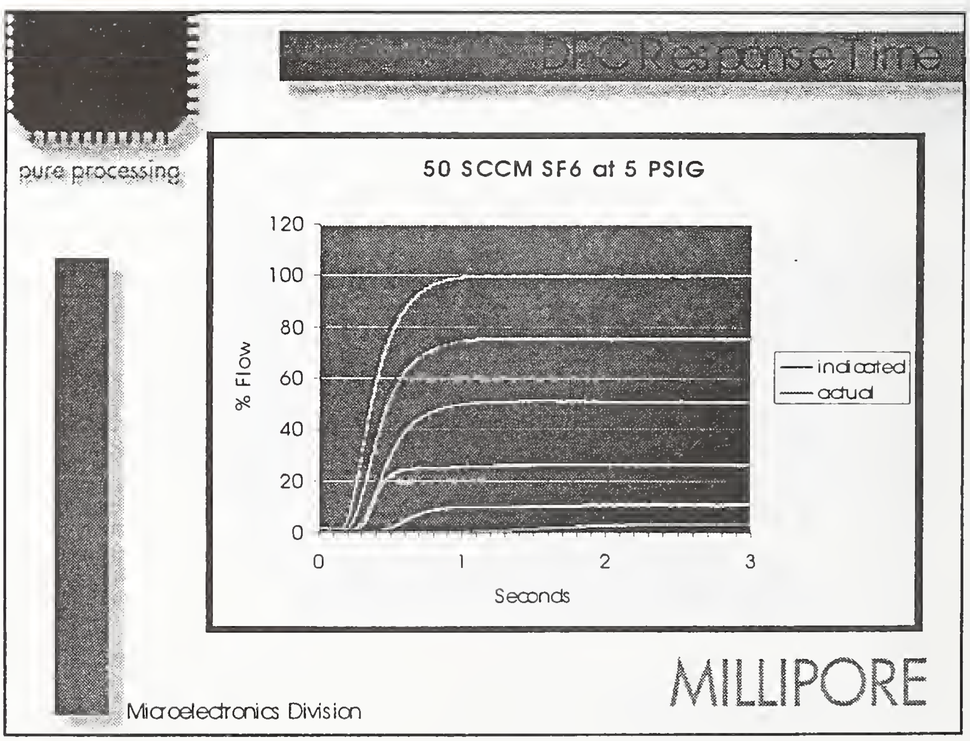

DFC Response Time
pure processing
50 SCCM SF6 at 5 PSIG
120
100
80
60
40
20
0
% Flow
0
1
2
3
Seconds
indicated
actual
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Sensor Bus Assessment Criteria

- Candidates
  - World FIP
  - CAN* (DeviceNet, SDS)
  - LonWorks
  - Seriplex
  - ISP
  - Bitbus /IEEE-118
- *CAN= Controller Area Network

- Factors considered
  - Interoperability
  - Availability
  - Survivability
  - Repeatability
  - Speed
  - Flexibility
  - Node Cost
  - Track record
  - Determinism
  - Node Size
  - Tools & development Cost

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Sensor Bus Trend

- CAN based (Controller Area Network) protocols will expand rapidly in the next few years.
- DeviceNet is the front runner and is the protocol of choice with several major OEMs.
- DeviceNet has formed ODVA (Open DeviceNet Vendor Association).
- European PNO (ProfiBus User Organization) and its north American arm PTO, are supported by Siemens and many European OEMs and will be strong in Europe.

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Summary

- New Platform Digital Mass Flow Controller would be the heart of the Chamber Process Control.
  - Pressure Insensitive
  - Multi- Gas
  - Wide Dynamic Range
  - Peer to Peer Communication
  - Distributed Control
  - DeviceNet and ProfiBus are protocols of the choice.
  - In-Situ Chamber Gas Constituency monitor to control the Mass Flow of Gas, eventually would replace the conventional "Downstream Pressure Control" techniques.

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NIST *Technical Publications*

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Journal of Research of the National Institute of Standards and Technology—Reports NIST research and development in those disciplines of the physical and engineering sciences in which the Institute is active. These include physics, chemistry, engineering, mathematics, and computer sciences. Papers cover a broad range of subjects, with major emphasis on measurement methodology and the basic technology underlying standardization. Also included from time to time are survey articles on topics closely related to the Institute's technical and scientific programs. Issued six times a year.

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