

Industrial Sampling Systems

Reliable Design & Maintenance for Process Analyzers

By Tony Waters

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Foreword

For more than 65 years, process instrumentation engineers and technicians have relied on Swagelok® products to connect and deliver stable samples to plant analyzers. Absolutely critical to process control, analyzers deliver a precise measure of process conditions quickly so that facility control systems can adjust parameters as needed to ensure the quality of a finished product.

Sampling technology has evolved steadily from early grab sampling to today's automated online systems. The fact remains, however, that analyzers can only be as accurate and responsive as the system of components that supplies them with a process sample.

The engineer in charge of designing these sampling systems and the technician managing them must be highly trained and experienced. Sampling system mistakes are always costly, are sometimes dangerous, and often go undetected. Incredibly, few colleges and universities offer sampling system design in their curricula. Perhaps it's because little has been written that could appropriately be used as a textbook. Until now.

Authored by Tony Waters, who is acknowledged by many as the leading expert in the design of sampling systems, *Industrial Sampling Systems* captures the experience and knowledge Tony has acquired during a career of more than 50 years. Its balance of theory and practical examples makes it the perfect reference for students as well as experienced sampling system engineers, designers, and technicians.

We're proud to be a part of the creation of this work and believe firmly that it will prove to be a valuable resource for those who are charged with the critical responsibility of designing, installing, and maintaining process analyzer systems. You, the reader, are the final judge of course, and we welcome your comments and feedback as you put this reference to work.

Arthur F. Anton
President and CEO
Swagelok Company

Preface

At first, it might not appear so. But this book is really about measurement, a peculiar kind of measurement that has given us all quite a lot of trouble since its inception in Germany, circa 1937, when the first process infrared analyzer debuted.

Process analyzers were a new breed of instrument. Instead of measuring the *quantity* of the stuff flowing through the pipes, they measured its *quality*—its clarity or purity, for instance.

I would not want to imply that this new kind of measurement has let us down: quite the opposite, in fact. Over the years, our ability to measure the quality of a process fluid has improved tremendously, and it continues to do so.

The trouble is not so much due to the measurement. It's due to the poor reliability of the process interface, the *Industrial Sampling System* that connects these delicate analytical instruments to harsh industrial processes.

Connecting a process analyzer to an industrial plant may seem to be a simple task; but really, it's quite complex. It demands a melding of instrumentation, analytical chemistry, and chemical engineering knowhow, and few people are skilled in all of those technical arts. I sincerely hope that those in colleges and training institutions will use this textbook to teach a new cadre of analyzer professionals the science and art—and yes, the fun—of sample system design.

Those of us now retiring learned all this the hard way. For 50 years, I've watched sampling systems fail in balmy places and icy places, and all places in between. Always for the same tired old reasons. And for more than half of those years, I've learned more about sampling from my students on six continents. Perhaps at last, I know how to do it.

Many friends and colleagues also learned the hard way. They built a body of knowledge and experience—what works and what doesn't—gleaned from oily jobsites, and from scattered talks and articles. Until now, that store of pragmatic insight and theory has not been conveniently accessible to the design engineer or maintenance technician.

Now, you have it.

We hope you enjoy the book. More so, we hope you act upon it to improve the performance of all your industrial sampling systems.

Tony Waters
Atascadero, California
April 2013

Acknowledgements

What an experience! Five years of oftentimes lonely but forever supported and uplifting work. I have so many to thank for their wise counsel, for their patience, and most of all for their valuable time. This book would not have left the starting gates without the enthusiasm of Swagelok executives, **Art Anton**, **Mike Butkovic**, and **Fran Dacek**; and would never have finished the course without their long patience and yes, their occasional scolding. In that long process, colleagues have become friends and friends have become mentors. A heartfelt high-five to **Doug Nordstrom** who from day one has been by my side as editor-in-chief, and to my mentors **Jimmy Converse**, **Bert Laan**, and **Zoli Hajdú** for sharing their real-world experience with sampling. And thanks to my technical review team who on their own time studied every word (really) and made so many good suggestions, and some not so good; particularly to **Ron Edmondson** and **Don Negrelli** who never missed a beat over four years of weekly meetings, and to **Sarah Liston**, **Chuck Hayes**, **Mike Gallagher**, **Jim Gotch**, **Andy Marshall**, **Brandon Fry**, and **Eric Kvarda**.

A book is so much more than the author and his technical team: it has to be produced. **Dave Waters** and **Jill Waters** set the tone with their delightful diagrams, while **Jim Peck** and **Jim Geshke** added the colorful page layouts and cover designs. Yet it wouldn't have happened at all without direction by **Fran Dacek**, coordination and proofreading by **Heather Gaynor**, editing by **Andy Evridge**, illustrations and permission by **Stephanie Hileman**, project management by **Gayle Poots**, brand reviews by **Jen Horn**, **Sunniva Collins**, **Rick Monreal**, **John Karkosiak**, and **Mark Rechner**, and some help with the Glossary from **Joe Patella**, **Mike Adkins**, **Joe Krance**, and **Mike LeRoy**.

And most of all, a big hug for my wife **Marilyn** who endured five years of solitude so I could get this out of my system. Perhaps we can go on vacation now?

My hearty thanks to you all.

Tony

How to Use This Book

Layout and Structure

The book responds to the needs of two different readers—the qualified practitioner who wants a quick answer to a pressing problem, and the newcomer studying the subject privately or in a formal learning course.

People working in industry will pick up the book to access information on a subject of particular interest at that time. They'll quickly look up a principle or an equation to assist them with a current need. These users are familiar with the subject and don't need multiple levels of explanation. They can go straight to the text and quickly find the information they need.

Newcomers and students working methodically through the text may need help with the basic science and technology used in sampling systems. We separate those explanations from the text. To describe the basic science of sampling, we use single-page *SCI-FILES* located throughout the book.



As an example, the *SCI-FILE On Motion* included in Chapter 1 outlines Newton's Laws and defines the measurement units for the common variables of motion that we will need in subsequent chapters.

The table opposite lists the title and location of each *SCI-FILE*.

To describe the underlying technology of sampling and analysis we use the Glossary in Appendix B. In each chapter, first occurrence of a technical term appears in **colored text** to indicate that more information about that term is included in the Glossary. As well as defining technical terms, the Glossary describes many process analyzers, defines measurement variables and their units, and gives useful information on selected chemical compounds. Separating all these descriptions from the text allows faster access for the experienced user.

In addition, readers who are unfamiliar with the principles of measurement will find that Appendix A gives an adequate primer on measurement science and its application to analytical instruments.

Quick Reference

A separate listing of numbered equations precedes the text in each chapter. As an aid to traceability, any equation used in another chapter retains its original reference number, and that number appears in parentheses alongside the equation.

A separate listing of the variables and symbols used in each chapter precedes the text in that chapter. An italic font distinguishes the symbols for variables, with vectors in bold. Symbols for measurement units appear in a roman (upright) font.

A convenient key to the graphical symbols used in illustrations is on the inside front cover, and there's a periodic table of the elements on the inside back cover.

As is common practice, a list of *References* at the end of each chapter provides sources for works cited in the text. In addition, the extensive bibliography in Appendix C catalogues selected

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books and articles that pertain to process sampling. This compilation may help those interested in the development of sampling to track the long history of the technology.

Use of SI Units

This book uses **SI units** for data and calculations. SI units are standard practice for international trade and commerce and almost universally used in science and technology. The big advantage of working in SI units is that calculations always work out perfectly, without ever needing a conversion factor. For more information on the SI system of units, read Appendix A-02 before getting started.

Table A01 in Appendix A-01 lists the names and symbols of the units we use and provides factors to convert **US customary units** to SI units.

In addition, the SI system of units allows the use of certain standard prefixes to increase or decrease the value of the standard unit. Table A10 in Appendix A-02 lists the prefixes commonly used in sample systems work.

Sampling techniques always involve pressure P , temperature T , and volume flow rate \dot{V} . Let's briefly review the units used for those key variables.

Units of Pressure

The SI unit of pressure is the pascal. The pascal is a small unit compared with the pressures common in sampling systems. To put it into perspective, it takes 101 325 pascals to make one **standard atmosphere**. So we need a larger unit for general measurement and discussion. Sometimes it is convenient to use kilopascal, but mostly we prefer to use bar.

The bar is a very convenient unit. By definition, it equals *exactly* 100 000 Pa or 100 kPa. That puts it very close to the standard atmosphere. In sampling, we often need to adjust gas volumes and gas flow rates to atmospheric pressure. Although atmospheric pressure varies from day to day, a reference pressure of 1.0 bar is close enough for those calculations, so we have adopted it for that purpose throughout this book.

Most pressure gauges and pressure transmitters measure process and sample pressures in **gauge pressure**. This is an additional complication. When your pressure gauge reads zero, the real or **absolute pressure** is not zero; it's about 1 bar! Because of this false zero, you can't use gauge pressure in calculations.

In this book, we use the unit symbols **bara** and **barg** for absolute and gauge pressure, respectively. We use kPa only for absolute pressure, never for gauge pressure. If you have a gauge pressure in kPa, just add 100 kPa to convert it to absolute pressure.

Since real atmospheric pressure is always close to one bar, it follows that:

$$x \text{ barg} = (x + 1) \text{ bara}$$

If the application data sheet gives pressures in barg, simply add 1 bar before doing any calculations. If you get data in **psig**, first convert it to **psia**:

$$x \text{ psig} = (x + 14.7) \text{ psia}$$

Note that 14.7 psi used above is the American customary unit value for the standard atmosphere (equal to 101.325 kPa) rather than the 100 kPa (14.5 psi) standard atmosphere used throughout this book.

Then, to convert the absolute pressure to bara, divide the psia value by the conversion factor 14.5 psi/bar:

$$x \text{ psia} = x \text{ psia} \times \frac{1 \text{ bar}}{14.5 \text{ psi}} = \frac{x}{14.5} \text{ bara}$$

To avoid confusion or error, don't use gauge pressure in calculations; convert the gauge pressure to absolute pressure!

Don't use gauge pressure in calculations!

Units of Temperature

The SI unit of temperature is the **kelvin** *K*. It does not use the word *degree*, nor does it take the degree sign. One kelvin is conveniently equal to one Celsius degree.

The Celsius and Fahrenheit temperature scales have arbitrary zero points, so they don't work well in calculations. Instead, always convert temperatures to kelvins before entering the values in an equation.

Don't use °C or °F in calculations!

If your application data gives a temperature in degrees Fahrenheit, convert it to degrees Celsius:

$$x\text{ }^{\circ}\text{F} = \frac{x - 32}{1.8}\text{ }^{\circ}\text{C}$$

If your data is in degrees Celsius, the conversion to kelvins is easy. To get an exact conversion, you should add 273.15 to the Celsius value. But for the accuracy of calculation required in sampling systems, you can just add 273.

$$x\text{ }^{\circ}\text{C} = (x + 273)\text{ K}$$

$$x\text{ }^{\circ}\text{F} = \left(\frac{x - 32}{1.8} + 273 \right)\text{ K}$$

One sometimes sees the measurement of differential temperature expressed in Celsius degrees $^{\circ}\text{C}$, but those units don't work with SI units in calculations. Since one Celsius degree is exactly equal to one kelvin, we elected always to use kelvins for the measurement of temperature difference, e.g.,

$$\Delta T = 65\text{ }^{\circ}\text{C} - 32\text{ }^{\circ}\text{C} = 33\text{ K}$$

The kelvin units are compatible with other SI units in equations that employ differential temperature.

Units of Flow

The SI unit of volumetric flow rate is the *cubic meter per second*. It does not have a name. Unfortunately, a cubic meter is a large volume; it's equal to 1000 liters. The liter is a more convenient size (think of a four-inch cube), so we often measure volume in *liter* (L) and flow in *liter per minute* (L/min).

In sampling and analysis, it is very common to see volume or flow stated in cubic centimeter units, often abbreviated to cc or cc/min. Since one cubic centimeter is exactly equal to one milliliter, these statements are exact:

$$1\text{ L} = 1000\text{ cm}^3\text{ (cc)}$$

$$1\text{ L/min} = 1000\text{ cm}^3/\text{min (cc/min)}$$

$$1\text{ mL/min} = 1\text{ cm}^3/\text{min (cc/min)}$$

It's incorrect to use the abbreviations cc and cc/min in calculations because they are not real units.

Other Units

We use the abbreviations **ppm** and **ppb** without further explanation to refer to parts-per-million and parts-per-billion. When not otherwise stated, they refer to parts by volume.

Tubes and pipes in fractional inch sizes are still in common use, so we often use them in worked examples. To reduce monotony, we specify tube sizes without the obvious qualifier *outside diameter* or *o.d.* so “¼-inch tube” may be taken to be “¼-inch o.d. tube.” Similarly, we omit *nominal bore* or *NB* when specifying pipe, so “½-inch SCH80 pipe” means “½-inch NB SCH80 pipe.”

Calculations with Units

Sample system engineering involves a number of calculations, none of which is difficult to understand. We limit equations to those using simple algebra and give many worked examples to illustrate their use.

All numbered equations expect to receive input data in **coherent SI units** and return the calculated data in coherent SI units. Unnumbered equations and calculations in the text sometimes use other units. A prime after the symbol of a variable indicates that the calculated value is in noncoherent units.

Be careful when doing a calculation with prefixed units. Ideally, you should convert all data to the proper SI units, without the prefixes. Sometimes in the text, though, we take shortcuts. Consider the calculation of time delay in a liquid line for instance. Section 02-2 introduces this equation:

$$t = \frac{V}{\dot{V}} \quad (2-2)$$

The SI unit for volume V is m^3 and the SI unit for volume flow rate \dot{V} is m^3/s . But our sampling data is likely to be in much smaller units; we might have a volume of 500 mL and a flow of 250 mL/min. Since it's obvious that the volume units will cancel out, it's not worth converting them to coherent SI units; we can enter the data directly in the equation.

To avoid mistakes, always enter the units into the equation alongside the data thereby confirming the units of the answer. In this example, the milliliters cancel out leaving the time t' in minutes:

$$t' = \frac{500 \text{ mL}}{1} \times \frac{\text{min}}{250 \text{ mL}}$$
$$t' = 2 \text{ min}$$

Notice the prime added to the symbol for time. This is an example of how we use a prime to indicate that the answer is not in SI units.

If these methods of including units in calculations are unclear to you, read Appendix A-03 before moving on.

Accuracy of Calculation

Because of uncertainty in the input data, calculations in sampling are always approximate. It's a mistake to imply that calculated data are more accurate than the input data. It's best to assume that all given data is accurate to two significant figures and then round calculated values to two significant figures. That's the approach used in the book.

When specifying a flowmeter setting, round up the calculated value to the next marked division on your flowmeter. Don't ask users to set a flow rate to a higher accuracy than the flowmeter can achieve.

The Scientific Notation

The scientific notation is a convenient way to express a wide range of values without using prefixed units. For instance, we prefer to measure a length in *meters*, whether that length is the microscopic distance between two atoms or the astronomic distance between two stars!

Using the scientific notation, the distance between atoms in a hydrogen molecule is about 7.4×10^{-11} m, and the distance from here to Alpha Centauri is about 4.1×10^{16} m. Another way to write or print these two values is 7.4E-11 m and 4.1E+16 m.

The scientific notation is now the standard way to present measurement values, particularly for tabulated data. If you would like to review how this notation works, refer to Appendix A-04.

Feedback Welcomed

In keeping with our core value of continuous improvement, Swagelok is interested in your feedback on the book. We've done our best to ensure the quality of the information found here, but there may be things we missed. If you find anything that you think should be changed in a future edition, you can send us your thoughts at www.industrial-sampling-systems.com. Here we will post any updates to content that will be included in future editions. We look forward to hearing from you.