THE COLD FRONT

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IRC Staff

Director
Doug Reindl 608/265-3010 or 608/262-6381

Jim Elleson 608/262-6940
Todd Jekel 608/265-3008
Dan Dettmers 608/262-8221

Phone 608/262-8220
Toll-free 1-866-635-4721
FAX 608/262-6209
Mail
949 East Washington Ave
Suite #2
Madison, WI 53703-2937

e-mail info@irc.wisc.edu
Website www.irc.wisc.edu

Screw Compressors:

Selection Considerations for Efficient Operation - I

[This is the first in a two-part series of articles on screw compressors. In this article, we provide an overview of screw compressors with particular focus on capacity control and volume ratio characteristics. Consider it a "back-to-basics" primer. In the next issue of the Cold Front, we build on this article by evaluating the energy efficiency aspects of fixed vs. variable volume ratio screw compressors under full-load and part-load operation.]

Overview

Compressors are one of the most vital components in a vapor compression industrial refrigeration system. Compressors are the principal prime movers responsible for circulating refrigerant through a system. Collectively, compressors also account for the largest consumption of primary energy (usually electricity) in a refrigeration system. Although a number of alternative compressor technologies are available including reciprocating, screw, and rotary vane, many refrigeration end-users are gravitating toward the specification and installation of screw compressors. For that reason, we have developed this two-part series of articles to evaluate selection and operation considerations specific to screw compressors. Part 1 focuses on methods of capacity control and volume ratio concepts. Part II will discuss selection considerations for energy efficient operation.

The original twin screw compressor technology was first patented by Alf Lysholm in the 1930's and commercialized by the Swedish company, SRM (Svenska Rotor Maskiner). Since the issuance of the first patent on screw compressor technologies, screw compressors have undergone considerable advancement. Many of the advances in this technology were the result of progress in computer-controlled machining equipment to facilitate manufacture of complex rotor geometries while maintaining close tolerances. Screw compressors and their application continue to be fertile ground for the issuance of patents. In the period from 1976-2001, over 370 patents on screw compressors and associated applications were issued by the U.S. patent office alone.

Screw compressors are available in sizes ranging from 50-3,000 BHP for application in commercial and industrial refrigeration systems, gas compression, and air compressors. Screw compressors are the fastest growing compression technology segment in the industrial refrigeration marketplace today. Figure 1 shows the installation of an industrial refrigeration screw compressor in the engine room of a plant.

Two screw compressor configurations are in use for industrial refrigeration systems today: single screw and twin screw. The single screw is a relatively new technology and has found good success in the industrial refrigeration marketplace. The twin screw compressor has been around since the 1930s and has a greater share of the industrial refrigeration compressor marketplace.

Capacity Control

It is extremely rare for refrigeration loads in an industrial refrigeration system to remain constant. Since the loads vary with time, refrigeration compressors must be equipped with means of capacity control. Capacity controls modulate the compressor's capacity to match the prevailing load. There are multiple approaches for controlling capacity in screw compressors including: capacity control slide valve, plug or poppet valves, twin slide valves (for both volume ratio and capacity control), and variable speed drives.

One of the most common capacity control methods is the "capacity control slide valve". Figure 2 shows a single screw compressor† with dual slide valves (capacity and volume ratio). On the figure, the suction side is on the right and the discharge is on the left of

† Schematics of single screw compressors are used for ease of visualization.

Upcoming Ammonia Courses

Ammonia Refrigeration Piping
October 28-30, 2002 Madison, WI

Intermediate Ammonia Refrigeration
December 4-6, 2002 Madison, WI

Process Safety Management Audits
January 22-24, 2003 Madison, WI

Energy Efficiency Improvement Strategies
February 10-12, 2003 Madison, WI

Introduction to Ammonia Refrigeration
March 5-7, 2003 Madison, WI

Ammonia Refrigeration System Safety
April 23-25, 2003 Madison, WI

Design of Ammonia Refrigeration Systems
September 15-19, 2003 Madison, WI

See http://www.engr.wisc.edu/epd/ for more information.

Figure 1: Twin screw compressor installation.

the schematic. The capacity control slide valve (upper slide valve) is in its maximum position, which traps the largest volume of gas into the suction side of the screw to undergo the compression process. In this position, the compressor will have maximum capacity.

Figure 3 shows the same compressor but with the capacity control slide valve in its minimum position. By moving the slide valve to the left, the start of the compression process is delayed until the gas filling the thread of the screw is closer to the discharge port. With the start of the compression process delayed, the volume of suction gas that can be sealed or trapped is reduced. As the volume of refrigerant vapor to undergo compression is reduced, the compressor's capacity is reduced, and the effective volume ratio of the compressor also decreases.

Alternatively, some twin screw compressor slide valves are equipped to decrease the discharge port area and allow some of the discharge gas to shunt back to the compressor suction. This approach allows a single slide valve to achieve capacity control and volume ratio control.

Part II of this article will investigate the impact of part-load operation on screw compressor performance. For now, let's move on and discuss the concept of volume ratio and review methods for achieving volume ratio control.

Volume Ratio

A screw compressor is inherently a "fixed geometric compression device". That is, a screw compressor operates by capturing or trapping a fixed volume of gas on its suction side and decreasing that volume of trapped gas to expel it at a higher pressure on the discharge end. The ratio of the volume of trapped gas in the thread of the screw at the start of the compression process to the volume

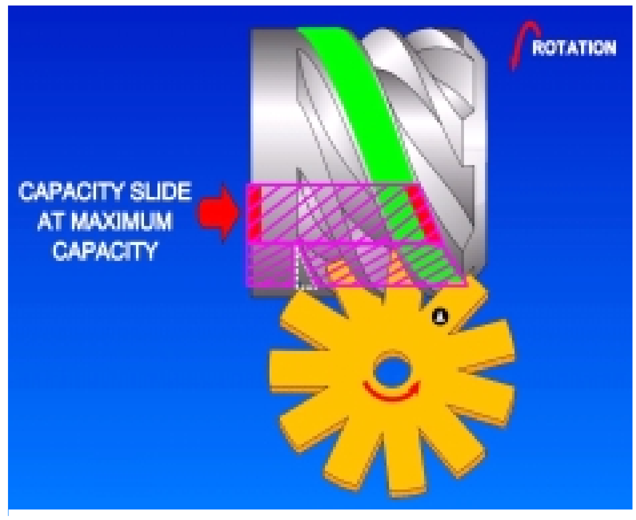

Figure 2: Illustration of a single screw compressor at full-load *(Photo courtesy of Vilter Manufacturing).*

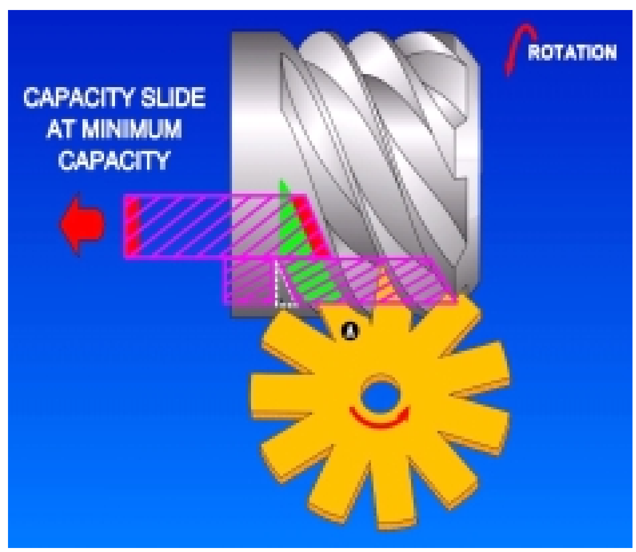

Figure 3: Illustration of a single screw compressor at part-load *(Photo courtesy of Vilter Manufacturing).*

of trapped gas when it first begins to open to the discharge port is known as the compressor's "volume ratio" or "volume index", *Vi* (ASHRAE 1996). Figure 4 illustrates basic volume ratio concepts for a screw compressor. The volume of trapped gas on the suction side (internal to the compressor), $V_{suction,int}$, is larger than the volume of trapped gas on the discharge side (internal to the compressor), $V_{discharge,int}$. The ratio of suction volume to discharge volume is the screw compressor's volume ratio or volume index, *Vi*.

There is a relationship between the compression or pressure ratio a screw compressor is able to develop and the compressor's volume ratio as given by the following equation.

$$\frac{P_{discharge,int}}{P_{suction,int}} = (Vi)^k$$

where $P_{discharge,int}$ is the pressure of the trapped gas in the thread or gulley of the rotor at a point just as the rotor's leading lobe begins to uncover the discharge port and $P_{suction,int}$ is the pressure of the gas in the rotor gulley on the suction side of the compressor just prior to the trailing rotor lobe closing off the suction port to begin the compression process. The specific heat ratio, *k*, is the ratio of the constant pressure specific heat to the constant volume specific heat for the refrigerant. The specific heat ratio is not constant but varies with temperature and pressure. Usually, an average value from suction to discharge conditions can be used to establish an estimate of *k*.

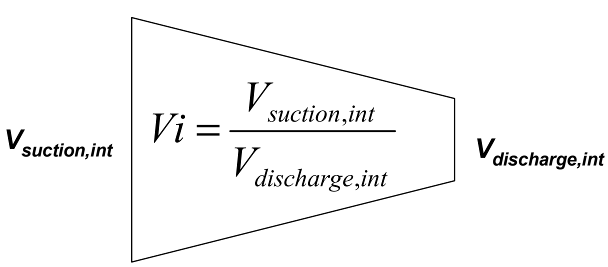

Figure 4: Volume ratio illustration for a screw compressor.

Historically, screw compressors were only available in fixed volume ratio designs. Today, screw compressor manufacturers have developed approaches vary the volume ratio.

What is variable volume ratio and why is it important? First, let's look at the relationship that volume ratio has with the operation of a screw compressor. Consider a screw compressor that has a fixed volume ratio of 3.6 (that is, the volume of trapped gas on the suction side of the compressor is 3.6 times larger than the volume of trapped gas on the discharge side). In our example, the compressor is configured in a single stage arrangement and operates at 0ºF saturated suction temperature (30.4 psia saturation pressure). The pressure of the trapped gas just before the screw opens to the discharge port can be estimated by using the above equation assuming a ratio of specific heats of *k*=1.37 (for ammonia)†.

$$P_{discharge,\,int} = P_{suction,\,int} \cdot (Vi)^k = 30.4 \cdot (3.6)^{1.37} = 176 \; psia$$

In situations where the prevailing condensing pressure is above 176 psia, a compressor with a volume ratio of 3.6 would "under-compress" the refrigerant. That is, the pressure of the trapped gas when the discharge port is uncovered by the leading edge of the rotor lobe is not high enough to immediately move out into the discharge port. In this case, the screw must continue to rotate further and raise the pressure of the refrigerant vapor to "push" it out into the discharge side of the compressor.

When the prevailing condensing pressure is below 176 psia, the screw compressor has "over-compressed" the refrigerant vapor. If the condensing pressure is 125 psia, the screw compressor will have raised the refrigerant vapor to 176 psia (internally) just before the lobe on the rotor begins to uncover the discharge port and the over-compressed

† k for anhydrous ammonia varies in the range between 1.34 – 1.51.

refrigerant will quickly drop in pressure as it "sees" significantly lower pressure in the discharge line. The impact of over-compression is a loss in efficiency since the compressor had to work harder than necessary to accomplish the compression process. Another consequence of over compression is that the discharge temperature (or oil cooling load) is higher than it would be if the compressor's volume ratio were matched to meet the required discharge pressure conditions. Figure 5 illustrates the volume ratio required to match condensing pressures that range from 120 psia (wintertime operation) to 195 psia (design summertime operation). Notice that the volume ratio of the compressor would have to vary from 2.5 to 4.0. Figure 5 also shows the compression ratio for the previous example at a saturated suction temperature of 0ºF. As expected, the compression ratio increases proportionally with the discharge pressure for a fixed suction pressure

Virtually, all of the screw compressor manufacturers have developed approaches to vary the effective volume ratio of their machines. The general principle behind a variable volume ratio or variable Vi screw compressor is that the location where the compressed refrigerant vapor is allowed to move through the discharge port is variable. When the compressor is required to operate in low condensing pressure conditions, a "volume ratio slide valve" in the compressor moves toward the suction side; thereby, allowing the trapped refrigerant vapor to leave the compressor earlier in the compression process, before it has the opportunity to be over-compressed. During high condensing pressure conditions, the discharge of the compressed gas is delayed until further in the compression process (the volume ratio slide valve is moved away from compressor suction).

How is the volume ratio controlled in a variable Vi screw compressor? Some manufacturers have developed discrete volume ratio control, which allows the volume ratio to be changed to discrete values, e.g. 2.6, 3.2, 3.8, etc. Others use infinitely variable volume ratio control. Figure 6 shows the configuration of dual slide valves (infinitely variable volume ratio control) for a Vilter single screw compressor. The volume ratio slide valve is shown in its minimum Vi position, where it allows the trapped gas to leave the compression process earlier, at a lower developed internal pressure. The volume ratio slide valve is typically found in this position for operation under low head pressure situations.

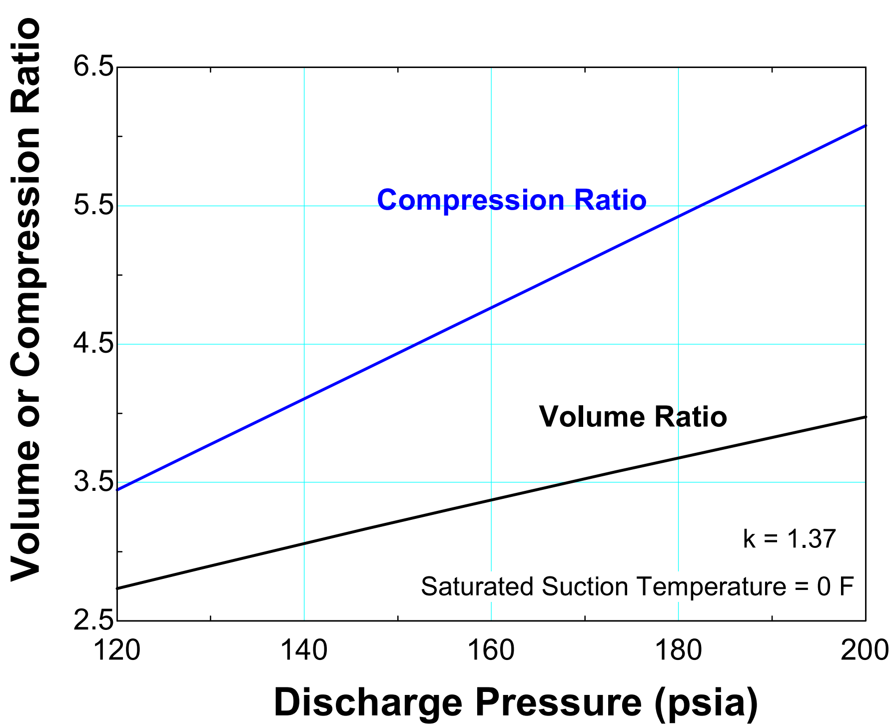

Figure 5: **Compression & volume ratios for fixed suction pressure variable volume ratio screw compressor.**

For higher head pressure conditions, the compressor will have to raise the refrigerant to a higher pressure to match the system discharge or condensing pressure. To accomplish this, the volume ratio slide valve moves to its maximum position as shown in Figure 7. In this case, the compressor has delayed the discharge of gas out into the system until later in the compression process; thereby, allowing the refrigerant to be compressed to a higher pressure.

The goal in varying the volume slide position is to match the pressure of the gas just leaving the discharge port with the prevailing system discharge pressure. The volume ratio slide valve effectively repositions the location of the discharge port. In contrast, the capacity control slide valve effectively repositions the location of the suction port (the starting point for the compression process). By better matching the compressor discharge pressure with the system discharge pressure, variable volume ratio screw compressors eliminate the inefficiency caused by over-compressing or under-compressing the refrigerant. Variable volume ratio screw compressors are recommended for application where the discharge and suction pressures will vary significantly over the operational life of the machine. Recognize that variable volume ratio screw compressors will have higher maintenance costs and potential for greater reliability problems due to the operation of the volume ratio control slide valve, hydraulic circuitry, and controls.

In the next issue of the Cold Front we will look at the energy efficiency impacts of both fixed and variable volume ratio screw compressors. Which is the better choice: fixed or variable volume ratio compressors? Stay tuned and make an informed decision.

If you have questions or comments on this article, please contact Doug Reindl at (608) 265-3010 or dreindl@wisc.edu.

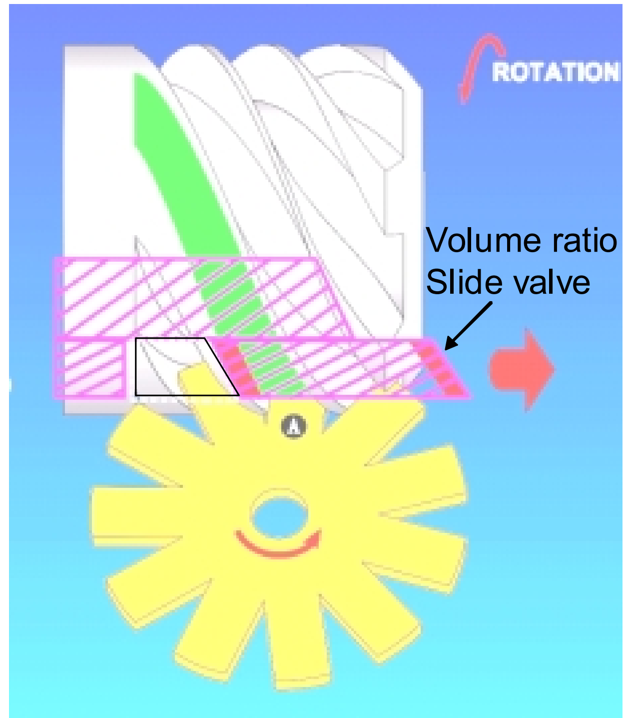

Figure 6: Single screw compressor volume ratio slide valve at its minimum position *(courtesy of Vilter Manufacturing).*

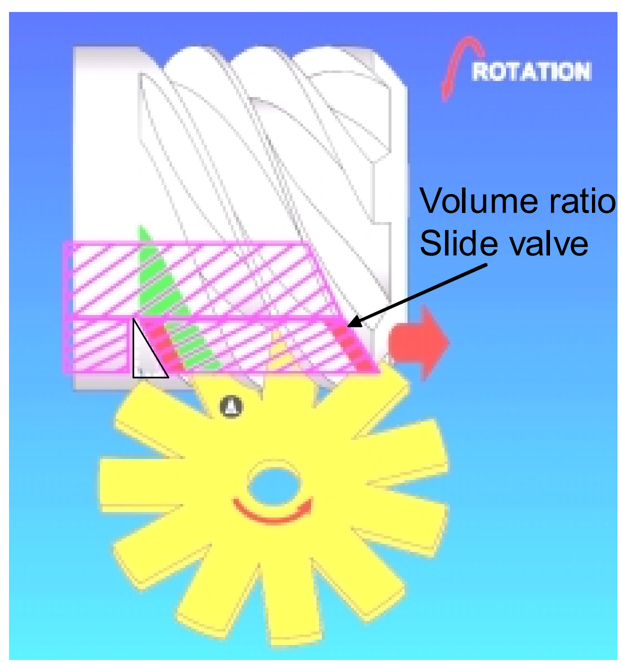

Figure 7: Single screw compressor volume ratio slide valve at its maximum position *(courtesy of Vilter Manufacturing).*

2003 IRC Research & Technology Forum

Are you interested in keeping current on regulatory changes that impact industrial refrigeration systems? Are you wondering about current research and emerging technologies in the area of industrial refrigeration?

The Industrial Refrigeration Consortium is pleased to announce the 3rd Annual Research & Technology Forum to be held on January 8th, 2003. This event will feature presentations by IRC staff and IRC member organizations, and industry experts. This year's forum begins at 10:00 am CST and ends at 5:00 pm.

The 2003 IRC R&T forum will provide attendees an opportunity to exchange information about current refrigeration research, regulatory updates, emerging technologies, refrigeration education, and to explore needs for future research in the area of industrial refrigeration.

The 3rd Annual Research & Technology Forum session topics will tentatively include:

IRC Research Activities

- ✓ Overview of Energy Efficiency Guidebook
- ✓ Review of Non-Destructive Evaluation Methods for Mechanical Integrity

Around the Industry

- ✓ Kraft's Ammonia Leadership Team
- ✓ Auditing Process Safety Management Systems
- ✓ World-class Refrigeration Update

Regulatory Update

- ✓ OSHA Process Safety Management Update

Technology Transfer Activities

- ✓ IIAR Ammonia Refrigeration Operator Training Guidelines

Technology Transfer Activities

- ✓ Case Studies in Energy Efficiency
- ✓ Current Practices & Emerging Trends in Water Treatment Technologies

The forum will be held at the Pyle Center on the University of Wisconsin-Madison campus. The forum is open to all interested in industrial refrigeration. IRC members and prospective members should plan to stay for the IRC's annual business meeting to be held on January 9, 2003. To obtain registration materials, please contact us. The materials will also be downloadable from our website shortly. If you have any questions regarding travel arrangements or presentation topics, please contact the IRC at 866-635-4721 or info@irc.wisc.edu.

IRC Awarded Contract to Study Defrost

The Energy Center of Wisconsin has awarded the University of Wisconsin-Madison a contract to study defrost in industrial refrigeration systems. The project titled "Improving Energy Efficiency of Refrigeration Systems: Alternative Defrost Strategies" will be led by Mechanical Engineering faculty Sanford Klein and Douglas Reindl in collaboration with ME graduate student Nathan Hoffenbecker.

The aim of the project is to better understand the energy impacts of various defrost strategies. The project will evaluate sequences of control for defrost as well as assessing equipment alternatives for frost control in low temperature air cooling applications. Equipment alternatives to be explored will include hot gas defrost with defrost relief regulators or liquid drainers, and no-frost configurations using sprayed glycol.

The defrost requirements for a system analyzed by former Mechanical Engineering graduate student Kyle Manske accounted for 13 percent of the total system electrical energy consumption. "The defrosting strategies used in this system are commonly practiced in the industry and system performance can be enhanced by pursuing alternative defrost strategies." says Klein. Reindl added "We intend to investigate a range of alternative defrost strategies with the ultimate goal of improving the energy efficiency of industrial refrigeration systems."

New Course! Process Safety Management Audits

January 22-24, 2003 Madison, WI

What Did You Gain from Your Last Compliance Audit?

Most users of ammonia-based industrial refrigeration systems are required to comply with OSHA's Process Safety Management (PSM) Standard 29 CFR 1910.119. The PSM standard requires that compliance audits be conducted at an interval not to exceed three years. Did your last compliance audit make you an integral member of the audit team? Did that audit:

- Demonstrate that all of your facility's written program elements were properly in place?
- Identify gaps between your written program and worker-level implementation?
- Ensure that production workers were considered as well as refrigeration workers?
- Uncover PSM omissions that would likely result in fines?
- Conclude in a timely manner?
- Use teams comprised of members with varying backgrounds and expertise?
- Provide specific direction for improving your overall PSM program and the reliability of your production of "cold"?

Learn Sound Principles and Practices

If your answer was "NO" to any of the preceding questions, this course is for you! Attend this course and learn sound principles and practices for conducting effective PSM compliance audits. Compliance audits of PSM systems should be one of the most effective means of continuously improving your plant's PSM program. Perform quality audits and reap the resultant benefits in enhanced safety and more reliable "cold".

Boost Your Understanding

The workshop format of this new course will help you conduct high-performance, effective process safety management systems audits. Our goals are to help you

- understand a range of approaches for conducting PSM compliance audits
- assess and allocate required resources to conduct the audits
- continuously improve PSM programs, and
- continuously improve the reliability and deliverability of "cold" as a result of conducting a compliance audit

Upon completion of this course, you will understand

- a wide range of audit types
- techniques for conducting effective PSM audits
- strategies for staffing and executing audits
- approaches for turning your audit results into PSM program improvements

Roll Up Your Sleeves

Come prepared to roll up your sleeves! This course will provide a true "workshop" atmosphere. Your course leaders will mix classroom sessions with interactive workshops. The design of the course will maximize knowledge transfer and attendee interaction. Because of the workshop format, we must limit attendance.

Attend and Benefit

This course has been designed for

- PSM coordinators
- managers responsible for safety
- refrigeration personnel (operators, mechanics and supervisory staff)
- audit team members
- managers concerned with the reliability and dependability of "cold"
- others who want to learn more about enhanced refrigeration system safety and reliability

Take Home Valuable Compliance Audit Tools

As an attendee you will receive a complete set of course notes. In addition, you will receive a CD-ROM with valuable tools for conducting compliance audits at your facility. The value of the tools alone well exceeds the cost of the course.

Download a complete brochure including a course outline and registration materials by clicking here.