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Guidance for ASME EA-4, Energy Assessment for Compressed Air Systems

AN ASME TECHNICAL REPORT

The American Society of Mechanical Engineers

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Guidance for ASME EA-4, Energy Assessment for Compressed Air Systems

A TECHNICAL REPORT PREPARED BY ASME AND REGISTERED WITH ANSI

The American Society of Mechanical Engineers

Three Park Avenue • New York, NY • 10016 USA

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FOREWORD

This guidance document provides technical background and application details in support of the understanding and application of ASME EA-4, Energy Assessment for Compressed Air Systems. This guidance document provides background and supporting information to assist in carrying out the standard. The guidance document covers such topics as rationale for the technical requirements of the assessment standard; technical guidance, application notes, alternative approaches, tips, techniques, and rules-of-thumb; and example results from fulfilling the requirements of the assessment standard. This guidance document was developed to be used as an application guide on how to utilize ASME EA-4.

ASME EA-4 provides a standardized framework for conducting an assessment of compressed air systems. A compressed air system is defined as a group of subsystems composed of integrated sets of components used to deliver compressed air energy to manufacturing equipment and processes. Assessments performed using the requirements set by ASME EA-4 involve collecting and analyzing system design, operation, energy use, and performance data and identifying energy performance improvement opportunities for system optimization. These assessments may also include additional information, such as recommendations for improving resource utilization, reducing per unit production cost, and improving environmental performance of the assessed system(s).

ASME EA-4 provides a common definition for what constitutes an assessment for both users and providers of assessment services. The objective is to provide clarity for these types of services that have been variously described as energy assessments, energy audits, energy surveys, and energy studies. In all cases, systems (energy-using logical groups of industrial equipment organized to perform a specific function) are analyzed through various techniques such as measurement, resulting in the identification, documentation, and prioritization of energy performance improvement opportunities.

This Guide is part of a portfolio of documents and other efforts designed to improve the energy efficiency of industrial facilities. Initially, assessment standards and guidance documents are being developed for compressed air, process heating, pumping, and steam systems. Other related existing and planned efforts to improve the efficiency of industrial facilities include

(a) ASME assessment standards, which set the requirements for conducting and reporting the results of a compressed air, process heating, pumping, and steam assessments.

(b) a certification program for each ASME assessment standard that recognizes certified practitioners as individuals who have demonstrated, via a professional qualifying exam, that they have the necessary knowledge and skills to apply the assessment standard properly.

(c) an energy management standard, A Management System for Energy, ANSI/MSE 2000:2008, which is a standardized approach to managing energy supply, demand, reliability, purchase, storage, use, and disposal and is used to control and reduce an organization's energy costs and energy-related environmental impact.

NOTE: ANSI/MSE 2000:2008 will eventually be superseded by ISO 50001, now under development.

(d) an ANSI measurement and verification protocol that includes methodologies for verifying the results of energy efficiency projects.

(e) a program, Superior Energy Performance, that will offer an ANSI-accredited certification for energy efficiency through application of ANSI/MSE 2000:2008 and documentation of a specified improvement in energy performance using the ANSI measurement and verification protocol. Superior Energy Performance is now using the ISO Draft International Standard 50001 for plants. ISO 50001 is not yet final. The Measurement and Verification Protocol is anticipated to be a normative reference to ANSI/MSE 50021 and ANSI/MSE 50028.

The complementary documents described above, when used together, will assist organizations seeking to establish and implement company-wide or site-wide energy plans.

Publication of this Technical Report that has been registered with ANSI on July 27, 2010 has been approved by ASME. This document is registered as a Technical Report according to the Procedures for the Registration of Technical Reports with ANSI. This document is not an American National Standard and the material contained herein is not normative in nature. Comments on the content of this document should be sent to the Managing Director, Technical, Codes and Standards, ASME.

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Proposing Revisions. Revisions are made periodically to the technical report to incorporate changes that appear necessary or desirable, as demonstrated by the experience gained from the application of the technical report. Approved revisions will be published periodically.

The Committee welcomes proposals for revisions to this technical report. Such proposals should be as specific as possible, citing the paragraph number(s), the proposed wording, and a detailed description of the reasons for the proposal, including any pertinent documentation.

Attending Committee Meetings. The EA Committee holds meetings or telephone conferences, which are open to the public. Persons wishing to attend any meeting or telephone conference should contact the Secretary of the EA Standards Committee.

GUIDANCE FOR ASME EA-4, ENERGY ASSESSMENT FOR COMPRESSED AIR SYSTEMS

1 SCOPE AND INTRODUCTION

1.1 Scope and Purpose

1.1.1 Scope. This guidance document was developed to be used as an application guide on how to utilize ASME EA-4, Energy Assessment for Compressed Air Systems. This guidance document provides background and supporting information to assist in carrying out the standard.

1.1.2 Purpose. ASME EA-4 does not provide guidance on how to perform a compressed air systems energy assessment, but sets the requirements that need to be performed during the assessment. ASME EA-4 was written in a form suitable for a standard, with concise text and without examples or explanations. This document was developed to be used in conjunction with the standard to give basic guidance on how to fulfill the requirements of the standard. This document is only a guide, it does not set any new requirements, and ASME EA-4 can be used with or without this document.

1.2 Limitations

This guidance document does not set any new requirements for application of ASME EA-4.

1.3 Introduction — Using the System Assessment Standard

ASME EA-4 (the standard) is organized in the following sections:

(a) Section 1: Scope and Introduction. This section includes the scope for the standard, limitations of the standard, and an introduction on how to use the standard that includes information on the systems approach and the system engineering process. Guidance is provided in section 1 of this document.

(b) Section 2: Definitions. This section provides definitions of terms used in the standard. No guidance is provided for this section, although a glossary with definitions for additional terms is included as Nonmandatory Appendix A of this document. Section 2 of this document presents key elements and characteristics of industrial compressed air systems.

(c) Section 3: References. This section lists documents that are referenced in the standard. No guidance is provided for this section of the standard. Section 3 of this document provides background and rationale for the criteria that define an effective compressed air system assessment.

(d) Section 4: Organizing the Assessment. This section outlines requirements on how to organize an assessment including identification of team members and responsibilities; requirements for preliminary data collection and analysis; and requirements on the development of assessment goals and a plan of action. Guidance is provided in section 4 of this document.

(e) Section 5: Conducting the Assessment. This section describes that requirements for conducting an assessment (the implementation phase of the plan of action). Guidance is provided in section 5 of this document.

(f) Section 6: Analysis of Data From the Assessment. This section presents requirements for analyzing the data collected during an assessment, including the development of a baseline profile. Guidance is provided in section 6 of this document.

(g) Section 7: Reporting and Documentation. This section provides requirements for information presented in the assessment report. Guidance is provided in section 7 of this document.

Guidance on section 1 of ASME EA-4 is provided below. Sections 2 and 3 of this guidance document provide an introduction to industrial compressed air systems and background/rationale for that criteria that define an effective compressed air system assessment. Sections 4 through 7 of this guidance document parallel the sections in the standard at each subheading level.

1.3.1 The System Assessment Process. ASME EA-4 presents requirements for compliance when conducting a compressed air system assessment to reduce energy use and improve performance. It also describes a framework for a more extensive system assessment to address performance issues and related energy opportunities.

Compressed air is used in many different industries for many different purposes. No two compressed air systems are the same; therefore, no two compressed air system assessments will be the same. The framework of the standard includes some elements of assessment work that are required for adherence to the standard. Other assessment activities are described as supplemental elements of the system assessment.

Required elements of an assessment apply to virtually all compressed air systems and have direct impact on system energy use.

Supplemental elements of an assessment may or may not apply to an individual compressed air system or primarily affect system performance rather than energy use, or both.

Within the framework of the standard, members of the assessment team are responsible to plan the assessment and create a statement of work (SOW) that addresses the technical and business objectives of the assessment.

The standard recognizes that an energy assessment must be economically justified. The framework of the standard is designed to provide flexibility so that the extent of assessment objectives and the rigor of the methodology applied are appropriate to the system complexity. This will be different for a small- to mid-size facility with a relatively low amount of compressor horsepower from a large facility.

For all systems, it is necessary to assess the entire system including supply, transmission, and demand.

The standard states, "An assessment complying with this Standard need not address each individual system component or subsystem within an industrial facility with equal weight; however, it must be sufficiently comprehensive to identify the major energy efficiency opportunities for improving the overall energy performance of the system."

A system assessment for small plants will take less time and be less costly than assessments for large plants. It is the responsibility of the assessment team to develop an SOW for an individual assessment that makes sense and is economically justified. Refer to para. 4.9 of the standard and this guidance document. The last step in planning the assessment is to do a goal check for relevance, cost effectiveness, and capacity to produce the desired results. The guidance in para. 4.9 suggests seven points to consider.

The outcome of the goal-checking activity may determine that the goals can be achieved or may result in modification of the assessment SOW. For users who elect full conformance to the standard, the team's application of the assessment standard may be subject to third-party review by a certified practitioner. To assist with review of the assessment, the assessment team can consider documenting decisions made when determining the SOW. This information can be added as an appendix to the assessment report.

A compressed air system assessment must consider diverse needs and priorities. For many stakeholders energy efficiency is a secondary priority. Their highest priority is a reliable compressed air system that supports manufacturing equipment and processes; however, energy use and system performance are interrelated. Thus, the key to energy efficiency is frequently related to improving system performance.

Compressed air system performance is not always as it seems. Highly visible symptoms often mask the true underlying root cause of inefficiency and poor performance. Operational solutions often involve increased energy use, whereas root cause analysis will often identify a more energy efficient solution. As a consequence, an effective compressed air system assessment is a discovery process of investigating system operation to baseline energy use, identifying opportunities to improve performance, and reducing energy input to the compressed air system.

1.3.2 System Energy Efficiency. Individual components of a compressed air system such as compressors, air dryers, and filters can be more or less efficient. How individual air system components are integrated together and how they respond to the collective compressed air demand of the many end use applications found in most systems have the greatest impact on system efficiency. System efficiency is most affected by the interaction of compressed air supply and demand.

1.3.2.1 Compressed Air Energy Conversion. For most industrial plants, compressed air is a self generated secondary energy resource converted from a purchased primary energy resource, typically electricity. The electric motor efficiency when combined with thermodynamics of the compression process results in 85% of the primary energy resource being converted to heat. That heat is most often rejected as waste heat; however, recovery of heat may be possible in some applications and should be examined.

1.3.2.2 Energy Reduction Opportunities. Improvements in compressed air supply efficiency are constrained by the inefficiency of converting electrical energy input to compressed air energy; 85% of input energy is converted to heat. Reducing compressed air demand has the potential to shut down running compressor capacity, eliminating the energy input in its entirety.

In situations where compressors cannot be shut down, reducing the amount of compressed air produced will often decrease compressed air supply efficiency. The change in supply efficiency is dependent on compressor control strategy. In this situation, the savings associated with reduced air use will be proportionate to the performance of available controls.

1.3.3 Systems Approach. The systems engineering process must begin by discovering the real problem that needs to be solved; the biggest failure that can be made in systems engineering is finding an elegant solution to the wrong problem. [1]

1.3.4 Systems Engineering Process. Paragraph 1.3.4 of ASME EA-4–2010 discusses the systems engineering process. As part of this process, the assessment team needs to determine what is required and what needs to be done, and develop a plan as to how best to accomplish the assessment. The team should check the plan to see if it is reasonable and cost effective and if it can produce the desired results. The team should conduct the assessment, analyze data collected, baseline current operation, and identify opportunities for improvement. The assessment should provide remedial measures with conceptual designs and energy reduction estimates. The assessment should report and document how the assessment was conducted, and give findings, recommendations, and expected results. The systems engineering process should also include the following:

(a) What requirements does the compressed air system have to meet?

(b) What is the present compressed air system and current method of operation?

(c) What is the statement of system assessment goals based on requirements and the existing system?

(d) For planning the system assessment, what activities should be done, and how will they be done?

(e) For testing the system assessment, is it relevant and cost effective, and will it produce results?

(f) For conducting the system assessment, how is the plan detailed and executed, and how is data gathered?

(g) How is the data analyzed to create a baseline, identify opportunities and remedial measures, and show results?

(h) How will the assessment — including findings, recommendations, and expected results — be reported?

2 INTRODUCTION TO COMPRESSED AIR SYSTEMS

A compressor is a machine that is used to increase the pressure of a gas. A typical modern industrial compressed air system is composed of several major subsystems and many subcomponents as shown in the example compressed air system in Fig. 1. Major subsystems include the supply side, the transmission system, and the demand side. ASME EA-4 considers the entire system, from energy inputs to the work performed as the result of these inputs. Each component subsystem is now described.

2.1 Elements and Characteristics of Industrial Compressed Air Systems

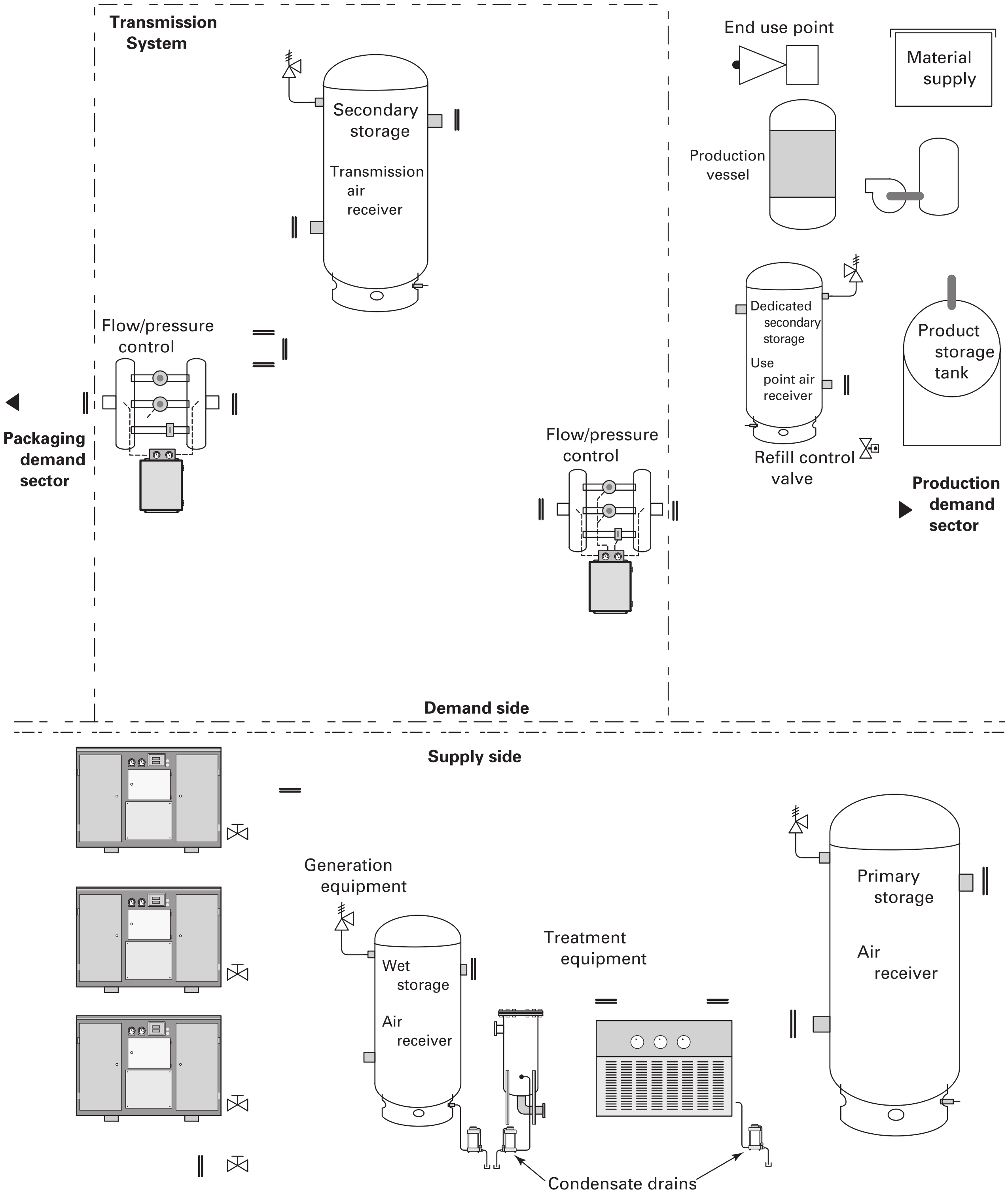
As illustrated in the example compressed air system shown in Fig. 1, industrial compressed air systems, as defined in ASME EA-4 and this guidance document, have three basic functional areas. They are the supply side, the transmission system, and the demand side.

2.1.1 Supply Side. The supply side of an industrial compressed air system is where the air is compressed, treated, stored, and sent out into the system. The supply side may include a single centralized compressor room, or may be composed of multiple compressor rooms within the plant site. Effective management of energy reduction efforts on the supply side requires using a minimum amount of energy to generate the required quantity of air, at the proper air quality, with the necessary storage to provide a consistent reliable supply of compressed air to the system. Key supply side components are generation, treatment, primary storage, and instrumentation that measures performance.

2.1.1.1 Generation. Generation of compressed air is most often accomplished as a self-generated secondary energy resource converted from a purchased primary energy resource, typically electricity. The thermodynamics of the compression process result in 85% of the primary energy resource being converted to heat, which is often rejected as waste heat. The energy conversion efficiency is therefore very low at 15% or less. After being generated, compressed air normally passes through treatment equipment. In some instances, responsibility for compressed air generation is assumed by a subcontractor and is therefore a directly purchased energy resource.

2.1.1.2 Treatment. Treatment of compressed air is necessary to ensure that the air quality supplied is consistent with point of use requirements. Three types of contamination are typically present in compressed air: particulates, oil (or hydrocarbon), and water vapor. There is an energy requirement associated with equipment used to treat compressed air. Coolers, separators, filters dryers, and other treatment equipment have frictional resistance to compressed air flow resulting in irrecoverable pressure loss that must be overcome by increased energy input at the air compressors. In addition, various types of air dryers have varying energy input requirements associated with removal of water vapor from the compressed air. In general terms, greater removal of contamination from compressed air has an associated increase in energy use.

Fig. 1 Example Compressed Air System



GENERAL NOTE: Not all systems will include all demand side components as illustrated.

2.1.1.3 Primary Storage. Primary storage helps manage the dynamic performance characteristics of a compressed air system in which the energy demand of point of use applications is variable and constantly changing. Optimum energy performance is achieved by maintaining an energy balance between compressed air supply and demand. Energy supply is available from rotating generation capacity of the compressors and compressed air energy storage. In the ideal system, air compressors would supply the average air demand while storage supplies energy for peak air demand. Energy storage is then replenished when air demand is below average. For compressed air energy storage to be usable to the system, storage pressure must be greater than the minimum required pressure. As such, there is an energy requirement associated with creating useable storage capacity. Compressed air storage is a recoverable pressure differential in the system. When properly applied, storage improves system efficiency; however, operating the system with more energy storage than the system will ever use increases the system's energy requirement with no additional benefit.

2.1.1.4 Instrumentation. Instrumentation measurement provides the necessary oversight of system performance to achieve sustainable long-term compressed air system efficiency. It is important to quantify the amount of primary energy input to the system (kWh), the quantity of secondary energy resource, and compressed airflow (scfm) that is produced. Operations, maintenance, control adjustment, response of automation, changes in system dynamics, and many other factors affect supply side efficiency. Sustainable efficiency requires monitoring of key performance indicators to provide oversight of operation.

2.1.2 Transmission System. The transmission system serves to deliver compressed air energy to the many use points that require compressed air. Effective transmission maintains air quality while delivering the necessary airflow and pressure to the point of use at the time pneumatic energy is required to perform the production task. To save energy, the transmission system seeks to minimize irrecoverable pressure loss in the system. Key components of the transmission system are distribution piping, piping drops to point of use connections, secondary storage, transmission controls, and instrumentation that measures performance.

2.1.2.1 Distribution Piping. Distribution piping carries compressed air from the supply side of the system to all areas of the plant that are served by the compressed air system. Distribution piping includes the main lines and branch headers. Proper distribution system performance delivers the necessary airflow to any area of the system while minimizing irrecoverable pressure loss. An effective distribution system has the capacity to transport the peak airflow rate imposed by the connected points of use. Distribution pipeline design should consider that the peak airflow rate caused by concurrent, high volume, intermittent air demands may occur at random, and can significantly exceed the average airflow rate for the system. An energy efficient distribution system should minimize irrecoverable pressure loss resulting from the interaction of airflow with the fixed frictional resistance of the distribution piping.

2.1.2.2 Piping Drops. Piping drops deliver compressed air from the header to the point of use connection and are a key element in the transmission system. The point of use piping begins at the inlet of the first control component associated with the point of use application. That component may be a shut-off service or lock out valve, a filter/regulator/lubricator combination, a solenoid control valve, or other control component. Piping drops should be properly sized and configured to deliver the peak airflow required by the connected point of use application while causing a minimal amount of pressure loss. Total transmission pressure loss including mainline, branch headers, and the piping drop should not exceed 10% of the supply side pressure delivered to the transmission system.

2.1.2.3 Secondary Storage. Secondary storage installed as a component of the transmission system serves to provide a buffer during demand events. Secondary storage will slow the rate of pressure decay and, to a limited degree, reduce pipeline velocity during high volume intermittent demand events. Other forms of secondary storage applied at the point of use can be more effective in serving high volume intermittent flow demands of specific point of use applications.

2.1.2.4 Transmission Controls. Transmission controls can serve to control and stabilize delivered air pressure (e.g., pressure/flow controls). In large systems there may be multiple logical demand sectors (e.g., individual buildings, production areas, departments, and business units). Different point of use requirements in the various demand sectors may allow lower supply pressure in some sectors as compared to others. Since any unregulated leakage and point of use applications will consume less compressed air energy at lower pressure, it is desirable to identify and operate demand sectors at the lowest optimum pressure associated with the point of use applications in that sector. Some production sectors may require compressed air supply at all times, whereas other sectors may be used on a seasonal basis or single shift of operations. The transmission control applied to these types of demand sectors might be a simple shutoff valve. Transmission controls can reduce energy use by effectively controlling and minimizing compressed air demand.

2.1.2.5 Instrumentation. Instrumentation that measures performance in the transmission system monitors the distribution of compressed air to record irrecoverable pressure loss and establish accountability for compressed air energy use. For large systems, having multiple physical or logical demand sectors (e.g., individual buildings, production areas, departments, and business units) is good practice. Compressed air energy use of individual sectors should be metered and recorded, with reporting of usage trends.

2.1.3 Demand Side. The demand side of the system encompasses all of the compressed air use in the plant air system. Leakage is one component of compressed air demand and in many systems represents 30% or more of compressed air demand. Artificial demand is an additional component of waste that occurs when demand side pressure is higher than required, causing all unregulated leakage and use points to consume a greater amount of airflow. The typical industrial compressed air system includes many points of use of compressed air, perhaps hundreds or more. Compressed air demand is the total cumulative airflow of connected leakage, artificial demand, and point of use applications. Key components of the demand side are point of use, point of use piping, point of use controls, secondary storage, and instrumentation that measures performance.

2.1.3.1 Point of Use. Point of use in a compressed air system is where compressed air energy is converted to mechanical work or accomplishes a production related task. Given the poor conversion efficiency of primary energy to compressed air energy, the use of compressed air should be limited to uses that cannot be served by an alternative, more efficient energy technology. Inappropriate use of compressed air is any point of use application that can be better and/or more efficiently served by an alternative energy technology. High volume intermittent point of use demands have the potential to be served by compressed air storage thereby reducing peak energy requirements. Points of use that are perceived to require supply pressure higher than the majority of the air demands on the system should be investigated. If the need for high pressure is valid, an alternative means of serving this need may allow the overall system pressure to be reduced, resulting in overall energy reduction.

2.1.3.2 Point of Use Piping. Point of use piping includes all components of piping that extend from the point of use connection to the actual end use. Point of use piping may include both field-installed piping as well as piping within machinery or equipment built from an original equipment manufacturer. Point of use piping must be sized with sufficient capacity to allow the peak airflow rate to be supplied with minimal pressure loss. Perceived high pressure point of use applications are often observed to malfunction at a specific connection pressure. The assumption is that system pressure must be increased, while the root cause of the malfunction is excessive point of use pressure drop occurring for a few seconds or less during the peak airflow demand of the point of use application. Energy efficient point of use piping supplies the peak airflow with minimal pressure loss meeting the dynamic performance of the point of use application.

2.1.3.3 Point of Use Storage. Point of use storage is a specific type of secondary storage applied at selected point of use applications to improve the speed, thrust, and/or torque of the point of use application. In addition, if secondary storage is applied with appropriate refill control, high volume intermittent demands can be supplied from storage while controlled refill provides a more average air demand on the transmission system. By averaging the air use, peak pipeline velocity in the transmission system is reduced, and the supply side is not subject to peak air demand that may cause additional generation to come online.

2.1.3.4 Point of Use Controls. Point of use controls include service isolation or lock-out valves, filters/regulators/lubricators, directional control valves, flow/speed controls, check valves, secondary storage controls, and any other device in the system located between the point of use connection (at the piping drop) and the point of use. Point of use controls are also a potential source of excessive pressure loss or poor control response time during the peak airflow demand of the point of use application. Energy efficient point of use controls respond appropriately to the dynamic airflow and pressure requirements of the point of use application.

2.1.3.5 Instrumentation. Instrumentation that measures performance at critical points of use in the system may be considered. Compressed air serves as a utility system providing pneumatic energy to production equipment and processes. In some critical applications compressed air system performance has a direct impact on production rate, product quality, scrap rate, and rework cost. For these critical applications, compressed air is a processes variable that should be controlled, monitored, and recorded in a manner consistent with other process controls.

3 AN EFFECTIVE COMPRESSED AIR SYSTEM ASSESSMENT

An effective compressed air system assessment, which is the focus of ASME EA-4 and this guidance document, is a discovery process of investigating system operation to baseline energy use and identification of opportunities to improve performance and reduce energy input to the compressed air system. The assessment process defines specific informational objectives appropriate to the system's design and function. Those objectives form a roadmap to study the system. The assessment process includes developing and executing a plan to measure the behavior of different portions of the compressed air system and analyzing how each can affect other system elements. The measured data should prove or disprove the system performance characteristics that are thought or known to exist.

Performance of a compressed air system is not always as it seems. Highly visible symptoms often mask the true underlying root cause of inefficiency and poor performance. For example, the dynamic interaction of an existing high volume intermittent demand may induce a high pipeline velocity in distribution piping, which causes a temporary pressure upset affecting other points of use in the system. Alternatively, a perceived high-pressure point of use caused by point of use pressure drop can establish the minimum air pressure requirement for the system. It is important to validate the pressure requirements. In these examples, the entire system is often operated at increased pressure in an attempt to overpower the problem. For an effective compressed air system assessment, the appropriate performance of generation, treatment, storage, transmission, and point of use requirements must be evaluated. Compressed air symptoms of poor performance must also be investigated to identify the root cause system issues resulting in the observed performance.

Application of a systems approach to a compressed air system assessment directs the focus toward total system performance rather than individual component efficiency. It is necessary to

(a) understand compressed air point of use as it supports critical plant production functions

(b) correct existing poorly performing applications, and those that upset system operation

(c) eliminate wasteful practices: leaks, artificial demand, and inappropriate uses

(d) create and maintain an energy balance between supply and demand

(e) optimize compressed air energy storage and air compressor control

ASME EA-4, Energy Assessment for Compressed Air Systems, applies to all compressed air systems large and small, simple and complex. When applying the standard, the goal is to reduce energy use and achieve a cost savings. Improving system performance, enhancing system reliability, and increasing productivity can create cost savings above and beyond the energy savings alone.

The standard recognizes that assessment work must be cost effective. That is why preliminary assessment activity is used to develop a site-specific assessment plan of action and a measurement plan. Ultimately, use of this standard is at the discretion of those participating in the assessment. The assessment team, working with production, process information and compressed air system knowledge will establish the plan of action and SOW for the assessment.

The standard allows for one or more methodologies to be used for various assessment action items. Note that the extent of work will vary with facility size and system complexity. The site-specific assessment plan of action should be based on economic justification and other factors the assessment team agrees upon during preliminary assessment activity.

4 GUIDE TO ORGANIZING THE ASSESSMENT

4.1 Identification of Assessment Team Members, Roles, and Responsibilities

The assessment team should include stakeholders in all areas of plant operations. To represent stakeholders' needs, the assessment team should include representatives from

(a) management
(b) production
(c) facilities
(d) maintenance
(e) environmental health and safety

4.1.1 Required Functions and Personnel. Potential assessment team members to fill the functional roles identified in ASME EA-4 could include those described in (a) through (c).

(a) Authorized Manager. An authorized manager should accept overall responsibility and have final decision-making authority. Responsibilities could include supervising the assessment team and providing resources necessary to plan and execute the assessment. Resources include such items as funding, availability of company personnel at the plant site and, as necessary, requisitioning internal work orders, and supplies. The manager should also allocate and authorize the participation of outside contractors and consultants, and facilitate the participation of any necessary outside personnel requiring contracts, scheduling, confidentiality agreements, and SOW.

(b) Assessment Team Leader. Plant management can demonstrate commitment to the assessment goals, objectives, and activities by appointing a system assessment team leader familiar with the processes, systems, and equipment related to the compressed air systems in the plant. The team leader should be familiar with operating and maintenance practices for the compressed air system equipment (or should have access during the assessment to people who are) and should be empowered to obtain necessary support from plant personnel and other individuals and organizations during the assessment.

(c) Compressed Air Expert. The team should include a compressed air expert. This individual, either a corporate or plant employee or outside consultant, should have the requisite qualifications, background, experi-

ence, and recognized abilities to perform the assessment activities, data analysis, and report preparation.

NOTE: Also see para. 4.8.1, "Identification of Other Assessment Team Members Required," in the standard.

4.1.1.1 Resource Allocation. Resource allocation is necessary to plan and execute the assessment. Resources may include such items as funding, availability of company personnel at the plant site, and, as necessary, requisitioning internal work orders, and supplies. When allocating resources, there may be a need to authorize the participation of outside contractors and consultants. Consider how to oversee the participation of outside personnel including contracts, scheduling, confidentiality agreements, SOW, etc.

The person given authority and responsibility for resource allocation should have experience with various plant energy systems and involvement in this and other plant energy management initiatives.

4.1.1.2 Coordination, Logistics, and Communications. Assessment objectives and action items involve a wide cross-section of plant personnel including facility management, production management, equipment and machine operators, and skilled trades including electrical, mechanical, and machine repair personnel.

The responsible person should provide information to plant personnel and coordinate the necessary support activities required for the assessment.

The assessment is a fluid process. Unexpected conditions at the plant site or initial assessment findings may warrant modification of the assessment plan of action and SOW. When changes to the SOW become known, the assessment team should communicate the proposed changes for approval.

The person given authority and responsibility for coordination logistics and communication should be knowledgeable in many aspects of the plant's operations, have experience with various energy systems, and have some familiarity with the plant's compressed air system.

4.1.1.3 Compressed Air Systems Knowledge. The assessment team should work within the framework of the standard to create a process that leads to the completion of an appropriate assessment. Using preliminary information, the assessment team should identify areas of the system that offer the best potential results for energy and system performance improvement and prioritize areas to receive more detailed study.

The assessment team should develop a plan of action consistent with assessment goals and site-specific goals, and outline the SOW and supporting documentation.

The person given authority and responsibility for systems knowledge should be knowledgeable in the function of various compressed air system components. This person also should be familiar with overall compressed air system operation from the air compressors through end-use applications of compressed air. In addition, this person should be experienced in application of the systems approach applied to compressed air system assessment.

4.2 Facility Management Support

Management commitment can communicate the assessment's importance to the organization. It is an opportunity to align the assessment work with organizational goals and objectives. Some general purposes of system assessments are to

(a) improve resource utilization and cost reduction

(b) contribute to the organization's growth and stability

(c) improve product quality

(d) improve customer satisfaction

(e) reduce life cycle cost of process performance

(f) provide accountability of compressed air energy use

(g) identify opportunities for process and product improvement

(h) provide knowledge and training for compressed air energy optimization

(i) provide management information for continuous improvement

The greatest success of compressed air system management can result from an interactive spirit of cooperation to identify and achieve common goals. The assessment does not by itself result in system improvement; however, the assessment provides information needed to plan and implement energy reduction and performance improvement.

It is important to recognize that people have a natural resistance to being measured. Therefore, it is appropriate to express that system issues and opportunities drive measurement of the compressed air system. The purpose is to empower the people who design and operate the compressed air system with information that has not been previously available to them.

Application of systems engineering principles is a new approach as compared to the traditional component level design and evaluation of compressed air systems. It can be acknowledged that following traditional approaches in engineering is common practice and has been the norm for compressed air system design. Conducting a system assessment is a change in approach to compressed air system design and evaluation that is an improvement over traditional methods.

4.3 Communications

There is no additional guidance for this clause.

4.4 Access to Equipment, Resources, and Information

Several days may be necessary to comply with certain site access requirements. For example, security clearance requirements or documenting insurance coverage is best done well in advance of the planned date for site access.

NOTE: Also see para. 5.2, Site Access Procedures, which are requirements that are typically done upon arrival at the plant site.

Digital photos or videos, or both, can help document the assessment process and findings. Determine requirements and procedures necessary to allow digital photos and videos to be taken and identify the terms under which images can be used in analysis of data, reporting of findings, and documentation of the assessment.

Document and communicate to members of the assessment team including plant personnel, contractors, and consultants all pre-access site requirements necessary to gain access to all areas of the facility required to perform the assessment.

Site access requirement could include but are not limited to items listed as follows:

(a) basic safety training requirements [e.g., Occupational Safety and Health Administration (OSHA), Mine Safety and Health Administration (MSHA)]

(b) personal protective equipment (e.g., hard hat, safety glasses, safety shoes, gloves)

(1) respirator requirements

(2) special safety gear (e.g., fire-resistant clothing, metatarsal guards, fall protection)

(c) site requirements for drug and alcohol testing

(d) lockout/tag out procedures

(e) hazardous (classified) area requirements for instruments/measurement equipment

(f) insurance requirement

(g) security clearance requirements

(h) written safety plan for onsite activity when conducting the assessment (section 5)

4.5 Assessment Goals and Scope

The basic goal of a compressed air energy assessment is stated in the Foreword of the standard: "Assessments involve collecting and analyzing system design, operation, energy use, and performance data and identifying energy performance improvement opportunities for system optimization."

How that goal is applied to different compressed air systems and the scope of assessment activity will vary among systems. Fundamental goals such as measuring baseline energy use, compressed air demand, and system operating pressure are obvious. Other goals are somewhat less apparent.

4.5.1 Example Goal and Assessment Scope. Refer to Mandatory Appendix I, section I-2, Plant Function, c.2). This part of the standard states the assessment team should talk with the compressor operators to determine the problem and the severity of the impact on system operation. The assessment team should determine past problems and their solutions. When problems exist with a compressed air system, quick solutions are often necessary but are often not very energy efficient. Often these quick solutions are intended to be temporary. However, once the problem is resolved, the temporary solution often becomes permanent.

For example, in systems with high-volume intermittent air demands, a low-pressure condition may occur when it is necessary to start up a compressor to supply the high volume demand event. If the system does not have enough compressed air storage to maintain adequate system pressure during the permissive start-up time of the compressor, production operations can be affected. A common quick-fix solution is to keep the "stand-by" compressor running. This can be done by running the compressor manually or by preventing the automatic shutdown control from stopping the compressor.

The energy-efficient solution treats the root cause of the problem, which is inadequate air storage. The scope of work would include measurements to determine the characteristic signature of the demand event and analysis to design a properly applied storage solution.

Working through Mandatory Appendix I, Preliminary Data Collection Matrix, the assessment team will create a list of goals and an associated assessment scope to achieve each goal. This list will become the site-specific assessment goals (para. 4.7), which together with the assessment scope for each of the goals can be used to develop the assessment plan of action (para. 4.8).

Then in para. 4.9, Goal Check, the assessment team can evaluate the assessment plan of action. If the assessment team finds that the goals are not being met, they should modify the goals or assessment scope, or both, to create a revised assessment plan of action that satisfies the goal check evaluation.

4.6 Initial Data Collection and Evaluation

Some of the information about the plant and the compressed air system in the ASME EA-4 Mandatory Appendix I, Preliminary Data Collection Matrix can be collected without the physical presence of all team members at the plant. If key members of the assessment team do not work at the plant, other members of the assessment team can collect this information before the rest of the team arrives. The following elements of Mandatory Appendix I could be included in the following categories: I.1, I.2.a, I.2.b, I.2.e, and I.3.a.

Designing the assessment begins by gathering as much information as possible about the compressed air system and its operation. Mandatory Appendix I, Preliminary Data Collection Matrix, guides this process. There are many different ways to gather this information in advance of the assessment team's meeting to define goals and the assessment scope. Holding individual meetings with all stakeholders of the system can be a lengthy, time-consuming process. As an alternative to individual meetings, the team might consider developing questionnaires for distribution to stakeholders. Exchanging existing documentation among interested parties for comment can be effective. Webcasts and teleconferences can also be an efficient way to get good information.

Table 1 Site-Specific Assessment Goals

I-4 Inventory Key End Use Air Demands

- a. What are the high energy use equipment in the plant?
  - 1) What equipment and processes use large amounts of compressed air?
  - 2) How often and how long do these equipment or processes use air?
  - 3) Does the large compressed air use have a negative impact on other end-use applications?
- b. What high volume intermittent end-use applications do you know of in the plant?
  - 1) What equipment and process requirements are using large amounts of compressed air for short periods of time, followed by an interval of time with minimal air demand?
  - 2) Does the high volume intermittent compressed air use have a negative impact on other end-use applications?

GENERAL NOTE: The letter and number designators correlate with the letters and numbers in Mandatory Appendix I, section I-4 of ASME EA-4–2010.

4.7 Site-Specific Assessment Goals

If some members of the team do not work at the plant, they can work together with plant personnel on the assessment team to develop the plant's assessment goals (Table 1) before they arrive at the plant.

Typical goals for an assessment include improving efficiency, improving performance, reducing downtime, having a more reliable source of compressed air, and reducing maintenance.

The information in Mandatory Appendix I, Preliminary Data Collection Matrix, is designed to provide a list of possible site-specific assessment goals. For example, Mandatory Appendix I, section I-4, Inventory Key End-Use Air Demands, can be used to create a questionnaire, webcast, or meeting agenda to help determine site-specific assessment goals (shaded items are supplemental elements of assessment).

Other parts of this section of the matrix address the following end use objectives:

(a) perceived high pressure use
(b) low pressure use
(c) poorly performing applications
(d) end use applications with air quality issues

Similarly, the rest of the matrix can be used to collect information that will allow the assessment team to develop overall site specific assessment goals.

4.8 Assessment Plan of Action

Using information from the previous three sections — Assessment Goals and Scope, Initial Data Collection, and Site-Specific Assessment Goals — the assessment team will develop an assessment plan of action and develop an SOW for the assessment.

As stated in the standard's second-to-last paragraph of para. 4.8, "The assessment team using information and knowledge gained with respect to organizational, energy, and system performance goals, together with system requirements and stakeholders' needs, shall incorporate the plan of action into a SOW for the assessment."

Meeting the plant site goals and information needs may include objectives and action items that are not listed in the plan of action matrix. Where the plan of action matrix does not meet plant site goals, adhere to the principles of systems engineering, apply the systems approach, and be sufficiently comprehensive when developing the plan of action for the assessment. ASME EA-4 addresses the systems engineering process (para. 1.3.4) and the systems approach (para. 1.3.3).

If the plant desires full adherence to the standard, a third party could evaluate the SOW of the assessment. Key elements of the review are as follows:

(a) The assessment considers the entire system, from energy inputs to the work performed as the result of these inputs.

(b) The assessment is sufficiently comprehensive to identify the major energy efficiency opportunities for improving the overall energy performance of the system.

(c) Where the standard is silent or inconsistent for any specific application, the assessment process is guided by the following:

(1) Adhere to the principles of systems engineering.
(2) Apply the systems approach.
(3) Be sufficiently comprehensive.

4.9 Goal Check

The following checklist is adapted from *Systems Engineering Measurement Primer* [2] and may provide guidance in reviewing the assessment plan of action.

(a) *Relevance*. Why perform this action item? Is there more than one reason for this action item? Is it a result of ambiguity in the related assessment objective? Only select action items that are pertinent to an objective to be obtained.

(b) *Completeness*. Are goals, stakeholder's needs, and system requirements being met? Has any key parameter needed to analyze data and achieve results been omitted? Has a balanced set of objectives among supply, transmission, and demand that adheres to the systems approach been identified? Is the assessment sufficiently comprehensive?

(c) *Timeliness*. Can the system assessment meet the required time schedule? Be sure data collection, analysis, and reporting will provide results in the time allowed. Is more time required or should the SOW be modified?

(d) Simplicity. Can data be collected and analyzed easily and cost effectively? Will the assessment produce results that can be presented in a manner such that stakeholders will understand what it means?

(e) Cost Effectiveness. Is the budget sufficient? Will the system assessment provide more value than it costs? Is the SOW appropriate, or should it be modified?

(f) Repeatability. Will the same plant operating conditions provide the virtually the same data and information twice? Are accuracy and precision adequate? This is important for future use of the system assessment's baseline measurement.

(g) Accuracy. Are objectives, action items, methodology, and the resultant data relevant to system assessment goals? Are proposed measures reliable, and are measurements being made at the appropriate time? Measurements should be accurate, and the resulting analysis should accurately serve the intended purpose of making the measurement.

4.9.1 Evaluating the Cost Effectiveness of an Assessment SOW. The economic benefit of an energy assessment depends on the assessment cost as compared to the potential savings and cost of implementation. Evaluating the cost effectiveness of an assessment's SOW requires an estimate of present energy cost of the system and possible cost savings. There are simple straightforward calculations that can provide an estimate of present annual energy cost for air compressor operation. Two methods are described below: using the manufacturer's rated performance for brake horsepower (bhp), and performing a spot check measurement of the air compressor's amperage. Cost savings are much more variable (between 15% and 50% savings) and difficult to estimate but should be considered by the assessment team as justification for the SOW.

4.9.2 Using Compressor Rating: Annual Electrical Energy Cost ($) Estimate [3]

$$\frac{(\text{bhp}) \times (0.746) \times (\text{number of operating hours}) \times (\$/\text{kWh}) \times (\text{percent time}) \times (\text{percent full-load bhp})}{\text{motor efficiency}}$$

where

0.746 = conversion between hp and kW
bhp = motor full-load horsepower (frequently higher than the motor nameplate horsepower; check equipment specification)
motor efficiency = motor efficiency at this operating level
number of operating hours = the total number of hours the compressor runs during the year
percent full-load bhp = bhp as percentage of full-load bhp at this operating level
percent time = percentage of time running at this operating level (percent full-load bhp)

4.9.2.1 Example. A typical manufacturing facility has a 200-hp compressor (which requires 215 bhp) that operates for 6,800 hr annually. It is fully loaded 85% of the time (motor efficiency = 0.95) and unloaded the rest of the time (25% full-load bhp and motor efficiency = 0.90). The aggregate electric rate is $0.05/kWh.

Cost when fully loaded =

$$\frac{(215\text{ bhp}) \times (0.746) \times (6{,}800\text{ hr}) \times (\$0.05/\text{kWh}) \times (0.85) \times (1.0)}{0.95} = \$48{,}792$$

Cost when unloaded =

$$\frac{(215\text{ bhp}) \times (0.746) \times (6{,}800\text{ hr}) \times (\$0.05/\text{kWh}) \times (0.15) \times (0.25)}{0.90} = \$2{,}272$$

Annual energy cost = $48,792 + $2,272 = $51,064

4.9.2.2 Factors That Can Affect the Calculation. The following factors can affect the calculation:

(a) motor operation in service factor (above nameplate horsepower)

(b) part-load operation and the air compressor's control type

(c) operating pressure at the compressor discharge (as compared to equipment specification)

(d) utility rate structures using average $/kWh instead of actual rate that may be seasonal, based on time of day, or using different block rates

(e) motor efficiency (especially after poor-quality repairs and rewinds)

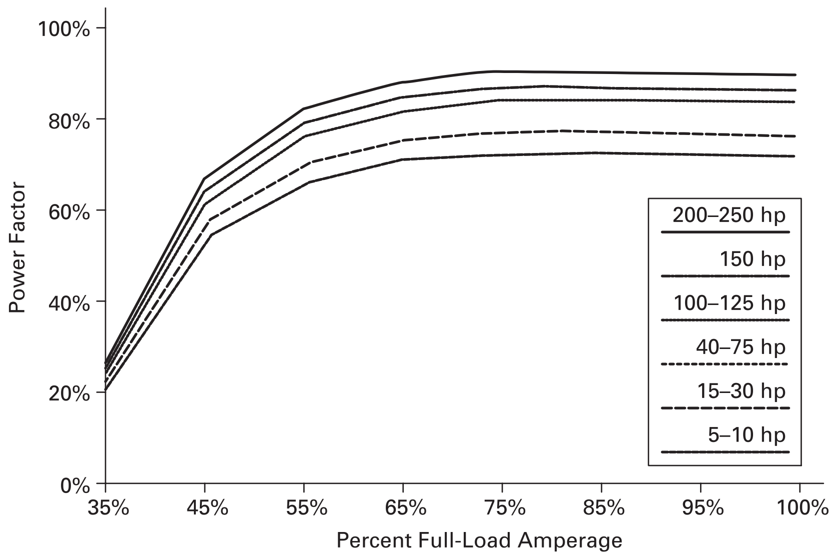
4.9.3 Using Spot Check Measurement (Amps): Annual Electrical Energy Cost Estimate

$$\frac{(\text{voltage}) \times (\text{measured amperage}) \times (1.732) \times (\text{PF}) \times (\text{hours}) \times (\text{percent time}) \times (\$/\text{kWh})}{1{,}000}$$

where

1.732 = a factor used for three-phase power (i.e., the square root of 3)
divisor of 1,000 = converts watts to kilowatts
full load amps = the average of amperage for all of the three phases supplying electricity
hours = the total annual operating hours for the electric motor

Fig. 2 Motor Power Factor as a Function of Percent Full-Load Amperage



$/kWh energy cost = usually an aggregate cost considering energy cost, demand charge, time of day or seasonal energy cost variation

percent time = percentage of time running at this operating level (measured amperage)

PF = the operating power factor of the electric motor

voltage = the average voltage for all of the three phases supplying electricity

4.9.3.1 Example. A typical manufacturing facility has a 200-hp compressor that operates for 6,800 hr annually. It is fully loaded 85% of the time and unloaded the rest of the time. The aggregate electric rate is $0.05/kWh. The compressor's nameplate motor amperage is 218 amps with 1.15 service factor (SF) rating.

Spot check measurements of voltage and amperage for a full load are as follows:

Voltage	Value	Amperage	Value
V_{ab}	467	A_a	238
V_{bc}	473	A_b	241
V_{ac}	469	A_c	240
$V_{average}$	469.7	$A_{average}$	239.7

For the operating power factor of the electric motor (PF), the full load is assumed to be 0.89.

Cost when fully loaded =

$$\frac{(469.7) \times (239.7) \times (1.732) \times (0.89) \times 6{,}800 \times 85\% \times (\$0.05/\text{kWh})}{1{,}000} = \$50{,}156$$

Annual energy cost of a full-load operation = $50,156

When using measured amperage to calculate the power of an air compressor motor running at less than the full load condition, it is important to consider the changing power factor (PF) of a motor operating at a fraction of its full load rating.

Spot check measurements of unloaded voltage and amperage are as follows:

Voltage	Value	Amperage	Value
V_{ab}	469	A_a	94
V_{bc}	470	A_b	97
V_{ac}	472	A_c	95
$V_{average}$	470.3	$A_{average}$	95.3

The measured unloaded amperage is 95.3 amps as compared to nameplate FL amperage of 218 amps indicates that the unloaded amperage is 43.7% of full-load amperage. Referring to the chart shown in Fig. 2, [4] the unloaded power factor can be estimated for unload at 43.7% of FL amperage to be 0.57.

Cost when unloaded =

$$\frac{(\text{voltage}) \times (\text{unloaded amps}) \times (1.732) \times (\text{PF unloaded}) \times (\text{hours}) \times (\text{percent time}) \times (\$/\text{kWh})}{1{,}000}$$

$$\frac{(470.3) \times (95.3) \times (1.732) \times (0.57) \times 6{,}800 \times 15\% \times (\$\ 0.05/\text{kWh})}{1{,}000} = \$2{,}257$$

Annual energy cost: unloaded operation = $2,257
Annual energy cost: total = $50,156 + $2,257 = $52,413

4.9.3.2 Factors That Can Affect the Calculation. Factors that can affect the calculation are as follows:

(a) motor operation in service factor (above nameplate horsepower)

(b) part-load operation and the air compressor's control type

(c) operating pressure at the compressor discharge (as compared to equipment specification)

(d) utility rate structures using average $/kWh instead of actual rate, which may be seasonal, based on time of day, or using different block rates.

(e) changing motor power factor as motor load falls below full load output.

5 GUIDE TO CONDUCTING THE ASSESSMENT

Time and effort applied to action items for the system assessment should be traceable to issues, opportunities, remedial measures, and implementation of compressed air system improvements. Most projects cannot afford to collect data or gather information that will never be used.

5.1 Measurement Plan

Something that is not defined cannot be measured. For each measured parameter, the measurement plan should identify the measurement location, the sample rate, data interval, and duration of measurement. The measurement plan should consider the end-to-end measurement accuracy for each parameter.

Measured data should include a statement of estimated quantification uncertainty declaring both coverage interval and confidence level.

"The quantification uncertainty is estimated as ±10% with 90% confidence."

A statement of coverage interval without confidence level could result in an exceedingly narrow coverage interval if confidence is very low (e.g., ±0.1% with 30% confidence). A broad coverage interval together with low confidence should result in more conservative statements, estimates, and projections.

Quantification uncertainty is not intended to be the result of a rigorous statistical process, but an unconfirmed estimate. Many factors affecting end-to-end measurement accuracy, listed in (a) through (c), are difficult to quantify for in situ field measurement.

(a) Accuracy. Accuracy reflects the cumulative effect of all errors introduced in measurement and analysis including factors such as instrument error, sampling error, resolution error, planned and unplanned assumptions, etc. Accuracy is improved by using measured values in place of assumed or stipulated values. A more efficient sample design, increasing sample size, and improved measurement techniques will also improve accuracy. In general, improving accuracy of the measurement plan increases cost. The assessment should remain cost-effective (see para. 4.9).

(b) Transparency. All aspects of the measurement plan should be clearly and fully disclosed.

(c) Reliability. Reliability considers the measurement plan's adherence to the system assessment goals. The measurement plan should address key parameters, represent all operating modes of the plant, and fairly represent normal operating conditions. Measurement technique requires appropriate placement of instruments, stable electrical signals, appropriately interpreted in engineering units, with sample rate and data intervals so as to properly characterize the measured parameter.

5.1.1 Measurement Instruments. The readings of many instruments will "drift" over time due to wear and physical properties of the sensing element. The magnitude of errors for various types of sensing elements is generally available in manufacturers' specifications and various instrument handbooks.

Instrument drift can be identified through "as found" testing where the instrument under test is compared to the reading of an instrument that has undergone recent calibration. Instrument drift is managed through re-calibration following procedures of recognized measurement authorities such as the National Institute of Standards and Technology (NIST). For calibration, primary standards and no less than third-order standard traceable calibration equipment should be used wherever possible.

Instrument accuracy is only one aspect of the measurement system accuracy. Other factors such as poor placement of the instrument so it does not get a proper "view" of the parameter being measured, electrical interference, signal conversion error, and analog to digital conversion resolution all act to reduce the instrument's accuracy or precision. The instrument accuracy and precision specified by the manufacturer probably overstates the measurement system's end-to-end accuracy and precision for actual readings in the field.

5.1.2 Measurement Techniques. There is no additional guidance for this clause.

5.1.3 Baseline Period and Duration of Data Logging. The baseline period should include all "typical periods" of plant operation. It is common practice to use 24-hr days as the basic operating period. However, other time periods can be used. Typical days are representative of the plant's planned or unplanned changes in production. Changes may be seasonal, based on the day of the week, market conditions, availability of raw materials, or other factors. Compressed air system energy profiles exhibit both time-dependent and production-dependent variation. Depending on a particular day's production operation, the production-dependent portion of the plant's compressed air energy baseline will exhibit different characteristics. Days with similar compressed air energy profiles (typical days) are grouped together as different "day types."

When considering the duration of baseline measurement, it is necessary to measure all typical days of operation. Some typical days such as holidays may represent a small fraction of the plant's compressed air energy base year operation. Baseline performance for a typical day may be stipulated based on historical operating information. Stipulated baseline performance should not exceed 10% of the plant's base year energy use.

5.1.3.1 Example: Determining Baseline Duration for Food Processing Plant [5]. A food processing plant produces canned fruit and operates with a peak production period for 13 weeks of seasonal operation. For the remaining 39 weeks the plant has continuous operations including repackaging product to fulfill ongoing customer orders.

The assessment team recognized two typical operating periods: seasonal production and continuous packaging. Each of the two operating periods has potential for variations by day of the week, particularly weekend operation. Seasonal peak operation typically lasts for 13 weeks, and the baseline measurement was done during a week in August. A continuous packaging production profile is taken for a week in February.

The measurement plan included combining data from the plant's existing DCS with data measured using portable data loggers and transducers. The DCS monitors all points necessary to establish the operating profile for the continuous packaging production period. However, during the seasonal peak time one plant air compressor and two rental compressors have no input to the DCS.

The portable data loggers and transducers sample at a rate of 10 msec and recorded data at a 6-sec interval. This data allowed overall system dynamic assessment while some individual events and end use applications were measured at up to a 25 Hz data interval.

5.1.4 Direct Versus Indirect Measurement

5.1.4.1 Direct Measurement. Direct measurement of a parameter is accomplished with an instrument designed for such a task.

For example, if someone has a bucket of water, how many gallons of water are in the bucket?

Direct measurement of a parameter is accomplished with an instrument designed for such a task.

Making a direct measurement requires a measurement container — for example, a measuring cup. By pouring water from the pail into the measuring cup repeatedly until all of the water has been measured and adding up each individual measurement, the number of gallons of water in the bucket has been directly measured.

5.1.4.2 Indirect Measurement. Referring to the example in para. 5.1.4.1, suppose there is no type of measurement container. How is the amount of water in the bucket indirectly measured?

Indirect measurement of a parameter is inferred through the measurement of a sufficiently comprehensive group of associated parameters so as to quantify the desired parameter.

Using a scale, the weight of the water and bucket is measured. Then, the water is emptied from the bucket, and the empty bucket is weighed. It is determined that the difference (weight of the full bucket − the weight of the empty bucket) is 8.34 lb. Knowing that the density of water is approximately 8.34 lb/gal (at 60°F), it is indirectly determined that the bucket held 1 gal of water.

Suppose that the water is not near room temperature but is much hotter. If the water is hot, only a measure of weight may be insufficient to determine the volume of water. Another associated parameter that affects the measurement is the temperature of the water, because the weight density of water decreases (or specific volume increases) with increasing temperature. In this example, the temperature of the water is 150°F. The weight density of water at 150°F is 8.18 lb/gal. At that temperature a bucket holding 8.34 lb of water is actually 1.02 gal — a small difference. It is up to the measurement practitioner to determine the associated parameters to be measured and the resultant accuracy interval and confidence of the inferred value for the desired parameter.

5.1.4.3 Example Direct Versus Indirect Measurement. Measurement of power consumed by an electric motor is one example of a compressed air system parameter that can be directly or indirectly measured.

Factors that determine kilowatts are as follows:

(a) voltage for each of the three phases supplying electricity

(b) amperage for each of the three phases supplying electricity

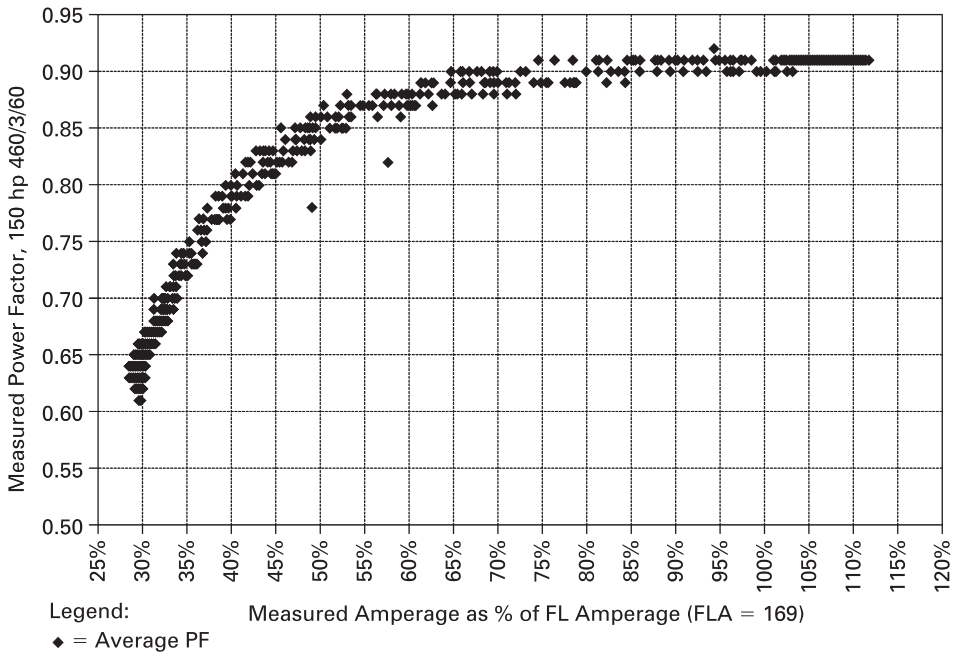
(c) the operating power factor (PF) of the electric motor

(d) balance or imbalance of voltage, current, or power factor (or all) among the three phases

For direct measurement, a range of kilowatts and kilowatt-hour transducers are commercially available. Differences are measurement of true RMS power or average power (average power is 11% lower than RMS power). Transducers may measure based on an assumption of balanced load or may measure actual phase imbalance.

Indirect measurement may be made by data logging amperage and making assumptions for voltage, power factor, and load imbalance. Allowable voltage variation for NEMA B design motors is ±10%. Power factor

Fig. 3 Measured Power Factor Versus Percent Full-Load Amperage



depends on motor design and also varies with actual load on the running motor. Data in Fig. 3 is measured performance of motor power factor versus measured amperage as a percent of full-load (FL) nameplate amperage for a 150 hp premium efficiency NEMA Design B; 460 volt, 3 phase, 60 Hz electric motor. Notice the variation in the measured performance of Fig. 3 as compared to "typical data" presented in Fig. 2, para. 4.9 of this guidance document.

For both direct and indirect measurements, the assessment should document all relevant application data from the manufacturer's instrument specification (e.g., calibration information, accuracy, precision, installation, and application considerations). The assessment should identify and document any in situ installation factors that deviate from the manufacturer's recommendations. The assessment should estimate accuracy and confidence of the in situ end-to-end field measurement.

For each instrument used, document the relevant data from the manufacturer's instrument specification (e.g., calibration information, accuracy, precision performance).

5.1.5 Transducer Installation. Transducer installation has the potential to affect the measurement system's end-to-end accuracy and confidence. Poor placement of the transducer may prevent it from having a representative "view" of the parameter it is measuring. For example, a pressure transducer's reading may be affected by its location relative to a check valve installed in the pipeline, or a flow meter's readings may be affected by its proximity to an elbow in the pipe and induced swirl in the flow velocity profile.

Other considerations of the transducer's installation environment including extreme temperature (hot or cold) or mechanical vibration may affect the transducer's performance.

5.1.6 Electrical Signal Integrity. Industrial sites have many pieces of equipment that can interfere with the electrical signals associated with measurement equipment. Common electrical signals used for measurement instruments are voltage (±mV DC to ±10 VDC), current (commonly 0 ma to 20 ma with some 0 ma to 50 ma), and frequency (0 Hz to 500 Hz through 0 kHz through 100 kHz). The following influences can seriously degrade signals: capacitive or magnetic coupling, ground loops, common mode voltage difference, over-voltage and transients, and electromagnetic and radiofrequency interference.

5.1.7 Planning and Measurement Techniques. There is no additional guidance for this clause.

5.1.7.1 Sample Rate and Data Interval. Compressed air system performance is continually changing. As a result, system parameters including airflow rate, pressure, and power use of air compressors are changing. End use applications such as automated packaging or assembly equipment may operate at high speeds. Air demand can undergo large changes, increasing or decreasing in a few seconds of time as high volume air demands come on-line and off-line.

5.1.7.1.1 Dynamics. Evaluating dynamics of system operation and end use application performance often requires a high frequency sample rate and also high frequency data intervals. To capture dynamic performance it is necessary to have a data interval equal to at least one order of magnitude greater than the time base of the event being measured. For example, to capture the dynamic pressure profile of an air cylinder that extends in 0.5 sec, it is necessary to use a data interval of at least 0.05 sec (20 Hz data rate). To provide oversampling for signal noise reduction, a sample rate of 100 Hz might be indicated.

5.1.7.2 Signal Noise. Signal noise is a random disturbance to the measurement's electrical signal. Noise is often caused by factors that affect electrical signal integrity.

5.1.7.2.1 Sample Averaging. In random fashion throughout a given time period, noise-induced signal variation will produce an equal number and amplitude of signals above and below the actual measurement value. One method of minimizing the impact of signal noise is "oversampling." Using a high frequency sample rate, multiple samples are averaged throughout a fixed time interval, and the resultant average value is stored as the measured data. This sample averaging method results is one data point per time interval.

5.1.7.2.2 Power Measurement. Power measurements typically serve two objectives: determine energy use and assess the compressor's control response to changing conditions.

Energy use is determined by post processing individual power (kW) measurements, integrating them over time, and calculating energy use (kWh). The greater the frequency of sample rate, the more accurate the resultant integration of power to energy values. However, storing high frequency data readings for long periods of time increases the amount of data involved in calculating the measurement of energy. Sample averaging described above can be used as a data management method. Since each averaged data point recorded represents an average of power readings, the accuracy of the calculated energy measurement is unaffected.

5.1.7.2.3 Energy Measurement. Watt-hour transducers integrate power measurement over time and provide a pulse output with each pulse representing some number of watt-hours. Based on energy measurement alone it is difficult to assess the dynamic response of compressor controls to changes in system performance. For dynamic analysis, power measurement is more relevant.

5.1.8 Identify Test Points and Parameters. There is no additional guidance for this clause.

5.2 Site Access Procedures

The assessment should comply with plant site-specific safety training and safety requirements including but not limited to

(a) appropriate personal protective equipment and access to any specialized safety gear that is required

(b) lock-out procedures and access to equipment and appropriate plant site contacts

(c) hazardous areas requiring special safety rating for measurement equipment

(d) review of emergency evacuation procedures, location of muster points, and process for accountability of personnel

5.3 Assessment Kick-Off Meeting

There is no additional guidance for this clause.

5.4 Deploy Data Collection Equipment

Installation of portable instruments can be used for short-term measurement activities. Short-term data is recorded with a portable digital data acquisition system (data logger). Multiple data loggers independently assign time and date values to logged data. Align the time and date values of each separate data logger as closely as possible. The assessment should document the expected time variation that will occur between data systems.

The assessment should verify that the digital system is reading the transducer at the sample rate and data interval as required by the measurement plan and convert the values to correct engineering units. This can be accomplished with a short test-run of data and comparison with independent instrumentation where available, or comparison with a group of associated stipulated values and/or indirect measurements.

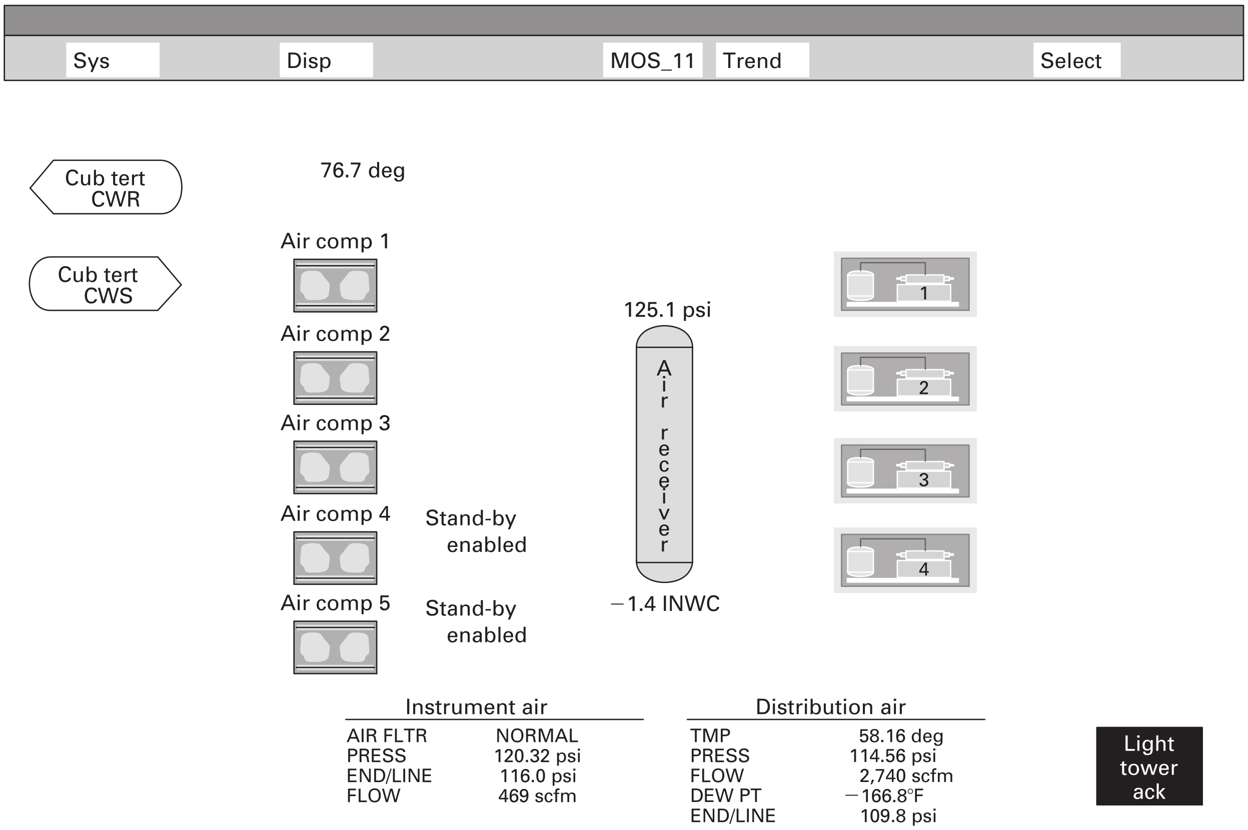
If the data is erroneous, the team should troubleshoot and correct equipment and/or instrument installation issues such that recorded data is appropriate. If unresolved measurement installation issues increase uncertainty with respect to the recorded data, these should be documented along with the impact on the measurement confidence level.

After collecting large amounts of data, it is very common for that data to be unusable. Such results are not only disappointing, but they lead to additional unplanned time and cost for the assessment.

Before collecting data, ensure that the instrument's batteries are functioning, and, if possible, power up the equipment and use the battery power as a backup. Ensure the power outlet is working. Label the power cord and data logger with the following message:

Compressed Air System Testing in Progress. Please Do Not Disconnect Power.

Fig. 4 Example Installed Data System



When setting up the data logger, check and re-check. Be sure the data logger is set, running, and getting reasonable data. Forgetting to put the memory card in, failing to start the logger, and forgetting to open the isolation valve on the pressure transducer are all common ways to get incorrect data.

Determine if the data are reasonable and look at the display on the data logger and see if the readings make sense. If there is no display, download a short run of data and see if it makes sense. Do not forget to restart the data logger after downloading. It can be easy to spot the pressure transducer with a closed isolation valve, but difficult without reviewing the collected data.

Ensure that the data logger is set up properly. Check the measurement plan for the planned sample rate and data interval. Make sure the time clock on the data logger is set correctly. Make sure the data interval makes sense. If the plan calls for a slow data interval but the equipment being measured operates at a fast cycle rate, review the plan and see if the assessment team wants to revisit the measurement plan.

Perform daily checks, making the rounds once a day, and see that the data loggers are still running and that the data still looks good. Check the batteries and ensure that nothing has been unplugged.

5.5 Coordinate Data From Permanently Installed Data Systems

The assessment should gather data available from permanently installed systems [e.g., Supervisory Control and Data Acquisition System (SCADA)].[1] If data from a short-term measurement activity (logged data) will be used together with SCADA data, align the time and date values of each separate system as closely as possible. The assessment should document the expected time variation that will occur between data systems (see Fig. 4).

The team should verify that the SCADA is reading the transducer at the sample rate and data interval as required by the measurement plan, and convert these values to correct engineering units. If the data is erroneous, the team should troubleshoot and correct equipment and/or instrument installation issues such that recorded data are appropriate. If left unresolved, measurement installation issues increase uncertainty with respect to the recorded data, document issues, and the impact on measurement confidence level.

[1] Permanently installed data systems have various designations [e.g., Distributed Control System (DCS), Building Management System (BMS)]. For reference such systems will be referred to as SCADA.

5.6 Validate Data

Instruments, digital systems, and methodologies used for data collection differ in complexity and degree of difficulty. Measuring and collecting large amounts of data often result in some amount of missing or erroneous data.

(a) Data can be interpolated from, or populated with, valid measured data taken during another time period of similar operation.

(b) Incorrect scaling of engineering units can be corrected through post processing to rescale to correct engineering units.

(c) Indirect measures of related parameters along with stipulated values or spot check measurements can be used to derive reasonable methods of post processing data to apply appropriate correction factors.

Validation of data is a more rigorous process than "verifying data," which is described in para. 5.4 of this guidance document. Validation of data identifies elemental errors and uncertainties that ultimately affect the coverage interval and confidence of the result. In addition to identifying and correcting erroneous or missing data, other corrections for calibration adjustments, errors of method, or known corrections are applied to the data.

5.6.1 Example: Calibration Adjustment. A group of pressure transducers with ±1% FS accuracy are used for measurement. The transducers have improved repeatability of ±0.07%. On-site test measurements for the "as found" pressure reading of each transducer recorded the systematic offset pressure of each individual pressure transducer as compared to a calibrated ±0.015% pressure transducer. Post processing pressure data for each individual pressure transducer should be done, correcting the measured value by the tested systematic offset pressure of the transducer. By this process the overall coverage interval for pressure data is improved as compared to the accuracy specification of the original pressure transducers used for measurement.

5.6.2 Example: Correcting Errors of Method. For a given measurement, validation of data reveals that an incorrect scaling factor was set in the data logger's configuration. A pressure transducer scaled as 0 VDC to 5 VDC signal with a 0 psig through 200 psig range should have been configured with a 1 VDC to 5 VDC signal. The incorrect scaling was 40 psig/V. If the measurement made at the incorrect signal scale is 132 psig, the electrical signal would have been 3.3 V (132 psig / 40 psig/V). The proper slope for the transducer signal should be 50 psig/V and 1 V offset. With 1 V offset, the transducer's offset pressure at 0 V signal is -50 psig.

Correct scaling for a linear pressure transducer with 1 VDC to 5 VDC electrical signal scaled to a pressure range from 0 psig to 200 psig uses the equation of a straight line

$$y = mx + b$$

$$y = (50 \text{ psig/V}) \times (3.3 \text{ V}) + (-50 \text{ psig}) = 115 \text{ psig}$$

The correct value for a 3.3-V signal should be 115 psig.

5.6.3 Example: Known Correction Applied to the Data. An averaging style kilowatt transducer is used to measure compressor power. Real power is measured as the RMS (root mean square) value of the sinusoidal electrical voltage and current wave form. For a sine wave the RMS value is equal to 0.707 times the peak value, and average is equal to 0.637 times the peak value. Therefore, the RMS value is equal to 1.11 times the average measurement (0.707 / 0.637 = 1.10989). Post processing of average kilowatt measurements would add 11% to the measured value as a correction to RMS power.

5.7 Plant Functional Baseline

The assessment should record data associated with plant function and production process information. Base year energy use is measured according to Mandatory Appendix II, Plan of Action Matrix in ASME EA-4. To completely define base year conditions, it is necessary to document the plant's functional baseline through gathering relevant production operating data. These data are the basis of future system performance comparison. A well designed and executed system assessment records plant operating conditions in a way that can be accessed in the future.

5.7.1 Static Factors. Comparisons of future performance will require adjustments for changing plant function. Factors that govern compressed air energy use over the short term are normally considered static factors. Over the long term the normally static factors such as those listed as follows may change:

(a) amount of production space or number of production shifts per day

(b) type of products being produced

(c) the amount or type of pneumatically powered production equipment

5.7.2 Base Year Production Performance. The assessment team should determine the necessary plant functional data and appropriate method to record and organize the data necessary to define base year performance. The team should investigate and document base year production performance including

(a) production rate during baseline measurement, annualized for the base year, based on the plant's normal measurement of production output (e.g., number of units produced, tons of product produced)

(b) type of production processes, square footage of production area, and number of machine and/or production lines

(c) baseline operating practice, number and time duration of production shifts, seasonal schedules, number of employees, etc.

Table 2 Production Rates Recorded During the System Assessment

Day of the Week	Typical Operating Period	Date	Production Volume
Thursday	Partial production	11/6/08	178,845 lb
Friday	Limited production and maintenance	11/7/08	14,070 lb
Saturday	Down day	11/8/08	No production
Sunday	Production startup	11/9/08	50,003 lb
Monday	Full production	11/10/08	301,821 lb
Tuesday	Full production	11/11/08	307,523 lb
Wednesday	Full production	11/12/08	336,578 lb
Thursday	Full production	11/13/08	269,503 lb

(d) present production outages, including tools, machines, processes, and production areas that are shut down for repair, maintenance, retooling, business cycles, market conditions, etc.

5.7.3 Example: Plant Functional Baseline. The plant's measure of production output is pounds of product. According to production records during the assessment baseline period, the plant produced 1,279,498 lb of product from Thursday, November 6 through Thursday, November 13. Production information for the baseline period is shown in Table 2. Detailed production operating schedules were provided by each production manager and are included in an appendix.

The plant operates a total of eight production lines: three specialty lines and five standard lines. The packaging area has a total of 28 packaging machines. The number of packaging machines operating varies with production rate; normally full production typically operates 22 packaging machines.

There are three material handling systems supplying raw material to the production process. Material handling systems in the plant use compressed air for dense phase transfer of raw material. One system serves two storage hoppers: one storing material A and the other storing material B. The second system transfers material to the batching system. The third handling system conveys a measured weight of mixed material to one of the eight production lines.

Operating periods are 24 hr. Annually operating periods include 170 full production periods, 50 production startup periods, 50 limited production and maintenance periods, 35 partial production periods, and 60 down days.

If the plant's production includes seasonal operation, the baseline may need to consider several additional typical operating periods.

Establishing a well documented functional baseline is important to post implementation measurement and verification. If the production process had not changed and production volume is equal to the baseline period, then the functional baseline has little relevance. However, implementation of compressed air system improvements often take between several months and 1 yr to 2 yr before all changes are complete. During the time of implementation, production levels may change, or physical changes to the production process may have taken place. Adjustments to the plant's production baseline may be necessary during a future post implementation assessment. Routine adjustments are factors affecting production that are expected to change. One example of a possible routine adjustment may be changing market conditions that cause changes in production schedules. Nonroutine adjustments are a result of factors that are less likely to change (e.g., a major addition to the plant changing the type or number of production lines operating in the plant).

To evaluate routine or nonroutine adjustments properly, a well documented baseline of the physical plant, production equipment/processes, and production output is essential.

5.8 Functional Investigation

There is no additional guidance for this clause.

5.9 Progress and Wrap-Up Meetings

The assessment team can communicate a number of ways during the progress and wrap-up meetings. Knowledge and findings obtained during the assessment should be communicated among the team members. This can be done through computer-generated slides (e.g., PowerPoint) or other means.

Charts and graphs of data can effectively summarize performance information. Photos of existing plant equipment can serve to document the present production process and the type of equipment in use. Excerpts from original equipment manufacturer (OEM) manuals for production equipment with diagrams, description of operation, recommended maintenance, and other information can document production process requirements. Opportunities for energy reduction (e.g., inappropriate use of compressed air) can be documented with photos.

Table 3 Example Baseline Summary

Day Type	Total Operating Hours	Average Airflow, acfm	Average Airflow, %Cs.	Peak Demand, kW	Load Factor, %	Annual Energy, kWh	Annual Energy Cost, $ / yr
Production	6,000	538	40.9	182.5	58.9	769,950	$30,798.00
Weekends	400	630	47.9	103.6	47.5	41,440	$1,637.00
System totals	6,400	544	41.4	182.5	58.2	811,390	$32,435.00

The meeting can be held with all team members attending in person. Other alternatives exist such as teleconferencing. However, given the importance of visual presentation of findings discussed above, a webinar (webcast) style meeting is preferred over teleconferencing, as it allows all team members to view visual presentations that can facilitate discussions.

6 GUIDE TO ANALYSIS OF DATA FROM THE ASSESSMENT

6.1 Baseline Profiles

The team should

(a) determine baseline performance for the system power profile and the associated airflow rate of demand

(b) assess total baseline performance to hourly profiles of energy use and total air demand

(c) baseline the system's compressed air supply efficiency

(d) analyze daily performance and identify the profile for typical days of operation

(e) annualize data for the expected number of operating days for each day type profile (see para. 6.1.5)

(f) project base-year energy and air demand totals

An example baseline is shown in Table 3.

Detailed data such as the baseline profile for individual typical operating periods shown in Table 4 may be best presented in an appendix to the assessment report.

As a supplemental element of an assessment (see ASME EA-4, Mandatory Appendix II, II-1 a.2), the total energy use reported would include all parasitic energy consumption related to the compressed air delivered. Some parasitic energy sources are treatment equipment such as air dryers and filters. Depending on system design, parasitic energy use may be minimal or significant; if the latter, the assessment team may decide that it should be included as a supplemental element of the assessment.

The energy use for irrecoverable pressure loss in filters is included in the compressor power measurement due to the impact on compressor discharge pressure. Air dryers have various energy sources depending on the dryer's design.

Refrigerated dryers have a separate electrical input to power the refrigeration system. Noncycling-style air dryers have constant energy use independent of airflow rate through the dryer, while cycling-style dryers have reduced energy use when airflow rate or inlet temperature are lower than the dryer's rated design. Since the air dryer's energy use is low as compared to that of an air compressor, the dryer energy use can be stipulated by manufacturer's rating and be within the 10% limit set forth in ASME EA-4 (para. 5.1.3). Direct measurement of kilowatt input to refrigerated air dryers in the system will yield the most accurate measure of dryer energy use.

For heatless regenerative-style air dryers, purge airflow is the major energy supply to the dryer. The energy use is measured in the compressor energy that generates the purge airflow. Heatless air dryers require a small energy input to operate electrical controls, but this is generally considered negligible. For the heat of compression-style air dryers, the energy of regeneration and pressure drop are also measured within the air compressor power measurement.

Heat-regenerated and blower-purge air dryers use a significant amount of external energy input for processing the airflow. The energy input is usually from electricity required to drive the purge blower and to power electrical heaters used to heat the purge airflow. Alternatively, some heat-regenerated air dryers may use steam or direct-fired gas heaters for purge-air heating. For a regenerative air dryer equipped with standard controls, dryer purge and energy use are controlled with a fixed time cycle. Energy-saving controls such as dew-point demand cycle controls are becoming more common. Dew-point demand cycle control initiates purge cycles as needed to maintain design dew point. When the moisture load to the air dryer is below the design rating, extended drying time reduces the frequency of regeneration cycles, thus lowering overall energy consumption.

Other parasitic energy consumption may include water-pumping energy or ventilation fans to support compressor cooling requirements. In some instances, compressor heat may impact energy requirements for air-conditioning the compressor room. The practitioner should evaluate all energy flow necessary to support the compressed air system and account for all energy input.

Table 4 Example Baseline Profile for Production Day Type

Hour of Day	1	2	3	4	5	6	7	8	9	10	11	12
Comp #1												
Measured power, kW	72	72	72	72	72	72	84	84	84	84	84	84
Calculated airflow, acfm	190	190	190	190	190	190	380	380	380	380	380	380
Calculated % capacity	40	40	40	40	40	40	80	80	80	80	80	80
Cascade #	1	1	1	1	1	1	1	1	1	1	1	1
Comp #2												
Measured power, kW	20	20	20	20	20	20	56.8	56.8	56.8	56.8	56.8	56.8
Calculated airflow, acfm	0	0	0	0	0	0	277	277	277	277	277	277
Calculated % capacity	0	0	0	0	0	0	33	33	33	33	33	33
Cascade #	2	2	2	2	2	2	2	2	2	2	2	2
Total power, kW	92	92	92	92	92	92	140.8	140.8	140.8	140.8	140.8	140.8
Total airflow, acfm	190	190	190	190	190	190	657	657	657	657	657	657
% System capacity	14.4	14.4	14.4	14.4	14.4	14.4	50	50	50	50	50	50
Hour of Day	**13**	**14**	**15**	**16**	**17**	**18**	**19**	**20**	**21**	**22**	**23**	**24**
Comp #1												
Measured power, kW	90	90	90	90	90	90	78	78	78	78	78	78
Calculated airflow, acfm	475	475	475	475	475	475	285	285	285	285	285	285
Calculated % capacity	100	100	100	100	100	100	60	60	60	60	60	60
Cascade #	1	1	1	1	1	1	1	1	1	1	1	1
Comp #2												
Measured power, kW	92.5	92.5	92.5	92.5	92.5	92.5	20	20	20	20	20	20
Calculated airflow, acfm	546	546	546	546	546	546	0	0	0	0	0	0
Calculated % capacity	65	65	65	65	65	65	0	0	0	0	0	0
Cascade #	2	2	2	2	2	2	2	2	2	2	2	2
Total power, kW	182.5	182.5	182.5	182.5	182.5	182.5	98	98	98	98	98	98
Total airflow, acfm	1,021	1,021	1,021	1,021	1,021	1,021	285	285	285	285	285	285
% System capacity	77.7	77.7	77.7	77.7	77.7	77.7	21.7	21.7	21.7	21.7	21.7	21.7

6.1.1 Power and Energy Profiles. There is no additional guidance for this clause.

6.1.2 Demand Profile. There is no additional guidance for this clause.

6.1.3 Supply Efficiency. There is no additional guidance for this clause.

6.1.4 Identify Operating Period Types. There is no additional guidance for this clause.

6.1.5 Annualize Energy Use and Air Demand. There is no additional guidance for this clause.

6.2 System Volume

System volume is an important parameter necessary to assess system events and compressor control response. As system pressure increases, compressed air energy is entering storage, and that energy is released from storage as system pressure decreases. To calculate the amount of compressed air entering or leaving storage, two parameters are required: the storage volume and the pressure increase or decrease occurring within that volume.

The mechanical volume of a system is simply the sum of the individual volumes of each air receiver, pipeline, or other vessel within the compressed air system.

The effective volume of the system is the system's mechanical volume adjusted for the actual pressure increase and decrease that occurs. All components and pipelines in a compressed air system have frictional resistance to airflow. As a result, the magnitude of pressure change is not constant throughout the entire system.

6.3 Pressure Profile

Using the cumulative result of all remedial measures related to the system pressure profile, including mitigating the effect of pressure variations, drawdown events, dynamic pressure instability, irrecoverable pressure loss, and excessive end-use dynamic pressure loss, the team should establish specific recommendations for an appropriate system pressure profile.

There are many different system performance characteristics that affect the air pressure delivered to end-use equipment. During the assessment, information is gathered about the system's existing pressure profile and its dynamic performance. Problems with system performance often result in an unacceptably low pressure supplied to end-use applications. A common solution to low systemwide pressure, low pressure in a particular part of the system, or occasional low-pressure problems is to increase the compressor control set points or run additional compressor horsepower as necessary to ensure acceptable pressure at all times throughout all parts of the compressed air system. While this solution has the potential to satisfy pressure requirements of production equipment, it can be very energy intensive.

The assessment team should determine the proper target pressure for the compressed air system. Starting with end-use pressure requirements, the team can develop a system pressure profile accounting for reasonable recoverable pressure loss throughout the system and necessary recoverable pressure differential for effective compressed air energy storage. The team needs to consider the present system performance and the impact on compressed air pressure throughout the system.

There are many operating conditions that can contribute to excessive, irrecoverable pressure loss. Some conditions are transient; they occur for short periods of time and are a result of temporary operating conditions that are a consequence of changes in air demand of a specific end use, or group of end-use demands. Several system design characteristics affect the airflow / pressure relationship and will impact the system's dynamic pressure profile. Analysis of the measured dynamic pressure profile may identify characteristic signatures of various transient conditions that have a negative impact on system pressure performance.

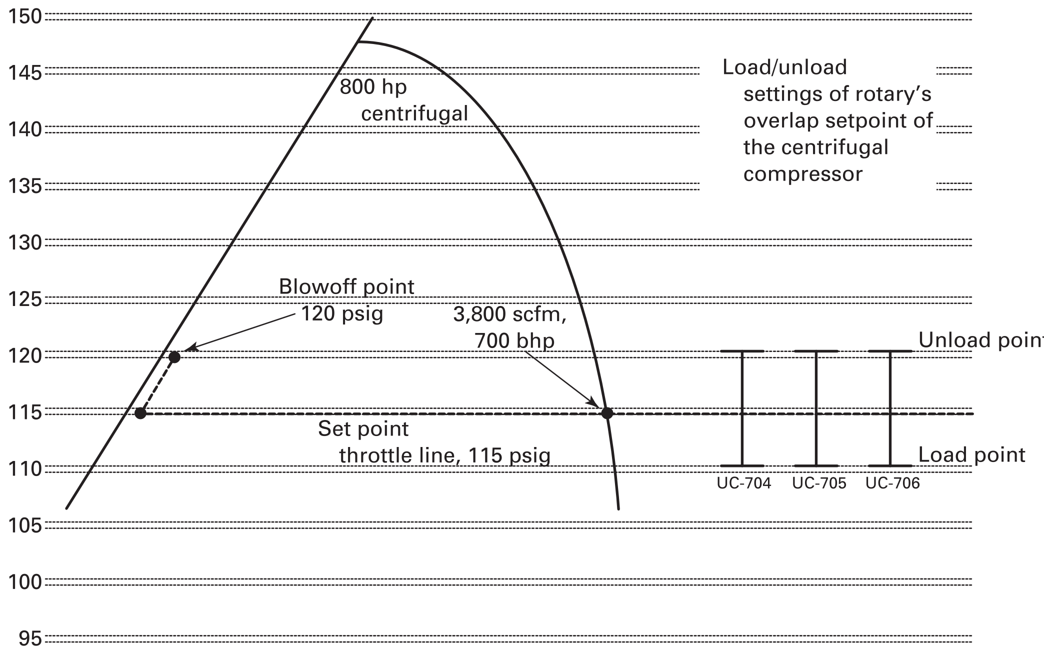
Dynamic pressure performance conditions may include the following:

(a) Pressure Variations. Pressure variations are changes that are observed to be systemwide, affecting the entire pressure profile. Pressure variations can result from many aspects of system performance. For example, a cascade compressor control strategy may result in the system pressure operating at the high end of the control range during periods of low air demand. As air demand increases and additional compressors are added to generation capacity, the system pressure operates at lower and lower portions of the compressor control range.

Multiple compressor systems where each compressor operates with local control response can experience pressure variations that are a consequence of interaction among the various independent compressor control systems.

(b) Drawdown Events. These events are characterized by the continual decay of overall system pressure affecting the entire pressure profile. When total compressed air demand exceeds rotating online generation capacity, system pressure will decrease as time goes on. The rate of pressure decay, or drawdown rate, depends on the supply deficit (how much air demand exceeds generation capacity) and the storage volume of the system. The highest pressure-drawdown rate occurs with a large supply deficit and low storage volume. The supply deficit can be a result of increased air demand, such as operation of a high-volume, intermittent air use causing total air demand to exceed generation capacity. Another source of a system drawdown event is the unanticipated shutdown of an air compressor (for example, in response to a high-temperature or motor-overload condition) that may create a supply deficit.

Fig. 5 Example Pressure Profile 1



(c) Dynamic Pressure Instability. This pressure instability results from changes in airflow rate interacting with system resistance of a portion of the compressed air system and causing a change in compressed air pressure loss through that portion of the system. The pressure drop through a fixed resistance in a compressed air system will change as a squared function of change in airflow rate. For example, if a filter has 3 psid at 100-scfm airflow rate, that pressure loss will increase to 9 psig at 200-scfm airflow rate. Dynamic pressure instability can occur in any part of the compressed air system. Pressure variations occur as airflow changes through restrictions, such as treatment equipment, main line distribution piping, branch sections of distribution piping, or any part of the system, and these cause restriction to air flow. Dynamic pressure instability usually affects the pressure profile in localized sections of the restriction and points downstream of the restriction. An exception is dynamic pressure instability resulting from the interaction of airflow change with fixed resistance of supply-side air treatment equipment, which affects the compressor control signal pressure upstream of the treatment equipment.

(d) Irrecoverable Pressure Loss. Irrecoverable pressure loss is the resultant pressure reduction caused by individual components of the system and the airflow rate through the component.

(e) End-Use Dynamic Pressure Instability. Dynamic pressure instability is the resultant pressure performance of air flow change [as discussed in para. 6.3(c)] localized to the end-use point. End-use dynamic pressure instability is generally considered in the pipe drop from a header to the machine connection point and from there to the end-use pneumatic device.

After investigating pressure profile performance, the compressed air system assessment team can develop solutions to issues that negatively impact the system pressure profile. Possible solutions may include changes to compressor controls, overall control strategy, air storage piping, component size, end-use piping connection, and other designs that will provide optimum pressure profile performance. The assessment team should provide specific remedial measures to address opportunities to optimize the pressure profile. Based on proper implementation of recommended remedial measures, the assessment team should provide specifications for an appropriate system pressure profile.

Example pressure profiles are shown in Figs. 5 and 6, and Fig. 7 shows an example measured pressure profile.

6.3.1 Average Pressure and Pressure Variations. There is no additional guidance for this clause.

6.3.2 Peak Airflow: Effect on the Pressure Profile. As a result of isolated demand events or the simultaneous

Fig. 6 Example Pressure Profile 2

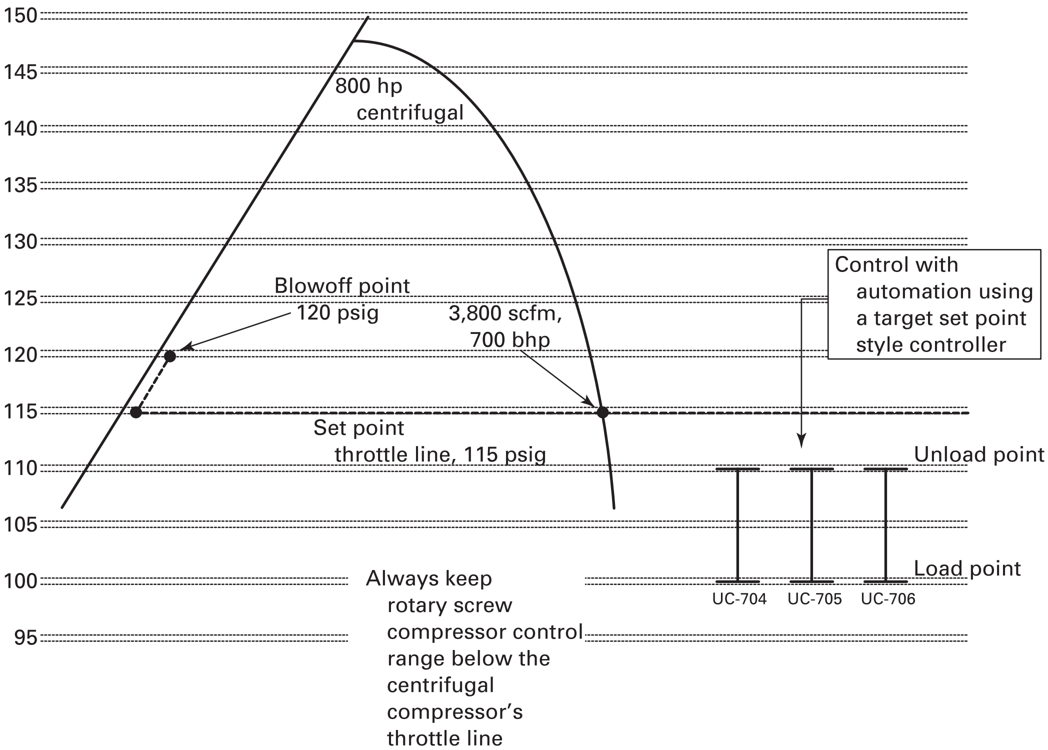
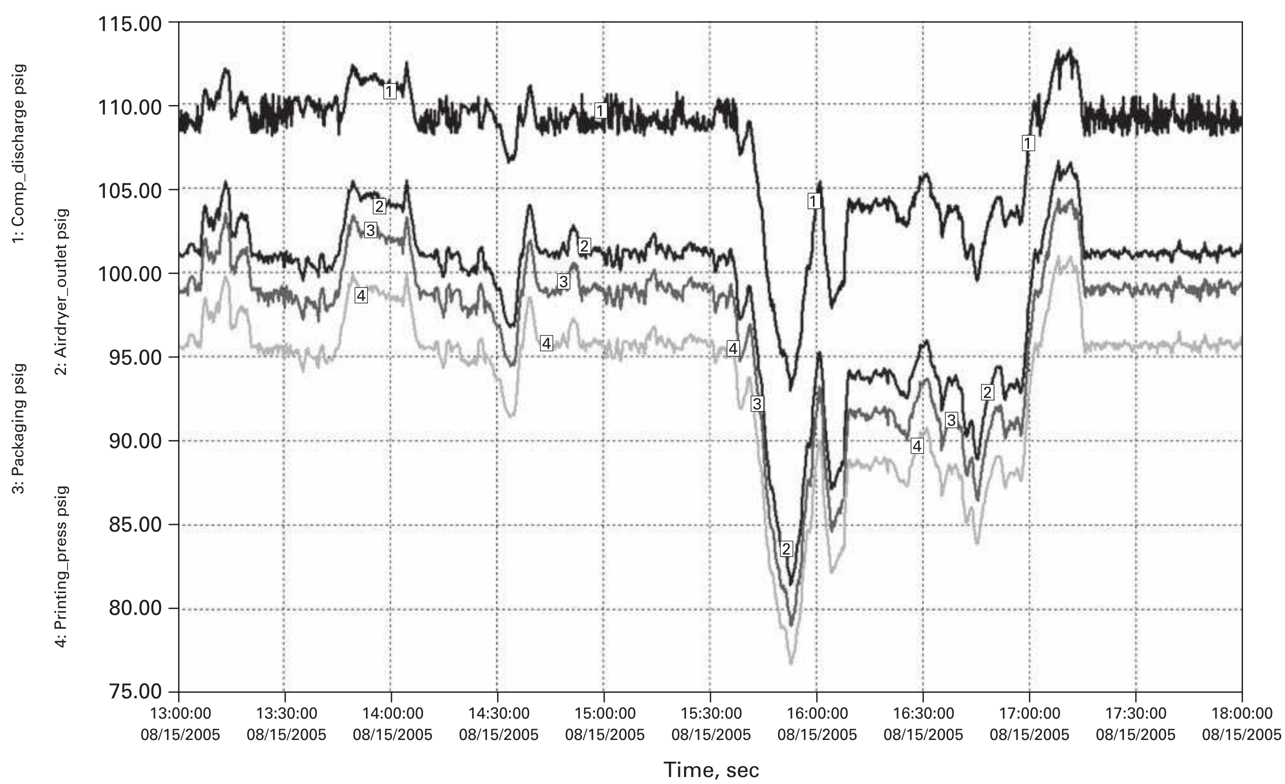


Fig. 7 Example Measured Pressure Profile



occurrence of multiple random demand events, the peak airflow rate of a compressed air system can at times be much greater than average airflow. With the impact of compressed air storage, peak airflow can at times exceed the total generation capacity of the system's air compressors. Peak airflow in a system has two potential effects on the system's pressure profile.

(a) Pressure Drawdown. The continual decrease in system pressure that occurs as a result of a demand event whereby the air demand exceeds available generation capacity of the system's operating air compressors.

As drawdown is occurring, compressed air energy is released from storage. The amount of storage that is available and the degree to which demand exceeds supply combine to determine how rapidly system pressure decreases (drawdown rate). The duration of the demand event and the drawdown rate determine how much the system pressure goes down during the event (drawdown pressure).

(b) Pressure Instability. The increase or decrease in compressed air pressure due to the interaction of changing airflow rate with the fixed resistance to flow represented by system components and piping through which the airflow must pass.

For compressed airflow (at a given pressure and temperature) through any component or pipeline having fixed resistance, the change in pressure loss is a squared function of the increase or decrease in airflow rate. Due to starting and stopping of various air demands and the cyclic nature of many air demands, compressed airflow rate throughout a compressed air system frequently changes. The changing airflow rate interacts with the fixed resistance of the system components and piping, resulting in frequent changes in pressure drop causing pressure instability, which is observed in the system's dynamic pressure profile.

6.3.3 Excessive Irrecoverable Pressure Loss. There is no additional guidance for this clause.

6.3.4 Excessive Pressure Gradient. There is no additional guidance for this clause.

6.4 Perceived High-Pressure Demand

There is no additional guidance for this clause.

6.4.1 Rated / Recommended End-Use Pressure. There is no additional guidance for this clause.

6.4.2 Dynamic Flow/Pressure Relationship. There is no additional guidance for this clause.

6.4.3 Stability of Supply Pressure. Piping of the proper diameter ensures air gets where it needs to go, when it needs to get there, close to the originating pressure, and in the quality and quantity required. Minimizing pressure drop requires a systems approach in system design and maintenance. The team should evaluate air treatment components such as aftercoolers, moisture separators, dryers, and filters to ensure they have the lowest possible pressure drop at specified maximum operating conditions of flow and temperature. The pressure drop through the system also increases as the square of airflow rate (velocity). High-volume, intermittent demands create peak airflow rates, causing significant pressure fluctuations. The pressure profile is the key to identifying whether high dynamics from end users are causing the instability or undersized piping is responsible.

Interruption of production operations at the point of use can be a symptom of low pressure supply at the use point. Casual analysis and anecdotal information often lead to the conclusion that compressed air system pressure must be increased at the source to prevent production interruption. Often, intermittent low-pressure conditions at the point of use can be attributed to transient pressure disturbances that exist on the demand side of the system and cannot be detected by observation of the supply-side pressure. The perception that low system pressure is the cause should be investigated further to assess the root cause of the production interruption.

When assessing the stability of supply pressure to a perceived high-pressure end use, dynamic pressure profile measurements often include three or four key pressure measurement locations, such as the following:

(a) header pressure in the area of the perceived high-pressure use that is being evaluated

(b) on the piping drop to the machine at the equipment connection point

(c) downstream of the filter, regulator, lubricator supplying the equipment

(d) as close as is practical to the end-use pneumatic device that is believed to require higher pressure

Dynamic interaction and the flow/pressure-drop relationship may cause pressure upset to the end-use device because of excessive pressure loss between the plant air header and the use point. Pressure loss during the end-use air demand can be evaluated by performing dynamic measurement of pressure at the points described above.

It is also important to note that pressure instability at the header could also cause random production interruptions even when the dynamic pressure profile from the header to end use operates with minimal pressure loss. It is possible that operation of equipment in other parts of the compressed air system is creating performance conditions that upset pressure in the local distribution header at the perceived high-pressure use that is being assessed.

Comprehensive investigation should include efforts to rule out upstream pressure instability as a causative effect of unacceptable pressure performance. These efforts should include measuring the local pressure profile for a sufficiently long duration of time to experience potential pressure upsets caused by other equipment in the system. If there are suspect high-volume, intermittent air demands that may cause system pressure upset (such as dense phase transports or high-volume blowing applications), efforts should be made to monitor these demands during operation of the suspect air demand events.

6.4.4 Remedial Measures and Quantify Savings. There is no additional guidance for this clause.

6.4.4.1 Existing Pressure Anomalies. There is no additional guidance for this clause.

6.4.4.2 Valid High-Pressure Use. There is no additional guidance for this clause.

6.5 Demand Profile

When measuring dynamic airflow rate to the system (see Mandatory Appendix II, II-7 a.1), it is best to take the measurement at a point downstream of primary storage. By measuring at this location, airflow supplied from primary storage will be directly measured. If the flow measurement is made upstream of primary storage or inferred by measurement of compressor operation, it is necessary to account for airflow delivered from primary storage. The contribution of compressed air primary storage to dynamic airflow rate can be evaluated based on the storage volume and pressure drawdown rate (dP/dT) (see also para. 6.4.3).

When assessing the demand profile, it is necessary to identify any large supply/demand imbalance. For example, if rotating generation capacity far exceeds the average air demand, an improved control strategy should consider automatic shutdown of excess compressor capacity. If peak air demand exceeds the rotating generation capacity, a short-term pressure drawdown may cause additional compressors to come online. Alternatively, increased compressed air energy storage may allow the peak air demand to be satisfied without the power consumption of starting additional air compressor capacity to meet the short-term peak air demand.

Other possible remedial measures for this situation may include

(a) application of dedicated storage with controlled refill at high-volume, intermittent air demands to allow the supply side of the system to operate at a lower average airflow rate. At the same time, dedicated storage serves the high-volume, intermittent demand requirement.

(b) for high-volume, low-pressure demands, installation of an alternate, more appropriate air source, such as low-pressure blowers.

(c) improved primary storage with larger storage volume and optimized storage pressure differential.

(d) elimination of the artificial demand that results when storage pressure requirements increase pressure throughout the entire system. Installation of a pressure/flow control can separate the relatively higher-pressure compressed air storage receivers from the downstream air demands. This will serve to protect unregulated demands from being supplied at the elevated storage pressure that is necessary to create usable compressed air energy in storage.

6.5.1 Average Airflow and Airflow Variations. The contribution of compressed air storage to dynamic air demand can be evaluated based on the system's storage volume and pressure drawdown rate (dP/dT). Note the pressure drawdown may not be equal throughout the entire compressed air system (see also para. 6.4.3).

6.5.2 Transmission System Performance. There is no additional guidance for this clause.

6.5.3 Remedial Measures and Quantify Savings. There is no additional guidance for this clause.

6.6 Critical Air Demands

6.6.1 Effect on Productivity and Energy. When productivity impact outweighs an increase in energy use, it is important to consider the positive effect on productivity and associated financial benefit of improved performance.

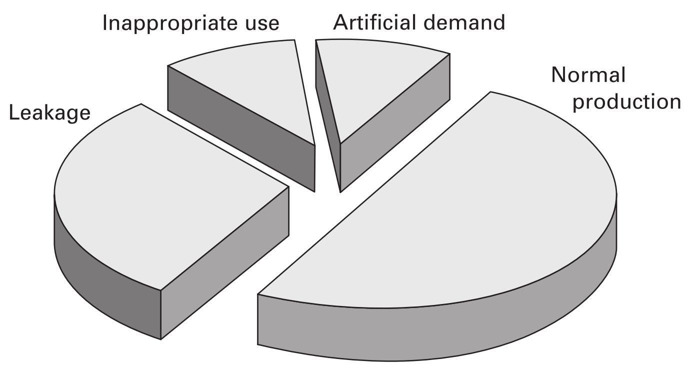
One method is to consider energy intensity or energy input per unit of production output. The team should consider that this analysis of critical air demands may benefit from narrowing the measurement boundary. Narrowing the measurement boundary may allow energy performance to be more easily compared to production variables.

If greater production output is not necessary, consideration should be given to time-dependent and production-dependent components of energy use. Production-dependent energy use may increase but could be offset to varying degrees by reduction in time-dependent energy use.

If an increased production rate is necessary, alternative energy scenarios to achieve the production goals may be considered. Energy reduction may be the result of avoided energy use that would result from an energy-intensive method of increased production as compared to a more efficient alternative. This approach may require adjustments to the energy baseline and/or post-implementation energy analysis. Adjustments should be based on identifiable physical facts associated with the critical air demand and related production process within the measurement boundary.

6.6.1.1 Example of Narrowing the Measurement Boundary. An existing machining cell in a manufacturing plant has a group of various machine tools, including drills, lathes, mills, and grinders. It has been

Fig. 8 Compressed Air Waste



proposed to replace equipment in the machining cell with new multi-axis NC machining centers. The airflow rate consumption of the new machining centers will be greater than the existing variety of machine tools consume. However, the production rate of parts produced will also be increased. As a result of the increased capacity, new levels of production can be achieved. Or if production requirements remain constant or decrease, there will be reduced run time for the machining cell.

While the amount of compressed air energy for every hour of production at the machining cell will increase (kscf/hr), the number of parts (parts/hr) is expected to increase to a greater proportion. As a result, the overall energy intensity (kscf/part) is expected to decrease.

For the assessment baseline and future post-implementation measurement and verification, it is necessary to identify the change in both air consumption and production rate of the machining cell. Measurement of total plant air demand will not allow sufficient resolution of airflow data to quantify the change that is attributed only to performance of the machining cell.

The solution is to narrow the measurement boundary and make baseline measurements for only the machining cell separate from the total plant profile. The assessment measurement plan should include a separate baseline of the machining cell's present production rate and airflow profile. Post-implementation, measurement and verification can then include measurement of the new production rate and airflow profile, which will prove or disprove that the anticipated reduction in energy intensity has been achieved.

6.6.2 Critical End-Use Characteristics. When evaluating critical end-use requirements, it is helpful to classify the end use as "Flow Static" or "Flow Dynamic." Flow-static end-use applications will primarily address the dynamic pressure profile, while flow-dynamic applications must consider the dynamic performance of both airflow and pressure.

6.6.2.1 Flow-Static End Use. Flow-static end-use applications of compressed air are characterized by operating situations where the peak airflow requirement of the end use and the critical end-use pressure occur at different times. One example is a clamping cylinder wherein the peak airflow occurs as the cylinder is moving into position and the critical pressure is necessary after the cylinder is stopped and clamping force is being applied.

6.6.2.2 Flow-Dynamic End Use. Flow-dynamic end-use applications of compressed air are characterized by operating situations where peak airflow rate and the critical supply pressure must be supplied simultaneously. For example, an air motor requires airflow to maintain speed and pressure to develop torque.

6.6.3 Analyze Process Limits. There is no additional guidance for this clause.

6.6.4 Remedial Measures and Quantify Savings. There is no additional guidance for this clause.

6.7 Compressed Air Waste

Using data collected during the assessment, the team should quantify various components of compressed air waste. The assessment should provide specific remedial measures necessary to eliminate waste and quantify energy savings estimates. Figure 8 shows compressed air waste for an example system.

Demand for compressed air goes beyond what is needed to do work. The typical industrial compressed air system delivers half or less of its compressed air to productive end-use air demand. The other 50% or more is wasted. Types of waste include inappropriate use, leakage, and increased demand due to excessive system pressure. To effectively cut costs in a compressed air system, wasteful air demands need to be minimized.

The unproductive demands are defined as follows:

artificial demand: additional compressed air usage due to pressure levels higher than what is necessary to keep equipment operating properly.

inappropriate uses: any application that can be done more effectively or more efficiently by a method other than compressed air

leaks: an unintended loss of compressed air to ambient conditions

6.7.1 Leakage. As the assessment team develops a target for the amount of leak reduction and an estimate of energy savings, they should apply reasonable expectations of how much leak reduction is possible. For example, it stands to reason that greater leak reduction is achievable when there are relatively fewer large leaks as compared to numerous small leaks. These larger leaks are easier to find, and also there are fewer leaks to repair. On the other hand, numerous small leaks may be a result of widespread use of poor piping practice in which small leaks are likely to occur. Effectively dealing with this type of leakage may require changes to existing piping practice. For example, minimizing the use of rubber hose with clamps and using harder pipe or tubing can be a change to existing methods that can take time to produce measurable results.

Other practical considerations include the following:

(a) Is time available for skilled trades to repair leakage?

(b) Is equipment downtime available to allow repair to be done?

(c) Will overtime work be necessary and will it be approved?

6.7.2 Inappropriate Use. There is no additional guidance for this clause.

6.7.3 Artificial Demand. There is no additional guidance for this clause.

6.8 Optimize Air Treatment

There is no additional guidance for this clause.

6.8.1 Appropriate Air Quality

NOTE: ISO 8573 has changed significantly — use current version.

6.8.2 Redundant Treatment Equipment. There is no additional guidance for this clause.

6.8.3 Treatment Effect on Pressure Profile. There is no additional guidance for this clause.

6.8.4 Remedial Measures and Quantify Energy Result. There is no additional guidance for this clause.

6.9 Reduce System Operating Pressure

To minimize system operating pressure, the team should

(a) establish the recommended target pressure for system operation

(b) analyze the recorded system pressure profile and apply the cumulative result of all remedial measures related to the system pressure profile, including mitigating the impact of pressure variations, drawdown events, dynamic pressure instability, irrecoverable pressure loss, and excessive end-use dynamic pressure loss

(c) establish specific recommendations for an appropriate system pressure profile (see also para. 6.3 of this guidance document)

The assessment should state the recommended demand-side target pressure and pressure variation tolerance for each demand sector. The team should evaluate system operation at the reduced target pressure and estimate energy reduction.

Implementing the necessary remedial measures to effectively operate at reduced pressure, as outlined in the assessment team's recommended pressure profile, is a step-by-step process. Operating the system according to a new pressure profile will depend on implementing a comprehensive group of remedial measures addressing things such as air storage, irrecoverable pressure loss, distribution piping upgrades, removal of restrictions in point-of-use piping, and perhaps modification of the actual end-use pneumatic equipment.

The assessment team needs to be sure that all necessary measures are in place to ensure system reliability as operating pressure is reduced. Even then pressure reduction should be done slowly over days or weeks. All stakeholders in compressed air system operation should be alert to the fact that unintended consequences of lowering system pressure may need to be dealt with. If problems arise, increase pressure to an acceptable level, assess the problem, implement a solution, and then continue reducing system pressure. Simply put, if the system experiences an event that causes a production curtailment or outage, the energy-efficient operating scenario will be quickly abandoned in favor of the (former) less efficient but more reliable operating methodology.

6.10 Balance Supply and Demand

The team should analyze system control methods necessary to maintain real-time balance between supply and demand with sufficient transmission capacity to move compressed air energy from supply to demand as required by the dynamic characteristics of the system.

The optimum supply-and-demand balance would be achieved if the full load generation capacity of all running air compressors exactly matched the compressed air demand. Of course, the likelihood of maintaining that exact balance is virtually impossible. In most systems, the air demand is not constant; rather, it changes as machines and production processes start and stop during their normal operating cycles.

Over a given time period, for example, 1 hr, the system would have some average air demand with periods of peak air demand above and valley periods below the average air demand. The goal when balancing supply and demand is to have rotating online compressor capacity slightly greater than the average air demand. Peak air demand should be supplied from storage, and storage refill would occur during the valley periods of air demand.

To implement proper storage for the operating strategy described above requires measurement of the system's dynamic air demand with analysis of average, peak, and valley air airflow rate and time durations. These data allow the practitioner to determine the feasibility of implementing compressed air energy storage. When engineering storage, the amount of usable compressed air storage is dependent on the volume of receiver capacity and the pressure differential between the storage pressure and system's target pressure as defined in the pressure profile.

It is also necessary to consider that shifts in air demand (increases or decreases in air demand that have a long time duration) will require adding to the rotating compressor capacity with increased demand and provide the opportunity to shut down rotating compressor capacity with decreased demand. The practitioner must consider that all air compressors have a permissive startup time period (the amount of time from when the compressor receives a signal to start and when it actually begins delivering compressed air into the system). Permissive startup times vary based on the type of air compressor, the capacity control method of a compressor, and possibly how control parameters are set within the air compressor's control panel.

Compressed air energy storage must be sufficient to supply air to the system during the permissive startup time for the various air compressors. In systems where there is insufficient storage to support air demand during permissive startup time, a control strategy may use "spinning reserve" capacity. An air compressor operating in spinning reserve has its electric motor running and is operating at its unloaded power while delivering no compressed air into the system. Spinning reserve capacity is an inefficient strategy and can be improved with proper application of storage, which allows the compressor to be shut down when its capacity is not needed.

The team should analyze the total effect of compressed air demand reduction, including the elimination of inappropriate use, leakage, and artificial demand, together with the impact of recommended compressed air storage to reduce peak airflow supplied from generation. Given the baseline demand profile, the team should calculate projections for the reduced demand profile with implementation of recommended measures. The assessment should optimize compressor control strategy to the reduced demand profile. Examples of optimal control strategies include the following:

(a) Shut down any compressors that are not needed to support the reduced demand profile.

(b) Where possible, operate compressors at their most efficient performance condition, which is typically at their full-load design point.

(c) Apply trim capacity operation with the most efficient part-load capacity given the available mix of compressor sizes and control types.

(d) In multiple compressor systems, consider application of control automation to maintain supply-and-demand balance under normal variations in the demand profile.

The assessment should provide specific remedial measures necessary to implement the proposed control strategy. The assessment should quantify the expected energy reduction and estimate savings.

6.11 Assess Maintenance Opportunities

Like all electromechanical equipment, industrial compressed air systems require periodic maintenance to operate at peak efficiency and minimize unscheduled downtime. Inadequate maintenance can have a significant impact on energy consumption via lower compression efficiency, air leakage, or pressure variability. It can also lead to high operating temperatures, poor moisture control, and excessive contamination. Most problems are minor and can be corrected by simple adjustments, cleaning, part replacement, or the elimination of adverse conditions.

Common maintenance mistakes include not maintaining filters, end-use filters, and lubricators; ignoring air dryer and condensate trap maintenance issues; not providing adequate ventilation; and not performing lubricant analysis.

Preventive maintenance is defined as a maintenance activity performed at a regular interval of time or run-hours to prevent systems from failing. Predictive maintenance uses diagnostic equipment to monitor and detect the onset of deterioration; this extends service life by controlling the degradation. Other maintenance actions can be classified as breakdown (fixing broken equipment), corrective (repairing equipment that is not meeting operating specifications), and tune-up (a special kind of preventive maintenance on an entire subsystem).

Most of the issues covered in Mandatory Appendix II, II-14 fall into the tune-up category, or they could be the first action in establishing a predictive or preventive maintenance program.

6.12 Evaluate Heat Recovery Opportunities

As air is compressed, the temperature of that air increases, and the heat generated by this temperature increase must be removed from that air. The heat generated during this process can be as much as 80% to

93% [6] of the input power. Such a high percentage of input power represents a significant quantity of heat generated. However, the energy quality of the heat generated is low. In other words, while compressing air generates a large amount of heat, the available temperature, typically in a range of 130°F to 200°F, limits the heat recovery opportunities to those applications that can take advantage of these lower temperatures. However, despite the low energy quality, there are opportunities that can make use of 50% to 90% of the waste available heat.

When considering applications, the first variable that should be considered in an assessment is whether the air compressor being evaluated is air cooled or water cooled. The reason for this is because the heat rejection medium will influence what type of heat recovery opportunities make the most sense. In addition, those opportunities that can make use of the heat rejection medium directly with no intermediate heat exchanger will typically recover the most heat and have the best paybacks.

The following includes some applications that might be appropriate for either air-cooled or water-cooled air compressors; this list is not intended to be exhaustive:

(a) *Air-Cooled Compressors*
- *(1)* space heating
- *(2)* process air drying

NOTE: Ducting from units can be used to direct the cooling air from enclosed compressors directly into the space to be heated or to the drying application. When using ducting, the assessment team should consider the following:

(a) the ability to redirect hot air to outside the facility during periods when heating or drying is not desired

(b) the need for a booster fan to overcome the head pressure created by the addition of ducting

(b) *Water-Cooled Compressors*
- *(1)* process-water heating or preheating
- *(2)* potable-water heating or preheating
- *(3)* boiler-makeup preheating

6.12.1 Equations to Approximate Energy Recovery Opportunity

energy savings (MMBtu/yr) = (fraction of heat recoverable) × (load factor) × [compressor break horsepower (hp)] × [hours of operation (hr/yr)] × [conversion (0.002545 MMBtu/hp-hr)] / (compressor efficiency)

cost savings = energy savings (MMBtu/yr) / (efficiency of offset heating equipment)

7 GUIDE TO REPORTING AND DOCUMENTATION

An effective compressed air system assessment is a discovery process that includes investigating system operation, baselining energy use, and identifying opportunities to improve performance and reduce energy input. The written report documents system performance improvement opportunities and includes an implementation action plan. The report addresses all parts of the compressed air system, including supply, transmission, and demand. The report quantifies baseline energy use and projected energy reduction associated with the opportunities identified.

7.1 Final Assessment Report

The essential information here is the title of the project indicating the company's name, project manager, assessment team leader, assessment technical leader, and the date. The title of the report can be a statement of the subject.

7.2 Final Assessment Report Contents

A table of contents is recommended and should include report headings and page numbers that accurately reflect the material that appears beneath them.

7.2.1 Executive Summary. The executive summary is used by decision makers (managers) to determine what actions need to be taken as a result of the assessment. This section condenses and summarizes the report in brief. The executive summary is independent of the body of the report. The executive summary emphasizes the objective (which states the goals) and the analysis of the results (including recommendations, projected savings, and costs to implement).

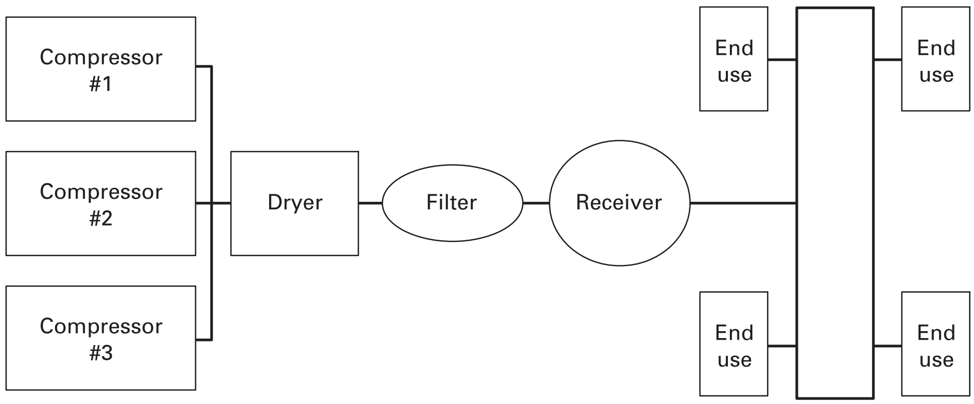
7.2.2 Facility Information. This section provides plant background information with a brief description of manufacturing processes and products.

7.2.3 Assessment Goals and Scope. The introduction and scope of work provides the reader with the background information needed before reading the body of the report. It should also give the reader a clear idea of what material is to follow; it should describe the project and define the scope of the report.

Using Mandatory Appendix II (Plan of Action Matrix) of ASME EA-4, describe what system assessment objectives, action items, and methodologies were used for your plan of action.

The assessment goal is to successfully improve the compressed air system energy efficiency. ASME EA-4 presents a comprehensive set of tasks and analyses that must be accomplished to provide a proper assessment of a compressed air system. This Standard outlines certain fundamentals that must always be included in a system assessment to ensure the end user receives the expected benefits. However, to properly address the wide range of systems and applications of compressed air in industry, a certain flexibility must also be allowed so that a wide variety of users can gain the benefit of having their system appropriately assessed.

Fig. 9 Example of a Simple Block Diagram



7.2.4 Description of System(s) Studied and Significant System Issues. The plant's compressed air system(s), including the scope of the system's supply-side characteristics, transmission equipment, and demand-side characteristics, should be described. To allow for better understanding of any system, the report shall provide a graphical representation of the system, such as a block diagram, so that those reading and reviewing the report can have at least a basic understanding of the system's configuration.

7.2.4.1 System Block Diagram. The block diagram should be as simple or detailed as necessary to match the required level and intent of the assessment and the complexity of the system. A simple block diagram is a one-line diagram that depicts the supply side or the demand side or both. The monitoring points should be identified on the diagram. Any proposed modifications to the compressed air system should be shown as dotted lines or as a separate "new system" drawing.

For basic assessments on relatively straightforward systems, the block diagram may be as simple as the one shown in Fig. 9. Figure 10 shows a more complex system.

A more detailed schematic may be required on more complex systems or when the assessment warrants added detail. In addition, transducer locations may also be included to enhance clarity, as illustrated in Fig. 10. Each measurement point should be identified with a unique address.

Notes accompanying any block diagram should list the ratings and end uses of the various pieces of equipment (compressors, dryers, filters, etc.). Tables 5, 6, and 7 show very simple examples.

Finally, should significant system changes be recommended that involve new equipment or relocating or repiping existing equipment, a block diagram or schematic should be provided if it adds clarity.

7.2.4.2 Site Issues. An operational review of system, energy/utilities consumption and cost, demand-side issues, transmission issues, and supply-side issues should be included. Best practices (i.e., methods and procedures found to be most effective at energy reduction) should be noted.

7.2.5 Assessment Data Collection and Measurements. The report shall document the measurement techniques used. The report shall clearly identify the processes and methodology used in the study so that the customer and other third parties can judge the accuracy and validity of the assessment. It should include the following information:

(a) study time of the assessment: number of days onsite, duration of data collection, start and end date of the assessment period, similarity of study period to actual annual operation, etc.

(b) data collection equipment used: instruments, metering, data loggers, gauges, etc. For instance, a table of all of the instrumentation used and its accuracy may be presented, as shown in Table 8. Instrument manufacturers have various specifications used to describe the performance of their products. Many descriptions of performance are based on customary specifications used and recognized in markets they serve rather than current practice in the field of metrology. Common parameters include percent of full scale (F.S.), hysteresis, nonlinearity, sensitivity or drift, effect of operating temperature, etc. Installation factors — such as pipe geometry, pipe dimensions, inner pipe surface roughness, etc., in the case of flow transducers — will affect the instrument's performance as applied in the field. The practitioner, using available data, experience, and judgment, should perform a Type B uncertainty estimate for the measured parameter.

(c) sample rates and duration of any data logging or sampling methods.

Fig. 10 Complex Block Diagram Showing Transducer Locations

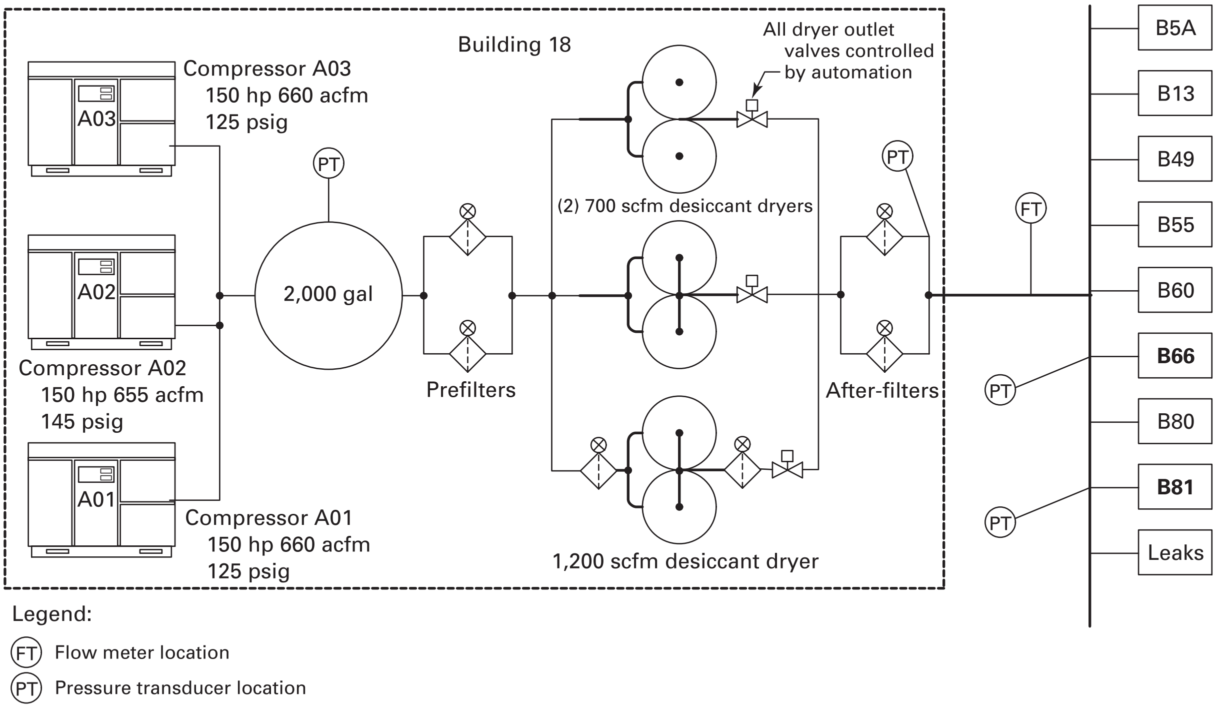


Table 5 Example Equipment-Rating Notes

Equipment ID	Manufacturer	Model	Nominal hp / bhp Rated Performance	Type	Control Type
Comp A01	Company A	RSL 150	150 hp / 165 bhp 660 acfm / 125 psig	Lubricated rotary screw, water cooled	Load / unload
Comp A02	Company B	RSH 150	150 hp / 171 bhp 15 hp cooling fan 665 acfm / 145 psig	Lubricated rotary screw, air cooled	Inlet modulation
Comp A03	Company A	RSL 150	150 hp / 162 bhp 10 hp cooling fan 660 acfm / 125 psig	Lubricant-free two-stage rotary screw, air cooled	Load / unload
Receiver	Company E	. . .	150-psig MWP	2,000 gal	. . .
Air dryers 1 and 2	Company C	RHL 1000	700 scfm, 15% purge 150 psig MWP	Regenerative heatless	10-min time cycle
Prefilter	Company D	FC 1200	1,200 scfm 150 psig MWP	Coalescing	. . .
After filter	Company D	FP 1200	1,200 scfm 150 psig MWP	Particulate 1 micron	. . .
Air dryer 3	Company D	RBP 1200	10 hp blower, 30 kW heater 1,200 scfm 7% purge 150 psig MWP	Regenerative blower purge	Dew-point demand
Pre-filter	Company D	FC 1200	1,200 scfm 150 psig MWP	Coalescing	. . .
After-filter	Company D	FP 1200	1,200 scfm 150 psig MWP	Particulate 1 micron	. . .

GENERAL NOTE: MWP = maximum working pressure

Table 6 Example Equipment Age / Comments

Equipment ID	Age / Comments
Compressor A01	Very old; used for backup; water-cooled
Compressor A02	10 yr old; air cooled with 15 hp cooling fan
Compressor A03	Brand new; air cooled with 10 hp cooling fan
Air dryers 1 and 2	10 yr old
Air dryer 3	New
All filters	New; timer-style drain valve
Receiver	Timer-style drain valve

Table 7 Example Key End-Use Air Demands

End-Use ID	Building Location	Pressure Minimum Required (Present), psig	Type of Use	Required Airflow (Quality)	Comments
End use 1	B49	90 (100)	Conveyors, welders, chip blow-off	Intermittent (general plant)	Very intermittent low average usage
End use 2	B5A outdoors	80 (100)	Actuators, valves, pumps	100 scfm – 300 scfm (–20°F)	2-in. supply line with flow meter
End use 3	B81	100 (100)	Air hoists, hand tools, blow-offs	Unknown (Not specified)	Intermittent except continuous blow-off
End use 4	B66	60 (100)	Tank agitation, diaphragm pumps	400 scfm – 500 scfm (Oil free / 37°F)	Constant usage

Table 8 Example Accuracy Information

Instrument Specifications — Manufacturer's Data				
Instrument Type	Manufacturer	Percent F.S.	As Applied	Calibration Interval, yr
kW transducer	kwPro	0.50%	1%	1
Amp/volt multimeter	MultiPro	2%	5%	2
Pressure	PressurePro	0.25%	+/– 1 psig	1
Dew point	DewPro	. . .	+/– 2°F	1
Temperature	TempPro	. . .	+/– 2°F	1
Flow	FlowPro	1%	10%	1
Data logger	DataPro	0.20%	0.50%	2

GENERAL NOTE: F.S. = full scale

7.2.6 Data Analysis. The methodology and results from the data analysis shall be documented, including estimated energy savings. Additional analysis may address other energy and nonenergy benefits such as improving resource utilization, reducing per-unit production cost, and improving environmental performance, and may include a range of implementation costs, which can be mutually agreed upon. The assessment should include the minimum identified estimates of energy cost savings from recommended improvements. Additional calculations may address other energy and nonenergy benefits. The analysis shall state uncertainty, including coverage interval and confidence level of any cost estimate that may be variable.

Data quality analysis should be considered in business decisions. Assessment activities strive to provide comprehensive, high-quality data. "No test data should be reported or used without knowledge of its quality, its measurement uncertainty. Violating this precept causes undue risk of incorrect business decisions." [7]

The data analysis report should also include the following information:

(a) Software programs that were used to evaluate data, model systems, and create reports or recommendations (AIRMaster+, MotorMaster, dynamic modeling software, proprietary software, etc.) should be identified. Calculation methods of publically available software such as AIRMaster+ are known. Proprietary software, privately developed spreadsheet calculations, or manual calculations applied to assessment data should be documented with a brief statement of methods applied.

A description of dedicated storage calculation methods should be provided.

EXAMPLE: Recommended compressed air energy storage is calculated using the present system storage volume and the measured rate of pressure decay during the system drawdown event associated with operation of the XYZ process. These data define the system's present supply deficit during normal production operations. That deficit is the basis for calculation of the recommended storage volume and operating pressure differential for dedicated storage to support the XYZ process. The recommended refill flow rate is designed to support the average air demand of the normal production cycle using a fixed Cv refill control.

(b) Nonstandard formulas and calculations should be listed where applicable. For instance, where formulas are used to create indirect or inferred measurements, the formula or calculation methodology should be discussed or listed.

(c) Assumptions and other pertinent information, such as manufacturer's data/ratings, ambient conditions, energy costs, etc., should be provided.

NOTE: This information may be provided in the body of the report (where appropriate and as part of the explanation of the facts of the report) or may be presented in an appendix or supplemental table.

7.2.6.1 Sample Statement of Methodology. A statement of the methodology may be as simple as the following example:

(a) This system assessment for XYZ Company was prepared using ABC System Analysis Software and data-logging equipment. This software uses the principles and equations as adopted for compressor load profiles from the CAGI standard performance curves and manufacturer's CAGI data sheets. The data-logging tools were used to analyze and record data every 15 sec and store more than 322,552 data points. The evaluation started at midnight on 11/15/2004 and ended at midnight on 11/21/2004 for a total data-logging period of 7 days. During meetings with plant personnel, this period was established as typical and representative for their annual operation.

(b) The site conditions are based on NOAA standard site conditions for this area.

(c) Annual operating hours are the reported scheduled hours as provided by plant personnel.

(d) The energy rate information is based on information gathered from utility bills.

(e) All equipment ratings are obtained from a combination of site-gathered nameplate data and published manufacturer's data.

(f) Economic payback and system improvement options were analyzed and evaluated using the AIRMaster+ software program.

7.2.6.2 Reporting Assessment Findings. Findings can be classified as

(a) positive findings, which provide information contributing to proof of the operation theory

(b) pertinent negative findings, which provide information to disprove or rule out the operation theory

(c) unremarkable findings, which provide no valuable information, positive or negative

Unremarkable findings should not be included in the report. However, pertinent negative findings shall be reported.

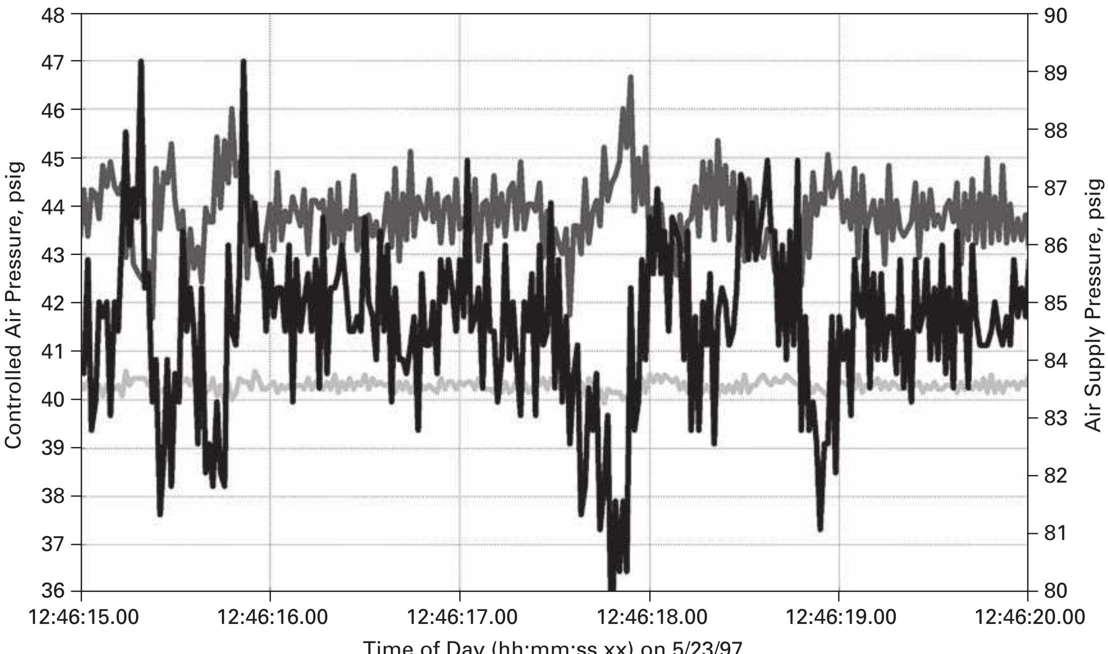
7.2.6.2.1 Example of a Positive Finding. A dual-spindle honing machine finishes the wrist pin bore on a high-volume production line for automotive-piston machining. The symptom of operation is a high rate of reject scrap parts due to unacceptable wrist pin bore tolerance and surface finish.

The bore tolerance control is accomplished with a precision compressed air regulator supplying an air/oil hydraulic intensifier with a 4:1 ratio. A hydraulic cylinder actuates a linkage that applies force to the radial segments of the hone tool.

Troubleshooting has developed two theories of operation that may result in a seemingly random failure to maintain proper tolerance and surface finish of the wrist pin bore.

(a) Mechanical vibration in the machine spindles causes forces on the tool that the bore tolerance control cannot compensate for.

Fig. 11 Dynamic Pressure Trend



Legend:
Air head 1
Air head 2
Air supply

GENERAL NOTES:
(a) Air system assessment was taken from May 20, 1997 through May 23, 1997.
(b) Bore tolerance control (line 8); data at 50 Hz; sample rate chart 2.

(b) Operation of the compressed air supply, precision control, and hydraulic intensifier is inconsistent and does not apply proper force to the hone tool.

A pressure trend measured at a 50-Hz sample rate (see Fig. 11) shows that as the air supply pressure (represented by the black line in Fig. 11) decreases from 85 psig to 80 psig, the controlled air pressure on head 2 (the light gray line) remains stable while the controlled air pressure on head 1 (the dark gray line) increases from 43 psig to over 46 psig. The pressure increase is amplified 4 times by the hydraulic intensifier, and the result is an out-of-tolerance part from head 1 and a properly machined part from head 2.

This is a positive finding for an inappropriate response of the controlled pressure, which provides information that there is a correlation between pneumatic performance and rejected parts.

7.2.6.2.2 Example of a Pertinent Negative Finding. The wrapping machine shown in Fig. 12 surrounds a carton with plastic heat-shrink film. A pneumatically operated cutoff knife heat-seals and cuts the plastic wrap. Periodically the machine malfunctions, resulting in incomplete sealing of the wrap along the entire knife edge. Dynamic data logging for the point-of-use pressure profile recorded the characteristic signature of pressure performance, as shown in Fig. 13.

Dynamic pressure data was taken while the machine was functioning properly and while it malfunctioned. The machine wraps product at a rate of 1 case every 1.6 sec. Pressure measurements were taken at a sample rate of 1 KHz with data averaging, to 25-Hz data interval. Pressure transducers used had a range of 0 psig to 200 psig, and were accurate to $\pm$0.15% with response time (10% to 90%) of 1 msec or less.

Operation of the machine was observed for 1 hr. During this time, there were periods when the machine performed well and times when it malfunctioned. Data for the dynamic pressure profile are illustrated in Fig. 13.

Figure 13 shows three pairs of data tracing. The supply pressures (TP17) are the highest pressure, manifold pressures (TP18) are the center, and the end-use pressures (TP19) are the lowest. The lighter gray lines plot the data gathered when the machine functioned correctly, and the darker black lines plot the data from when the machine was observed to be malfunctioning.

These data represent a pertinent negative finding. The similarity of signatures in these data suggests that the malfunction observed is not related to compressed air performance. This dynamic analysis for the point-of-use

Fig. 12 Wrapper Machine and Test Pressure Locations TP17, TP18, and TP19

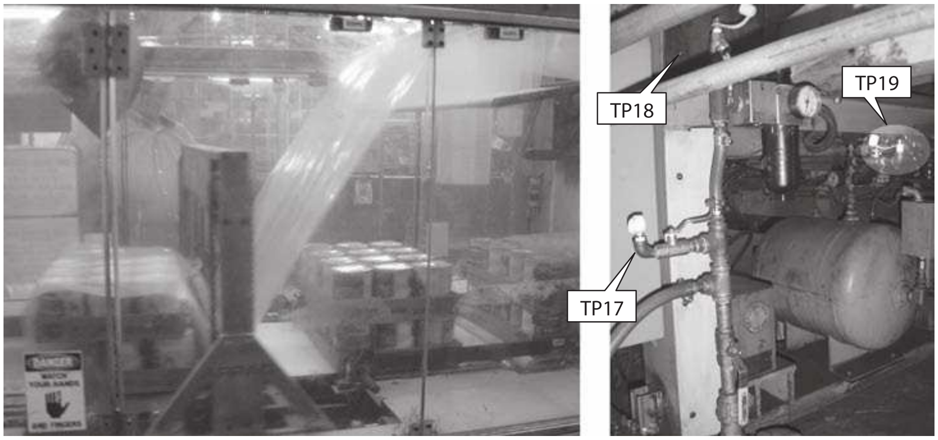
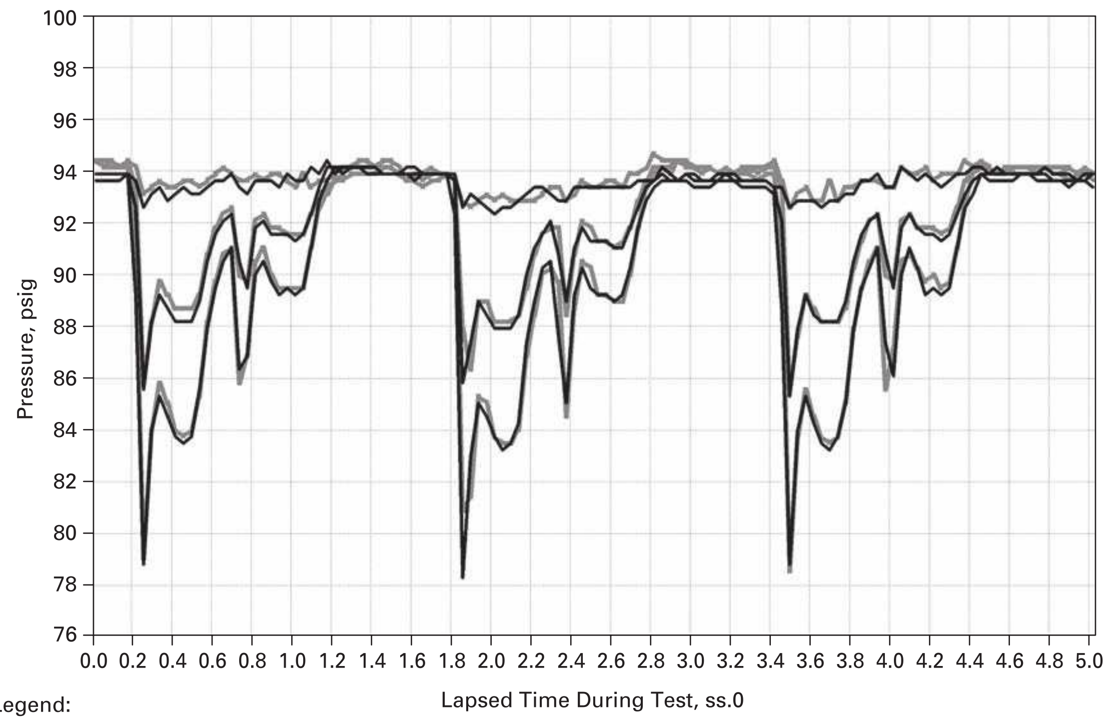


Fig. 13 Wrapper Dynamic Pressure Profile Signature (25-Hz Data Interval)



Legend:

Correct function
Incorrect function

GENERAL NOTES:
(a) Plant air system assessment.
(b) Wrapper; comparison correct and incorrect function; dynamic pressure performance (25-Hz data interval)
(c) Supply pressures (TP 17) are the highest pressure.
(d) Manifold pressures (TP 18) appear in the center.
(e) End-use pressures (TP 19) are the lowest pressure.

pressure profile tends to rule out compressed air pressure variation as a root-cause factor in the malfunction of the wrapping machine.

7.2.7 Annual Energy Use Baseline. There is no additional guidance for this clause.

7.2.8 Performance Improvement Opportunities Identified and Prioritization

7.2.8.1 Energy/Performance Opportunities. The report should list all potential energy savings. Start at the end uses of the system and work back up the energy supply path. For example, look for ways to reduce the flow rate, pressure, etc., at the end use. End-use reductions, with proportionate compressor energy reductions, tend to yield the greatest energy benefits. Use data from the data analysis to back up claims.

7.2.8.2 Nonenergy Opportunities. The report should include information on production output levels, emissions reductions, lower maintenance costs, and product quality improvements that are an outcome of your recommendations.

7.2.8.3 Key Findings. When performing root-cause analysis, it is common practice to think about possible problems that contribute to performance issues. When evaluating operating theories related to system performance, is it helpful to ask yourself the following questions:

(a) What do I think?
(b) What do I know?
(c) What can I prove?

The plan of action often includes observation, data logging, and dynamic analysis of specific aspects of system performance. These data can serve to prove or disprove various theories of operation.

7.2.8.4 Recommendations for Implementation Activities. The report shall show how to implement the identified energy-saving opportunities. Report on strategies to execute improvements. Prioritize the list. Prioritizing is the process of deciding which actions will have the most significant impact, which are the most important, and which are the most feasible.

Set a high priority on the options that offer the greatest potential savings. Preparing metrics such as return on investment and payback period can determine which items to pursue first and help convince management that they are worthwhile investments.

The overall result of any assessment is ultimately an action plan or basically a "to do" list for plant personnel. This action plan needs to provide enough detail for the plant personnel to clearly understand what needs to be done to improve their system, as well as provide a relative ordering of the items. It may also provide some indication of economic justification and costs as appropriate to help the plant personnel better understand the need for improvements and their overall value. A simple example of an action plan with ordered action items and their relative costs and benefits is detailed in para. 7.2.8.4.1.

7.2.8.4.1 Example Action Plan

(a) Correct maintenance issues with Compressor 2 (RS-100 100 HP compressor). Controls not responding to demand — plant pressure drops and causes production issues.

(b) Reduce nonproductive demand. Current nonproduction demand of 385 cfm in a plant that averages a production-based demand of approximately 450 cfm is unacceptably high (85%).

NOTE: Nonproductive demand is primarily composed of overall leak rate and unused manufacturing equipment with open orifices that bleed air or keep nonoperational devices idling in standby mode. High nonproductive demand in facilities of this type is not uncommon as a high percentage of end-use equipment is of the constant-bleed and blow-off variety.

(c) Perform an internal leak audit to identify leaks and fix as many leaks as possible, and then verify required compressor load to meet new leak demand.

NOTE: This may be performed in-house or by an outside contractor with ultrasonic leak detection.

(d) Implement and install a compressed air supply shutoff program for all end-use equipment with constant bleeds or idling devices.

NOTE: This may be as simple as installing/identifying the manual shutoff valves on the compressed air supply connection to the machine along with training the operators to close the valve when the machine is not in use or is shut down. Or, this may be as complex as installing automatically actuated, timed solenoid valves interlocked with the machinery to shut off the air to the machine automatically when it is not required.

(e) Install air-free drains on all main condensate collection points in the compressor room — approximately 12 points in existing system and 8 points in new system (compressor separators, dryers, compressor room filters, and tanks). Air-free drains will help reduce compressed air waste but will also more effectively drain water from the system. See action plan item 3 for further comment and analysis.

(f) Install new compressed air treatment system to eliminate compressed air contamination problems throughout the facility. See compressor room schematic and item 4 below for proposed new layout.

NOTE: From information provided by plant personnel, estimated maintenance and production-downtime issues attributable to poor air quality (water and oil contamination) are at least $5,000. See attached supplemental information and economic analysis for details.

Table 9 Example Operational Summary

Final Plant Operational Summary		
Measured Parameter	**Current System**	**Proposed System**
Production flow range	375 cfm to 535 cfm	225 cfm to 460 cfm
Production pressure range	80 psig to 105 psig	90 psig to 95 psig
Total annual cost	$55,000 to $57,000	$35,000 to $40,000

(g) Install new, dry 3,000-gal compressed air storage system and 1,000-cfm flow control to stabilize pressure and reduce peak demands and resultant pressure fluctuations.

NOTE: The piping in the plant compressed air room is unnecessarily complex and problematic. Compressed air leaves the room and feeds into the plant from at least six different lines. See compressor room schematic and economic analysis for layout and detailed payback analysis. Table 9 summarizes operational and cost parameters for the current versus the proposed system.

7.2.9 Recommendations for Implementation Activities. ASME EA-4 recognizes that cost estimates are a component of the decision process that leads to recommendations for implementation activities. These estimates are described as an optional activity and are intended to be screening or feasibility estimates. This level of project estimate is further described as a Class 5 estimate [8] with effort index of 1, the lowest preparation effort.

7.2.10 Appendices. An appendix is for added or appended material that may be relevant to your report but that cannot be placed comfortably in the body of the report. Use it for supplementary material that, if included in the body of the text, would interrupt the flow. For example, a lengthy derivation of an equation or many days of raw data would be included in the appendix. A bulky folded map or drawing should also be put in an appendix, as should commercial material, such as product specifications or engineering documents. Refer to the appendix at the relevant point in the text.

7.3 Data for Third Party Review

Have enough raw data from the assessment available for any third party review. Documentation should be prepared in a fashion that is easily accessed by verifiers and other persons not involved in its development, since several years may pass before this data is accessed or needed. State that typical compressed air systems will change over time and any future review may not be representative of conditions at the time of the survey.

Certain parts of this data will clearly be included as part of the report (compressor ratings, calculations, etc.), but actual volumes of logged readings typically cannot be included. On the other hand, this hard-logged data can often be conveniently included electronically on appropriate media (CD, DVD, or portable drive) for future review.

7.4 Review of Final Report by Assessment Team Members

There is no additional guidance for this clause.

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[2] Antony, P., et al., *Systems Engineering Measurement Primer* (Seattle, WA: INCOSE, International Council on Systems Engineering, 1998), 15.

[3] Industrial Technologies Program, "Compressed Air Tip Sheet #1," Energy Efficiency and Renewable Energy, U.S. Department of Energy, Washington, DC, DOE/GO-102004-1926, 2004.

[4] Motor Challenge, Fact Sheet "Determining Electric Motor Load and Efficiency," U.S. Department of Energy, Washington, DC, ITP Fact Sheet DOE/GO-10097-517.

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[6] Improving Compressed Air System Performance: A Source Book for Industry, Compressed Air Challenge, U.S. Department of Energy, Washington, DC, 2003, p. 59.

[7] Diek, R., *Measurement Uncertainty Methods and Applications,* 4th ed., The Instrument, Systems and Automation Society (ISA), Research Triangle Park, NC, 2007.

[8] ASTM E 2516-06 *Standard Classification for Cost Estimate Classification System,* ASTM International, West Conshohocken, PA, www.astm.org, 2006.

NONMANDATORY APPENDIX A
EXPANDED GLOSSARY

A-1 DEFINITIONS

accuracy, measurement (accuracy of measurement): the closeness of agreement between the measured value of a parameter and a true value of the parameter (see also uncertainty in section 2 of ASME EA-4).

NOTE: A measurement is said to be more accurate when it offers a smaller measurement error.

accuracy, transducer (accuracy of a transducer): the ratio of the error to the full-scale output or the ratio of the error to the output, as specified, expressed in percent. (Source: ISA S31.1–1975 R1982)

NOTES:
(1) Accuracy may be expressed in terms of units of the measured parameter, or as a percentage of full-scale output.
(2) Use of the term "accuracy" should be limited to generalized descriptions of characteristics. It should not be used in specifications. The term "error" is preferred in specifications and other specific descriptions of transducer performance.

action item outcome: system information obtained through implementation of action items.

causal analysis: a systematic method for identifying specific problem areas in work products, project progress, and processes; determining the causes of problem areas; and developing and implementing solutions to prevent the problem areas from occurring in the future. (Source: INCOSE Systems Engineering Measurement Primer)

characterize: to gain an understanding of processes, products, or both, and establish baselines for future assessment.

confidence level (coverage probability): the quantification of confidence (probability) that the true value of a parameter is within a specified coverage interval.

coverage probability: see *confidence level.*

data: raw facts without context.

direct measurement: a method to determine the value of a measured parameter that is done with an instrument designed for such a task.

ECM: see *energy conservation measure.*

EEM: see *energy efficiency measure.*

energy conservation measure (ECM): an activity or set of activities designed to increase the energy efficiency of a facility, system, or piece of equipment. ECMs may also conserve energy without changing efficiency.

energy efficiency measure (EEM): a specific change to a compressed air system that results in improved efficiency as well as other system benefits (for example, increased equipment life and reliability).

energy management project: course of action, with a definite beginning and end, used by the organization to achieve energy goals and targets.

energy profile: regularly updated overview of the organization's energy status that serves as a means to connect an organization's energy use to its primary business output.

energy system: any logical equipment grouping that uses and/or produces primary or secondary energy resources.

error (measurement error): the difference between the measured value of a parameter and a true value of the parameter.

estimate: the result of estimation.

estimation (estimating): the process of determining the value of a parameter through the use of stipulated values, assumptions, observation, calculation, and judgment.

goal: ends toward which effort is directed to achieve the energy policy.

information: one or more meaningful conclusion(s) resulting from action items, or significant questions used to organize additional assessment activities.

knowledge: a degree of understanding a subject from application of measurement, insight, and experience.

measured value: the result obtained by making a direct measurement.

MMscf: million standard cubic feet. A measurement of compressed air used to express total air mass. It is frequently applied over a specified time period. For example, 2 scfm (standard cubic feet per minute) delivered for 1 yr would result in 1,051,200 scf (standard cubic feet) of air delivered, expressed as 1.05 MMscf or (1.05 MMscf/yr). (See also ASME EA-4 Nonmandatory Appendix A, Units of Measure for Compressed Air System Assessment).

observe: a careful, methodical, deliberate act of an observer to examine a subject using cognitive analysis, empirical factual knowledge, and sensory processes.

parameter: a physical quantity, property, or condition having a value that can be expressed as a number with corresponding unit of measure. For example, in the expression 100 psig, the value is 100 and the unit of measure is pound-force per square inch gauge.

parameter, true value: see *true value of a parameter.*

primary energy resource: raw resources that enter the facility from an energy supplier.

NOTE: Primary energy resources may include electricity, natural gas, petroleum products, solid fuels, and water.

qualitative analysis: the evaluation of parameters to determine relevance without measuring them precisely.

quantitative analysis: the measurement and evaluation of parameters to express their behavior in numerical terms.

remedial measure: a specific change, or one of a group of multiple changes, to a compressed air system that results in improved performance, reliability, efficiency, or other system benefits. Changes may affect the facility, equipment, software, training of personnel, maintenance, or any other aspect of compressed air system design or operation.

research: a discovery process of information gathering and validation through discussion and reference to existing documentation. [Source: http://www.reference.com/browse/wiki/Root_cause (accessed: February 22, 2008)].

secondary energy resource: converted form of primary energy resource.

NOTE: Secondary energy resources may include steam, compressed air, chilled water, and hot water.

sensing element: the part of a transducer that responds directly to the physical property to be measured.

significant energy uses: primary or support equipment, processes, applications, or activities identified by the energy profile as a significant component of an organization's energy cost or consumption or both.

NOTE: Significance criteria is determined by the organization.

stipulated value: the value of a parameter based on assumption, reference to literature, calculation, etc.

system: functional group of energy-using industrial equipment organized to perform a specific function.

systems approach: a method for managing and correcting system issues that focuses on total system performance rather than individual component efficiency.

target: a measurable performance requirement to be set and met to achieve part or all of a goal.

transducer: a device that provides a usable output in response to measurement of a physical parameter. For example, a pressure transducer measures pressure and outputs an electrical signal such as voltage or current proportional to the measured pressure.

true value of a parameter: the unique true value of a parameter's physical property.

NONMANDATORY APPENDIX B
MEASUREMENT UNCERTAINTY

Time and effort applied to action items for the system assessment should be traceable to issues, opportunities, remedial measures, and implementation of compressed air system improvements. Most projects cannot afford to collect data or gather information that will never be used.

"No test data should be reported or used without knowledge of its quality, its measurement uncertainty. Violating this precept causes undue risk of incorrect business decisions." [7]

Everything in the world around us has physical properties. We use those properties to describe what we observe. Many properties can be measured; for example, an object's size and weight can be measured. Other properties can be described but are not measured (e.g., the shape or color of the object). The shape or color are observations[1] by comparison, measurements are made using some type of instrument. For example, a ruler can be used to measure the size of an object, and a scale to measure its weight.

B-1 COVERAGE INTERVAL AND CONFIDENCE OF MEASUREMENT

Every measurement has error, which is the difference between the measured value and the true value of the parameter being measured. Furthermore, since there is no way to know the exact true value with absolute confidence, the amount of error cannot be exactly known. Every measurement has some inexact error or coverage interval.

(a) Coverage interval is the range of values believed to include the true value of a measurement.

(b) Confidence of measurement is the degree of certainty that the true value of a measurement lies within the coverage interval.

Practically speaking, there is a relationship between confidence and coverage interval. A very narrow coverage interval may have a low degree of confidence, whereas a broad coverage interval can have a very high degree of confidence.

EXAMPLE:

A standard sheet of paper is 8.5 in. wide and 11 in. long. Is that an exact size?

(1) Assuming a coverage interval is ±0.001 in., what is the confidence that the true size of the paper is within 8.499 in. to 8.501 in. wide and 10.999 in. to 11.001 in. long?

(2) Assuming a coverage interval is ±0.1 in., what is the confidence that the true size of the paper is within 8.4 in. to 8.6 in. wide and 10.9 in. to 11.1 in. long?

The measurement in example (1) would have a low confidence, perhaps 50% or less, and in example (2) a high confidence, maybe 99% or more. The quantitative value for confidence is arrived at through statistical analysis of factors that affect the result of a measurement.

Reporting a value, coverage interval, and confidence clearly states a measurement's result.

B-1.1 Uncertainty

Every measurement has inherent uncertainty that the measurement represents the true value. There are many sources of error that contribute to the total uncertainty of a measurement's result. Error can be introduced by

(a) the measurement instrument, range, sensitivity, precision, accuracy, and response

(b) operator error

(c) measurement techniques, sample rate, data interval, and duration of measurement

(d) loss of electrical signal integrity, interference, ground loops, reference voltage error

(e) accuracy of signal conditioners

(f) analog-to-digital resolution (quantization error)

B-1.2 Error Types

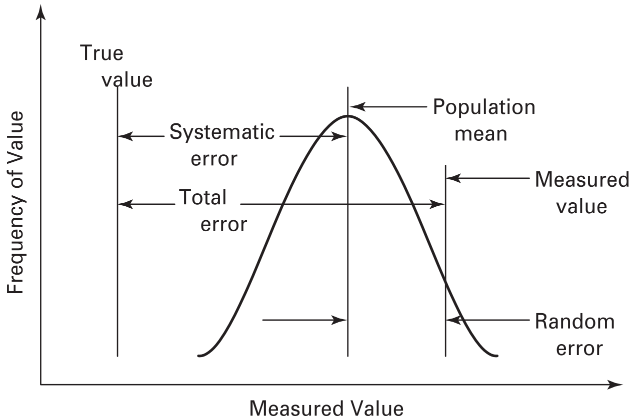
There are two types of measurement error, systematic error and random error.

(a) Random Error. Random error is the measurement error that causes repeated measurements to be randomly different. For a truly random error in a given period of time, repeated measurements will be equally above and below the measured value. If so, making a greater number of measurements and averaging the results will more accurately estimate the measured value. Oversampling with data averaging is one method used to minimize the impact of random error.

(b) Systematic Error. Systematic error is the measurement error that introduces the same error in the measured value for each repeated measurement. Systematic error can result from repeatable calibration error, incorrect scaling of transducer signals, poor measurement methods,

[1] It is acknowledged that colorimetry is the science and technology used to quantify and describe the human perception of color. In general terms, an object's color is described as red or blue without reference to quantifying red or blue.

Fig. B-1 Illustration of Measurement Errors



GENERAL NOTE: This figure was adopted from ASME PTC 19.1-2005, Fig. 4-2-1.

and other independent sources of error. Identification of systematic error requires comparison of separate independent measurements or calculations or both.

Figure B-1 illustrates the relationship of systematic and random measurement errors for a population of repeated measurements.

Systematic errors should be identified and eliminated to the extent practical. Data verification during deployment of data collection equipment (refer to ASME EA-4, para. 5.4) and coordination of data from permanently installed data systems (refer to ASME EA-4, para. 5.5) can assist in identification of systematic errors, providing an opportunity to correct the measurement error.

Data validation before post-processing analysis (refer to ASME EA-4, para. 5.6) is an additional opportunity to identify and correct systematic measurement errors. The assessment team can determine reasonable methods to apply corrections to the measured data.

Random errors can be minimized through application of existing best practices related to measurement equipment, installation methods, and measurement techniques.

Total error in measurement is the cumulative effect of all individual components of both random and systematic error. When reporting measurements, account for all components of error when expressing the coverage interval and confidence of the result. The graphs shown in Fig. B-2 illustrate the effect of varying degrees of both systematic and random error as they affect measurement results for a population of repeated measurements.

B-2 DETERMINING COVERAGE INTERVAL AND CONFIDENCE IN MEASUREMENT

As illustrated in Figs. B-1 and B-2, one method of quantifying coverage interval and confidence in measurement is to gather a population of repeated measurements and apply statistical evaluation to develop a comparative distribution of measured values. This statistical approach to evaluate uncertainty is defined as a Type A evaluation of measurement uncertainty.

B-2.1 Type A Uncertainty Estimate

A Type A uncertainty estimate is the result of rigorous statistical evaluation of repeated results of the same measurement.

This method is applicable in measurement of a controlled steady-state process or laboratory setting where tests can be replicated, allowing for repeated results of the same measurement. However, in the realm of in situ performance measurement of industrial compressed air systems, steady-state performance and replicate testing are virtually impossible. As a consequence, repeated results of the same measurement are unavailable for a Type A estimate of uncertainty.

For industrial compressed air systems, the practical approach to evaluate uncertainty in measurement is a Type B estimate.

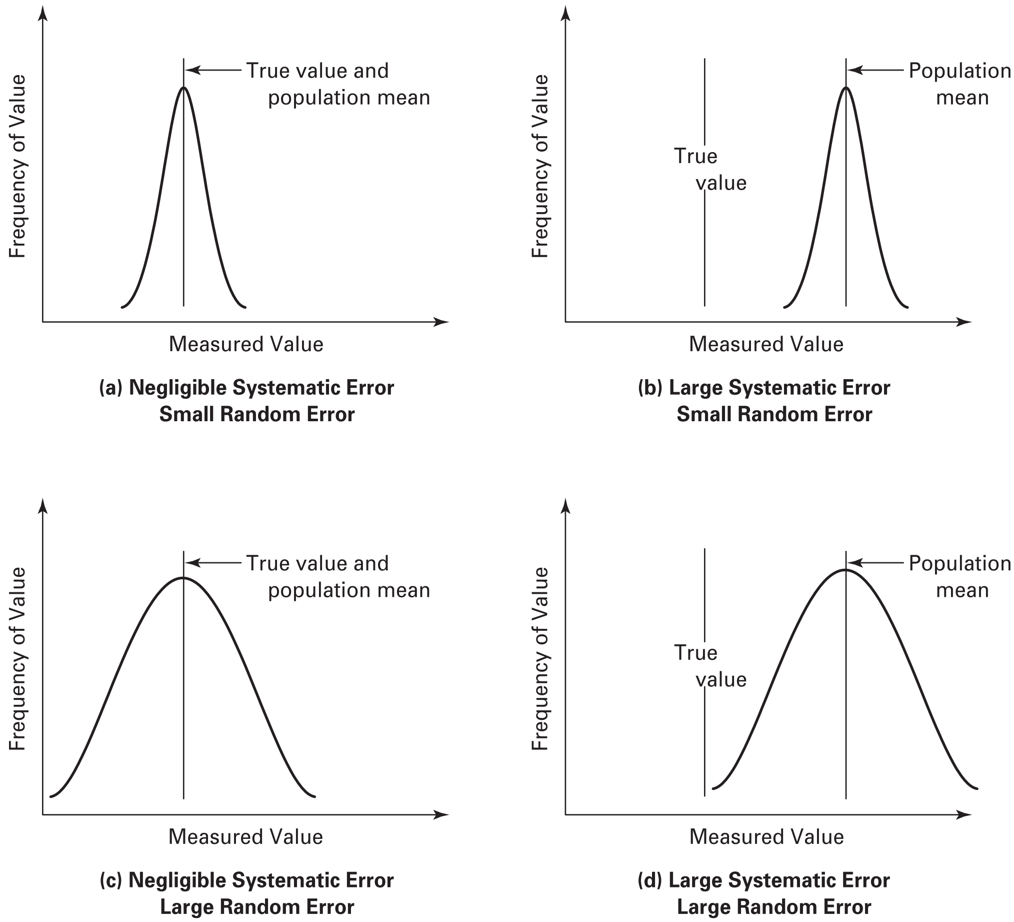
B-2.2 Type B Uncertainty Estimate

A Type B uncertainty estimate is the result of informed judgment, experience, and knowledge of the measurement instrument and measurement process along with reference data taken from handbooks or other authoritative sources.

When making a Type B estimate of uncertainty, the assessment team considers the error caused by factors affecting the measurement. For example, the accuracy or error of individual transducers used is known from the manufacturer’s data or calibration information for the transducer. In some cases, a measurement may be calculated as a result of multiple measurements. For example, power can be calculated based on measured amperage, voltage, and power factor.

$$\frac{\text{voltage} \times \text{amperage} \times 1.732 \times \text{power factor}}{1{,}000}$$

Fig. B-2 Measurement Error Components



GENERAL NOTE: This figure was adopted from ASME PTC 19.1-2005, Fig. 4-2-2.

The accuracy of the value for power calculated using the equation above is dependent on the accuracy of each individual variable that is either measured or assumed. The uncertainty of each individual variable is one element of uncertainty that ultimately affects the uncertainty of the result.

B-2.3 Combined Uncertainty

Combined uncertainty is the result of combining elemental uncertainties given that each of the measured variables has its own effect on the total error in the result. Individual elemental errors (a, b, c, etc.) are evaluated and then combined by taking the root of the sum of the squares.

$$u = \sqrt{u_a^2 + u_b^2 + u_c^2 + \ldots etc}.$$

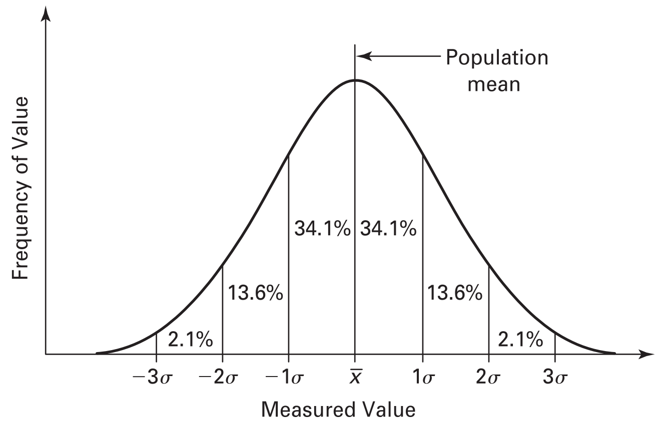
In addition to instrument accuracy, other and perhaps less obvious sources of potential error can affect the uncertainty of measurement. Identifying and estimating error from these other sources relies on the judgment and experience of the team. For example, many flow measurement transducers sense mass velocity (standard feet per minute) in the pipeline, which is then multiplied by the cross-sectional area (square feet) of the pipeline to calculate mass flow rate (standard cubic feet per minute). For insertion-type meters that have not been calibrated in the job-site pipeline, variation in the pipeline's area introduces error in the measured mass flow rate. Old steel pipe may have internal corrosion, effectively reducing the pipeline's inside diameter.

B-2.4 Normal Distribution (Gaussian Distribution)

Observation of randomness in nature causes a distribution of data with a particular kind of shape sometimes described as the bell curve (see Fig. B-3). Mathematicians have studied the normal distribution and have developed equations to describe its characteristics.

The center of the population of data is the arithmetic mean of the measured value, x, also called average; and

Fig. B-3 Normal Distribution of Data



for a number N of individual measurements of x_i, x is defined as

$$\bar{x} = \frac{1}{N}\sum_{i=1}^{N} x_i$$

B-2.4.1 Standard Deviation. Standard deviation describes how much the population of data varies from the mean. A small standard deviation indicates that data is grouped closely to the mean, whereas a large standard deviation indicates the data is spread over a larger range more distant from the mean. Standard deviation, σ, is calculated as the square root of the variance in data.

$$\sigma = \sqrt{\frac{(x_1 - \bar{x})^2 + (x_2 - \bar{x})^2 + \ldots (x_N - \bar{x})^2}{N}}$$

or using summing notation

$$\sigma = \sqrt{\frac{1}{N}\sum_{i=1}^{N}(x_i - \bar{x})^2}$$

Standard deviation is calculated such that a known portion of the data population exists within specified proportions of standard deviation. For a normal distribution, the 68 – 95 – 99.7 rule applies; about 68% of data is within 1 standard deviation (1σ) of the mean, approximately 95% is within 2σ, and about 99.7% is within 3σ.

Standard score (zs) (other terms of art for various fields of study: *Z*-score, *Z*-values, *Z*-factor) indicates how many standard deviations a particular value is above or below the population mean.

For various values of z, the percentage of values expected to lie in and outside the symmetric interval ($-z\sigma$, $+z\sigma$) are as shown in Table B-1.

B-2.5 Other Types of Distributions

In addition to normal (Gaussian) distribution, there are other types of distribution, including, but not limited to, rectangular (uniform) and triangular. In a uniform distribution, a source of uncertainty affecting any single measurement results in equal probability that the value of X is at any point in the distribution range of $-X$ to $+X$. The calculation of standard deviation of a rectangular distribution given that the end points of data are $-X$ and $+X$ is

$$\sigma = \frac{1}{\sqrt{3}} \times X$$

The uniform distribution leads to the most conservative estimate of uncertainty; that is, it gives the largest standard deviation.

B-2.6 Confidence

Confidence is calculated with consideration of the distribution of measurement results. Distributed random variables affecting a measurement result tend toward a normal distribution of data, as shown in Fig. B-3. At a confidence level of 90%, the allowable error is $\pm 1.96\sigma$ standard deviations.

B-2.6.1 Precision Standards. The need for precision standards has been the subject of some debate. In the context of evaluation, a 90/10 standard indicates a ±10% coverage interval at 90% confidence. Another way of looking at this standard is that there is a 90% chance that the measurement result is within ±10% of the true value. The 90/10 precision standard is referenced in ASHRAE Guideline 14, IPMPV–2007 (International Performance Measurement and Verification Protocol), and other literature on the subject. ASME EA-4, para. 5.1 identifies the 90/10 rule as a “target” for the measurement plan.

Table B-1 Standard Score $z\sigma$ and Coverage Interval for Normal Distributions

$z\sigma$	Percentage Within Coverage Interval [Note (1)]	Percentage Outside Coverage Interval	Ratio Outside Coverage Interval
1s	68.2689492%	31.7310508%	1 / 3.1514871
1.645s	90%	10%	1 / 10
1.960s	95%	5%	1 / 20
2s	95.4499736%	4.5500264%	1 / 21.977894
2.576s	99%	1%	1 / 100
3s	99.7300204%	0.2699796%	1 / 370.398

NOTE:
(1) The percentages within bounds are defined by the formula %perc = erf($n\sigma$ / √2) × 50% + 50%.

B-2.7 Expanded Uncertainty

Expanded uncertainty, U, defines an interval about the measurement result that the measurement is believed to lie within to a specified confidence. Expanded uncertainty is calculated by multiplying the combined uncertainty, u, by a coverage factor, k. The coverage factor is selected from the Z-score for the desired coverage interval. For example, if the desired coverage interval is 95%, $k = 2$ (or 1.960); for 90% coverage interval, $k = 1.645$ would be selected.

$$U = k \times u$$
$$U = k\sqrt{u_a^2 + u_b^2 + u_c^2 + \ldots etc}.$$

B-2.8 Example of Pressure Transducer Measurement

A pressure transducer and data logger are going to be installed at an end-use application in a steel mill to measure the point-of-use pressure profile at the door-operator cylinder of a reheat furnace. It is necessary to determine the in situ end-to-end measurement uncertainty and confidence for the pressure measurements. Pressure measurement locations are at the air header in the reheat area, the connection point to the FRL inlet upstream of the solenoid control valve, and the pneumatic cylinder port at the end of cylinder that lifts the furnace door. The temperature in the area is elevated, plus there is radiant heat from the furnace. An infrared thermometer has determined that the pressure transducers operate at a maximum temperature of 120°F.

Since the furnace and compressed air system do not operate at a steady-state condition that would allow taking a population of repeated measurements, a Type A uncertainty estimate is not possible. Therefore, a Type B estimate of uncertainty must be made.

First, list the elemental uncertainties, u, to be considered. Elemental uncertainties must be expressed in similar terms before they are combined. Therefore, all of the elemental uncertainties must be given in the same units and the same level of confidence.

u_a = pressure transducer calibration. Shows expanded uncertainty, U, from the calibration certificate or manufacturer's data. Specified as ±1% of F.S. including nonlinearity, nonrepeatability, zero offset, and span-setting errors.

u_b = pressure transducer thermal coefficient. Manufacturer's data shows a reference temperature of [68°F (20°C)] % of span/°F. The manufacturer's specified thermal coefficient is ±0.04% / °F.

u_c = data-logger analog input accuracy. The manufacturer's data shows the analog input accuracy is ±0.25% F.S.

u_d = quantization error for analog-to-digital (A/D) conversion. The data logger used is an 8-bit A/D converter providing 255 ($2^8 - 1$) increments of resolution. Error is uniformly distributed between –1/2 least significant bit (LSB) and +1/2 LSB, and signal to quantization noise ratio is assumed to be negligible.

To calculate combined uncertainty, the elemental uncertainties must be expressed in the same units of measure, usually output units. In the example, pound-force per square inch gauge (psig) will be used. Elemental uncertainties that are given as expanded uncertainty will be converted to a coverage interval of ±1 standard deviation to give a consistent level of confidence for all elemental uncertainty.

Calculate elemental uncertainty for calibration; expanded uncertainty U is assumed to be a Type A evaluation for normal distribution with coverage factor of $k = 2$ (Z-score = 2 for 95% confidence). Therefore, the elemental uncertainty is U divided by 2. The pressure transducer range is 0 psig to 200 psig with ±1% or ±2 psig expanded uncertainty.

$$u_a = \frac{U}{k} = \frac{\pm 2 \text{ psig}}{2} = \pm 1.0 \text{ psig}$$

Elemental uncertainty for operating temperature is calculated assuming Type B evaluation. This is a more conservative assumption of uniform or rectangular distribution of data as compared to normal distribution. In a rectangular distribution, there is equal probability that a given measurement will be near the mean, or at the limits of the coverage interval, or anywhere in between. For Type B evaluation, the coverage factor k is equal to the square root of 3.

From manufacturer's data, at 120°F operating temperature the possible effect on the reading is ±2.08% [(120°F – 68°F) × ±0.04%] or ± 4.16 psig.

$$u_b = \frac{U}{\sqrt{3}} = \frac{\pm 4.16 \text{ psig}}{1.732} = \pm 2.4 \text{ psig}$$

Elemental uncertainty for the data-logger's analog input accuracy is calculated assuming expanded uncertainty, U, is a Type A evaluation for normal distribution and a coverage factor $k = 2$ for 95% confidence. The data-logger manufacturer's information shows ±0.25% F.S., which is ±0.5 psig for 0 psig to 200 psig full-scale range.

$$u_c = \frac{U}{k} = \frac{\pm 0.5 \text{ psig}}{2} = \pm 0.25 \text{ psig}$$

Elemental uncertainty for A/D quantization error is calculated assuming Type B evaluation. Given 255-bit increments for 0 psig to 200 psig range, the LSB value is 0.78 psig.

$$u_d = \frac{U}{\sqrt{3}} = \frac{\pm 0.78 \text{ psig}}{1.732} = \pm 0.45 \text{ psig}$$

B-2.8.1 Combining Elemental Uncertainty. Elemental uncertainty is combined in quadrature, or calculated as the root sum of the squares of all elemental uncertainties.

$$\begin{aligned} u &= \sqrt{u_a^{\,2} + u_b^{\,2} + u_c^{\,2} + u_d^{\,2}} \\ &= \sqrt{1.0^2 + 2.4^2 + 0.25^2 + 0.45^2} \\ &= \pm 2.65 \text{ psig} \end{aligned}$$

B-2.8.2 Expanded Uncertainty. Combined uncertainty reflects a coverage interval that represents a normal distribution of results. Therefore, expanded uncertainty, U, is equal to the combined uncertainty multiplied by a coverage factor (Z-score) as appropriate for the desired expression of confidence. A coverage factor of 2 is generally used for a confidence of 95% [however, the actual confidence is 95.4499736% (see Table 8)]. For confidence of 90%, a coverage factor of 1.645 should be used.

$$U = k \times u$$
$$U = \pm 5.30 \text{ psig} \quad (\text{for } k = 2.0 \text{ or } 95\% \text{ confidence})$$
$$U = \pm 4.36 \text{ psig} \quad (\text{for } k = 1.645 \text{ or } 90\% \text{ confidence})$$

B-2.8.3 Proper Expression Quantifying the Result of Measured Pressure *X*. A proper expression of the result has three components.

(a) a value for the measured result X
(b) the coverage interval of the measurement
(c) the confidence of the measurement

Therefore, the pressure measurement above could be expressed as

X psig ± 5.30 psig with 95% confidence

or as

X psig ± 4.36 psig with 90% confidence

The resultant statement of pressure measurement shown above represents the end-to-end accuracy of the measurement system. Field measurements need to consider all of the factors that contribute to measurement error. Ultimately, the practitioner should evaluate the entire measurement process and report a Type B estimate of coverage interval and confidence for the in situ end-to-end field measurement.

B-2.9 Example of Converting Uncertainties From One Unit to Another

A power transducer has an output of kilowatts. The output of the kilowatt transducer also depends on the uncertainty of current transducers (CTs), which have an output of amperes. The dissimilar units of kilowatts and amperes cannot be used for combining uncertainties.

Fractional uncertainty can be used to combine uncertainty of dissimilar units. For example, a power transducer has an accuracy of ±0.5%, and a current transducer has ±1.5% accuracy measuring at 200 A. The kilowatt transducer at 200 A and 500 V max. input has a range of 0 kW to 173 kW. The kilowatt measurement is ±0.86 kW expanded uncertainty. The current is ±3 A expanded uncertainty. For normal (Gaussian) distribution, the elemental uncertainty is the expanded uncertainty divided by 2, in this case, ±0.43 kW and ±1.5 A, respectively. The fractional uncertainty is the elemental uncertainty divided by the value.

$$f\left(u_{kw}\right) = \frac{u_{kW}}{kW} = \frac{0.43 \text{ kW}}{173 \text{ kW}} = 0.0025$$

$$f\left(u_A\right) = \frac{u_A}{A} = \frac{3.0 \text{ kW}}{200 \text{ kW}} = 0.015$$

The fractional uncertainties are dimensionless and can therefore be combined. You will note that the fractional uncertainty expressed as a percentage is the original expanded uncertainty percentage divided by the coverage factor for a normal (Gaussian) distribution. The fractional method is shown for the situation in a Type B estimate where measurement uncertainty can be given a value but is not necessarily expressed as a percentage.

The elemental fractional uncertainty is combined in quadrature or calculated as the root sum of squares as in the pressure transducer example in para. B-2.8.

B-2.10 Direct Versus Indirect Measurement and Precision

Generally, direct measurement of a parameter with an instrument designed for the task provides the highest precision. Indirect measurement is accomplished by measuring multiple related parameters, each of which contributes to the total error. Furthermore, assumptions and stipulated values used in the process of calculating the indirectly measured parameter add elements of error.

For example, indirect measurement of delivered airflow from a compressor might include measurement of compressor power and a stipulated value of the compressor's rated airflow, and assumptions regarding the compressor's part-load performance profile that describes a relationship between power and airflow rate. It is necessary to consider many factors that introduce error to the indirect measurement. Inlet conditions including air temperature, relative humidity, and absolute pressure along with mechanical condition of the compressor will affect the compressor's rated airflow. The part-load performance profile is affected by adjustment of the compressor's controls, mechanical condition, and the effect of system dynamic performance on control signal pressure.

ASME EA-4 (para. 5.1.4) requires in situ validation of assumptions and stipulated values associated with indirect measurements. In other words, what was done to evaluate the various on-site conditions affecting the indirect measurement and to quantify their contribution to measurement error? The end-to-end accuracy of field measurement needs to consider all of the factors that contribute to measurement error. Ultimately, the assessment evaluates the measurement process and reports a Type B estimate of coverage interval and confidence for the in situ end-to-end field measurement.

B-2.11 Propagation of Uncertainty in the Result of Mathematical Calculations

Measured values are often used for mathematical calculations. The resultant value of a calculation may be objective of testing, or in the case of indirect measurement, may be the value of a desired measured parameter. Whenever measurement results are used in calculations, the uncertainty of individual values propagate through the calculation and affect the uncertainty of the calculated result.

B-2.11.1 Summation in Quadrature for Addition and Subtraction. When a calculated result involves the addition or subtraction of measured values, the combined uncertainty, u, is equal to the root sum of squares for the elemental uncertainties.

$$u = \sqrt{u_a^2 + u_b^2 + u_c^2}$$

B-2.11.2 Summation in Quadrature for Multiplication or Division. When a calculated result involves multiplication or division of measured values, the combined uncertainty should apply fractional elemental uncertainties. For example, for measured values A, B, and C resulting in a calculated value of X, the following expression is used for combined uncertainty:

$$\frac{u_X}{X} = \sqrt{\left(\frac{u_A}{A}\right)^2 + \left(\frac{u_B}{B}\right)^2 + \left(\frac{u_C}{C}\right)^2}$$

B-2.11.3 Summation in Quadrature for Squared or Square Root Functions. For calculated results involving measured values affecting calculation of squared or square root functions, combined uncertainty is expressed using elemental uncertainties in the following forms:

$$\frac{2u_A}{A} \text{ for a squared value}$$

or

$$\frac{u_B}{2B} \text{ for a square root}$$

When the calculated result involves a multistep calculation, propagation of uncertainty applies summation in quadrature for the proper form of elemental uncertainty at each step. Once the combined uncertainty has been evaluated, the practitioner should apply the appropriate coverage factor k (or Z-score) for the desired confidence of the result.

B-2.11.4 Other Considerations in Measurement Uncertainty. Metrology and measurement uncertainty are constantly evolving areas of science and technology. The analysis presented here is rudimentary. It assumes that variables have no interdependent correlation to each other. If parameters exhibit some degree of covariance where change or error in one parameter has some effect in the error of other related parameters' errors, many other methods are available to account for uncertainty.

NONMANDATORY APPENDIX C
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