

CODES AND STANDARDS ENHANCEMENT INITIATIVE (CASE)

Compressed Air Systems

2013 California Building Energy Efficiency Standards

California Utilities Statewide Codes and Standards Team

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1. Introduction

This report is a part of the California Investor-Owned Utilities (IOUs) Codes and Standards Enhancement (CASE) effort to develop technical and cost-effectiveness information for proposed regulations on building energy efficiency design practices and technologies.

This report investigates the potential for additions to the Title 24 code regarding the efficiency of compressed air systems. This code proposal addresses the energy losses caused by inefficient part load use of the compressors supplying the system. Specifically this report proposes requirements for multi-compressor systems to use system master controls to limit the cases where compressors are unnecessarily run at part load. This report also proposes that all compressed systems include a compressor with a relatively constant specific power across a broad range of loads (such as variable-speed drive (VSD) compressor) to serve as a relatively efficient trim (ie part load) compressor. To prevent the savings of these measures from being compromised, this report also proposes that an already widely accepted minimum standard for primary air storage of 2 gallons per acfm trim be required. These requirements would apply to compressed air systems installed in new construction and to systems retrofitted in major renovations.

Throughout 2010 and early 2011, the CASE Team (Team) evaluated costs and savings associated with each code change proposal. The Team engaged industry stakeholders to solicit feedback on the code change proposals, energy savings analyses, and cost estimates. The contents of this report were developed with feedback from vendors, manufacturers, compressed air industry consultants, industry groups, utility and federal voluntary incentive programs, and the California Energy Commission (CEC) into account.

All of the main approaches, assumptions and methods of analysis used in this proposal have been presented for review at three public Stakeholder Meetings hosted by the IOUs. At each meeting, the CASE Team asked for feedback on the proposed language and analysis thus far, and sent out a summary of what was discussed at the meeting, along with a summary of outstanding questions and issues.

A record of the Stakeholder Meeting presentations, summaries and other supporting documents can be found at www.calcodesgroup.com. Stakeholder meetings were held on the following dates and locations:

- ◆ First Stakeholder Meeting: May 25, 2010, Webinar
- ◆ Second Stakeholder Meeting: January 19, 2011, Webinar
- ◆ Third Stakeholder Meeting: March 30, 2011, Webinar

2. Overview

2.1 Measure Title

Air Compressor Smart Controls and Trim Compressor Requirements

2.2 Description

The proposed code change would require all new industrial plants' compressed air systems to include at least one trim compressor that performs efficiently in part load conditions and primary storage, both sized appropriately to meet the minimum trim needs of any other compressors in the system. Multi-compressor systems would also be required to implement a smart system master controller.

Compressed air systems are typically sized (and often oversized) based on full load operating conditions and are designed to operate most efficiently at full load. However, the demand on most compressed air systems varies throughout the day and the system is often operating at less than full load. Some types of compressors are very inefficient at part loads and if not controlled properly a system could have several or all of its compressors simultaneously running at part loads, crippling the overall efficiency. These two measures would address these inefficiencies in the supply side of compressed air systems.

2.2.1 Variable Speed Drive Compressors

Variable Speed Drive (VSD) compressors use variable speed motors to modulate their output. The advantage of this is that it allows the compressor to have a relatively linear cfm output to kW input efficiency curve compared to other mechanism such as inlet modulation and load/unload operation. This makes VSDs ideal trim compressors, supplying the variable demand on top of the stable base demand.

This measure proposes that every compressed air system include at least one compressor that is efficient at part loads. It is possible that other types of compressors could have comparable part load performance, though at this time VSDs are the most common such technology. In order to address this, the proposed code language sets part load performance requirements rather than explicitly requiring VSDs.

2.2.2 Smart Controls

Smart controls consist of an independent control unit which can receive inputs from sensors and the compressors, make control decisions based on those signals, and return control signals to the compressors.

Historically, controls have been applied at the individual compressor level. Each compressor monitors the pressure at its own discharge header and cycles based on that reading. The only way to coordinate multiple compressor systems is for the system operators to base individual compressor settings on an overarching system control plan.

As mentioned in the previous section, poor part load performance can cause significant drops in efficiency. Smart controls can help improve efficiency by ensuring that at any given time the most appropriate set of compressors is being used to meet the current demand. Using smart controls will

limit the number of compressors that are operating at sub-optimal efficiencies, so at worst a single compressor will be operating in an inefficient regime (and if paired with the trim compressor measure, then even that compressor will be relatively efficient).

One additional way in which isolated compressor controls contribute to inefficiency is by requiring a wide pressure control band. Each compressor has its individual control band dictating the points in which it loads and unloads (or the VSD speed, input modulation setting, etc.). For multiple compressors to operate in conjunction these bands must be staggered in an overlapping cascade, producing a much larger overall system pressure control band. Because the overall system pressure must be kept above some minimum level, the net effect is a higher average system pressure, which decreases the overall efficiency. Smart controls allow a much smaller single pressure band to be used to control all of the compressors.

2.3 Type of Change

The proposed measures would be mandatory requirements in a new section of Title 24 that would cover specific process loads. Title 24 does not currently cover compressed air systems.

2.4 Energy Benefits

Energy savings are realized at a compressed air system level, with typically one (though sometimes multiple) system in each building. However, factors such as building size have no direct relation to compressed air system size so the standard prototype buildings and savings by square foot are not applicable.

As there is no current standard in place for compressed air systems, energy savings estimates must be made relative to assumed common practice. These are outlined in the Methodology Section 3.2.1.

Per minimum unit energy savings for each measure are presented below. These savings values are presented below in [Table 1](#).

Table 1: Per minimum unit energy savings for smart controls and trim compressors requirement.

	Electricity Savings (kWh/yr)	Demand Savings (W)	Natural Gas Savings (Therms/yr)	TDV Electricity Savings	TDV Gas Savings
Smart Controls: savings per average system	4,940	0	n/a	\$8,395	n/a
Trim Compressors: savings per average system (100 hp trim)	50,382	0	n/a	\$104,498	n/a

The Analysis and Results section 4.1.1 and 4.1.3 outline the minimum expected energy savings and TDV benefit for individual systems in conservative savings scenarios.

Statewide savings estimates are still being refined. This report will be updated with the statewide savings values at a later date. An estimate of new construction for each scenario would result in a conservative estimate of statewide savings, though the CASE Team believes the actual savings for average systems will be considerably larger.

2.5 Non-Energy Benefits

Smart controls have the potential for numerous non-energy benefits. The most significant non-energy benefits include reduced maintenance costs due to reduced compressor run times and cycling, avoiding system management problems caused by control gaps, and potentially improving system uptime or even product quality by providing a more stable and consistent compressed air supply.

2.6 Environmental Impact

This measure would have no significant impact on water quality or consumption. It would not create a significant change in materials use, including use of Mercury, Lead, Copper, Steel, or Plastic.

2.7 Technology Measures

Measure Availability:

Smart controls are manufactured by both traditional compressor manufacturers and companies that focus specifically on controls. Examples include Pneulogic, EnergAir, Kaeser, FSElliot, etc. They are a relatively new addition to the market, but are increasingly being added to industrial repertoires.

The majority of compressor manufacturers now offer VSD compressors, including Atlas-Copco, Kaeser, Sullair, CompAir / Gardner Denver, etc.

Useful Life, Persistence, and Maintenance:

Smart controls are a new enough product that their full life expectancy is not yet clear. At this point in time most installations are less than a decade old, with few failures and replacements. A reasonable lifespan for smart controls is fifteen-years. Control performance is not expected to decrease with age. The energy and cost savings from controls would actually be expected to increase over time as other components in the system degrade or fall out of balance.

VSD compressors, and compressors in general have very long lifespans when properly maintained..

2.8 Performance Verification of the Proposed Measure

A fairly basic acceptance test is proposed for controls, requiring a check to ensure that the system can operate at some mid-range point efficiently. The ideal method to verify performance of compressed air systems would be long term monitoring over a week or longer. This would provide a much more accurate assessment of the setup and control as well as the match between air supply and demand, and could be added as a separate measure at a later date.

2.9 Cost Effectiveness

Smart controls (in multi-compressor systems) and efficient trim compressors are cost effective in the vast majority of practical scenarios. This measure would not be cost effective for systems with a constant rate of flow demand and operating near full load for all compressors. Cases such as this would be highly uncommon.

2.10 Analysis Tools

AirMaster+ was used to model system level savings for controls improvements. It is described in more detail in *Section 3.2.1 Controls Energy Savings*.

Spreadsheet analysis was used to evaluate savings for trim compressors and cost savings for both measures.

2.11 Relationship to Other Measures

This measure would have no direct impact on any existing measures or measures currently being proposed.

3. Methodology

3.1 *Developing Code Change Proposal*

3.1.1 Existing Conditions – Process Load Regulation

Most process loads (which are defined in Part 6 of Title 24 as energy loads that are “not related to the space conditioning, lighting, service water heating, or ventilating of a building as it relates to human occupancy”) have historically been exempted from many of the Title 24 efficiency requirements, with the exception of the recently added requirements for refrigerated warehouses.

3.1.2 Existing Conditions – Compressed Air System Efficiency Regulations

Currently there are no federal or state energy efficiency requirements for compressed air systems. The closest regulations are those that apply to the motors powering compressor units. To the best of our knowledge, China is the only country that has implemented compressed air system minimum efficiency requirements [McKane 2005]. Some performance and design requirements for compressed air systems exist in California’s mechanical and plumbing codes, but none of these address efficiency (see ASME B31.1-2004; IAPMO PS 42-96; NFPA 99C-2002; UL 252-2003; CGA V-1; CGA S-1.3; and Title 24: Part 4, Chapter 14; Part 5, Chapter 13)

Voluntary programs do exist to encourage compressed air system efficiency. The three primary areas of focus for these programs are education, audits, and incentives. Educational programs such as the courses taught by the Compressed Air Challenge¹ empower the individuals operating, overseeing, or selling these systems to take steps to improve efficiency on their own. Audit programs such as the one implemented by the Department of Energy Industrial Assessment Center provide detailed analyses of specific sites and recommendations for improvement. Incentive programs such as those administered by the California IOUs evaluate the potential savings for particular efficiency measures at specific sites and provide incentives for the successful implementation of those measures.

Additionally the International Organization for Standardization is developing ISO 50001, a standard for industrial energy management. ISO 50001 is currently in draft form and expected to be released in late 2011. Based on initial drafts and conversations with those involved in its development, the standard will provide guidance and best practices (and focusing on audits), but not set specific mandatory requirements for compressed air systems.

3.1.3 Measures Considered

Numerous strategies exist for improving compressed air system efficiency and many were considered as potential Title 24 measures. They ranged from variable speed drive compressors, lossless drains,

¹ The Compressed Air Challenge is a voluntary collaboration of industrial end-users; manufacturers, distributors and their associations; consultants; state research and development agencies; energy efficiency organizations; and utilities. The mission of the CAC is to be the leading source of product-neutral compressed air system information and education, enabling end users to take a systems approach leading to improved efficiency and production and increased net profits.

,cycling dryers, leak testing, performance monitoring, and total system efficiency metrics. Each was evaluated based on the following criteria:

1. Potential for impact
2. Applicability to the vast majority of systems
3. Ability to be codified
4. Simplicity for compliance
5. Opportunities to address system level issues under Title 24 that would not be possible in other regulation

If these measures are adopted, this would be the first time many of the users and manufacturers would be required to take into consideration and comply with Title 24 requirements. Therefore it was very important to emphasize simplicity. This point was raised repeatedly by stakeholders from the very beginning of the process. The decision was made to focus on a small number of broad measures rather than a large number of highly specific ones.

The two measures that showed the most promise for broad applicability to many systems and considerable savings were smart controls and variable speed drive (VSD) compressors. Smart controls have the potential for large energy savings as well as the potential to amplify the savings achieved from other efficiency measures. Smart controls also have significant non-energy benefits for the system, and the distinct advantage that there is no system that would lose efficiency from their implementation. VSD compressors also have large savings potential because of its steady efficiency across an expansive load range. VSD compressors are becoming common practice and are very frequently recommended by voluntary programs. As such they are well positioned for acceptance as a Title 24 requirement.

The Team recognizes that there may be other ways to achieve a reliable efficiency across a range of operating conditions. For example, the Team considered the option of increasing storage as a way of achieving reliable efficiency.. The results of the analysis are presented in section 4 this report. After the analysis was completed and reviewed by stakeholders, it was determined that increasing storage does not achieve the same scale of savings as VSD compressors and increasing storage is not applicable to every compressor.. Recognizing the possibility that multiple technologies could be used to achieve the desired results and to allow for flexibility in code compliance, the code change language requires a trim compressor that meets a part load performance metric rather than limiting the options to one or two specific technologies.

Many of the measures not included in this CASE study also have significant potential and should be considered in future code cycles. The full list of measures considered, along with commentary, is included in the Appendix.

3.2 Smart Controls Cost and Savings Analysis

Smart controls costs and savings are highly dependent on the details of the individual system and there exists no ‘typical’ system to use as a model. In order to address this, a set of conservative systems was selected to explore the boundary of cost effectiveness. These are relatively small systems, with few compressors, and moderately stable load profiles. Systems that are larger, more variable, less ideally sized for their load, or with a greater number of compressors, will have

considerably more savings. The cost of controls for these systems is significant, but there are also significant energy savings that outweigh the incremental first cost. If the measure is cost effective in the most conservative cases, then the measure is cost effective in the vast majority of practical cases.

3.2.1 Energy Savings

To estimate energy savings, the CASE Team used AirMaster+ to model hourly energy use from representative compressed air systems operating under specific load profiles. Energy use was modeled using conventional controls and smart controls. Per-unit energy savings is the difference between energy consumption from these two configurations.

AirMaster+ was used to model energy savings because it is the industry-accepted standard modeling tool, and it has the functionality to conduct the analysis required to evaluate the cost-effectiveness of the proposed code change. AirMaster+ was developed as part of the Department of Energy's Industrial Technology Program. The outputs of the AirMaster+ models are energy consumption on a per hour basis.

The general approach taken for the energy savings modeling was to assume a given set of compressors and a load profile, and to calculate the energy use with and without the use of smart controls. The case without smart controls was modeled using a best-case simple cascade. The case with smart controls was modeled by taking the hourly simple cascade results and manually adjusting the demand to each compressor during the points that were not optimal, to mimic the functionality of smart controls.

Comparison with Proposed Code Requirements

It's important to note that the code requirements were refined after the initial energy analysis was complete. The energy analysis compares the performance of a smart control on four different baseline systems with the performance of a sequencer on these same systems. This approach allows for a comparison in energy use of particular systems, but some potential energy savings are not currently captured in the analysis.

In the baseline systems, the trim compressor is sized almost perfectly for the given trim load. Though somewhat ideal, this is atypical – the trim load can be estimated, but is difficult to plan for until all components of the system are operating. This is not to say that these configurations are unreasonable, but that these configurations are in fact quite conservative.

Furthermore, the trim compressor identified for each system was sized appropriately to avoid control gaps (see discussion in Section 3.3.3). If the trim compressor was not sized properly the system would not operate as efficiently outside of the chosen load profile because a base compressor would be forced to operate at part-load. While some systems use properly sized trim compressors, it is not unheard of for systems to have incorrectly sized trim compressors. This is another indication that the analysis is very conservative. More savings could be demonstrated given a different load profile and adjusting the trim compressor size.

Assumptions

Key assumptions made for all modeled systems include:

- System discharge pressure of 100 psig.
- Load profile generally 80% constant base load and 20% variable trim, with some greater variation at shift change.
- Primary receiver sized to 2 gal/cfm of trim load as designated by the load profile.
- 10% loss of total output due to leaks.
- Unloaded power for load/unload compressors is 25% of full load power.
- System in use 4160 hours/year (16 hours a day, 7 days a week.)
- Results are not dependent on Climate Zone.

Auto-shutdown timers, which turn a compressor off after it has been unloaded for a preset time period, are also an effective part of smart controls, but there was not a consensus on whether they should be considered typical practice as part of the basecase for this analysis. Therefore, the basecase was modeled both with and without auto-shutdown timers in the energy analysis.

For the cost effectiveness analysis, the team chose the conservative case (which assumes auto-shutdown timers exist in the basecase) to guarantee that the analysis does not overstate savings. [Table 2](#) describes the representative systems used in the energy savings analysis, including compressor models and other hardware along with the base load and trim load (described in *acfm* or cubic feet per minute at the given pressure). [Figure 1](#) presents the load profiles that were modeled.

Table 2: Specifications of Representative Systems

	Baseline System 1	Baseline System 2	Baseline System 3	Baseline System 4
Nominal Base Load (acfm)	400	800	1600	3200
Nominal Trim Load (acfm)	100	200	400	800
Primary Receiver Size (gal)	200	400	800	1600
Compressor 1	75 hp, load/unload, single stage, lubricant-injected, rotary screw	150 hp, load/unload, single stage, lubricant-injected, rotary screw	300 hp, load/unload, single stage, lubricant-injected, rotary screw	500 hp, inlet vane, multiple stage, centrifugal
Compressor 2	50 hp, load/unload, single stage, lubricant-injected, rotary screw	50 hp, load/unload, single stage, lubricant-injected, rotary screw	150 hp, load/unload, single stage, lubricant-injected, rotary screw	150 hp, load/unload, single stage, lubricant-injected, rotary screw
Compressor 3	n/a	n/a	n/a	150 hp, load/unload, single stage, lubricant-injected, rotary screw

Two load profiles were modeled for each system, a weekday profile and a weekend profile. The weekend profile was slightly smaller and slightly more variable than the weekday. While not all systems will differ in behavior on the weekend, this slight variation is a very small proxy for any deviation from expectations: such as the difference between the system designer's estimates and the actual system demands, change in demand over time, change in performance over time, etc.

The load profile shapes are the same for all of the systems, simply sized to match the sum of the nominal base and trim demands.

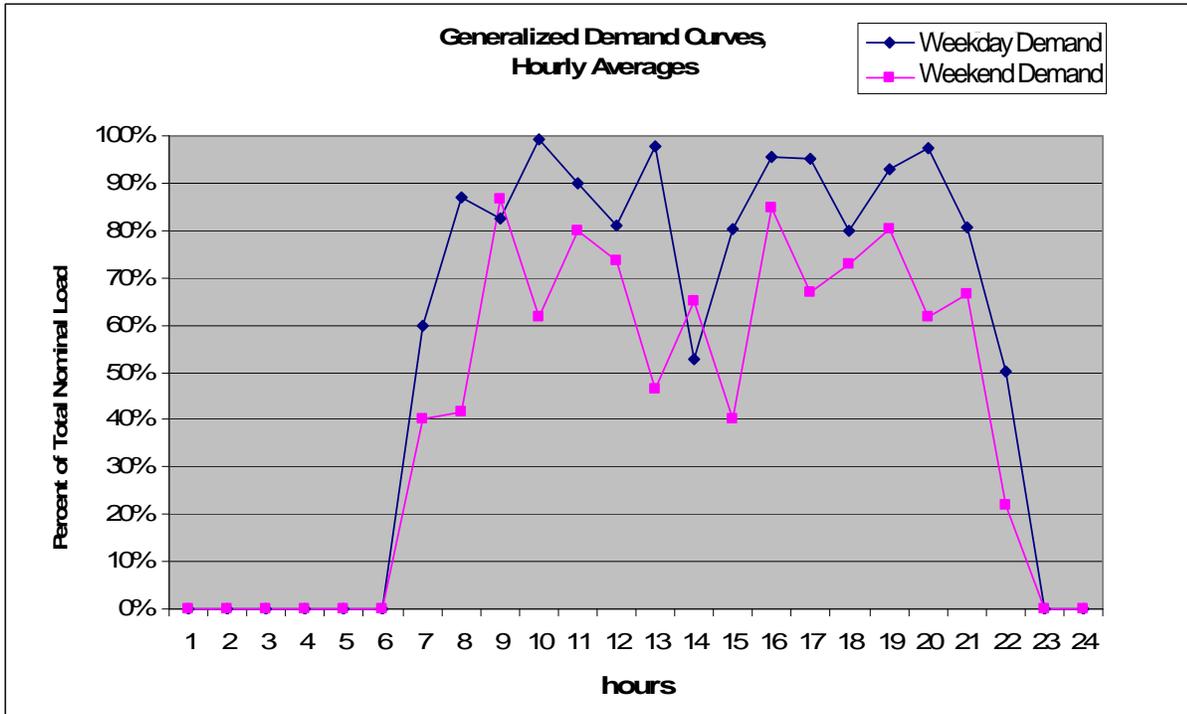


Figure 1: Modeled load profiles

3.2.2 Costs

Measure Costs

The incremental cost to add smart controls is the full cost to purchase and install the control system. Cost estimates for smart controls are based on the catalogs and estimates provided by three controls manufacturers. Costs can vary considerably depending on the specifics of the system to be controlled (number and types of compressors, control features, etc.). The cost estimates for the systems used in this analysis are displayed in [Figure 2](#). The estimates include the cost for the hardware (control unit, compressor interface units, sensors) and the installation labor.

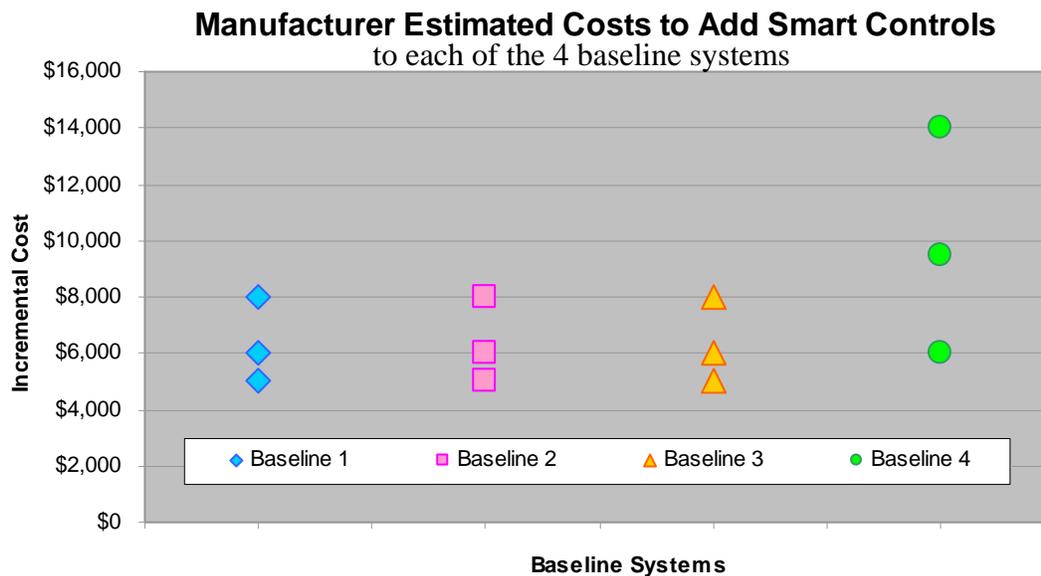


Figure 2: Cost to install a system to meet the minimum requirements of the smart controls measure for the 4 baseline systems as estimated by three manufacturers.

Maintenance Costs

Maintenance costs and savings are not included in the cost-effectiveness analysis, because the savings are assumed to at least balance out the costs. Based on stakeholder feedback, control systems such as these can require a small amount of maintenance, primarily adjusting control settings over time. Meanwhile, the controls can significantly decrease the maintenance cost for the compressors and other components of the system. Smart controls provide a greater awareness of the current state of the system, facilitating early detection of maintenance issues for the system as a whole. As a result, most systems would experience net maintenance cost savings.

3.2.3 Cost Effectiveness

The cost effectiveness of the measure was evaluated using the CEC LCC methodology, based on a 15-year nonresidential measure life.

3.2.4 Final Code Development

As mentioned previously, this is the first proposed measure for compressed air systems. Since compressed air systems have not been covered under Title 24 previously, the proposed language includes all of the relevant definitions and nomenclature. Translating the conceptual idea of how smart controls should be applied to compressor systems into clear and concise code language has required significant deliberation. In addition to proposing concise language, the goal was to propose a code that is relatively easy to comply with. This section discusses how the Team arrived at the definition of “smart controls”, the types of compressor systems the proposed change would apply to, and the proposed acceptance tests to ensure compliance.

Defining Smart Controls

In order to measure current demand of a compressed air system, a sensor (or sensors) need be installed. Sensors can measure a variety of things, including pressure, flow, temperature, power, and other metrics. However, which of these measurements is used, and how that translates into a demand signal, depends on the individual type of controller.

At a given demand, a smart controller will use the measured information along with knowledge of the compressors available, to determine the best combination of compressors necessary to supply the required airflow. The exact criteria used to make the selections are specific to the individual controllers and system design.

The intent of this measure is not to dictate the control mechanism or algorithm, but to simply mandate the use of some smart control system that is capable of such control.

Applicability

Smart controls are applicable across the board for multi-compressor systems. Even systems with just two compressors can operate more efficiently across a wide range of demands if a smart control is employed.

This code is recommended for all systems with a combined total compressor power over 100 hp. Smaller systems would also benefit and could be cost-effective, but advanced compressed air control is a fairly new market and currently only larger systems are well supported.

Acceptance Testing

In talking to controls manufacturers and other industry stakeholders, the CASE Team received feedback that it is not uncommon for controllers to be set up incorrectly.

There are a variety of ways that smart controls can measure current air demand and make decisions on what the best combination of compressors is for a given load. Variations in how different controls operate can lead to confusion in how the controls are commissioned. It also makes it difficult to establish a standardized way to test the controls. The Team also received feedback that there was no industry standard way to test a smart control. Given that it is not possible to prescribe a standard industry test for approved controllers but compliance could be an issue, an acceptance test must be provided.

An acceptance test consists of two components: The construction inspection, described before the system is installed, and a functional test following installation. The functional test, again, must confirm that the smart control is choosing an energy efficient combination of compressors based on input from a sensor measuring current demand. The construction inspection will be dependent on this functional test. A few functional tests are described in the following sub-section.

Functional Tests

Three functional tests were considered. Each of these tests is described below.

In depth *commissioning* would be most ideal functional test. The system would be measured and monitored for an extended period of time (at least 24 hours, but preferably a week or longer), showing the state of the system continuously over this period of time. Analyzing this information would show exactly how the controls work in real operating conditions.

A *ramp-up test* would evaluate the system at set levels throughout its entire range. This would force the system to demonstrate efficient operation for both the expected points of operation and possible future demand, should the load profile change. The construction inspection would include a form to demonstrate expected behavior at each level. One possible ramp-up test would run the system at increments of 10% of total system capacity.

Spot testing would run a system steadily at a single specific level, rather than across a wide range. This would provide a quick check to ensure that the system can operate at some mid-range point efficiently. The test would also offer a degree of freedom to choose which demonstration point to test.

In comparing the three different proposed functional tests, spot testing was chosen for the acceptance test. Proper commissioning, though preferable, is expensive, intrusive, and beyond the scope of a typical acceptance test. Commissioning is important and the CASE Team recommends it for consideration as a future measure, but is not appropriate at this time for smart controls. A ramp-up test is extensive and achieves the goal of testing the full system range but would require exceptions for a few special case compressed air systems that cannot achieve certain points (especially the low end of demand). Isolating these types of systems is difficult. Furthermore, this test still would take significantly more time than a typical acceptance test.

A spot test, as previously mentioned, allows the freedom to choose a convenient demonstration point and avoids potential disruption of sensitive equipment. It is also quick and low cost, but would still provide some assurance that the system is correctly installed and calibrated. If a system cannot at least pass the spot test, something is indeed amiss. Along with a spot test, a couple other checks can be implemented to further confirm that the system is operating properly, namely avoiding short-cycling and blowoff.

The spot check, while not the most comprehensive test, will effectively prevent poor operation and flawed setup without meticulously picking apart a system with a variety of time-intensive and potentially costly tests.

Construction Inspection

The construction inspection should confirm that the system can gather all the information to verify performance and pass the test. This information includes the current state of each compressor in the system and the current state (indicating demand) of the system as a whole. The CASE Team has discovered that different controller products offer various options for measuring the states of the compressors within a system and the system itself. Rather than requiring a specific set of equipment, suggestions are made with the ultimate plan being drafted by the system owner. Again, this allows flexibility for those controllers that already have system testing capabilities built-in, as well as options for more basic models.

Acceptance Test Costs

For the most part, the costs to perform the acceptance test are already built in to the measure costs outlined in Section 3.2.2. The industry quotes used to estimate cost already included labor to set up, test, and calibrate the controls.

3.3 Trim Compressor Requirements

The purpose of a trim compressor is to function well at part loads so that other compressors in the system can operate solely at their optimum performance points, typically fully loaded. This also allows a system to avoid ‘control gaps’ where no combination of compressors can achieve the exact necessary load without forcing one or more into an undesirable state such as short-cycling.

Every compressor can operate well over some range and there are a variety of ways to achieve good performance over a large range. This analysis examines two of the most common: a VSD compressor and increasing the storage for a constant speed load/unload compressor.

3.3.1 Energy Savings

To determine the energy savings of requiring a VSD motor driven compressor as the trim compressor or additional storage in conjunction with the trim compressor, the CASE Team compared the performance of a baseline trim compressor with the proposed trim compressor configurations. Energy savings were calculated using three representative trim load profiles. By focusing on the trim load, the difference between single compressor systems and multi-compressor systems is eliminated.

The following baseline profiles were created based on examples from past utility incentive programs and select energy audits. They are scaled to represent fractions of full load of the trim compressor. Though it is difficult to assume a typical load profile, the profiles were carefully selected to represent two conservative baselines (see Profile B and C in [Figure 3](#)) and a mid-range variability baseline (see Profile A in [Figure 3](#)) to identify both a conservative savings estimate and a more typical savings estimate.

Profiles B and C have been scaled down by 10%. This is to account for oversizing of compressors. Typical practice is to oversize a system beyond the actual demand to ensure safe operation of the system. Stakeholder feedback confirms that 10% oversizing is a conservative figure.

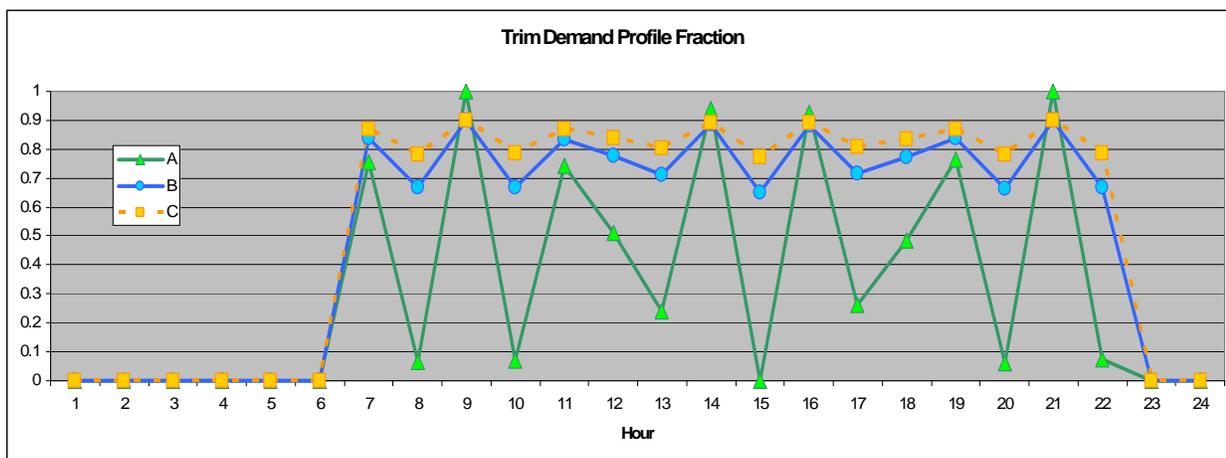


Figure 3: Trim Load Profiles (scaled) for use in energy analysis of trim compressor measures.

Compressor performance curves were used to determine energy use given a certain load. These curves are based off of data used in AirMaster+ for both constant speed compressors and variable speed compressors. For constant speed compressors, storage plays an important role in the performance (see [Figure 4](#)), more closely aligning the energy input to the airflow output as storage is increased. Based on stakeholder feedback and information gathered from utility incentive programs, the CASE Team is

assuming storage of 2 gal/cfm of expected trim load in the base case. That is to say, if a system has an expected base load B and an expected trim load of T , the storage tank size is set at $2T$ gallons.

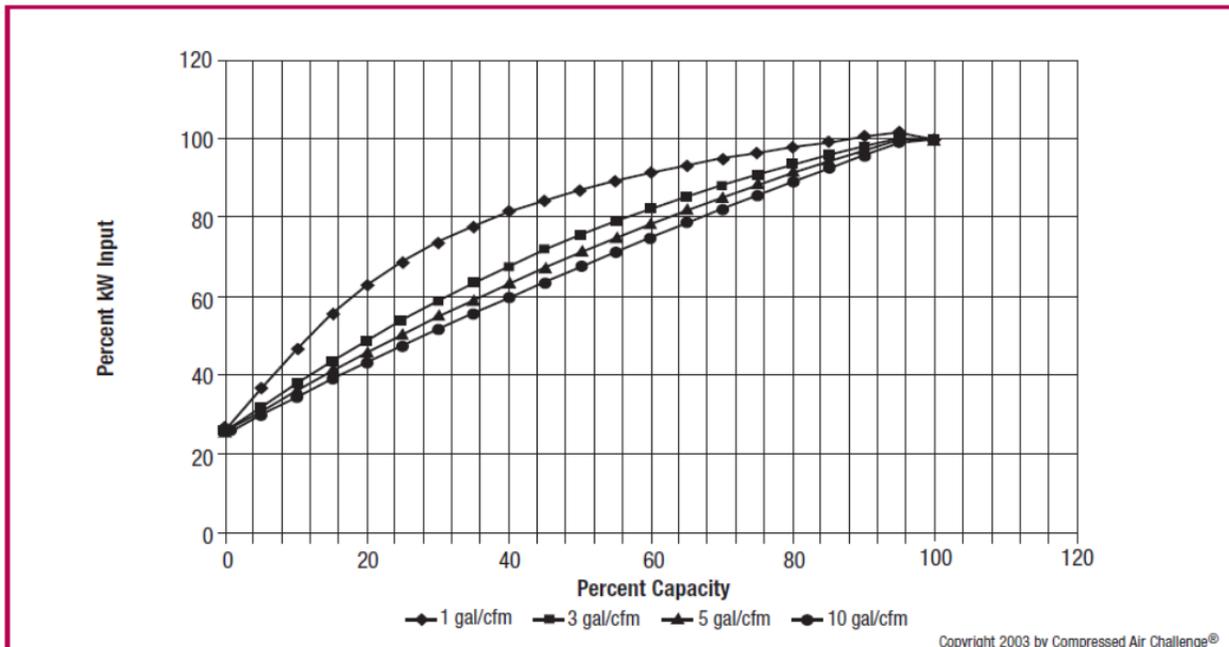


Figure 4: Percentage of energy input vs. capacity for lubricant-injected rotary screw compressors with varying amounts of storage. (CAC Sourcebook, 2003)

Given the expected load and the performance curves, the power (kW) input required by either a rotary screw load/unload or VSD compressor can be calculated for any given point in time. The hourly energy savings is the difference in energy consumption between the load/unload rotary screw (base case) and the chosen trim compressor configuration (either VSD or base case compressor with additional storage). Hourly energy savings are used to find time-dependent valuation savings, as per established CEC methodology.

3.3.2 Costs

Based on the methodology for energy savings, the CASE Team compared the average cost of a load/unload rotary screw compressor with the average cost of a similarly sized VSD motor driven compressor to determine the incremental measure cost. Based on interviews with stakeholders, VSD prices are trending down relative to constant speed compressors. However, to be conservative, this analysis is using the current cost of VSDs rather than forecasting the expected future reduction in VSD price.

[Figure 5](#) shows incremental costs based on original prices and manufacturer-offered discount prices, but for this analysis, the full price costs are considered to continue being conservative. The costs for both types of compressors have been collected from just one manufacturer, but these have been vetted by representatives from other manufacturers and are considered to represent average costs. A trend line has been calculated from this data to show a relationship of VSD costs to horse power. This equation will be used to determine the incremental costs of trim compressors of a specific size.

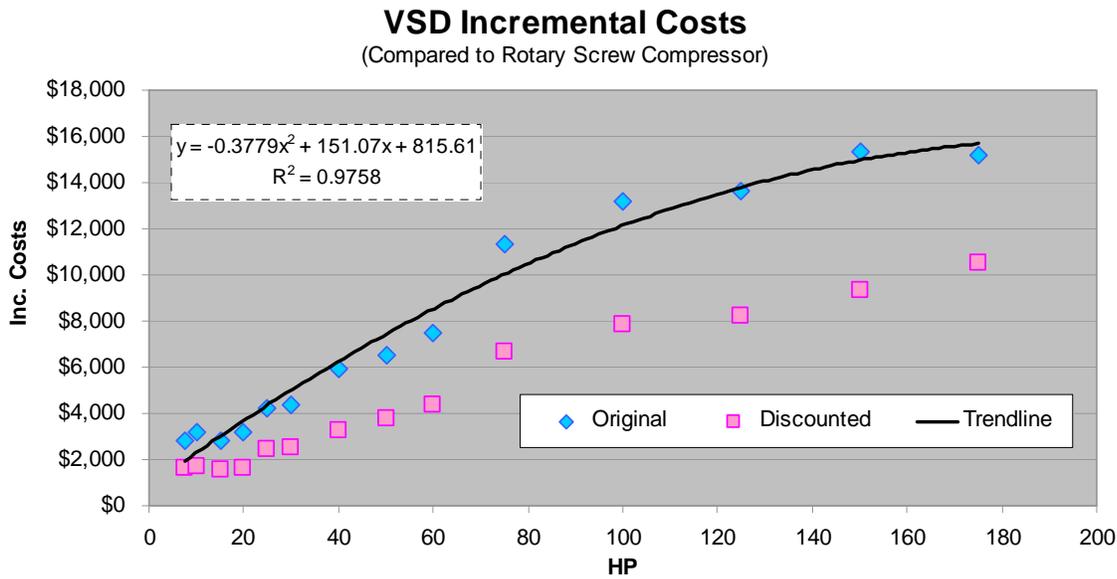


Figure 5: Incremental costs between a VSD compressor and a lubricant injected load/unload rotary screw compressor.

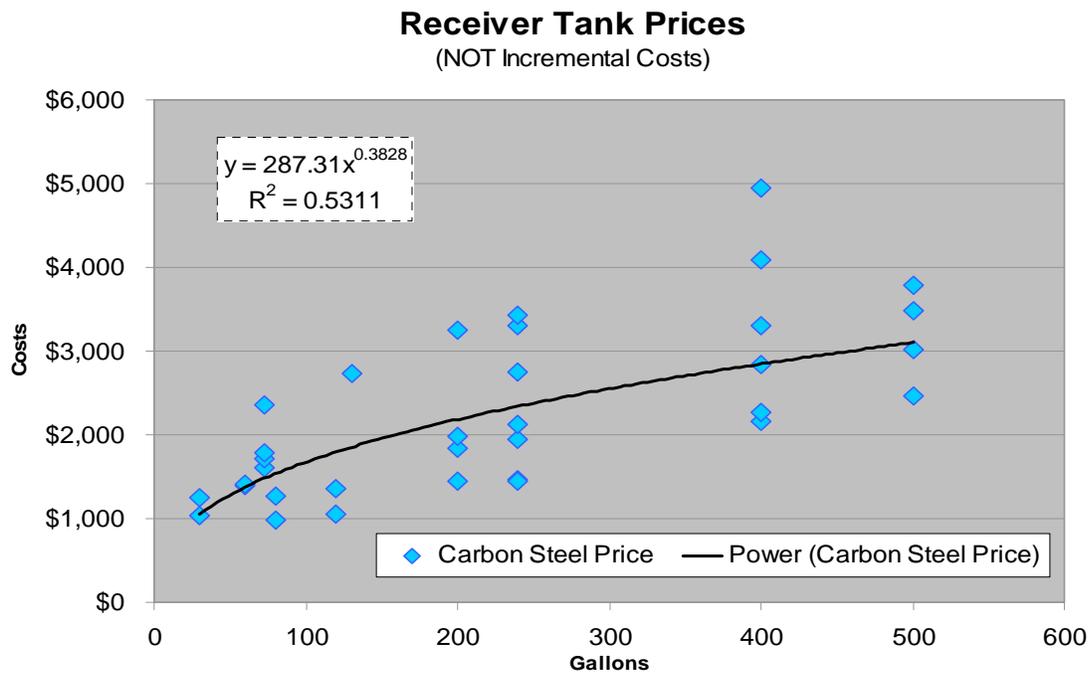


Figure 6: Costs for various carbon steel receiver tanks.

For the alternate compliance option to increase storage, the incremental cost is calculated as the difference between tanks of two different sizes (as the specific compressor used will not change). Similar to incremental VSD costs, a trendline has been calculated to aid in determining the incremental costs. [Figure 6](#) shows the costs (not incremental costs) of receiver tanks. Using the rated

airflow of the given trim compressor and this trendline, approximate incremental costs can be determined between two tanks of a calculated size.

3.3.3 Code Development

The goal of this code proposal is to ensure that control gaps and poor part load performance do not cause poor overall system performance. There are a number of different ways to achieve this and it is not the intent to prescribe a specific technology, but rather to create a structure for evaluating the needs of a system and the ability of specific compressors to meet that need.

System Needs and the “Largest Net Increment”

For any multi-compressor system there is discrete set of loads that can be provided solely by combinations of fully loaded base compressors. It is function of the trim compressor or compressors to fill and bridge between these points so that the system as a whole functions well over a full continuous range. As such it is important to size the trim compressor so that it is large enough to span the largest jump in capacity going from one combination of base compressors to the next. In other words, the trim requirement of a system is equal to the “largest net increment” in the difference in capacity of combinations of the base compressors.

This is a fairly intuitive concept and familiar to anyone working on compressed air system design, but is difficult to express in a precise mathematical fashion. In practice, with multi-compressor systems The CASE Team proposes a simple methodology be included in the compliance manual to guide users in determining the largest net increment for a set of base compressors:

1. Create a list of combinations of base load compressors and their total combined capacities.
2. Sort by total combined capacity.
3. Determine the largest increment between any two adjacent entries in the sorted list.

A summarized example of this is illustrated graphically in [Figure 7](#) and detailed in [Table 3](#). In this case a set of 50, 100, and 250 acfm base compressors have a largest net increment of 100 acfm. A trim compressor that is effective across a 100 acfm range would ensure that the system could function well across its range.

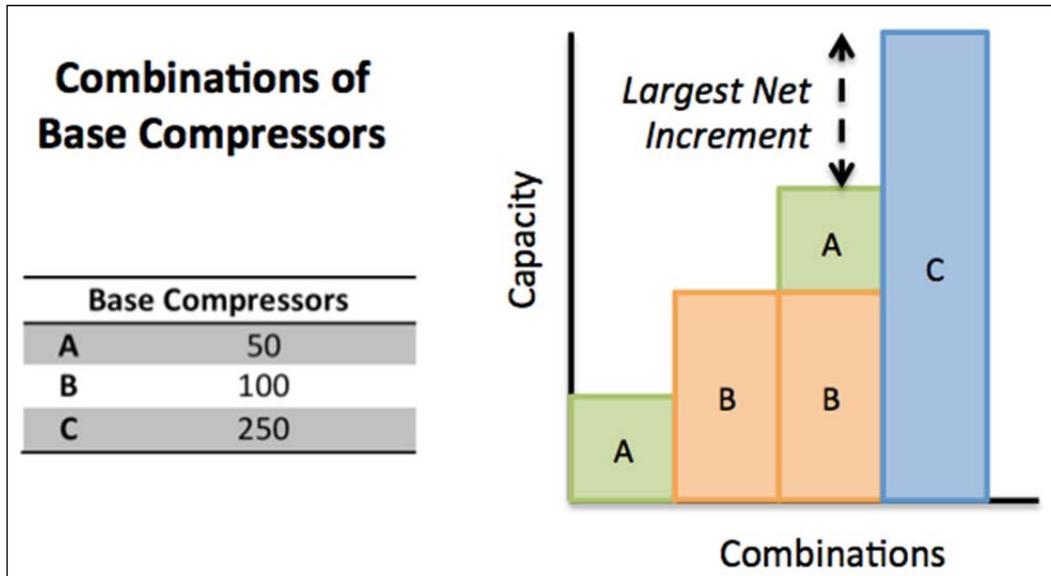


Figure 7: For this example system the Largest Net Increment would be 100 acfm.

Table 3: Ordered combinations of base compressors and the net increment capacity between these combinations.

Ordered Combinations and Net Increment		
Combinations	Net Capacity (acfm)	Net Increment (acfm)
-	0	0
A	50	50
B	100	50
A+B	150	50
C	250	100
A+C	300	50
B+C	350	50
A+B+C	400	50

As described at the beginning of Section 3.3.3, every compressor has some degree of flexibility in operation and output. A methodology is needed to evaluate and compare the efficiency of compressors at various output levels. The CASE Team proposes the use of an “effective trim capacity” metric. This would allow a functional trim output range for an individual compressor to be determined based on its published efficiency curve.

The effective trim capacity of a compressor is the range of outputs where its specific power is within a given percentage of its minimum (most efficient) point.

To determine the effective trim capacity of a compressor, following the steps below. [Figure 8](#) is presented to graphically illustrate this process.

1. Obtain a published efficiency curve from the manufacturer or vendor (typically given as specific power in kW/100 acfm plotted against the output in acfm).
2. Determine the point with the lowest specific power (kW/100 acfm).
3. Multiply that lowest specific power by $1 + N\%$, where $N\%$ is the threshold value that dictates the stringency of the trim performance requirement. This specific power will be the compliance cutoff.
4. Find the continuous set of points below the compliance cutoff on the efficiency curve.
5. The capacity range covered by these set of points is the effective trim capacity of the compressor.

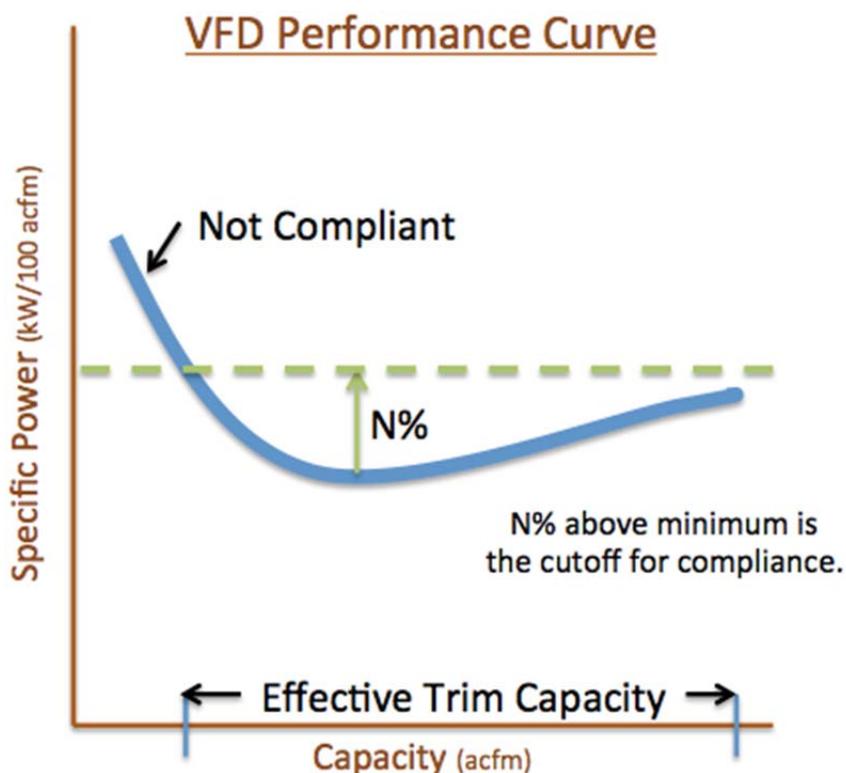


Figure 8: The effective trim capacity of a compressor is the size of the continuous range of outputs for which the specific power of the compressor is within a specified tolerance from its most efficient point.

There are several advantages to this methodology. It does not prescribe or proscribe the use of a particular technology, just a performance requirement. It acknowledges and accounts for the fact that all compressors have some trimming faculty. It evaluates the relative efficiency and ‘flatness’ of the efficiency curve rather than an absolute efficiency so that it can be applied equally well and without prejudice in cases where the end uses demand inherently less efficient compressor technologies (such as applications that require very high pressures or very low impurity levels). It allows the stringency of the requirement to be updated over time by reducing the threshold value, but without changing the underlying structure of the methodology.

One possible disadvantage to this methodology is its reliance on published efficiency curves. Efficiency curves of this type are currently published for many variable speed drive compressors, but not typically for other compressor types. Additionally the efficiency curves for some compressor types such as load/unload are highly dependent on the amount of primary storage available. For these compressors the storage used in the test would have to be published as well. This is a reasonable tradeoff because compressors that meet the requirements can currently be found on the market without difficulty, the barrier to entry for compressors that do not currently publish their efficiency curves is relatively low, and the increase in published efficiency data will benefit the users.

To determine the threshold value to use in this round of regulation, current market data for variable speed drive compressors was examined, as well as standard model for a load/unload compressor at several storage levels. VSDs appear to be becoming a standard solution for trim requirements and load/unload compressors with adequate storage represent a possible alternative when a moderate amount of trim capacity is needed. The CASE Team proposes that a performance threshold of 15% above the minimum specific power will best meet the goals of the measure.

Figure 9 displays the published efficiency curves for typical VSD compressors from three different manufacturers normalized relative to their total capacity and minimum specific power. Several sizes are included, as are both oil flooded and oil free compressors and both air-cooled and water-cooled models. The 15% threshold is called out to show the cutoff point for effective trim.

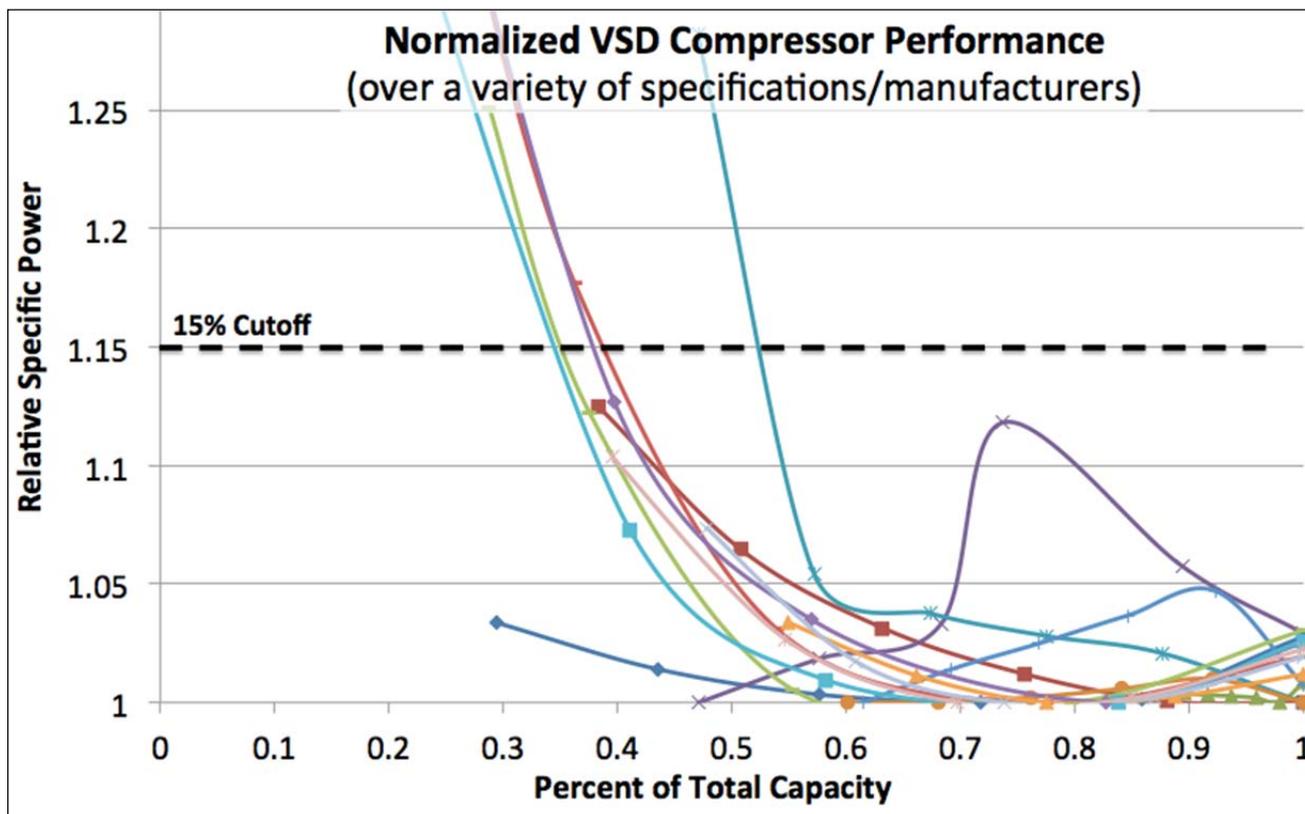


Figure 9: VSD performance curves for a number of models in the market. The curves have been normalized against the rated max capacity and minimum specific power for each compressor.

At this cutoff point all of the VSDs sampled are effective trim compressors for at least 40% of their total range, and some are efficient for 60% or more. It is likely that several of the VSDs effectively trim beyond the data points currently provided by the manufacturer. If this measure is adopted, the manufacturers could publish more of the curves to demonstrate the full potential of their compressors.

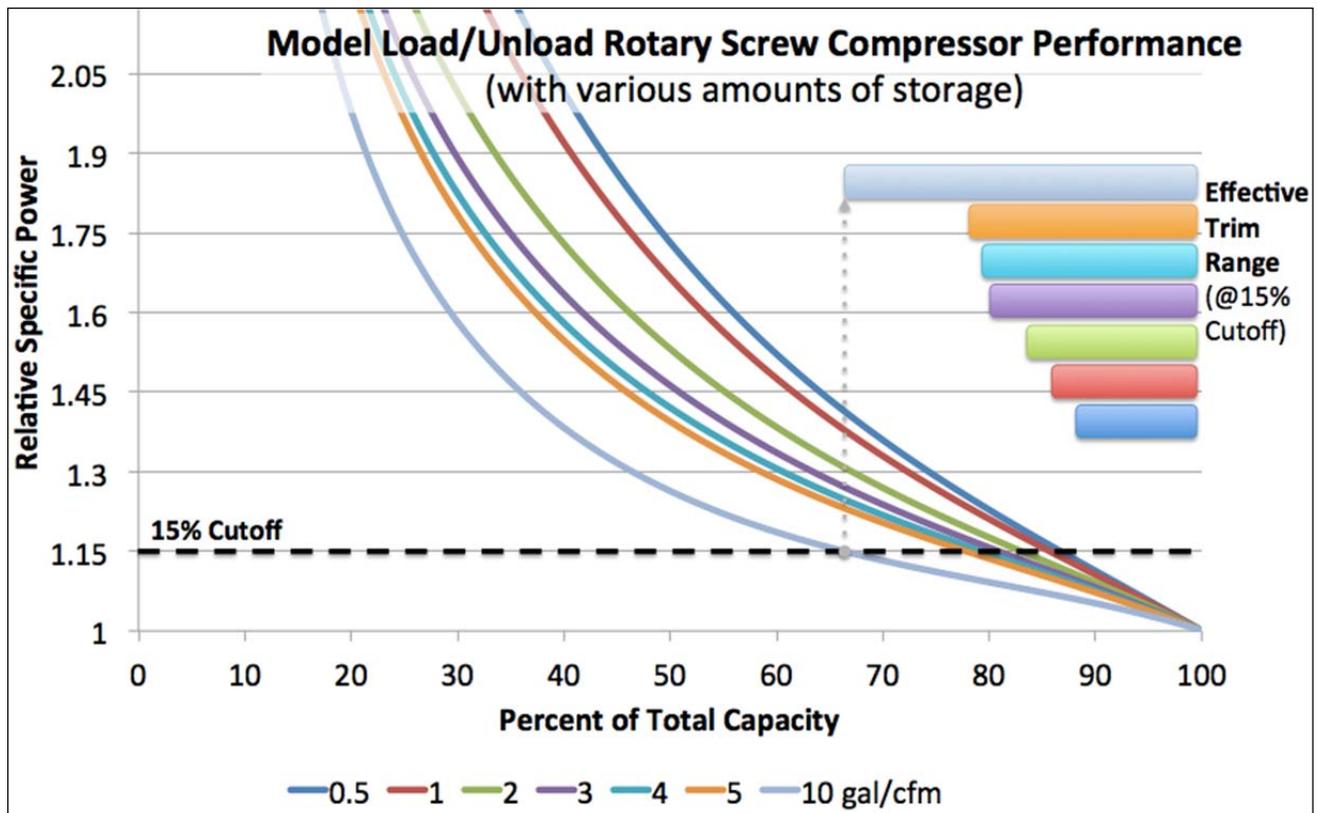


Figure 10: The normalized efficiency curves for a model (CAC Sourcebook, 2003) load/unload compressor at varying storage levels.

The same data for a model load/unload compressor from the Compressed Air Challenge shown in [Figure 4](#) can be redrawn in terms of specific power versus percent capacity, see [Figure 10](#). The 15% is again shown to illustrate the effective trim cutoff. A manufacturer could publish data such as this to demonstrate the trim capabilities of other non-VSD compressors. This generic load/unload compressor could be an effective trim in some scenarios, particularly if ample storage is used. Manufacturers wishing to improve the trim capacity of such a compressor could utilize strategies such as including a shutdown timer with a short fuse or improving the unloaded power use, and republishing the curves.

Matching Trim Capacity to System Need

By selecting a trim compressor with an effective trim capacity at least the size of the largest net increment of the base compressor combination, a system designer can go a long way toward ensuring that a system will perform well across its full range.

An alternative considered for sizing trim would be to base it on the varying trim demand of the end uses of the system. However, this approach requires (currently quite uncommon) extensive long term system monitoring to establish an accurate picture of the varying demand for most systems. New systems can only be expected to accurately estimate their varying demand in practice if they are near identical copies of well characterized existing systems. Furthermore nearly every system changes significantly over the course of its useful life as equipment is added or removed, production levels change, leaks develop, etc. It is far better practice to design a robust system than to design to demand projections that are unlikely to be accurate from the beginning and highly likely to change in unexpected ways over time.

There does remain an unresolved issue of how to address single compressor systems. It is not feasible to require that a single compressor system have a flat efficiency curve across its entire range. At the same time, part load efficiency still has as great an impact on power consumption. Additionally, the CASE Team does not wish to unintentionally push the market toward large single compressor systems.

The question of single compressor system trim requirements requires continued consideration. One possible solution is as follows: For single compressor systems the trim requirement could simply be a set portion of the capacity of the compressor. Furthermore, the CASE Team proposes that portion be 30% of the rated compressor capacity. This trim requirement attempts to strike a balance between efficiency and availability and other practical considerations.

Storage Requirements

When presenting trim requirement proposals to industry, one of the most common pieces of feedback the CASE Team received was that in actual practice, even an effective trim compressor such as a VSD requires a reasonable amount of primary storage to function well. A common industry standard is a bare minimum of 2 gallons per acfm of trim load. In the case of these requirements that would be 2 gallons per acfm of the trim compressor's largest net increment.

It is recommended that minimum storage be included as part of the trim requirement. Additional savings and costs for this storage are not included in the savings calculations because this is taken to be the current industry standard and included as part of the base case. It is, however, still important to include in the requirements because the industry standards are not always followed. The storage requirement does not improve expected trim performance significantly, but is in place to ensure that the system is not highly compromised.

Existing Systems

For retrofits of existing systems, stakeholders have raised concerns that because of possible physical factory floor constraints, the potential significant space requirements needed for one or more new compressors and especially for added storage tanks may prove an undue burden.

The CASE Team proposes a compromise granting exceptions to existing systems provided they are altering less than 50% of the total capacity of their system. That is to say, adding or replacing compressors with total combined capacity less than 50% the total combined capacity of the existing compressors. Systems undergoing more substantial alterations will already require extensive modifications to the space and are more certain to be able to accommodate these requirements.

3.4 Statewide Energy Savings

The statewide energy savings associated with the proposed measures will be calculated by multiplying the per unit estimate for each scenario (from the controls measure) by the new construction rate for each scenario in 2014. Once stakeholder input is incorporated, the details on the method and data source of the new construction forecast will be presented here.

4. Analysis and Results

4.1 Smart Controls

4.1.1 Energy Savings

Savings analyses were performed on the four baseline systems both with and without the assumption of auto-shutdown timers on the individual compressors. When a compressor with an auto-shutdown timer has been in the unloaded state for a preset period of time, the compressor is fully shut down. In this case the auto-shutdown timers were assumed to be set for a relatively short period of time (half an hour or less), though longer times are common. In the end, assuming systems without auto-shutdown timers was judged not sufficiently conservative, and only the cases including them were used for the final analysis. The results from the cases without auto-shutdown timers do, however, provide a good example of the markedly greater savings that can be realized with a single deviation from the most conservative case. As detailed in Section 3.2.1, the results presented below are the most conservative savings estimates that could be expected from compressed air systems.

By comparing the energy use found from AirMaster+, the annual savings (in kWh) were found for each baseline. These annual savings were multiplied out over 15 years. This was then weighted to find the 15 year benefit to society (both in kBtu and monetary benefit).

Table 4: Energy savings for implementing smart controls on 4 baseline systems. Italicized values will be used in cost-effective analysis.

	Baseline 1 2 compressors 125 hp total		Baseline 2 2 compressors 200 hp total		Baseline 3 2 compressors 450 hp total		Baseline 4 3 compressors 800 hp total	
Auto-shutdown Timer in Base Case?	no	yes	no	yes	no	yes	no	yes
Total Annual Savings (kWh)	31,738	8,788	27,890	4,940	74,048	7,025	197,733	25,812
Total 15 Year Savings (kWh)	476,072	131,817	418,355	74,100	1,110,725	105,380	2,965,991	387,180
Total 15 Year TDV (\$) Savings	\$67,941	\$18,812	\$57,523	\$8,395	\$155,499	\$12,026	\$418,515	\$48,832

4.1.2 Costs

The incremental costs for each baseline system are summarized in [Table 5](#). As mentioned in the previous section, these costs are based on estimates from controls manufacturers and averaged.

Because incremental costs are driven by the number of components within a system, the first three baselines (all 2 compressor systems) have the same incremental costs.

Table 5: Incremental costs for smart controls, averaged.

	Baseline 1	Baseline 2	Baseline 3	Baseline 4
Incremental Costs	\$6,173	\$6,173	\$6,173	\$10,159

4.1.3 Cost Effectiveness

By comparing the incremental costs and energy savings, the 15-year life-cycle cost savings were found. [Table 6](#) shows that all 4 baseline systems are found to be cost-effective.

Table 6: Cost Effectiveness analysis.

Baseline	Incremental Costs	Energy Cost Savings (TDV\$)	LCC Savings	Benefit/Cost Ratio
System 1	\$6,173	\$18,812	\$12,639	3.05
System 2	\$6,173	\$8,395	\$2,222	1.36
System 3	\$6,173	\$12,026	\$5,836	1.95
System 4	\$10,159	\$48,832	\$38,673	4.81

4.2 Trim Compressor Requirements

4.2.1 Energy Savings

By comparing the energy use found from modeling runs in AirMaster+, the annual savings (in kWh) were found for a variety of trim compressor configurations and three different demand profiles. These annual savings were multiplied out over 15 years, then weighted to find the present value 15 year benefit (both in kBtu and monetized benefit to society), using the CEC-approved Time Dependent Valuation (TDV) methodology. This is graphed in [Figure 11](#) and [Figure 12](#) for both VSD compressors and increased storage.

For the smallest compressed air system, the annual energy savings range from 8,293 kWh to 19,669 kWh, which is dependent on how variable the trim load is. The minimum savings assumes a 25 hp compressed air system with a fairly constant load operating below 10% of full load of the trim compressor. The fairly constant load is a conservative assumption and the savings are likely closer to the mid and high end of the energy savings range (>13,000 kWh/yr). These savings scale proportionally as the size of the trim compressor increases.

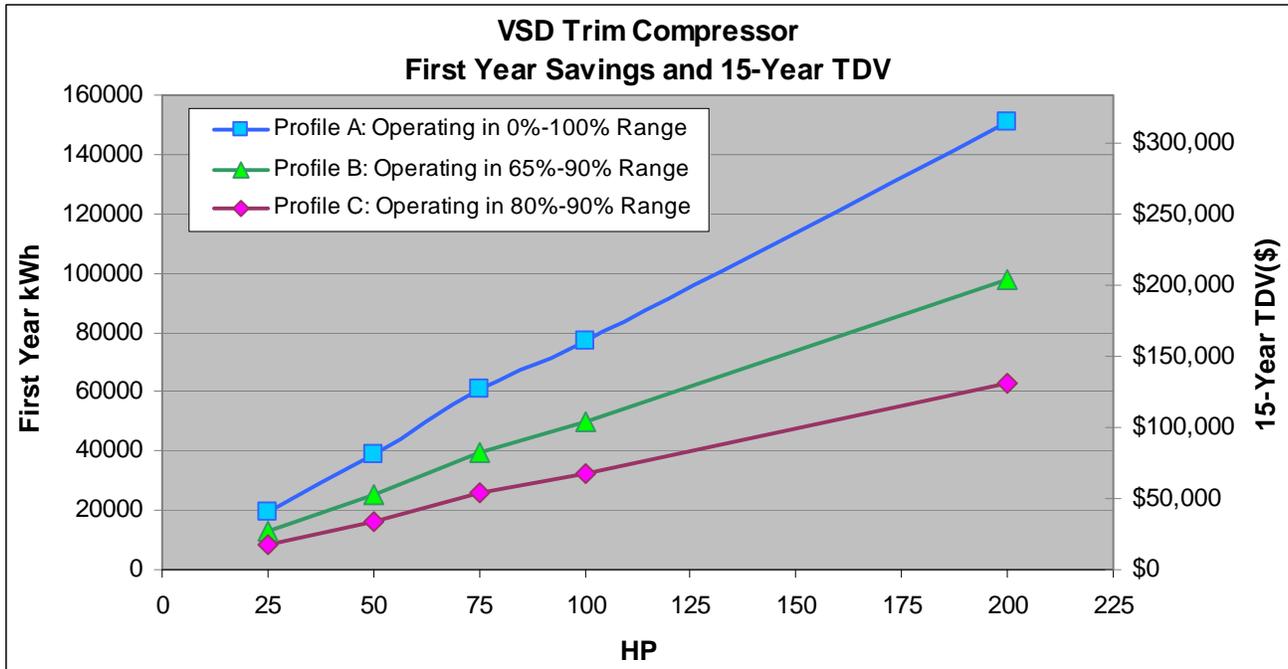


Figure 11: First-year energy savings and 15-year TDV \$ savings from replacing the constant speed trim compressor with a VSD compressor.

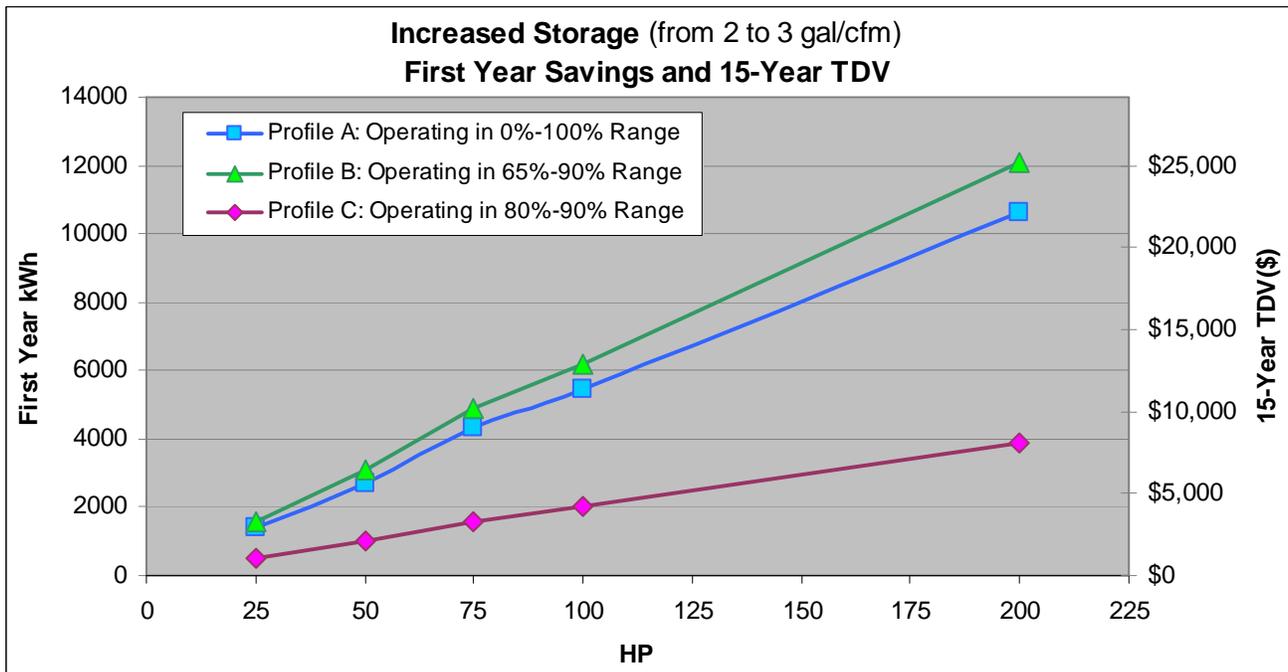


Figure 12: First-year energy savings and 15-year TDV \$ savings from increasing storage (2 gal/cfm to 3 gal/cfm).

4.2.2 Costs and Cost Savings

Using the trend-line equations formulated from the incremental costs gathered, the following shows the incremental costs used for the cost effectiveness analysis.

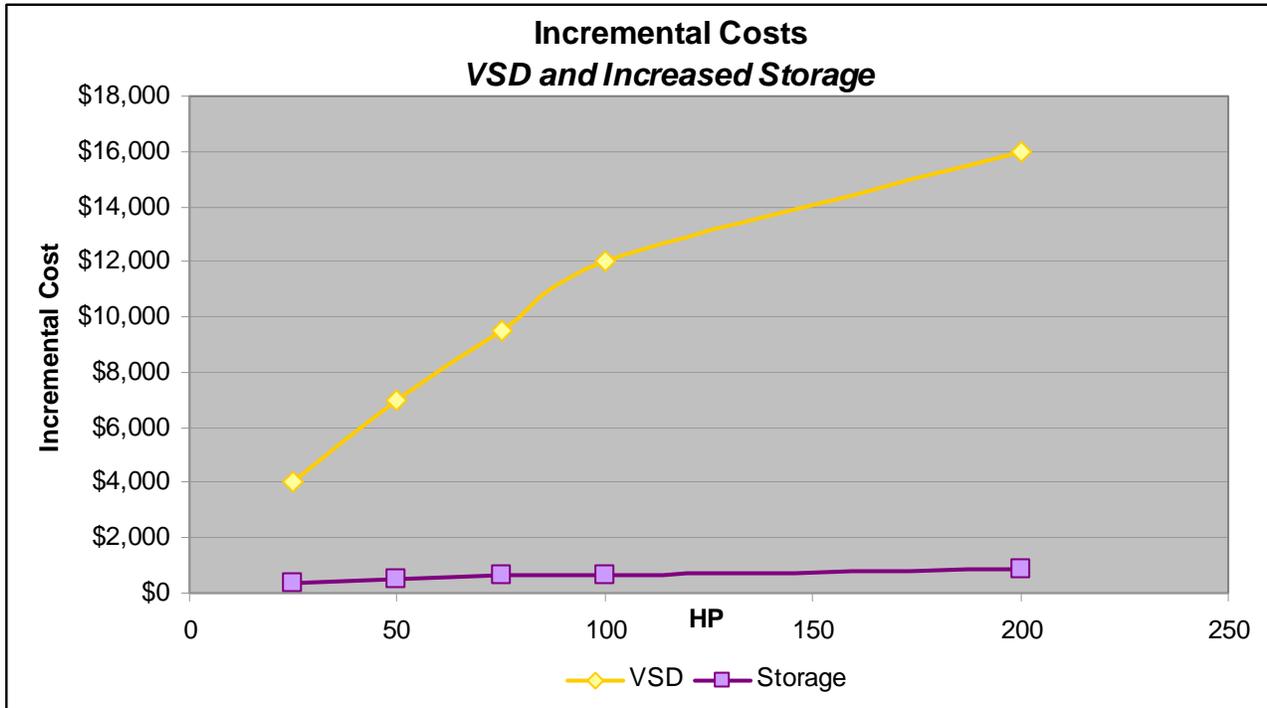


Figure 13: Incremental costs for VSD compressors and increased storage.

4.2.3 Cost Effectiveness

The life cycle cost savings are shown below, comparing the incremental cost of each system and the TDV savings. This shows both options to be cost-effective, though the savings resulting from the VSD option is an order of magnitude higher than increased storage. Based on the results of this analysis and stakeholder feedback, the CASE Team is proposing to require part load performance comparable with expected VSD levels. Other mechanisms such as increased storage may be used, but only to the extent that they can provide comparable part load efficiencies.

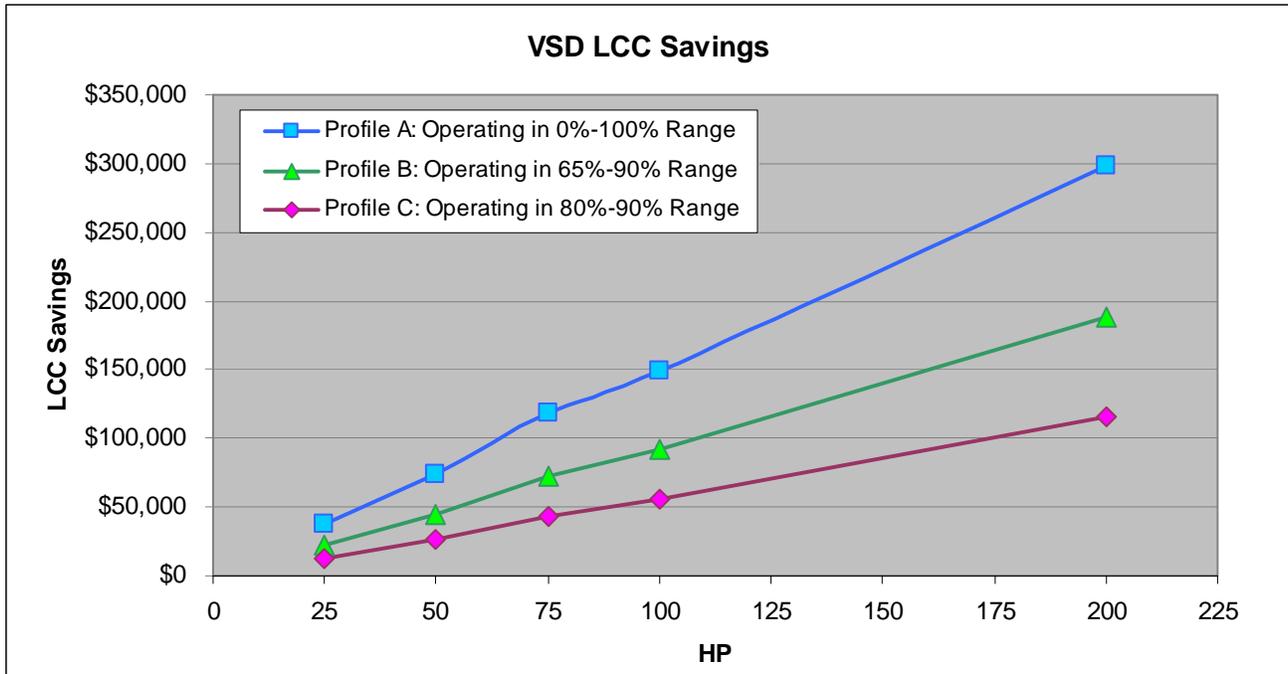


Figure 14: LCC Savings for VSD Trim Compressor

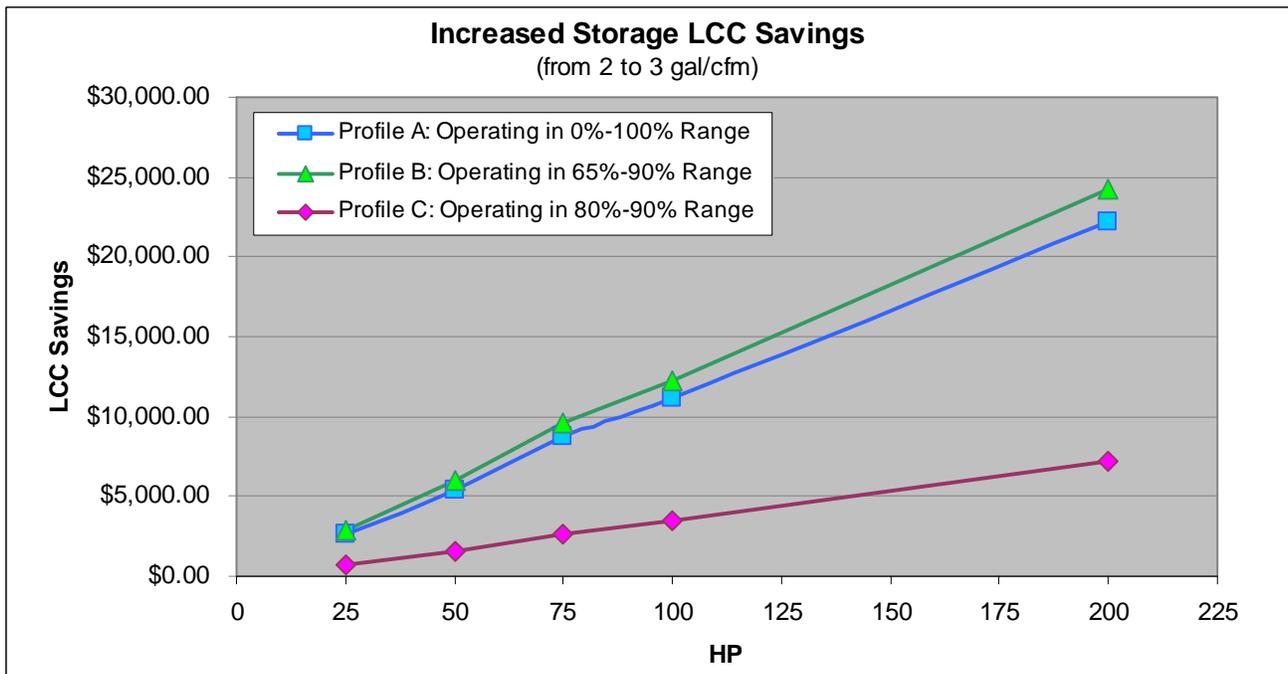


Figure 15: LCC Savings for Increased Storage

4.3 Statewide Savings Estimates

As mentioned in section 3.4, the statewide savings still require further investigation. This section will be updated once a method and data sources are finalized.

5. Recommended Language for the Standards Document, ACM Manuals, and the Reference Appendices

As this is a new area of Title 24, the majority of the recommended language will be new code rather than a code change. To address the measures noted in the previous section, the CASE Team is recommending the following language in the standards document.

5.1 NR Mandatory Equipment

SECTION 120.6 (e)– MANDATORY REQUIREMENTS FOR COMPRESSED AIR SYSTEMS

All new compressed air systems where the total combined horsepower (hp) of the online compressor(s) is 25 hp or more shall meet the requirements of this Section.

(1) **Trim Compressor and Storage Requirements.** Compressed air systems with more than one compressor shall include a compressor or set of compressors with total effective trim capacity at least the size of the largest net increment between combinations of base compressors. Single-compressor systems shall have a total effective trim capacity of at least 30% of the rated compressor capacity. The systems shall also include primary storage of at least 2 gallons per actual cubic feet per minute (acfm) of the required trim capacity.

(2) **Controls Requirements.** Compressed air systems with more than one compressor and having a combined horsepower rating of more than 100 hp, must operate with an approved controller that is able to choose the most energy efficient combination of compressors within the system based on the current air demand as measured by a sensor. The approved controller shall pass acceptance testing specified in NA7.9.1.

(3) **Compressed Air System Acceptance.** Before an occupancy permit is granted for a compressed air system subject to 120.6(e), the following equipment and systems shall be certified as meeting the Acceptance Requirements for Code Compliance, as specified by the Reference Nonresidential Appendix NA7. A Certificate of Acceptance shall be submitted to the enforcement agency that certifies that the equipment and systems meet the acceptance requirements specified in NA 7.13.

5.2 NR Additions Alterations Repairs

SECTION 141.x (x)– MANDATORY REQUIREMENTS FOR COMPRESSED AIR SYSTEMS

All supply side alterations (excluding air treatment equipment and maintenance) in systems where the total combined horsepower (hp) of the online compressor(s) is 25 hp or more shall meet the requirements of this Section.

(1) **Trim Compressor and Storage Requirements.** Compressed air systems with more than one compressor shall include a compressor or set of compressors with total effective trim capacity at least

the size of the largest net increment between combinations of base compressors. Single-compressor systems shall have a total effective trim capacity of at least 30% of the rated compressor capacity. The systems shall also include primary storage of at least 2 gallons per actual cubic feet per minute (acfm) of the required trim capacity.

EXCEPTION to Section 120.6(e)(2): Compressed air systems in existing facilities that are altering less than 50% of the total online capacity of the system.

(2) **Controls Requirements.** Compressed air systems with more than one compressor and having a combined horsepower rating of more than 100 hp, must operate with an approved controller that is able to choose the most energy efficient combination of compressors within the system based on the current air demand as measured by a sensor. The approved controller shall pass acceptance testing specified in NA7.9.1.

(3) **Compressed Air System Acceptance.** Before an occupancy permit is granted for a compressed air system subject to 120.6(e), the following equipment and systems shall be certified as meeting the Acceptance Requirements for Code Compliance, as specified by the Reference Nonresidential Appendix NA7. A Certificate of Acceptance shall be submitted to the enforcement agency that certifies that the equipment and systems meet the acceptance requirements specified in NA 7.13.

5.3 Compliance

SECTION NA7.9.1 – COMPRESSED AIR SYSTEM CONTROLS ACCEPTANCE TEST

Construction Inspection

Prior to functional testing, compressed air system with 2 or more air compressors must verify and document the following:

- Rated horsepower, rated capacity, and control type of each air compressor
- Total online system capacity (the sum of the individual capacities)
- System operating pressure
- Compressor(s) designated as trim compressors
- Method and tools for observing and recording the states of each compressor in the system, which shall include at least the following mutually exclusive states:
 - Off
 - Unloaded
 - Partially loaded
 - Fully loaded

and the presence of the following behaviors:

- Short cycling (loading and unloading more often than once per minute)
- Blow off (venting compressed air at the compressor itself)
- Method and tools for measuring the current air demand as a percentage of the total system capacity, including any necessary calibrations.

Functional Testing

Step 1: Per the test methods outlined in the Construction Inspection, verify that these methods have been employed, so that the states of the compressors and the current air demand can be observed and recorded during testing.

Step 2: Run the system steadily (at as close to a constant load as can be practically implemented) at a mid-range point, between 50% and 85% of total system capacity, for a duration of at least 10 minutes.

Step 3: Observe and record the states of each compressor and the current air demand during the test.

Step 4: Confirm that the combinations of compressors states meet the following criteria:

- No compressor exhibits short-cycling.
- No compressor exhibits blowoff.
- For new systems, the trim compressors shall be the only compressors partially loaded, while the base compressors will either be fully loaded or off by the end of the test.

In addition to the new code in these sections, the CASE Team recommends the following definitions be added to Section 101(b).

TRIM COMPRESSOR: compressor that is designated for part-load operation, handling the short term variable trim load of end uses, in addition to the fully loaded base compressors

SPECIFIC POWER: is the ratio of the power input into an air compressor to the 100 cubic feet per minute of air delivered at actual pressure (kW/100 acfm).

EFFECTIVE TRIM CAPACITY: is the (continuous) range for which the specific power is 115% of the minimum specific power or less of the trim compressor.

LARGEST NET INCREMENT: is the largest increase in capacity when switching between combinations of base compressors that is expected to occur under the system control scheme.

PRIMARY STORAGE: is compressed air storage located between the compressors and pressure regulating equipment, such as a pressure-flow controller.

6. Bibliography and Other Research

6.1 Annotated Bibliography

Compressed Air Challenge, and Tom Taranto. DOE - CAC Qualified AIRMaster+ Specialist Participant Workbook. Washington, D.C.: DOE, 2001.

Compressed Air Challenge, and Ron Marshall. "VSD Compressor Control." *AirBestPractices.com*. Ed. Bill Scales. Compressed Air Challenge, Mar. 2011. Web. June 2011. <<http://www.compressedairchallenge.org/library/articles/2011-03-CABP.pdf>>.

Lawrence Berkeley National Laboratory, and Resource Dynamics Corporation. Improving compressed air system performance: a sourcebook for industry. Washington, D.C.: Industrial Technologies Program, U.S. Dept. of Energy, Energy Efficiency and Renewable Energy, 2003.

McKane, Aimee. "Creating a Standards Framework for Sustainable Industrial Energy Efficiency." *Energy Efficiency in Motor-Driven Systems* (2005).

Xenergy, Inc. Assessment of the market for compressed air efficiency services. Washington, D.C.: Office of Industrial Technologies, Office of Energy Efficiency and Renewable Energy, U.S. Dept. of Energy, 2001.

6.2 Stakeholder Feedback

The following table is a list of stakeholder feedback that was received throughout this process and the response from the CASE Team to address these concerns. Some of these concerns will require additional feedback throughout this process.

Stakeholder Feedback	CASE Team Response
1. There are numerous energy efficiency measures that can be implemented. Not all are applicable to every system.	The CASE Team listed out all the energy efficiency measures and took into consideration both energy savings potential (and cost effectiveness), and feasibility for Title 24 code compliance and enforcement.
2. The market is varied and a typical system does not exist. It will be difficult to model energy savings without a proper baseline.	Originally, the CASE Team addressed this concern by creating a number of baseline systems that were very different in an attempt to capture the majority of the market. In moving forward, the CASE Team decided to instead use systems that would have a conservative amount of savings for both measures. The CASE Team also shared the proposed baselines with stakeholders and incorporated significant feedback before proceeding with savings analysis.

<p>3. Smart controls do not save energy for systems with a constant load profile.</p>	<p>From various sources, the CASE Team has determined that systems that have loads so constant that the system would not benefit from a smart controls measure would be extremely rare. Furthermore, even for systems that are sized exactly to the load when new, load profiles almost always change over time and having smart controls allows system operators to continue to maximize efficiency.</p>
<p>4. VSDs are not cost-effective for systems with a constant load profile.</p>	<p>As mentioned previously, there are few load profiles that are very constant. Furthermore, feedback from industry stakeholders suggests that compressors are almost always slightly oversized, to avoid system failure. As VSDs are more efficient during part load operation, there will be energy savings for the vast majority of systems. Finally, the CASE Team also considered adding an exception to the VSD requirement by giving the option of adding more storage in lieu of installing a VSD. In response to additional stakeholder input (addressed below), the CASE Team decided against allowing this option.</p>
<p>5. Leaks are a large opportunity for energy savings.</p>	<p>The CASE Team agrees that this is a large opportunity, but also that the largest energy savings are from fixing leaks in an existing system. It is difficult to assume more than a certain percentage of leakage will exist within a system at the time of new construction.</p>
<p>6. Increased storage should not be a comparable (or available) option in place of requiring a VSD compressor. There is also concern about this providing a loophole.</p>	<p>This feedback was taken into account and increased storage is no longer being proposed.</p>
<p>7. Increasing storage alone will not result in energy savings. Additional controls are needed for the system to actually utilize the storage. Sump unloading is more important.</p>	

<p>8. Spiral Valve control is more efficient at a higher range as compared to VSDs. Why not require this as an option in place of VSDs?</p>	<p>Based on research done with major compressor manufacturers, it seems that this technology is not widely available from many manufacturers. However, requiring a set of specifications for a trim compressor in lieu of requiring a specific technology allows owners the flexibility to install a trim compressor that accomplishes the same thing as a VSD.</p>
<p>9. Definitions need to be explicit for a compressed air system, trim compressor, and standard automation protocol.</p>	<p><i>Compressed air system</i> definition needs to incorporate the intricacies of what a system means. If the CASE Team is not careful about how this is defined, this could lead to undesirable system design.</p> <p><i>Trim compressor</i> was equally important to define, when the storage option was being considered. This is not as important now.</p> <p><i>Standard automation protocol</i> was included in the code language to address the requirement of having a controller that worked with compressors of various types and from various manufacturers. This was included so an owner was not tied to a specific vendor in the future for when an expansion would occur. Stakeholder feedback confirms that this is not a big issue and this has been dropped from the current code language.</p>
<p>10. How will this code change language affect booster compressors?</p>	<p>The CASE Team is investigating this issue, as the current code language would require controls on these booster compressors.</p>

7. Appendices

7.1 *Alternate Recommended Language for the Standards Document, ACM Manuals, and the Reference Appendices*

The following is alternate wording for the recommended language in 120.6 (e)(1). The intent behind this alternate wording is to show a different approach to presenting the same information. Instead of defining the effective trim capacity, the definition is laid out in 120.6 (e)(1).

(1) **Trim Compressor and Storage Requirements.** Compressed air systems with more than one compressor shall include a compressor or set of compressors that shall maintain a specific power of 115% of the minimum specific power or less for a continuous range of at least the size of the largest net increment between combinations of base compressors. Single-compressor systems shall maintain a specific power of 115% of the minimum specific power or less for all loads above 70% of full load. The systems shall also include primary storage of at least 2 gallons per actual cubic feet per minute (acfm) of the required trim capacity.

In addition to the new code in these sections, the CASE Team recommends the following definitions be added to Section 101(b).

TRIM COMPRESSOR: compressor that is designated for part-load operation, handling the short term variable trim load of end uses, in addition to the fully loaded base compressors

SPECIFIC POWER: is the ratio of the power input into an air compressor to the 100 cubic feet per minute of air delivered at actual pressure (kW/100 acfm).

LARGEST NET INCREMENT: is the largest increase in capacity when switching between combinations of base compressors that is expected to occur under the system control scheme.

PRIMARY STORAGE: is compressed air storage located between the compressors and pressure regulating equipment, such as a pressure-flow controller.