A systems approach: Evaluating and meeting large intermittent compressed-air demands

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Does a ceramics processing plant really need another air compressor to meet large intermittent compressed-air demands from its dense-phase conveying systems, or is there a better solution? In this article, a compressed-air consultant and DOE Qualified Energy Expert describes his step-by-step approach in evaluating this compressed-air system’s supply and demand sides to help the plant engineer answer this question. The approach can be applied to solving similar problems in other bulk solids plants. A related sidebar covers information about the Compressed Air Challenge, a nonprofit organization that helps users improve compressed-air system performance and cost efficiency.

On Brian’s first day as plant engineer in a Georgia ceramics processing plant, he found a proposal on his desk to purchase a 150-horsepower rotary screw air compressor. The plant already had six of these compressors to supply the plant compressed-air system, and all the compressors ran almost continuously. The system powered dense-phase conveying systems and other pneumatic equipment throughout the plant; some air from the system was also used as instrument air. The new compressor would replace a rental compressor that was already onsite as a backup in case one of the six permanent compressors failed.

From Brian’s previous work with my company to match another plant’s compressed-air supply to demand, he recognized that nowhere did this proposal state that the existing six compressors were being used efficiently. Nor did it identify the problem the new compressor would solve. The proposal contained just one mention of the plant air system’s symptoms: Not only did all the compressors run continuously, but the supply air pressure was unstable, fluctuating by as much as 25 psi.

The cause wasn’t clear: It could be on the demand side or in the compressor controls, or the problem could simply be a lack of capacity. Brian suspected that if he could understand the underlying problem, he could use the existing compressors more efficiently, allowing one to be turned off and used as a backup for the other five and eliminating the need to buy a new compressor. Brian contracted me for help assessing the unstable pressure problem so he could determine whether buying a new compressor was the right solution.

Gathering data

We needed more data to thoroughly understand how compressed air was being applied in the plant. The proposal for the new compressor included data that showed the amps used by each existing compressor, with a separate trend line for each. This information showed that all compressors remained online continuously (or nearly so), but that several compressors were simultaneously running at part load, indicating inefficient operation. My guess about why this happened was that production events in the plant created significant demand peaks that caused all six compressors to load. Then when the events ended, some compressors would unload and run unloaded until the next event occurred.
However, no one in the plant knew why the air demand peaked at certain times or even if such peaks existed. How much air volume was involved? What did the airflow's profile — that is, its rate and magnitude of change — look like? What was the maximum airflow rate? How long did the events triggering the demand peaks last? What actual air pressure did production require? My goal was to provide Brian with a clear picture of the plant’s production needs so he could decide how to solve the problem.

The first step was to measure airflow in the system. Why? Compressors make air. Production demands air. To make sure that the air supplied by the compressors could meet production demand, we needed to measure the airflow through the system. My training has taught me that measuring actual airflow gives the most accurate results. However, we could obtain similar information from compressor kilowatt usage, amps, or pressure data, or by correlating airflow to compressor load-unload cycle times using the DOE’s AirMaster+ software (for more information on this software, see the sidebar “Compressed Air Challenge: Helping plants improve compressed-air system performance”).

Measuring demand-side airflow. I started at the 8-inch-diameter main air line leading from the compressor room, hot-tapping the line (making a hole in it while the system was operating) so I could temporarily insert a thermal mass flow meter and pressure transmitter into it. This flow meter is a single-point instrument — that is, it measures airflow at a single point near the line’s center and applies an algorithm to compensate for the air velocity profile (variations in air velocity across the line’s cross section).

I collected data continuously with the flow meter and pressure transmitter and fed the instruments’ output through a PLC into a laptop computer that used system control and data acquisition (SCADA) software to display and record the data. Later, I transferred the data to a spreadsheet for...
analysis, dividing the data into 12-hour blocks, with sampling at 5-second intervals, to simplify charting the results.

The results were a real eye-opener. Parts of the air demand trend line looked like the blue plot line in Figure 1. Changes in the demand airflow rate that exceeded the capacity of two compressors occurred in just seconds. In the figure, the airflow demand increased by 1,300 scfm in 15 seconds (between 34.45 and 35.00), doubling in less than 3 minutes (between 32.30 and about 35.00 minutes). These results made it obvious that we needed to examine the demand side to correlate production events with these airflow changes.

**Finding the source of demand peaks.** By comparing my airflow data with the on-off cycles of the plant’s dense-phase pneumatic conveying systems, I was able to see how much airflow was needed to cycle each system. (During each conveying cycle, plant air was required not only to refill [or pad] the pressure tank [or transporter] but to provide supplementary air for the system’s air boosters; in fact, the boosters created a greater air demand than refilling the pressure tank because they helped push the material through the conveying line.) While knowing how much airflow the conveying systems needed would be useful later to help manage the conveying air demand, it also revealed something we hadn’t known before: The demand peaks were significant, increasing by as much as 2,500 scfm, but just 60 to 90 seconds long.

In fact, the data showed that two compressors were running continuously to serve demand peaks lasting only 90 seconds. If these peaks could be served from air stored in a large-enough supply-side receiver, at least one compressor could be turned off. While the compressor room already held two storage receivers with a capacity of about 1,500 gallons each, they weren’t large enough to serve the demand peaks. (And the other well-known approaches to meeting intermittent air demand — supplying each conveying system with a dedicated compressor or storage receiver — wouldn’t be practical because the conveying systems were in widely different locations in the large plant.)

So how large should the additional storage receiver be? Would just five compressors provide enough off-peak surplus air to store? And how much would the system’s supply-side pressure need to change? Rather than guess, I collected more data to be sure that it included the worst-case demand scenarios. The data would also let us validate the pressure required by production events so we could adjust the plant air system to deliver air at the lowest appropriate pressure while still meeting production needs.

With the new data, we learned not only which production events created demand peaks that required all the compressors to run and how large the peaks were, but also how long they lasted and how often they occurred. Each event was brief, so we suspected that all of them could be served by compressed air stored in a larger receiver, the same solution we’d arrived at for handling the high demand peaks. But we also identified repeated 2-hour periods when a continuous series of dense-phase conveying events occurred, which established the highest average airflow demand. The plant’s production manager explained that during each of the three 8-hour production shifts, the final product was stored in vessels near the process and checked for quality control, but during the shift’s final 2 hours, the dense-phase conveying systems moved all the material to storage silos. We wanted to have enough stored air to be able to turn off one compressor during these high-demand periods and reduce power use.

**Measuring and modeling supply-side airflow.** To solve the problem of large, intermittent airflow demand, we needed data to determine what capacity the existing compressors could provide so we could compare this with the demand airflow and find an equilibrium. Using airflow analysis software, I entered supply information for each compressor, including maximum pressure capability, capacity (in standard cubic feet per minute) at maximum full-flow pressure (MFFP, when the compressor is fully loaded), power consumed (in kilowatts) at MFFP, and power consumed (in kilowatts) when unloaded. I also entered the plant’s power cost per kilowatt-hour. Finally, I entered the demand information — the actual system airflow data we’d already collected.

With all the information entered, the software generated a model simulating the plant air system’s behavior. Now we could manipulate various operating parameters in the

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**Figure 1**

Airflow demand trend recorded by thermal mass flow meter

Airflow rate (scfm) vs. Time (minutes) and Pressure (psig)
model, including the volume of the storage receiver we proposed adding to the system, to simulate how each would affect the compressors.

Using airflow analysis software to model the system airflow provides the flexibility to manipulate:

- The recorded airflow value. (This would be useful if the plant air system had a few leaks or other forms of air waste that we could fix to suppress the demand, or, if the plant wanted to add production equipment in the future, we could increase the airflow demand to reflect the addition of the new equipment.)
- The storage receiver’s total volume.
- The pressure setpoints used to control the compressors.

The software algorithms compare the supply (compressor) airflow to the recorded demand airflow for every data entry (every 5 seconds, in our case). When there’s a supply airflow surplus compared with demand, the plant air system pressure rises; if there’s a supply airflow deficit, the system pressure decays. If pressure decays to the compressor controls’ “load” setpoint, the software models the starting and loading of another compressor. If pressure rises to the “unload” setpoint, the model simulates the unloading and stopping of a compressor after a timer on the compressor controls runs out.

By using the software to increase the storage receiver’s volume and change the span between the compressor controls’ load and unload setpoints, we can manipulate the volume of air stored. This can model how, as the receiver volume increases, the frequency of compressor loading and unloading decreases or, better, how one (or more) compressor shuts down and doesn’t restart. The model can also reveal that if the receiver’s total volume is too small, system pressure will decay below an acceptable point no matter how high the unload setpoint is or how wide the load-unload control span is, requiring one (or more) additional compressor to be started and loaded. While increasing the receiver’s total volume will avoid this problem, there’s a practical limit to this increase because of a large tank’s prohibitively high cost.

Figure 2 shows the modeling results for the minimum storage receiver pressure we’d be able to maintain during the worst-case demand event as the receiver volume changes and only five compressors are allowed to run. It reveals that even with a compressor control load-unload span of 15 psi, if the receiver has less than 14,000 gallons of storage volume, the worst-case series of conveying events will draw down the air supply, causing system pressure to decay to a critical level. This would require the running the sixth compressor.

However, the modeling results also demonstrated that even after adding the 14,000-gallon storage receiver, the fifth and sixth compressors would still cycle. This meant that the fifth compressor still had unrealized capacity, so we’d need a larger receiver to make use of it. The math showed that we needed to add at least 27,000 gallons of receiver volume to eliminate a need for the sixth compressor (with a load-unload span of 15 psi).

### Estimating power cost

We also used the airflow analysis software to estimate the plant air system’s annual power cost. With this estimate, we could see whether the new storage receiver’s cost would be justified by power cost savings.

This would also tell us how much the pressure would change on the system’s supply side. The volume of usable air stored in the receiver (that is, the air volume that causes pressure to rise above the minimum pressure required to support production) depends both on the receiver’s size and the pressure change. Reducing the pressure change could allow us to reduce the compressor discharge (supply-side) pressure and, therefore, the power cost, but it would increase the receiver’s size and cost. Reducing the supply-side pressure could also allow each compressor drive motor to operate at or below its nameplate full-load amps, not in its service factor (that is, the percentage increase over the motor’s rated horsepower that the motor can tolerate).

### Adding the large storage receiver

Based on these analysis results and the plant’s technical and budget considerations, we decided to purchase a used 30,000-gallon storage receiver for the compressed-air system. While this receiver had the capacity to eliminate one of the plant’s six compressors, we now had another problem: While the pressure in the receiver had to be able to change so the receiver could function properly, the plant needed sta-
ble system pressure. Even with adding the large receiver, we still needed to change the supply-side pressure by nearly 14.5 psi to handle demand peaks, and this was a greater change than we wanted in the plant. Higher overall demand-side pressure increases artificial demand for air (that is, excess air consumption), and in this plant artificial demand was already a problem. Lowering the overall system pressure is also more difficult when the pressure isn’t stable.

To solve the problem, we used an airflow-control valve assembly (which we typically call an intermediate controller), designed and built on-site, to handle the system’s large, rapid flowrate changes. We installed the intermediate controller’s two valves in a redundant arrangement, with both valves controlled as one, to provide good airflow control with a low pressure loss (less than 0.5 psi) at peak airflow rates. I replaced the temporary thermal mass flow meter in the main air line with a permanent averaging pitot tube (this solved a problem with the flow meter output’s momentary distortion during rapid airflow increases). I also replaced the temporary pressure transmitter in the line with a pressure transmitter more appropriate for permanent installation. The intermediate controller and transmitter were wired to, and controlled by, the plantwide SCADA system so the intermediate controller could be tuned and monitored from the process control room.

Once the intermediate controller was operating, we began to lower the system pressure and create the pressure change necessary to store the volume of air needed to handle the largest intermittent demand events.

**Dealing with new issues**

We kept investigating ways of lowering the plant air system pressure to reduce both artificial demand and power costs. However, as soon as we began to lower the system pressure, the instrument air system’s low-pressure alarm sounded, forcing us to raise the pressure back up to 110 psig. The instrument air was supplied by the main plant air system, where we had lowered pressure to about 100 psi, but the instrument air low-pressure alarm was set 15 psi below this. What’s more, despite its name, no instruments received air from the “instrument” air system. We also noticed that a twin-tower, pressure-swing desiccant air dryer was being used to suppress the dew point in the instrument air system. While all the air in the plant air system was passed through refrigerated dryers to suppress the dew point to about 38°F, the desiccant air dryer further lowered the instrument air’s dew point to about –40°F. We wondered both what was causing the additional 15-psi drop that tripped the alarm and whether the desiccant air dryer was needed.

**Air dryer.** I then installed a pressure transmitter and data logger downstream of the dryer outlet. The data revealed that the instrument air system pressure was dropping by 15 psi or more at regular intervals. This interval precisely matched the dryer’s tower-switching interval, when the flow of compressed air was switched from one desiccant-filled tower to the other and the desiccant in the offline tower was dried by purging it with dry air from the online tower. We called a dryer service technician, who diagnosed and repaired a problem with the dryer’s tower-switching operation, which virtually eliminated the short-term pressure dips. We also walked the instrument air system and discovered that it supplied dust collectors and valve actuators outside the plant’s heated spaces, revealing that the desiccant dryer was intended to suppress the dew point to prevent the system from frosting or freezing in the winter. But since the plant was in the South, we wondered how often the system would really require a low dew point. At the very least, the system could bypass the dryer in warmer months, eliminating the dryer’s purge-air requirement for this period.

**Dust collector.** Brian again lowered the plant air system pressure, this time to 80 psig. The pressure held there for a while until a group of pulse-cleaned dust collectors developed a filter-cleaning problem, so he increased the pressure to 90 psi. In investigating the filter-cleaning problem, he noticed that a pressure gauge at the dust collectors indicated a drop greater than 40 psi. When the system pressure was high, this drop wasn’t noticed, but at 80 psig — a more appropriate pressure for the rest of the plant — the air delivered for pulsing the filters wasn’t at high enough pressure to dislodge the dust cake from the filters. In fact, pressure regulators that had been installed to lower the pressure in the dust collectors were restricting the airflow needed to pulse the filters, so the plant air system’s high pressure (110 psi) had been needed to compensate for this problem. The dust collectors’ filter-cleaning cycles represented another large intermittent air demand in the plant, and we knew that we could eventually handle the resulting pressure fluctuations by adding local compressed-air storage (that is, a small receiver for each collector, located between the regulator and the collector). In the meantime, Brian removed the pressure regulators and again reduced the system pressure to 80 psig.

After the plant had been operating successfully for several days with 80-psig air, Brian reduced the system pressure...
to 70 psig. The pressure was held there until a conveying system problem surfaced. Since this problem remains to be investigated, he increased the pressure to 80 psig again. But when the problem’s source is found and corrected, he’ll lower pressure again and adjust the compressor control load-unload setpoints accordingly. For now, they’re set at 94 psig (load) and 108 psig (unload).

**Compressor controls.** When the plant was running with air supplied at 80 psig, the compressors were unloading and turning off, as we wanted. But they wouldn’t stay off. Each compressor’s local controls (which were factory-supplied as part of the compressor package) were designed to communicate with the other compressor controls and control all the compressors as a system — that is, with one controller acting as a “master” — but this feature wasn’t being used, and each machine operated autonomously. This arrangement kept restarting compressors when they weren’t needed. At times all six ran, with two or more unloaded. We needed to control the group so that only one would run at part load, eliminating unnecessary starts. We thought that “retuning” using the factory-supplied controls’ master feature could accomplish this.

Brian decided to prove this by taking manual control of the plant air system. During this experiment, he found that he could supply the demand pressure with just three compressors at full load and one more that was lightly loaded until the worst-case series of dense-phase conveying events that lasted more than 2 hours. It was during this series of events that we had the highest, most dynamic airflow demand and the most difficulty controlling the plant air system. During these periods, the fourth compressor went to full load and one more that was lightly loaded. We needed to control the group so that only one would run at part load, eliminating unnecessary starts. We thought that “retuning” using the factory-supplied controls’ master feature could accomplish this.

We asked the compressor supplier to adjust the network of local controls to operate as it had under Brian’s control. Now, the controls manage the compressors efficiently: only one compressor (the *trim compressor*) runs at part load, and at least one no longer starts at all. The compressors’ shutdown timers were also adjusted to turn off the compressors after just 2 minutes of running unloaded. This resulted in about two starts per hour for the trim compressor during the high-demand periods and reduced the unloaded runtime for the other compressors by about 50 percent.

We also discovered during this control experiment that by reducing demand by just a little more (about 350 scfm), we could turn off another compressor, leaving just three compressors online. Demand was already down because we’d lowered the pressure from 110 to 80 psig, reducing artificial demand. Yet we had done little to fix leaks or eliminate inappropriate compressed-air usage in the plant (simply because this was not part of my contract). But Brian planned to address these waste sources later, which we expected would suppress demand by more than the 350 scfm required to turn off the fourth compressor.

During the control experiment, Brian had also observed that during the prolonged high-demand period, the system pressure decayed slowly, and that after about 15 to 20 minutes, the fifth compressor had to start. But this compressor restored pressure in just 15 to 20 minutes, suggesting that only half of its capacity was needed. We expected that reducing demand by eliminating air waste would be enough to not only keep the fifth compressor offline during high-demand periods, but keep the fourth compressor offline, as well — at least usually. But if not, we had one more ace to play.

**Uninterrupted demand.** During our demand-side investigation, the plant’s production manager had explained that the downstream process could tolerate short (10- to 20-second) interruptions in the continuous series of dense-phase conveying events. We made some calculations that showed that interruptions even this brief would make a big difference in reducing the average air demand. This would shift the supply-demand balance in favor of supply, eliminating the system pressure decay and the need for the fifth compressor.

**Evaluating the solution’s energy efficiency**

By now, we’d taken several steps to reduce the number of compressors the plant air system required, including collecting and evaluating data about the plant air system’s supply and demand sides, adding the large storage receiver, adjusting the controls, taking the desiccant dryer offline during warmer months, repairing the dust collector filter-cleaning systems, and adding brief interruptions between conveying events. But a big question remained: Did the project’s final power savings make this project worth the effort?

The plant air system’s pressure was now stable and at a much lower level, meeting Brian’s goal to eliminate unstable pressure. And the sixth compressor had been turned off, accomplishing his other goal of using it as a backup so he could send the rental unit home. But wouldn’t simply buying another compressor have provided a simpler solution? No, because it wouldn’t have achieved the same results. In fact, it would have increased the plant’s power costs.

To understand why, let’s look at each issue in turn.

**Stabilizing system pressure.** Unstable plant air system pressure is a symptom of poor supply-demand balance. Adding a compressor would have increased the supply, but not until the new compressor was running and loaded. The control signals to the compressors — to start and load, and to unload and stop — are based on system pressure...
changes. So, pressure must change for the compressor controls to respond and the change must be large enough (about 10 psi works well) to keep the controls from responding to every little system hiccup.

In addition, if a compressor needs to be started, some time — around 20 seconds for a typical 150-horsepower rotary screw compressor — will pass before it loads and begins supplying airflow. This means that the system pressure will drop by as much as 10 psi to the control range’s bottom and then continue decaying for a while. When the compressor finally does load, the increased airflow through the system’s shared air-treatment equipment (filters and refrigerated dryers) will cause a greater pressure loss, aggravating the problem. The total pressure change would vary because of all the variables at work here, but we can be sure of one thing: The system pressure won’t be stable. So adding another compressor couldn’t have stabilized pressure because the problem wasn’t a lack of compressor capacity, but a lack of compressor control.

**Providing a backup compressor.** Adding another compressor wouldn’t necessarily have provided a backup for the others, either. By definition, a backup compressor isn’t intended to support routine production demand. However, because six machines couldn’t supply the demand, the additional compressor would immediately have been called into service and run almost continuously — most of the time unloaded.

In fact, not only would an additional compressor not have solved the plant’s original problems, it would have used more power, resulting in higher costs. System pressure would have risen, increasing the cost of every cubic foot of air compressed, and we would have had to compress more air because artificial demand would also have increased. It’s also likely that the compressors’ unloaded runtime would have increased. Another compressor would also have increased the plant’s maintenance costs.

Because we had collected good data about the plant air system’s supply and demand sides, Brian was able to make informed decisions about the best ways to stabilize system pressure and provide a backup compressor.

### Evaluating the solution’s cost efficiency

One more big question remained: Was this project cost-effective? We examined this issue by comparing the costs of implementing and operating the system with the additional large storage receiver to the costs of implementing and operating it with an additional compressor, as shown in Table I. While our investigation data showed that power and maintenance costs drop when compressors are turned off, both costs would increase if we added another compressor.

Improving the plant air system’s efficiency by reducing its power and maintenance costs clearly had a big impact on overall cost — in this case, saving $170,600 (the compressor’s $131,200 cost plus the receiver’s $39,400 savings) in just 2 years and $1,145,000 over 10 years. Sweetening the deal, the compressor discharge pressure can be further reduced in the future, and it may even be possible to turn off the third compressor for about 18 hours a day. (These savings aren’t included in the table.)

### References

1. The author used software that he developed, called Flow Based Analysis; however, similar results can be obtained with the DOE’s AirMaster+ software (see the sidebar “Compressed Air Challenge: Helping plants improve compressed-air system performance”) and other software available from compressor manufacturers.

2. Contact the author for more information on the formulas applied by the Flow Based Analysis software.

### For further reading

Find more information on this topic in articles listed under “Compressed air” and “Pneumatic conveying” in *Powder and Bulk Engineering*’s article index (in the December 2012 issue and at [PBE’s website](http://www.powderbulk.com)) and in books available on the website at the [PBE Bookstore](http://www.powderbulk.com). You can also purchase copies of past *PBE* articles at [www.powderbulk.com](http://www.powderbulk.com).

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*Note:* Based on 50 percent load.