A Review of Up-rating Process Plant Compressors

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SYNOPSIS/ABSTRACT

Most operators of manufacturing plants will, at some time during the life of the assets, wish to consider increasing production capacity by up-rating the existing assets. Finding the optimum solution for increasing existing compressor capacity is often a major activity in any up-rating study, with significant impact on energy consumption, capital cost, operability and reliability.

This paper will review, from an operator’s viewpoint, the key issues and options associated with the feasibility stage of compressor up-rating projects.

A number of examples of the problems that can arise will be presented.

1 INTRODUCTION

Up-rating process plant compressors, as part of any project to increase production capacity, should be a relatively straightforward exercise. Unfortunately this is not always the case, with many of the related problems having their origin in issues arising at the project feasibility stage. This paper will review, from an operator’s viewpoint, some of the key issues and options, which if correctly covered during the feasibility studies, can facilitate optimum and effective solutions. The key areas covered include energy consumption, understanding current performance, the available options and project cost or payback issues. A number of typical problems, that illustrate some of the pitfalls, will also be briefly described.

Some of the points made during the course of this paper may seem obvious, but it’s amazing the number of times that problems of this type arise at the latter stages of the project and have serious impact on its viability after time and money has been spent working up the solution. Even worse, they occasionally turn up during commissioning, with at best embarrassing and at worst disastrous results.

Nothing is guaranteed, but getting the basics right at the earliest possible stage is fundamental to the success of any project.

*If you do all the little things right, the big, bad things don’t happen.* - David Ormandy (1)
2 INITIAL ESTIMATES OF ENERGY REQUIREMENTS

A common expression associated with the Laws of Thermodynamics is that ‘Energy cannot be created or destroyed’. The importance of this expression against the topic of compressor up-rates is that it reminds the project team that the energy to drive the up-rated compressors has to come from somewhere!

There are numerous established methods for estimating the power demand for compressors. These are dependant on a detailed understanding of the up-rated process conditions, require detailed calculation and will change as the process model is developed. However, it is good practice to start with a simple estimate to make sure that solutions to the power demand problems are at least feasible.

If we consider the synthesis gas compression train of an ammonia plant, with an existing plant capacity of 1200 tonnes/day, an up-rate to 1600 tonnes/day represents an increase of 30%. If the existing installed power for the compressors is 21 MW, then, however the increase is achieved, either by up-rating the existing compressor internals, suction boosting or parallel capacity, an increase in available power of approximately 7 MW will be required. This simple approach can be extended to each machine requiring up-rate.

This allows existing electrical supply and steam (for turbines) to be investigated and potential problems identified at an early stage. Additional HV (high voltage) electrical supplies or steam raising capacity can present major logistical problems and costs. In some cases, as with ammonia production, the process is exothermic and the up-rate in itself will provide the potential for further steam raising capacity. An early understanding of the likely steam demands, particularly in terms of pressures and condensate capacities, can help the process engineer in developing the process model.

Even if the power capacity is available, it still has to be brought to the point of use. Running new steam mains or HV cables is neither simple nor cheap.

Loading existing steam or electrical capacity to its limits may also present hidden problems. Reliability may become an issue. The systems will have to be maintained at some point and maybe the existing capacity was installed to allow maintenance. Will this be possible in the future within existing Turn-Around schedules? What will be the impact on plant availability? The life cycle costing of any proposal needs evaluating and the optimum solution found.

Even where the up-rate is apparently simple, maybe only confined to a single compressor casing and driver, the ability to provide and associated cost of the extra power can make the project unviable. A new HV electrical 7MW supply, including transformers and switchgear, can easily cost Euro 150,000 to Euro 300,000, which is approximately 50% of the cost of up-rated internals for a single casing, 7MW compressor.
3 CURRENT OPERATING CONDITIONS

There are normally 4 data sources for machine operating conditions

1. The original design data sheets
2. Manufacturer’s factory test data
3. ‘As built’ or performance guarantee data
4. Actual data taken from the plant

When performing feasibility studies for up-rating a compressor, it is important to understand the origin and probity of the data.

3.1 Original Design Data Sheets

These can represent a combination of what the process designer wanted and what the machine manufacturer could supply. It is important to look at any revision notes to establish the status of the data. Machines specified to standards, such as API 617, may show an apparent over capacity on the original Design Data Sheets. This may or may not exist in reality. The standards specify a design margin such that the compressor will deliver its duty, despite any design or manufacturing inaccuracies. Even with modern methods, machine design and manufacture is not an exact process, nor is the original process design, despite the powerful process modelling tools available. It is important not to take any information from these sources at face value and confirm any data before getting too far into the up-rating project.

3.2 Manufacturer’s Factory Test Data

Most contracts for the supply of a major machine will specify a factory test. Standards, such as API, set the rules by which the tests are performed. The data will normally consist of results tables and a series of curves showing head, in a variety of units (isentropic head, polytropic head, metres of head etc), efficiency and power consumption, for a variety of speeds, generally plotted against suction or discharge flow-rate or capacity. Head data is normally presented as a differential across the machine, but not always. The data will also include a surge line or curve, indicated further prohibited operating areas.

This data represents a very accurate picture of the machines capability and, subject to a few cautionary notes, can be used most effectively to determine up-rate potential.

1. The head and efficiency will be quoted as polytropic, isentropic or even adiabatic, depending on the compression process. Some process models will estimate these, or apparently similar, figures. Comparisons can only be made if the calculations are done on the same basis, using the same parameters. This is not always the case. It is easy, for example, to confuse polytropic or isentropic power, efficiency and absorbed power, but such errors can have a significant impact.
2. When testing the machine, the manufacturer will have a power limit for the test bed. Also, they cannot always test the machine on the exact service gas, particularly if it’s a manufactured material, such as a hydrocarbon or a synthesis gas. The machine will be tested on a test gas and the results modelled to give the performance for the service gas. This can cause problems if, for example, the test gas has a significantly different molecular weight to that for the service gas, by introducing errors in head calculations and Mach Numbers. The modelling calculations will be based on the design case for the gas. It is not unknown for the actual service composition to differ from that predicted, particularly for gas mixtures. In this case, care is required when extrapolating test results to a possible up-rate case.

3.3 ‘As built’ or performance guarantee data

A normal activity at commissioning is to record the actual performance of the machine, normally for guarantee reasons. This data is usually provided to the operator, sometimes as a revision to the original Design Data Sheets. Apart from its obvious probity, it is also invaluable for comparisons with current performance data, as it helps highlight deteriorations in performance. Understanding such deteriorations is essential in producing a reliable up-rate option. It might give the up-rated performance when new, but not after a few years of service. Addressing and minimising the deterioration mechanism may provide the desired up-rate without expensive modifications.

When using such data, it is important to remember that the measurements were probably taken using the installed instrumentation and could be subject to inaccuracy or calibration issues. The instrument measurement positions may not be the same as those used in the factory tests and care is required when making comparisons. The operating conditions prevalent at the time of the measurements may not be the same as for current readings. Some basic care is required to establish the probity with these, as with any other readings or data.

3.4 Actual data taken from the plant

It is very difficult to evaluate potential up-rate options without actual, current performance data. It can be done, but only with extreme caution. Comparing the actual data with that produced by process modelling programmes or as described in the previous sections can be quite challenging and cannot be done without a detailed understanding of the assumptions inherent in any of the calculations.

Differences between the various data sets could be explained by measurement errors. Plant instrumentation may not always be totally accurate; buts its accuracy errors are generally known and can be allowed for. A useful reality check is to perform a basic error calculation, say for the power demand, assuming standard measurement errors and compare it with the design figures.

Some situations are notoriously difficult to calculate from plant data and compare with design data, due to measurement errors, the power generated by a condensing steam turbine being the classic example. Differences can also exist due to machine deterioration, as described in the previous section.
4 Up-rating Options

There are a number of up-rating options for centrifugal compressors. They differ slightly between single shaft and ‘geared’ compressors, but the principles and pitfalls are similar. The common options are:

1. New compressor internals (dimensional changes)
2. Speed increases
3. Supercharging (Suction Boosting)
4. Suction Chilling
5. Additional Parallel Capacity

This paper will not cover the technical aspects of these options to any great depth. There are numerous textbooks and publications available that cover the topics in a rigorous manner. A detailed understanding is not required when establishing the feasibility of the options, but a number of simplistic explanations are helpful. Invariably, the detailed work will require the input of a machine manufacturer whose input can be better targeted by a clearer understanding of the options and their limitations by the up-rating project team.

The normal up-rate requirements are either increased mass flow rate or increased head. Simple increases in volumetric flow rate are less common, although they are a common element to the other two.

4.1 New Compressor Internals

Capacity up-rates by increasing impeller and diaphragm widths or diameters are a common option, assuming that there is sufficient space within the casing to accommodate the new components. The impeller changes often require a completely new rotor, due to increased mechanical stresses. The lateral and torsional critical speed prohibited ranges may change with possible impact on operability. The operating ranges may also change due to ‘surge’ and ‘stone wall’ limits.

As the compressor is being up-rated, its power requirement will also increase and must be checked against the capacity of the existing driver and transmission components, such as couplings and gearboxes.

The technology associated with compressor design has improved markedly over the last 10 or 15 years. Modern rotor and diaphragm design can offer significant improvements in efficiency and can often offset, even if only in part, the increased nominal power demand from the up-rate. On the other hand, the increase in capacity may result in losses at unchanged areas, such as casing nozzles, openings and stationary ducts.

Drivers specified to standards such as API may, according to the data sheets, appear to have excess power capacity. This is intended, in part, to provide a design margin and may not in reality exist. The same margin should be applied to the up-rated case, as it also may have to take advantage of a design margin!

A major feasibility consideration when costing an up-rate is that of spares. Major machines are often single stream. Rotors and diaphragms are long delivery items, possible up to 12
months lead-time and are usually held as strategic spares. Purchasing new spare rotors and diaphragms to match the up-rate will have a major impact on the capital cost. An alternative would be to, in the event of a failure, refit the original internals and accept a lower rate while the failed components are repaired. Assuming that this is physically possible, the cost impact can be evaluated using a simple model, based on generic reliability data, as shown in Appendix 7.1.

4.2 Speed Increases

Up rating via speed increases is a relatively common approach and can be relatively straightforward for minor increases, particularly if the compressor driver is a steam or gas turbine. Where the driver is via an electric motor, hardware changes will be required, normally by changes to the gearbox or maybe by introducing a variable speed drive. As with turbines, variable speed drives require over-speed protection to be considered. The greater the speed increase, the more work is required to check rotor stresses, gearbox and coupling limits, aerodynamic issues such as choking and surge, efficiencies and so on. Subject to driver power and speed limitations, such up-rates can usually be achieved without modifying the compressor, giving considerable savings in capital cost.

The up-rated performance has to match the system curve, as speed increases raise both head and flow rate and may turn out not to be the best option in terms of efficiency.

It also relatively common to combine changes to compressor internals with speed changes to optimise performance.

4.3 Supercharging (Suction Boosting)

Increased mass flow can be achieved by increasing the gas density inlet the compressor. A simple compressor, blower or fan is used to compress the gas to the main compressor inlet, thereby increasing the inlet gas density. An increase in inlet density results in increased head, absorbed power and the potential for volumetric overload or choking within the compressor stages. Consequently, the main compressor either has to be modified internally (removal or trimming of impellers) or run at a lower speed. There is maximum up-rate limit for suction boosting, depending on the booster parameters, the main compressor detail design and the process gas (2). The limit generally reduces with decreasing gas density, e.g. hydrogen compressors normally have the least potential.

The principle advantage of this approach is that, should the booster compressor fail, the main compressor can usually continue in operation at or near to its original capacity.

4.4 Suction Chilling

Reducing the compressor inlet temperature increases the gas density. Up-rates adopting this principle follow broadly the same issues as suction boosting. Significant up-rates on large machines normally require a large refrigeration plant to provide the chilling. The capital cost and space requirements usually make this approach unviable. Sometimes, where the process allows, such as on an Ammonia Plant, flash gas can be economically used to provide the chilling, particularly where the capacity increase is small.

Process air compressors are normally sized to cope with summer and winter ambient temperatures, with inlet temperatures ranging from -10°C to +35°C being typical. Chilling the inlet air to duplicate or move towards winter conditions in summer months provides an up-
rate in capacity over a 12-month period and has the advantage that compressor modifications will not be required. However the problem of providing the chilling capacity does not change.

4.5 Additional Parallel Capacity

Additional parallel capacity is normally the easiest option technically but the most expensive. It has the advantage that the existing machines should be unaffected and turndown issues are simplified. The new capacity can be installed while the plant is on-line, thus reducing the size of any Turn-Around to make final break-ins and commission.

4.6 Common Factors

Irrespective of the up-rate method selected, there will be other issues to consider. Power requirements have been covered in Section 2, but process design issues and control systems changes will be different for each option and need to be factored into any feasibility study. Other changes directly related to the increase in capacity, such as pipe sizes, relief capacity and so on are the same irrespective of up-rate method.

5 Cost and Payback

The starting point for many Up-Rate Feasibility Studies is a new capacity based on the ability to sell the product. When the final project cost is compared with the commercial benefits it may be found to be unviable. However, up-rate costs are not generally linear with increase in capacity, but tend to follow a relationship similar to that shown in Figure 1. The project costs associated with a lower capacity increase could be viable commercially. A true feasibility study should consider a range of capacity increases at an early project stage before pre-sanction costs become excessive.

![Figure 1: Capital Cost versus Capacity Increase](image-url)
6 Some examples of where things can go wrong!

The following brief examples illustrate the sort of things that can go wrong when up-rating compressors. They are chosen to illustrate some of the small, but subtle problems that can arise. All had a significant impact, mainly due to the circumstances under which the problem was discovered.

6.1 Drive Coupling Capacity and Rating

A design verification study revealed that various compressor up-rates, over a number of years, on the Synthesis Gas Compressors of an Ammonia Plant had resulted in the power transmitted through the couplings increasing by up to 25%. The effective service factors were significantly below the API 671 recommendations. A detailed study showed that the couplings were just acceptable for the duties and were subsequently replaced to restore the operating margins. A check had been done for the first up-rate, but not for the subsequent ones.

6.2 Turn Down Capability

A compressor providing process air for a small refinery was up-rated by fitting new internals. The machine operated with no problems at maximum rates. However, the minimum IGV (Inlet Guide Vanes) position wasn’t physically low enough to give the necessary turn down for certain operating cases. The IGVs could provide the control aerodynamically, but physical stops were fitted! The necessary mechanical modifications were straight forward, but took a few days, delaying commissioning.

6.3 Operating Cases – Normal and Start-Up

A gas circulator on a methanol plant was up-rated to a new duty. At plant start-up, it was required to circulate a gas with a lower density than normal. The desired circulating rate couldn’t be achieved without surge, which wasn’t detected by the surge prevention system, as the surge algorithm differed to the normal operating case. A lower rate and extended start-up sequence was the result.

6.4 Power Limits and Maintainability

A fertiliser complex was up-rated in stages over a number of years, largely by adding electrically driven machines, such as extra or larger pumps, suction boosters and bigger fans. The complex is required to be self sufficient in power, due to its location and the limited capacity of the local supply grid. The site power demand was within the on-site generating capacity, just! The problem came when maintenance, specifically the testing of the protection systems, was required to either of the two on-site generators. It could now only be scheduled for the planned Turn-Arounds. This testing frequency was inconsistent with the hazard rates required by the company’s standards and local legislation. Lost production was accepted until extra capacity was installed.
7 Appendices

7.1 Cost impact of Spares Policy

| Capital cost of compressor spares for up-rated case (rotor and diaphragms) | C | Euro |
| Original Capacity | P1 | Tonnes per day |
| Up-Rated Capacity | P2 | Tonnes per day |
| Value of product | V | Euro/tonne |
| Mean Time to Refurbish up-rated rotor and diaphragms following failure | R | Days |
| Plant shutdown to re-install refurbished items | S | Days |
| Failure Rate | H | Failures per year |
| Capital Item charges (interest on capital) | I | % per year |

The cost of holding the spares can be taken as the capital cost or book value multiplied by a percentage to cover interest charges on the capital. It is assumed that other costs, such as storage costs and insurance are the same for the original spares and the up-rated spares and therefore not an additional cost. Similarly, the spares repair costs are a common item.

**Spares Costs** = C x I Euro per year

If the up-rated compressor fails in service, the annualised costs can be estimated using a generic failure rate, the value of the production lost by refitting the original spares and the time taken to refurbish the up-rated spares and refit them.

**Cost penalty** = [(P2-P1) x R + P2 x S] x V x H Euro per year

Comparison of the figures identifies the optimum solution.

This is a simplified approach to illustrate the principal. The calculations can be as sophisticated as the available information allows.

**Example**

Plant production has been up-rated from 1250 to 1500 tonnes per day by up-rating the main plant air compressor. The product is valued at 225 euro per tonne. The up-rated spare rotor and diaphragms have a capital value of euro 1,000,000 and the capital charges are 10% per year. Generic data suggests a significant failure of the compressor rotor and diaphragms of 1 failure in 250 years. The time to repair the failed rotor and diaphragms is taken as 90 days and the outage to re-install is 10 days.

Annualised Spares Costs = 1,000,000 x 0.1 = euro 100,000

Cost Penalty = [(1500 – 1250) x 90 + 1500 x 10] x 225 x 0.004 = euro 33,750

Therefore it is the better option not to hold up-rated spares and use the original spares in the event of failure.
8 References

1. Ormandy, D., Quotation in ‘Making Common Sense Common Practice’ by Ron Moore, published by Cashman Dudley, Houston, Texas
2. Lüdtke, K., ‘Rerate of centrifugal process compressors – wider impellers or higher speed or suction side boosting?’ published by MAN Turbo GmbH