

COST EFFECTIVE RE-ENGINEERING OF A PROPYLENE COMPRESSOR STRING

by

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ABSTRACT

The discussed rerate method will provide users of turbomachinery with a new, cost/leadtime saving approach to plant upgrades. Although rerates of existing turbomachinery are common, this approach is unique in that the rerate was not performed by the original equipment manufacturer (OEM), yet it involved the utilization of existing aerodynamic hardware instead of the more common situation where all internals are replaced.

This involves extensive engineering and design with limited data and increased cooperation between the rerate engineer and the end user. However, the resulting savings have proven to be worth the effort as evidenced by the project discussed.

The following key areas of the project are covered in detail.

- Project definition and quotation phase
- Aerodynamic modelling
- Design drafting

- Manufacturing and assembly process
- Operating performance from startup to present

The methods used and the lessons learned in each of the above areas are discussed with the intent to provide turbomachinery users with a detailed example to follow in pursuing the savings that are available through this rerate process.

INTRODUCTION

The project discussed involves a propylene compressor string owned by E.I. DuPont de Nemours and Company and rerated by Elliott Turbomachinery Company. The string was originally built by an overseas manufacturer. Although it is common practice for rerates to be performed by the original equipment manufacturer (OEM), leadtime considerations on this project did not make that a feasible option. Therefore, the customer was inclined to seek an alternative solution. This study is a cooperative effort by DuPont and Elliott. The intent is to provide an understanding of this non-OEM rerate process from the perspective of both the rerate engineer and the enduser.

PROJECT DEFINITION AND QUOTATION PHASE

General Description of Ethylene Plant

The ethylene plant in a major petrochemical plant in Texas was designed and built in the late 1960s. The unit takes ethane/propane gas feedstock and thermally cracks the gas in 10 short residence time furnaces, and then cryogenically separates the ethylene and other olefin components. Original plant design was to produce 750 million lb/yr of ethylene, with capacity being uprated over the years to 1.3 billion lb/yr of ethylene and associated byproducts. The cracked gas is compressed and delivered to a cryogenic distillation system by a 45,000 hp, five-stage compressor train. Refrigeration is provided by four additional compressor trains; a 35,000 hp, four-stage propylene compressor (which is the string to be discussed); a 6,000 hp, three-stage ethylene compressor; a 5,000 hp, three-stage purge propylene compressor; and a 5,000 hp, four-stage methane compressor.

Reason for Plant Uprate

As the ethylene plant was uprated over the years, the original feedstock flexibility of 50 percent propane/50 percent ethane to 100 percent ethane had been sacrificed for higher ethylene yields. So much so, that after 1992, in order to run 80 percent ethane/20 percent propane feedstock, the plant production rate was severely restricted. In 1994, a program was developed to provide feedstock flexibility from an 80/20 feedstock ratio to purity ethane at maximum plant rates to take advantage of significant variations in feedstock and byproduct pricing. A major part of this program was

rerating the propylene refrigeration compressor to accommodate an 80/20 feedstock ratio at higher rates and to match energy reduction program requirements.

Customer Goals of Project

(As Pertaining to the Propylene String)

For the new 80/20 case flow requirements, the propylene string (Figure 1) was a "bottleneck" in the uprate project. The goal was to eliminate this bottleneck by rerating the compressor internals to handle the proposed 80/20 flow requirements.

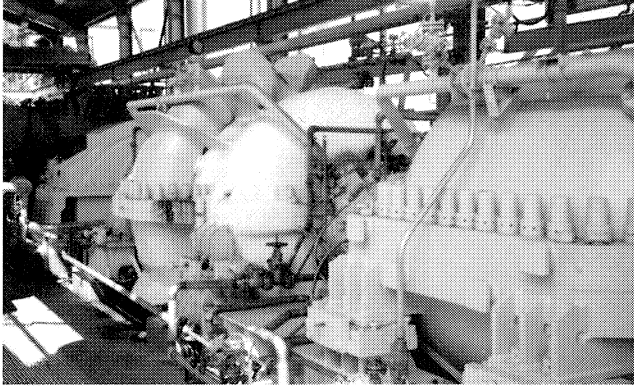


Figure 1. Picture of Propylene Compressor String.

The rerate would also save energy on the back end of the compressor by keeping the last stages off of minimum flow and into a more efficient operating range.

Manufacturer's Scope of Responsibility

The propylene compressor string to be rerated, as shown in Figure 2, consisted of two compressor bodies, direct driven by a steam turbine. The low pressure (LP) body was a double flow, drive through compressor with one sideload. The high pressure (HP) body was a straight through compressor with two extractions.

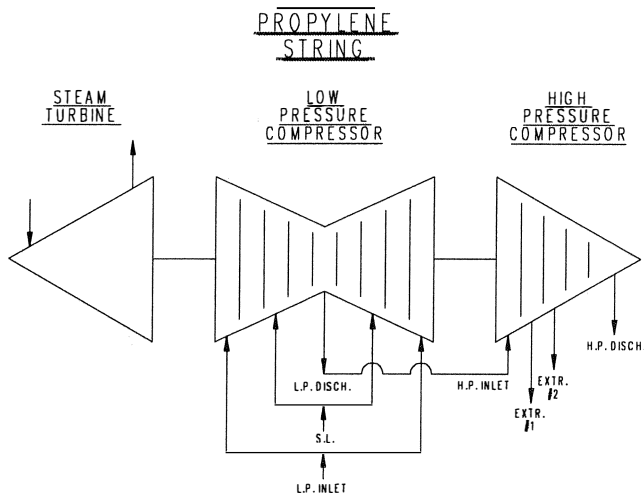


Figure 2. Schematic Diagram of Propylene Compressor String.

The rerate was to provide guaranteed performance at the new conditions, while minimizing cost and leadtime to meet the customer's requirements for budget and schedule.

In order to reduce cost and leadtime for the project, it was decided to attempt to reapply the following hardware:

- Compressor casings
- Couplings and guards

- Steam turbine driver
- All piping (lube, seal, buffer, process)
- Baseplates
- Lube and seal oil system
- Shafts
- Bearings and seals
- Instrumentation, wiring, and conduit
- Control systems
- As many impellers, shaft sleeves, and diaphragms as possible

New parts would include only those components (impellers, shaft sleeves, and diaphragms) that could not be utilized due to the new performance requirements.

The scope also included overspeed spin testing of the new impellers. Since the casings and bearing housings have already been proven in the field, the rerated rotors were at speed balanced (Figure 3) instead of the mechanical run test typically required for new equipment.

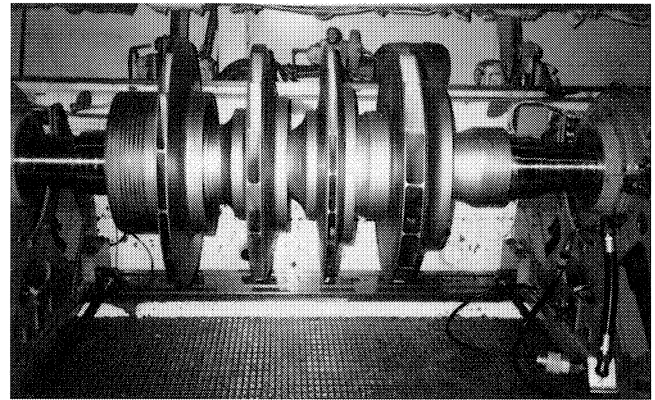


Figure 3. High Pressure Rotor in At-Speed Balance Machine.

What Makes this Project Unique?

Rerate Philosophy

The typical response to a non-OEM rerate is to replace the rotor and all diaphragms. This is primarily due to the lack of information available in terms of internal dimensions and aerodynamic performance characteristics of the existing hardware.

OEM experience and knowledge provide for an accurate assessment of the optimum rerate design. In some cases, existing hardware may be reapplied and in others, due to mechanical or performance requirements, it may be necessary to replace all existing hardware.

In this particular application, by new application of existing technology, it was believed that existing aerodynamic hardware could be accurately modelled mechanically and aerodynamically and reapplied without undue risk of compromising performance or integrity of design. This would greatly reduce the cost of the rerate. It was with this mindset that this project was approached.

Project Timing and Schedule

Complicating this approach, however, was the schedule. The project schedule required that the rerate be performed during the next scheduled shutdown which provided 29 weeks for the rerate hardware to be designed and manufactured. This also meant that no shutdowns would occur prior to the turnaround, thus providing no opportunity to dimensionally inspect the inside of the casing or the internal hardware. In addition, only 28 days were allotted for the turnaround itself. This timing made it critical that the new parts fit

right the first time since very little time was available for modifications during the turnaround.

AERODYNAMIC MODELLING

The first step was to aerodynamically model the existing hardware to determine what parts could be reused to meet the new requirements.

Data Available

Since very little existing data were available, it was necessary to accurately obtain as much additional information as possible to create the model and to design the new components. The primary sources of this information included spare rotors and customer supplied sketches, drawings, and design data from the instruction books. Information from spare bearings and seals was obtained and used for the lateral and torsional analyses.

Data Acquisition Methods

The spare rotors were dimensionally documented so that axial spacing and positioning of the impellers could be determined relative to inlet and discharge volutes in the casing. The rotors were then disassembled. The shafts and sleeves were dimensionally documented as well, so that the shaft scallops could also be incorporated into the aerodynamic model.

To model the impellers required accurate, three dimensional, internal flowpath dimensions that were difficult to obtain using conventional measuring methods. A coordinate measuring machine (CMM) was used to obtain these critical dimensions. The CMM is capable of accurately measuring the contours inside the impellers (Figure 4). Use of the measuring equipment also provided the opportunity to read these dimensions directly into a computer where the data were collected for future use by computer aided design (CAD) software. This eliminated the time required and the potential for error introduced by entering these data manually.



Figure 4. Impeller Flowpath being Measured by Operator on Fixed CMM.

Note that due to the emergence of portable CMM equipment (Figure 5), it is now possible to obtain this impeller data on site, without disassembling the rotor.

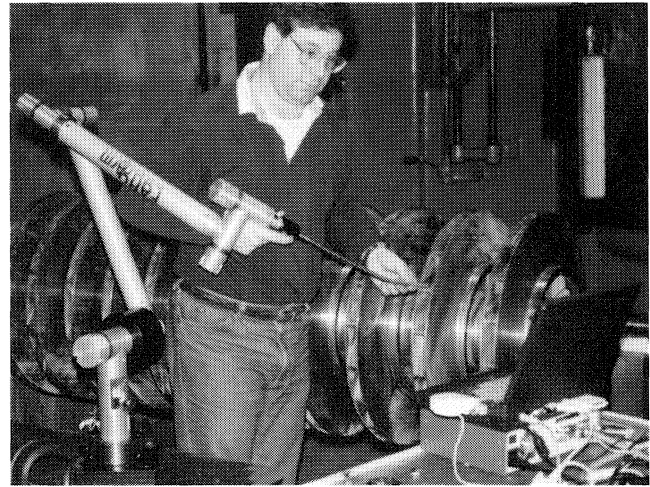


Figure 5. Portable Coordinate Measuring Machine (CMM).

Data Compilation Methods

The information mentioned previously was loaded into CAD systems where true, three-dimensional models of each impeller, including the contour of the shaft scallops were created. The diaphragm diffusers and return channels, along with the shaft scallops, were also modelled. These data were then compiled by a gas path program for use by the aerodynamic modelling software.

Data Analysis Methods

Upon completion of the dimensional model of the aerodynamic flowpath, development of the performance model was initiated. The first hurdle to overcome was the absence of information regarding the vane angles and number of vanes in the existing return channels. This angle is critical to the performance of the stage, since it sets the incidence at which the flow contacts the vanes in the return channel. This information was not available, since the units could not be opened for inspection. Therefore, the angle and number of vanes had to be back calculated. Since the existing impellers had been custom designed for this application, it was assumed that the blade angle and number of vanes would correspond to the optimum design for the original conditions. The optimum angle and number of vanes were calculated using the flow conditions at design and the impeller and diffuser geometry leading into each return channel. Note that in cases where standard staging (as opposed to custom designed) is used, the vane angle may not as closely correspond to the optimum angle for that application and this approach may not be as accurate.

A second critical issue in the modelling process was the determination of the impeller throat areas. This throat area is critical to accurately calculate the capacity of an existing impeller. Accurate dimensional data and CAD modelling of the impeller blade, hub, and shroud improved the accuracy of this calculation.

Once the model was completed, it was run on a proprietary 1-D mean streamline analysis program [1] using the original design conditions, and comparing the output to the design and past performance of the units. The model was then fine tuned until the results of the model accurately reflected the performance of the unit at design conditions.

Design Constraints

The next step was to run the model at the new performance conditions and to begin to optimize the re-rate selection with the following constraints in mind.

- *Horsepower and speed rating of existing driver*—This was to be maintained so that the driver could be used as is.

- *Maintain design compressor speed range*—This assured that existing impeller speed limits would not be exceeded and also increased the likelihood that lateral and torsional limits would not necessitate new bearings or couplings.

- *Space in existing casings (axial and radial)*—All new parts would be designed to fit into existing casings, to mate mechanically and aerodynamically with reapplied hardware, and to properly align with existing casing volute locations.

- *Optimum performance vs minimized cost*—To maximize performance while minimizing cost involved an iterative process to use as much existing hardware as possible and still meet the performance requirements, while staying within the limits set by the other constraints. Interaction with the customer to clearly define goals and assess priorities was critical during this operation.

Optimization Process

The iterative process described above involved three main factors:

- Efficiency
- Flow
- Cost

Compressor efficiency was critical to maintain power requirements and reduce the cost of steam. Flowrates affected the product output and plant profitability. However, to maximize flow and efficiency could negatively impact the use of existing hardware, thus increasing the cost of the rerate.

In order to maximize the balance between each of these variables, several selections were analyzed and the various options discussed with the customer, until a selection was obtained that best met all requirements.

The selection process involved several nonconventional methods including: using existing impellers and diaphragms in new locations within the compressor, mixing new impellers with existing diaphragms and *vice versa*, and modification of some existing diaphragms. (The modification of existing diaphragms was possible since the diaphragms were bolted together, which allowed for modification of the diffuser widths.)

Results of Analysis

The final selection for the rerate utilized seven of the 12 impellers and all but the two inlet diaphragms in the double flow body. The remaining diaphragms were either modified or used "as is." This selection resulted in a cost savings of more than 50 percent when compared to complete replacement of the compressor rotors and diaphragms.

Problems Encountered/Lessons Learned

- *Volute sizing/losses*—One of the problems realized, following the aerodynamic modelling, was that the second extraction volute in the HP casing was not large enough to pass the desired flow. This necessitated additional iterations to adjust the flow between the two extractions until performance was adequately met, while minimizing negative impact on plant output. The sizing of the existing volutes and the resulting pressure losses, velocities, and flow limitations should be determined early in the analysis so that these conditions can be considered throughout the modelling process.

- *Diaphragm vane angles and impeller throat areas*—The largest risk factor in assessing the performance of the rerate was the accuracy of the calculation of diaphragm vane angles and impeller throat areas. Accurate measuring and geometric modelling can improve this accuracy.

DESIGN DRAFTING OF REQUIRED PARTS/MODIFICATIONS

A layout drawing was required in order to design the rerate parts and to provide new assembly drawings to the customer. The data

obtained for the modelling were used in creating these layout drawings. This included composites, shown in Figures 6 and 7, of the existing casings and rerated rotor assemblies, followed by design and fit of the new, modified, and existing diaphragms into the layouts.

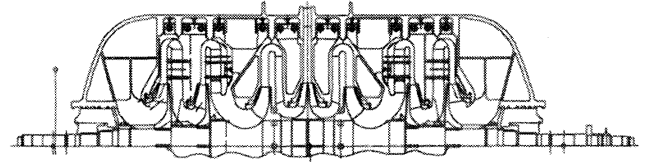


Figure 6. Layout of Rerated Low Pressure Compressor.

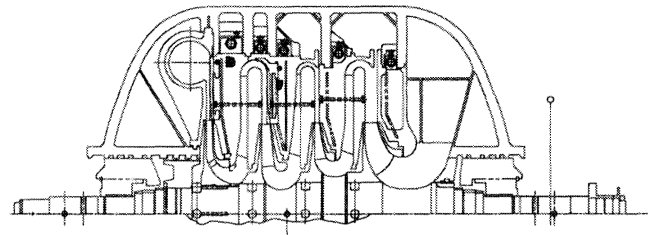


Figure 7. Layout of Rerated High Pressure Compressor.

Due to the lack of finish dimensions, coupled with the need to manufacture the diaphragms prior to acquisition of these dimensions, the modification and new design diaphragm drawings were created with excess stock left on the outer diameter (OD) and on the axial faces. The finish machining would be performed during the turnaround, after final dimensions were taken from the inside of the casings.

For all new parts, materials were selected using API standards for the intended service, rather than attempting to identify and match the materials used for similar existing parts.

Problems Encountered/Lessons Learned

Two areas of uncertainty in the creation of the layout were the casing to diaphragm fits and the vertical centering system. Assumptions were drawn from past experience and from the available sketches to overcome this lack of information.

A technique that proved beneficial and accurate in the geometric modelling of the impellers was to use arcs and lines rather than splines to model the flow contours. One reason for this is that for many impellers, the draftsmen and designers primarily use arcs and lines in the design. So it is reasonable to assume that splines are not necessary to create an accurate model. Also, spline data do not always transfer from CMM to CAD, and from CAD to the aerodynamic modelling software as accurately as arcs and lines.

MANUFACTURING AND ASSEMBLY PROCESS

Manufacturing

The new diaphragms were rough machined with excess stock to allow for finish machining once final dimensions were obtained. The diaphragm rough machining was done using precision flame cutting.

As dimensions were obtained and parts were received during the turnaround, the new diaphragms were finish machined to fit into the existing casings and some existing diaphragms were disassembled, modified, and reassembled per the modification drawings made earlier.

Mating parts were machined in the order in which they would be assembled in order to ensure a proper fit.

Assembly

The assembly was performed onsite so the compressor bottom half casings did not have to be removed and the bottom process

connections were not disturbed. The rerated diaphragms (Figure 8) and rotors (Figure 9) were installed and aligned in the casings. Top halves were then assembled in place to complete the installation.

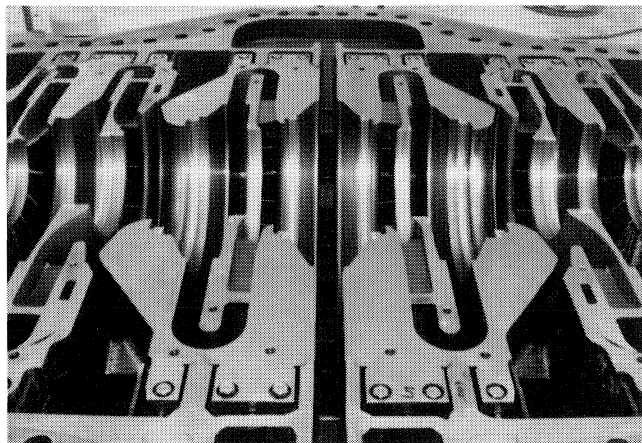


Figure 8. Low Pressure Casing with Diaphragms Installed.

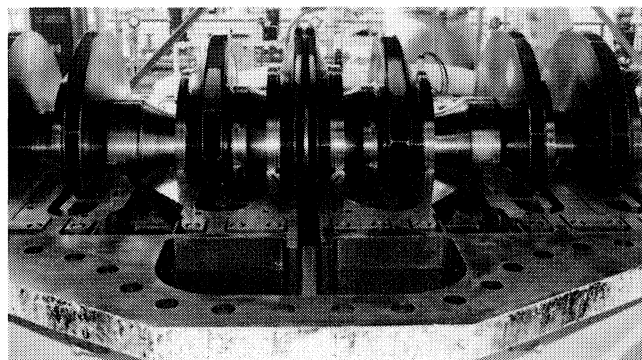


Figure 9. Low Pressure Casing with Rotor Installed.

Of note is the massive amount of machine rework required on the existing hardware during a very limited time frame of the ethylene turnaround. Close coordination between the manufacturer and the user was critical to address problem areas and meet an extremely ambitious schedule. This entire process was completed within the allotted time and the ethylene plant was started on schedule.

OPERATING PERFORMANCE FROM STARTUP TO PRESENT

Startup of the propylene refrigeration compressor was excellent from a mechanical standpoint. Vibration levels are extremely low,

with the entire train running smoothly. At the current operating conditions, the design conditions have not been reached; however, extrapolations of the operating data have shown that when the plant attains full rates on the 80/20 feedstock ratio (the plant has only run up to 85/15 to date due to business conditions), the compressor should match design conditions. The low pressure case and high pressure case design flows have been demonstrated at different times. However, the plant has not been able to achieve these flows together because of other plant constraints.

CONCLUSION

This rerate provides benefits to the end user in the areas of cost, leadtime, and reliability.

- Cost—As in this example, the cost can be reduced by as much as 50 percent when compared to a standard rerate in which all compressor internals are replaced. When compared to complete replacement of the entire unit with a new unit and all of the foundation and piping changes that go with it, the cost savings are even more substantial.
- Leadtime—The time required to rerate existing equipment is significantly less than that required to replace with new.
- Reliability—This is the area that often overwhelms the value of the first two. If the uprate is accomplished cheaper and faster, but does not perform well, the up front savings can be quickly lost in reduced output or costly downtime. In this type of rerate, however, reliability is comparable to that of new equipment. The mechanical and aerodynamic designs were evaluated similarly to that of new equipment. Materials for new parts were selected to be suitable for the service. The same testing that is used for new equipment can be applied. And the rerate included a full, API type mechanical and performance guaranty.

Based on these three areas of benefit, it is apparent that this type of rerate is an attractive option in the uprate of plants utilizing turbomachinery equipment.

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