UPGRADING CENTRIFUGAL COMPRESSORS WITH POLYMER SEALS IN AN ETHYLENE PLANT—A CASE HISTORY

by
John K. Whalen
Engineering Manager/President
TCE/Turbo Components & Engineering
Houston, Texas
and
John R. Dugas
Technical Associate, P&IP Department
E. I. duPont deNemours and Company, Inc.
Sabine River Works
Orange, Texas

ABSTRACT
Thermoplastic use as labyrinth seals in rotating equipment is continuing to gain acceptance in the process industries. Presented in this paper is a discussion on thermoplastic use as a labyrinth seal material in centrifugal process compressors. Labyrinths made from engineering thermoplastics are used to improve efficiency, reliability, and installation time. An introduction to the polymer materials commonly used for these applications is followed by a discussion on polymer labyrinth seal engineering. Finally, the case history is discussed. This particular case history involves the upgrading of seven compressors at an ethylene plant in Orange, Texas. The process involved upgrading and evaluating one compressor then converting the remaining six. A discussion on this process is presented followed by coverage of the installation and subsequent efficiency gains. Included is the presentation of results from an advanced computational fluid dynamic (CFD) analysis of two labyrinth seal designs.

INTRODUCTION
Hundreds of centrifugal compressors are running today with the benefit of thermoplastic labyrinth seals. These seals replaced aluminum parts in order to realize increased efficiency and reliability. Often an additional benefit includes reduced installation times due to easier fitting of the seals to the compressor. The thermoplastics covered in this paper include PEEK and Torlon® (generically referred to as PAI) based products. There is also a short discussion on Fluorosint® (mica filled PTFE). Forthwith the term polymer will be used to address these materials.

Dowson, et al. (1991), presented data on the use of abradable seal materials in centrifugal compressors and steam turbines. This paper covered the use of various materials for abradable seals where rotating teeth seal against a smooth bore seal. They presented efficiency improvements of 0.5 percent per stage for high flow machines and 2.5 percent per stage for low flow machines, by reducing clearances.

Whalen (1994) presented an introduction to the use of engineering thermoplastics for centrifugal compressor labyrinths. Among other things he covered an introduction to the materials used, the design of the labyrinths, and several case histories, demonstrating the efficiency gains possible with upgrades of this type.

Whalen and Miller (1998) presented a case history involving two of NOVA chemicals ethylene plants in Alberta, Canada. In 1996, the company upgraded three compressors in its Ethylene 1 unit, two cracked gas compressors and the propylene refrigeration compressor. Efficiency gains of 2 to 3 percent per compressor are reported. Based upon the success of the upgrade in Ethylene 1, they proceeded to upgrade four compressors in Ethylene 2 during their 1998 outage. Also covered in this paper are justification
disscussions, seal design, and installation. Significantly reduced seal installation times are reported.

The efficiency gains are realized by designing the polymer seals with closer running clearances. These clearances can be reduced because the flexibility of the polymer teeth affords a certain “forgiveness” during the inevitable contact between the seal and the shaft. Contact is assumed to occur when the compressor transverses critical speeds and when the compressor is momentarily surged. As such, these rubs are transient in nature. Since seal and rotor damage are avoided during these transients, the reliability of the machine is improved. Another factor regarding reliability has to do with the damage that does occur during prolonged hard rubs. It has been found that, although the seal may be damaged beyond use, the rotor comes through essentially unscathed. With aluminum seals, hard rubs can damage the shaft by galling.

POLYMER SEAL MATERIALS
FOR ROTATING EQUIPMENT

Most plastics belong to one of two groups, thermoplastics or thermosetting plastics. Thermoplastics soften when heated, and harden when cooled; they are melted and frozen into their desired shape during processing. Most thermosets harden when heated and they chemically change during processing so they will never melt again. The materials covered here are all thermoplastics.

When evaluating thermoplastics, it is helpful to compare their thermal properties:

- \( T_g \) —Glass transition temperature is the temperature at which the polymer chains of a thermoplastic become active and the polymer begins to soften and become “rubbery.”
- \( T_m \) —Melt temperature is the temperature at which the polymer begins to “melt.”
- \( HDT \) —Heat distortion temperature is the temperature the material’s flexural modulus drops to 100,000 psi.
- \( CUT \) —Continuous use temperature relates to “thermal aging” of polymers. The \( CUT \) is the temperature a polymer can be exposed to for 100,000 hours (11.4 years) and maintain 50 percent of its mechanical properties.

Subcategories under thermoplastics are amorphous (PAI) and crystalline (PEEK and mica filled PTFE). Crystalline thermoplastics have a crystalline order structure below their \( T_g \), and become amorphous above their \( T_g \). They can be used above their \( T_g \) with reinforcement, usually in the form of mica in mica filled PTFE and carbon fibers in PEEK. Their \( T_g \) is usually well below their \( T_m \).

Amorphous thermoplastics have no crystalline structure; their \( T_g \) is close to their \( T_m \) and they are not usually used above their \( T_g \). They normally do not require reinforcement.

The Materials

Mica Filled PTFE

Mica filled PTFE is considered an advanced engineering plastic. It is a crystalline high performance polymer with superior chemical resistance. This material is PTFE (polytetrafluoroethylene) filled with synthetic mica. The material is very weak (750 to 1200 psi tensile strength), which, of course, needs to be carefully evaluated for each application. The best application of mica filled PTFE in centrifugal compressors is smooth bore segments secured in a metal holder, which is rolled as an assembly into the compressor. Here, rotating laby teeth can cut into this very abrableal material. It is an excellent choice when the seal teeth are machined onto the rotating element. Because of its low strength, and the availability of superior materials, it is not recommended for use when the teeth are machined into the stationary part.

PEEK

PEEK (polyetheretherketone) as commonly used in rotating equipment, is either filled with 30 percent carbon fibers or 15 percent carbon fibers, 10 percent graphite powder, and 2 percent PTFE. The carbon fibers are added for strength while the graphite and PTFE are added for lubricity. The 30 percent carbon fiber material is usually used for pump wear rings while the other is usually used for compressor labyrinths. Due to the heat caused by the shearing of carbon fibers while machining, the 30 percent carbon fiber material is more difficult to machine. PEEK is highly resistant to chemical attack but will be attacked by concentrated, strong acids at high temperature. PEEK is sensitive to chromic, hydrofluoric, nitric, and sulfuric acids. It is unaffected by acetic acid, amines, and hydrocarbons.

Another use of PEEK in pumps is when it is combined with continuous carbon fibers. Here a carbon fiber ribbon is impregnated with PEEK, which acts as a binder. The ratio is about 70 percent carbon fiber, 30 percent PEEK. This is wound, under tension and heat, around a mandrel. This material is very strong in the direction of the fibers and has a low coefficient of thermal expansion (CLTE) in this direction. It is nongalling/nonseizing, has good impact resistance, good chemical resistance, and can be used at high temperatures.

PAI

PAI (polyamide-imide) is referred to as an imidized material, which is used in extreme service environments. Its properties usually classify this material as an amorphous thermoplastic. The grade commonly used in centrifugal compressors is filled with 12 percent graphite powder and 5 percent PTFE, both added for lubricity. This is referred to as a friction and wear grade. Note that no fillers are normally required for strength and as such this material is easier to machine than the PEEK blends. PAI is hygroscopic, which means it can absorb moisture (to 5 percent by weight and 2 percent by volume). Proper design, machining, storage, and installation prohibit this moisture absorption potential from being a problem.

For highly stressed and/or high temperature applications, a 30 percent carbon fiber, 1 percent PTFE blend of PAI is used. The carbon fibers reduce the thermal expansion coefficient and increase the strength of the material. The lower thermal expansion reduces thermally imposed circumferential compressive stresses thereby minimizing yield and creep concerns. The high carbon fiber content, coupled with the poor heat conduction of PAI, makes machining the material difficult and expensive, limiting its use to high stress, high temperature applications.

PAI is less resistant to chemical attack than PEEK. It is sensitive to amines, ammonia, oxidizing acids, and strong bases. It is unaffected by aliphatic, aromatic, and halogenated hydrocarbons.

Which Material to Use

For smooth bore applications in centrifugal compressors, mica filled PTFE is often the material of choice. PTFE based products are rarely used where the teeth are machined into the plastic.

Figure 1 is a bar graph of the thermal properties of PEEK and PAI. The “Laby” column represents a current recommended maximum use temperature for that material. For PAI, the current maximum application temperature is 325°F for the standard friction and wear grade and 375°F for the 30 percent carbon fiber filled grade. The “laby” temperatures assume normal continuous application temperatures and momentary swings of 25 to 50 degrees are acceptable. The points to notice here are the \( T_g \) and \( CUT \), which actually drive the maximum use temperature. The \( T_g \) for PAI is 510°F and for PEEK it is 300°F. The \( CUT \) for PAI is 392°F and for PEEK it is 500°F. The fillers have no effect on the \( T_g \) of the material.
The material of choice for centrifugal compressor labyrinths is the friction and wear grade of PAI, assuming it will not be subjected to chemical attack and the temperature is low enough (usually below 375°F). If PAI is susceptible to chemical attack, then PEEK can be used provided the temperature is low enough (below 250°F). For temperatures between 325 and 375°F, or for highly stressed applications, the 30 percent carbon fiber filled grade should be used.

In pumps, PEEK and continuous carbon fiber materials (wound) are used. The high CLTE of PEEK and the low CLTE of the wound material dictate where they are used. If running above manufacturing temperature, PEEK is used, up to 250°F, as the case wear rings. Between 250 and 600°F, the wound material is used as the impeller wear ring. Below manufacturing temperature, PEEK is used as the impeller wear ring.

**POLYMER SEAL DESIGN**

Figure 2 is a drawing of three typical labyrinth tooth configurations, a polymer seal and two aluminum style seals. The polymer tooth and the first aluminum tooth are shown with a "rake" toward the high-pressure side. This rake is believed to increase turbulence, and, therefore, sealing efficiency. More importantly, however, with the polymer seal, the rake allows the seal to act as a cantilever during rotor to stator contact. As shown in Figure 3, the raked polymer tooth deflects while the aluminum teeth "mushroom" over. After the contact (Figure 4), the polymer tooth regains its shape and clearance, while the permanently damaged aluminum teeth are now running with increased clearances. This ability of the polymer tooth to close back to its original clearance is termed "clearance integrity." Some aluminum seals have been designed with the polymer tooth style shown. However, since they are made from aluminum, they will still increase clearance after a rub and hence do not exhibit any clearance integrity.

Another important factor to consider in polymer seal design is proper accounting for the high thermal expansion coefficient of most of these materials. Relative thermal expansion calculations of the diaphragm, seal, and shaft need to be performed to accurately predict the running clearance of the polymer seal. The seals discussed in this paper were designed to have running clearances equal to the machine’s bearing clearance.

Stress levels with polymer seals become important since these polymers are weaker than the aluminum being replaced and they have low ductility, making them susceptible to failure initiating in stress riser areas. Proper analysis is required to assure a successful upgrade. The main area of concern is seals that see a high pressure drop (like balance piston seals) and seals in high temperature service, since strength drops off rapidly with increasing temperature.

A related issue is thermal aging. The base PAI material loses 40 to 45 percent of its strength when subjected to high temperatures (470°F) for prolonged periods of time (three to five years). Thermal aging was evident in the last wheel or two of compression in an air machine that ran for three years. In this machine, the discharge temperatures exceeded 400°F. The seals were fine, but the reduced strength made them very susceptible to damage upon removal. This thermal aging penetrates the material and as such acts on areas of low cross sectional area (like labyrinth teeth). It also manifests itself by further reducing the ductility of the material, making the part much more susceptible to brittle fracture. This is one of the factors that influence the maximum recommended use temperature of the PAI products.

**CASE HISTORY**

Polymer compressor labyrinths were first installed into a centrifugal compressor in a process plant in 1988. Since that time, hundreds of compressors have been upgraded with polymer labyrinth seals. Through the early to mid 1990’s, personnel in the Sabine River Works complex had considered upgrading some of their compressors in an attempt to increase plant output without sacrificing reliability.

The Sabine River Works (where the coauthor is employed), located in Orange, Texas, is a major ethylene producer. The plant has six primary compressor trains. The booster train is a single body double flow compressor driven by a 9500 hp steam turbine; it feeds the charge gas train, which is composed of three...
compressor bodies driven by a 36,000 hp steam turbine. The propylene refrigeration train is two compressor bodies driven by a 35,000 hp steam turbine. The ethylene refrigeration train is a single body compressor driven by a 6500 hp steam turbine. Sabine River Works also has a single body purge propylene refrigeration compressor driven by a 5000 hp electric motor and a two body methane train driven by a 2500 hp motor. In all, there are 10 compressor bodies driven by a combined 94,500 hp.

Research

Of course, retrofitting seals from proven aluminum to plastic was a cause for concern. A trip on either the charge gas, ethylene, or propylene refrigeration trains will shut down the plant. Meanwhile, a trip on the booster, purge propylene, or methane trains will seriously curtail production. The engineers at the facility did however understand the capabilities of today’s high performance thermoplastics. Review of the available literature assured them that the polymers used were suitable for the application. The fact that several similar compressors had already been retrofit demonstrated that an upgrade of this type is now a proven concept.

The next step, after reviewing the literature, was to contact other users who had installed polymer seals in their compressors. The coauthor’s company contacted an ammonia plant and two other ethylene plants that had experience with polymer seal upgrades. They also contacted two other of their facilities that had installed polymer seals. They asked for, and received, candid responses that ultimately gave them positive feedback from all parties contacted. The range of efficiency gains reported by these five facilities was 3.5 to 14 percent.

The Test Compressor

The booster compressor was selected as a test compressor because the ethylene plant can run without it, although at significantly reduced rates. Efficiency gains in the booster would be useful to plant output and energy savings. The coauthor’s company used a rule of thumb efficiency gain predictor of 0.5 percent per wheel, which equated to 3 percent for the compressor. Whalen (1994) estimated efficiency gains of 0.5 percent to 1 percent per wheel and proposed using numbers of 0.25 to 0.5 percent per wheel for justification calculations. He also noted that if there is a balance piston seal the higher end number could be used, while if there was no balance piston seal (as with the booster) the lower numbers should be used.

After the upgrade, the compressor flow increased 3.1 percent and steam consumption was 2.7 percent less. Depending on plant operation, the excess compressor flow was utilized to increase plant output. If the flow could not be used, the reduced steam flow was still a significant energy savings and by itself could justify the project. Figure 5 is a photograph of a shaft seal from the booster compressor as it was inspected after a one and a half year run.

Installation time with these seals did take a little longer than with aluminum. The seals are more fragile than aluminum and extra care is required in handling and installation. In addition, plant personnel wanted to give the seals a good chance of success, so extra time was spent fitting the seals and checking the internal alignment of the compressor, however no internal alignment changes were made. The seals were installed and no other work was done to the compressor that would appreciably impact efficiency. Typically, once a comfort level is reached installing these seals, installation time decreases.

Upgrading the Remaining Compressors

Based upon the positive experience with the booster compressor, the plant prepared a project to upgrade six other compressors to thermoplastic seals. Project economics were extremely attractive. Included in the upgrade were the first two cases of the charge gas train. The third case was not upgraded because it was already running an abradable seal material (nickel graphite) with close clearances against rotating teeth. In order to upgrade to PAI, the rotating teeth would have to be machined off the sealing surfaces. It was felt that further efficiency gain by installing PAI in the third case could not be justified at this time. Although there is additional cost to remachine the teeth off the sealing surfaces, this is something that should be considered since it does eliminate the rotating teeth, which some users find undesirable.

The two propylene refrigeration compressors were also selected to be upgraded. These machines were rerated a few years ago but increased refrigeration would mean more ethylene product could be produced. Also, lower energy consumption is always beneficial. The last two compressors selected were the ethylene and the purge propylene. The methane train was not chosen because it was slated to be rerated in the future and the conversion to polymer seals would be delayed until that time. (A project to upgrade the methane train to thermoplastic seals is underway at this time.)

The upgrade process comprises several steps. Sample aluminum seals were sent to the vendor to make drawings. Sealing diameters had to be forwarded along with the compressor speeds, and gas temperatures and pressures. Bearing clearances and other data had to be made available to complete engineering. Interstage shaft seals as installed in the ethylene refrigeration compressor are shown in Figure 6.

During this process, a couple of concerns arose regarding the propylene compressors. These machines were rerated previously and the company performing the rerate replaced some of the stages. These new stages were more conventional in design as compared to the OEM design. The original OEM stages incorporated seals that are axially bolted to the diaphragm and have
stepped bores. A discussion on the stepped bores led to indecision as to whether the sealing surfaces should be machined straight (no step). If the steps were machined off, then the replacement seals could incorporate more teeth. However, the effect of the step on sealing efficiency was not clear. Current conventional labyrinth leakage analysis tools do not adequately model this phenomenon. The lead author’s company recommended, and the coauthor’s company agreed, that a computational fluid dynamics analysis (CFD) be performed to determine the best seal configuration. Meanwhile the axial bolting concern was not adequately addressed at this time. This will be covered in more detail when the seal installation is discussed.

**CFD Analysis**

As mentioned, it was decided that a CFD analysis needed to be performed to determine the optimum seal design for the propylene compressors. The user contracted with the manufacturer to have this analysis completed. The manufacturer contacted several potential sources for an analysis of this type, and results are presented from a selected engineering firm in the northeast.

As shown in Figure 7, the OEM design uses a step on the eye sealing surface and a corresponding high-low tooth labyrinth configuration. Also presented is an alternative design where the stepped portion is removed from the eye and additional teeth made available in the seal. The question to be answered was which configuration is more efficient.

![Figure 7. OEM Designed Labyrinth and Alternative Labyrinth Design.](image)

Since conventional labyrinth seal codes are not sophisticated enough to address these design differences, a CFD analysis was performed (Sommer, 1998). For consistency, cases were run for air at 67°F, an upstream pressure of 87 psia, and a downstream pressure of 58 psia. Several turbulence models were run with the Baldwin-Lomax algebraic model yielding the more reasonable results. This analysis is complicated by the grid requirement to accurately model the relatively small clearance gap and the large space between teeth. A two-dimensional multiblock grid generator was well suited to this type of modeling. Between 12,000 and 14,000 grid points were used to discretize the flow domain for the two cases evaluated. A viscous steady-state, axis-symmetric CFD analysis was then conducted for each case. The code used an explicit time-marching scheme with central finite differences for spatial discretization.

The OEM model is represented in Figure 8. Note the three-tooth configuration with the short tooth in the middle riding on a step on the impeller eye. As the flow path is followed through this seal, observe that the step does increase turbulence on the left side. However, the trailing edge of the step does nothing to reduce the leakage flow. Also, note the flow recirculation on the left side of the figure.

The alternative geometry seal is represented in Figure 9. Here there is an additional tooth fitting into the same area as the OEM seal. The clearance is the same as the OEM seal. Note the very large region of recirculation between the teeth. Also, note the relatively unobstructed flow path through the clearance between the teeth and the eye. This would confirm that decreasing clearance would have a strong effect on reducing leakage flow rates.

![Figure 8. Plot from CFD Analysis of the OEM Labyrinth.](image)

![Figure 9. Plot from CFD Analysis of the Alternative Seal Design.](image)

The OEM seals predicted leakage is 0.92 kg/s while the alternative designed seal leakage was calculated at 1.15 kg/s. This is a 25 percent increase in leakage by redesigning to a seal without the middle step. Based upon the analysis, it was decided to retain the OEM seal configuration.

**Problems with the Propylene Compressors**

As discussed earlier, the OEM eye and shaft seals still in the propylene compressors are installed with axial bolts. These seals are multisegment and each one has 40 bolts holding the seal to the diaphragm. Figure 10 is a drawing illustrating this seal design. The seal segment shown is from an eight segment seal. Figure 11 is a photograph of some of the diaphragms in the high-pressure propylene compressor. This photograph shows the seals as installed with the axial bolting. Note the fits for the three balance piston seals on the far end of the photograph, these seals roll in and therefore do not require any bolting.

![Figure 10. Drawing of OEM Propylene Compressor Seal.](image)
The low-pressure propylene compressor (LPC) is a double flow machine with four stages of compression (eight wheels). The first two stages were retrofitted during the previous rerate but the last two still had OEM style seals. Therefore, this machine has four eye seals and two shaft seals that are bolted in, this works out to 240 axial bolts. The high-pressure compressor (HPC) is a straight through four-stage machine. Only the last eye seal was retrofitted during the rerate so all the other eye and shaft seals are bolted in. This again adds up to 240 axial bolts. Luckily, the balance piston seal rolls in with a conventional hook.

With the aluminum seals, staking around the bolt head could deform the metal. This mechanically prohibited the bolt from backing out. With the polymer seals, staking the seal material was not an option. It would not deform like the aluminum, so this mechanical locking feature was not available. Various adhesive and other methods of securing the bolts in the diaphragm were investigated but none proved satisfactory during the time frame available. A bolt coming out could bring the machine down and shut down the plant; the old style aluminum seals were reinstalled into the compressor at these locations.

A redesign has been completed that will put polymer seal inserts into steel holders that can then be installed into the compressor with the axial bolting staked in place. Other redesigns were investigated that involved reworking the diaphragms but the material left to work with was minimal; since there was no hook fit, there was no material in the bore of the diaphragm to remachine. The redesign is illustrated in Figure 12. Note the polymer insert installed in the steel holder, which can be bolted into the machine without modification. The cross sectional area to work in is very limited resulting in thin cross sections of the polymer. A concern over the strength of the seal was addressed by performing a finite element analysis (FEA) of the polymer inserts.

**FEA of Redesigned Seal**

Two redesigns utilizing the existing aluminum seal bored out to accept a PAI labyrinth insert were considered. The FEA of the first design yielded unacceptably high stresses forcing a redesign that dramatically limited stresses on the PAI insert. This second design is illustrated in the drawing in Figure 12. In order to keep stresses and deflections in the holder at acceptable levels, the holder material was upgraded from aluminum to steel. This also allowed the use of four segment seals at all locations (instead of the unwieldy eight segment seals used in some locations).

The FEA assumed pressure to build in the axial junction between the insert and the holder since this could be a clearance space. Pressure buildup between the OD of the insert and the holder was also considered. It was decided that this pressure should not be allowed to build up, as a reduction of the bore of the insert was possible. This was because the insert OD would be at the high pressure and the bore would be a decreasing pressure, as the pressure dropped though the labyrinth portion of the seal.

To prevent this pressure buildup, an annular vent was designed into the seal holder. High-pressure gas that makes it to this vent is collected here and vented to the low-pressure side of the seal by the use of milled slots at the four splitlines. This forces a low-pressure boundary condition from the annulus back.

Figure 13 is a plot from this analysis. Note the very low stresses in the holder and PAI insert.
Results from Upgrades

Other upgrades to some of the rotating equipment were performed during this outage. The following are estimates of the gain attributed to the polymer seal upgrades:

- Directly attributable—
  - Ethylene refrigeration train: 7 percent reduction in steam flow
  - Purge propylene refrigeration train: 17 percent increase in head, 5 percent increase in flow, with a corresponding 5 percent increase in electric power consumption
- Difficult to differentiate savings due to other technology changes made—
  - Propylene train: Increased flow 9 to 16 percent (depending on stage) with 8 percent speed increase and 4 percent steam flow increase. Note that only about half the potential gain was achieved since many seals were not upgraded due to the bolting problem.
  - Charge gas train: 14 percent gas flow increase with 5 percent steam flow increase

It is estimated that overall ethylene plant output increased about 5 percent attributable to the polymer seal upgrades. This benefit is achieved when the charge gas train is the plant constraint, which is about 50 percent of the time. The remainder of the time significant energy savings are realized. The user feels the installation of the polymer seals has improved plant reliability due to being less susceptible to hard rubs like aluminum seals.

CONCLUSION

This paper brought the literature up-to-date on compressor labyrinths made from engineering thermoplastics. Discussed were materials’ properties, engineering, the upgrade process, installation, and results. This was a successful case history and the user is extremely pleased with the performance gains attributed to the polymer seals.

REFERENCES


ACKNOWLEDGEMENT

The authors of the paper would like to thank Julia Postill of TCE for performing the propylene seal redesign and subsequent finite element analysis. We would also like to thank Steve Sommer and NREC for permission to publish the results of the CFD analysis. Lastly, we would like to thank all parties involved from TCE and DuPont for their contribution to a successful project.

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