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POLYMER SEAL USE IN CENTRIFUGAL COMPRESSORS – TWO USERS' EXPERIENCES OVER 15 YEARS

John K. Whalen, PE
Technical Director
John Crane Engineered Bearings
Houston, TX, USA

Jim Allen
Senior Rotating Equipment Specialist
Engineering Technologist
Nova Chemicals Corporation
Joffre, Alberta, Canada

Jonathan D. Cardell
Mechanical Engineering Consultant
Ethylene Technical Group
DuPont Packaging & Industrial Polymers
Sabine River Works
Orange, TX USA

John R. Dugas
Consultant
Orange, TX, USA

ABSTRACT

For over 20 years now, the efficiency and reliability of centrifugal compressors has been enhanced by the application of engineered thermoplastic materials to the eye, shaft, and balance piston labyrinth seals. Traditionally these seals have been manufactured from metallic materials (such as aluminum) and have required relatively large clearances for reliability reasons. By upgrading to carefully selected engineered thermoplastics the clearances can be reduced without sacrificing reliability. Polymer seals maintain their clearances even after typical start up rubs, whereas metallic seals open up during these rubs and are then open for the remainder of that run cycle (3, 4, 5 years or more). Polymer seal upgrades result in increased compressor efficiencies with the added benefit of easier installation.

Of course whenever an upgrade of this type is first pursued the question of reliability and long term sustained success needs to be considered. Replacing a metallic component with a plastic one, in a service where running 24/7 for several years is imperative, needs to be carefully considered. Now that the seals have been successfully applied for over 20 years now, and individual seals have run for 9 years and more, we can evaluate the applicability of these materials to this type of application.

INTRODUCTION

The installed base of centrifugal compressors upgraded with thermoplastic seals is continually increasing; due in large part to the experiences of those who pioneered this concept several years ago. The proven success of these retrofits has allowed others to confidently pursue upgrade projects of their own. The thermoplastics covered in this paper include Polyetheretherketone (commonalty referred to as PEEK) and Duratron® (generically referred to as polyamide-imide; or PAI) based products. Forthwith the term polymer or thermoplastic 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. Their 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 presented 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 charge 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 discussions, seal design, and installation. Significantly reduced seal installation times are reported.

Whalen and Dugas (2000) reviewed polymer seal material selection and seal engineering prior to presenting an extensive case study from DuPont's Sabine River Works plant in Orange, Texas. At this facility a charge gas booster compressor was first upgraded and the results of that upgrade analyzed. Based upon the considerable efficiency gains found DuPont decided to upgrade the remaining compressors in the facility. There were some challenges that had to be overcome due to a unique OEM seal design in the propylene compressors and the results of that study and seal redesign are presented. The paper concludes with performance gains reported by DuPont attributed to the polymer seal upgrades.

A thorough review of the state of thermoplastic seal use in centrifugal compressors was presented in tutorial format by Whalen, Alvarez, and Palliser (2004). The tutorial started with an introduction to labyrinth seal design, theory, and nomenclature and then proceeded to explain how thermoplastic seals differ from metallic in this type of application. An introduction to thermoplastics is then presented, including how the materials used were selected. A discussion on engineering a typical upgrade and engineering concerns is followed by two case studies (the NOVA and DuPont projects).

The present paper will briefly review seal material selection and design and then revisit the two case studies previously published (NOVA and DuPont). The majority of the current presentation will then focus on polymer seal experiences at these facilities through the years.

THERMOPLASTIC SEALS

Labyrinth Seals

A labyrinth seal is essentially a series of annular orifices utilized to seal a region of high pressure from a region of low pressure. These are "clearance seals" and as such, leak. In a centrifugal compressor the impeller eye seals, the shaft seals between impellers, and the balance piston seal (Figure 1) all are sealing a high pressure area from a low pressure area.

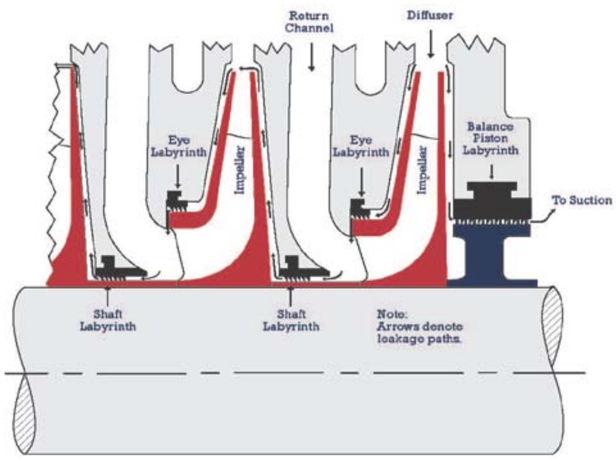

Figure 1. Partial Section Through a Typical Centrifugal Compressor Illustrating Eye, Shaft, and Balance Piston Seals as Well as Typical Leakage Paths.

Labyrinth seals (labys) in centrifugal compressors can have a significant impact on compressor efficiency. In a centrifugal compressor, work is done to increase the gas pressure and this pressure is contained by labyrinth seals throughout the compressor. Compressor efficiency can be improved by reducing labyrinth seal leakage. However, the seal clearance cannot just be arbitrarily reduced, because reduced clearance metallic seals can rub and open up; resulting in a negation of the efficiency gain, potential rub related vibration problems, and possible damage to the rotating element.

Labyrinth seals made from high performance thermoplastics, when properly designed and installed, can be utilized because when they rub, during normal transients such as traversing a critical speed, they will "give" and then regain their original "pre-rub" geometry. This is the main driving force behind the use of reduced clearance thermoplastic labyrinth seals in centrifugal compressors.

A typical metallic labyrinth seal in the "as-installed," "during rub," and "after rub" conditions is illustrated by the drawings in Figure 2. Note the seal is installed with clearance to the shaft in the "as-installed" case. The "during rub" drawing depicts the rotor contacting the seal and causing permanent deformation of the seal tooth tip. Therefore, in the "after rub" case the tooth remains deformed and excessive clearance results, leading to increased leakage. As shown, it is also possible that galling can take place on the rotating surface as contact between the metallic seal and the rotor occurs. Also during the rub, enough energy may be imparted to the rotor to cause vibration problems and the associated reliability concerns.

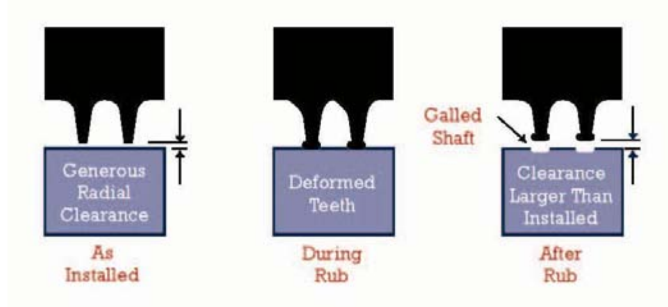

Figure 2. Typical Metallic Seal Pre-rub, During Rub, and Post Rub. (Note the permanent deformation of the metallic tooth and the possibility of galling damage to the rotating element.)

The drawings in Figure 3 depict a similar scenario but with a thermoplastic seal installed. In this case, the "as-installed" clearance is typically tighter than with the metallic seal. During the rub, the tooth deflects, moving with the rotor during this transient. After the rub the tooth regains its original "as-installed" configuration, no damage occurs to the rotor, and the initially reduced clearances are regained.

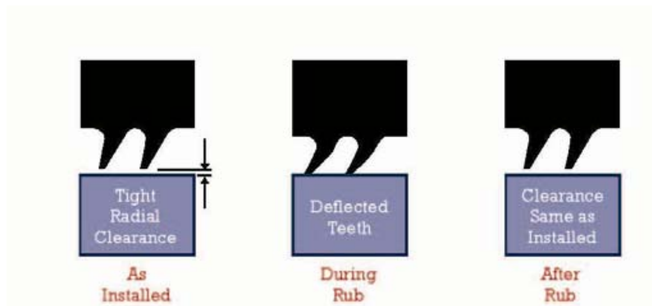

Figure 3. Typical Thermoplastic Seal Pre-rub, During Rub, and Post Rub. (Note the flexing of the tooth during contact and the damage- free rotating element after the rub.)

Thermoplastics

The most common thermoplastics used to manufacture labyrinth seals for centrifugal compressors are DURATRON® and PEEK™. Other materials used include Fluorosint® and Vespel® products. All of these thermoplastics are supplied in various grades where the blending of the final product can influence mechanical properties and chemical compatibility.

Fluorosint® is considered an advanced engineering plastic. It is a crystalline high performance polymer with superior chemical resistance. Fluorosint® is Teflon® (PTFE, or polytetrafluoroethylene) filled with synthetic mica. This material, being Teflon® based, lacks strength (750 to 1200 psi tensile strength), and needs to be carefully evaluated for each application. The best use of Fluorosint® is smooth bore segments secured in a metal holder, which is then rolled as an assembly into the compressor. Here, rotating laby teeth can cut into this very abradable 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 rarely recommended for use when the teeth are machined into the stationary part.

PEEK, when used as a laby seal material, is typically either filled with 30% or 15% carbon fibers, 10% graphite powder and 2% PTFE. The carbon fibers are added for strength while the graphite and PTFE are added for lubricity. 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.

Duratron® (PAI or 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 typically used for compressor labyrinths is filled with 12% graphite powder and 5% PTFE, both added for lubricity. Note that no fillers are required for strength, making this material easier to machine than the PEEK products. Duratron® is hygroscopic, which means it can absorb moisture (to 5% by weight and 2% by volume). Proper design, machining, storage, and installation prohibit this moisture absorption potential from being a problem. Duratron® is less resistant to chemical attack then PEEK. It is sensitive to amines, ammonia, oxidizing acids, and strong bases. It is unaffected by aliphatic, aromatic and halogenated hydrocarbons. See Whalen, et al, (2004) for a more detailed discussion of these materials.

Selecting the Thermoplastic to use

For smooth bore polymer seals in centrifugal compressors, Fluorosint® is often the recommended material. The material of choice for centrifugal compressor labyrinths is Duratron®, assuming it will not be subjected to chemical attack and the temperature is low enough (usually below 350° F (177 °C)). If Duratron® is susceptible to chemical attack, then PEEK can be used provided the temperature is low enough (below 250° F (121 °C)). Thermoplastic use in rotating equipment can increase efficiency and reliability. Understanding their properties is critical to successful applications.

CASE STUDIES

Nova

Next, two case histories are reviewed. In the first all major compressors were upgraded at two of Nova's near identical ethylene plants near Calgary, Canada (Figure 4). Their E1 unit is rated at 1.6 billion pounds/year (725,000 Tonnes/year) and the E2 unit is rated at 1.8 billion pounds/year (816,000 Tonnes/year). The Propylene compressor is one of the largest compressors ever upgraded. The first stage eye seal has a 45 inch bore (1,143 mm) and the balance piston seal has a bore of 36-1/2 inches (927mm). Due to its size special manufacturing processes had to be utilized to manufacture seals with bores in excess of 40 in (1016 mm) while using ingots with OD's limited to 36 in. (914 mm), this is done by segmenting the seals.

The majority of the data presented here is taken from Chow and Miller (1998) and from Whalen and Miller (1998). The Chow and Miller (1998) paper presents their experiences on coatings and thermoplastic seals as well as a discussion on compressor performance monitoring. The Whalen and Miller (1998) paper mostly covers the thermoplastic seal upgrade from this same outage, which took place in 1996. During this turnaround, thermoplastic seals were installed in two charge gas compressors and the propylene compressor. One point addressed was the upgrade of the original balance piston sealing arrangement, which used rotating teeth on the balance piston sealing against a smooth babbitt surface in the balance piston (BP) seal. The upgrade involved machining the teeth off the balance piston and utilizing a toothed Duratron labyrinth seal. This did result in a minimal reduction in the BP diameter which had no measurable impact on thrust loading. This new seal arrangement allowed for an easier seal installation.

Figure 4. NOVA Chemicals' Joffre manufacturing facility.

As discussed earlier, the fitting of thermoplastic seals can be easier, and therefore faster, than the fitting of aluminum (or babbitted) seals. Chow and Miller (1998) reported: "Installation and fitting thermoplastic seals vs. aluminum labyrinths and babbitt balance drum seals has proven to be a real time saver. Memories of fighting, fitting, hammering and occasional breakage of the aluminum seals and memories of scraping, checking and more scraping of balance drum babbitt seals are a thing of the past." As outlined in the paper these polymer seals can be easily sanded to obtain the desired installed clearances. Chow and Miller also wrote, "Evaluation of process data has shown a 2-3% efficiency increase per compression stage with the installation of thermoplastic seals."

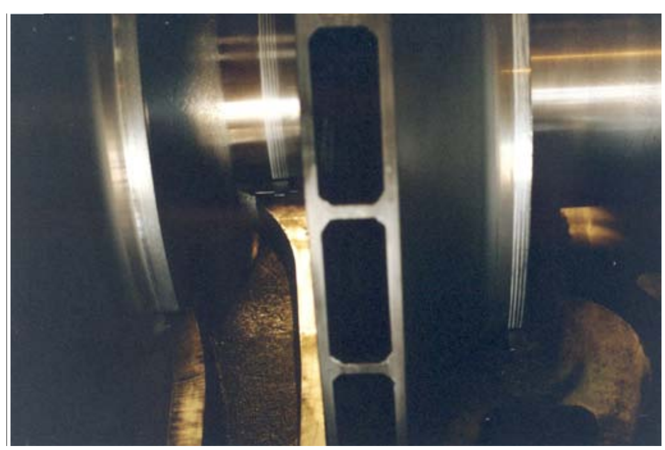

Figure 5. Nova - picture of as found aluminum rotor damage.

Nova was pleased with the upgrade and went on to upgrade the compressors in their other unit two years later; "The Rotating Equipment Specialists at the Joffre site believe that the use of thermoplastics is important in optimizing performance, increasing run lengths, and reducing turnaround costs."

An example of the galling damage that can take place when aluminum seals rub against sealing surfaces is illustrated in figure 5. Note the score marks at each tooth location on the eye and shaft sleeve. A newly installed polymer seal is shown in the photograph in figure 6.

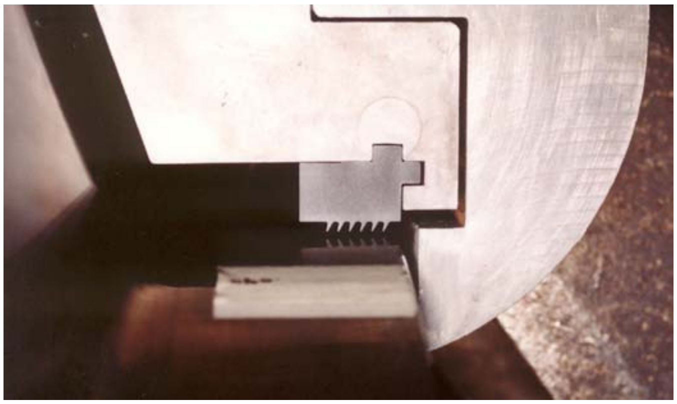

Figure 6. Nova - picture of an installed Duratron eye seal.

DuPont

This case history is documented in a paper by Whalen and Dugas (2000). It discusses the upgrade of seven compressors at a 1.5 billion pounds/year (680,000 Tonnes/year) ethylene plant in Orange, Texas.

This case history follows the upgrade process and includes the upgrade of a single compressor as a benchmark for performance improvement expectations. At this facility, there is a 10,000 hp (7.5 MW) booster compressor ahead of the traditional charge gas train. The charge gas train is shown in the photograph in figure 5 and schematically in figure 6. This booster compressor can be removed from service without forcing the rest of the unit down. It was decided to upgrade this compressor to evaluate thermoplastic seals. The seals were installed in September of 1997.

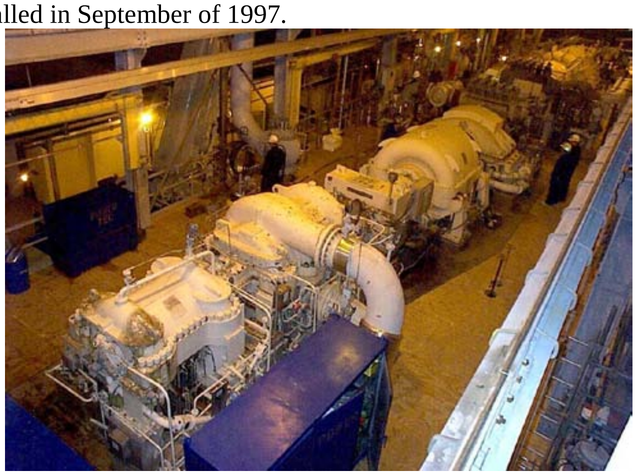

Figure 7. Photograph of DuPont's charge gas train.

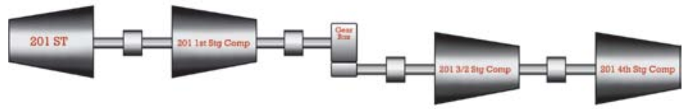

Figure 8. Schematic of DuPont's 36,000 hp (27 MW) charge gas train.

When the compressor was brought down to install the polymer seals, the only work performed that would affect efficiency was the installation of the upgraded seals. This allowed the efficiency change to be attributed solely to the thermoplastic seals. After the upgrade, the plant personnel determined the compressor flow increased 3.1 percent and the steam turbine driver steam consumption was reduced 2.7 percent. Based upon this, the plant easily decided to upgrade the other six candidate compressors that would be opened during the major turnaround in March of 1999. The compressors upgraded include: the first two cases of the charge gas train (first three compression stages, figure 9), the two propylene compressors, the ethylene compressor, and the purge propylene compressor.

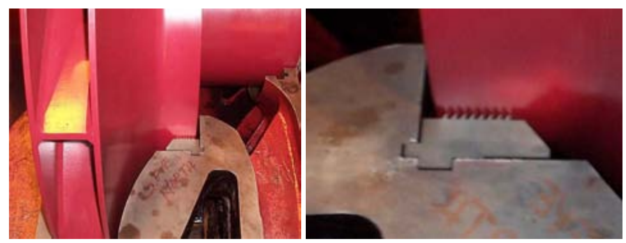

Figure 9. Polymer eye seals installed in DuPont's charge gas compressor.

Three compressors not upgraded at that time where the last stage of the charge gas, which had abradable seals running against rotating teeth, and the two methane compressors that were being considered for replacement or major rerates. Based upon the success of all of the other compressors upgraded, and considering some issues DuPont had in the past with the abradable seals in the 4^{th} stage charge gas compressor; the plant decided to go ahead and remove the teeth off the last charge gas compressor and upgrade with thermoplastic seals. These seals were installed in July of 2005 and spares supplied in January of 2006.

Often times it is difficult to accurately determine the true impact of a seal upgrade project. However, by carefully analyzing all factors DuPont was able to estimate the following (attributed to the thermoplastic seal upgrade project):

• A 7 percent reduction in steam flow to the ethylene driver.

• A 17 percent increase in head coupled with a 5 percent gas flow increase accompanied by a 5 percent increase in motor power consumption with the purge propylene train. Overall an efficiency gain even though the motor draw did increase.

• A 9 to 16 percent increase in flow with the propylene compressor coupled with an 8 percent speed increase and a 4 percent steam flow increase. (Note: due to the seal problem mentioned earlier only a fraction of the seals were upgraded.)

• A 14 percent flow increase in the charge gas train with a 5 percent steam flow increase.

EXPERIENCES TO DATE

Both plants have had outages since the initial installations and the remainder of the presentation will review the findings.

Nova

Nova has relatively clean service so they have been able to reuse most of the installed seals through two major outages. These seals are more fragile than metallic counterparts so when removing seals for inspection some were damaged and had to be replaced. The damaged Duratron seals were sent to the material vendor for analysis (Hebel, 2009): "Five (5) seals were sent for evaluation. Visually, the seals were fine, with the exception of damage obtained during the removal process. They each exhibited some form of damage ranging from a few chips to being completely broken". There was one seal from the second stage charge gas compressor and 4 from the 3rd case.

To evaluate the integrity of the Duratron seals, a few typical mechanical properties of the returned seals were compared to those of standard in-stock Duratron. Only one seal, the (B-case, 2nd wheel), was large enough to allow full-sized tensile test bars to be machined. This was important because full-sized tensile bars are needed to yield a full complement of tensile properties including strength, modulus, and elongation values. Tensile properties are a good indicator of a material's integrity. In addition, other mechanical properties were also evaluated, including compressive strength and modulus. Due to the limited sample size of the other four smaller cross-section seals, only compressive test samples could be machined and tested. The property values from the in-service Duratron were then compared to a Duratron baseline set of data. The Duratron baseline values were obtained from recent compression molded material representing the same production process as the returned parts. Two ingots were pulled from production and test plaques were machined, tested, and results documented.

Overall, the property values of the 9-year old Duratron compressor seals compared very well to typical data for this product. Tensile strength and elongation properties of the B-Case sample were a little lower than baseline, but the tensile modulus was higher. This can be attributed to slight embrittlement of the product in service. The flexural and compressive properties were higher than current production which can also be attributed to the same reason. The T_g, or glass-transition temperature, of the 9-year old part remained steady at 280 which shows no major degradation of the polymeric structure.

Next, compressive data for all the Duratron seals were compared. The compressive strength and modulus values were very close and within a 7% spread showing good data integrity amongst the returned seals.

Conclusion: After 9 years of service, the integrity of the Duratron seals test to be very similar to current production.

Figure 10. Tool developed to scrape between teeth.

Even though Nova's process gas was cleaner than DuPont's they still did experience some fouling in the charge gas compressor labyrinths. They wanted a way to scrape between the teeth in an attempt to reuse as many seals as possible. The tool shown in figure 10 was developed to help with this scraping. A used machining insert (an old polycrystalline diamond coated insert that was used to cut the seal teeth) was inserted into a handle for ease of use. Nova found this tool extremely useful and the only real issues they had involved seal removal breakage; getting the seals out to scrape them. As the material vendor noted the material did become slightly more brittle so the chance of breakage does increase over time. Figure 11 is a photograph of the scraping tool as it would be used in a typical seal.

Figure 11. Photograph showing tooth scraper in use.

Note that Duratron embrittlement over time at elevated temperatures is a known phenomena (Whalen, et al, 2004) and the higher the temperature the more of an issue this becomes. Of course for the typical compressors in an ethylene plant material degradation has proven to be a non issue for seals used for over 9 years. After the third run however (15 years or so) consideration should be given to replacing the seals. Likewise in hotter service (such as air compressors in refineries or ammonia plants) consideration should be given to replacing the "hot end" seals during every scheduled turnaround.

Figure 12 is a photograph of a shaft seal removed from the "B" charge gas compressor. This seal ran for 4 years, was removed, cleaned and inspected (it was still in tolerance) and reused. The seal then ran another 5 years (9 years total), was removed, cleaned and inspected (it was still in tolerance) and again reused. The next scheduled outage is 6 years from startup so this seal will then have 15 years of total run time. Figure 13 is a photograph of another seal inspected and subsequently reused after a 9 year run.

Figure 12. Polymer shaft seal as removed from Nova's 2nd case charge gas comp. after 4 and 5 year runs (9 year total run).

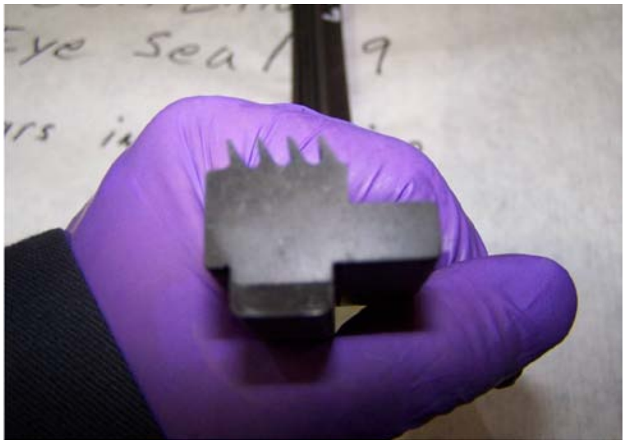

Figure 13. Polymer eye seal as removed from Nova's compressor after 4 and 5 year runs (9 year total run).

DuPont

As outlined above DuPont installed Duratron seals in the charge gas booster compressor in 1997. Based on this success, DuPont installed Duratron seals in the 1st, 2nd and 3rd stage charge gas compressors, the high case and low case propylene compressors, the ethylene and the purge propylene compressors during the 1999 turn around (TA).

Figure 14. Polymer eye seal in DuPont charge gas compressor after 5 year run.

Unfortunately, fouling in the booster and some of the charge compressors made it difficult to remove the seals intact for reuse. DuPont replaced these with new seals in each subsequent TA (2003, 2008) and several smaller outages in between. DuPont tried numerous methods of removal (solvent soak, tapping/beating, pressing, etc) with no success. Duratron seals in the clean, refrigeration compressors were in good condition and reused in the 2008 TA. The seals in the propylene compressors survived the ingestion of suction drum demister screens and are still running today.

Seals installed in a charge gas compressor, after a 5 year run, are shown in the photographs in figures 14 and 15. Note that with cleaner sections of this train the seals did not foul, and obviously they did not foul in the clean propylene and ethylene refrigeration compressors.

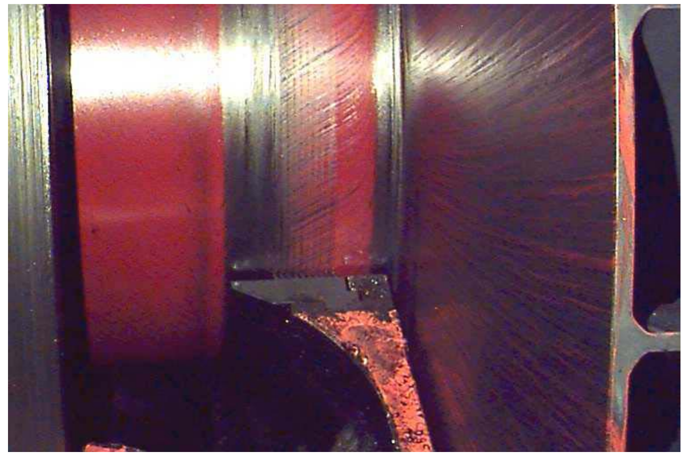

Figure 15. Polymer eye seal in DuPont charge gas compressor after 5 year run.

CONCLUSIONS

Polymer seals have been used in centrifugal compressors for over 20 years. In the early days there were some problem applications and several of these are well documented in the literature. However, as this paper illustrates, there are successful applications in a wide range of compressors as found in ethylene plants. The cases presented here represent up to 15 years of experience running polymer seals in critical turbomachinery. Analysis of material removed from service after 9 years demonstrated very low levels of material degradation. Indeed other seals were reinstalled and will run for another 6 years or longer before being reevaluated.

DISCLAIMER

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