THE USE OF WAVY FACE TECHNOLOGY IN VARIOUS GAS SEAL APPLICATIONS

by
Lionel A. Young
Senior Project Engineer
and
Michael B. Huebner
Manager of Product Development
Flowserve Corporation, Fluid Sealing Division
Temecula, California

Lionel A. Young is Senior Project Engineer with Flowserve Corporation, Fluid Sealing Division, in Temecula, California. He joined Flowserve Corporation (formerly BW/IP International) in 1991 as a project engineer in the Research Group where he has been involved in low emission sealing technology.

Mr. Young received his B.S. (1978) and M.S. (1980) degrees in Mechanical Engineering from the University of New Mexico. After graduation, he continued to do research and development work at the university in mechanical seal design and testing. In 1987, he went to work at Mechanical Seal Technology, Incorporated, where he was involved in seal research, product development, and other engineering services.

Michael Huebner is the Manager of Product Development at Flowserve Corporation (formerly BW/IP) Fluid Sealing Division, in Temecula, California. He has more than 14 years experience in the design of mechanical seals, centrifugal and positive displacement pumps, and fluid conditioning equipment. For Flowserve, he has served in design, testing, and applications functions in both Europe and the U.S.

Mr. Huebner received his B.S. degree (Engineering Technology) from Texas A&M University.

ABSTRACT

Wavy face technology in mechanical face seals is the use of circumferential waves manufactured into a seal face. This unique wavy shape is bidirectional, can be used in liquids, gases or combination, and incorporates a sealing dam that minimizes leakage. The combination of waviness, tilt at the valleys of the waves, and a seal dam has been referred to as the wavy-tilt-dam or WTD. The WTD shape provides both hydrostatic and hydrodynamic load support that is sufficient to enable the seal to operate in a noncontacting mode during dynamic operation. The smooth wave peaks present a low wearing condition during starts and stops when the seal faces make contact. Field results also indicate that the WTD shape is contamination resistant and exhibits lower leakage than grooved face technology.

Since its introduction in dry running noncontacting gas backup seals, wavy face technology has been applied in many different applications and seal design configurations. More than 2000 wavy face seals have provided successful performance since 1995. Other applications of this technology include its use as primary seals in liquid carbon dioxide, double gas seals in ANSI and API pumps, tandem seals in high vapor pressure NGL services, and compressor seals for high speed/high pressure conditions. Wavy face technology has been successfully applied in field applications from zero to over 1100 psig and up to 34,000 rpm. Laboratory testing has been successful up to 1350 psig.

This paper will discuss some of these applications and report on performance from field installations.

INTRODUCTION

The use of waviness as a deliberate mechanism for improved performance in mechanical face seals has been around since the 1960s and is well documented (Lebeck, 1991). A previous paper details the history and more recent application of this technology (Young, et al., 1996). A brief overview of the wavy-tilt-dam (WTD) shape (Young and Lebeck, 1989) and its specifications are given here.

Figure 1 shows an illustration of the WTD shape common to all seal designs presented and the key features associated with this shape. These features are waviness, tilt at the valley of wave, and seal dam. When mated against a flat seal face the waviness forms circumferentially converging and diverging regions. For an OD pressurized seal under dynamic operation, the circumferentially converging regions hydrodynamically compress the gas to develop a pressure at the wave peaks that is considerably higher than the surrounding bulk gas. This results in hydrodynamic load support that promotes noncontact operation. The WTD shape is nonpumping, which means that gas will not be forced across the face during dynamic operation.

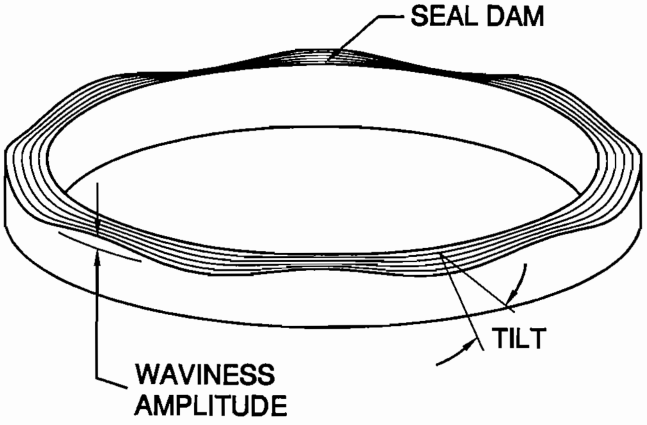

Figure 1. Wavy Face Ring with Tilt and Seal Dam.

Tilt at the wave valley forms a converging region in the radial direction from OD to ID. This promotes hydrostatic load support helping to provide liftoff during dynamic operation. In all seal designs, the seal balance ratio has been selected that will ensure that the faces remain in contact under static conditions, thus low leakage. During dynamic operation, the hydrodynamic component provides additional film stiffness above that created by hydrostatic pressure. The hydrodynamic component results in even greater film stability. The final feature of the wavy face is a seal dam that minimizes seal leakage.

Additional positive features of the wavy shape are its bidirectional characteristic, lower leakage than groove face geometries, and contamination resistance. The low leakage capability is due to two factors: waves do not pump, and wavy seals can be designed to operate at low film thicknesses. Figure 2 illustrates contamination resistance. Under pressurized and dynamic conditions gas enters the valley portion of the wave and then undergoes compression toward the wave peak. At the wave peak, the pressure is greater than the bulk gas, and so a small portion migrates across the seal dam as leakage. Some travels across the wave, but the majority is circulated back into the seal chamber, which is at a lower pressure. This circulation helps remove debris from the seal interface. Inhouse testing and examination of seals in field applications operating in dirty environments have verified this feature.

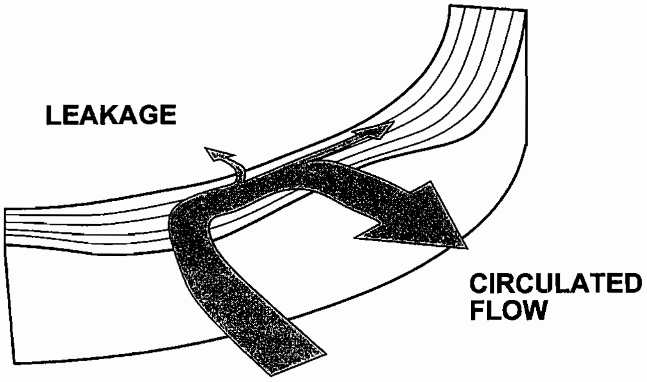

Figure 2. Wavy Face Section with Circulation Effect.

The WTD shape can be manufactured into any face material but is most commonly applied to either a reaction bonded or direct sintered silicon carbide face. Manufacturing the WTD shape into other face materials is also possible, but wear resistant materials are preferable due to contact conditions at starts and stops.

The first commercial use of wavy face technology was as a dry running noncontacting backup seal to a liquid primary. A brief update of those applications is presented after a discussion of the design basis for gas lubricated wavy face seals.

THEORETICAL BASIS OF DESIGN

Extensive studies of the WTD shape for liquid seals were previously done (Young and Lebeck, 1989, and Lebeck, 1991) and then optimized for gas seal applications (Young, et al., 1996). The design variables include:

- Balance.
- Face width.
- Number of waves.
- Waviness amplitude (peak to valley).
- Flatness of the wave peaks.
- Spring load.
- Effects of pressure distortion on seal faces.

Optimized designs were subjected to extensive testing under a variety of operating conditions. Depending on the particular seal design, wavy face seals were tested in the range from zero to 1350 psi, 500 to 34,000 rpm and up to 450°F. These results were then compared to theory based on leakage and face temperature. Figure 3 shows a comparison of leakage for a 3.625 inch seal at 3600 rpm in nitrogen. Comparable leakage indicates that the fluid film calculation, calculated pressure distribution and face distortion is in close agreement with actual performance.

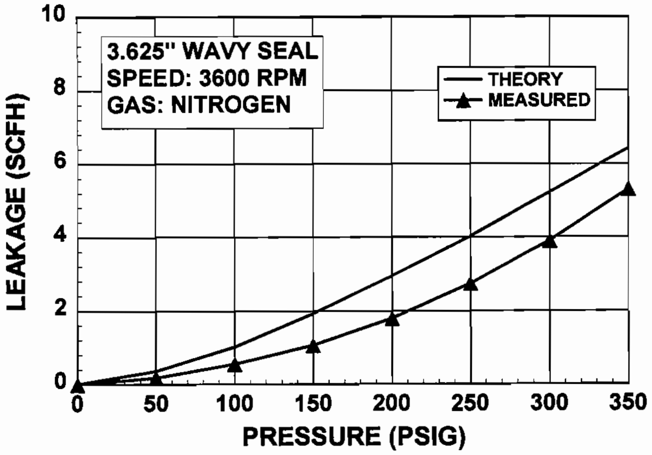

Figure 3. Leakage Versus Pressure; 3600 RPM, Nitrogen.

Figures 4, 6, and 7 show calculated data for a 1.500 inch balance diameter seal developed for a high speed/high pressure compressor. The wavy face has four peaks. Figure 4 shows the calculated three-dimensional plot of one wave. Waviness amplitude near the OD of the seal is 280 micro inches. This can be compared to the actual measured waviness as shown in Figure 5. The wave shapes are very similar with the only significant difference being the measured waviness near the ID. This variation can be attributed in part to the radial location of measurement near the ID.

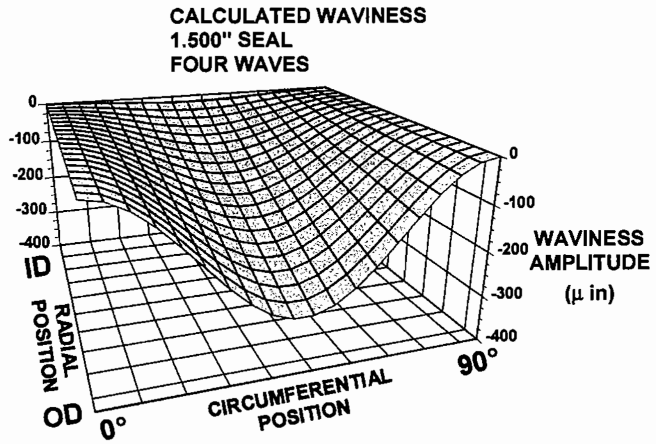

Figure 4. WTD Calculated Waviness.

Figure 6 gives the pressure distribution in nitrogen for one wave at zero pressure conditions and 18,000 rpm. The left side (gradually decreasing) of the pressure distribution is the trailing edge and the right side (rapidly rising) is the leading edge. This shows the hydrodynamic effect that can be generated by waves.

As sealed pressure is increased, the seal becomes predominately hydrostatic in function. This is illustrated in Figure 7. The pressure at the ID (~240 psia) is greater than atmosphere due to choked flow conditions. Laboratory testing has verified the theoretical model and the capability of the wavy face gas seal designs presented below.

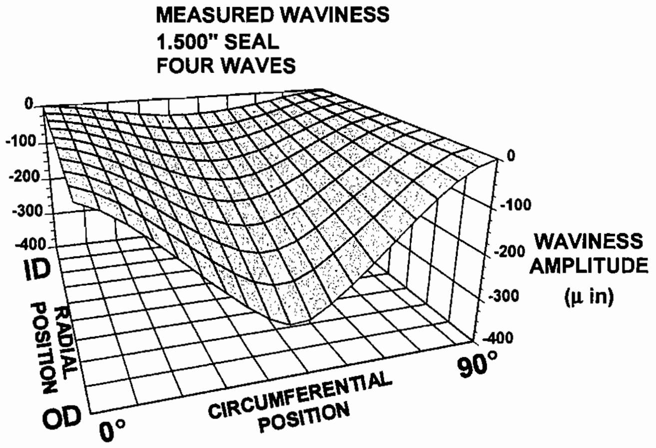

Figure 5. WTD Measured Waviness.

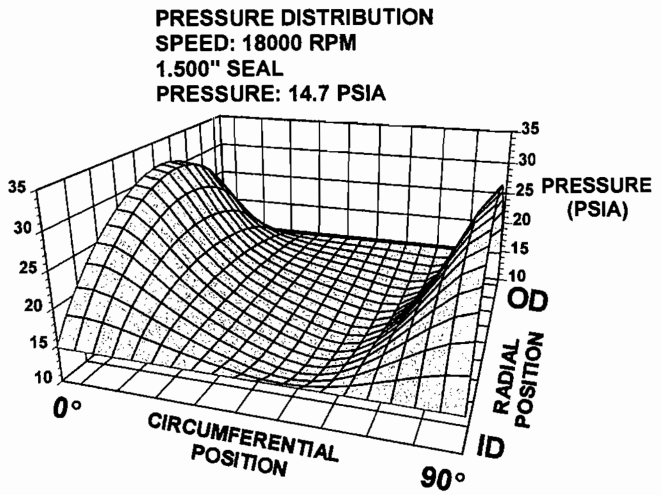

Figure 6. WTD Pressure Distribution at 14.7 PSIA.

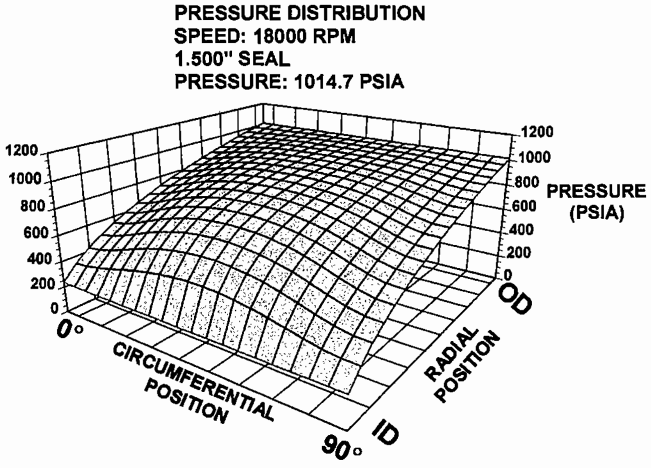

Figure 7. WTD Pressure Distribution at 1014.7 PSIA.

BACKUP SEAL APPLICATIONS

Figures 8, 9, and 10 show various arrangements that incorporate the use of the wavy face backup seal. More than 1000 of these seals have been put into operation since 1995. Products range from light hydrocarbons to crude oil with temperatures from −40°F to over 400°F, pressures from zero to 1100 psig, and speeds from 1000 to 5000 rpm. Shaft seal sizes range from 1.5 inches to 6 inches. In four documented cases where pump operating conditions caused a primary seal failure, it has been reported that the backup seal performed as expected. The wavy face backup seal contained the product with no visible leakage until pump shutdown. Face condition showed no measurable wear or damage.

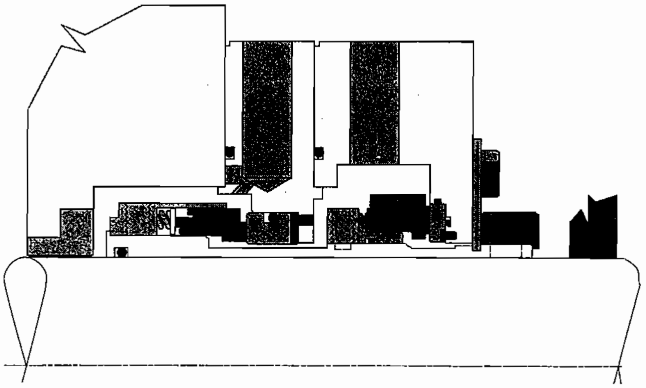

Figure 8. Backup Seal to a Liquid Primary (Multiple Spring Pusher).

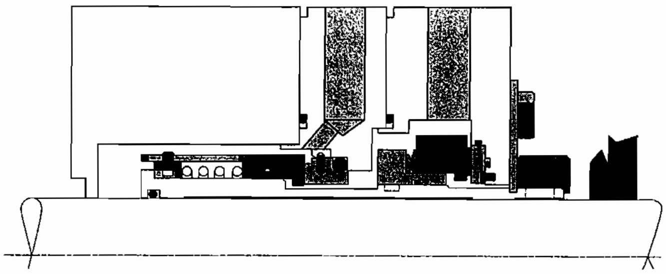

Figure 9. Backup Seal to a Liquid Primary (Single Spring Pusher).

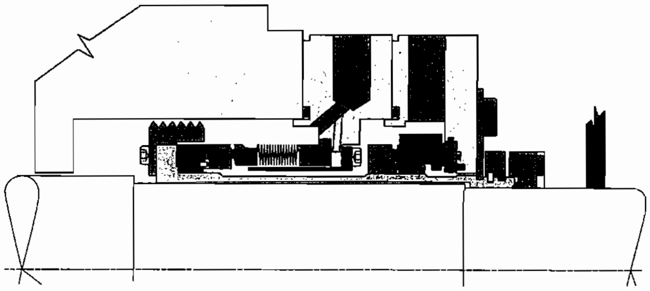

Figure 10. Backup Seal to a Liquid Primary (Stationary Bellows).

DOUBLE SEAL DESIGN

After the successful introduction of the wavy backup seal there was a desire to incorporate the design into a double gas seal as shown in Figure 11 for pump applications, blowers and centrifuges. One of the drawbacks to backup seal design was lack of reverse pressure capability. The other area of concern was the dynamic gasket. Gas seals must have floating faces that do not hang up or suffer unwanted distortions. In the backup seal design, the flange was designed to minimize contact of primary seal leakage with the dynamic gasket of the backup seal. For the double seal design, selection of the proper gasket material becomes critical, since continuous contact with the product may cause swelling, which in turn will introduce large face distortions and possible seal hangup.

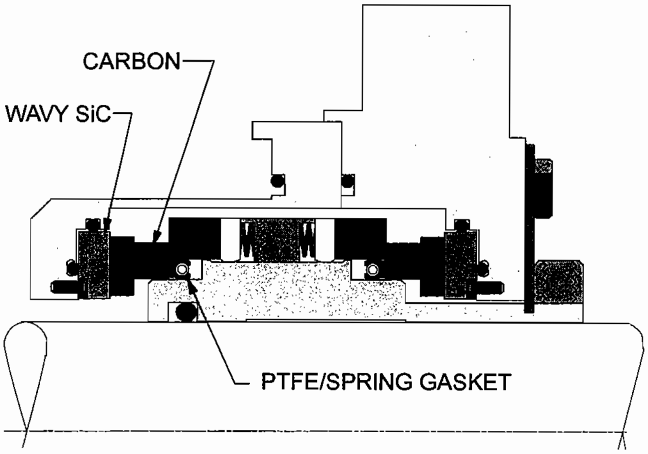

Figure 11. Double Gas Seal.

Figure 11 shows the reverse pressure capable double gas seal as designed with a spring energized PTFE dynamic gasket. This arrangement has stationary wavy face silicon carbide faces and rotating carbons with a common spring. The shaft sleeve under the dynamic gasket has a commercial tungsten carbide coating that significantly improves the sliding characteristics and corrosion resistance. The region between the two seals is pressurized with nitrogen or air to a pressure typically 30 to 60 psig greater than the pumped product. This arrangement results in zero emissions of pumped product to the environment.

The double wavy seal underwent extensive laboratory testing. Testing was performed in an actual pump as part of an outdoor slurry test rig, Figure 12, and on an indoor bench tester, Figure 13. The former was chosen so that realistic pump operating conditions could be simulated. Test data acquired included face temperature, speed, barrier gas pressure, process pressure, total barrier gas supply flow (by mass flow meter), process fluid temperature, barrier gas temperature, vibration, and face wear. Length of testing was varied up to 256 hours.

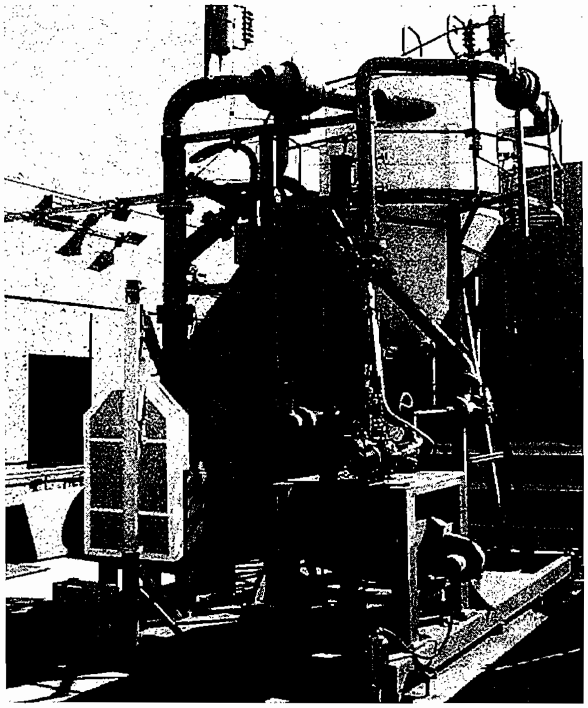

Figure 12. Outdoor Double Gas Seal Test Setup in Slurry Loop.

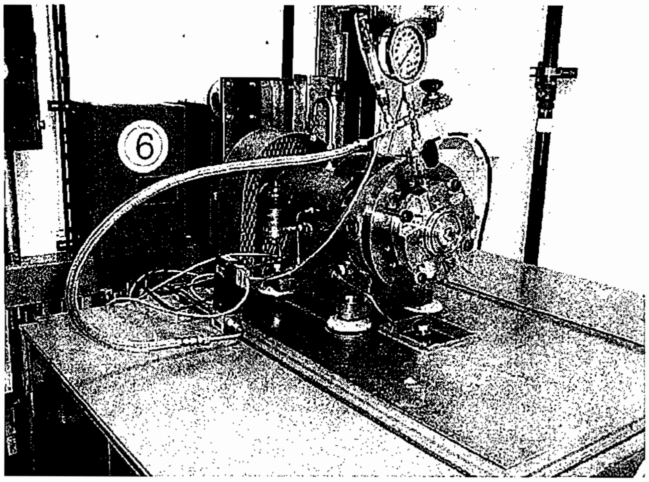

Figure 13. Indoor Test Setup for Double Gas Seal.

Of particular importance were the possible effects of vibration from pump cavitation and large variations in barrier pressure. To address the first issue a double seal, 1.375 inch shaft diameter, was installed in the pump of the slurry test rig. The ability to control pump suction pressure using pneumatic control valves made it possible to cavitate the pump during operation. Testing was done using water as the pumped product. Although the system was flushed prior to testing, water quality was extremely poor due to residual concentrations of fly ash (from prior slurry seal testing). The following test conditions were used:

• Process fluid:	Water (with fly ash contamination)
• Process pressure:	27 to 40 psig
• Seal size:	1.375 inch shaft size
• Barrier pressure:	50 to 75 psig
• Speed:	3600
• Length of test:	256 hours

During dynamic operation, the suction pressure was reduced to the point that the pump was put into cavitation. Severe pump vibration ensued. Vibration measurements both radially and axial showed motion as high as 0.55 in/sec. This condition was maintained for up to five minutes, while barrier gas flow and face temperature were monitored. During this time, face temperature was nearly constant while the barrier gas flow increased to about 1.2 L/min. This is shown in Figure 14. When pump suction pressure was again restored and cavitation ceased, barrier gas flow decreased to previous levels over time (Figure 15). Normal vibration levels, even in a noncavitating mode, averaged between .15 and .2 in/sec. The pump was also subjected to repeated water hammering by rapidly closing and opening a valve to pump suction. There were no adverse effects on face temperature or nitrogen barrier consumption. After approximately the first 18 hours of operation, the test was stopped and the seal examined.

Figure 16 shows how fly ash had contaminated the ID surfaces but not the seal faces. These parts were reassembled and the test continued. The test was successfully concluded at 256 hours.

During operation on the indoor bench tester, the barrier gas pressure was also cycled from high to low pressure to see if large and rapid pressure changes would have an adverse effect. Figure 17 shows a section of output illustrating this test phase. The pressure was varied from 350 psi to zero psi and back up to 350 psi in very rapid cycles. The leakage data show spikes that are simply the expansion and contraction of gas through the mass flow meter. This type of testing was performed numerous times, and as the output shows, the leakage always returned to its precycled level, and there was no significant change in face temperature and no face damage.

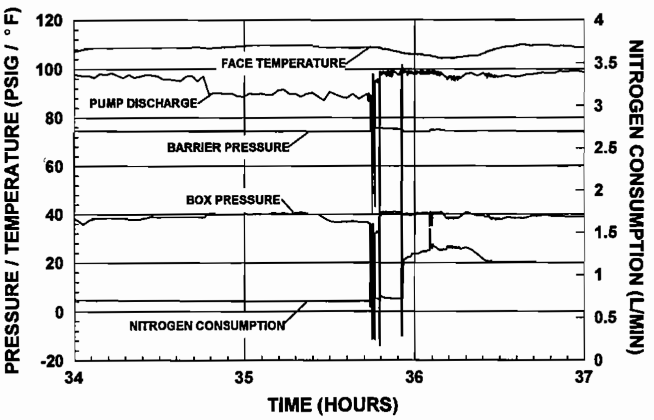

Figure 14. Plot of Temperature/Leakage During Pump Cavitation.

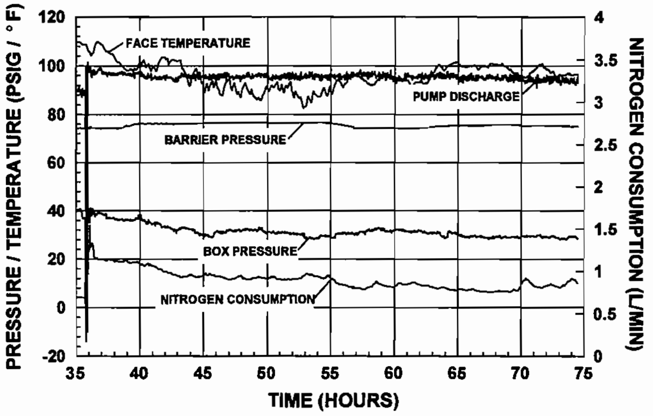

Figure 15. Long Term Trend of Double Gas Seal.

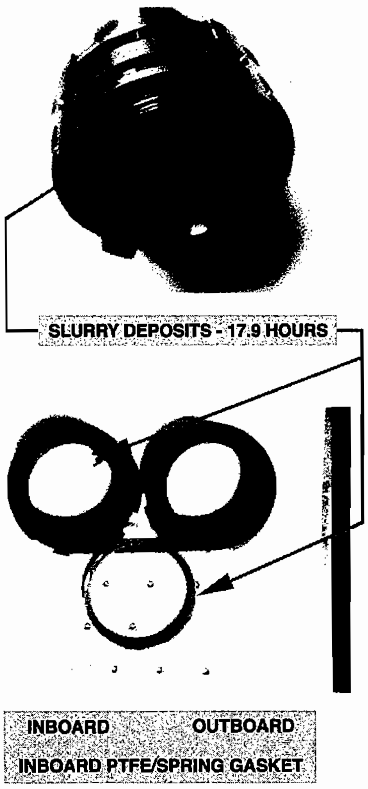

Figure 16. Photo of Fly Ash Contamination of Double Gas Seal.

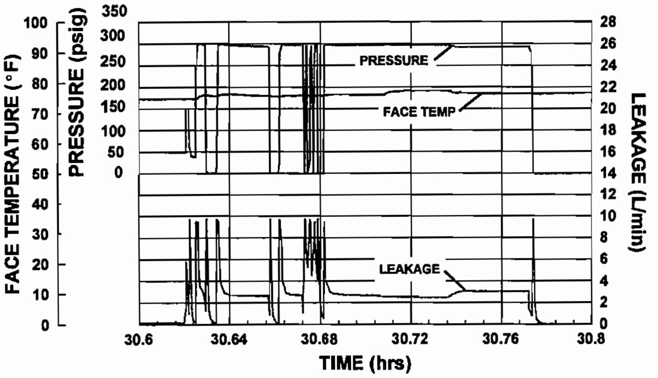

Figure 17. Rapid and Large Barrier Gas Variation Sequence.

DOUBLE GAS SEAL APPLICATIONS

Double gas seals are ideally suited for pump services where the user needs the features of a double seal without the requirement for a liquid barrier fluid support system. Actual applications have ranged from crude oil to propane and hot water to cold xylenes. Because the actual sealed medium is the buffer gas, seal performance is not dependent on the lubricating properties of the pumped fluid. Normally seals are operated with a barrier pressure 30 to 60 psi above seal chamber pressure. This results in a very low leakage of barrier gas into the pump.

Field and test experience has shown that it is not reliable to operate double gas seals on bottled gas. Normal seal leakage will empty a bottle within a few days. This problem can be compounded if there are any small leaks in the support system. In all installations, it is necessary to use a leak detection method (such as soap and water) on fittings to ensure proper installation.

FIELD PERFORMANCE

Presently, there are over 150 wavy face double gas seals in operation in a variety of services. A number of sample applications are shown below to illustrate actual performance.

A chemical plant specified 22 double gas seals for a new pilot project. The use of nitrogen as a barrier gas was a benefit, since it would not create compatibility problems with the processes. As a pilot plant, operating conditions were subject to variation along with a large number of intentional and unintentional shutdowns and startups. The wavy face design has performed well in these applications. Examination of eight seals pulled for evaluation have shown only expected face contact and no damage to the wavy faces. The range of applications in this plant are shown in Table 1.

Table 1. Application Range at Chemical Plant.

Fluids	Various Organic Chemicals
Suction Pressures	3 - 110 psi
Discharge Pressures	18 - 155 psi
Speeds	1750 - 3600 rpm
Temperatures	104 - 226°F

In another application, a hydrocarbon pump previously had a different design of dry gas double seal and was experiencing consistent failures. Average run times were two to three weeks. Failure was attributed to clogging of the grooves on the seal faces. Wavy faces were chosen for installation because of the ability of the seals to withstand contamination. The first seals were installed and have been operating successfully for six months at the time of this paper. The operating conditions are given in Table 2.

Table 2. Hydrocarbon Pump Application.

Fluid	Benzene/Toluene
Suction Pressure	135 psi
Discharge Pressure	200 psi
Chamber Pressure	140 psi
Seal Size	1.375 inch shaft
Speed	3540 rpm
Temperature	106°F

TANDEM SEAL APPLICATION ON NGL

In high vapor pressure NGL applications where the vapor pressure is close to the pump operating pressure, the possibility of running conventional design seal faces in the vapor region is quite high. The result is poor lubrication, dry running and premature failure of the seal due to excessive face wear. There are a number of contacting type seals in these applications, but they require extensive design work and testing to run well. One solution to this problem is to incorporate wavy face technology as both the primary seal and the secondary gas backup seal. This arrangement is depicted in Figure 18 for a Middle East application. In this particular arrangement, the leakage from the primary seal is captured by the secondary wavy face seal and vented to a vapor recovery system. A distinct advantage to this technology in this application is that for wavy faces, the interface conditions can be entirely gas, entirely liquid, or a combination of both and still operate successfully.

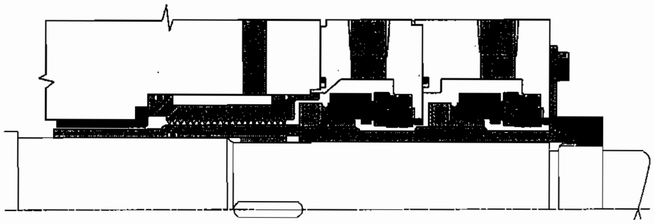

Figure 18. Tandem GSL for High Vapor Pressure NGL.

To verify this concept, two laboratory tests were run using the conditions shown in Table 3. Test data taken included:

- Primary seal face temperature.
- Primary seal leakage.
- Secondary seal face temperature.
- Secondary seal leakage.
- Primary and secondary pressures.
- Shaft speed.

Table 3. Tandem WTD Gas Seal Test Parameters.

	Test #1	Test #2
Process Fluid	Propane	Ethane
Process Pressure	500 psig	750 psig
Process Temperature	90°F	75°F
Secondary Seal Pressure	10 psig (Maintained by regulating check valve)	
Seal Size	3.000 inch shaft size	
Shaft Speed	3600 rpm	

The first test was run for 121 hours in liquid propane at 500 psig. Primary seal leakage averaged 13 L/min (0.5 scfm) and secondary seal emissions measured, using a volatile organic vapor analyzer, were 80 to 200 ppm without a nitrogen purge. Post test seal faces showed no measurable wear or distress.

Test #2 for this arrangement operating in liquid ethane at 750 psig was run for 24 hours. Primary leakage averaged 24 L/min (0.8 scfm) and secondary emissions were in the range of 200 to 300 ppm. Post test seal face condition showed that faces operated with noncontact operation.

The configuration used for this application was derived from the backup seal design, incorporating off the shelf components. The waviness amplitude is large for backup seals because of the need to operate at a zero pressure differential. Under high pressure conditions higher leakage can be expected. This leakage can be reduced significantly in this particular application by using smaller amplitude waves for the primary seal. The application for which this seal design was installed is given in Table 4.

Tandem seals were installed on both ends of the pump in September 1997 and are running well.

Table 4. Field Conditions for Tandem WTD Gas Seal.

Pump Configuration	Double Ended Overhung
Process Fluid	NGL
Suction Pressure	555 psig
Discharge Pressure	830 psig
Drive End Box Pressure	555 psig
Non Drive End Box Pressure	670 psig
Flare Line Back Pressure	2.5 to 4.0 psig

HIGH PRESSURE/SPEED APPLICATIONS

One area recently explored is the use of wavy face technology in high pressure/speed pumps and compressors. The particular application for which this technology was studied used a 1.5 inch balance diameter seal in a radially compact and axially restrictive seal chamber. Figure 19 shows an unpressurized dual wavy seal arrangement and Figure 20 a pressurized dual wavy seal. One of the unique features of this design is the use of an integrated wavy face silicon carbide wafer housed in a rotating face holder. Previous designs incorporated a clamped solid tungsten carbide rotor that was part of the overall stack up between shaft sleeves. Failure of the solid rotor would result in a loss of stack up and damage to the compressor. The new design eliminates the problem by clamping through the unbreakable holder instead. The silicon face is then virtually stress free, except for rotational stresses. Even at speeds of 34,000 rpm, the silicon face has a tensile stress safety factor greater than 12.

Lab testing of this seal was performed in an actual compressor as shown in Figure 21. The impeller was removed and the lower pump region was dead ended. The following test conditions were used:

- Process gases: Nitrogen and helium
- Process pressure: Zero to 1250 psig
- Shaft speed: 6000 to 34,000 rpm (approximately 40 to 220 ft/sec)

Measured quantities were:

- Face temperature.
- Seal chamber temperature.
- Sealed pressure.
- Speed.
- Leakage.

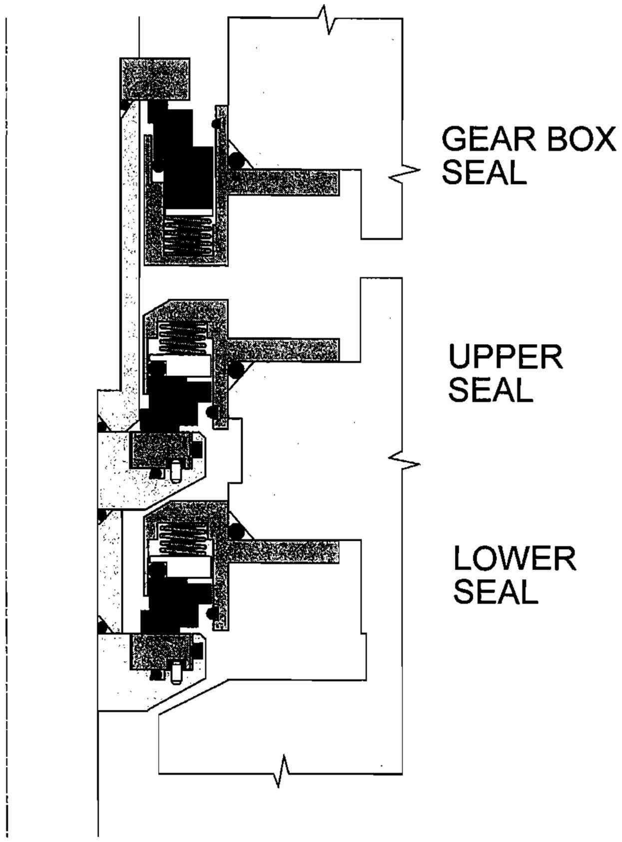

Figure 19. Unpressurized Dual Seal Arrangement for Compressor.

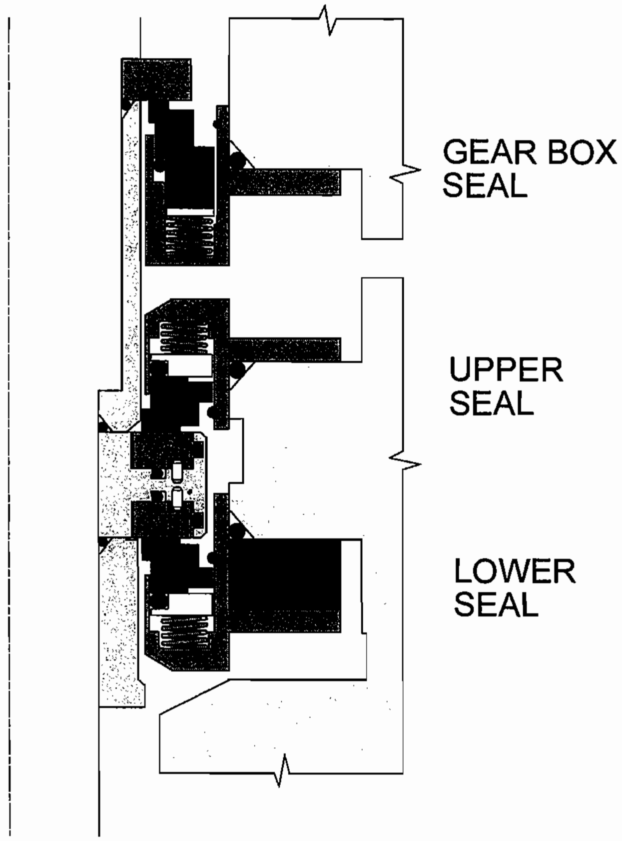

Figure 20. Pressurized Dual Seal Arrangement for Compressor.

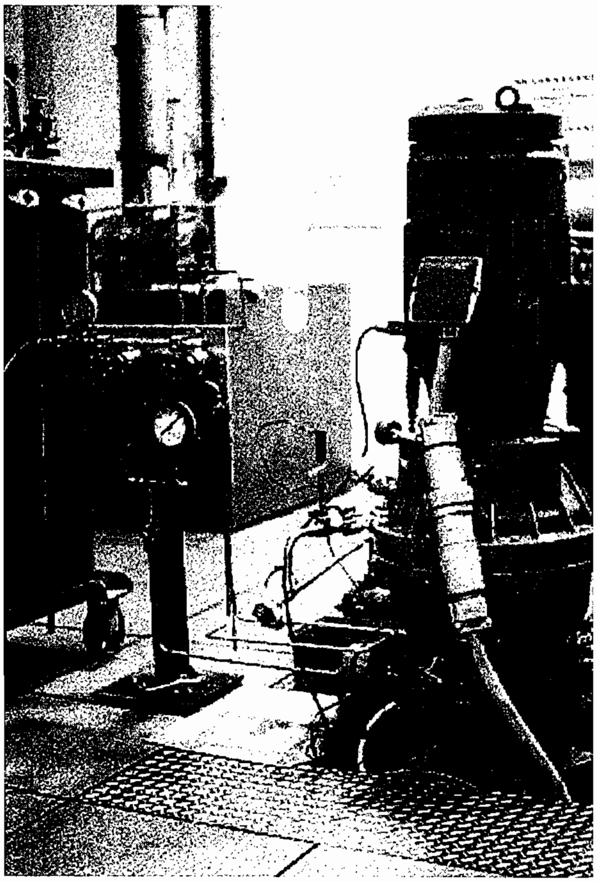

Figure 21. Test Apparatus for High Pressure/Speed Tests.

The unpressurized dual seal arrangement was tested first. Leakage from the primary seal was measured using a rotameter. Figure 22 gives the primary seal gas leakage as a function of pressure for 18,000 and 34,000 rpm using nitrogen. Figure 23 presents the results for helium gas. The data are comparable, showing little difference based on these two gases.

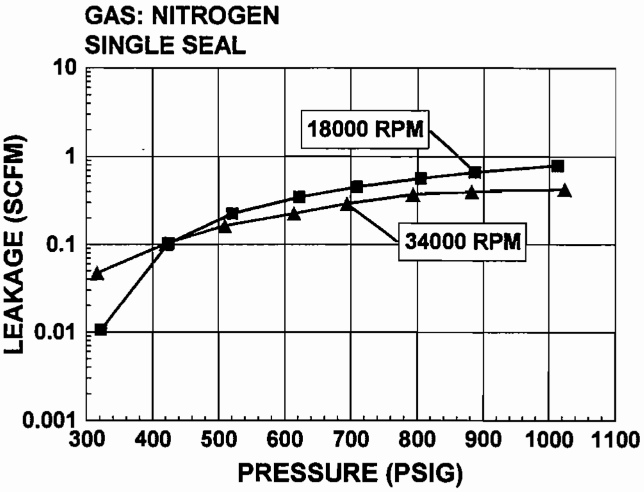

Figure 22. Single Seal Leakage Versus Pressure—Nitrogen.

The double seal arrangement that incorporates an integrated rotating face holder with back-to-back wavy silicon carbide faces was also tested. The leakage for a single seal in this configuration is shown in Figure 24. Again, these results are similar to the

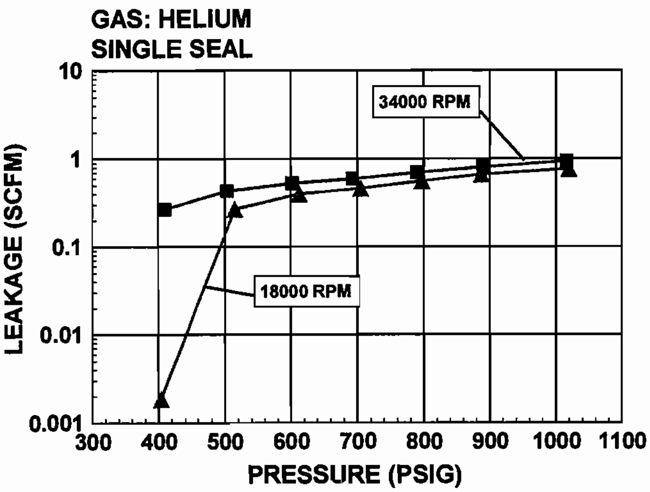

Figure 23. Single Seal Leakage Versus Pressure—Helium.

previous and show that the single and double seal designs have comparable performance based on leakage. In all testing, noncontact operation was verified based on low face temperatures (5°F to 10°F above box temperature) and no measurable wear.

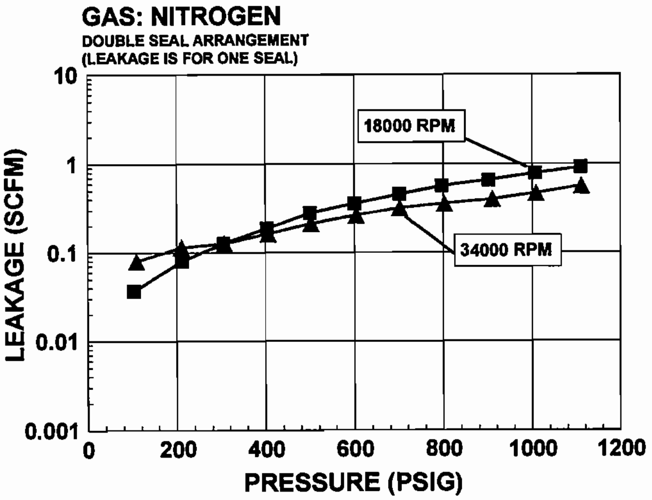

Figure 24. Double Seal Arrangement Leakage Versus Pressure—Nitrogen.

FIELD PERFORMANCE OF INTEGRATED WAVY FACE AND HOLDER DESIGN

These seals have been installed and running in a variety of applications since December 1996. Two particular applications that posed difficult sealing situations were selected to evaluate the ruggedness of the new design. The first utilized a pressurized dual gas seal arrangement in a pump where the pumped product was hot micro wax at 345°F. Speed was 8700 rpm and process pressure was approximately 60 psi. Barrier gas pressure was plant nitrogen set at 100 psi by means of a control panel.

One of the problems with this application was the frequent failure to maintain pump temperature in the standby mode. There were two identical pumps in the process loop. Each was brought online a week at a time, then switched. In the standby mode, the wax would solidify in the pump, resulting in dry running operation for approximately 20 minutes, until pump temperature could be raised and the pump brought back online. Conventional liquid seals experienced reduced life (less than two months) due to this operation.

Changing to the new gas seal design eliminated this problem and was successful even when the same starting operating procedure was encountered that caused the liquid seals to fail. Total nitrogen consumption was measured at 0.1 scfh. The second pump was also converted, and both pumps continue to operate with no problems.

Another application utilizing the pressurized dual seal arrangement was in a compressor operating at 34,500 rpm with approximately 40 psi nitric acid vapor in the stuffing box. Temperature was in the range of 86°F to 167°F. Nitrogen barrier pressure was set at 80 to 100 psig as supplied by a control panel using plant gas. Initial nitrogen consumption was less than 0.1 scfh (minimum scale reading on control panel meter). This particular compressor had measured vibrations on an average of 0.5 in/sec with excursions to almost 1 in/sec when process gases were changed during operation. When this occurred, it was observed that the nitrogen consumption would increase, sometimes higher than 10 scfh. Leakage was across the product seal. After stable operation was resumed, the nitrogen consumption would return to low levels. This same phenomenon was observed in the double seal laboratory testing previously discussed. After two months of operation, the seal was scheduled to be removed and examined. Before this occurred, a process upset caused by a slug of water in the suction line destroyed the compressor impeller and seals. A second set of dual seals was installed in a standby compressor and started in October 1997.

CONCLUSIONS

Wavy face technology continues to show capability over a wide range of operating conditions and design versatility. What has been observed is:

- Wavy face technology has been shown to operate successfully with zero pressure differential. This means the WTD shape is sufficient to generate hydrodynamic load support and run noncontact, provided surface speed is greater than 5 ft/sec.
- Wave technology has been applied in high pressure and high speed applications to as high as 1350 psi and 34,000 rpm (220 ft/sec) with success.
- Wavy faces have demonstrated, both in the laboratory and from field installations, contamination resistance.
- Wavy faces have shown the ability to operate in all gas, all liquid, or a combination of liquid and gas with success.
- Because of the smooth wave shape, contact conditions during starts, stops and possible pump upsets are not aggressive and generate no wear.

The successful application in such diverse operating and design arrangements as presented here illustrate some of the potential for the technology.

REFERENCES

Lebeck, A. O., 1991, *Principles and Design of Mechanical Face Seals,* New York, New York: Wiley Interscience, pp. 226-237.

Young, L. A. and Lebeck, A. O., 1989, "The Design and Testing of a Wavy-Tilt-Dam Mechanical Face Seal," *Lubrication Engineering,* 45, (5), pp.322-329.

Young, L. A., Key, W. E., and Grace, R. L., 1996, "Development of a Noncontacting Seal for Gas/liquid Applications Using Wavy Face Technology," *Proceedings of the Thirteenth International Pump Users Symposium,* Turbomachinery Laboratory, Texas A&M University, College Station, Texas, pp. 39-46.

US Patent Numbers 4,836,561 and 4,887,395.

ACKNOWLEDGEMENT

The authors wish to thank technicians Dave Terry, Brent Collins, Dave Debold, Joe Lewandowski, and Charlie Beier for their many hours of hard work and helpful suggestions.