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Rapid Gas Decompression Issues in Subsea Boosting Systems

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Abstract

The paper describes the Rapid Gas Decompression (RGD) process and how it occurs in Subsea Boosting & Pumping Systems (SBPS). It describes potential subsea equipment damage and how it can be prevented, or reduced, by elements of equipment design, seal choice and equipment operational philosophies. While no SBPS is completely immune to RGD effects, there are known and industry proven steps that can be taken towards mitigating this phenomenon.

Introduction

With the growing number of designed, installed and operated Subsea Boosting and Pumping Systems (SBPS), the Rapid Gas Decompression (RGD) phenomenon should be thoroughly studied and closely addressed in an effort to prevent system damage and potential shutdown or even severe equipment failure.

RGD is the process where gas is initially absorbed into soft goods, (elastomers, epoxy, rubbers, etc) at high pressures and then allowed to quickly expand due to a fast reduction in pressure. This fast pressure reduction causes the gas volume to rapidly increase while still inside the aforementioned soft-goods. The potential end result is the larger gas bubble tearing apart the soft goods in the process. This can dramatically damage the soft goods with detrimental effects on the subsea equipment, with potentially catastrophic effects, including shutdown or eventual system failure.

With subsea valve equipment limitations and communication delays inherent in subsea control systems, RGD can be difficult to control in a subsea installed boosting system. Implementing known RGD solutions into SBPS can dramatically reduce the effect of explosive decompression events, if not eliminate them entirely. Implementing these solutions will greatly increase the reliability of the pumping system from a recognized subsea and downhole decompression phenomenon.

RGD Definition

Rapid gas decompression can be classified as an extreme depressurization event from high pressure (thousands of psi) to low pressure (hundreds of psi down to atmospheric) in the order of seconds, or instantaneously. Ultimately, the composition of the soft goods, the environment and the mechanical design will dictate the tolerable decompression rate. RGD is also known as explosive decompression, for obvious reasons.

For the purposes of this document, a subsea boosting, or pumping, system is a self-contained pump system installed on the seabed aiding with artificially lifting hydrocarbons to the surface. Typically these systems are operated at high pressures and can sometimes observe full wellhead shut-in pressure, with a large reduction in pressure during later start-up activities. It is these high pressure transient events that can cause RGD episodes which in turn can potentially damage the subsea boosting and pumping system.

For RGD to occur there must be the presence of gas in the production system; an entirely liquid packed production system with little GVF should not experience severe RGD issues. However, for the purposes of this discussion, it is assumed that an elevated level of GVF is present in the subsea production system.

Why does the RGD Process affect Subsea Boosting Systems?

So what is so special about SBPS that may cause RGD? Typically it is the introduction of high operational pressures close to the pumping system with a potential for a rapid lower pressure equalization event that will introduce unfortunate explosive decompression opportunities. These opportunities can be devastating to typical soft goods found in SBPS.

Examples of typical soft goods found in SBPS are as follows:

- O-Rings
- Wet & Dry mate connectors (Back-end cable interface)
- Cable, penetrator & connector interfaces
- Subsea pump cable
- Seal/Protector, pump & subsea equipment compensation bladder sections

Equipment limitations typically found in subsea production systems can compound the RGD effect. Surface production equipment found on typical offshore and onshore installations can be more closely and quickly controlled than subsea equipment installed in deepwater.

Subsea valves are notoriously difficult to closely and accurately control, using either a motor operated valve or manual valve via remotely operated vehicle (ROV). This “coarse” control of subsea valves could cause a quick pressure equalization event during valve opening actions. Surface valves on a typical offshore petroleum installation can be closely controlled using human intervention; however this fine control is extremely difficult to achieve when valves are installed subsea.

Another limitation inherent in subsea boosting systems is the time delay for information to reach the surface and the delay to implement a control command back down to the subsea architecture. Even though modern subsea systems have fiber optic based control systems, the few seconds delay for information transmission (e.g. pressure signals or valve positions), control system analysis and an issued response in the control system can be too long to prevent a subsea RGD episode.

For a simple example, consider a SBPS, Figure 1, operating with intake and discharge pressures of 1500 and 3500psi respectively, that experiences a shutdown and automatic pump discharge valve closure prior to full well isolation. For this example, there are liquid, gas and chemical injection discharge valves that also close during this shutdown sequence. If the WHSIP is 10,000psi, then this could quickly result in the pump intake and discharge also experiencing the full 10,000psi pressure due to the close proximity to the wellhead and the time taken for full subsea wellhead system isolation, as shown on the left side of Figure 2. While the high pressure itself will not affect the pump in this static state, it is the later pressure equalization event during a subsequent restart that has the potential for causing the dramatic explosive decompression (RGD) effect on any soft goods present.

Before we can restart the pump system, the pressure inside the pump cavity should be equalized with the gas and liquid discharge flowlines, even if the well has been isolated from the pumping system. If this equalization event is done without close control, the equalization event will occur very rapidly. Since the pump’s volume is far smaller than the gas or liquid flowlines’ volume, the high pressure (10,000psi) will dissipate into the flowline cavity rapidly and equalize at a much lower pressure. This can be characterized as an RGD event, as demonstrated on the right side of Figure 2. This event will also allow any gas that has been compressed and absorbed into the pump’s soft goods (O-rings, epoxy, rubber, insulation, etc.) at 10,000psi to rapidly expand to its higher volume at the much lower flow line pressure, potentially with dramatic consequences. Care should also be taken to ensure that the chemical injection lines on the pump discharge, if any, are opened in the appropriate sequence, as this could also result in a rapid depressurization event.

A similar, and common, event can occur when an electric submersible pump (ESP) installed below a packer is started. The high reservoir pressure from the well perforations, below the packer, can be drawn down rapidly by the pump intake, causing a self-inflicted RGD event to the pump system’s soft goods!

How are soft goods affected?

Now that we know a fast pressure equalization effect can be classed as RGD, how does it affect these aforementioned “soft-goods” and why are they so damaging?

If this SBPS RGD process occurs as described previously, any gas trapped in the SBPS’s soft goods (o-rings, electric cable, penetrators, bladders, etc.) at the high pressure (10,000psi) will be held as a relatively small volume. If the RGD process occurs unchecked and the pressure is allowed to equalize rapidly, e.g. as previously shown on the right side of figure 2, then the gas will quickly expand before it has the opportunity to dissipate from inside the soft good(s). During this “in-situ” expansion process, the mechanical damage caused can be irreparable, potentially causing SBPS shutdown due to soft-goods mechanical failure, if not eventual system failure if important sealing surfaces are compromised.

There have been industry funded experiments and studies conducted showing that the main detrimental RGD effects are during fast pressure transients occurring below approximately 1,000psi. The explained theory states that above this pressure, the volume of the trapped gas “bubble” inside soft goods changes minimally, therefore pressure transitions above approximately 1,000psi cause little damage to soft goods. Below this pressure, the gas volume changes rapidly which in turn causes the soft-goods’ damage. In other words, it is possible to reduce the pressure from 10,000psi to 1,000psi instantaneously with little potential for RGD damage, but from 1,000psi to atmospheric must be done in a very controlled manner, as discussed in the later controlled pressure equalization section.

Figures 3, 4 & 5 show photographs of soft goods equipment (o-rings, ESP compensation bladders and ESP power cable) damaged due to RGD events. As can be seen, soft goods damaged in this fashion are no longer intact and are unlikely to perform their sealing duties for much longer after the damage occurs. It is this RGD damage that must be limited allowing expensive and complex Subsea Boosting and Pumping Systems to operate for as long as possible without failing for readily understood, yet not addressed, issues.

RGD Solutions

Since we now have a basic understanding of the RGD process, and how it can occur in high pressure subsea pumping equipment resulting in damage to soft goods, what can be done to prevent this phenomenon? The most commonly used methods for preventing RGD damage, as currently implemented within the petroleum industry, are as follows:

- Controlled pressure equalization
- Metal-to-metal sealing interfaces
- RGD compatible materials
- Mechanical Containment

These four main solutions, and their benefits, will be discussed in the following sections.

Controlled pressure equalization

As we have previously mentioned, it is the pressure transition below 1,000psi which is understood to cause the most explosive decompression damage. If the pressure equalization transition from the higher pressure (1,000psi) state to the lower pressure state (300psi-atmospheric) can be done in a controlled manner, then the small entrained gas bubbles will have a better chance of exiting the soft goods without detrimental damage. While a slow rate as possible is preferred, figures of 500-1,000psi/min have been identified in industry wide literature, and RGD compliant material specifications, as maximum decompression rates without major RGD damage for most applications.

For some systems, much lower rates in the range of 100-300psi/min are targeted to ensure system integrity. Testing and qualification of chosen subsea pump system soft goods is paramount, although there have already been extensive comparisons documented in published literature. There are even standards worth reviewing (e.g. Norsok M710 rev. 2) identifying testing regimes and inspection requirements for these applications. The test programs should be configured to find the maximum allowable decompression rate for the chosen materials, as this will ensure the worst case scenario has been identified prior to system design, manufacture, installation and operation. There are well documented criteria describing the acceptable damage to soft goods after an RGD test has been performed. The most widely used and accepted in the Oil and Gas Industry is Norsok M710 rev. 2, as can be seen in numerous specifications and many equipment manufacturers' data sheets. This decompression rate can actually exceed that of the manufacturer's recommendation if it is based on unconstrained testing of the materials, due to the potential constrained in-service design configuration. Once the maximum, as configured, allowable rate has been determined, the system can be configured with subsea or topside pressure relief systems. If this is not easily implemented, then appropriate operational constraints can be established on the subsea production system safeguarding against RGD damage.

These constraints can be as simple as determining the correct shut down sequence or identifying means in which to equalize pressure using existing hardware and systems. Exacting procedures for proper valve alignment in varying startup conditions may also prove to be invaluable as it is a common mistake to start the pump system with an upstream valve closed resulting in the pump self inflicting the damaging RGD conditions.

Operational personnel training is also key to this controlled pressure equalization solution. When the operations team understands the mechanical limitation of the subsea pumping system as they relate to RGD, they can be better prepared to implement known and documented protection solutions. Also, ongoing operations training and procedural improvements as conditions change should be implemented as part of the long term reliability and preventative maintenance plan. Analysis of RGD risk should be performed as changes to the downstream outflow mechanical system or flow path routes are made during ongoing field operations.

Metal-to-metal sealing

If all the soft goods sealing areas can be replaced with a metal-to-metal interface then the RGD problem can largely be ignored. As far as possible, a metal-to-metal seal should be applied if reliable system assembly, installation and operation can be ensured. However, if a metal-to-metal sealing solution is not practical, then a continuous hermetic barrier is another acceptable solution. If the gas can be prevented from migrating into the soft goods in the first place by isolating them with a gas impermeable barrier, the system can be assumed to be RGD immune. This hermetic sealing solution is used extensively in other pumping systems where RGD is prevalent.

Some pump systems have a hermetic seal (typically lead) along their entire electric cable system and into the connector and penetrator equipment, preventing gas migration into the cable system and explosive cable decompression events from occurring (as shown in Figure 6). There are also some Subsea Pumping Systems where metal bellows (as shown in Figure 7) have completely replaced industry standard elastomer “bags” used for pressure compensation purposes; all in the name of RGD avoidance.

However, the application of these novel solutions in complex Subsea Boosting and Pumping Systems should be carefully analyzed to weigh the features and benefits of this type of RGD solution against application and installation constraints. As mentioned previously, Figure 6 shows an entire lead sheathed ESP cable terminated into a specially designed hermetically sealed power connector system, ensuring no gas impregnation into any internal cable, connector or penetrator soft goods. It is this type of due diligence given to the entire pumping system that lends itself to a robust RGD solution. There are many paths for gas to migrate into the SBPS and it takes much analysis and thorough design reviews ensuring all gas leak paths are identified and addressed with a hermetic sealing solution. Testing should also be implemented ensuring the aforementioned solutions are indeed as robust as claimed.

Mention should be made briefly on the use of potting, or epoxy sealing, compounds. While some published literature states RGD immunity for a potted sealing solution, industry testing documents some level of gas impregnation. This basically states that epoxy based RGD solutions slow down gas ingress, rather than prevent it entirely. Therefore, it is generally accepted that an epoxy based sealing solution is not entirely RGD immune. However, an epoxy based sealing system will certainly perform better than having no RGD solution present. Most epoxy based solutions aim to slow down gas ingress for a long enough period so that the boosting system may require intervention or retrieval activities for another unrelated issue before gas migration effects, and subsequent RGD events, have had a detrimental effect.

RGD resistant materials

If a metal-to-metal interface is not possible due to assembly, installation or reliability issues, the next best solution is to use a material that is designed to cope with severe RGD profiles. There are numerous RGD compliant elastomers on the market today from multiple vendors and should be available in the sealing configuration most commonly used in SBPS.

However, there are potential trade-offs for these materials and the application specifications should be closely scrutinized ensuring no loss in system performance (e.g. temperature ranges, chemical compatibility, hardness, etc.) purely for RGD benefits. These materials should also be used with the controlled pressure equalization method mentioned previously and should be subjected to rigorous qualification programs prior to implementation, where applicable. These qualification programs should use a mixture of gas and liquid and closely mirror the full suite of application fluids wherever possible. This also includes any completion fluids, well or production additives (e.g. scale, wax, corrosion inhibitors, etc.) that may come in contact with the pumping system’s soft goods.

For implementing RGD compliant equipment, it is due diligence at the qualification stage that will pay off in later system performance and reliability.

Soft goods containment

One final solution to RGD events is soft goods containment. This is a simple solution, wherever possible, for most soft goods sealing areas, whether RGD compliant or standard soft goods sealing materials are used. This is the preferred design solution for most o-ring sealing configurations, but could be applied to other sealing area designs, e.g. face seals. This solution restrains the soft good material (e.g. o-ring or face seal) in a specific mechanical geometry and allows the entrained gas to escape from the soft goods in a controlled manner without distorting the soft goods in the process. Its main benefit is the prevention of the large expansion event which is the main cause of RGD material damage. While micro-tears may occur in the material as the entrained gas escapes, it is felt that the containment still provides sufficient sealing integrity allowing the system to reliably function as intended after RGD events. Figures 8 and 9 compare a contained versus non-contained o-ring sealing solution. Figure 9 also shows an enhancement of a basic containment solution, in which a back-up ring is used together with the o-ring ensuring a superior sealing solution and better RGD resistance.

RGD Solution Summary

While there are other potential solutions for subsea rapid gas decompression, these four previously identified areas are the most common solutions implemented widely, and most reliably, to date. Although these explosive decompression solutions are nothing new to other industries and even other oil and gas production applications, RGD is relatively new to Subsea Boosting and Pumping Systems. Lessons learnt from other applications should be wisely and carefully implemented, ensuring reliable SBPS operation.

Failure to recognize RGD as a potentially damaging phenomenon in Subsea Boosting and Pumping Systems can only lead to a potentially catastrophic failure mode later in the production phase. This failure mode can be nearly entirely eliminated with due diligence at the pump system’s design, qualification and testing phase, as well as correctly written and executed production system operational procedures.

Conclusions

As Subsea Boosting and Pumping Systems become more prevalent, together with higher wellhead shut-in pressures and longer and larger flowlines, Rapid Gas Decompression (RGD) issues and potential explosive decompression events should be examined carefully. Ideally, at least two, or more, RGD solutions, as previously identified and briefly described herein, should be implemented into the design and operation of the entire subsea boosting and pumping system. Once correctly designed and qualified, these solutions should ensure robust and reliable pumping system operation even after many RGD events.

Whenever possible, operational constraints need to be in place that will reduce the potential for excessive pressure changes to the system. For operating Subsea Boosting and Pumping systems, training is a key to RGD success. When the operations team understands the mechanical limitation of the pumping system as they relate to RGD, they can be better prepared to find solutions for protection. Also, ongoing operations training and procedural improvements required as conditions change should also be part of the long term reliability plan. Analysis of RGD risk should be performed as changes to the downstream outflow system are made.

Other industries and oilfield applications have many years' experience with RGD issues and have designed their equipment and operational procedures for protection against explosive decompression events. These known solutions should be readily implemented into Subsea Boosting and Pumping Systems early in the application design and qualification process ensuring that this known issue does not detrimentally affect reliable subsea pump system operation.

Nomenclature:

- *DSDV – (Pump) Discharge Shutdown Valve*
- *ESP – Electric Submersible Pump*
- *GSDV – Gasline Shutdown Valve*
- *GVF – Gas Volume Fraction*
- *psi – pounds per square inch*
- *RGD – Rapid Gas Decompression*
- *ROV – Remotely Operated Vehicle*
- *SBPS – Subsea Boosting & Pumping System*
- *WHIV – Wellhead Isolation Valve*
- *WHSIP – Wellhead Shut-in Pressure*

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Figures:

Typical Subsea Boosting & Pump System Configuration

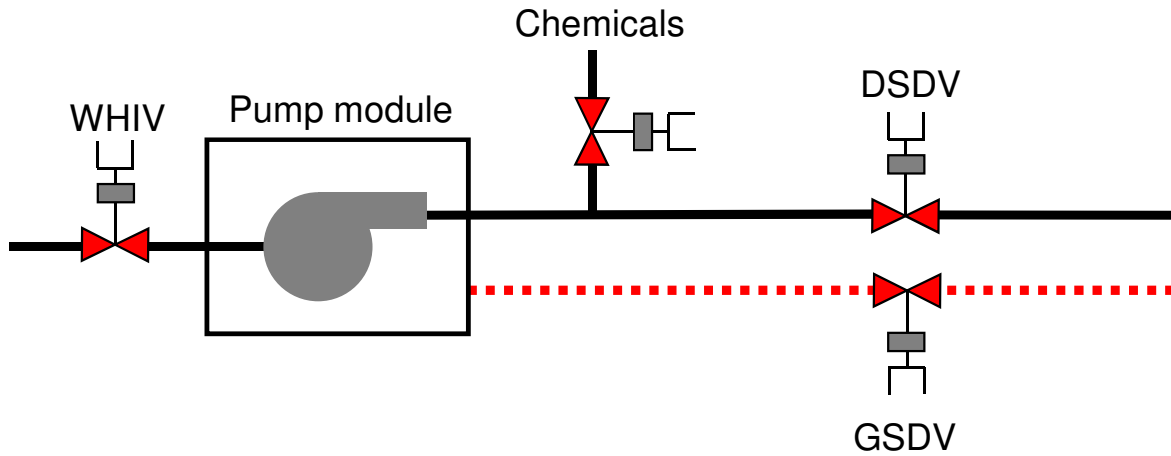


Figure 1 – Typical Subsea Boosting & Pump System

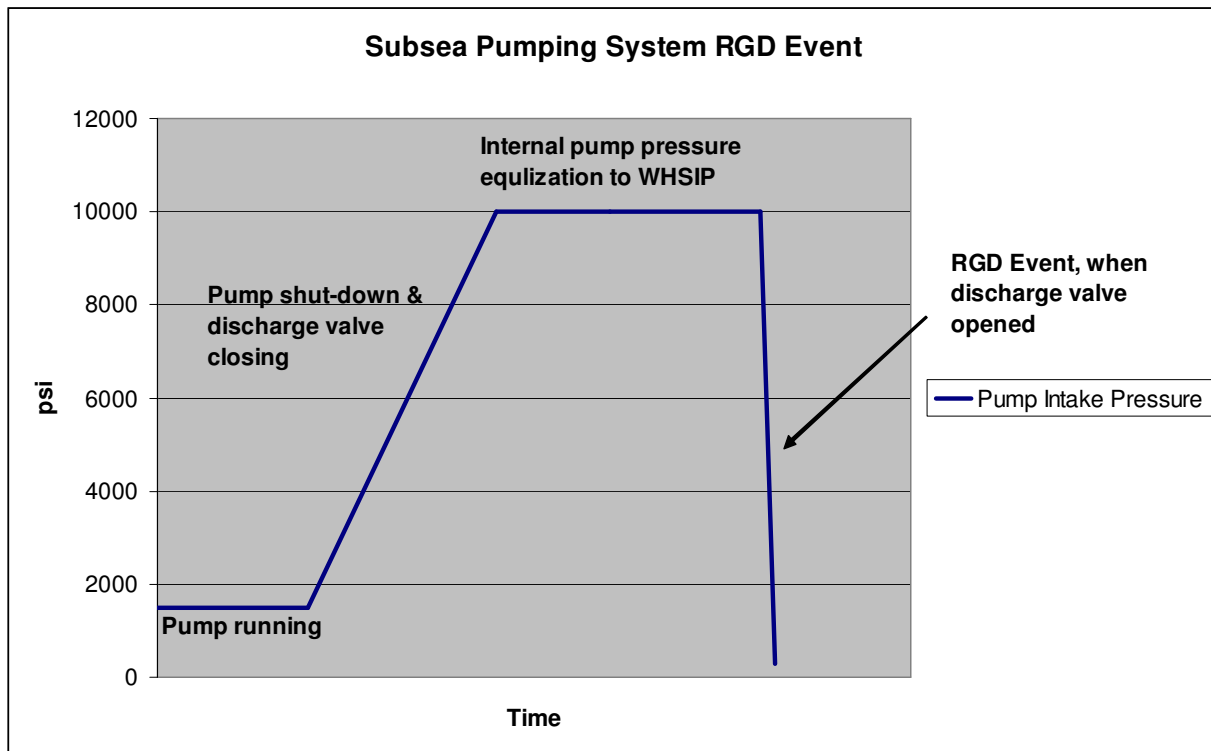


Figure 2 – RGD pressure equalization event

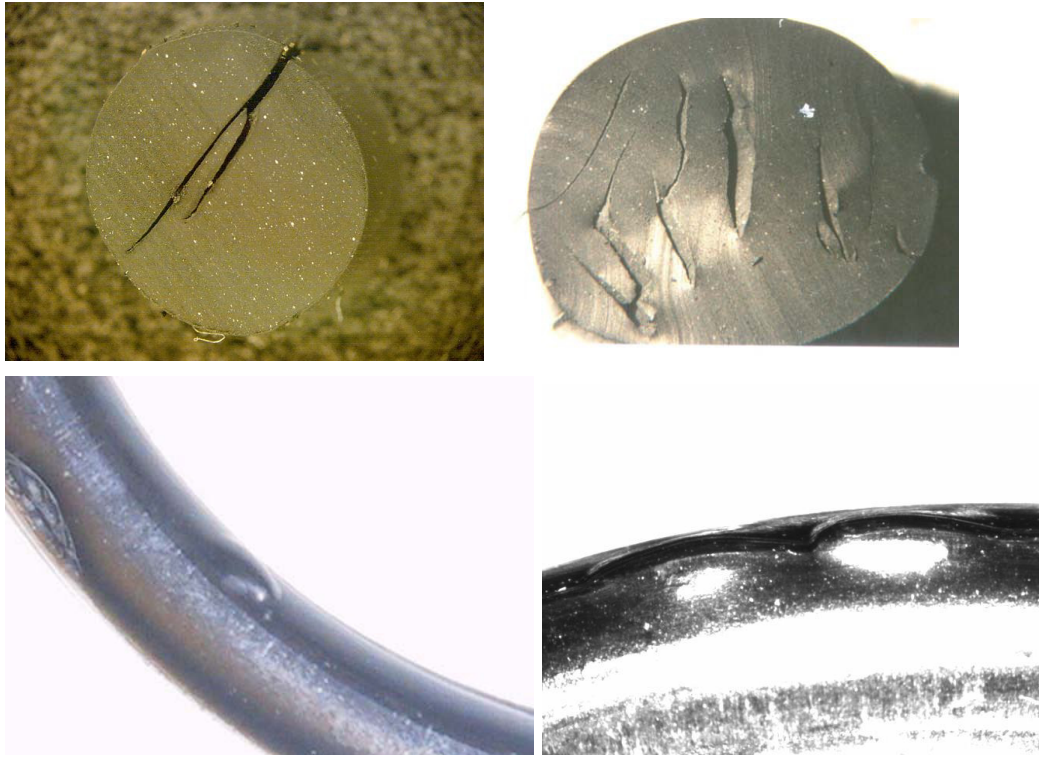


Figure 3 – RGD damaged o-rings (cracks & blisters)



Figure 4 – RGD damaged pump system compensation bladder

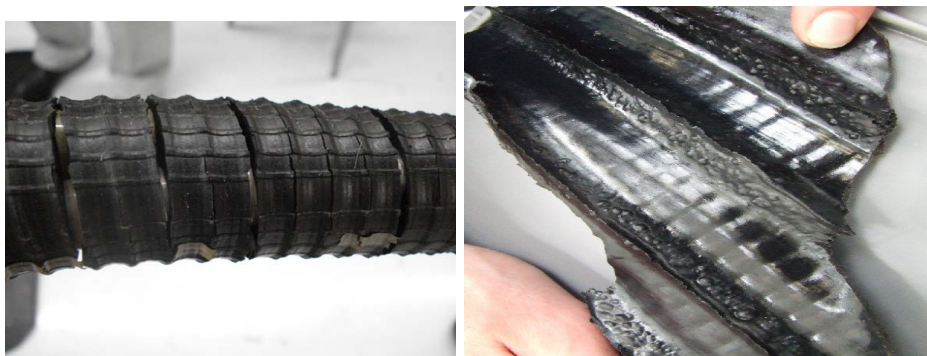


Figure 5 – RGD damaged pump power cable



Figure 6 – Hermetically sealed pump cable and connector RGD solution

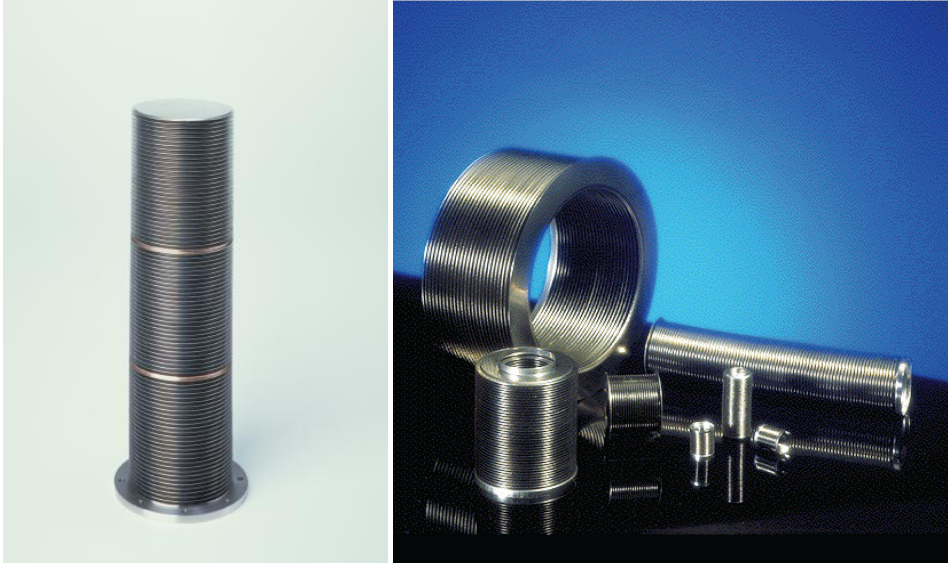


Figure 7 – Metal bellows for pump pressure compensation RGD solutions

Unconstrained o-ring sealing solution

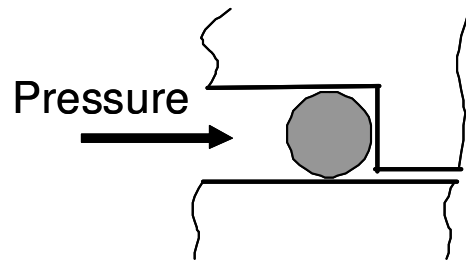


Figure 8 – O-ring sealing solution without containment

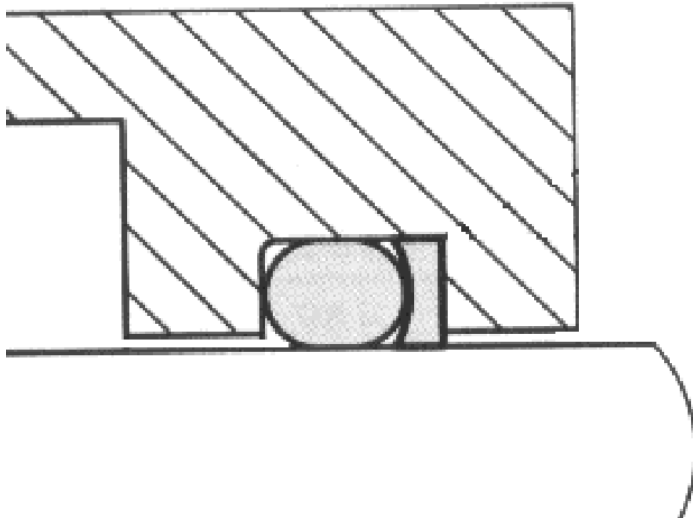


Figure 9 – O-ring containment sealing solution with back-up ring