The Evolution of Elastomeric Joints in Plastic Pipe Systems and the use of Long Term Stress Relaxation Testing to Predict Service Life

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Stress Relaxation, Contact Pressure, Force Decay, Long Term Durability

ABSTRACT
Until the late 1950's, water and sewerage pipe lines used predominantly rigid joints. These were often made from tarred rope and cement mortar. The introduction of 'flexible' elastomeric joints allowed angular deflection, transverse shear load and localized pipe deformation without leakage or failure of the joint. This paper presents a brief history of elastomeric seals in water and sewerage pipeline systems, looking at how the existing materials and designs of joints have evolved. It considers the current elastomeric material standards and how these specifications relate to the long-term durability of the joint.

The contact pressure in a joint, decreases over time due to relaxation of the rubber seal. In this time-dependent relaxation process, the rubber relieves a part of the imposed compressive stress by reorientation of the polymer chains in the rubber material. This reorientation is non-elastic and will result in a permanent reduction in contact pressure.

Using recognized and proven ISO methodology, the relaxation threshold value may be chosen as the maximum relaxation acceptable for the joint design and application. The time taken to reach this threshold may be estimated.

INTRODUCTION
PVC-U pipes for sanitary drainage systems were introduced as far back as the 1930's. Many pipelines installed during the 1940's for residential drinking water distribution and waste are still in-service today.
During the 1950's, there was a big increase in the use of PVC-U pipe due to the post war infrastructure re-construction.
Initially, the jointing systems used were spigot and socket solvent welded. However, this proved unsuitable for pipes greater than DN250mm and so, integral sockets and loose couplers with fixed rubber rings were developed.

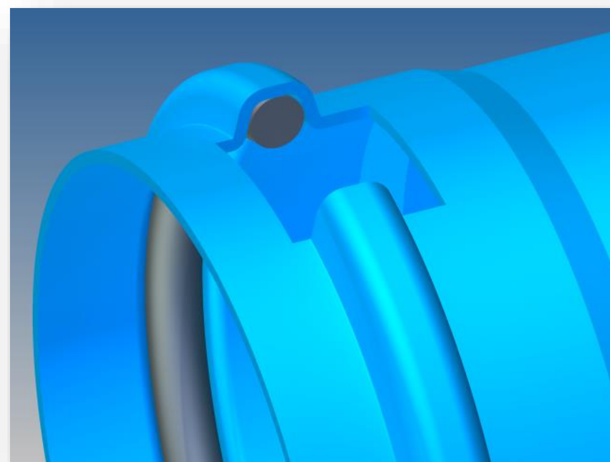
Rubber ring joints had already been established for clay, concrete and iron pipes using O-rings of various profile thicknesses and hardnesses.

The joint design for PVC-U pipes needed a little more thought because:

- The flexible nature of the material also meant greater sealing force from the rubber ring, which could cause distortion of the material
- The smooth surface meant the traditional system of 'rolling' the seal into the joint during assembly was not possible

This effectively meant that all joints used the 'fixed ring' design, with the O-ring seal nearly always located in the socket or sleeve of the joint.

As the pipes and fittings were extruded or injection moulded, tight tolerances on the joint dimensions could be assured. This meant that the seal dimensions and the degree of compression required could be calculated accurately.

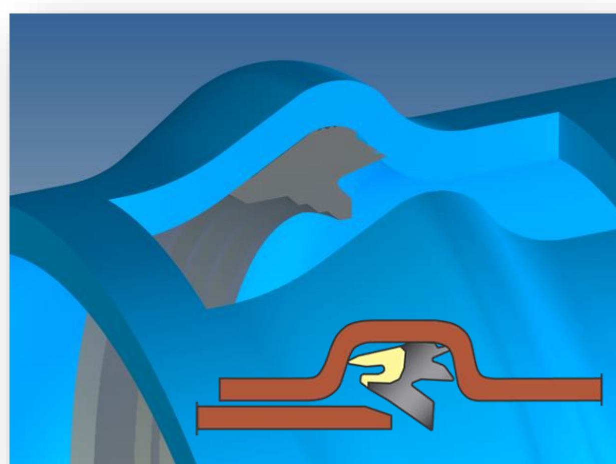


Typical Confined O-Ring Joint

Perhaps this is a good opportunity to state that 'compression' is not the correct term to use. Rubber acts hydraulically in a pipe joint and is not compressed but deformed. However, 'compression' is the term generally used to describe the change in geometry of a seal in a pipe joint, and it is well understood in the industry.

Once assembled, this configuration results in a robust and durable joint. It did however require a good quality chamfer to the spigot, relatively high jointing force, and a high quality, correctly applied lubricant. The O-ring could easily be displaced during jointing, often without the pipe layer noticing.

In the search for lower joint assembly forces and improved seal stability, the 'lip' seal was developed for both pressure and drainage systems. Using a rearward trailing lip, this design allows the pipe spigot to pass part way through the sealing zone before deforming the seal, thus pinning the seal into the socket groove and reducing the likelihood of seal displacement.



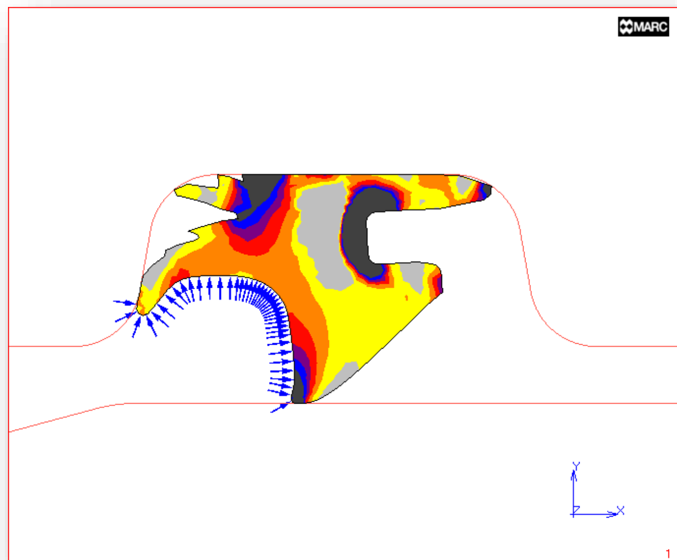
Typical 'Lip' Seal Joints

LEAK TIGHTNESS – INFILTRATION AND EXFILTRATION

When assembling a joint, the rubber seal is deformed into a pre-designed annulus between the socket and spigot. This deformation induces a contact pressure acting from the seal against the joint surfaces. This contact pressure must exceed the operating pressures, both inside and outside the joint, to prevent leakage or penetration of fluids through the joint.

O-ring joints can be considered to have the same level of performance against both infiltration and exfiltration. However, care must be taken in designing lip seal joints to ensure adequate levels of resistance to infiltration are maintained.

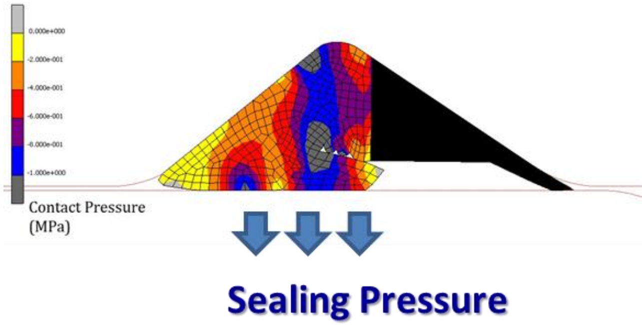
With the lip seal configuration, it is relatively simple to design a joint with good internal pressure resistance. The pressure from the fluid inside the pipe acts to expand the cavity at the back of the seal, increasing the sealing pressure of the rubber against the spigot and socket. Most excavator hydraulic cylinder sealing systems are based on this principle: the higher the internal pressure the higher the sealing force. However, the same joint may have poor resistance to infiltration as external pressure will force the lip to open relatively easily. It is for this reason that joints, utilising the assembly advantages of the lip seal combined with a central compression zone, offer the most robust design.

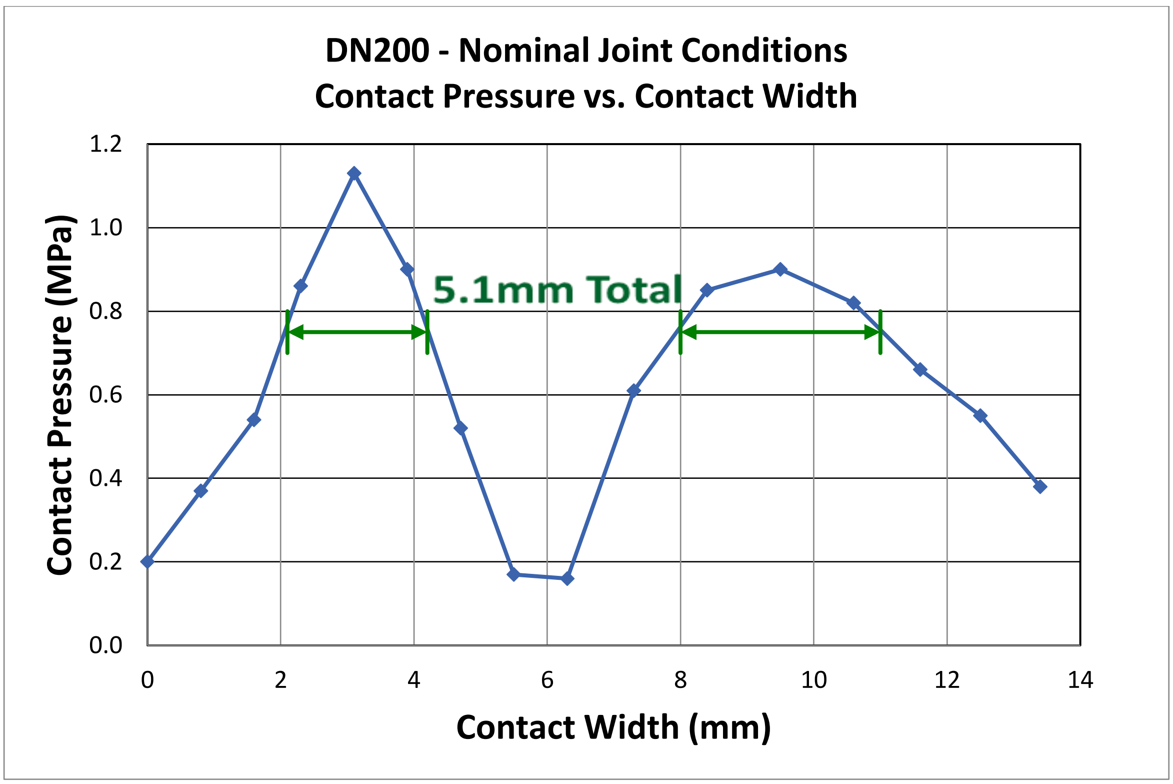


Lip Seal Joint – Blue Arrows Represent Internal Pressure

Various standards have started to specify minimum seal contact widths over which a minimum mean sealing pressure must apply. This type of specification was first introduced in the fight against root intrusion, where minimum interface pressures were proven to be the best safeguard against roots. Whilst this is good in principle, as with any joint design, there is a higher contact pressure in the centre of the sealing zone. To understand the full function of the joint, it is necessary to consider the contact pressure across the full contact width. This information can be used to predict the performance of the joint and is also used in determining service life and long-term durability.

For example, a typical DN200mm pipe joint may look like this:





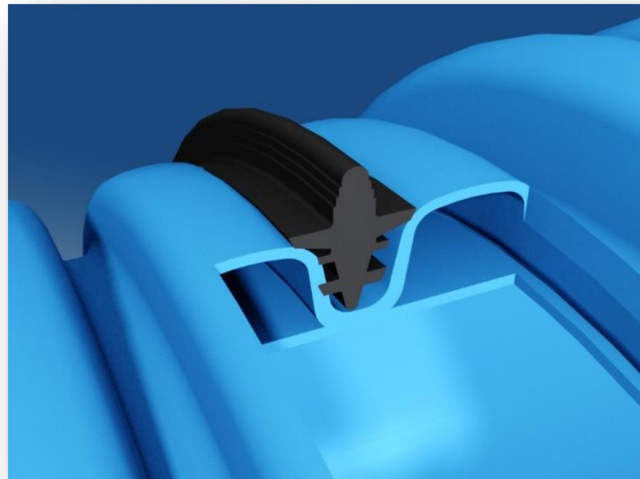
This joint shows:

- Peak contact pressure = 1.13 MPa
- 14.0mm of contact width > 0.2 MPa contact pressure
- 5.1mm of contact width > 0.75 MPa contact pressure

By careful consideration of these factors, joints can be designed and proven to perform as predicted in static situations.

CONSIDERATION OF PIPE MATERIAL AND STRUCTURAL DESIGN

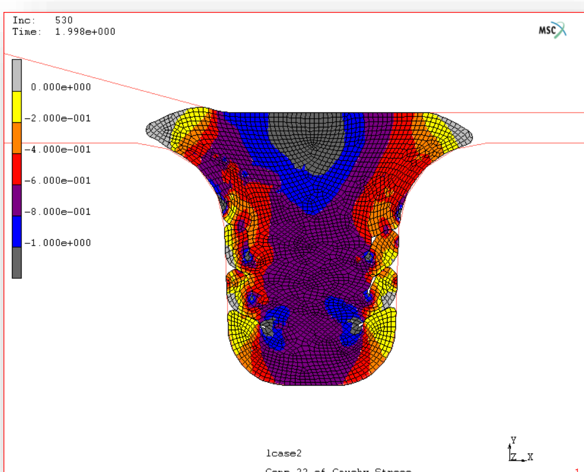
When designing seals and joints for PVC-U pipes, the housing of the joint can often be taken as a rigid body with little or no deformation resulting from the force applied by the rubber seal. For elastomeric joints in pipes produced from less rigid thermoplastics, especially when the pipe is corrugated or of a structured wall nature, it may be necessary to consider potential socket expansion both during and after jointing. It may also be necessary to determine whether the strength of the corrugation is sufficient to withstand the forces from the seal.



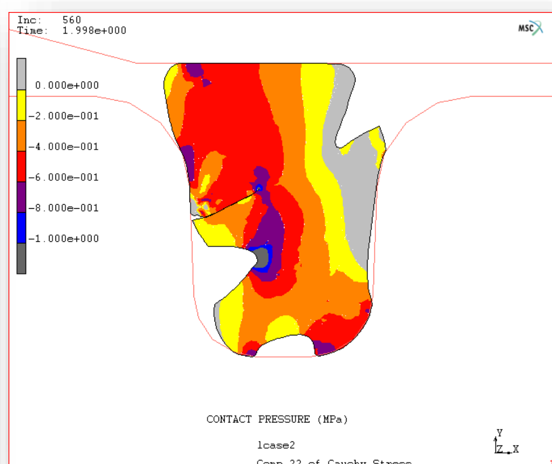
Section through a Corrugated 'Twin Wall' pipe and seal

There are existing applications where the design of the joint and seal has been based on the 'fill the groove full of rubber' principle. This results in excessive jointing forces. Often, the socket will have to expand to accommodate the seal and in extreme cases of joint tolerance the corrugations may be deformed or even collapse.

The images below, show a real example of how a joint, originally designed with excessive rubber volume, may be re-designed with the aid of Finite Element Analysis. This results in >30% lower jointing force and a significant reduction in rubber volume.



Original design
Excessive Jointing Force



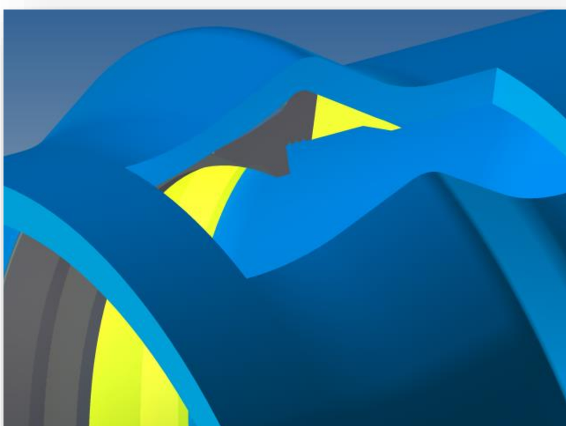
Re-design
>30% Lower Jointing Force

EASE AND RELIABILITY OF JOINTING ON SITE

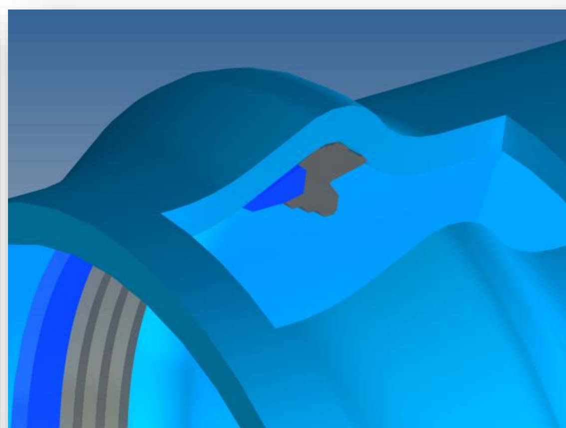
“Down in the trench, a man needs all the help he can get”. This was a phrase I heard many years ago and it has become somewhat of a philosophy in the development of push fit joints for plastic pipes. We can discuss contact pressure, joint performance, elastomer specification and durability, but all of this is of secondary importance if the joints are not installed correctly in the trench.

It often seems like a balancing act. On the one hand you need a sufficient elastomer deformation to ensure adequate performance across the tolerance range of the joint and provide a long service life. Whilst on the other hand, reducing interfacial pressure and contact width increases the ease of joint installation and reduces the risk of seal displacement.

Integrating the seal into the pipe socket either by hot-forming, using the ‘Rieber Process’, or by using composite seals incorporating a locking or retaining system, greatly reduces the possibility of seal displacement during jointing. Seals can no longer be lost or misplaced during pipe stocking and transportation, and the correct seal fitted in the correct position in the socket is ensured.



Integrated ‘Rieber’ System Joint



Composite seal with Retaining System

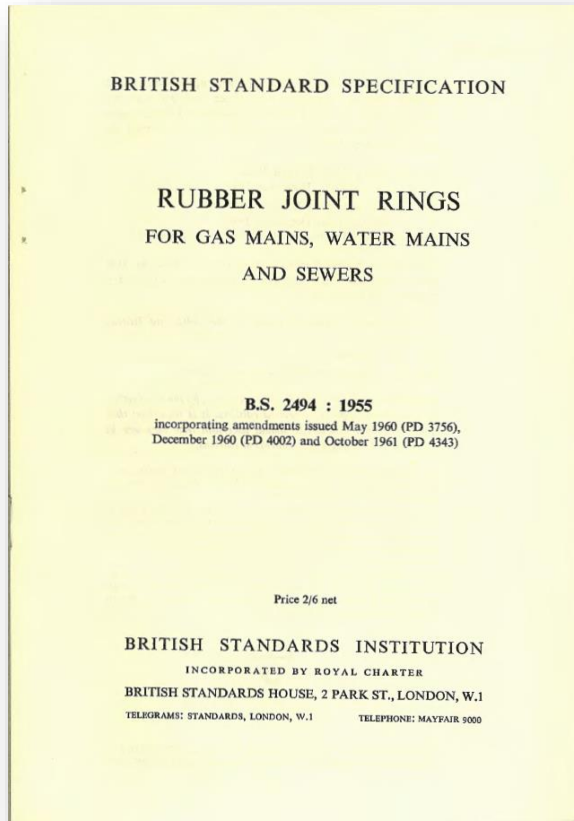
Low friction elastomer compounds are being developed to reduce jointing force. Personally, I believe there is a limit to lowering jointing force. Below a certain threshold, the pipe installer should question whether the joint will still be water tight.

ELASTOMERIC MATERIALS FOR PIPE JOINTS

One of the first Standards for Rubber Joint Rings for Water Mains and Sewers dates back to 1955[1]. The ASTM F477 Standard Specification for Elastomeric Seals (Gaskets) for Joining Plastic Pipe was published in 1976[2], followed by ISO 4633 in 1984[3] and EN681 in 1996[4]. All of these are 'materials' standards, providing direction on the physical requirements of the elastomer material including:

- Hardness classification
- Tensile strength
- Elongation at break
- Compression set
- Stress relaxation
- Volume change in water
- Ozone resistance

General requirements for finished joint seals are included, but additional requirements called for by the specific application, such as seal geometry, joint design and performance, are specified in the relevant product standard.


BRITISH STANDARD SPECIFICATION

RUBBER JOINT RINGS
FOR GAS MAINS, WATER MAINS
AND SEWERS

B.S. 2494 : 1955
incorporating amendments issued May 1960 (PD 3756),
December 1960 (PD 4002) and October 1961 (PD 4343)

Price 2/6 net

BRITISH STANDARDS INSTITUTION
INCORPORATED BY ROYAL CHARTER
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Over the years natural rubber was replaced by synthetic elastomers due in part to their superior microbiological deterioration resistance. The most common elastomers used for water, drainage and sewer applications are SBR and EPDM and TPE. NBR may be used when oil resistance is required.

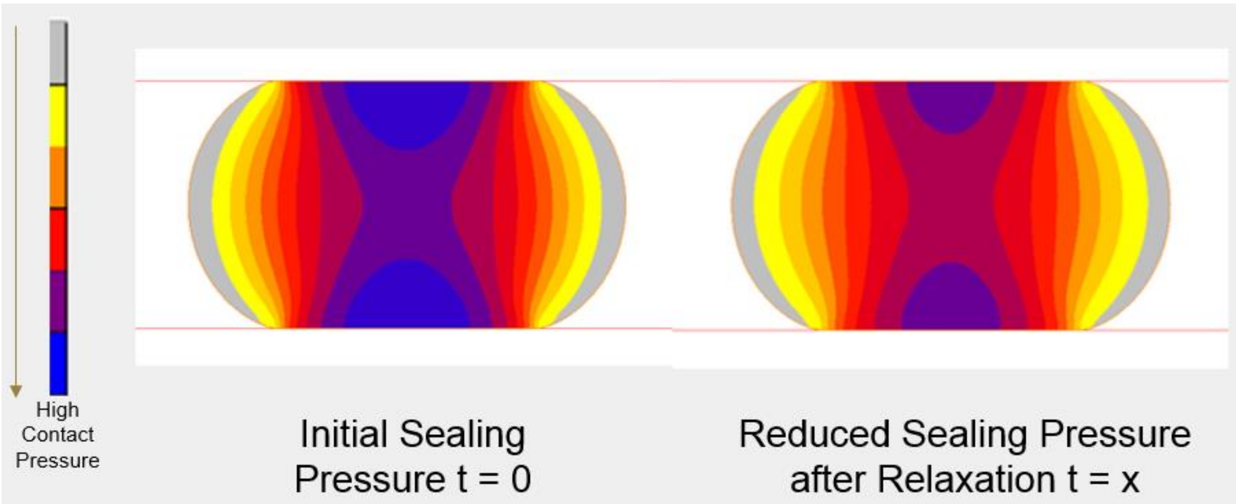
LONG TERM DURABILITY

It is important for engineers to understand all life cycle aspects of pipeline systems. They need to utilize current and complete data to assess the life cycle environmental impacts for piping infrastructure. There are many studies published, but most focus on the pipe material and the elastomeric seal is generally ignored.

A joint assembly must remain watertight throughout its working life. A significant factor in achieving this, is to ensure that the physical characteristics of the installed seal are sustained at or above accepted levels.

When rubber undergoes a constant strain, as it does in a joint, the force needed to maintain that strain decreases over time. This is referred to as Force Decay or Stress Relaxation.

In this time-dependent relaxation process the rubber relieves a part of the imposed compressive stress by reorientation of the polymer chains in the rubber material. This reorientation is non-elastic and will result in a permanent reduction in contact pressure.



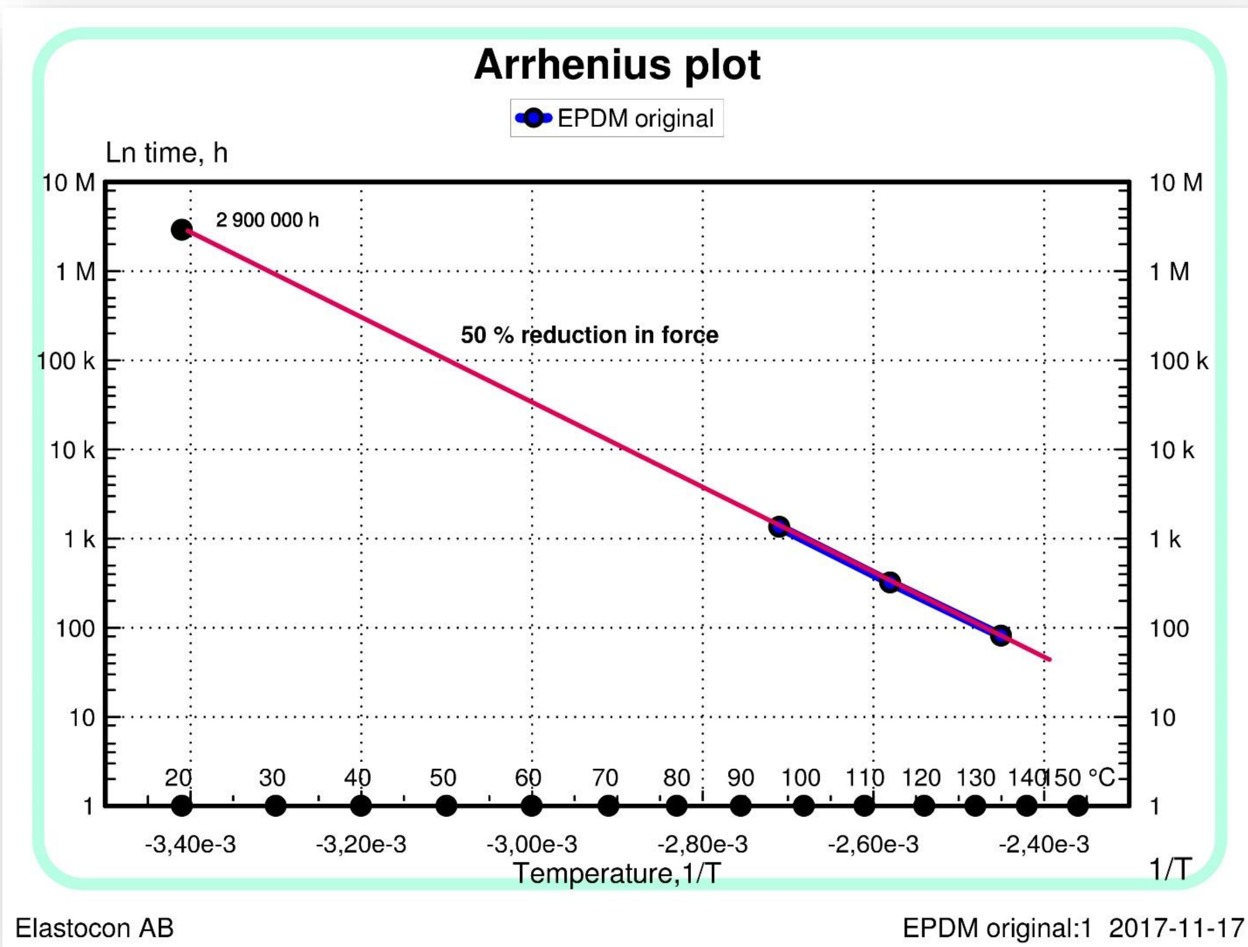
The illustration above shows the initial sealing pressure, achieved when the joint is first assembled, and the reduced sealing pressure after stress relaxation.

Elastocon AB of Sweden are acknowledged as one of the global leaders in providing both the equipment and the testing of stress relaxation in elastomers. Using ASTM and ISO methodology, a program was set up using test pieces taken from existing seals available on the market. Stress relaxation under compression was chosen as the critical value. This is caused by both physical and chemical relaxation.

The standardised test methods used by Elastocon AB are:

- ISO 11346: Rubber, vulcanized or thermoplastic - Estimation of life-time and maximum temperature of use[5]
- ISO 3384: Rubber, vulcanized or thermoplastic - Determination of stress relaxation in compression[6]
- ASTM D6147: Test Method for Vulcanized Rubber and Thermoplastic Elastomer-Determination of Force Decay (Stress Relaxation) in compression[7]

Once a pipe joint is assembled, there is a physical relaxation of the rubber seal which takes around 30 minutes. After this time, the sealing force is relatively stable. This sealing force value is then used in the estimation of the effective lifetime of the seal.
By exposing test pieces to a series of elevated temperatures, the relation between the rate of stress relaxation and temperature can be deduced. Estimates can then be made by extrapolation of the degree of stress relaxation after a given time at a given temperature. The relationship can be represented by the Arrhenius equation.



The threshold value is chosen as the maximum relaxation acceptable for the application. Commonly, 50% of the initial value is chosen (ref ISO 11346, section 6), but 30% and 40% were also measured.

RESULTS

			Stress Relaxation				Predicted Lifetime		
Sample	Material	Process	7 days 23°C		100 days 23°C		50% reduction (23°C)	40% reduction (23°C)	30% reduction (23°C)
			%	EN681	%	EN681	years	years	years
A	EPDM50	molding	14	<14	19	<20	790	664	251
B	EPDM50	molding	11	<14	16	<20	139	27	2
C	EPDM50	extrusion	12	<14	17	<20	927	255	39
D	EPDM55	extrusion	10	<14	19	<20	86	41	9
E	SBR60	extrusion	18*	<15	30*	<22	16	10	4
F	SBR40	extrusion	6	<13	10	<19	135	70	39
G	SBR50	extrusion	8	<14	12	<20	59	43	27
H	EPDM50	molding	7	<14	12	<20	293**	23**	2**
I	SBR40?	extrusion	6	<13	10	<19	20	15	10

*Does not pass 7 & 100 day requirements

**Sample not correctly vulcanized - high compression set

Compounds with the same designation, e.g. EPDM50, may pass the requirements of EN681, but they show very different ‘lifetime’ capabilities. This depends on the quality of the material formulation and processing. Compounds that do not meet the requirements of EN681 or samples that were incorrectly vulcanized, show very poor results.

CONCLUSIONS

High performance compounds show less relaxation in comparison to lower quality ones. A high-performance compound will have:

- High polymer content
- Low compression set
- Good crosslink density
- Good vulcanization system

This results in low stress relaxation, which is good news for the service life of the rubber seal, but it does have commercial implications.

The results of the studies indicate that, when applied correctly, high performance compounds will continue to apply the necessary interface pressures more than 100 years.

The information gained so far will be used to study existing pipe joints and predict service life of the systems in use today. Not only will it allow us to better understand the durability of existing joints, it will also provide valuable information to design new systems for the future.

REFERENCES

1. BS 2494:1955 Rubber Joint Rings for Gas Mains, Water Mains and Sewers
2. ASTM F477: 14 Standard Specification for Elastomeric Seals (Gaskets) for Joining Plastic Pipe
3. ISO 4633: 2015 Rubber seals. Joint rings for water supply, drainage and sewerage pipelines.
4. EN 681: 1996 Elastomeric seals. Material requirements for pipe joint seals used in water and drainage applications
5. ISO 11346: 2014 Rubber, vulcanized or thermoplastic. Estimation of life-time and maximum temperature of use
6. ISO 3384: 2011 Rubber, vulcanized or thermoplastic. Determination of stress relaxation in compression
7. ASTM D6147: 97(2014) Standard Test Method for Vulcanized Rubber and Thermoplastic Elastomer - Determination of Force Decay (Stress Relaxation) in Compression