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Sealing materials seals for arctic applications

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Summary

This thesis is about exploring the performance of rubber O-ring seals made of materials such as: ELAST-O-LION 101, base HNBR and HNBR 50 CB, under cold temperatures and compressions equal to 10% and 20%. Initially a test apparatus with cooling chamber was built to evaluate seal performance at different temperatures and contact pressures. This part of the project included building the environmental chamber in which the mechanical compression rig is located, as well as connecting the circulating unit for the cooling liquid to the chamber. In order to obtain the data, such as the applied force and the temperature inside the chamber, a load cell and a thermocouple was also attached. The data was initially collected with the use of Catman program.

The analysis of the obtained data delivered useful information about the materials performance under harsh conditions which are were similar to those which can be faced by a sealing arrangements operating in the arctic environment. The tests have shown a significant force drop while decreasing the temperature inside chamber. A part of the analysis was also to calculate contact pressure of the specimens at lowered temperatures. This was done on the basis of Hertz theory of contact of the bodies.

Further, this master thesis identified the need for further research and investigation of a specific arctic conditions and the factors that are influencing any machinery which is desired to find an application on Arctic.

Abbreviations

HNBR	Hydrogenated Nitrile Butadiene Rubber
ECI	Elastomers Compatibility Index
Tg	Transition temperature
EP	Ethlyene-Propylene
FKM	Fluorocarbon
PVMQ	Silicone
FVMQ	Fluorosilicone
ACM	Polyacrylate
AU	Polyurethane
IIR	Butyl
CSM	Chlorosulfonated Polyethylene
ECO	Epichlorohydrin
PNF	Phosphonitrillia Fluoroelastomer
$\boldsymbol{P}_{0}$	Contact pressure
F	Force
$\mathbf{a}_{\mathbf{Hertz}}$	Contact radius
R	Radius of curvature

1. INTRODUCTION

Arctic region is one of the most difficult environment to perform any kind of industrial activities due to extremely low temperatures that affects properties of almost every single material beginning form metals ending on polymers. As temperature decreases materials undergo some transitions (such as glass-rubber transition process) and lose their previous properties: become brittle and react differently for example under compression. There are several main factors that have an influence on the materials suitability for arctic applications. Those specific properties are often connected to ability of a material to withstand not only extremely low temperatures but also oil and chemical environment, as well as pressure fluctuations. Nowadays the main goal for engineers is to find a material that has the best combination of such properties. Unfortunately while trying to discover proper one they are struggling with contradictory guidance showing that a material can fulfill only one of the above features and the others are being excluded. It is either that a material is suitable for applications in the environments containing oils and chemicals, but then have a low ability to withstand extreme temperatures or it completes the temperature requirements but will not be resistant to all of the present chemicals or will not be able to withstand the pressure fluctuations. Therefore the main goal for scientists is to select a material having optimal features for a specific applications [1].

In this paper Elast-O-Lion 101 [15] (HNBR) was tested as a candidate for material appropriate for seals in arctic applications. The investigation involved checking its appearance while lowering operating temperature and additionally introducing compression. The tests were about to show the ability of this material to remain required tightness level since this is the most important feature of a component that an O-ring is made of.

1.1. Arctic environment

Arctic region is a place where average temperatures during winter can drop below −50 °C and during summer it may reach even up to +10 °C. In this region the ground is permanently frozen and the ocean is extremely cold, the phenomenon of sea ice also occurs there. The ocean's surface is covered by a frozen sea water. Shards of the ice are floating and moving due to the presence of strong winds and ocean currents [2]. All of this factors have a huge influence on every single industrial activity that are desired to be run within this region, which has become important due to its richness in oil. The extremely demanding conditions create a need for people to deeply investigate a behavior of materials while being exposed to very low and variable temperatures, often in harsh sea water environment. Highly salty sea water freezes at the temperature of approximately -2°C but this may also vary dependent on the degree of salinity. The higher it gets the lower the temperature of freezing of the water. What is more the ice formed from sea water initially differs from the one drawn up from fresh water. Due to the salt content at the beginning the ice is squishy. Then afterwards the salt is dissolving. In the end it is more flexible than fresh water ice and has a rough surface. However this information are not totally accurate [3]. It is not yet fully explained how the formation of the ice takes place and at the same time it is certain that the procedure differs under changing arctic circumstances [4]. This is a reason why it is hard to compare this environment to any other, what causes the specified tests of materials for its accurate future working conditions a great of importance [3].

The main characteristics that need to be monitored, while testing, are changes in strength and elastic properties in order to get general information about durability of particular material in specific habitat of use [3]. There are several factors that are said to be the key features regarding the hesitancy in exploring the arctic environment. Those are: insufficient experience in industrial activities within this region, little knowledge about the climate as well as economic doubts.

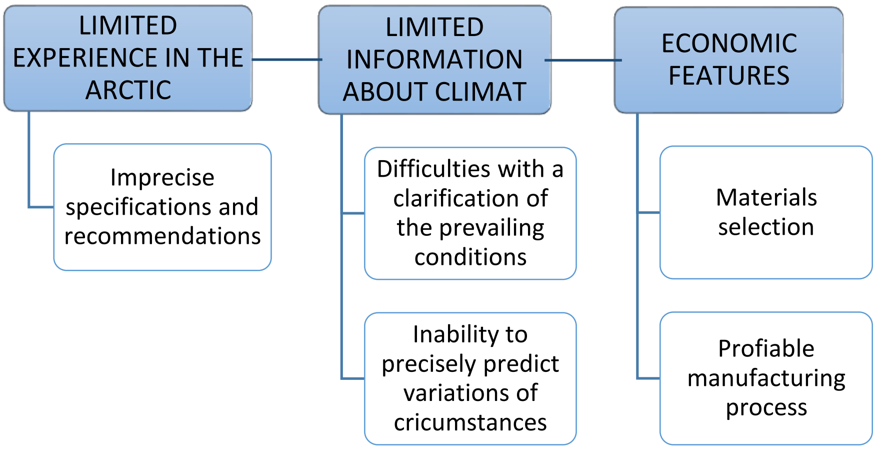


Fig.1 Factors affecting the difficulty of industrial development in the area of Arctica.

The above graph shows the main reasons contributing to problems with running any industrial activities with regard to the choice of materials. Limited experience is a reason of poor knowledge of possible dangers that may take place while working there. That is also leading to problems with the formulation of the correct and accurate standards. The latest standard ISO19906 Arctic Offshore Structures is still not very profound regarding material selection section. This applies mainly to steels that are supposed to work in Arctic conditions but situation with some additional components, like for example seals, is even worse because there is less interest on that, as it is considered less important [4]. The basic specifications should be provided by a manufacturer, but as long as we are dealing with an extraordinarily demanding conditions it is recommended to search for more detailed information at qualified research laboratories [3]. The information contained in all of the standards are generic and inexact. Therefore lots of researches and testing should be performed in order to improve standards and clarify the requirements for all materials that are supposed to be used in the Arctic environment [4].

What is more limited data on climate is also resulting in problems in the selection of materials for arctic applications. The climate is not completely described yet. It is described as a region with the highest temperature not exceeding 10°C, which is a quite superficial description. Even though there is an increasing interest in widening the knowledge about this climate, still the data that have been obtained applies only to a short, recent period so it cannot be the basis to accurately predict the conditions that will be there in the future. Additionally what needs to be taken into consideration, beside the low temperatures, are the strong winds with the speed in the range of 5-15 m/s, making the environment even more unpredictable and harsh [4].

Taking all of the above factors into account it must be also realized that the cost of materials should not be excessively high in order for the enterprise to be profitable. Since there are more and more materials developed, the possibility of obtaining one, which will fulfill all of the requirements is getting higher, but then obviously the price of it increases, so sometimes the point of unprofitability may be reached.

Even though the conditions that are being faced during setting up industrial activities in Arctic regions are very demanding, there is hope to find appropriate solutions. Recently many researchers have focus their interest on that topic and so the offer of new, potentially exquisite solutions is broadening all the time.

1.2. Sealing materials

The material for seal rings needs to possess unique properties especially if it comes to elasticity, but the requirements varies within the range of applications. There is plenty of the selection criteria, some of them are as following: chemical compatibility, working temperature, operating pressure, as well as size and cost. In order to select properly the material for the O-rings, the mechanical requirements should be carefully studied and the media with which the part will remain in contact during operation should be taken into account. By far the majority of the seals is made of polymeric materials. Polymers are macromolecules composed of the monomer creating chains through the processes of: polymerization, polyaddition, polycondensation. There are two types of polymers: homopolymers (consisting of one repeated monomer) and copolymers (within its structure at least two polymers can be found). In addition, polymeric materials can be divided according to the characteristics of mechanical deformations on: thermoplastics, elastomers (rubber), thermoplastic elastomers and thermosets. Most of the O-ring is made of elastomers and thermoplastic elastomers based on block copolymers, which is characterized by a block or segmented arrangement of monomers, as shown on the example below, where A and B are different monomers.

-A-A-A-A-B-B-B-B-B-A-A-A-A-

Furthermore, seals are sometimes made of thermoplastics materials or thermosets. However, these materials are not suitable for making the O-ring seals due to its high hardness and brittleness.

A seal is a component which is used to preclude leakage of fluids and it is extremely important part of, for example, hydraulic cylinders of machinery due to the presence of pressurized fluids. There are two main categories of seals: static and dynamic seals. Static seals are those which seal between the two motionless parts of the machine while dynamic seals are located between two surfaces that are moving. Static seals are to constitute obstacle for mixing the liquids or leakage of lubricant. The main property that a sealing material must have in order to serve its purpose is high elasticity, in order to ensure an adequate level of adhesion to the sealed parts, which are often in an irregular shapes. On the other hand it needs to be also quite rigid. Such requirements are quite well performed by elastomers. Second type of seals- dynamic, are placed between the moving surfaces. The demands for this seals are often excluding one another so the main challenge, while designing, is to obtain optimal properties that will partially cover all of the requirements. For example there is a need of high contact pressure between parts being sealed, but on the other hand the friction should be sufficiently low for long durability of the equipment.

Both of this seal types might be further divided as it is shown in fig. 2

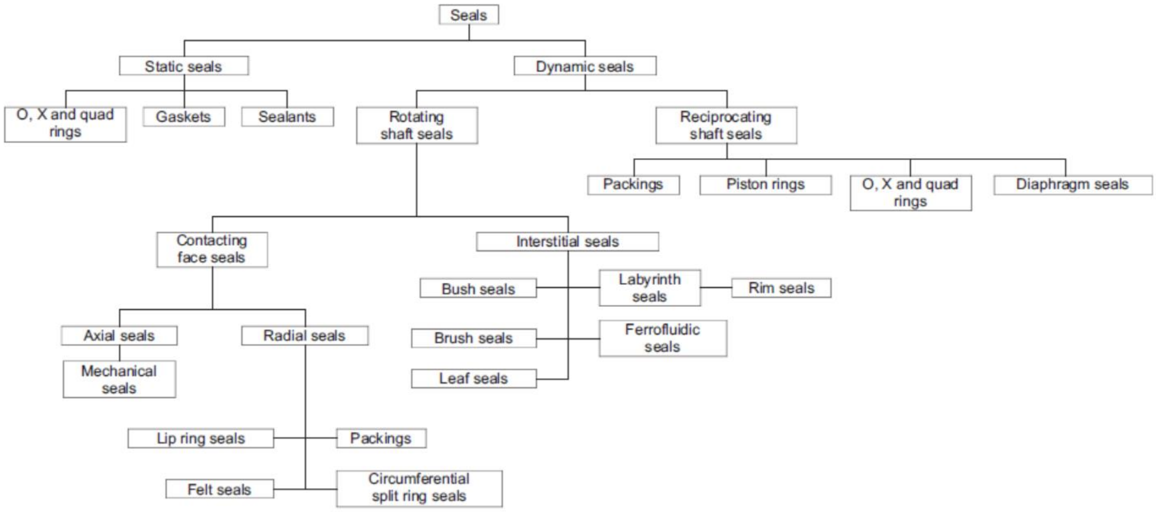


Fig. 2 Classification of seals. ESDU (2009).

The above graph presents many different sealing possibilities, but still the most important condition for all of those is to ensure lack of clearances between the parts. Otherwise the fluids exchange or leakage will arise. Possible exchange mechanisms are as following: diffusion, free or forced convection. If there is any gap within a sealing system then the liquid can diffuse. It occurs due to either mechanical factors or differences in densities of fluids. Fig 3 well illustrates the described problem.

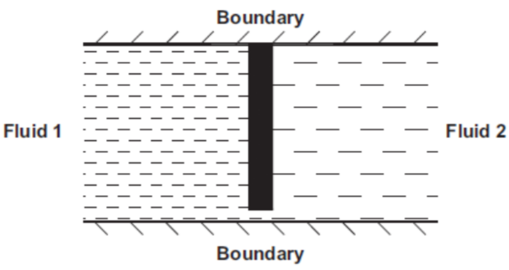


Fig. 3 Appearance of a sealing.

1.2.1 Selection of sealing

There are many various factors that needs to be taken into consideration when selecting the appropriate type of seal. First of all the analysis have to be based on the fluids characteristics. Another extremely important factor is pressure levels that will be obtained on seals while operating. What is more the type of movement of the sealing, relative to element being sealed, should be deeply examined thus it can be rotary motion, reciprocating with various speeds. Additionally there are some applications that requires high quality sealing, no leakage is admissible, but on the other hand some are less demanding, therefore the required level of sealing and the tolerance of leakage have to be assumed at the very beginning. Of course the basic parameters, such as the operating temperature and durability and also economic incentives, must be taken into consideration as well. [5]

Fig 4 sketches briefly how to choose the right type of seals, taking into consideration all the above factors.

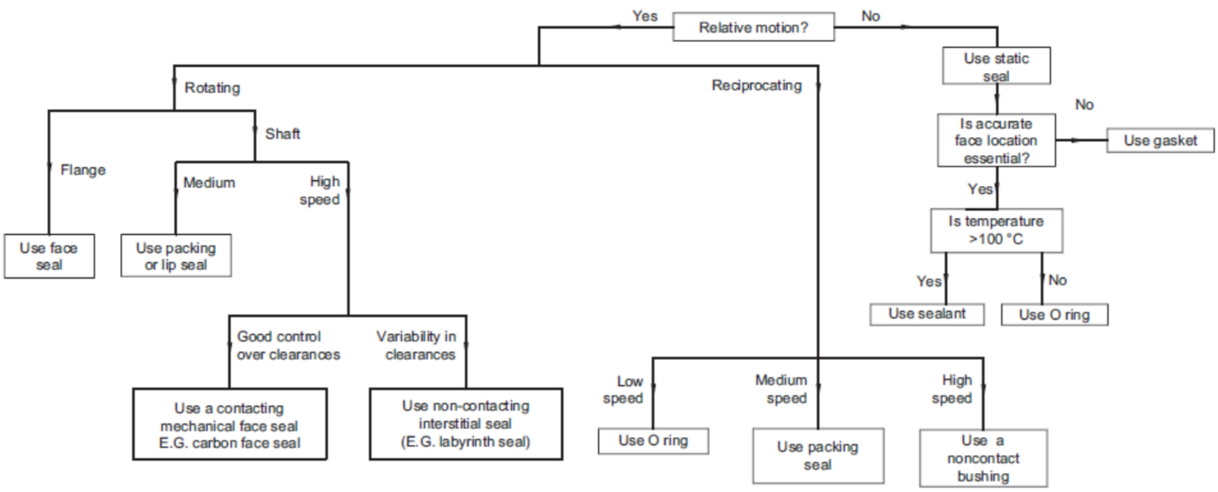


Fig.4 The procedure of sealing selection

1.2.2. Elastomers as sealing materials

Elastomers are an exceptional group of materials because of its high flexibility, which results in their wide range of applications as sealing materials. Even though their strength is quite low comparing to other materials. The main feature distinguishing this type of material from the others is their ability to revert into an original state (the one before deformation that have been induced by applied stresses) after release [7]. The phenomenon takes place on the condition that the energy used for stretching the rubber is higher than retraction energy and it is called hysteresis. The stress-strain graph below is an illustration of rubbers hysteresis.

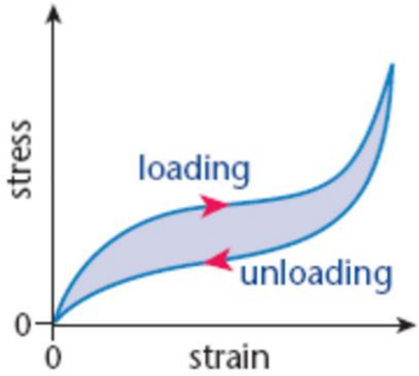


Fig. 5 The stress–strain graph for rubber [9].

As we can see in fig.5 the appearance of a rubber while being stretched (during loading) differs from the unloading behavior. The appearance though changes while the cyclic process is repeated several times as it is shown in the fig.6

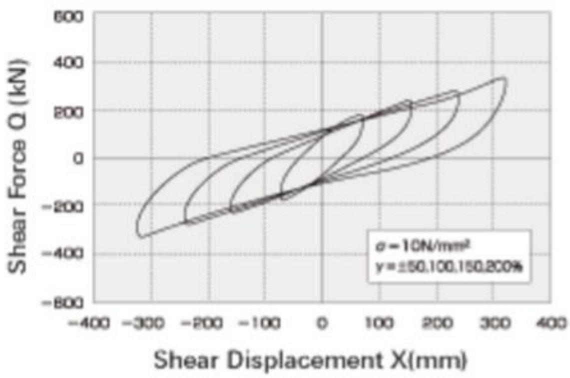


Fig.6 Hystesis loop [10].

When this material undergo couple of loading and unloading cycles then an elongation of a sample might be denoted. This phenomenon is known as permanent set, which is a measure of flexibility and it takes place during subjecting a sample to compressive stresses as well. The rubber suitable for seals should decay as little as possible and its permanent set needs to have a small value [8].

The fact that elastomers are a part of a group of polymeric materials, so they are consisting of long chains, enables the described phenomenon. Moreover, they are amorphous materials, so the chains are resilient. The structure therefore contains of several flexible monomers enclosed in a network [7]. It is necessary for a sealing material to be highly flexible in order for it to adhere well to the diverse sealed surfaces [8].

These materials, instead of polymer, are composed of other additives, which role is to accelerate and supervise the cross linking of chains, as well as restraining the decomposition in the specific working environment. By combining various types of additives and polymers, the desired properties, suitable for a given application, of the elastomer can be achieved [6].

What is more sealing materials should withstand abrasion caused by the movement of sealed surface. That is why it should have an optimal hardness, stiffness, which can be verified for example through appropriate shape choice, tear and fatigue resistance. One of the most frequent reason of leakages of liquids is vibration fatigue as the machinery is in use. The utilization of elastic rubber joints is a way to avoid this process.

In addition elastomers are incompressible, what makes them also a proper material for sealing. Even if it experience high pressures while operating, that cause a huge elongation, the noticed change in volume of a deformed rubber is not substantial [8].

Therefore the unique features and properties as well as the accessibility of elastomers are a reason for a wide range of applications of the material as sealing. The applications area includes common, uncomplicated seals, which are designed to provide protection against the ingress of dust from the environment into the machine and also more demanding applications, like for example preventing the natural environment pollution [7]. Therefore it is extremely important, while designing a seal, to have an overall knowledge about the material properties, in order to use a suitable type of rubber for a particular application, taking into account also the stresses and strains which will be present in the working environment [8].

1.2.2.1. General selection criteria

In order to find a suitable elastomer seal for a given application, many features must be considered. Researches on each of them are carried out separately, so the results of several tests of the material should be analyzed. Some of the important characteristics and the way of testing it are as following:

- Compatibility with media- the media contacting the elastomer may decrease or increase the volume of a material, or may even cause total disintegration of the material. Any change in volume can lead to changes in the mechanical properties of such material eg. hardness, tensile strength and elongation, what may cause complete destruction of the seal. In the presence of mineral oils, two opposing reactions may take place: swelling of the rubber under the influence of media penetration and dispersion of the elastomers, plasticizers or oxidants leading to reduced material volume. Generally the higher the acrylonitrile content of the elastomer, the better the compatibility with oil. The following table shows the compatibility of different media with elastomeric materials.

ECI for Various Oils	
Type of Oil	**ECI**
ASTM Oil Number 1	**2.2 - 3.2**
BP Energol HLP 100	3.7 - 4.7
Esso Nuto H-54 (HLP 36)	5.9 - 6.9
Houghton HD 20W/20	6.9 - 7.9
Esso Nuto H-44 (HLP 16)	7.1 - 8.1
DEA Rando Oil HDC (HLP 36)	7.7 - 8.7
Fina Hydran 31	8.5 - 9.5
Shell Tellus 923 (HLP 16)	9.2 - 10.2
ASTM Oil Number 2 (IRM 902)	**9.4 - 10.4**
Esso-Trafo oil 37	12.5 - 13.5
Agip F. 1 Rotra ATF	12.6 - 13.6
Mobil Vac HLP 16	14.0 - 15.0
Shell Tellus 15	14.7 - 15.7
Essocis J 43	15.0 - 16.0
Shell oil 4001	16.3 - 17.3
Texaco Rando Oil AAA	16.5 - 17.5
BP Energol HP 20	19.0 - 20.0
ASTM Oil Number 3 (IRM 903)	**23.0 - 24.0**
Shell Tellus 11	32.9 - 33.9
Shell Oil JYO	34.5 - 35.5

Table 1. Values of ECI indexes for different oils [13].

Elastomers compatibility Index (ECI) was created on the basis of the laboratory tests. It has been proves that there is a linear relationship between the ECI and the change in the volume of elastomers. Therefore using this index the change of elastomers volume, as a result of contact with the mineral oil, may be predicted.

- Abrasion - most of the abrasion tests reflects the actual operating conditions in an inaccurate way. Mechanical wear is a very complex process that is a reason why the wear resistance should be tested for the particular application.
- Aging – occurs as a loss of physical properties and it depends on the type of the molecular chain of the elastomer, as the bonding of chain and other parts of it can be exposed to some chemical reactions taking place during material lifetime. Aging is linked to three types of reactions: disintegration- chains of elastomer are shorten, crosslinking- oxidation process causes the formation of new bonds, and modification of groups of molecular chains- medium destroys elastomer and changes its molecular structure. In order to test this property the rubber samples are tested by artificial aging in an oven.
- Coefficient of thermal expansion- seals made of elastomer tend to volume change in extremely high or low temperatures. At low temperatures there is less elastic force acting on the seal surface, which may in turn result as loss of containment of the system due to the smaller volume of seal.
- Permanent deformation under compression- it depends on the type of elastomer, the mixture composition, production conditions, temperature and time of testing, the deformation of the sample and its thickness and the media used during the test. Tests are carried out in accordance with DIN ISO 815. This tests may also evaluate the flexibility at low temperatures. For this purpose, the samples are compressed by gradual cooling and measurements after releasing the pressure. Changes in dimensions of a sample are shown below.

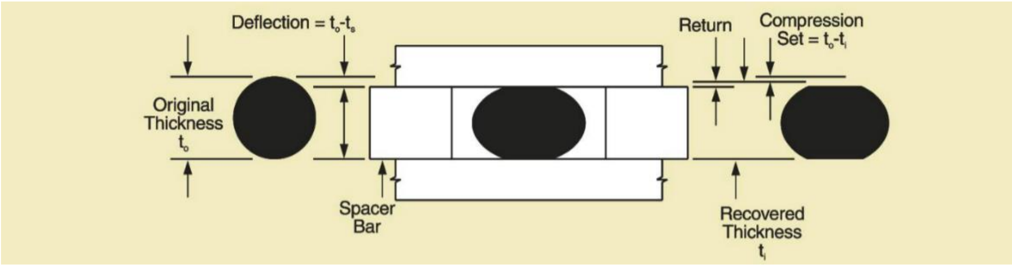


Fig.7 Compression set [13].

1.2.3 Rubbers appearance at low temperatures

Sealing materials used in arctic environment will experience harsh working condition and certainly will be exposed to very low temperatures. Therefore it is essential to study the rubbers behavior at a decreased temperatures to ensure protection of a machinery while being sealed [7].

There are several factors that have an impact on elastomers appearance in cold environment, which are as following:

- Molecular structure- the structure of elastomers consists of long polymeric chains that have an ability to move and rotate what is resulting in materials flexibility. At lower temperatures the possibility of chains movement decreases until transition temperature (Tg) when it becomes impossible, but the material becomes brittle at slightly lower temperature than Tg. This phenomenon may be, however, reduced by adequate molecular structure for example with crystallization counteract ingredients.
- Additives- the highest developed elasticity increment is caused by the addition of plasticizers and may be equal up to 8°C. However this phenomenon may be withdrawn by the volatile loss while material previously experiences increased temperatures, what is shown in fig. 7 presenting the appearance of several types of plasticizers after and before heating up to 180°C.

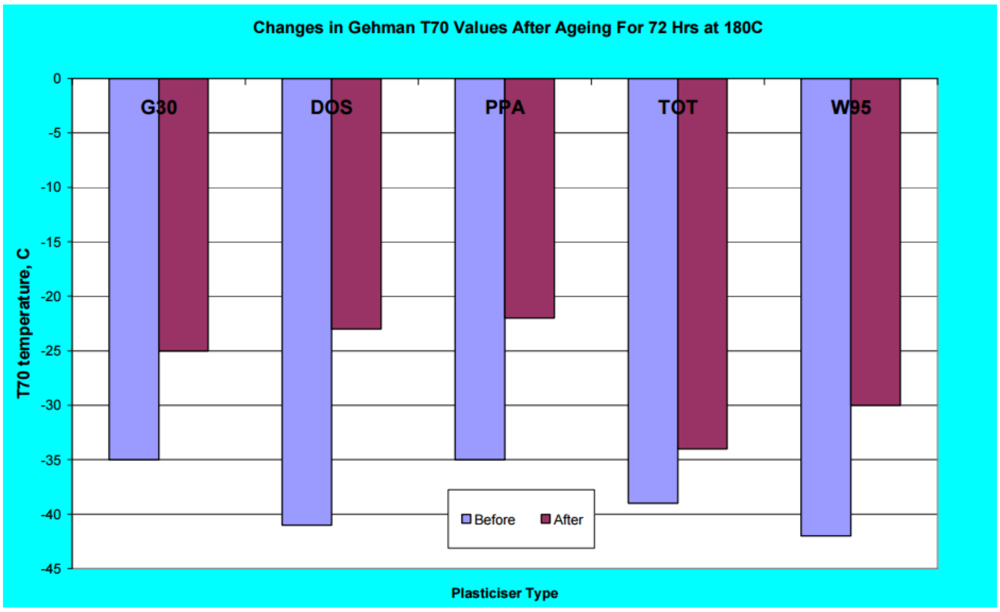


Fig. 8 Resistance to low temperatures of plasticizers before and after heating [11].

- Contact media- small amounts of adsorbed contact media lead to amelioration of low temperature properties as it acts as a lubricant within the elastomer structure extend the spacing between molecules resulting in bigger cross sectional area of the seal.
- Operating pressure- if the elastomer is flexible enough than it is possible to observe a decrease in Tg with increasing pressure. This phenomenon starting point is at approximately 50 bar as it is shown at fig. 8

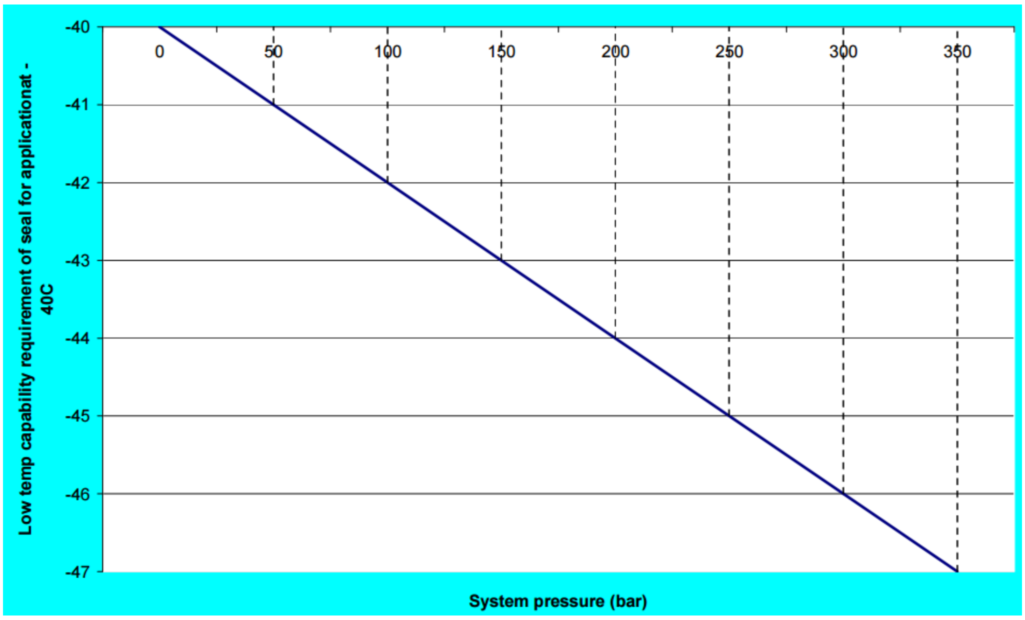


Fig. 9 Low temperature changes caused by increasing pressure [11].

While designing process in the case of O-rings we should take into account a small change in Tg while operating. Therefore the material with a wider range of remaining flexibility at low temperatures should be chosen [11].

All of the above factors lead to changes in a materials behavior while being exposed to low temperatures. There are two main processes that are a reason for this properties modifications, which are: low temperature crystallization and glass transition. Due to the occurrence of both of this phenomenon the elastomer becomes more brittle and is no longer flexible. As the stiffness increases and the elastic modulus is shifted the elastomer executes its ability to deform, what is, however, reversible by reheating [11].

1.2.3.1 Crystallization of rubbers at decreased temperatures

The ability of elastomers crystallization at low temperatures is a unique property of each type of this material. If a polymer can crystallize, than within its segments a crystallites are formed. This is resulting in increased stiffness by the same procedure as a reinforcing additives acts. What is more there are several differences between various types of rubbers crystallization. Some of them pass this process immediately after reaching the crystallization temperature, while the others are less prone to that and it takes more time for the nucleation and growth of the crystallites. However, each polymer has a defined, specific temperature of the highest crystallization speed, known as the crystallization temperature.

1.2.3.2 Glass transition process in elastomers

Glass transition is a typical process for rubbers, which involves the conversion of a flexible material in a brittle, glassy material. It takes place when the molecular interaction and motion energy values becomes approximately equal as an influence of low temperatures. This is a leading process for establishing the low temperature resistance of an elastomer. With decreasing temperature rubbers are undergoing structural changes resulting in changes in properties, especially the loss of elasticity. The transition path is shown at the graph below.

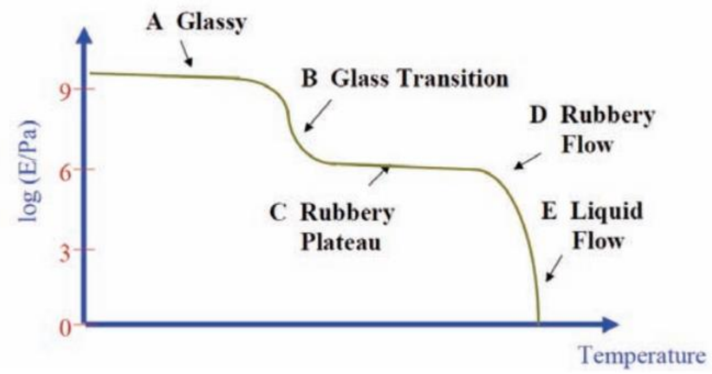


Fig.10 Dependence of the elastic modulus on the time [6]

As it is shown there is a particular range of temperatures, ending with reaching a transition temperature, in which this material has its special elastic properties. The lowest value of Tg is -70^{o}C for natural rubbers but is incomparable with other types of elastomers. Therefore it is highly important to know the precise value of Tg of rubbers that will be operating in arctic environment.

To sum up this chapter it is proved that both of the described processes have a great influence on low temperature resistance of rubbers. However if the desire is to outline the main characteristic which determines this property we need to consider each elastomer group separately. The resistance of the ones that are not crystallizing is determined by the glass transition process while the ones that are prone to quick crystallization obviously have this property designated by the crystallization. It is also worth to mention a group of polymers that are crystallizing with lower speeds because here we are facing two different factors influencing the temperature resistance. The determination of it, in case of short term, is subordinate to glass transition but in the case of long term, it is again determined by crystallization.

Generally the modification of all of the properties is dependent on the materials manufacturers, and may be performed through the designing process by altering both the composition and the form of the product [6].

1.2.4. O-rings

O-rings are types of a round mechanical gaskets that is placed within a groove, and it is being compressed, between sealed parts in order to avoid leakage and impairment of media. It is nowadays widely use, due to its simplicity and long lasting accuracy, in sealing for both moving and static applications. It has a shape of closed loop with the dimensions that are specified by the interior diameter d1 and the cord diameter d2 as it is shown at the figure below [12].

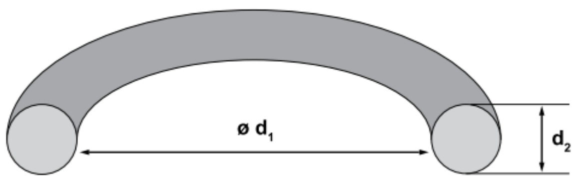


Fig. 11 O-ring seal specific diameters [12]

The manufacturers are producing O-rings with many varieties of this dimensions to enable perfectly fitting sealing for any application. According to Standard BS 4518 the internal diameters of O-rings varies between approximately 3 up to 249 mm and cord diameters in a range of 1,6-8,4 mm. The table 1 shows exemplary dimensions of the O-rings [5].

Reference number	Internal diameter (mm)	Section diameter (mm)	$d_{nominal}$ (mm) (Figure 14.6a)	$D_{nominal}$ (mm) (Figure 14.6a)	$D_{nominal}$ (mm) (Figure 14.6b)	$d_{nominal}$ (mm) (Figure 14.6b)	*B* (mm)	*R* (mm)
0031-16	3.1	1.6	3.5	5.8	6	3.7	2.3	0.5
0041-16	4.1	1.6	4.5	6.8	7	4.7	2.3	0.5
0051-16	5.1	1.6	5.5	7.8	8	5.7	2.3	0.5
0061-16	6.1	1.6	6.5	8.8	9	6.7	2.3	0.5
0071-16	7.1	1.6	7.5	9.8	10	7.7	2.3	0.5
0081-16	8.1	1.6	8.5	10.8	11	8.7	2.3	0.5
0091-16	9.1	1.6	9.5	11.8	12	9.7	2.3	0.5
0101-16	10.1	1.6	10.5	12.8	13	10.7	2.3	0.5
0111-16	11.1	1.6	11.5	13.8	14	11.7	2.3	0.5
0036-24	3.6	2.4	4	7.7	8	4.3	3.1	0.5
0046-24	4.6	2.4	5	8.7	9	5.3	3.1	0.5
0195-30	19.5	3.0	20	24.8	25	20.2	3.7	1.0
0443-57	44.3	5.7	45	54.7	55	45.3	6.4	1.0
1441-84	144.1	8.4	145	160	160	145	9.0	1.0
2491-84	249.1	8.4	250	265	265	250	9.0	1.0

Table 2. Some of commercially available dimensions of the O-rings [5].

In each application the O-rings should be chosen with the largest possible cross-section, which the design constraints allows. It is generally assumed that the circumference of the ring should not be stretched during assembly over 6% and not compress more than 3% (measuring inner diameter). The hardness of the O-ring is selected depending on the pressure and surface finish sealed parts. The appearance of the potential clearances should also be taken into account while sealing machine elements made out of metal due to the phenomenon of elastic elongation of this kind of material. These clearances should be filled with the O-rings.

Sealing by means of O-rings is carried out by axial or radial compression, as shown in Fig. 13. This is possible because the components included in the elastomers are incompressible liquids of high viscosity and high surface tension, therefore there is a possibility of deformation due to the pressure exerted during the sealing operation.

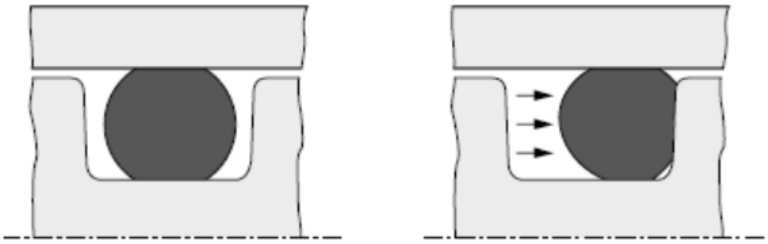


Fig. 12 O-ring deformation due to the pressure system [13].

1.2.4.1. Types of elastomers for O-rings

O-rings can be made from many different types of elastomers. Each type is characterized by different properties and therefore its choice should be adjusted for a particular purpose of the later product. That is why it is important to know the properties the types of elastomers, which are as following:

- Nitrite (NBR) – the main features, that makes it excellent for sealing applications, is its great resistance to oil and its derivatives and extremely wide range of service temperatures starting from -55°C up to 125°C. It consists of butadiene and acrylonitrile and those two polymers establish the properties. Acrylonitrile have positive influence on resistance to increased temperatures and oils but reduces the ability of nitrite to withstand low temperatures.
- Ethlyene-Propylene (EP or EPDM) – this elastomers are a combinations of propylene, ethylene and most often some additional monomer. It has extraordinary wear and chemical resistance and also exhibits high flexibility in decreased temperatures but it tends to being destroyed while being in contact with petroleum.
- Chloroprene, Neoprene, or CR- it has a uniquely good resistance of oils and atmospheric factors. Neoprene has service temperature range of -55°C-140 °C.
- Fluorocarbon (FKM) – its main disadvantage as a material for O-rings is a high hardness below -20°C but it is resistant to huge variety of chemicals and have sufficient compression set resistance.
- Silicone (PVMQ) – it is characterized by a remarkable resistance to huge range of temperatures. It may operate in low temperatures until even -115°C up to 250°C and it shows a great compression set resistance so it seem to be a unique material suitable for sealing applications but the problem is its low physical strength, that reduces significantly its applicability as seal.
- Fluorosilicone (FVMQ) – it has a very similar features as silicone but due to the Fluor content the oil resistance is increased.
- Styrene-Butadiene (SBR) - service temperature is between -55°C and 100°C and it is resistant to water environment. On the other hand it undergoes deterioration processes caused by weather conditions.

- Polyacrylate (ACM) – this elastomer has rather low compression set and decreased temperatures resistance but the petroleum and weather resistance are on a high level.
- Polyurethane (AU, EU) – it is prominent in terms of tensile strength in comparison with different types of elastomers. Main disadvantage of Polyurethane is though susceptibility to lose its mechanical properties while being exposed to high temperatures.
- Butyl (IIR) – butyl greatest merit is a weather resistance but it has unsatisfactory petroleum and fuel resistance.
- Chlorosulfonated Polyethylene (CSM)- this type of material is barely used for O-ring applications because of its low mechanical properties but it works when the main requirements for sealing are a high heat resistance or elevated temperatures.
- Epichlorohydrin (ECO) – this is not yet well known material. Though so far the tests results have shown its good resistance to decreased temperatures and oils, fuel and weather resistance. The disadvantage of this elastomer is low compression set resistance.
- Phosphonitrillia Fluoroelastomer (PNF)- this is a recently invented, promising elastomer which has most of the features that are important for use as seals, namely, resistance to high and low temperatures, extraordinary petroleum resistance and high resistance to compression set [14].

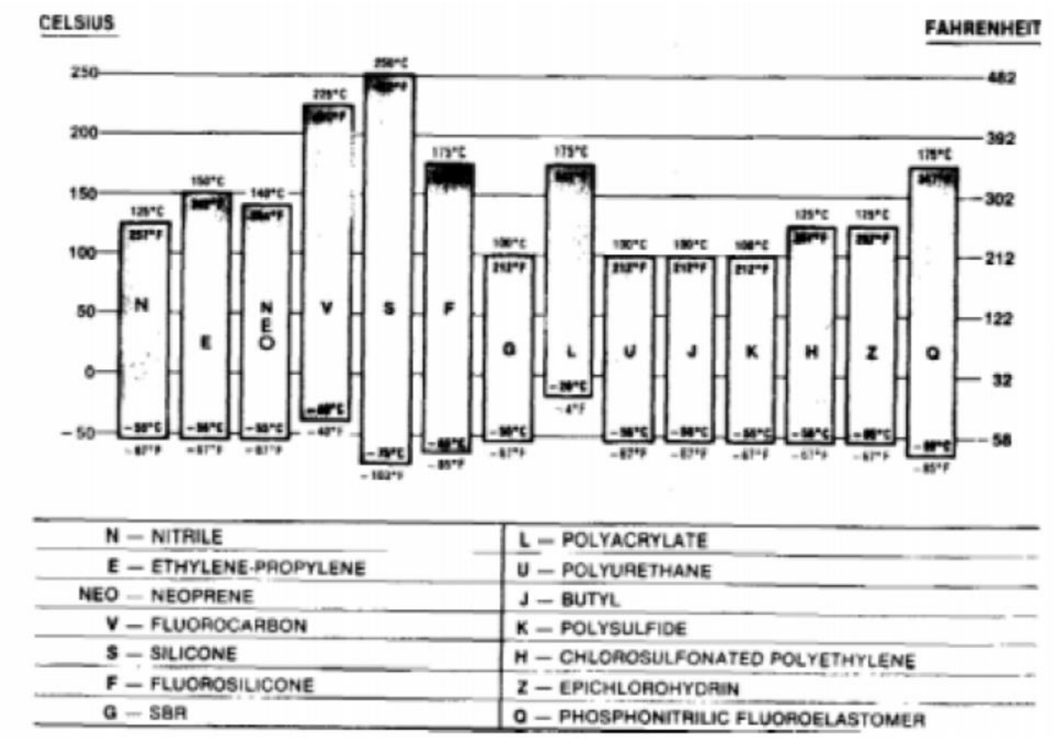
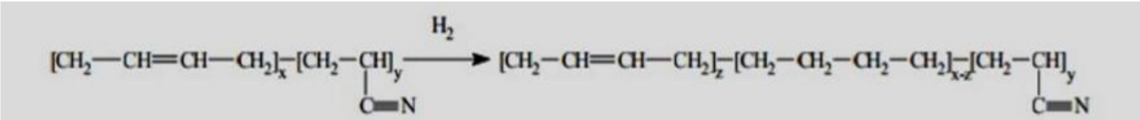


Fig.13 Operating temperature range of selected materials [14].

Fig. 14 Shows the breadth of range of temperatures of the described above elastomers. In this paper the feature of the main interest is a range of service temperature of O-rings material.

The research that will be described in this paper was carried out on O-rings made of Elast-O-Lion 101 material as well as two other specimens of elastomers compounded withnamely base HNBR and 50 phr CB HNBR. Elast-O-Lion 101 is a type of hydrogenated nitrile (HNBR) that is being manufactured by addition of a hydrogen to dissolved, polymerized NBR. The chemical reaction is as follows:



This type of material has a very good mechanical properties and extraordinary rapid gas decomposition resistance. Elast-O-Lion 101 has also a great chemical resistance, including oil and petroleum as well as abrasion resistance. This material is considered to be having a wide range of service temperatures [15]. In this paper the low temperature resistance of the three materials, in the form of O-rings, was tested.

Fig.14 O-ring seals.

1.2.4.2. Specifications of the tested O-rings materials.

The exact information about Elast-O-Lion 101, and elastomers compounded with base HNBR and 50 phr CB HNBR are given below.

James Walker

Material data sheets

Elast-O-Lion® 101

TOTAL GS PVV 142 03/01 | NORSOK M-710 | SHELL DODEP 02.01B.03.02 | JAMES WALKER ARD/20/RGD2009

Material data sheet	Compound number	701	Revision: 4
	Polymer type:	HNBR	02/03/2009

General description: Elast-O-Lion® 101 is a hydrogenated acrylonitrile/butadiene-based synthetic rubber with nominally 36% ACN, reinforced with carbon black and peroxide cured. It has excellent rapid gas decompression resistance, making it ideal for high-pressure gas applications.

General properties: Elast-O-Lion 101 has the excellent oil/fuel resistance of conventional nitrile (NBR) elastomers, combined with superior mechanical properties, improved chemical resistance, better weatherability, better thermal capability and outstanding abrasion resistance.

Temperature capability: -29°C to +160°C or +177°C intermittent (–20°F to +320°F, or +350°F intermittent)

TYPICAL PROPERTIES

Property	***Unit***	***Value***
Hardness	IRHD	**89**
Tensile strength (TS)	MPa (psi)	**32 (4641)**
Modulus @ 50% elongation	MPa (psi)	**6.9 (1001)**
Modulus @ 100% elongation	MPa (psi)	**13.5 (1958)**
Elongation at break (E @ B)	%	**210**
Low temperature torsion modulus T_{70}	°C (°F)	**–25 (–13)**
Compression set: 24 hours @ 150°C (302°F)	%	**16**
Compression set: 70 hours @ 150°C (302°F)	%	**32**
Tear resistance	kN/m	**41**
Air ageing: 70 hours @ 150°C (302°F)		
Change in hardness	IRHD	**+3**
Change in TS	%	**–10**
Change in E @ B	%	**–16**
Fluid immersion testing: Oil No 1 (ASTM No 1), 70 hours @ 150°C (302°F)		
Change in hardness	IRHD	**–1**
Change in TS	%	**–6**
Change in E @ B	%	**–4**
Change in volume	%	**+3**
Fluid immersion testing: Oil No 3 (IRM 903), 70 hours @ 150°C (302°F)		
Change in hardness	IRHD	**–12**
Change in TS	%	**–6**
Change in E @ B	%	**+7**
Change in volume	%	**+18**
Fluid immersion testing: Sweet gas [64%C_1: 12%C_2: 13%C_3: 10%N_2: 1%CO_2], 48 hours @ 80°C (176°F) and 200bar (2901psi)		
Change in hardness	IRHD	**–12**
Change in TS	%	**+22**
Change in E @ B	%	**–11**
Change in volume	%	**+16**
Fluid immersion testing: NACE-A, 5% in water, 28 days @ 80°C (176°F)		
Change in hardness	IRHD	**–4**
Change in TS	%	**–11**
Change in E @ B	%	**0**
Change in volume	%	**+18**

Fig. 15 Elast O-Lion 101 data sheet. Source : https://www.jameswalker.biz/en/products/253-elast-o-lion-sup-sup-hnbr

The O-ring of elastomer seal materials compounded with base HNBR specific additives content:

Component	Content, parts per hundred rubber
HNBR	100
Antioxidant	3
Stearic acid	0,5
Zinc oxide	5
Magnesium oxide	10
Plasticizer	20
Peroxide	10

Table 3. Components of base HNBR sample.

The O-ring elastomer seal materials compounded with 50 phr CB HNBR specific additives content:

Component	Content, parts per hundred rubber
HNBR	100
Antioxidant	3
Stearic acid	0,5
Zinc oxide	5
Magnesium oxide	10
Plasticizer	20
Peroxide	10
N-330 HAF carbon black	50

Table 4. Components of HNBR with 50 phr CB sample.

The HNBR is with 96 % saturated polybutadiene and with 36% acrylonitrile content. The procedure to produce the O- ring is as following: both compounds were first combined in an internal mixer, then in a two-roll mill. Preformed rubber compound sheets were later used to mold O-rings in a compression. Molding was carried out at 170 °C for 30 min in a hot press. Post curing was done at 150 °C for 4 h and afterwards followed in an oven.

1.3. Apparatus

The following project includes designing an apparatus for testing elastomers with different fillers to evaluate the effect of the fillers on performance at different temperatures. The apparatus consists of a chamber, circulating unit and a vacuum pump. Fig. 15 shows schematically the apparatus.

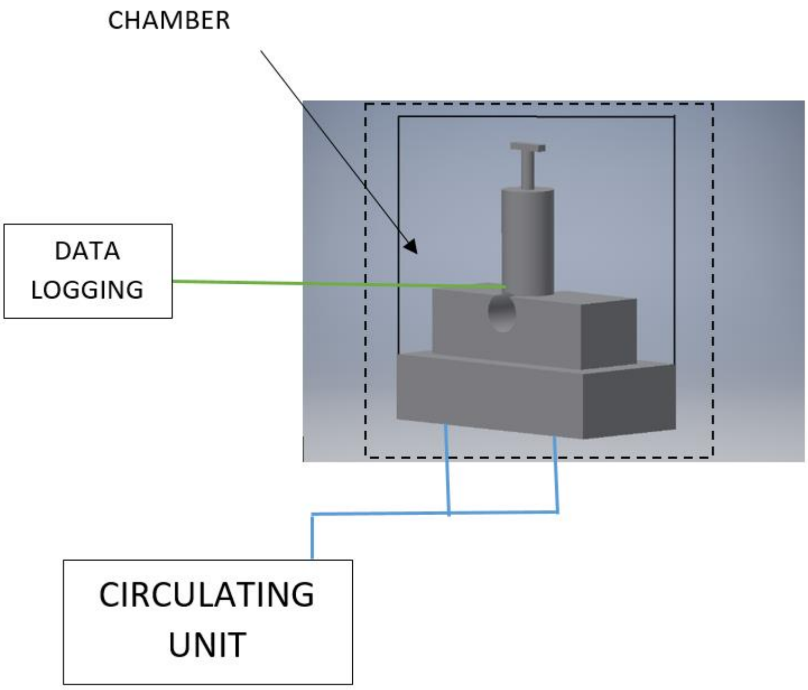


Fig. 16 Scheme of apparatus for testing elastomeric O-rings.

The chamber was isolated from the environment by the use of styrofoam blocks. The circulating unit have operational temperature range beginning with -60ºC up to +120ºC. The change of temperature within a chamber was achieved by the flow of a specific liquid (for this application, ethanol was used) through a copper wire, which is visualized at the picture below.

Fig. 17 O-rings compressor surrounded by copper wire.

1.4. Testing methodology

Several O-rings were tested with the use of the described apparatus. In order to achieve results, first the circulating unit was programmed to the desired operating temperature. In order to obtain this temperature quicker inside the chamber a fan was added. The samples were tested while compression equal to 10% and 20 %. The procedure was repeated with different parameters and the data were collected with the use of Catman program. Afterwards the analysis of the obtained data was performed. Calculations of contact pressure were done with the use of Hertz theory. The theory explains the effect of contact of two bodies under applied load. Initially the bodies touch each other at one point or along a surface. When the load is applied the deformation begins. Predictions of the shape of contact area and the changes while changing the load are based on Hertz contact theory [16].

2. Testing procedure and results

The table below is a matrix of the carried tests with changing parameters and specimens.

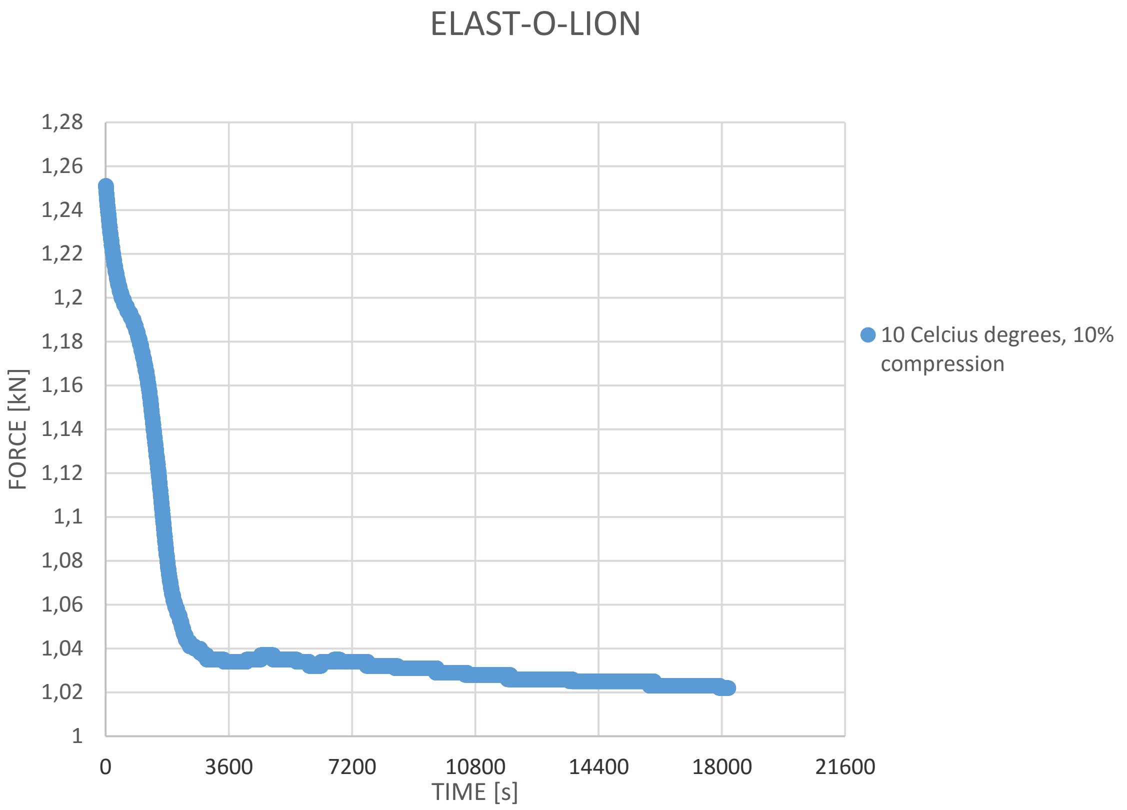
Name	ELAST-O-LION	BASE HNBR	HNBR 50 CB
Compression	10%	10%	10%
Temperature [^{o}C]	10	10	10
	-5	-5	-5
	-20	-20	-20
Compression	20%	20%	20%
Temperature [^{o}C]	10	10	10
	-5	-5	-5
	-20	-20	-20
	-30	-30	-30

Table 5. Tests matrix.

2.1. ELAST-O-LION 101

2.1.1. ELAST-O-LION 101 tested with 10% compression at the temperature of 10^{o}C

Fig. 18 presents the data obtained while decreasing an operational temperature of ELAST-O-LION 101 O-ring from the room temperature to approximately 10^{o}C.



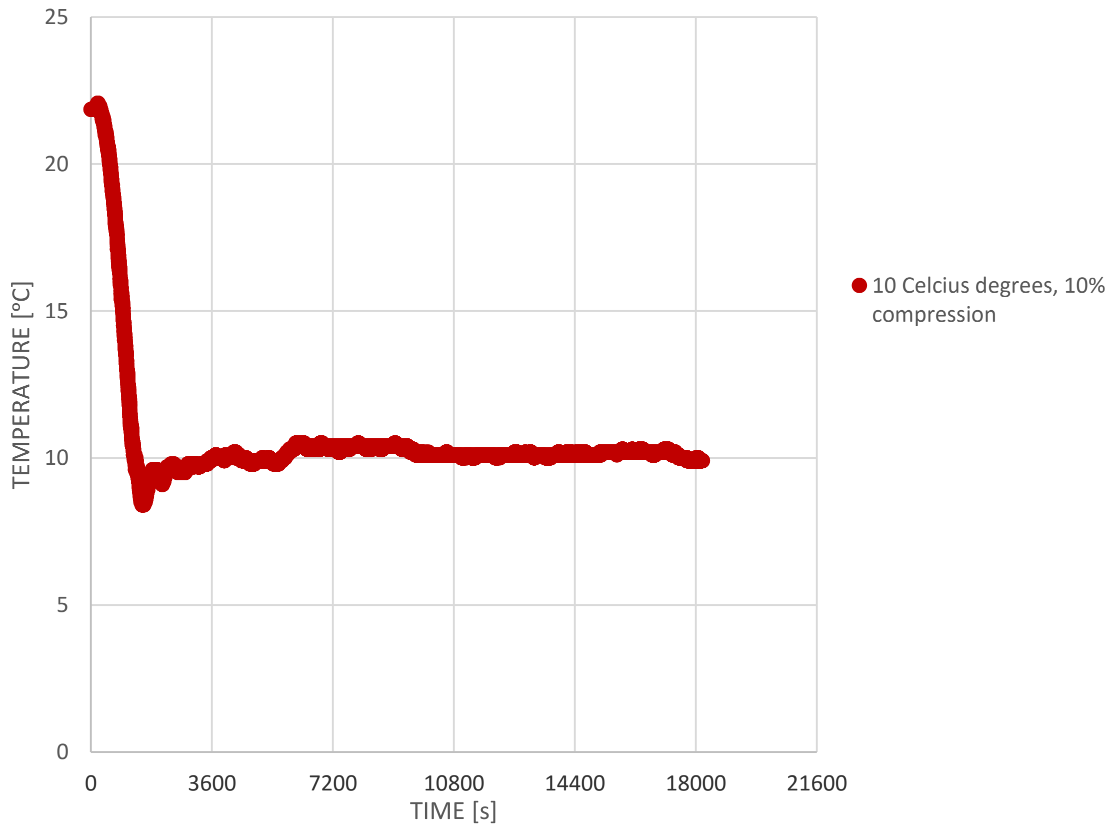


Fig.18 The force and temperature drop in time during Elast-o-Lion 101 test with 10% compression and ultimate temperature of 10°C.

Primarily sealing pressure increases while compression and eventually stabilizes at some point to ultimately decrease. To overcome this phenomena of pressure relaxation the tests were carried out long after applying the compression force. When the temperature of the O-ring is low it tends to shrinking. Due to the fact that it is being constrained the shrinking appears in decrease of pressure, what may affect the materials sealing properties. As we can see on the graph the initial force acting on the O-ring was equal to 1,25 kN and the final force, when the temperature was stabilized at approximately 10^{o}C was 1,02 kN. The decrease of an acting force is then ΔF = 1,25 – 1,02 = 0,23 [kN], what proves that even a small temperature drop leads to a visible change in sealing load.

Further analyze will be based on Hertz theory of elastic deformation [16].

Contact pressure: $p_0 = \frac{2\ x\ P}{\pi\ x\ a_{Hertz}}$

Contact radius: $a_{Hertz} = (\frac{4\ x\ P\ x\ R}{\pi\ x\ E*})^{1/2}$

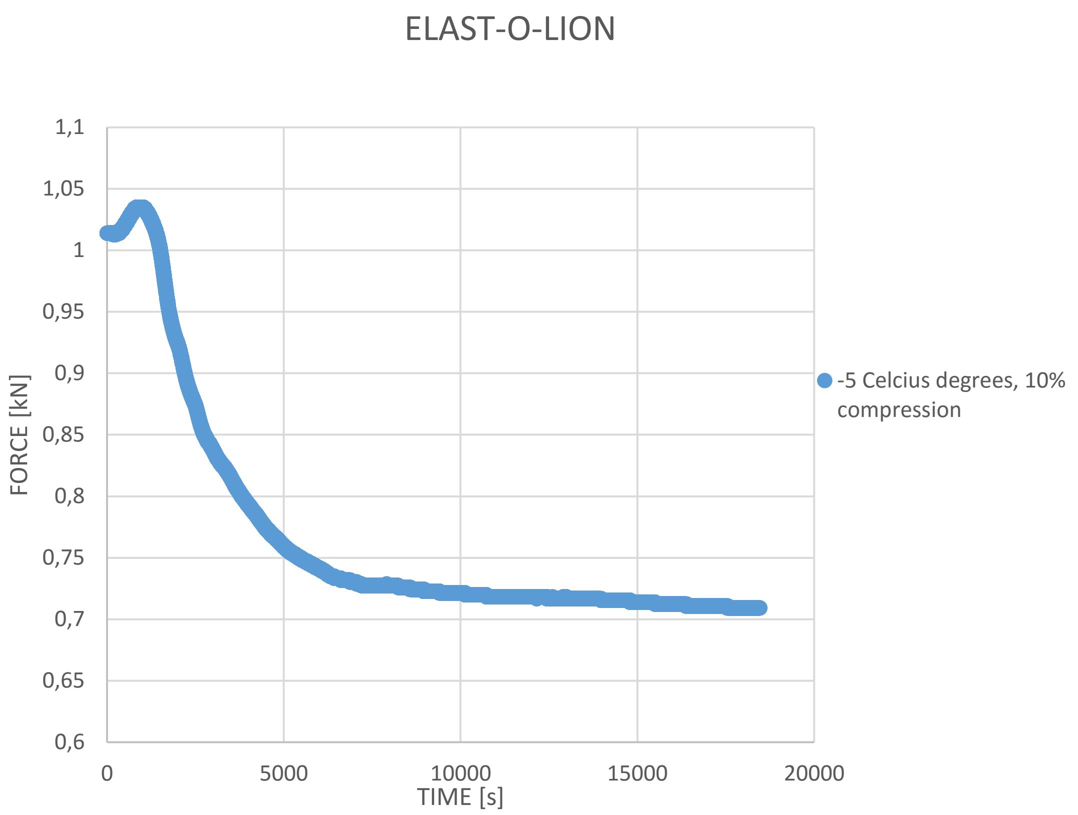
E* = $\frac{4\ x\ P}{\pi\ x\ L\ x\ d}$

NAME	VALUE	UNIT
P	1020	N
D	0,11265	m
Rring	0,056325	m
R	0,00263	m
P per L	2883,628623	N/m
E*	149564794,5	Pa
a	0,001176172	m
p_0	**1561596,867**	Pa

Ultimate contact pressure of Elast-O-Lion 101 at 10^{o}C and 10% compression was 1,56 MPa.

2.1.2. ELAST-O-LION 101 tested with 10% compression at the temperature of -5^{o}C

Fig. 19 presents the data obtained while decreasing an operational temperature of ELAST-O-LION 101 O-ring from the room temperature to approximately -5^{o}C.



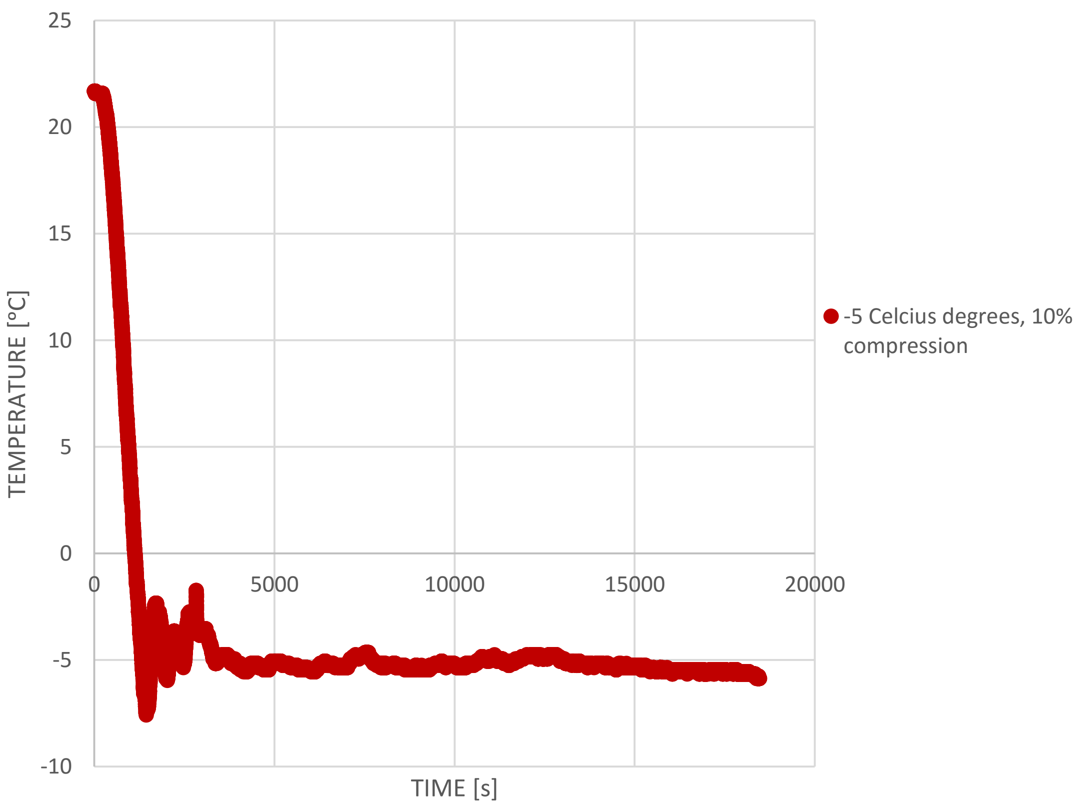


Fig.19 The force and temperature drop in time during Elast-o-Lion 101 test with 10% compression and ultimate temperature of -5°C.

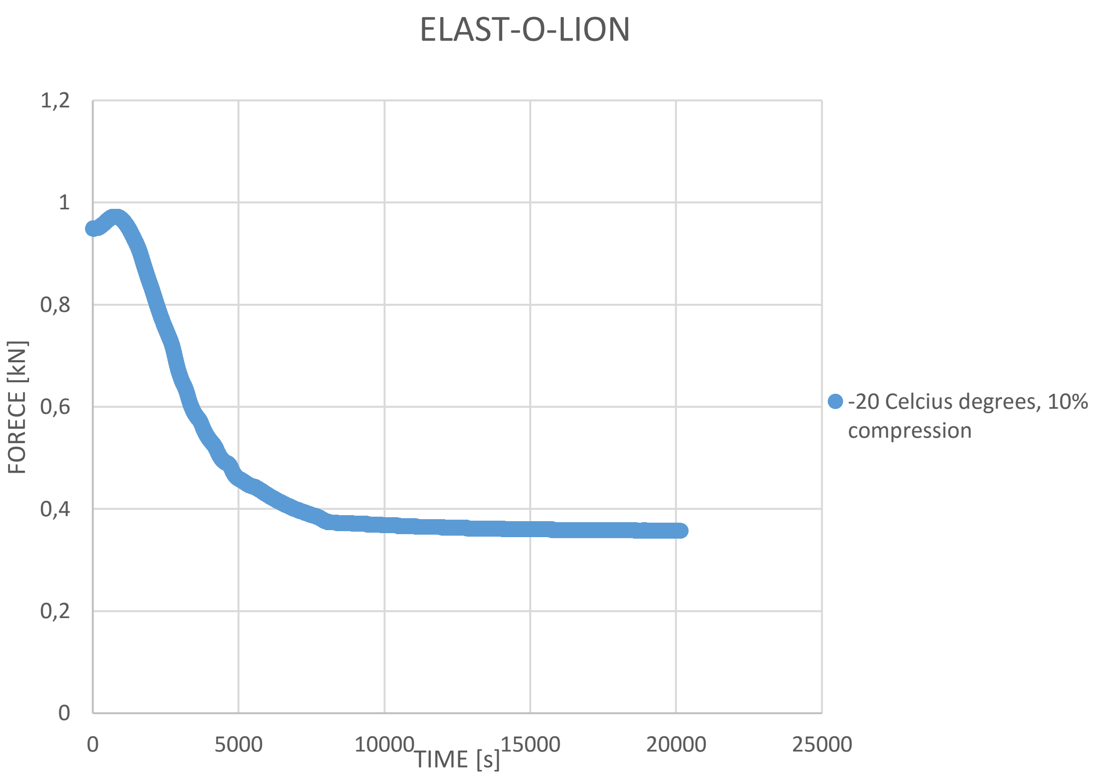
As we can see on the graph the initial force acting on the O-ring was equal to 1,01 kN and the final force, when the temperature was stabilized at approximately -5°C was 0,71 kN. The decrease of an acting force is then ΔF = 1,01– 0,71 = 0,30 [kN], which is a slightly higher value than the one obtained at 10°C.

NAME	VALUE	UNIT
P	710	N
D	0,11265	m
Rring	0,056325	m
R	0,00263	m
P per L	2007,231688	N/m
E*	104108827,6	Pa
a	0,001176172	m
p_0	**1086993,897**	Pa

Ultimate contact pressure of Elast-O-Lion 101 at -5°C and 10% compression was 1,08 MPa.

2.1.3. ELAST-O-LION 101 tested with 10% compression at the temperature of -20°C

Fig. 20 presents the data obtained while decreasing an operational temperature of ELAST-O-LION 101 O-ring from the room temperature to approximately -20°C.



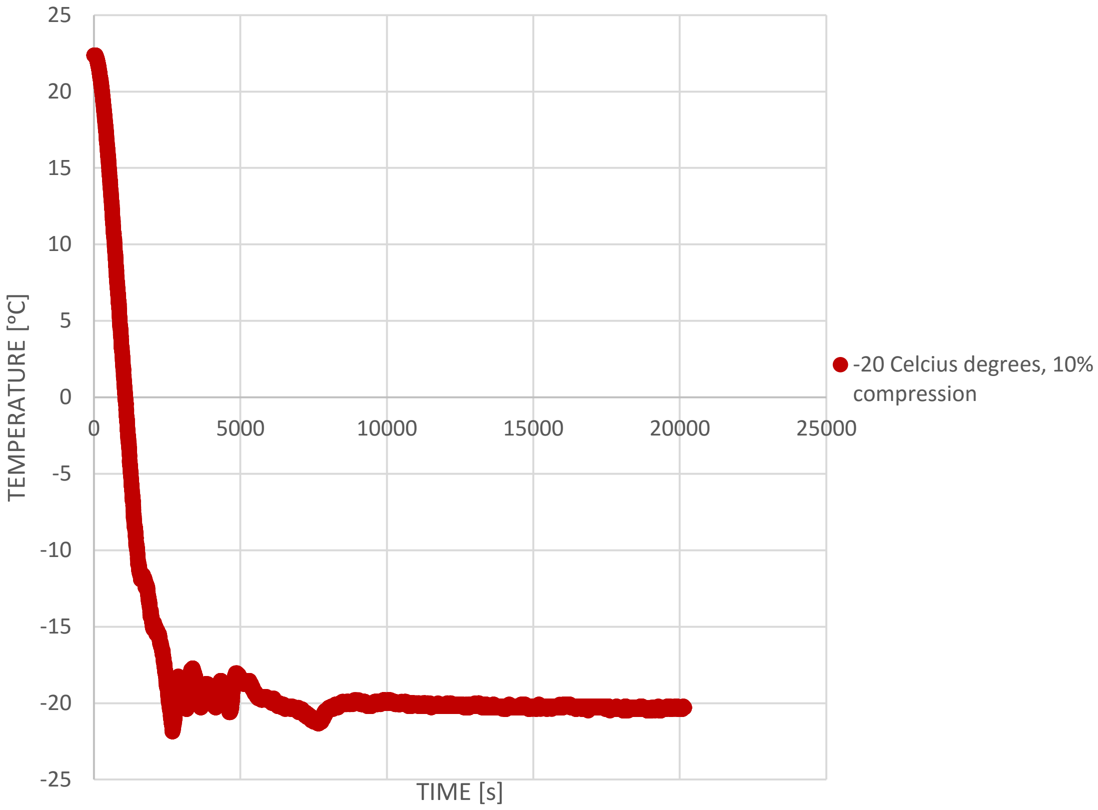


Fig.20 The force and temperature drop in time during Elast-o-Lion 101 test with 10% compression and ultimate temperature of -20°C.

As we can see on the graph the initial force acting on the O-ring was equal to 0,95 kN and the final force, when the temperature was stabilized at approximately -20°C was 0,36 kN. The decrease of an acting force is then ΔF = 0,95– 0,36 = 0,59 [kN], which is a higher value than the one obtained at -5°C and 10°C.

NAME	VALUE	UNIT
P	360	N
D	0,11265	m
Rring	0,056325	m
R	0,00263	m
P per L	1017,751279	N/m
E*	26393787,27	Pa
a	0,001663358	m
p_0	**389723,2002**	Pa

Ultimate contact pressure of Elast-O-Lion 101 at -20°C and 10% compression was 0,39 MPa.

Fig. 21 presents comparison of the obtained data while testing ELAST-O-LION O-ring under compression equal to 10%

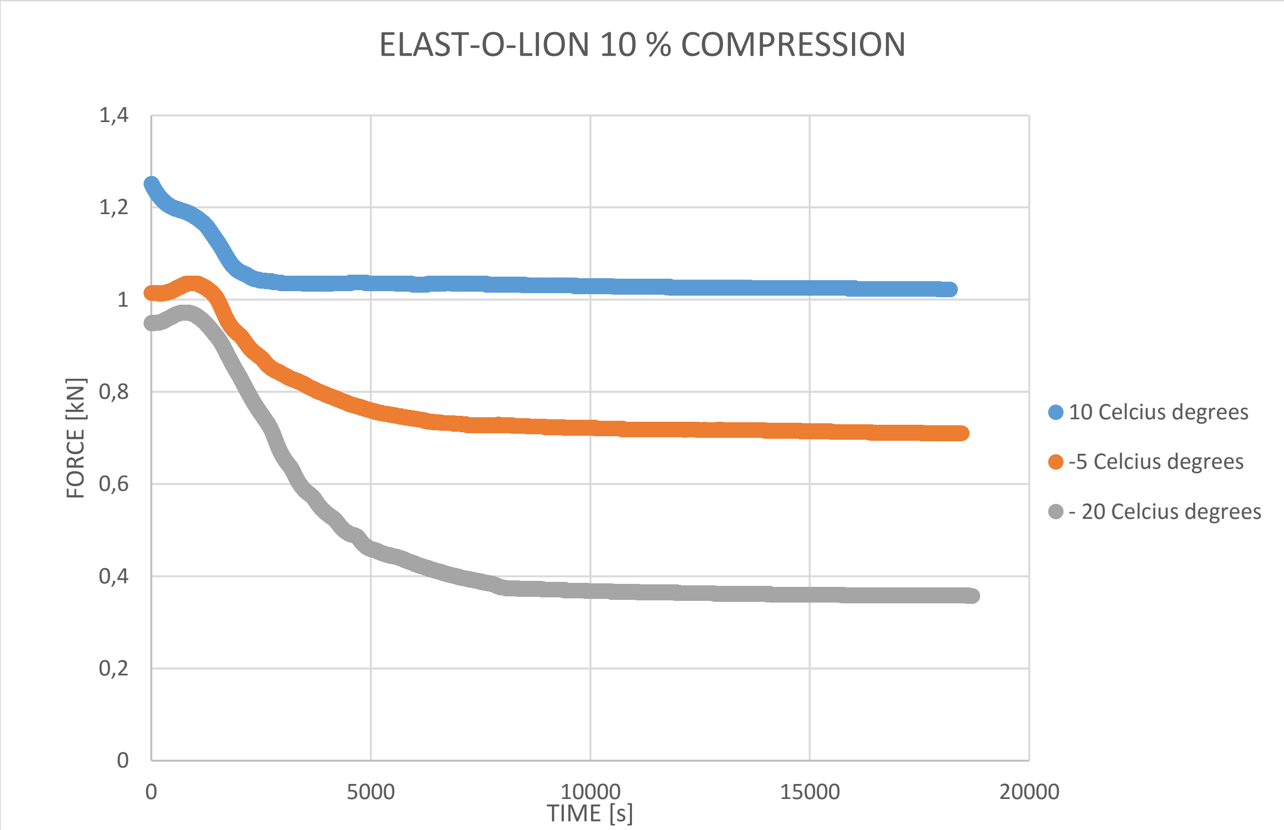
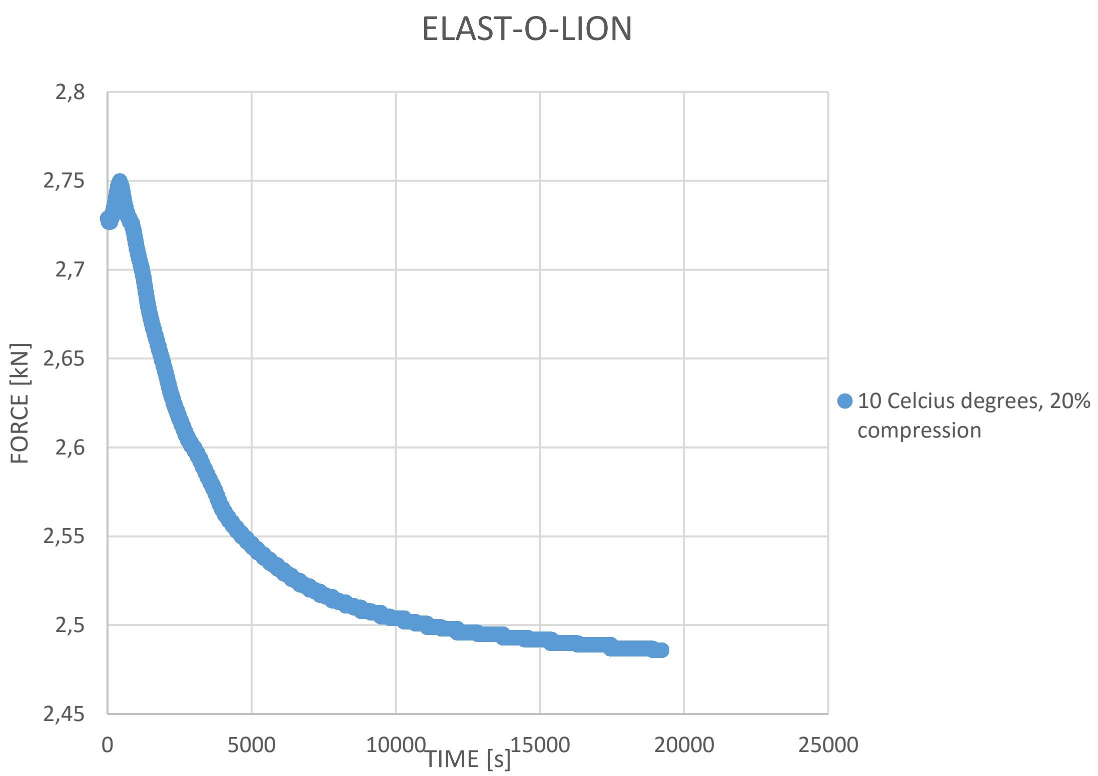


Fig.21 Comparison of force drop in time during Elast-o-Lion 101 test with 10% compression.

2.1.4. ELAST-O-LION 101 tested with 20% compression at the temperature of 10°C

Fig. 22 presents the data obtained while decreasing an operational temperature of ELAST-O-LION 101 O-ring from the room temperature to approximately 10°C.

As we can see on the graph the initial force acting on the O-ring was equal to 2,73 kN and the final force, when the temperature was stabilized at approximately 10°C was 2,49 kN. The decrease of an acting force is then ΔF = 2,73– 2,49 = 0,24 [kN], what proves that even a small temperature drop leads to a visible change in sealing load.



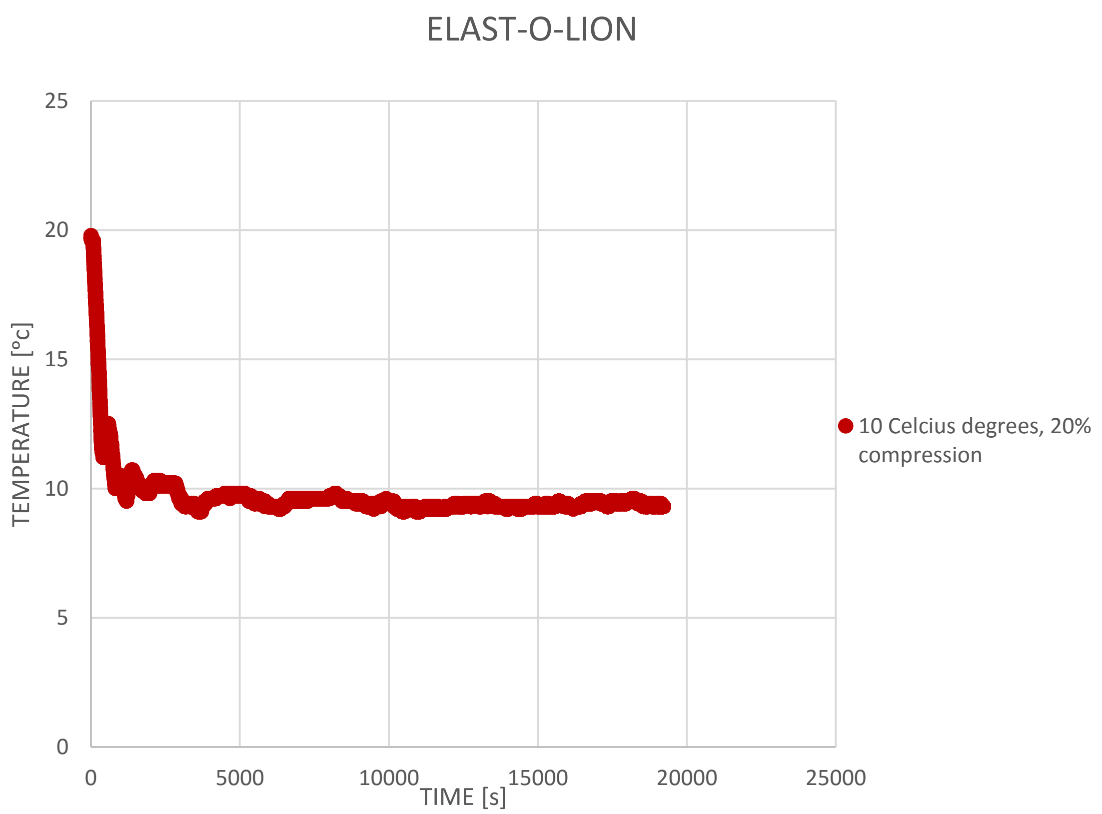


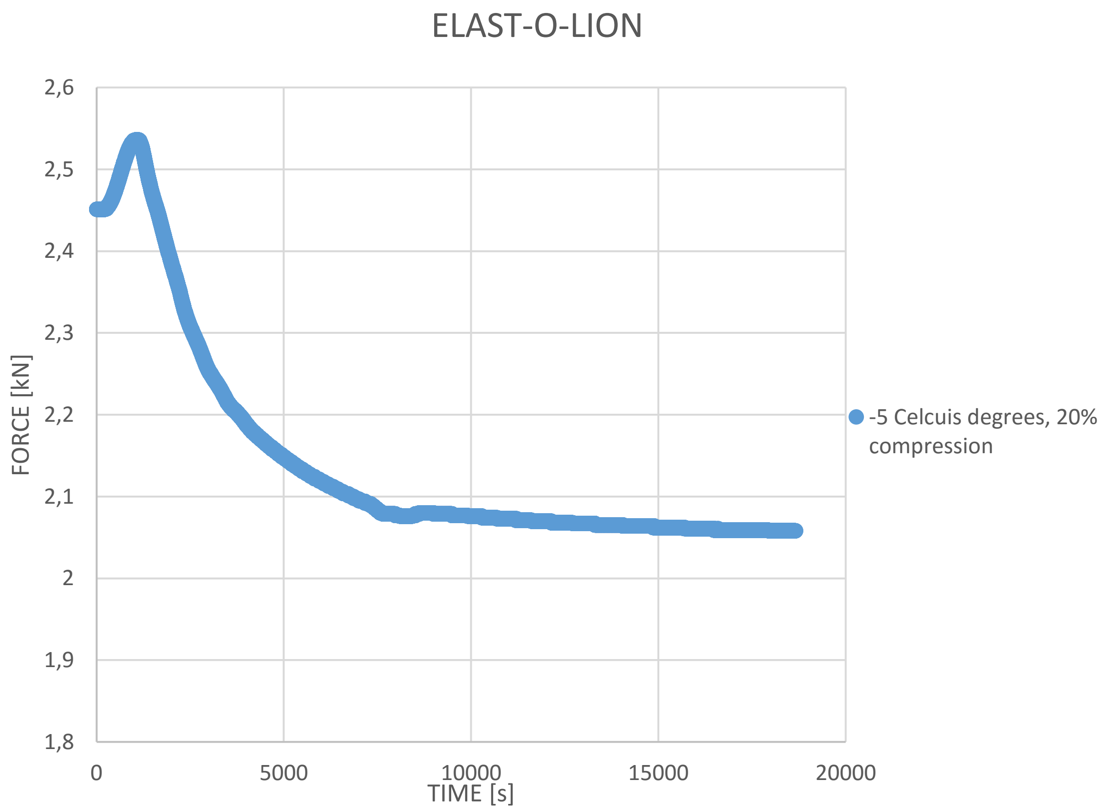
Fig.22 The force and temperature drop in time during Elast-o-Lion 101 test with 20% compression and ultimate temperature of 10°C.

NAME	VALUE	UNIT
P	2490	N
D	0,11265	m
Rring	0,056325	m
R	0,00263	m
P per L	7039,446343	N/m
E*	182557028,6	Pa
a	0,001663358	m
p_0	**2695585,468**	Pa

Ultimate contact pressure of Elast-O-Lion 101 at 10°C and 20% compression was 2,70 MPa.

2.1.5. ELAST-O-LION 101 tested with 20% compression at the temperature of -5°C

Fig. 23 presents the data obtained while decreasing an operational temperature of ELAST-O-LION 101 O-ring from the room temperature to approximately -5°C.



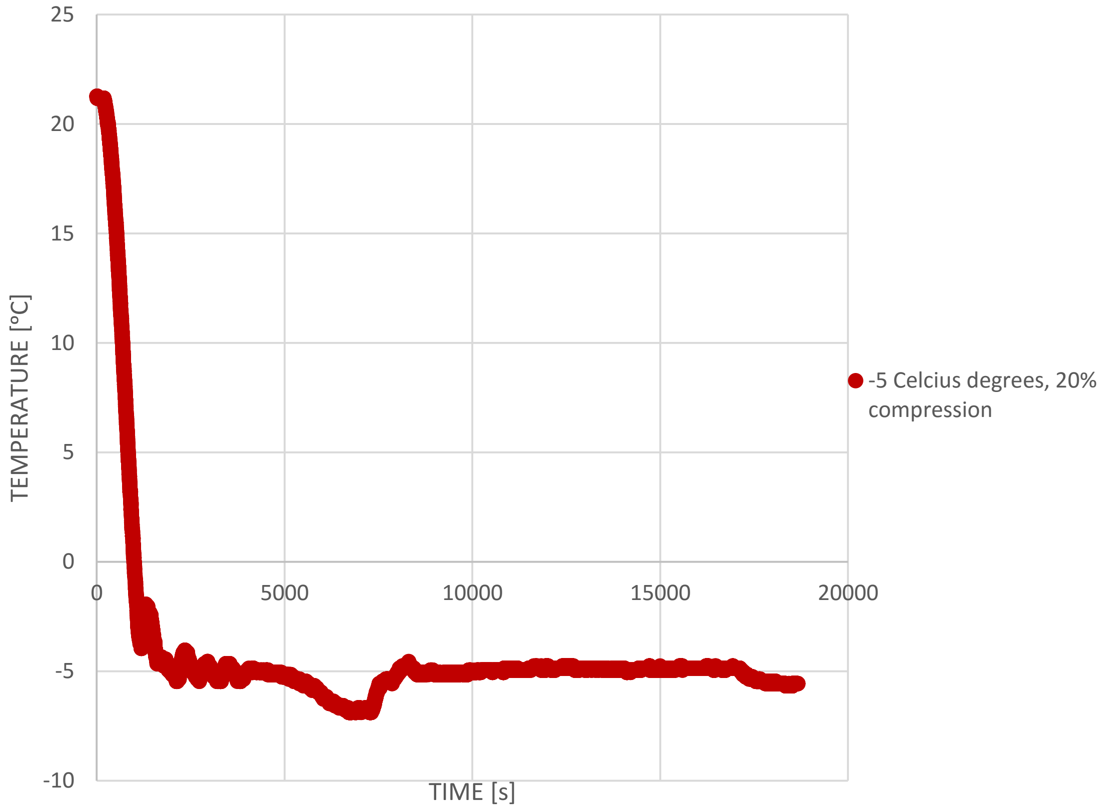


Fig.23 The force and temperature drop in time during Elast-o-Lion 101 test with 20% compression and ultimate temperature of -5°C.

As we can see on the graph the initial force acting on the O-ring was equal to 2,45 kN and the final force, when the temperature was stabilized at approximately -5ºC was 2,06 kN. The decrease of an acting force is then ΔF = 2,45– 2,06 = 0,39 [kN], which is a higher value than the one obtained at 10ºC.

NAME	VALUE	UNIT
P	2060	N
D	0,11265	m
Rring	0,056325	m
R	0,00263	m
P per L	5823,798983	N/m
E*	151031116	Pa
a	0,001663358	m
p_0	**2230082,757**	Pa

Ultimate contact pressure of Elast-O-Lion 101 at -5ºC and 20% compression was 2,23 MPa.

2.1.6. ELAST-O-LION 101 tested with 20% compression at the temperature of -20^{o}C

Fig. 24 presents the data obtained while decreasing an operational temperature of ELAST-O-LION 101 O-ring from the room temperature to approximately 10^{o}C.

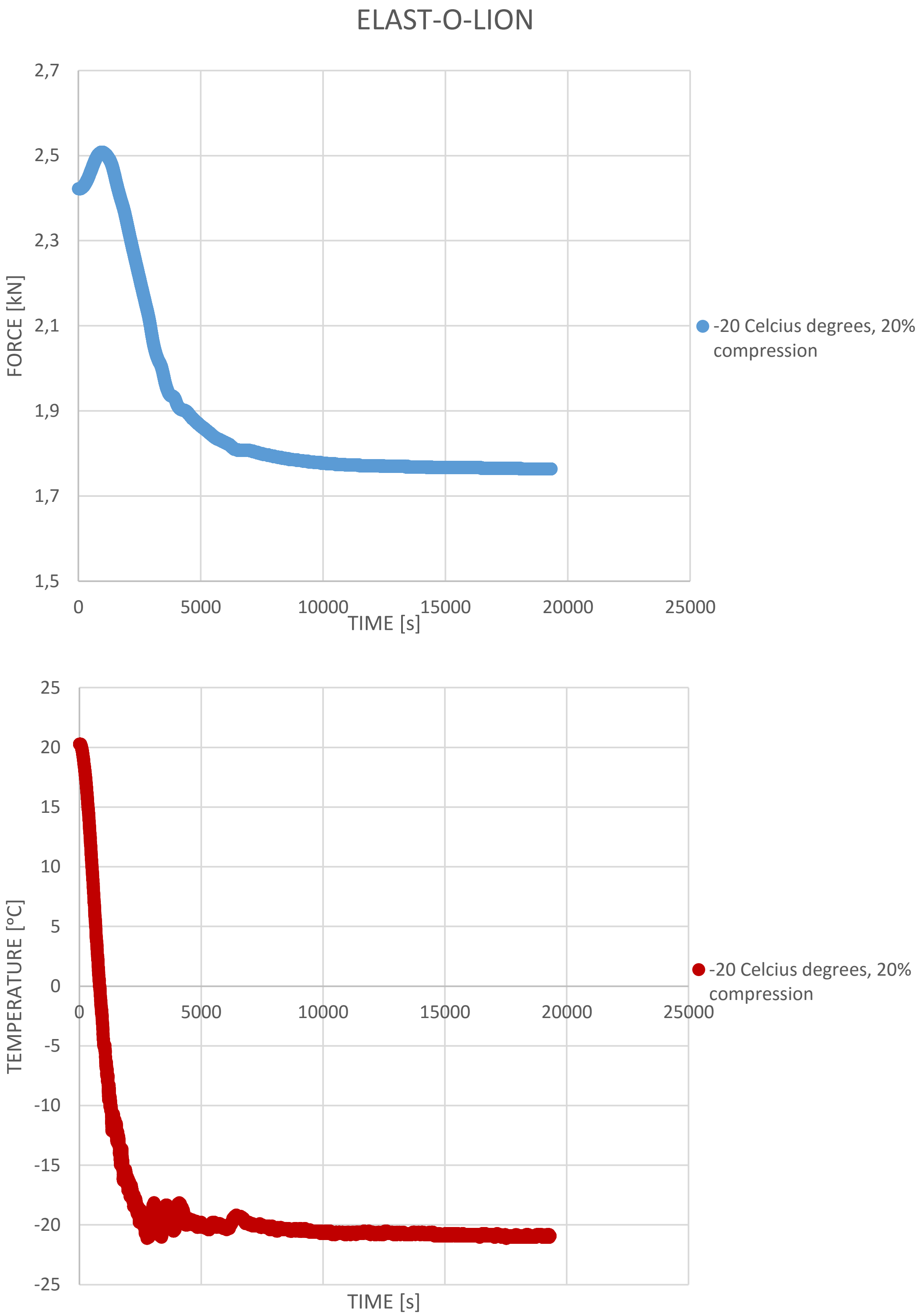


Fig.24 The force and temperature drop in time during Elast-o-Lion 101 test with 20% compression and ultimate temperature of -20°C.

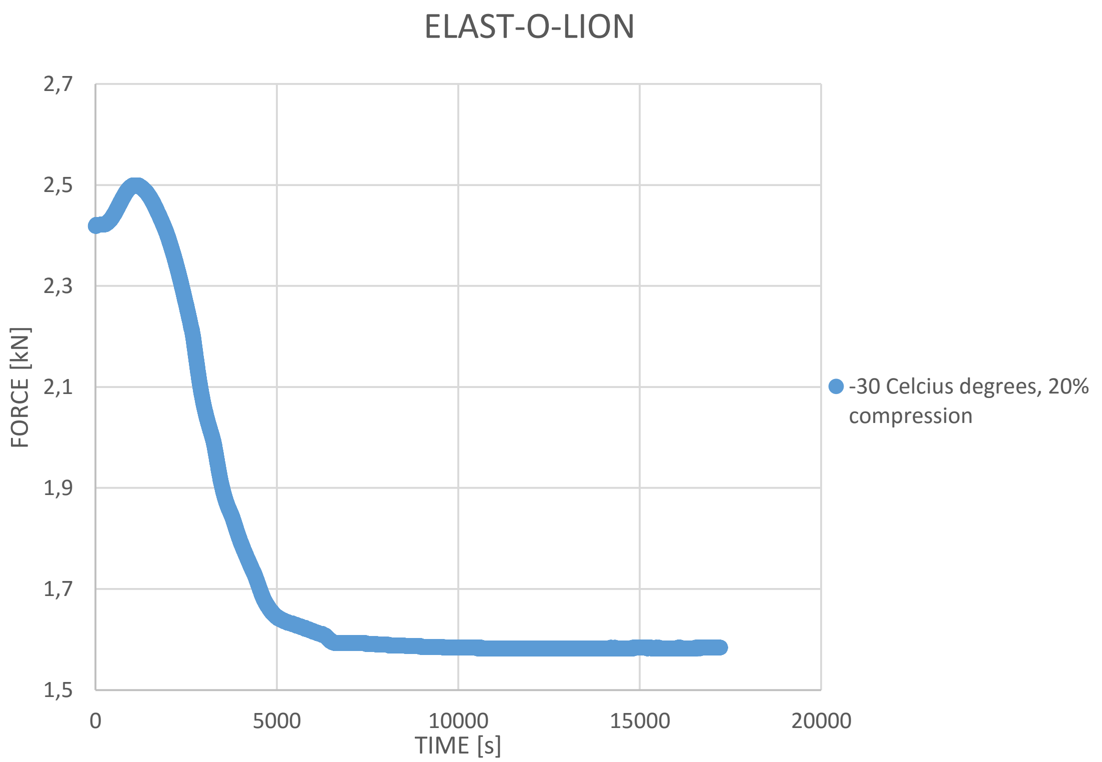
As we can see on the graph the initial force acting on the O-ring was equal to 2,42 kN and the final force, when the temperature was stabilized at approximately -20°C was 1,76 kN. The decrease of an acting force is then ΔF = 2,42– 1,76 = 0,66 [kN], which is a higher value than the one obtained at -5°C and 10°C.

NAME	VALUE	UNIT
P	1760	N
D	0,11265	m
Rring	0,056325	m
R	0,00263	m
P per L	4975,672917	N/m
E*	129036293,3	Pa
a	0,001663358	m
p_0	**1905313,423**	Pa

Ultimate contact pressure of Elast-O-Lion 101 at -20°C and 20% compression was 1,91 MPa.

2.1.7. ELAST-O-LION 101 tested with 20% compression at the temperature of -30°C

Fig. 25 presents the data obtained while decreasing an operational temperature of ELAST-O-LION 101 O-ring from the room temperature to approximately -30°C.



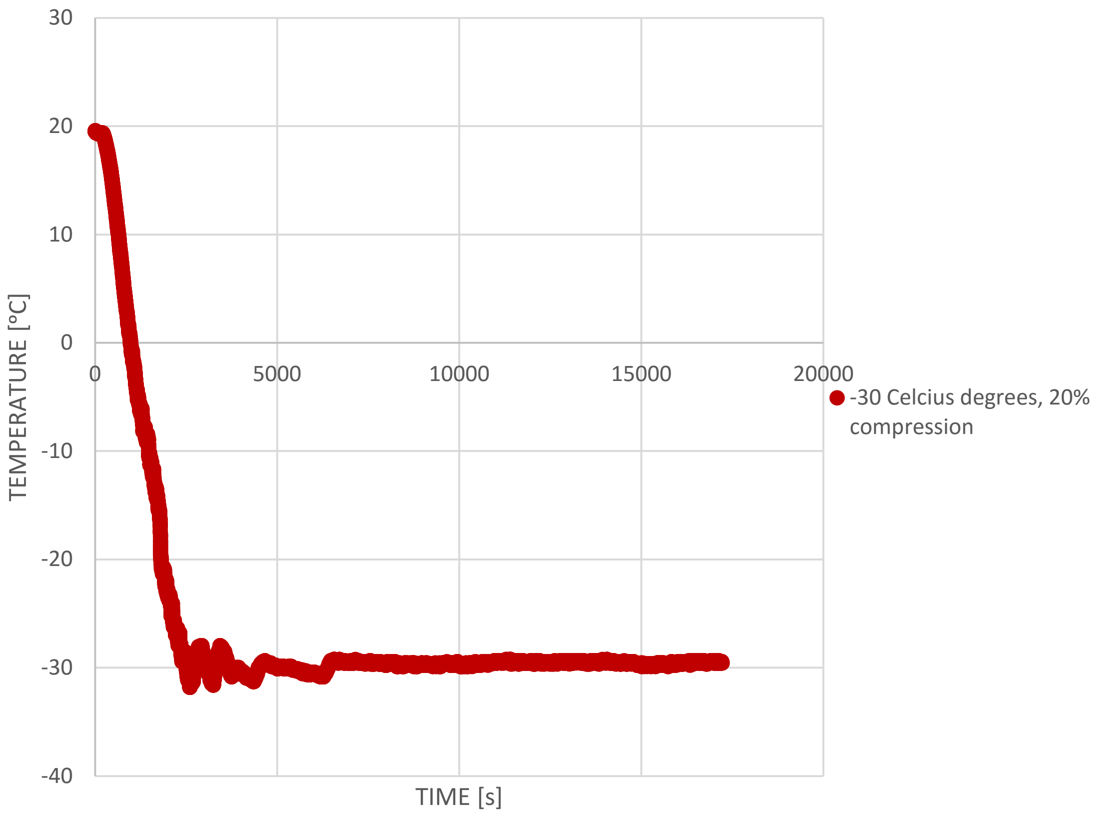


Fig.25 The force and temperature drop in time during Elast-o-Lion 101 test with 20% compression and ultimate temperature of -30°C.

As we can see on the graph the initial force acting on the O-ring was equal to 2,42 kN and the final force, when the temperature was stabilized at approximately -30°C was 1,58 kN. The decrease of an acting force is then ΔF = 2,42– 1,58 = 0,84 [kN], which is much higher value than all of the values obtained at higher temperatures.

NAME	VALUE	UNIT
P	1580	N
D	0,11265	m
Rring	0,056325	m
R	0,00263	m
P per L	4466,797278	N/m
E*	115839399,7	Pa
a	0,001663358	m
p_0	**1710451,823**	Pa

Ultimate contact pressure of Elast-O-Lion 101 at -30°C and 20% compression was 1,71 MPa.

Fig. 26 presents comparison of the obtained data while testing ELAST-O-LION O-ring under compression equal to 10%

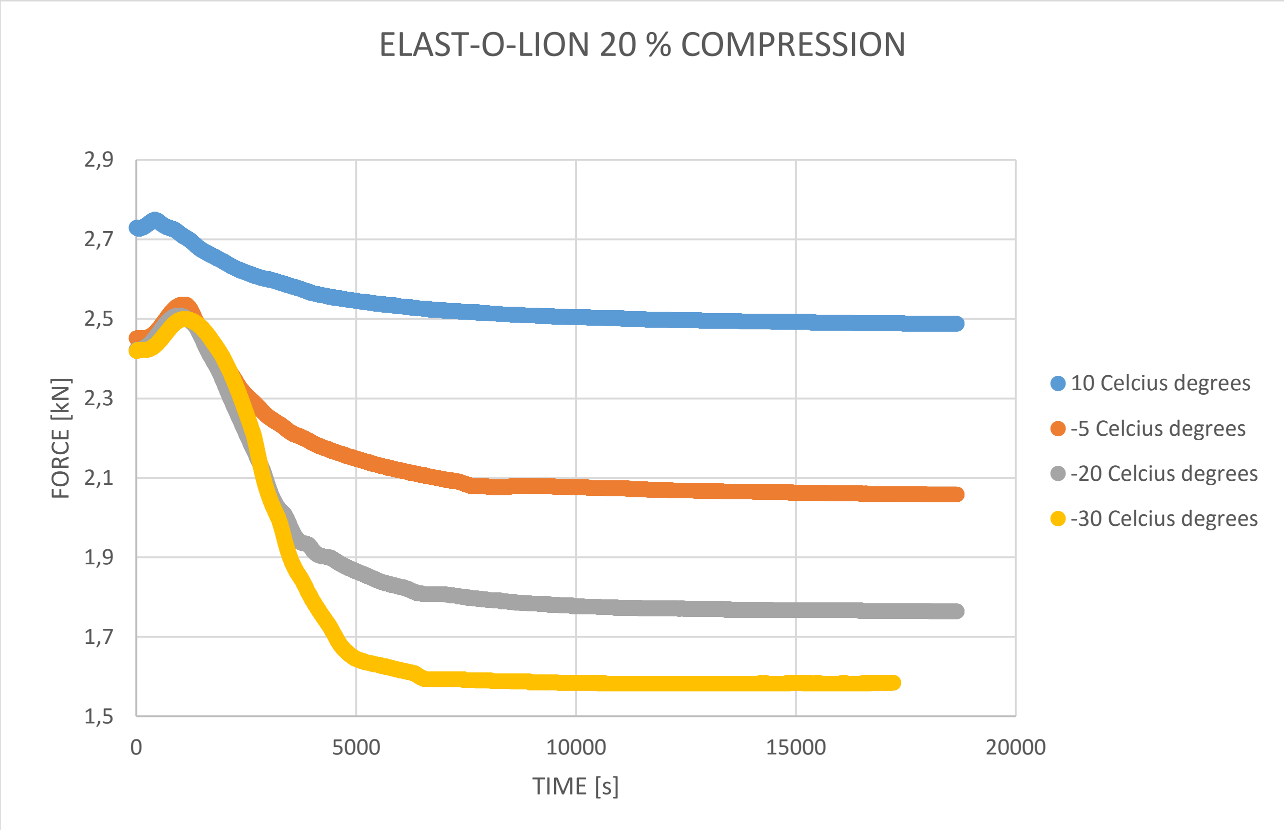


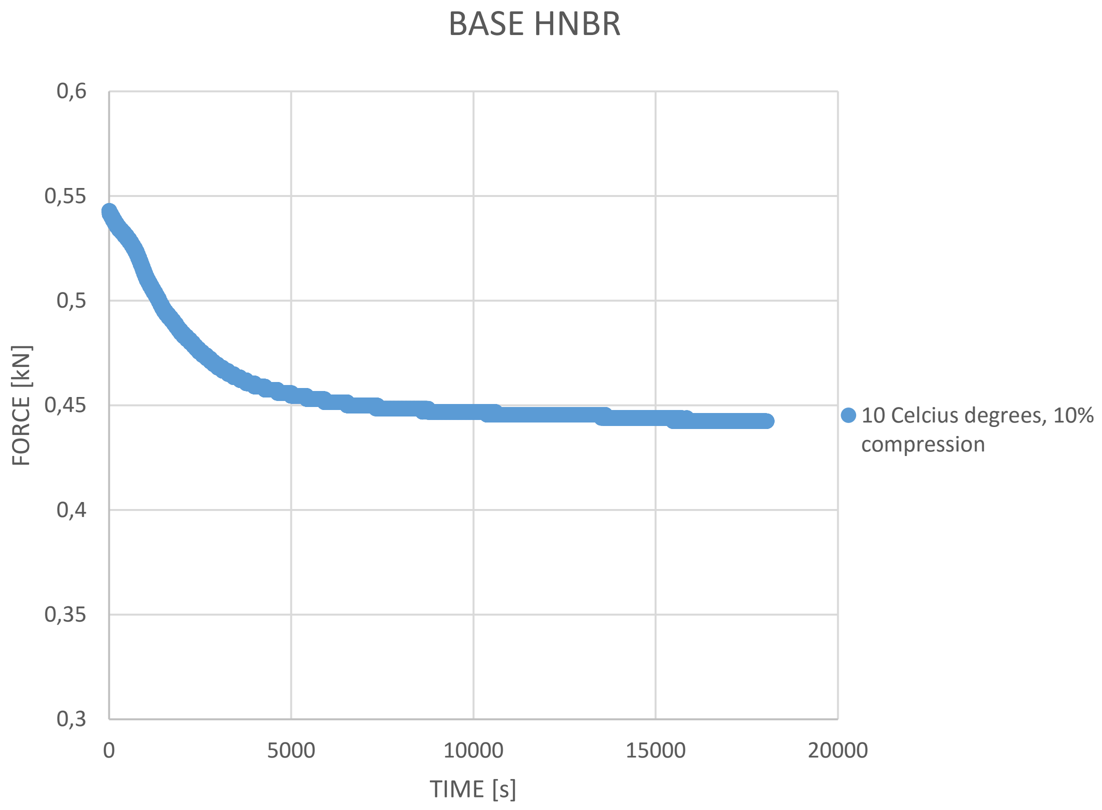
Fig.26 Comparison of force drop in time during Elast-o-Lion 101 test with 20% compression.

2.2. Base HNBR

2.2.1. Base HNBR tested with 10% compression at the temperature of 10°C

Fig. 27 presents the data obtained while decreasing an operational temperature of base HNBR O-ring from the room temperature to approximately 10°C.

As we can see on the graph the initial force acting on the O-ring was equal to 0,54 kN and the final force, when the temperature was stabilized at approximately 10°C was 0,44 kN. The decrease of an acting force is then $\Delta F = 0{,}54 - 0{,}44 = 0{,}10$ [kN], what proves that even a small temperature drop leads to a visible change in sealing load.



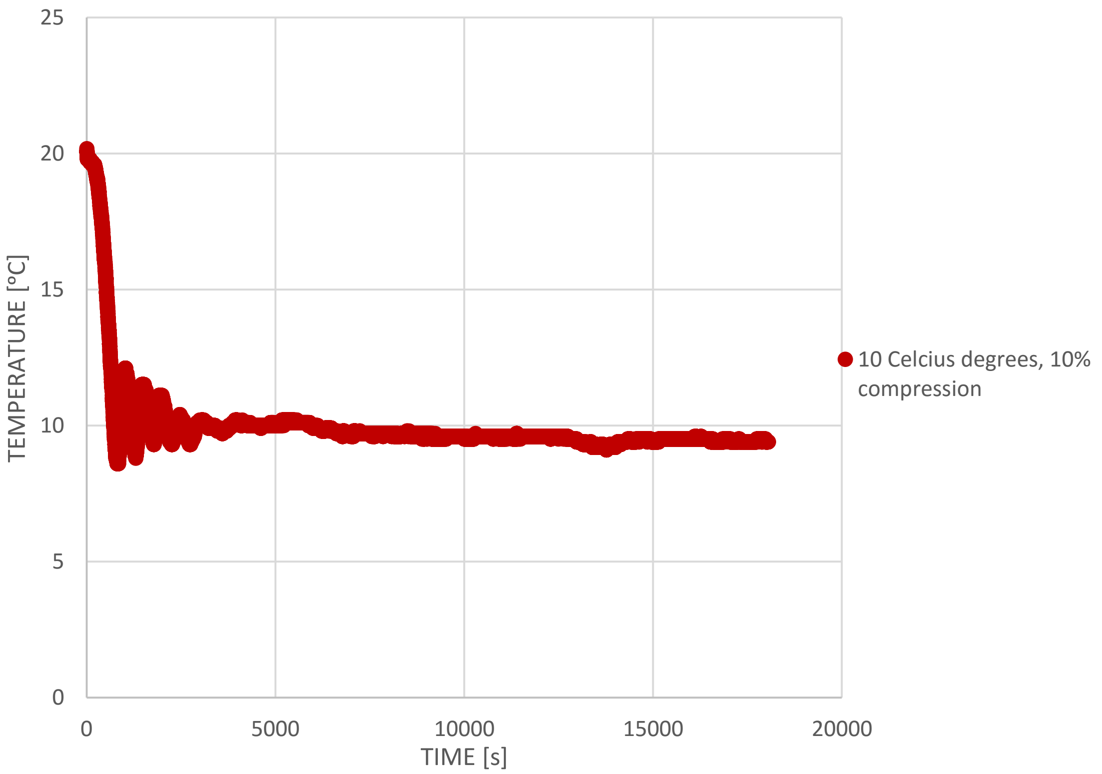


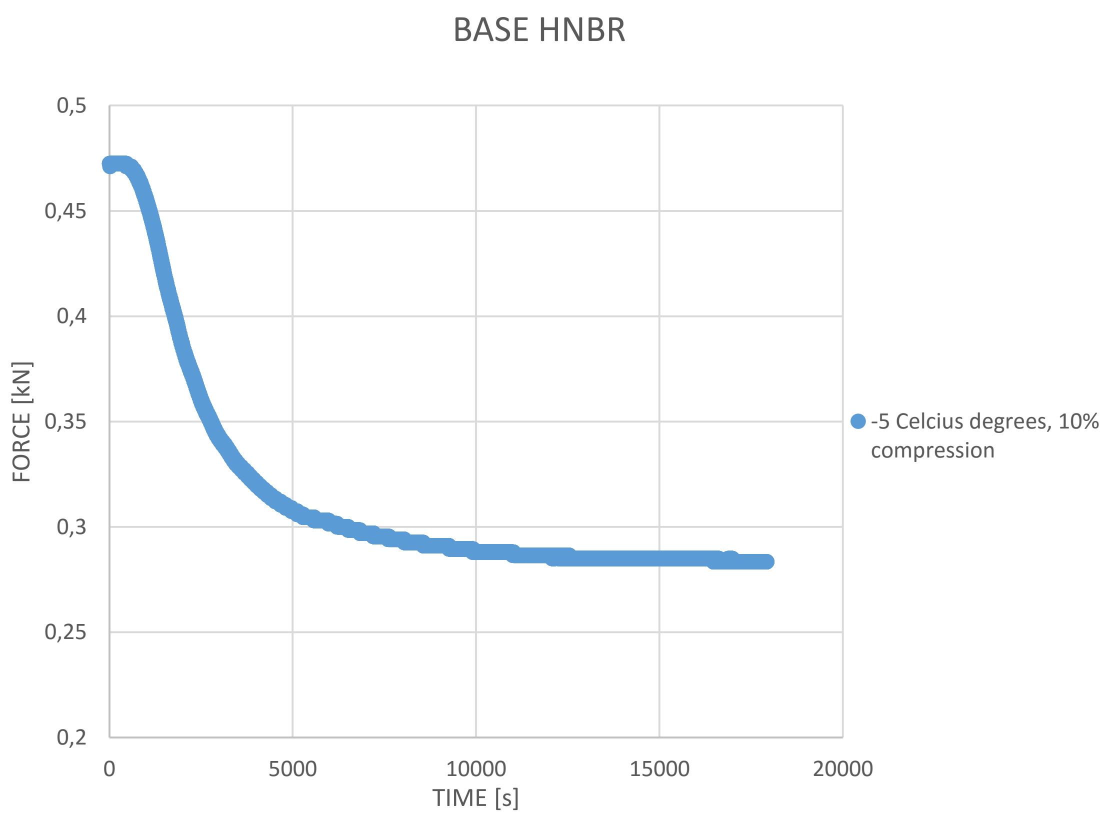
Fig.27 The force and temperature drop in time during test of an O-ring made of base HNBR, with 10% compression and ultimate temperature of 10°C.

NAME	VALUE	UNIT
P	440	N
D	0,11265	m
Rring	0,056325	m
P per L	1243,91823	N/m
R	0,00279	m
E*	57330400,2	Pa
a	0,00124773	m
p_0	**634998,909**	Pa

Ultimate contact pressure of base HNBR at 10°C and 10% compression was 0,63 MPa.

2.2.2. Base HNBR tested with 10% compression at the temperature of -5°C

Fig. 28 presents the data obtained while decreasing an operational temperature of base HNBR O-ring from the room temperature to approximately -5°C.



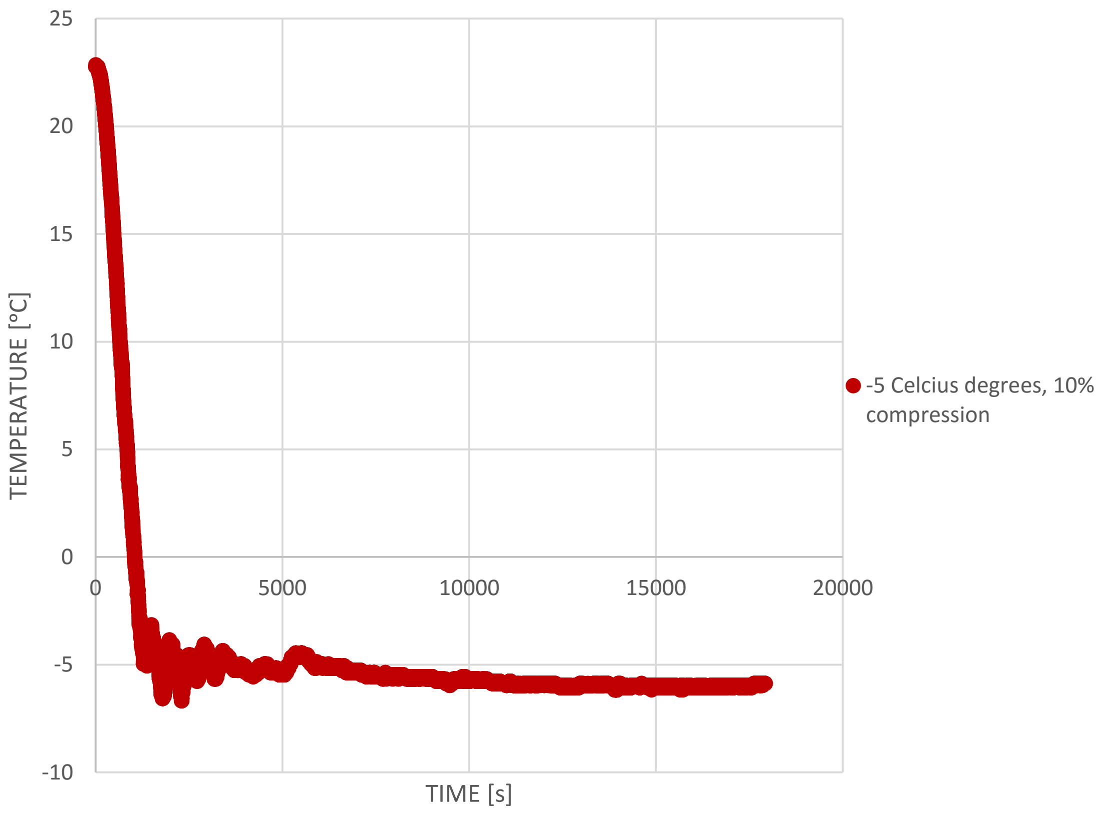


Fig.28 The force and temperature drop in time during test of an O-ring made of base HNBR, with 10% compression and ultimate temperature of -5°C.

As we can see on the graph the initial force acting on the O-ring was equal to 0,47 kN and the final force, when the temperature was stabilized at approximately -5°C was 0,28 kN. The decrease of an acting force is then ΔF = 0,47– 0,28 = 0,19 [kN], which is a slightly higher value than the one obtained at 10°C.

NAME	VALUE	UNIT
P	280	N
D	0,11265	m
Rring	0,056325	m
P per L	791,584328	N/m
R	0,00279	m
E*	36482982	Pa
a	0,00124773	m
p_0	**404090,215**	Pa

Ultimate contact pressure of base HNBR at -5°C and 10% compression was 0,40 MPa.

2.2.3. Base HNBR tested with 10% compression at the temperature of -20°C

Fig. 29 presents the data obtained while decreasing an operational temperature of base HNBR O-ring from the room temperature to approximately -20°C.

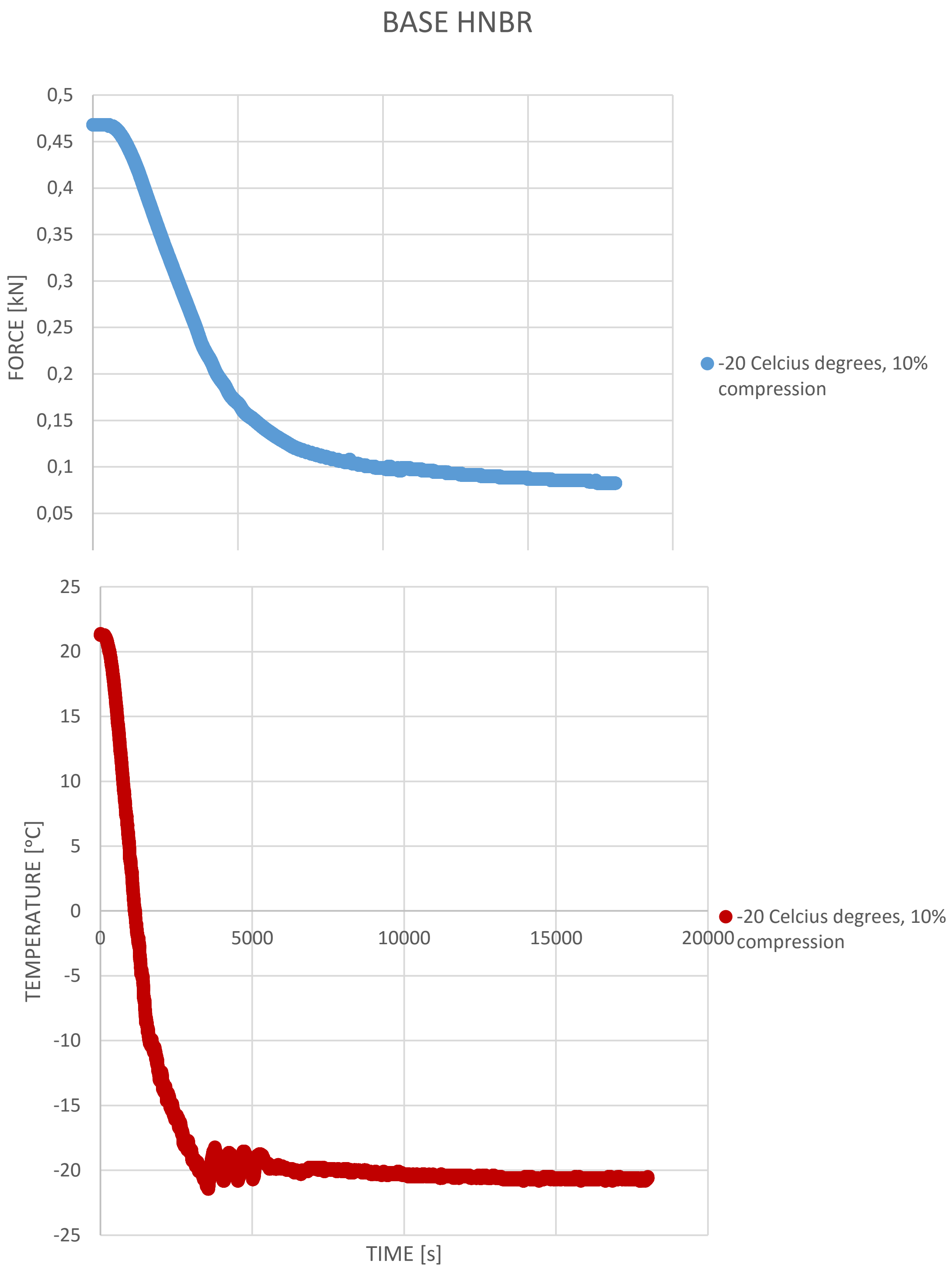


Fig.29 The force and temperature drop in time during test of an O-ring made of base HNBR, with 10% compression and ultimate temperature of -20°C.

As we can see on the graph the initial force acting on the O-ring was equal to 0,47 kN and the final force, when the temperature was stabilized at approximately -20°C was 0,08 kN. The decrease of an acting force is then ΔF = 0,47– 0,08 = 0,39 [kN], which is a higher value than the one obtained at -5°C and 10°C.

NAME	VALUE	UNIT
P	80	N
D	0,11265	m
Rring	0,056325	m
P per L	226,166951	N/m
R	0,00279	m
E*	10423709,1	Pa
a	0,00124773	m
p_0	**115454,347**	Pa

Ultimate contact pressure of base HNBR at -20°C and 10% compression was 0,12 MPa.

Fig. 30 presents comparison of the obtained data while testing base HNBR O-ring under compression equal to 10%

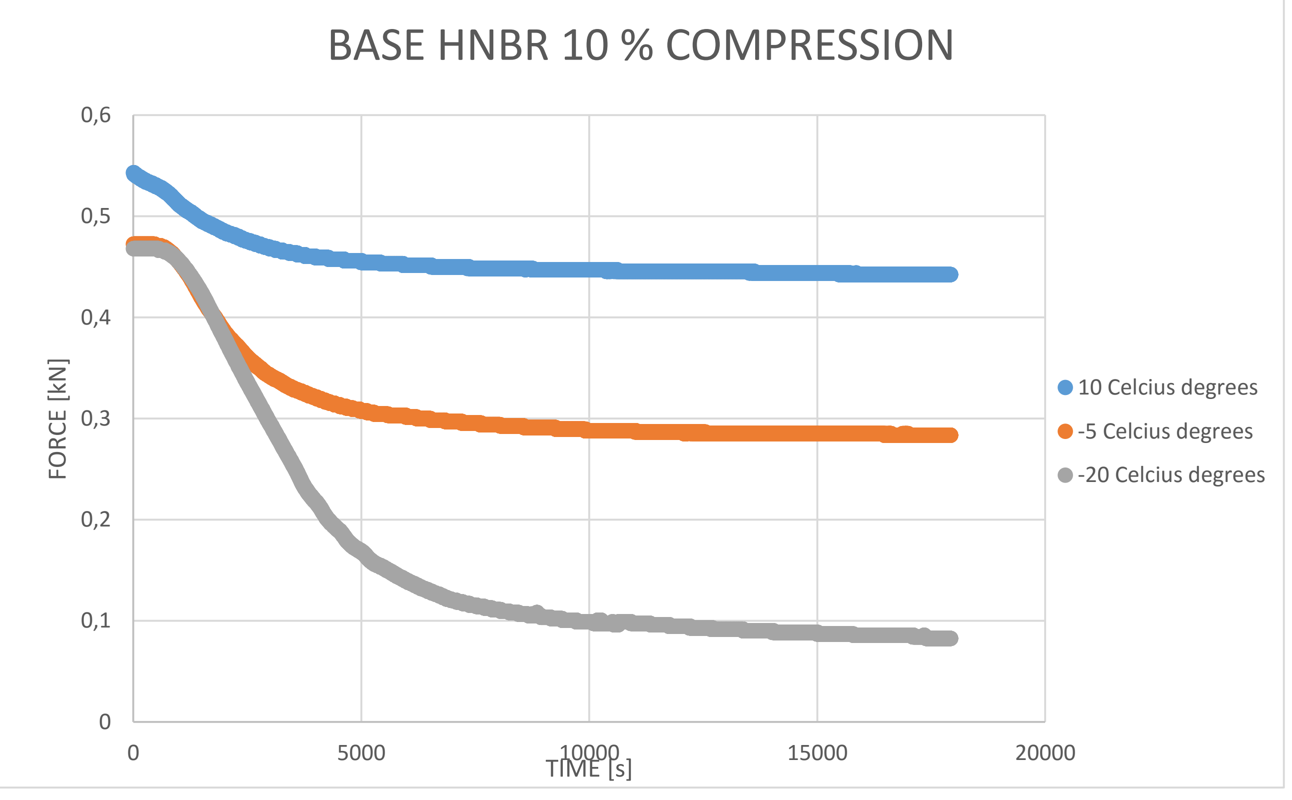


Fig.30 Comparison of force drop in time during base HNBR test with 10% compression.

2.2.4. Base HNBR tested with 20% compression at the temperature of 10°C

Fig. 31 presents the data obtained while decreasing an operational temperature of base HNBR O-ring from the room temperature to approximately 10°C.

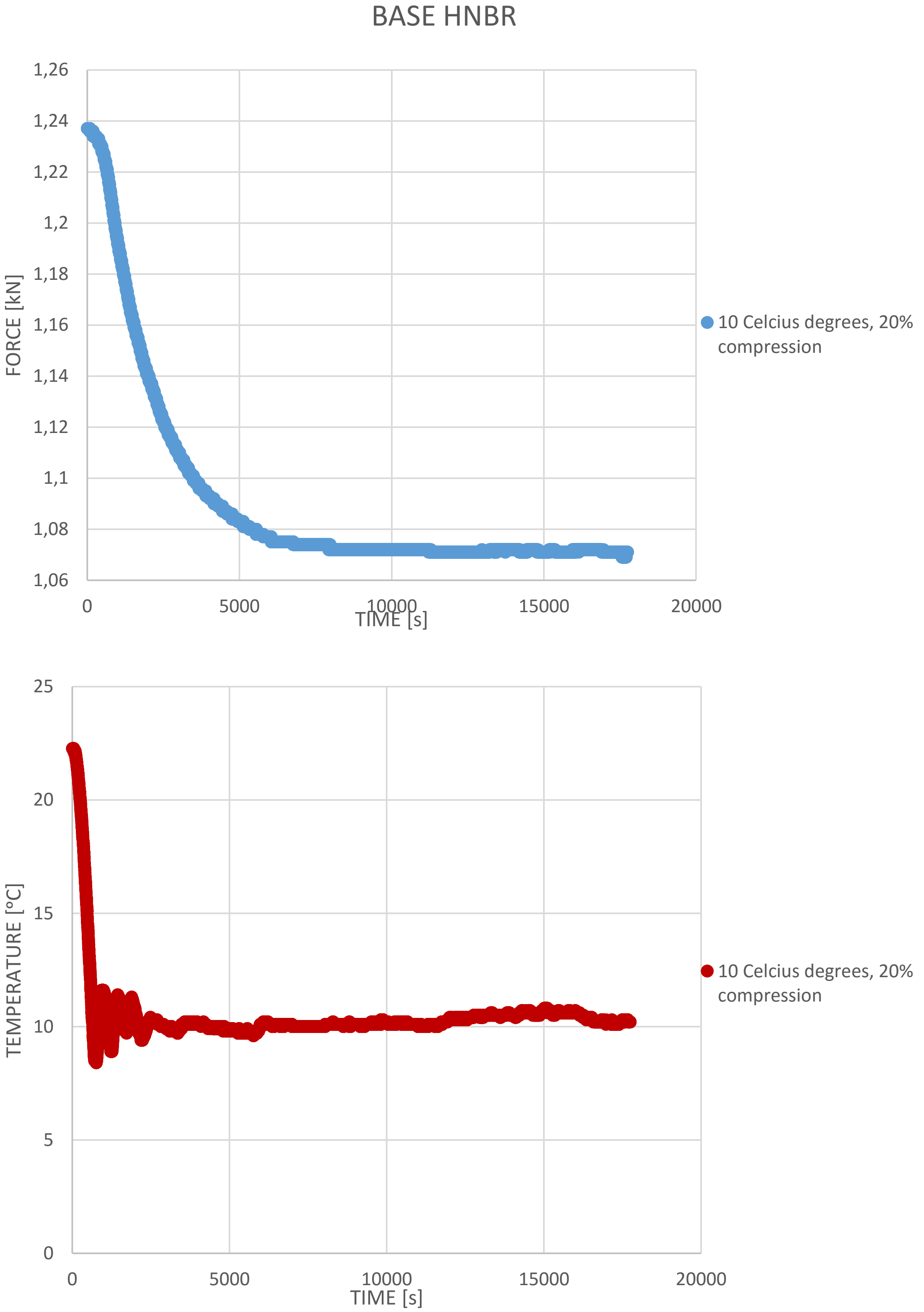


Fig.31 The force and temperature drop in time during test of an O-ring made of base HNBR, with 20% compression and ultimate temperature of 10°C.

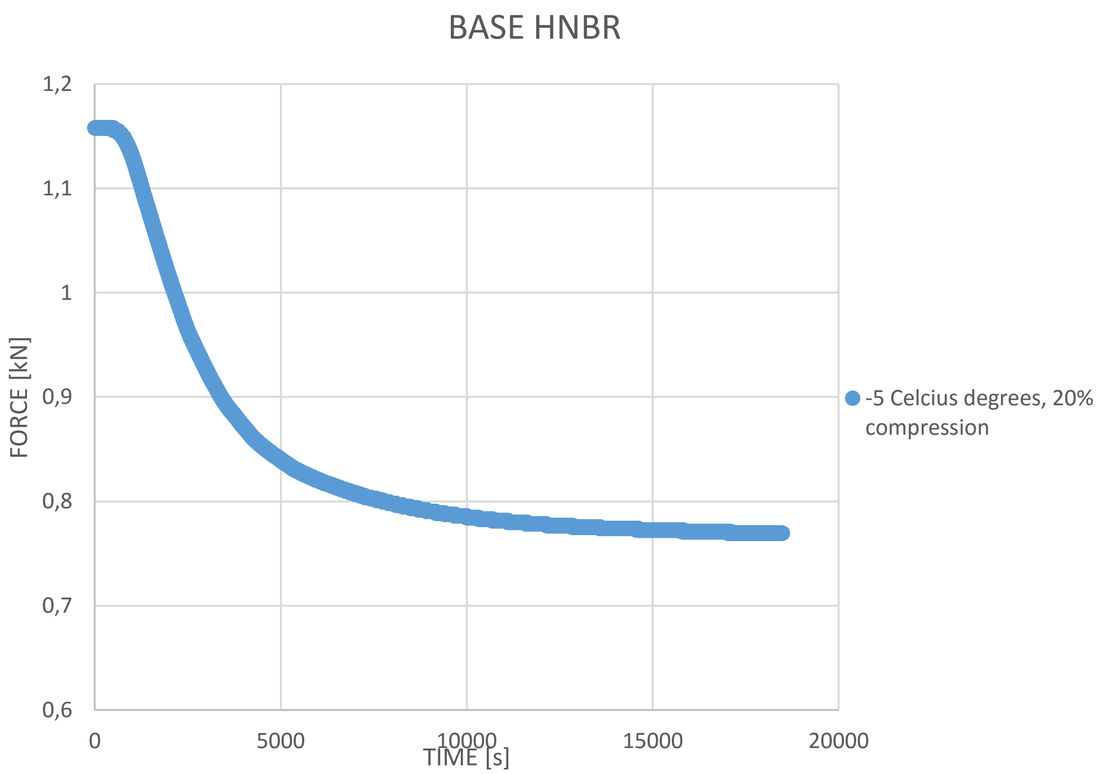
As we can see on the graph the initial force acting on the O-ring was equal to 1,24 kN and the final force, when the temperature was stabilized at approximately 10°C was 1,07. The decrease of an acting force is then ΔF = 1,24– 1,07 = 0,17 [kN], what proves that even a small temperature drop leads to a visible change in sealing load.

NAME	VALUE	UNIT
P	1070	N
D	0,11265	m
Rring	0,056325	m
P per L	3024,98297	N/m
R	0,00279	m
E*	69708554,8	Pa
a	0,00176455	m
p_0	**1091915,63**	Pa

Ultimate contact pressure of base HNBR at 10°C and 20% compression was 1,09 MPa.

2.2.5. Base HNBR tested with 20% compression at the temperature of -5°C

Fig. 32 presents the data obtained while decreasing an operational temperature of base HNBR O-ring from the room temperature to approximately -5°C.



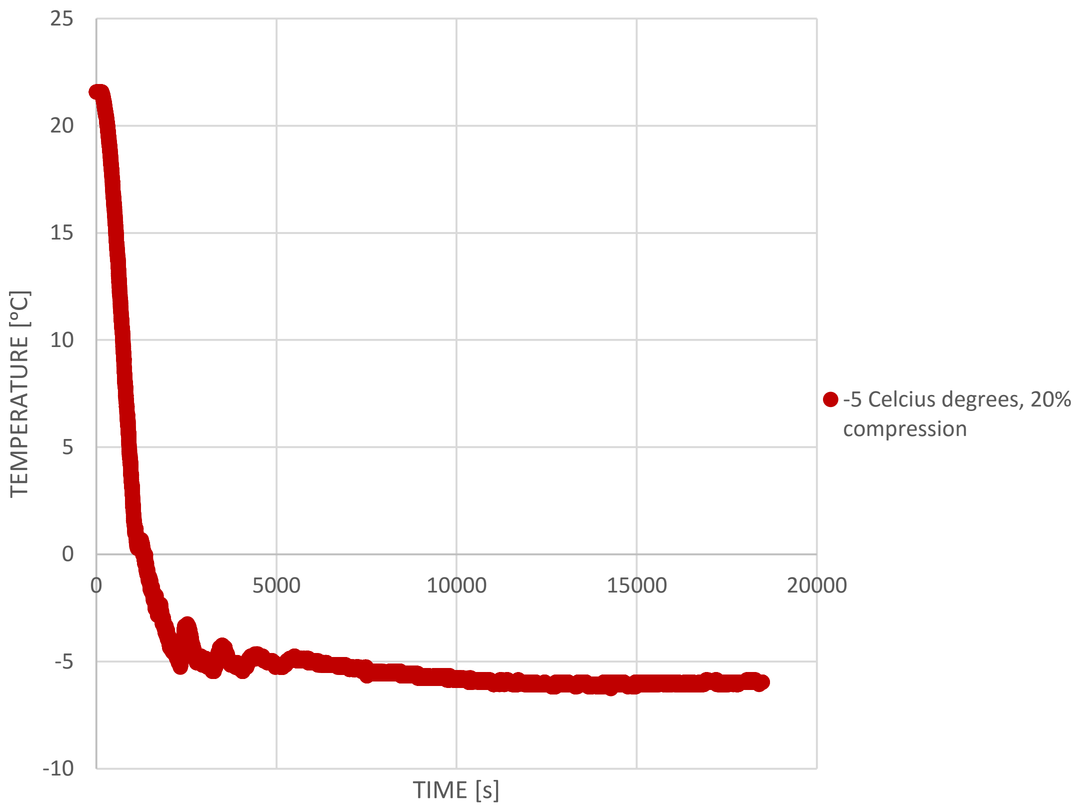


Fig.32 The force and temperature drop in time during test of an O-ring made of base HNBR, with 20% compression and ultimate temperature of -5°C.

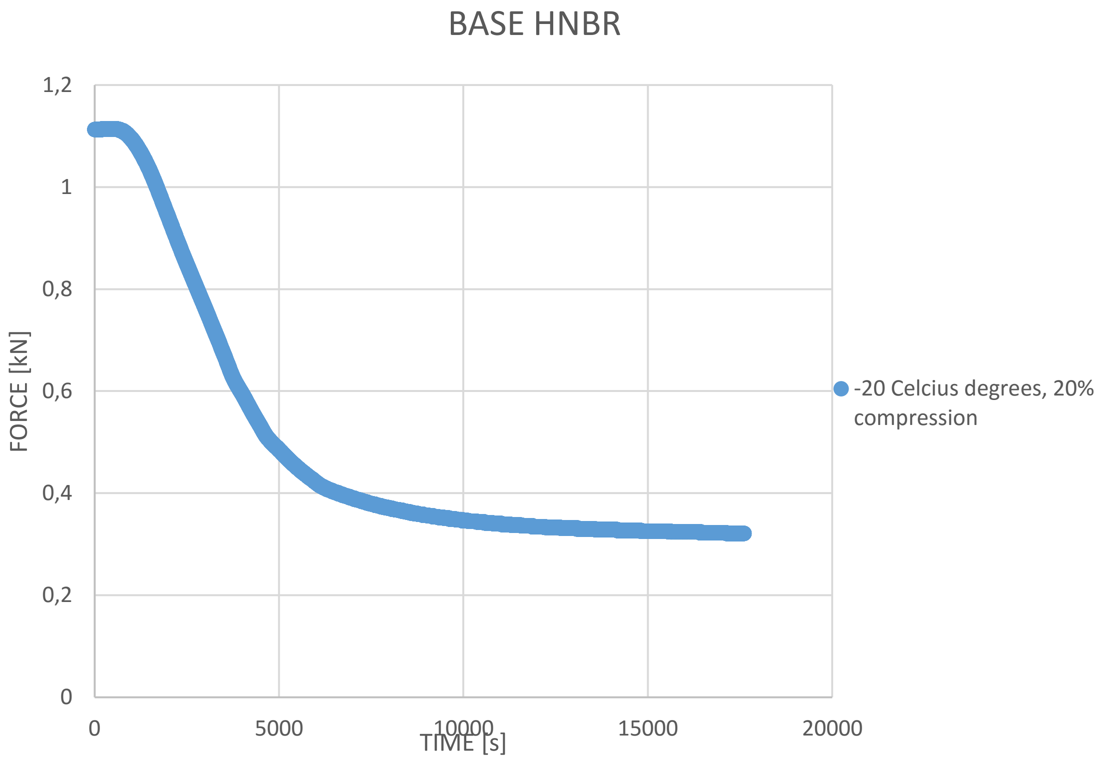
As we can see on the graph the initial force acting on the O-ring was equal to 1,16 kN and the final force, when the temperature was stabilized at approximately -5°C was 0,77 kN. The decrease of an acting force is then ΔF = 1,16– 0,77 = 0,39 [kN], which is a higher value than the one obtained at 10°C.

NAME	VALUE	UNIT
P	770	N
D	0,11265	m
Rring	0,056325	m
P per L	2176,8569	N/m
R	0,00279	m
E*	50164100,2	Pa
a	0,00176455	m
p_0	**785771,06**	Pa

Ultimate contact pressure of base HNBR at -5°C and 20% compression was 0,79 MPa.

2.2.6. Base HNBR tested with 20% compression at the temperature of -20°C

Fig. 33 presents the data obtained while decreasing an operational temperature of base HNBR O-ring from the room temperature to approximately -20°C.



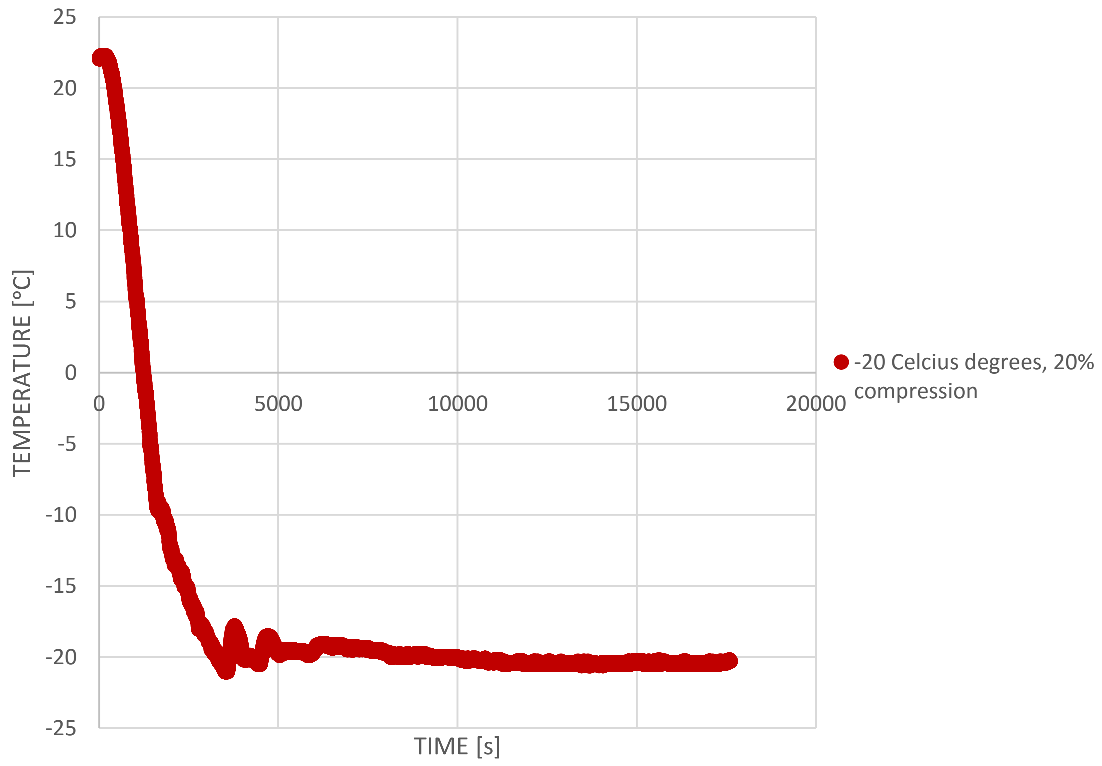


Fig.33 The force and temperature drop in time during test of an O-ring made of base HNBR, with 20% compression and ultimate temperature of -20°C.

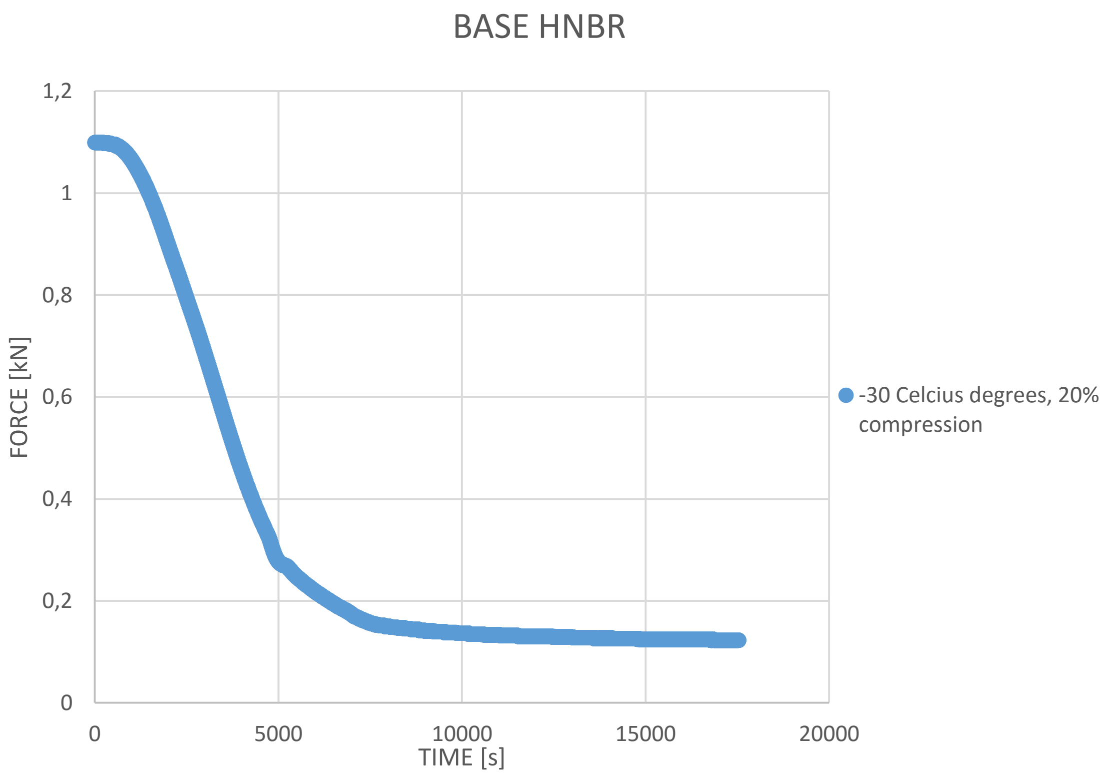
As we can see on the graph the initial force acting on the O-ring was equal to 1,11 kN and the final force, when the temperature was stabilized at approximately -20°C was 0,32 kN. The decrease of an acting force is then ΔF = 1,11– 0,32 = 0,79 [kN], which is a higher value than the one obtained at -5°C and 10°C.

NAME	VALUE	UNIT
P	320	N
D	0,11265	m
Rring	0,056325	m
P per L	904,667803	N/m
R	0,00279	m
E*	20847418,3	Pa
a	0,00176455	m
p_0	**326554,207**	Pa

Ultimate contact pressure of base HNBR at -20°C and 20% compression was 0,33 MPa.

2.2.7. Base HNBR tested with 20% compression at the temperature of -30°C

Fig. 34 presents the data obtained while decreasing an operational temperature of base HNBR O-ring from the room temperature to approximately -30°C.



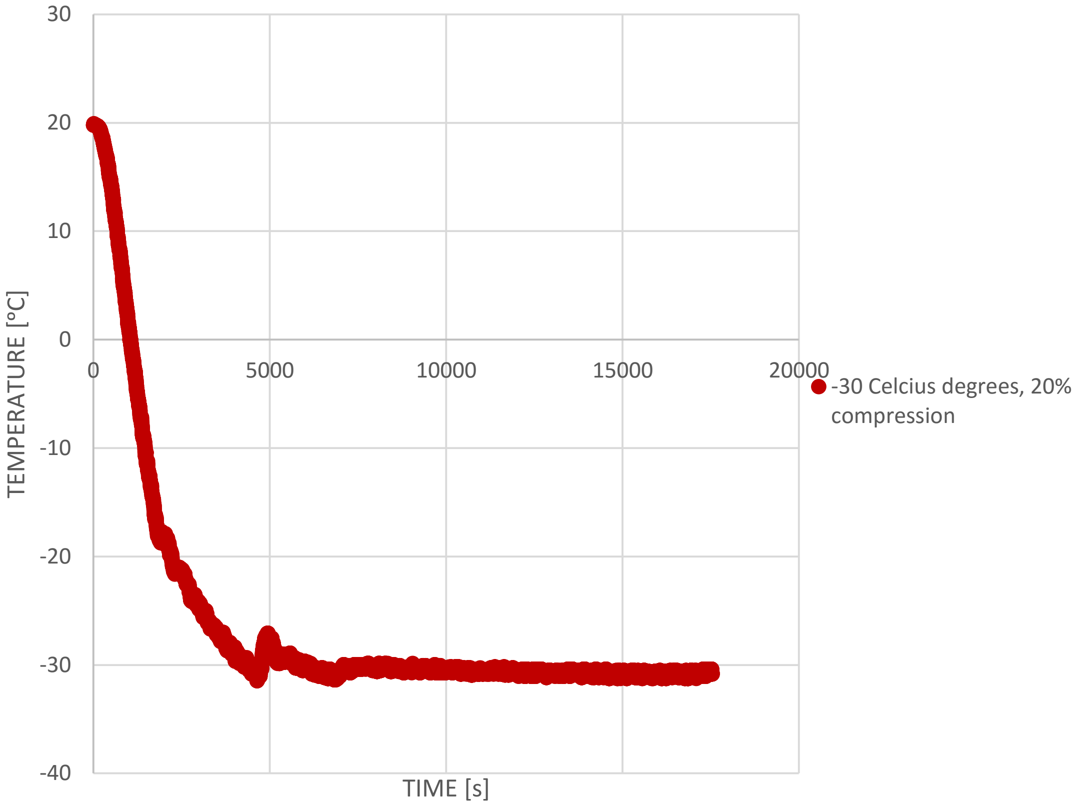


Fig.34 The force and temperature drop in time during test of an O-ring made of base HNBR, with 20% compression and ultimate temperature of -30°C.

As we can see on the graph the initial force acting on the O-ring was equal to 1,10 kN and the final force, when the temperature was stabilized at approximately -30oC was 0,12 kN. The decrease of an acting force is then ΔF = 1,10– 0,12 = 0,98 [kN], which is much higher value than all of the values obtained at higher temperatures.

NAME	VALUE	UNIT
P	120	N
D	0,11265	m
Rring	0,056325	m
P per L	339,250426	N/m
R	0,00279	m
E*	7817781,85	Pa
a	0,00176455	m
p_0	**122457,828**	Pa

Ultimate contact pressure of base HNBR at -30oC and 20% compression was 0,12 MPa.

Fig. 35 presents comparison of the obtained data while testing base HNBR O-ring under compression equal to 20%.

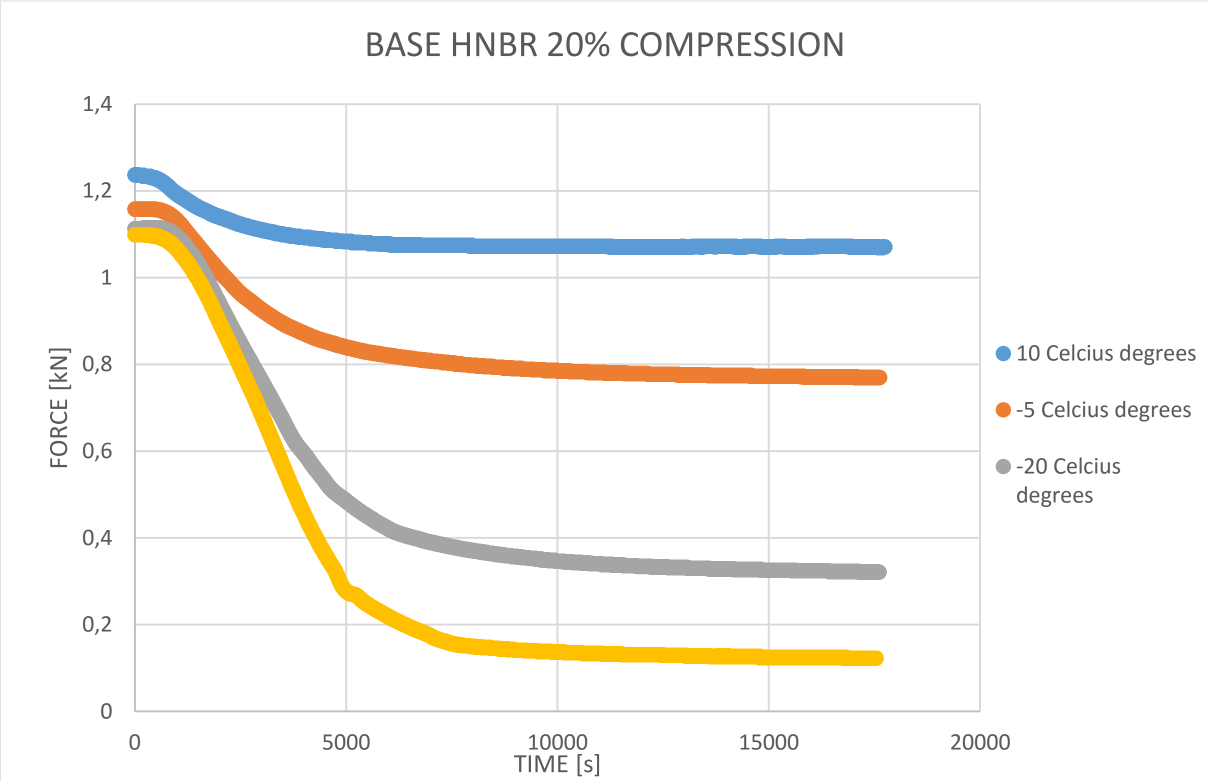


Fig.35 Comparison of force drop in time during base HNBR test with 20% compression.

2.3. HNBR 50 CB

2.3.1. HNBR 50 CB tested with 10% compression at the temperature of 10°C

Fig. 36 presents the data obtained while decreasing an operational temperature of HNBR 50 CB O-ring from the room temperature to approximately 10°C.

As we can see on the graph the initial force acting on the O-ring was equal to 0,90 kN and the final force, when the temperature was stabilized at approximately 10°C was 0,60. The decrease of an acting force is then ΔF = 0,90– 0,60 = 0,30 [kN], what proves that even a small temperature drop leads to a visible change in sealing load.

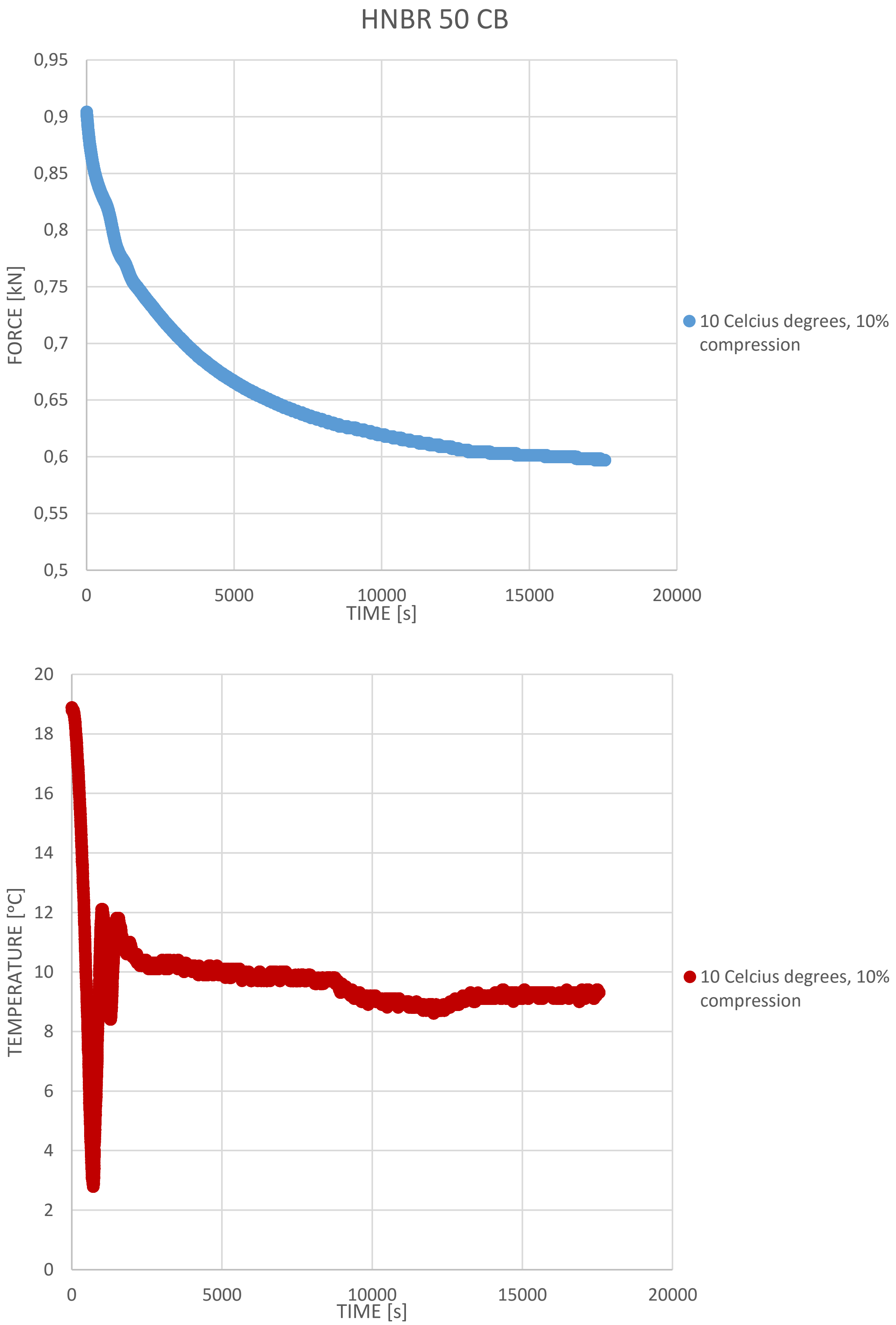


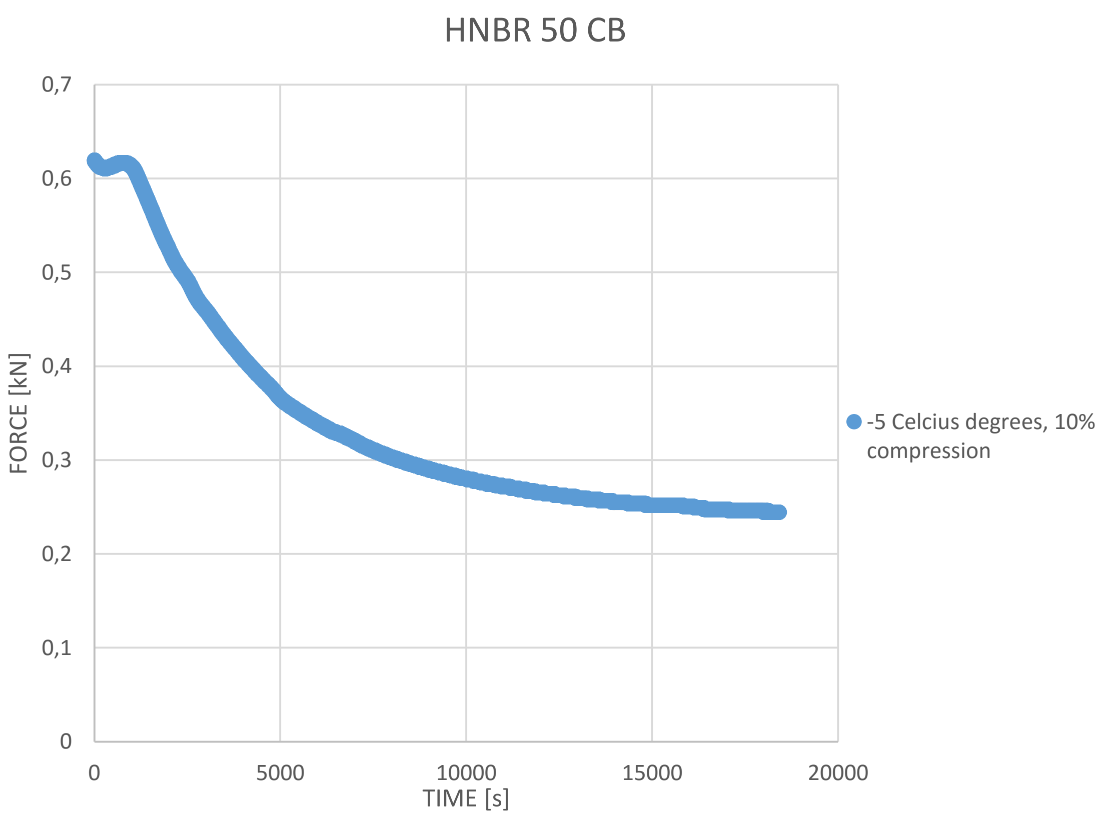
Fig.36 The force and temperature drop in time during test of an O-ring made of HNBR 50 CB, with 10% compression and ultimate temperature of 10°C.

NAME	VALUE	UNIT
P	600	N
D	0,11265	m
Rring	0,056325	m
P per L	1696,252131	N/m
R	0,00296	m
E*	69455802,27	Pa
a	0,001323752	m
p_0	**816176,4227**	Pa

Ultimate contact pressure of HNBR 50 CB at 10°C and 10% compression was 0,82 MPa.

2.3.2. HNBR 50 CB tested with 10% compression at the temperature of -5°C

Fig. 37 presents the data obtained while decreasing an operational temperature of HNBR 50 CB O-ring from the room temperature to approximately -5°C



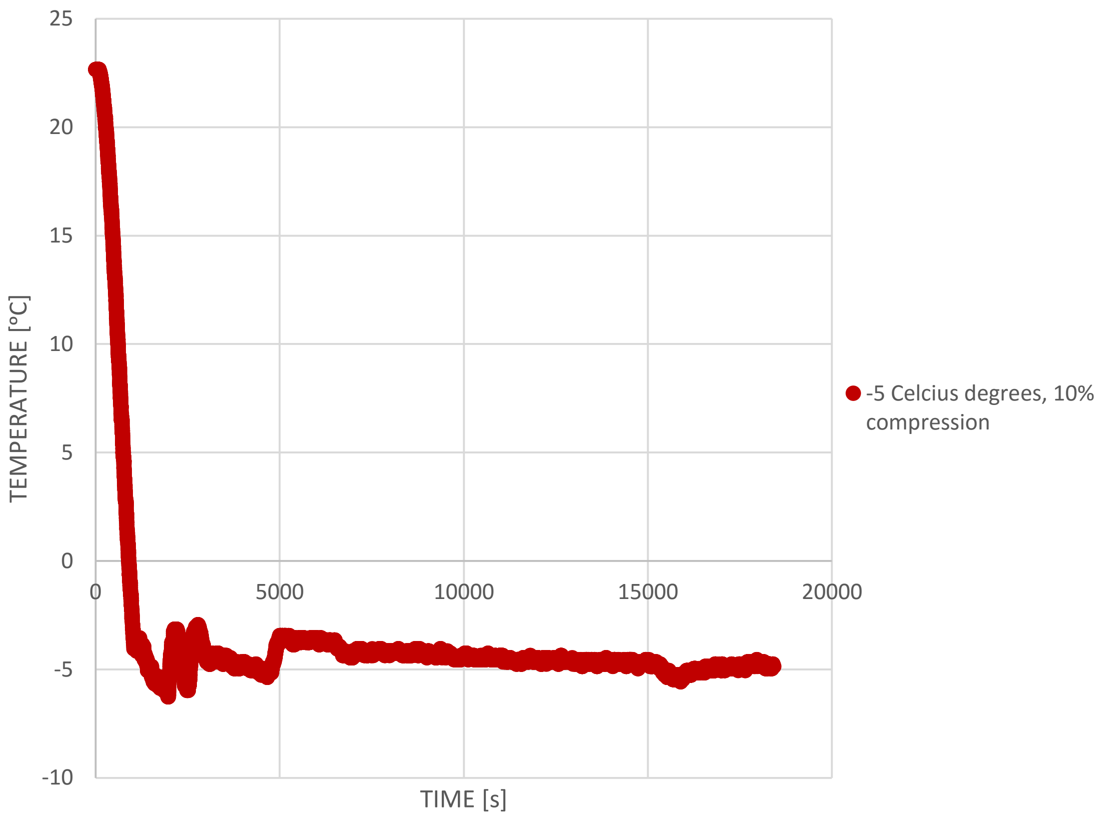


Fig.37 The force and temperature drop in time during test of an O-ring made of HNBR 50 CB, with 10% compression and ultimate temperature of -5°C.

As we can see on the graph the initial force acting on the O-ring was equal to 0,62 kN and the final force, when the temperature was stabilized at approximately -5oC was 0,24. The decrease of an acting force is then ΔF = 0,62– 0,24 = 0,38 [kN], which is a higher value than the one obtained at 10oC.

NAME	VALUE	UNIT
P	240	N
D	0,11265	m
Rring	0,056325	m
P per L	678,5008524	N/m
R	0,00296	m
E*	27782320,91	Pa
a	0,001323752	m
p_0	**326470,5691**	Pa

Ultimate contact pressure of HNBR 50 CB at -5oC and 10% compression was 0,33 MPa.

2.3.3. HNBR 50 CB tested with 10% compression at the temperature of -20°C

Fig. 38 presents the data obtained while decreasing an operational temperature of HNBR 50 CB O-ring from the room temperature to approximately -20°C.

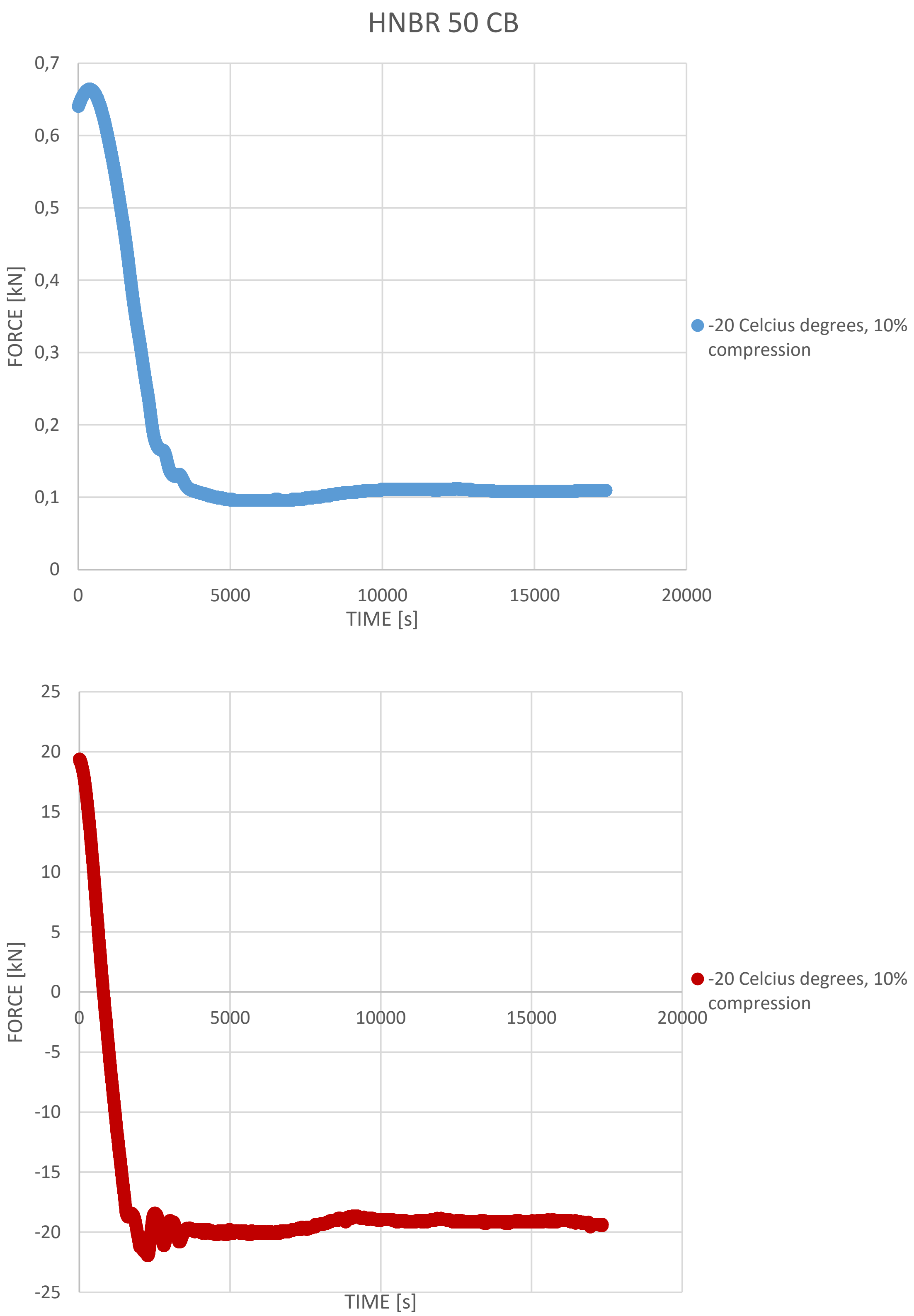


Fig.38 The force and temperature drop in time during test of an O-ring made of HNBR 50 CB, with 10% compression and ultimate temperature of -20°C.

As we can see on the graph the initial force acting on the O-ring was equal to 0,64 kN and the final force, when the temperature was stabilized at approximately -20°C was 0,11. The decrease of an acting force is then ΔF = 0,64– 0,11 = 0,38 [kN], which is a higher value than the one obtained at 10°C and -5°C.

NAME	VALUE	UNIT
P	110	N
D	0,11265	m
Rring	0,056325	m
P per L	310,9795573	N/m
R	0,00296	m
E*	12733563,75	Pa
a	0,001323752	m
p_0	149632,3442	Pa

Ultimate contact pressure of HNBR 50 CB at -20°C and 10% compression was 0,15 MPa.

Fig. 39 presents comparison of the obtained data while testing HNBR 50 CB O-ring under compression equal to 10%.

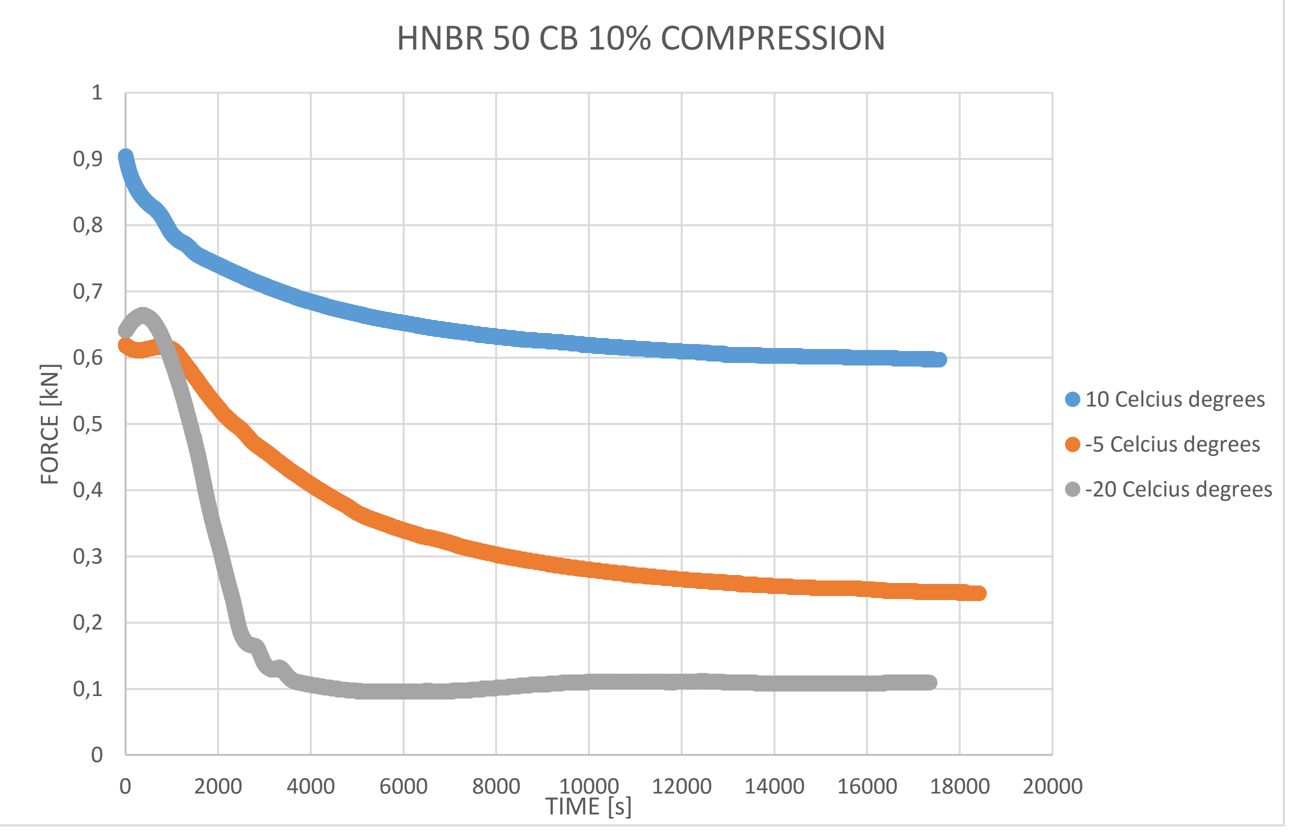
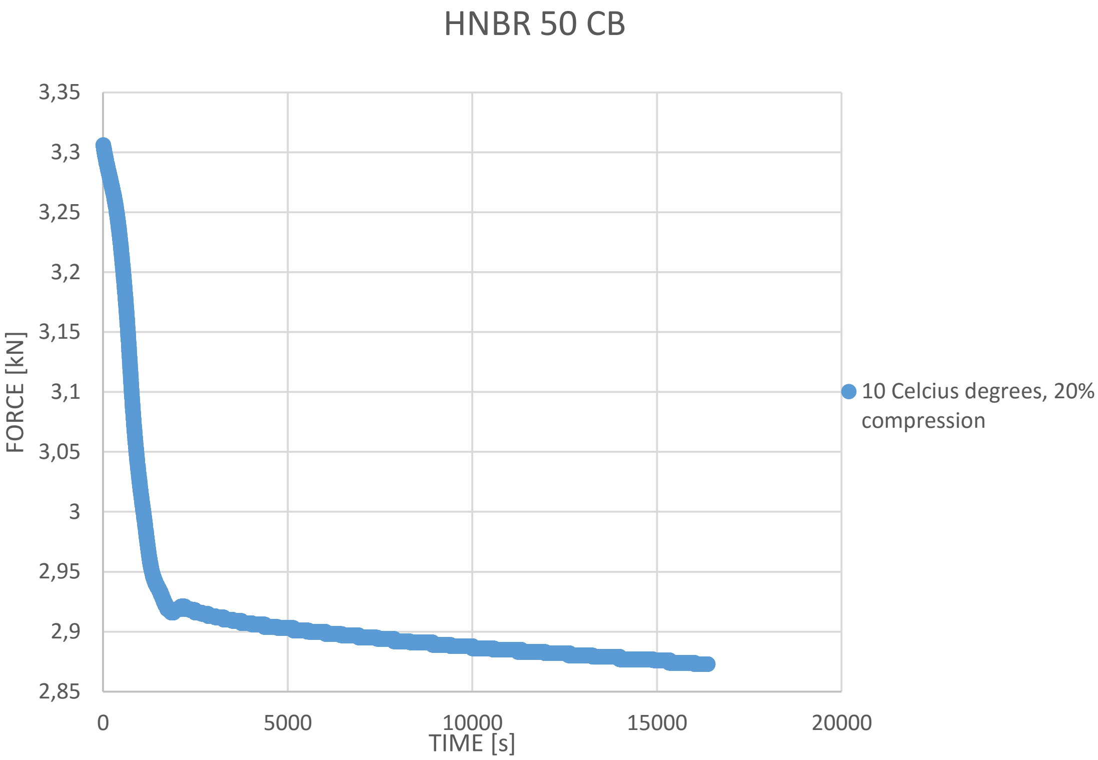


Fig.39 Comparison of force drop in time during base HNBR test with 20% compression.

2.3.4. HNBR 50 CB tested with 20% compression at the temperature of 10°C

Fig. 40 presents the data obtained while decreasing an operational temperature of HNBR 50 CB O-ring from the room temperature to approximately 10°C.



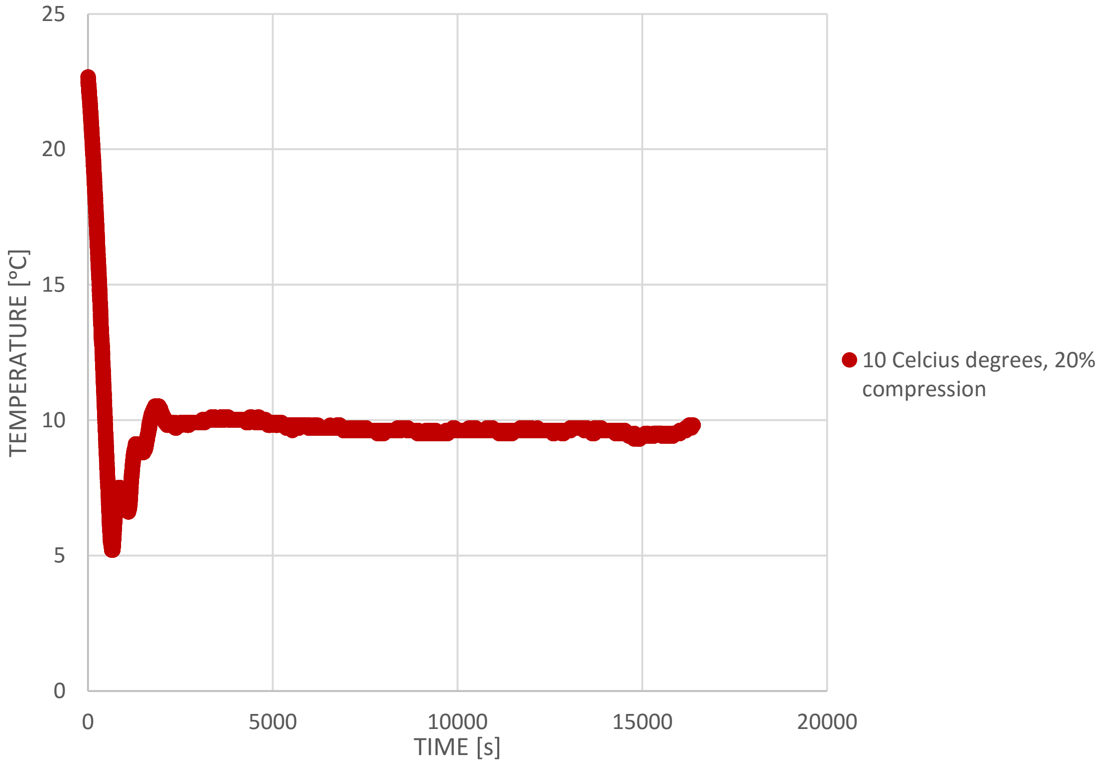


Fig.40 The force and temperature drop in time during test of an O-ring made of HNBR 50 CB, with 20% compression and ultimate temperature of 10°C.

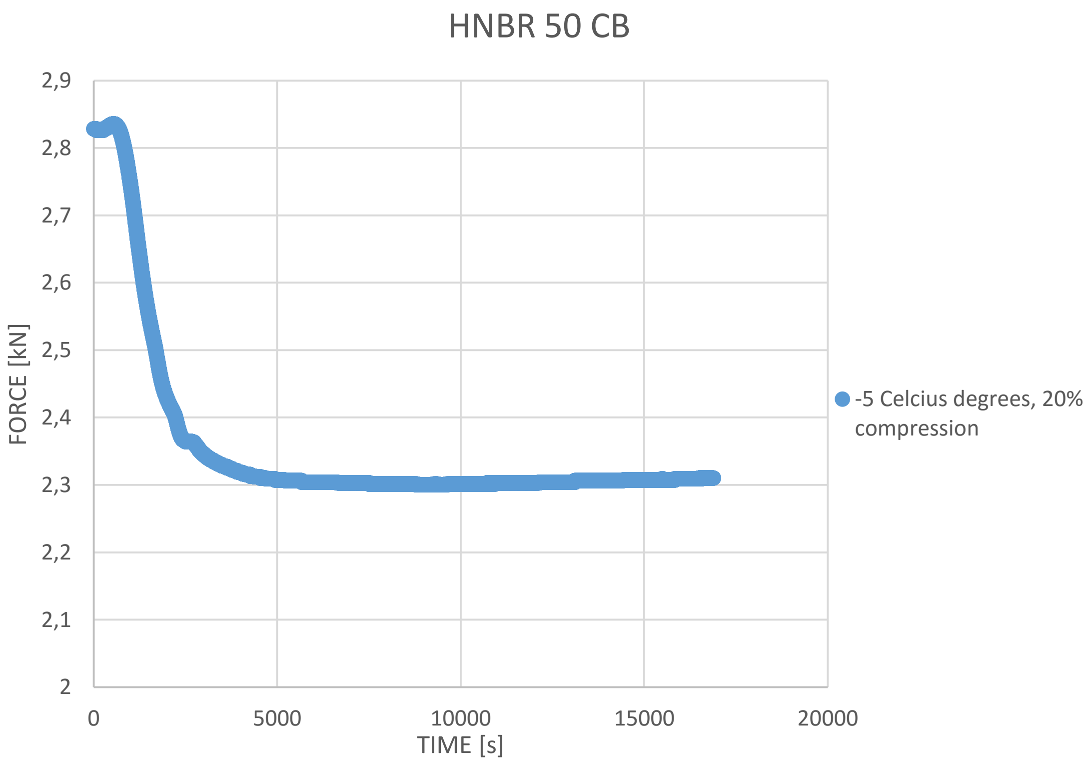
As we can see on the graph the initial force acting on the O-ring was equal to 3,36 kN and the final force, when the temperature was stabilized at approximately 10°C was 2,87. The decrease of an acting force is then ΔF = 3,36– 2,87 = 0,49 [kN], what proves that even a small temperature drop leads to a visible change in sealing load.

NAME	VALUE	UNIT
P	2870	N
D	0,11265	m
Rring	0,056325	m
P per L	8113,73936	N/m
R	0,00296	m
E*	166115127	Pa
a	0,00187207	m
p_0	**2760575,91**	Pa

Ultimate contact pressure of HNBR 50 CB at 10°C and 20% compression was 2,76 MPa.

2.3.5. HNBR 50 CB tested with 20% compression at the temperature of -5°C

Fig. 41 presents the data obtained while decreasing an operational temperature of HNBR 50 CB O-ring from the room temperature to approximately -5°C.



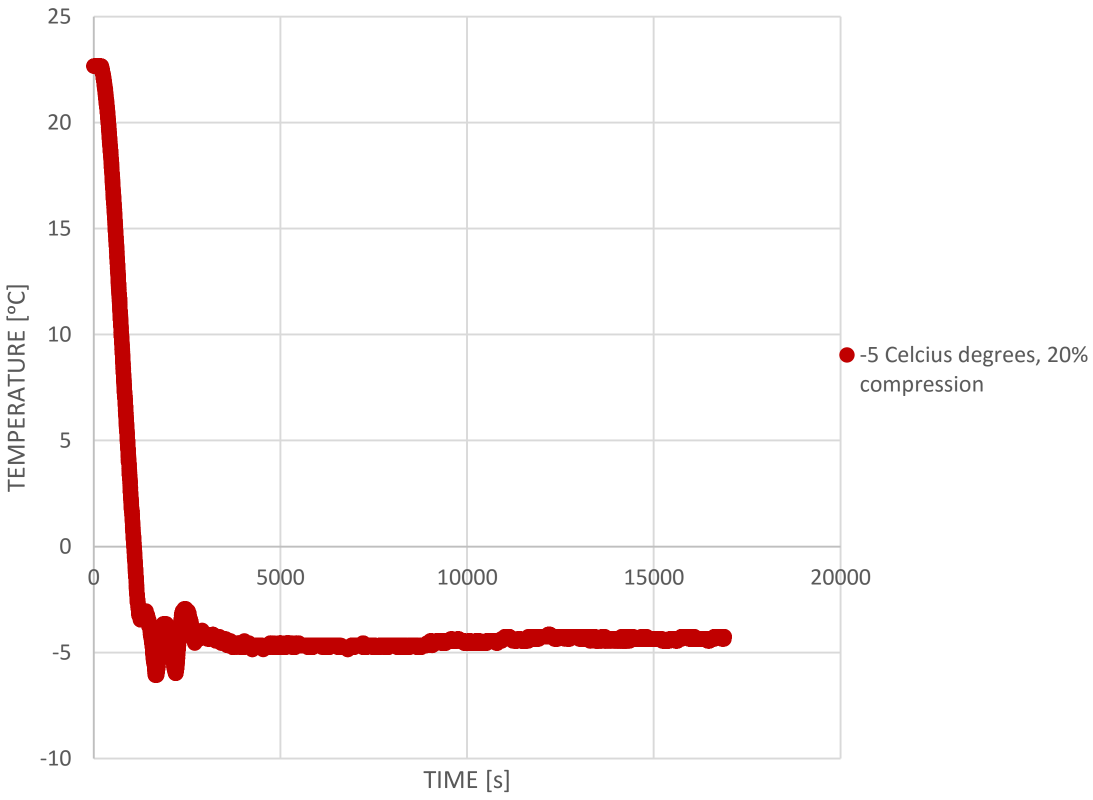


Fig.41 The force and temperature drop in time during test of an O-ring made of HNBR 50 CB, with 20% compression and ultimate temperature of -5°C.

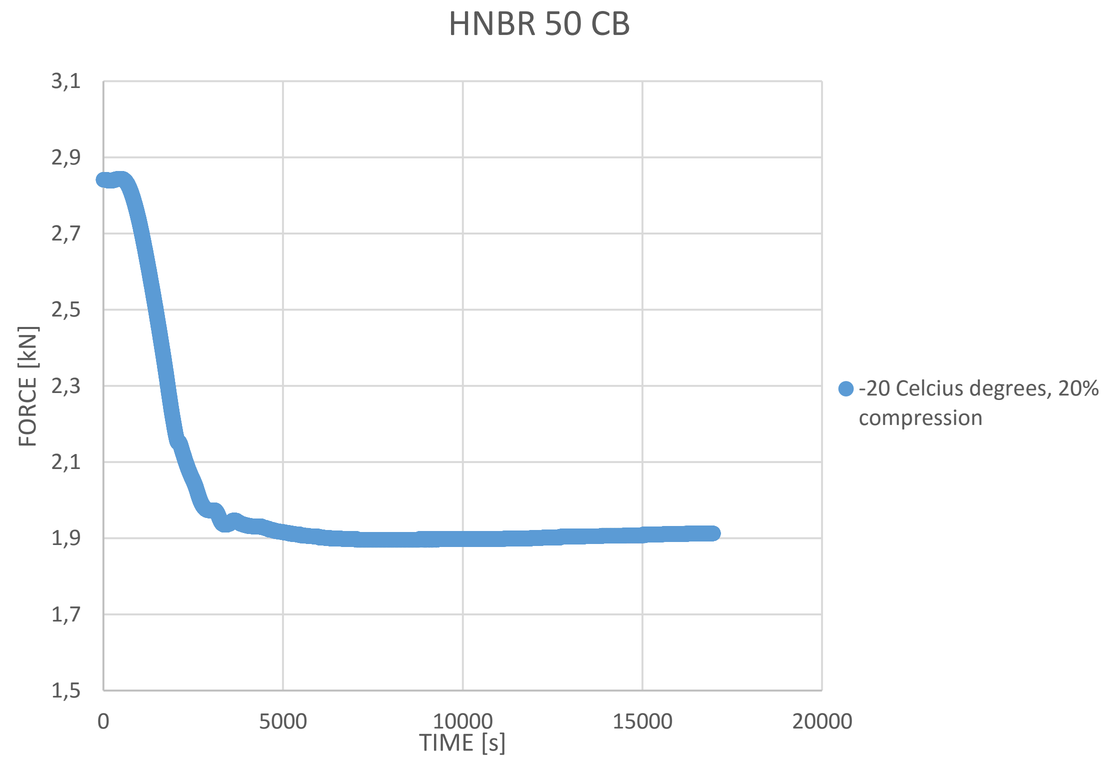
As we can see on the graph the initial force acting on the O-ring was equal to 2,83 kN and the final force, when the temperature was stabilized at approximately -5°C was 2,31 kN. The decrease of an acting force is then ΔF = 2,83– 2,31 = 0,52 [kN], which is a bit higher value than the one obtained at 10°C.

NAME	VALUE	UNIT
P	2310	N
D	0,11265	m
Rring	0,056325	m
P per L	6530,5707	N/m
R	0,00296	m
E*	133702419	Pa
a	0,00187207	m
p_0	**2221926,95**	Pa

Ultimate contact pressure of HNBR 50 CB at -5°C and 20% compression was 2,22 MPa.

2.3.6. HNBR 50 CB tested with 20% compression at the temperature of -20°C

Fig. 42 presents the data obtained while decreasing an operational temperature of HNBR 50 CB O-ring from the room temperature to approximately -20°C.



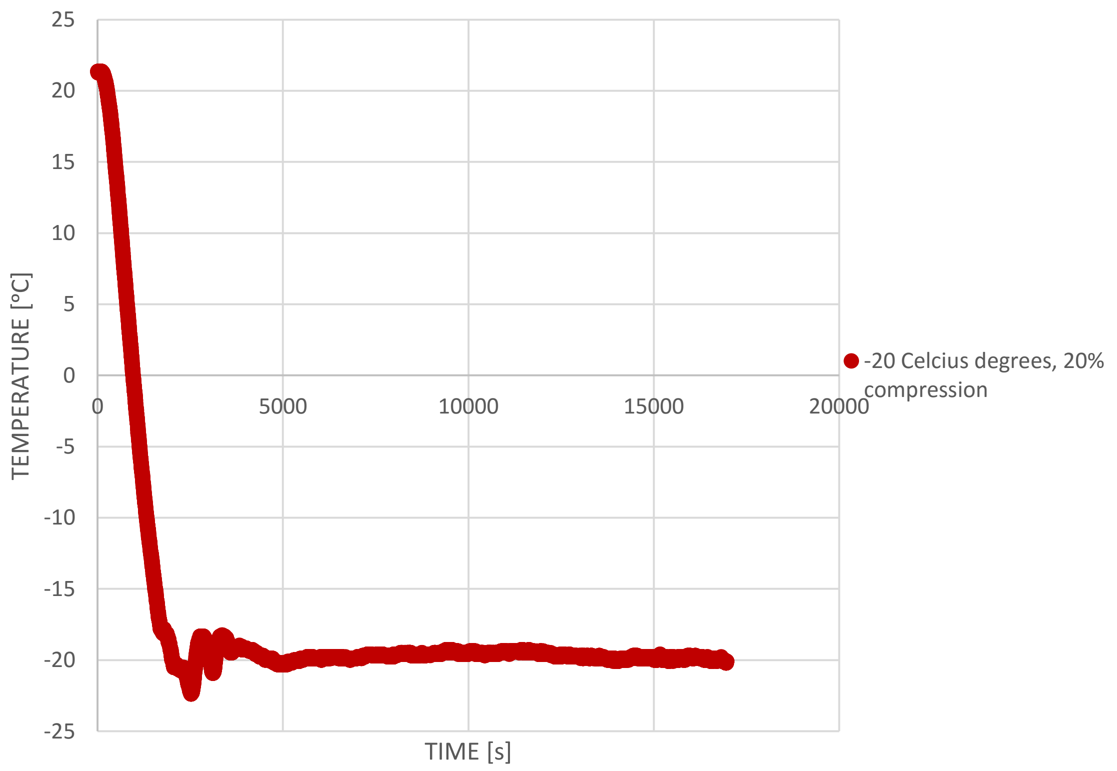


Fig.42 The force and temperature drop in time during test of an O-ring made of HNBR 50 CB, with 20% compression and ultimate temperature of -20°C.

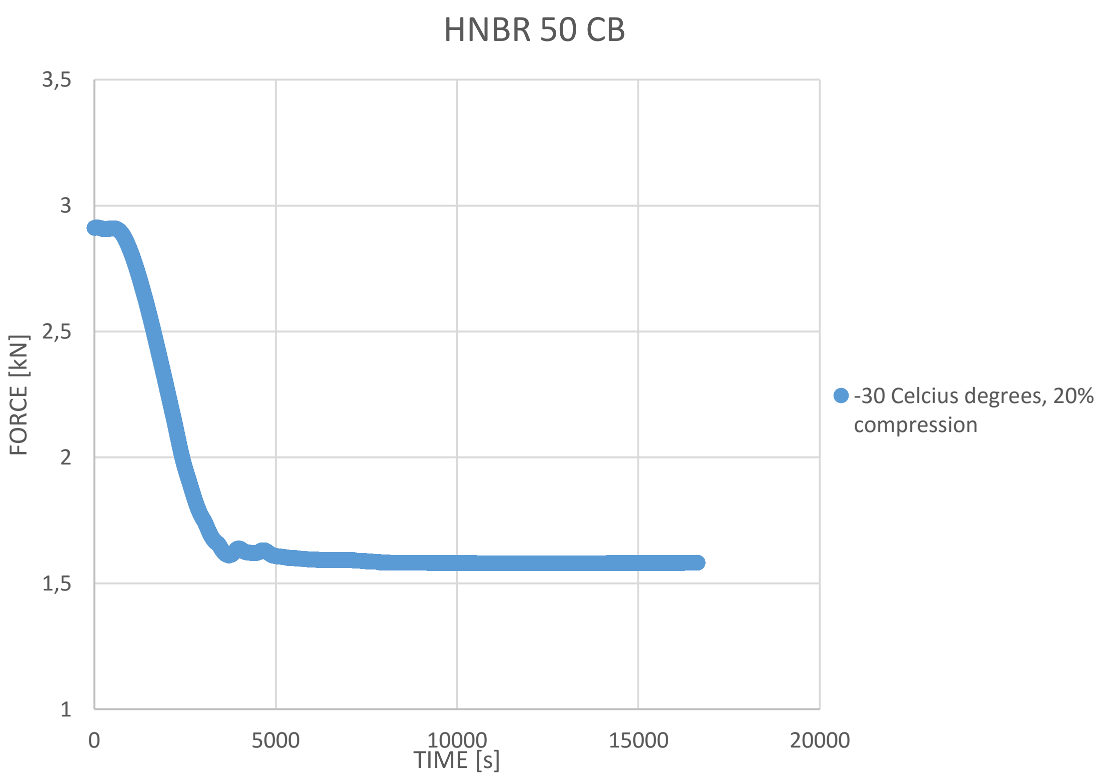
As we can see on the graph the initial force acting on the O-ring was equal to 2,84 kN and the final force, when the temperature was stabilized at approximately -20°C was 1,91 kN. The decrease of an acting force is then ΔF = 2,84– 1,91 = 0,85 [kN], which is a higher value than the one obtained at -5°C and 10°C.

NAME	VALUE	UNIT
P	1910	N
D	0,11265	m
Rring	0,056325	m
P per L	5399,73595	N/m
R	0,00296	m
E*	110550485	Pa
a	0,00187207	m
p_0	**1837177,69**	Pa

Ultimate contact pressure of HNBR 50 CB at -20°C and 20% compression was 1,84 MPa.

2.3.7. HNBR 50 CB tested with 20% compression at the temperature of -30°C

Fig.43 presents the data obtained while decreasing an operational temperature of HNBR 50 CB O-ring from the room temperature to approximately -30°C.



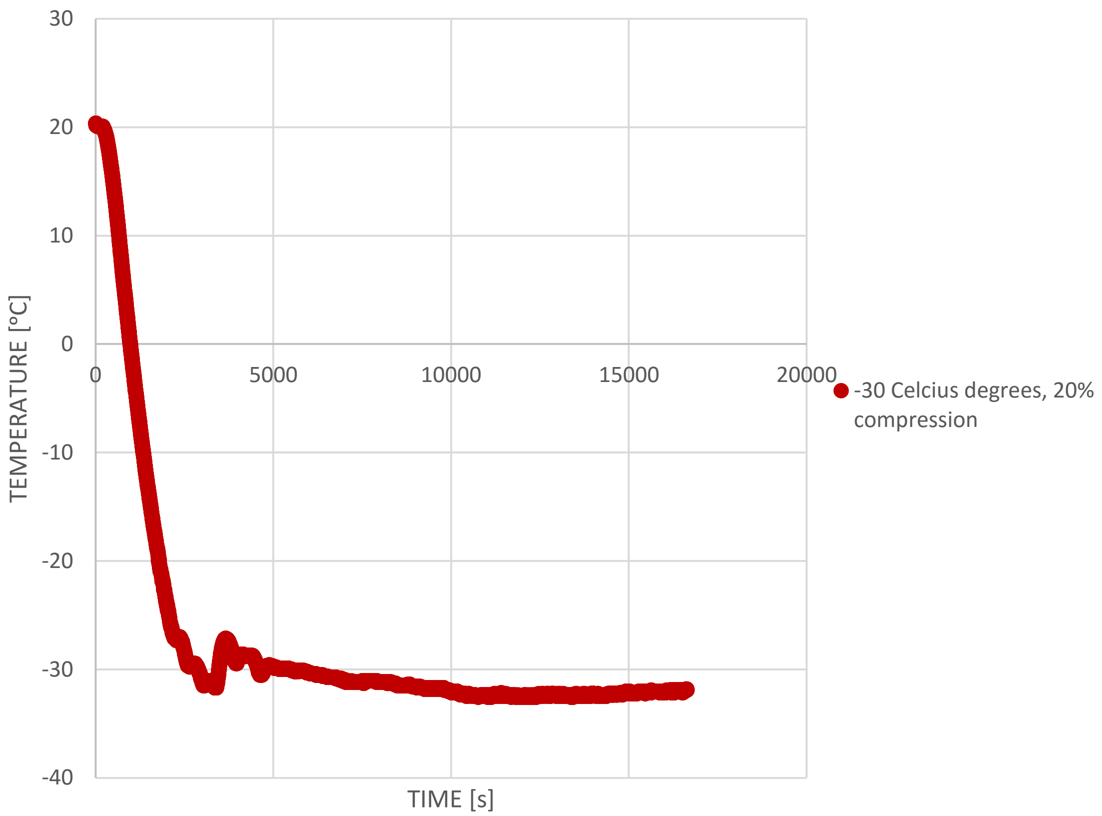


Fig.43 The force and temperature drop in time during test of an O-ring made of HNBR 50 CB, with 20% compression and ultimate temperature of -30°C.

As we can see on the graph the initial force acting on the O-ring was equal to 2,91 kN and the final force, when the temperature was stabilized at approximately -30°C was 1,58 kN. The decrease of an acting force is then ΔF = 2,91– 1,58 = 1,33 [kN], which is much higher value than all of the values obtained at higher temperatures.

NAME	VALUE	UNIT
P	1580	N
D	0,11265	m
Rring	0,056325	m
P per L	4466,79728	N/m
R	0,00279	m
E*	97022370,4	Pa
a	0,00181751	m
p_0	**1565375,88**	Pa

Ultimate contact pressure of HNBR 50 CB at -30°C and 20% compression was 1,57 MPa.

Fig. 44 presents comparison of the obtained data while testing HNBR 50 CB O-ring under compression equal to 20%.

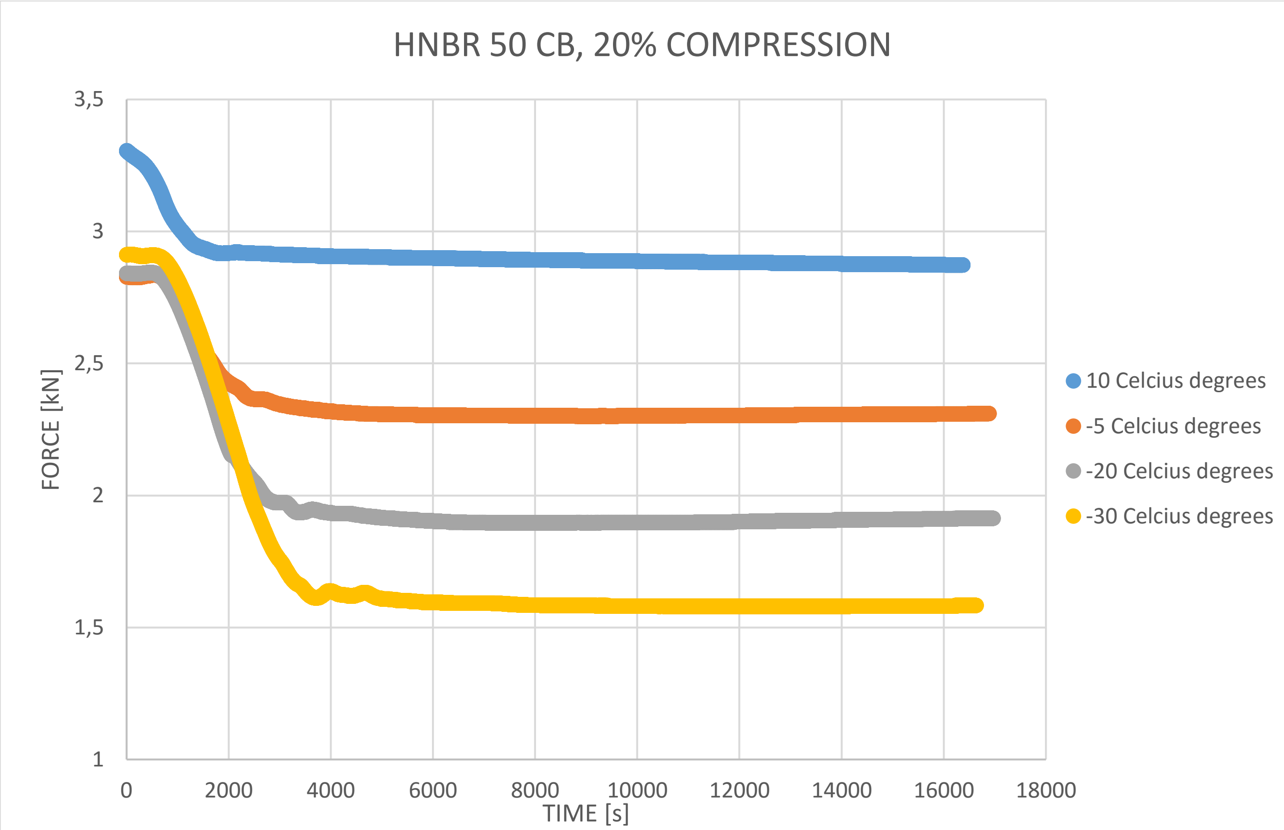


Fig.44 Comparison of force drop in time during base HNBR test with 20% compression.

2.4. Analysis of samples tested with the same parameters.

The aim of this chapter is to show the differences between the appearances of the three tested samples with exactly the same conditions.

2.4.1. Samples tested with 10% compression at 10°C.

Fig. 45 presents comparison of the obtained data while O-rings tests under compression equal to 10% and approximately 10°C.

Drop of the measured forces of the three specimens are as following:

- ΔF = 0,23 for ELAST-O-LION
- ΔF = 0,10 for BASE HNBR
- ΔF = 0,30 for HNBR 50 CB

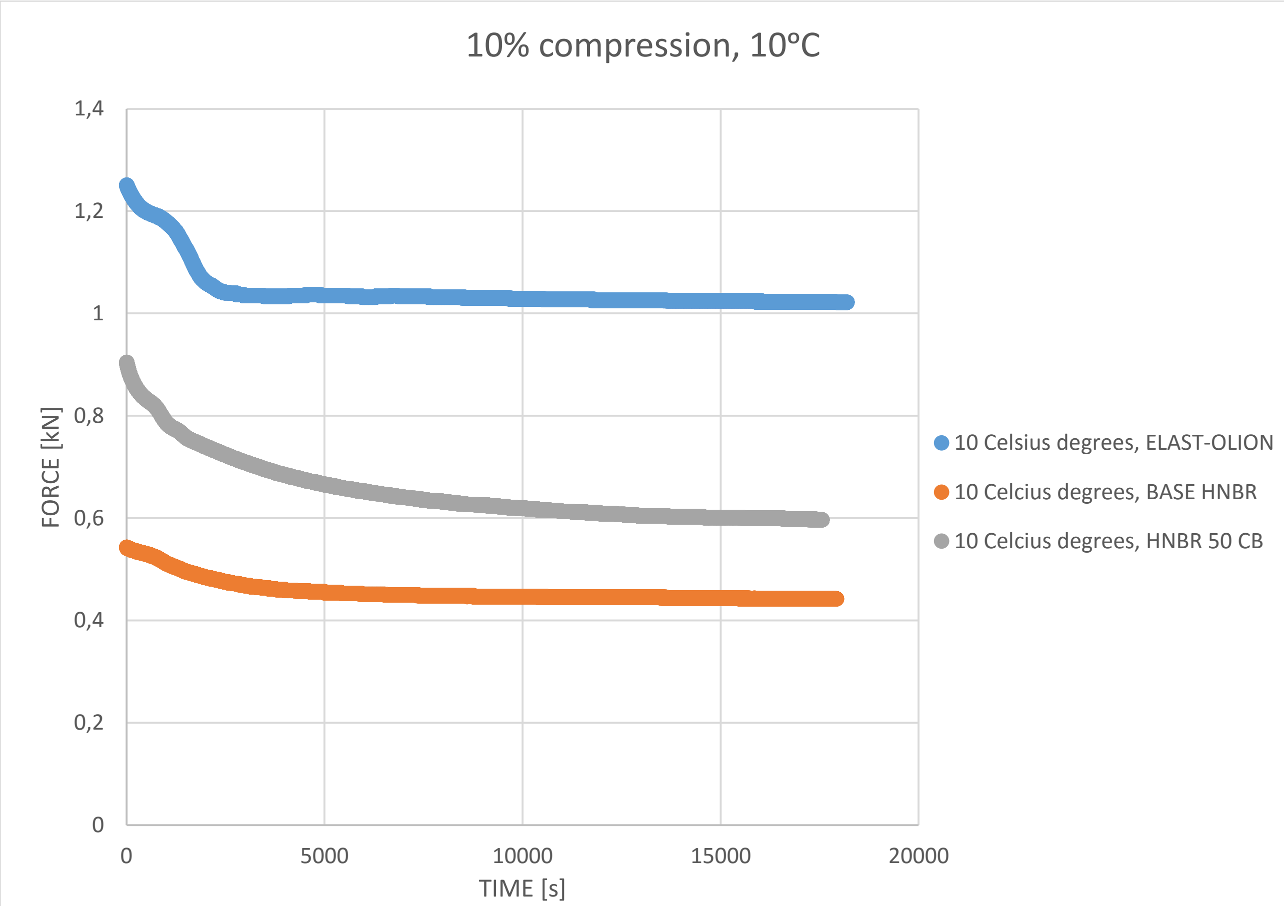


Fig.45 Comparison of force drop in time during specimens tests with 10% compression and 10°C.

2.4.2. Samples tested with 10% compression at -5°C.

Fig. 46 presents comparison of the obtained data while O-rings tests under compression equal to 10% and approximately -5°C.

Drop of the measured forces of the three specimens are as following:

- ΔF = 0,30 for ELAST-O-LION
- ΔF = 0,10 for BASE HNBR
- ΔF = 0,38 for HNBR 50 CB

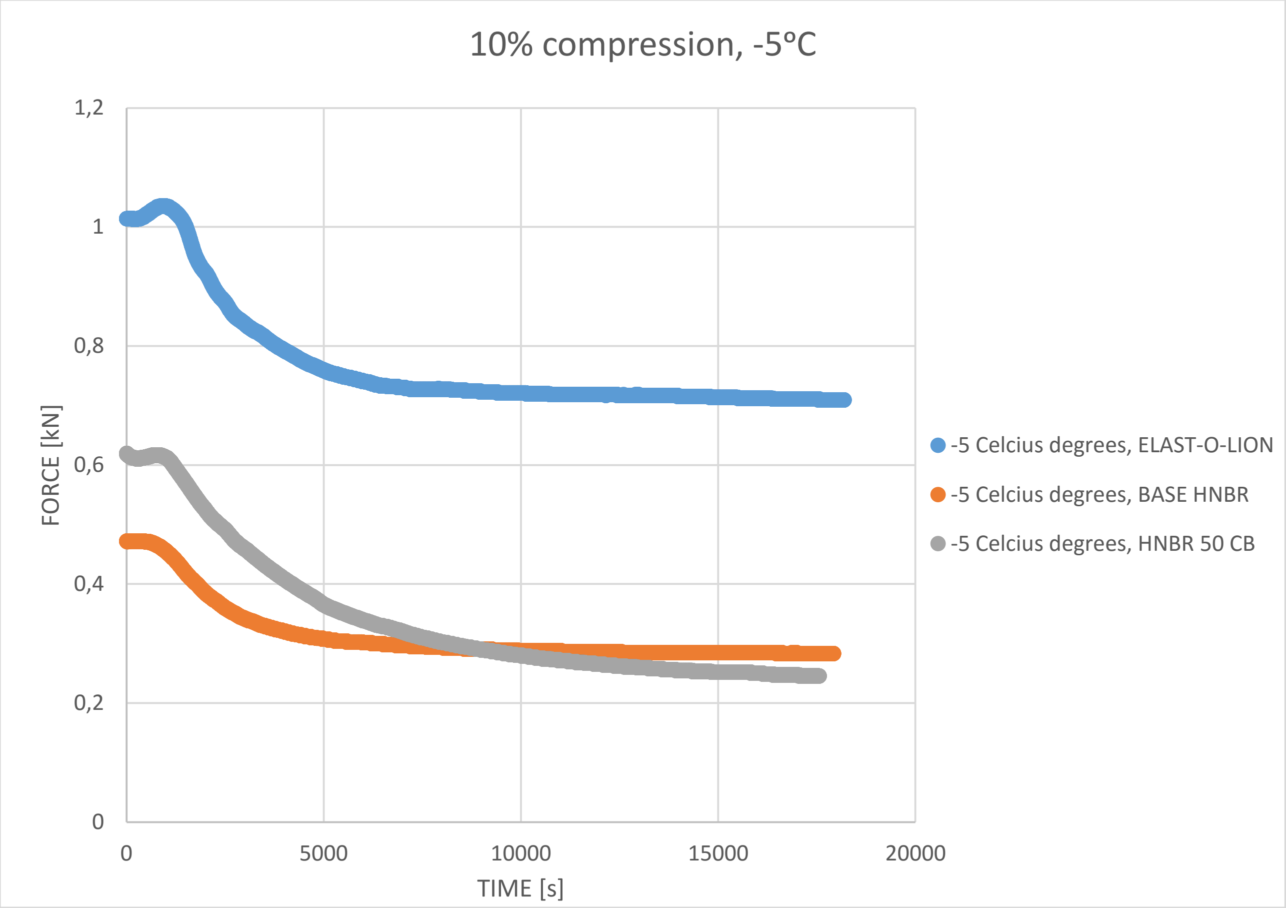


Fig.46 Comparison of force drop in time during specimens tests with 10% compression and -5°C.

2.4.3. Samples tested with 10% compression at -20°C.

Fig. 47 presents comparison of the obtained data while O-rings tests under compression equal to 10% and approximately -5°C.

Drop of the measured forces of the three specimens are as following:

- ΔF = 0,59 for ELAST-O-LION
- ΔF = 0,39 for BASE HNBR
- ΔF = 0,38 for HNBR 50 CB

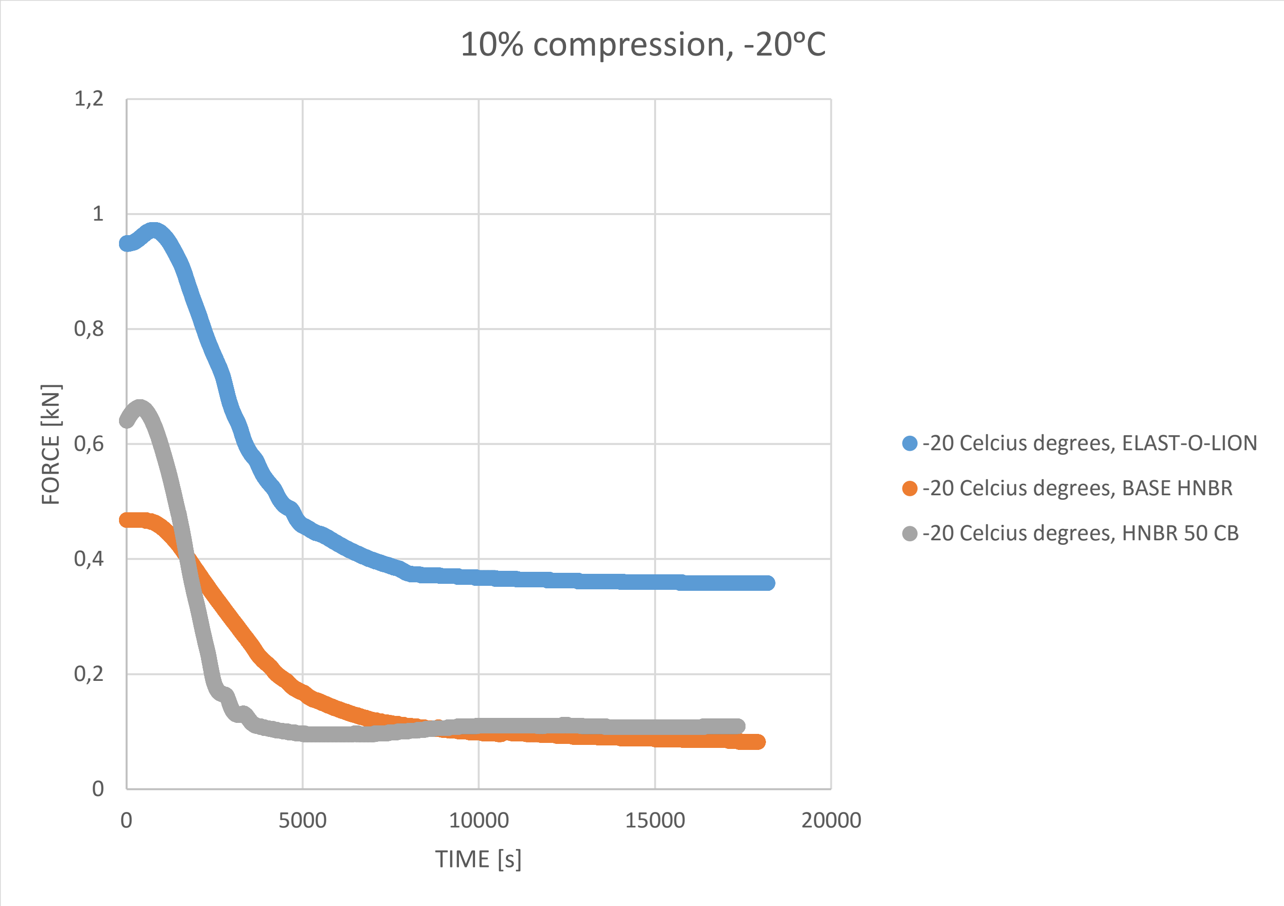


Fig.47 Comparison of force drop in time during specimens tests with 10% compression and -20°C

2.4.4. Samples tested with 20% compression at 10°C.

Fig. 48 presents comparison of the obtained data while O-rings tests under compression equal to 20% and approximately 10°C.

Drop of the measured forces of the three specimens are as following:

- ΔF = 0,24 for ELAST-O-LION
- ΔF = 0,17 for BASE HNBR
- ΔF = 0,49 for HNBR 50 CB

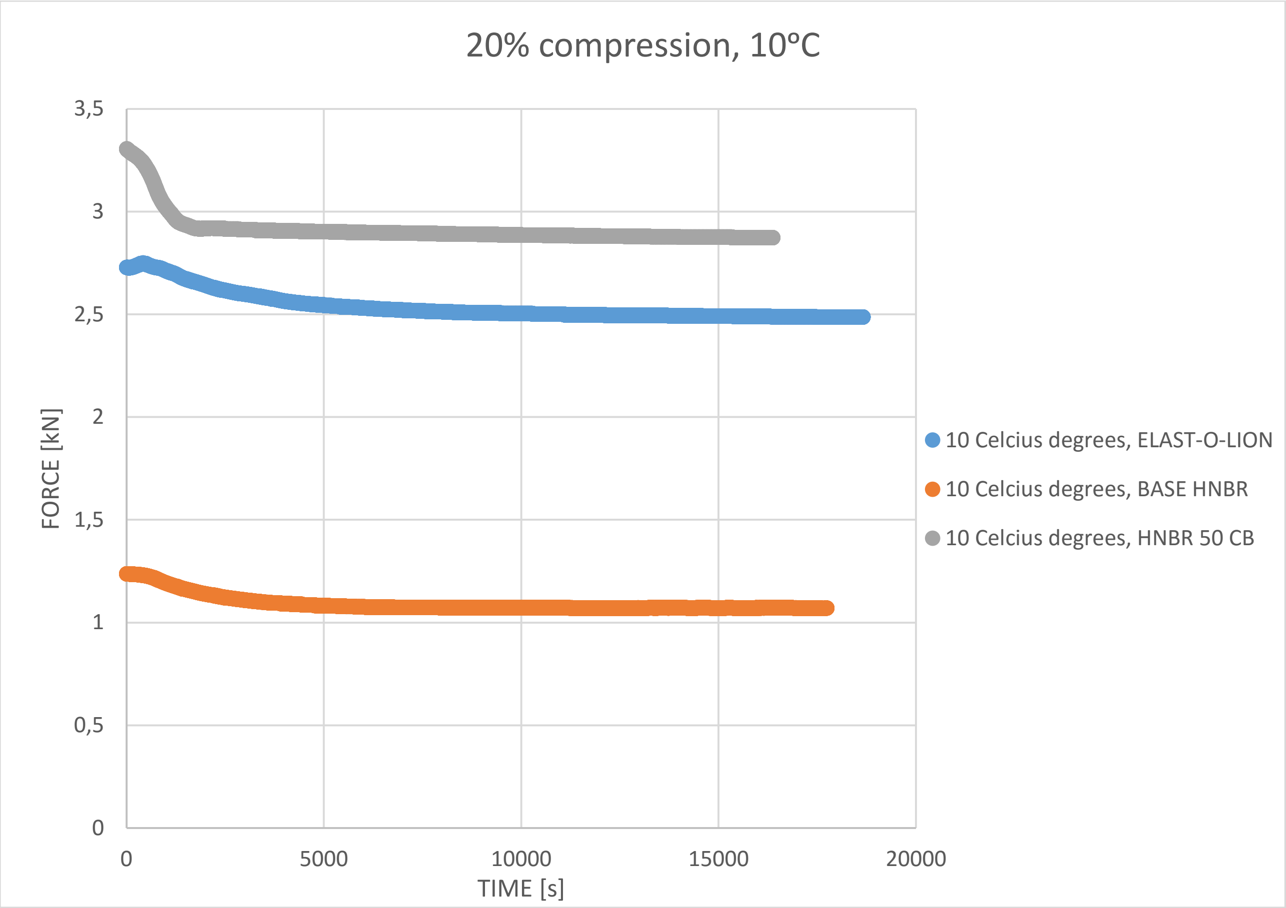


Fig.48 Comparison of force drop in time during specimens tests with 20% compression and 10°C

2.4.5. Samples tested with 20% compression at -5°C.

Fig. 49 presents comparison of the obtained data while O-rings tests under compression equal to 20% and approximately -5°C.

Drop of the measured forces of the three specimens are as following:

- ΔF = 0,39 for ELAST-O-LION
- ΔF = 0,77 for BASE HNBR
- ΔF = 0,52 for HNBR 50 CB

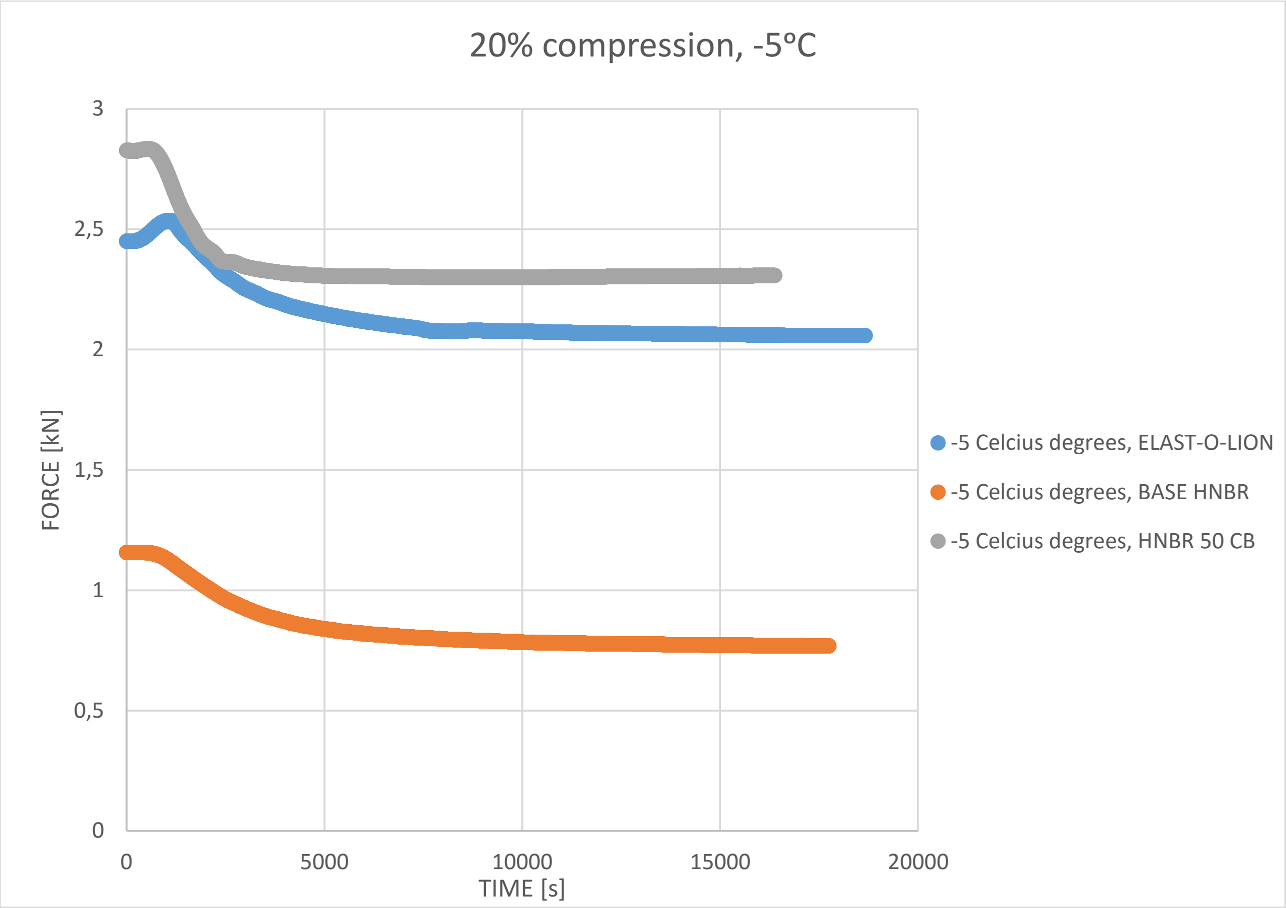


Fig.49 Comparison of force drop in time during specimens tests with 20% compression and -5°C

2.4.6. Samples tested with 20% compression at -20°C.

Fig. 50 presents comparison of the obtained data while O-rings tests under compression equal to 20% and approximately -20°C.

Drop of the measured forces of the three specimens are as following:

- ΔF = 0,66 for ELAST-O-LION
- ΔF = 0,79 for BASE HNBR
- ΔF = 0,85 for HNBR 50 CB

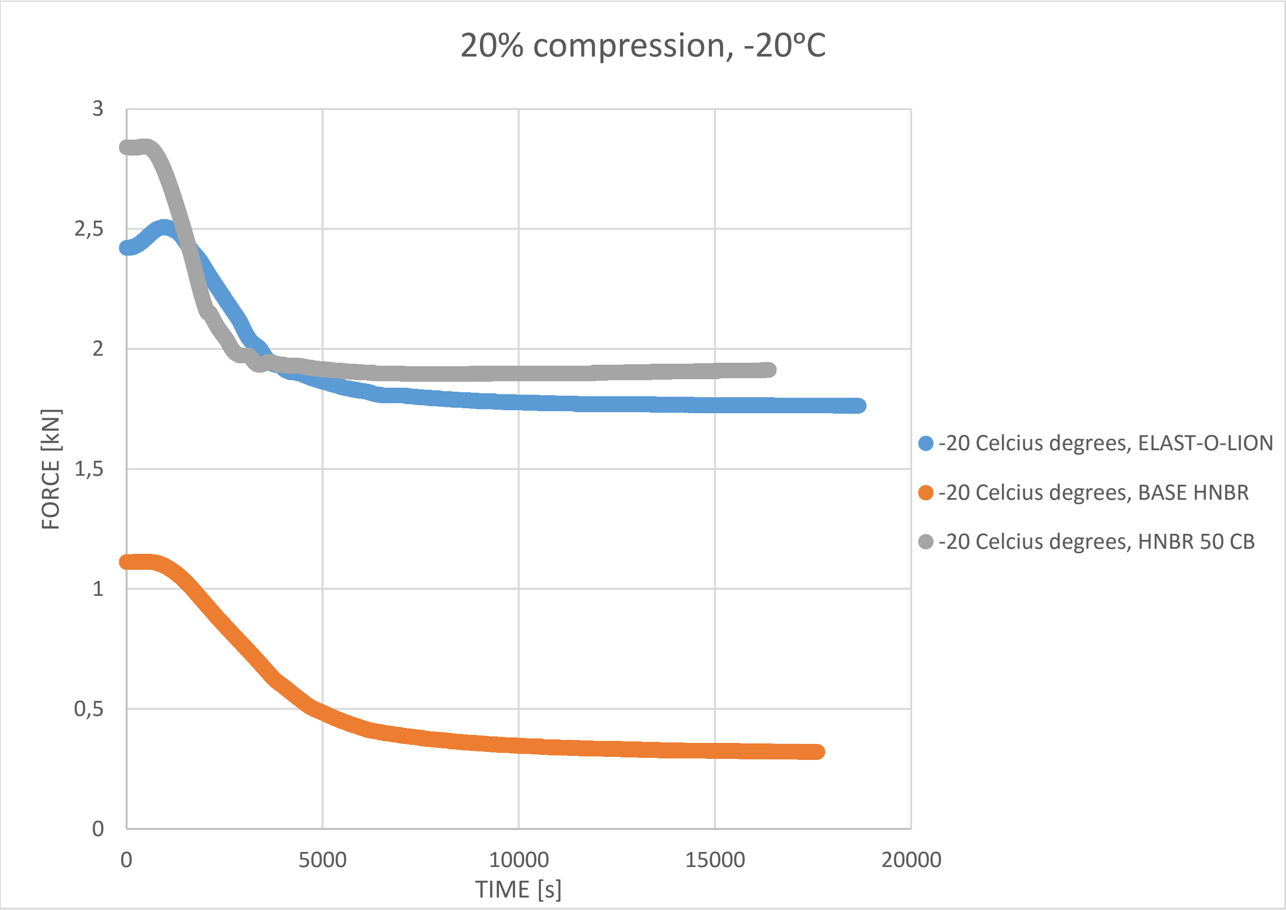


Fig.50 Comparison of force drop in time during specimens tests with 20% compression and -20°C

2.4.7. Samples tested with 20% compression at -30°C.

Fig. 51 presents comparison of the obtained data while O-rings tests under compression equal to 20% and approximately -30°C.

Drop of the measured forces of the three specimens are as following:

- ΔF = 0,84 for ELAST-O-LION
- ΔF = 0,98 for BASE HNBR
- ΔF = 1,33 for HNBR 50 CB

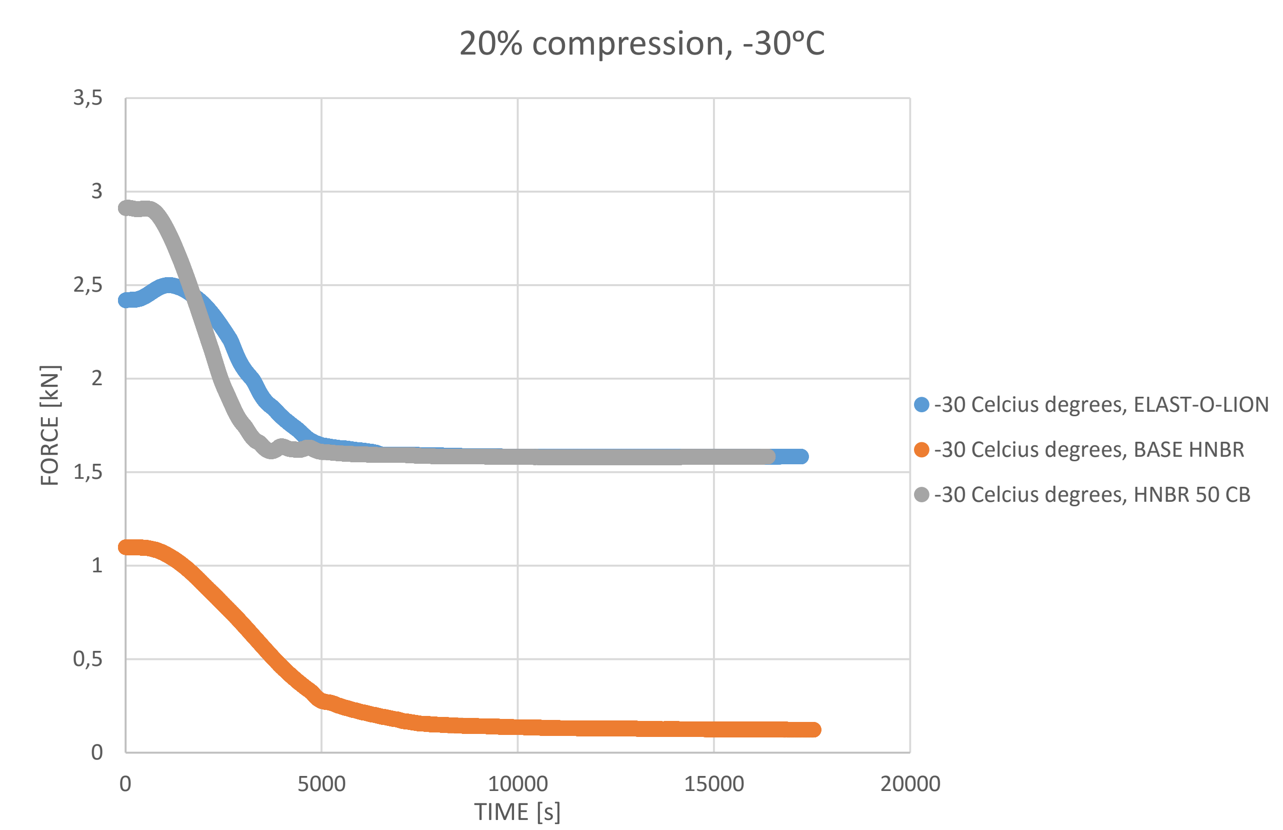


Fig.51 Comparison of force drop in time during specimens tests with 20% compression and -30°C

2.5. Comparison of contact pressure and force drop of all the tested specimens.

The table below presents the data calculated on the basis of the performed tests.

Name	ELAST-O-LION			BASE HNBR			HNBR 50 CB		
Compression	10%	ΔF [kN]	p_0 [Mpa]	10%	ΔF [kN]	p_0 [Mpa]	10%	ΔF [kN]	p_0 [Mpa]
Temperature [°C]	10	0,23	1,56	10	0,10	0,63	10	0,30	0,82
	-5	0,30	1,08	-5	0,10	0,40	-5	0,38	0,33
	-20	0,59	0,39	-20	0,39	0,12	-20	0,38	0,15
Compression	20%	ΔF [kN]	p_0 [Mpa]	20%	ΔF [kN]	p_0 [Mpa]	20%	ΔF [kN]	p_0 [Mpa]
Temperature [°C]	10	0,24	2,70	10	0,17	1,09	10	0,49	2,76
	-5	0,39	2,23	-5	0,77	0,79	-5	0,52	2,22
	-20	0,66	1,91	-20	0,79	0,33	-20	0,85	1,84
	-30	0,84	1,71	-30	0,98	0,12	-30	1,33	1,57

Table 6. Calculated force drop and contact pressure of three specimens tested with different operational conditions

3. CONCLUSIONS AND RECCOMENDATIONS

This research has confirmed that the sealing properties differs with changing operational parameters like compression and decreasing temperature. What is more the obtained data shows the differences of sealing properties between the three tested specimens under the same conditions. The samples properties description on the basis of the performed tests are as following:

- ELAST-O-LION 101- this material have shown loss of sealing properties with the decreasing temperature and increasing compression, but in the harsh environment will still provide a satisfactory sealing.
- BASE HNBR – this material occurred to not be the best sealing material, even with not demanding condition. The low value of a contact pressure of this specimen while being exposed to low temperatures expresses its inability to ensure a high quality sealing in cold climate.
- HNBR 50 CB – this material is a good sealing material, but of course also demonstrates a loss of properties under harsh conditions. Although the tests have shown that the compression has less influence on that material than low temperatures.

Although there might be small inaccuracy at the obtained data due to the fact that the measurements where performed on the apparatus with manually adjusted variables, as for example compression that have been set with the use of compressor with handmade scale and due to some approximations in the formulas used to calculate contact pressure, the obtained data is reliable.

Yet, this work has shown that the best sealing material in general does not exist, there is no universal material. The selection of it should be adjusted to the future working conditions, though it is extremely important to study the harsh environmental factors before performing any industrial actions in such a demanding climate as Arctica.

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