The study of the Permeability of Plastic Pipes to Air after their Irradiation with Neutrons and the Selection of Pipes for use in the TPC Water Cooling System.

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Abstract

- The thermal stabilization and cooling systems for the Time Projection Chamber “TPC” and Electromagnetic calorimeter “ECAL” detectors for the Multi-Purpose Detector “MPD” experiment (NICA project). The present experiment is focused on the verification of plastic hoses subjected to neutron irradiation as the candidate for supplying the distilled or deionized water to the cooling system of MPD. Presuming that the hoses will be located within the area of TPC Front End “FE” electronics, they should be resistant to neutron fluence of about 10^{11} n/cm^2 (with the energy of 1 MeV). So, candidate plastic hoses were irradiated with neutrons (with an energy up to 1 MeV) with the following fluences: F1 = 10^9 n/cm^2, F2 = 10^{10} n/cm^2, F3 = 10^{11} n/cm^2, and F4 = 10^{12} n/cm^2.

- Raman spectroscopy, and air permeability measurements were performed to check plastic hoses status before and after irradiation. COMSOL Multi-physics modelling software is also being used to study the selected candidate pipes. Based on the research conducted, the Reinforced Polyvinyl chloride “PVC” hose was selected to be the best candidate for installing the thermal stabilization and cooling system.

Objective

- The Time Projection Chamber (TPC) and the Electromagnetic Calorimeter (ECAL) are sub detectors of MPD experiment at NICA mega-science project (Nuclotron -based Ion Collider facility).
- Basic principles of operation of the thermal stabilization and cooling systems being created for the TPC and ECAL detectors. Both detectors use plastic hose pipes to supply the refrigerant with (distilled water or deionized water). The task is to choose a suitable material for pipes, which will ensure the operation of cooling systems about 10 years, and determine the permissible terms of their operation.

Cooling system of TPC Design

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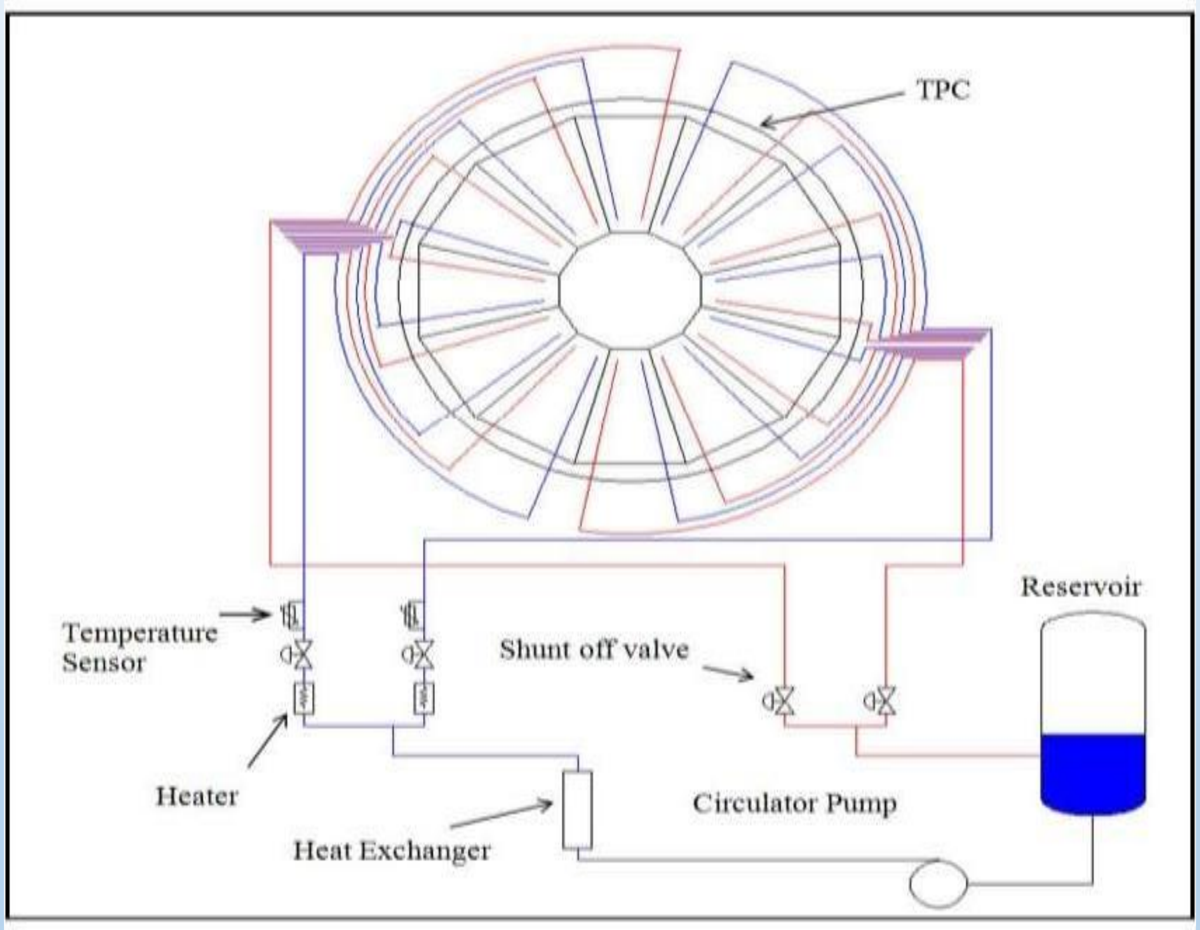


Scheme of the Cooling system of TPC Design.

The Irradiation Environment for the Cooling System

The TPC Cooling system consists of 24 sub-circuits so that each read out chamber "ROC" is cooled by a dedicated sub-circuit. The coolant pumps up from the reservoir to thermal stabilization systems for cooling of Field Programmable Gate Array "FPGA", ECAL, Low Voltage Distribution Board "LVDB", added to cooling with the thermal -stabilization of SAMPA Amplifier, ROC Cases, outer thermal screen, internal thermal screen, and flanges, then after cooling, return through the heat exchanger to the main reservoir in a closed loop .

The neutron fluence for 10 years of operation of the MPD experiment showing

Neutrons fluence (for 1 MeV neutrons) - **$5x10^{10}$ neutron/cm^2** (Neutron Flux: 250 n/cm^2 per sec);
Neutrons fluence (for the entire neutron spectrum) - **$8x10^{10}$ neutron/cm^2** (Neutron Flux: 400 n/ cm^2 per Sec).

Methodological

Due to the existence of the cooling pipes in the radioactive environment.

we start our procedure to choose the optimum cooling pipes from a variety of candidate hose pipes by applying a variety of analysis: chemical (Raman spectroscopy), diffusion tests for all the candidate pipes before and after irradiation.

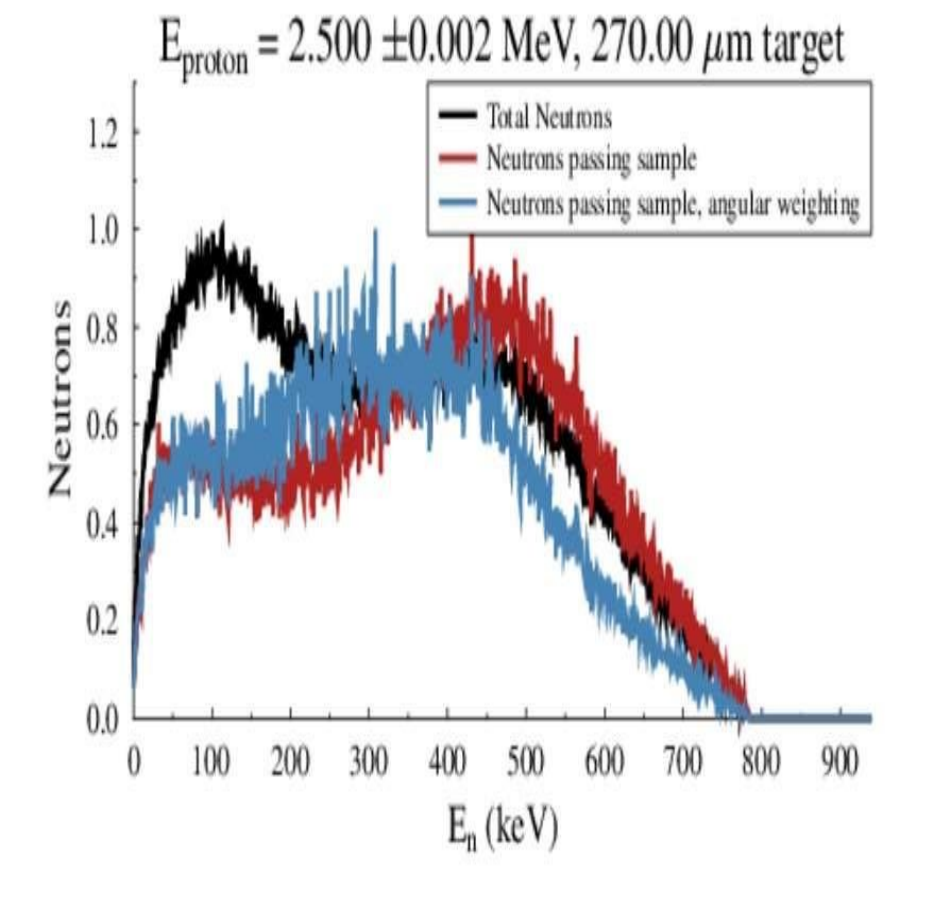
Table : Samples of candidate pipes into our study and their Young's modulus.

№	Title	Photo	E, kPa
1	Reinforced Polyvinyl chloride (PVC)		640
2	Reinforced Silicone		-
3	Polytetrafluoroethylene (PTFE) “Teflon”		78
Optional			
4	Polyurethane		260
5	Polydimethylsiloxane (PDMS) “Silicone”		130

The first procedure of practical analysis is initiated by neutron Irradiation for the candidate Cooling Pipes.

- The implementation of irradiation by neutrons occurred with the neutrons generated in the EG-5 electrostatic accelerator in the Neutron Physics Laboratory of the Joint Institute for Nuclear Research.
- Neutrons are generated on a lithium target 270 μ m thickness and 1 cm^2 in area. The threshold energy of the neutron spectrum from the ^7Li (p, n) and ^9Be (p, n) reactions is 1912 keV.
- The target was irradiated by a proton beam with an energy of 2.5 MeV on a van de Graaf electrostatic generator EG-5. The proton beam current was 10 μ A. The energy of the generated neutrons was in the range of 20–800 keV .
- The calculated neutron flux density was 0.87×10^8 n/ cm^2.sec.
- Cooling hose pipes are irradiated with neutrons (with an energy up to 1 MeV) with the following integral fluences values: F=10^9, 10^{10}, 10^{11}, and 10^{12} neutrons/cm^2.

Energy Spectrum for Neutrons Used for hose pipes Irradiation



Raman spectroscopy as a Chemical Analysis

- Raman spectroscopy provides a robust analytical instrument **that is capable of capturing vibrational frequencies with high resolution and specificity.**

- It provides detailed spectral information corresponding to the vibrational modes of the samples under examination.

- Furthermore, the fingerprint regions of Raman spectra provide insights into the changes that occur, which in turn **aid in the identification of critical structural motifs associated with the progression of degradation.**

- a Raman spectrometer **(Confo-tec MR 150, SOL Instruments) was employed for the analysis of the vibrational modes of the samples**, as well as for the recording of Raman frequencies both prior to and following irradiation.

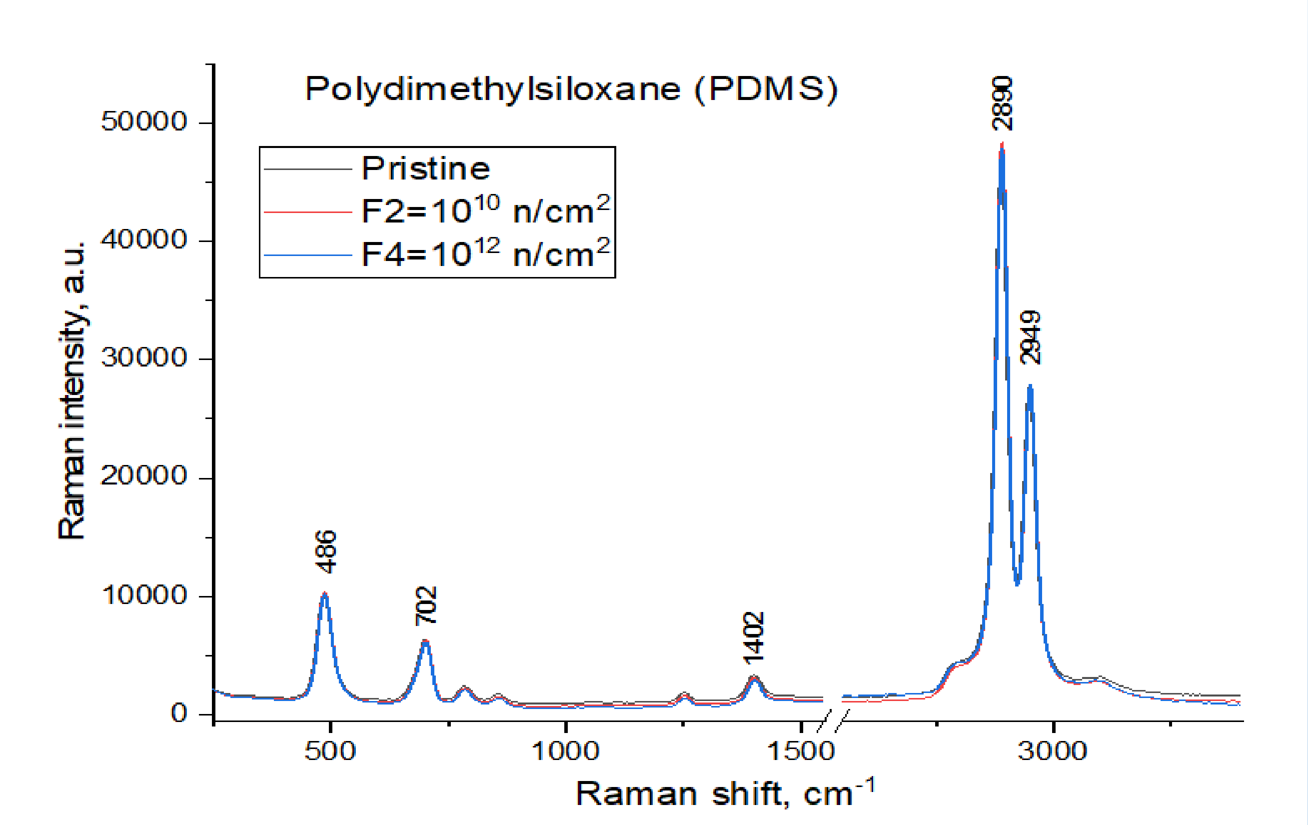
- **The laser light with a wavelength of 473 nm was focused on the sample with a 40x objective (NA-0.75), on a spot size of ~1 μ m.** The laser power at the sample was regulated by a variable neutral filter with an optical density range of 0–3.

Raman Spectroscopy Results for PDMS Samples

The Raman spectra of PDMS are shown A symmetric Si-O-Si peak was observed at approximately 486 cm^{-1}. The symmetric **Si-C stretching band was observed at 702 cm^{-1}.**

The peaks of the symmetric bending, symmetric and asymmetric rocking, and stretching of C-H of the –Si $(CH_3)_2$ – group were observed at 785 cm^{-1}, 858 cm^{-1}, 1253 cm^{-1}, and 1402 cm^{-1} respectively. The bands at 2890 cm^{-1} and 2949 cm^{-1} related to symmetric and asymmetric of the C-H bonds.

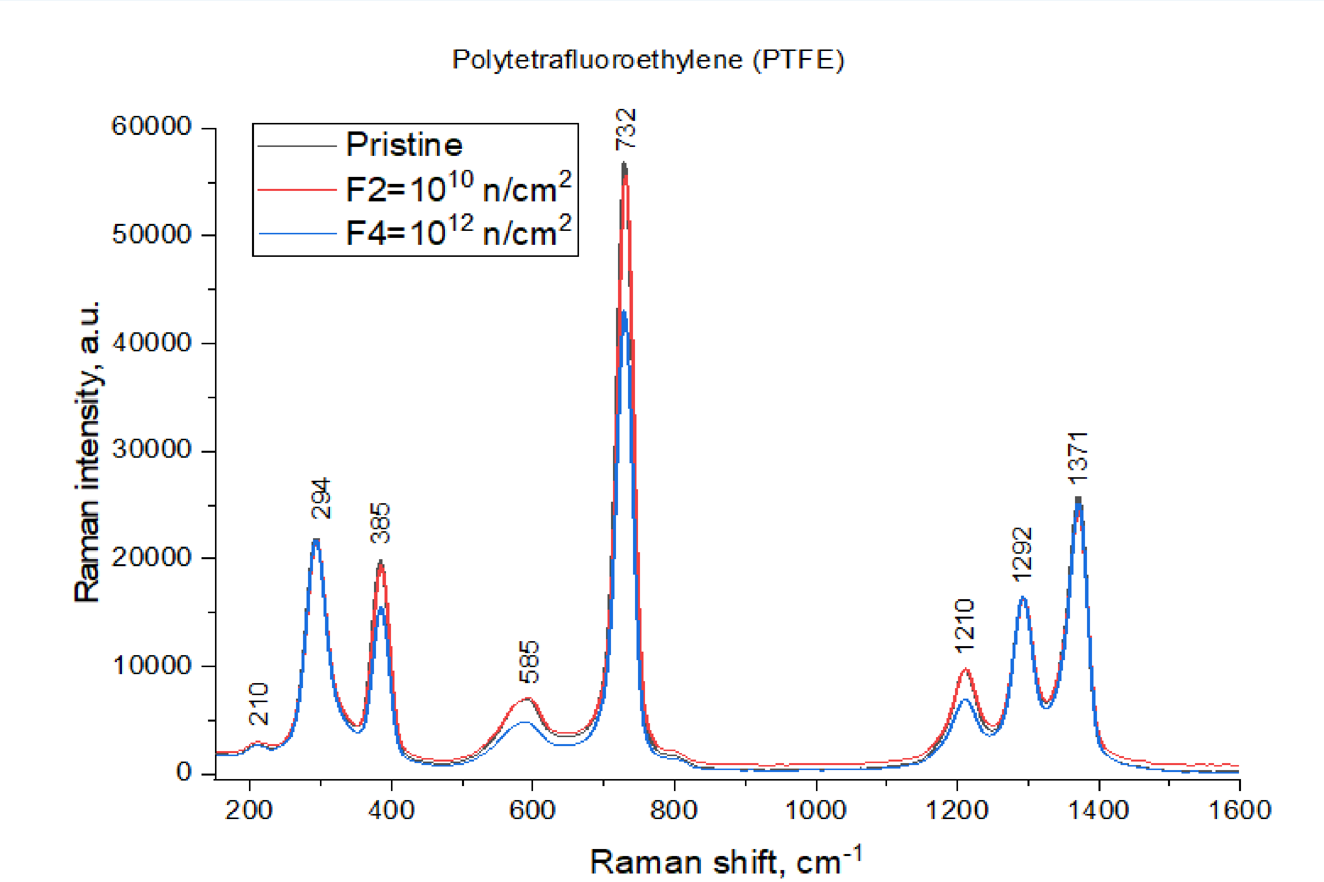
A comparative analysis of the pristine sample and those irradiated at fluencies of $F2=10^{10}$ n/cm^2 and $F4=10^{12}$ n/cm^2 revealed **no discernible structural alterations.**



The Raman spectra of the pristine and irradiated PDMS.

Raman Spectroscopy Results for PTFE Samples

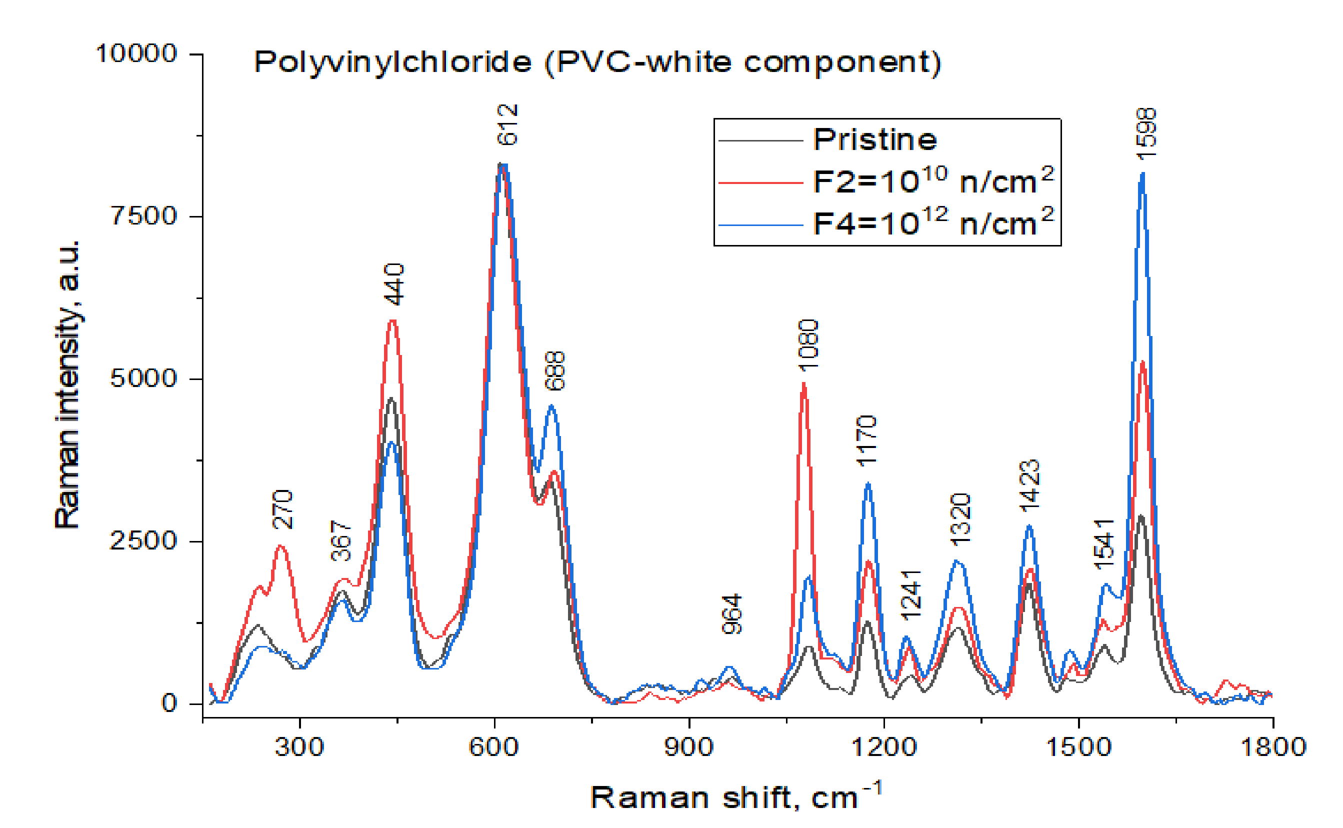
- Raman spectra of the pristine and irradiated Polytetrafluoroethylene (PTFE),one of the strongest bands of this co-polymer at 732 cm^{-1} is clearly observed and correspond to the **skeletal (C-CF_3) symmetric stretching mode.**
- The other vibrational bands belonging to copolymer were visible at 210 cm^{-1} and 294 cm^{-1} related to CF_2 twist mode, the CF_2 deformation and rocking modes was observed at 385 cm^{-1} and 585 cm^{-1} respectively. The peak at 1210 cm^{-1} related to asymmetric CF_2 stretching mode, 1292 cm^{-1} and 1371 cm^{-1} peak related to symmetric and asymmetric **C-C stretching modes**.
- The intensity of the peaks at 385 cm^{-1}, 585 cm^{-1}, 732 cm^{-1} and 1210 cm^{-1} is observed to decrease in the presence of defects, **which in this case indicates the occurrence of a thermal defect during the irradiation process.**



The Raman spectra of the pristine and irradiated PTFE.

Raman Spectroscopy Results for PVC- White component

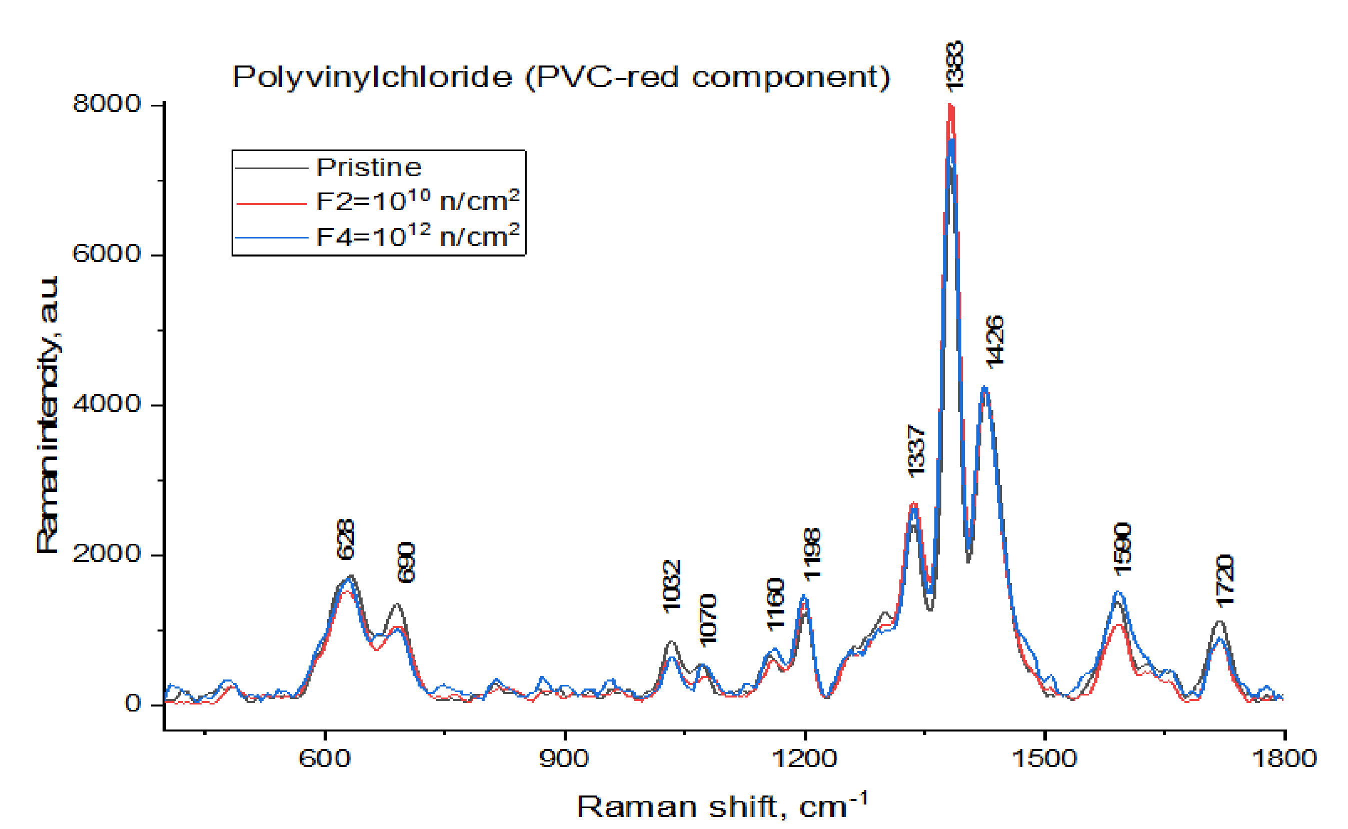
- The Raman spectra of the PVC copolymer, comprising two distinct components (designated white and red), respectively. The white component is more solid and predominantly comprises PVC, as evidenced by the presence of peaks at 612 and 688 cm^{-1}, which correspond to the skeletal and C-Cl stretching vibrations, respectively. Additionally, peaks at 1080, 1170, 1320, 1438 and 1598 cm^{-1} are attributable to the PVC copolymer .
- **The red component also comprises PVC with a minor addition of rubber, which endows the material with enhanced flexibility**. This is evidenced by the emergence of supplementary peaks at frequencies 1032, 1198 and1383cm^{-1}. **The degradation of PVC by the elimination of HCl and the formation of all-trans polyenes is a well-established phenomenon, with a substantial body of documented evidence .**



The Raman spectra of the pristine and irradiated PVC – white component.

Raman Spectroscopy Results for PVC- Red Component

- In this instance, the bands observed at 1383 cm^{-1} and 1598 cm^{-1} are indicative of degradation in the red and white components of the PVC, respectively.
- **The observed change in peak** intensity indicates that the red PVC component does not undergo structural alteration upon exposure to fluence $F4=10^{12}$ n/cm^2.
- **Conversely**, the white PVC component exhibits the formation of chemical bonds C=C polyenes, which are indicative of copolymer degradation.



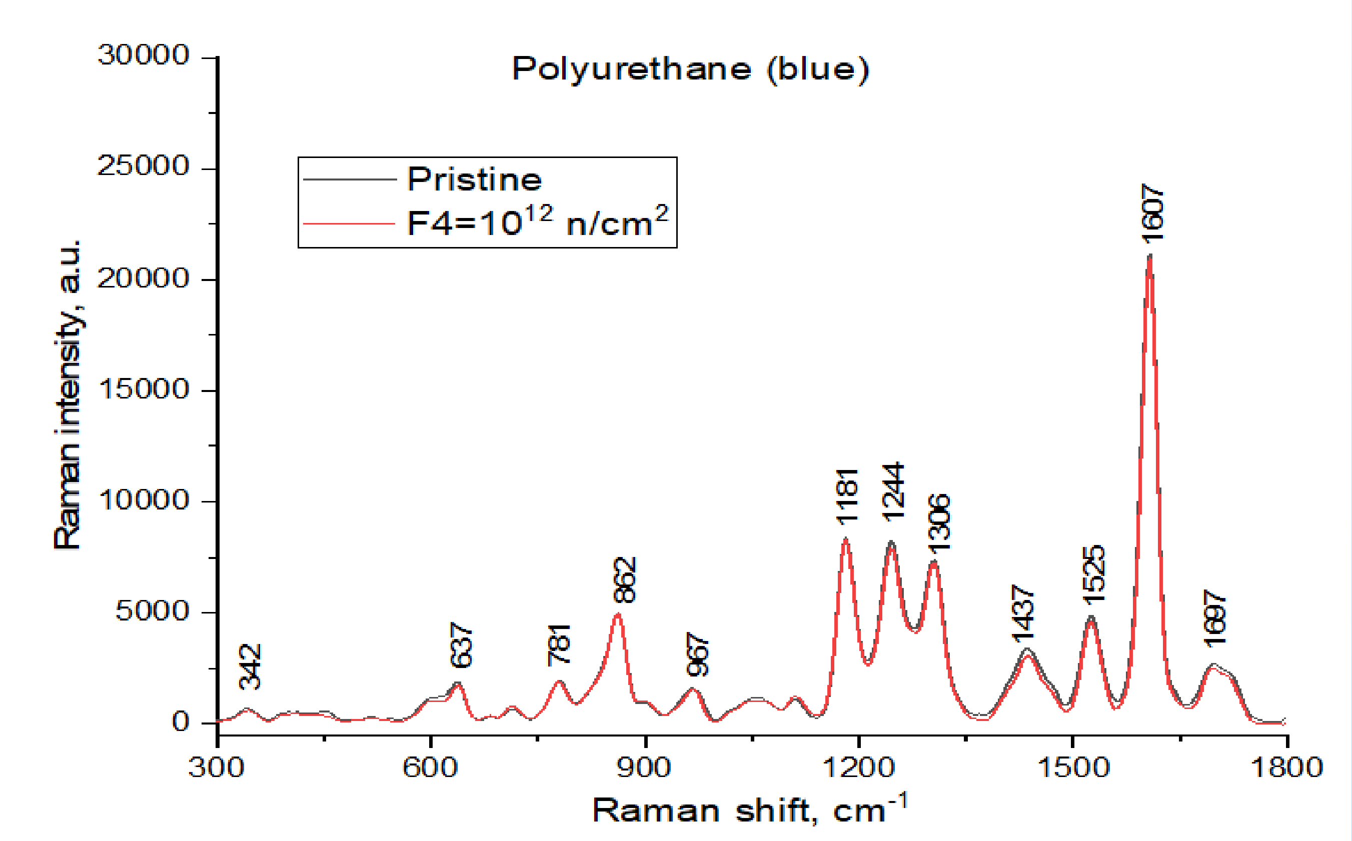
The Raman spectra of the pristine and irradiated PVC – Red component.

Raman Spectroscopy Results for Polyurethane

- The Raman spectra of pristine and irradiated at fluence $F4=10^{12}$ n/cm^2 polyurethane shown in Figure 7. The characteristic peaks of polymerized urethanes are typically observed at 1720, 1607 and 1525 cm^{-1}, which are indicative of stretching (C=) and NH_3.

- The spectrum demonstrates that prior to and following irradiation, there is no discernible alteration in either the intensity or the shift frequencies.

- **This** observation suggests that at the specified dose of irradiation, polyurethane exhibits greater stability than PVC.

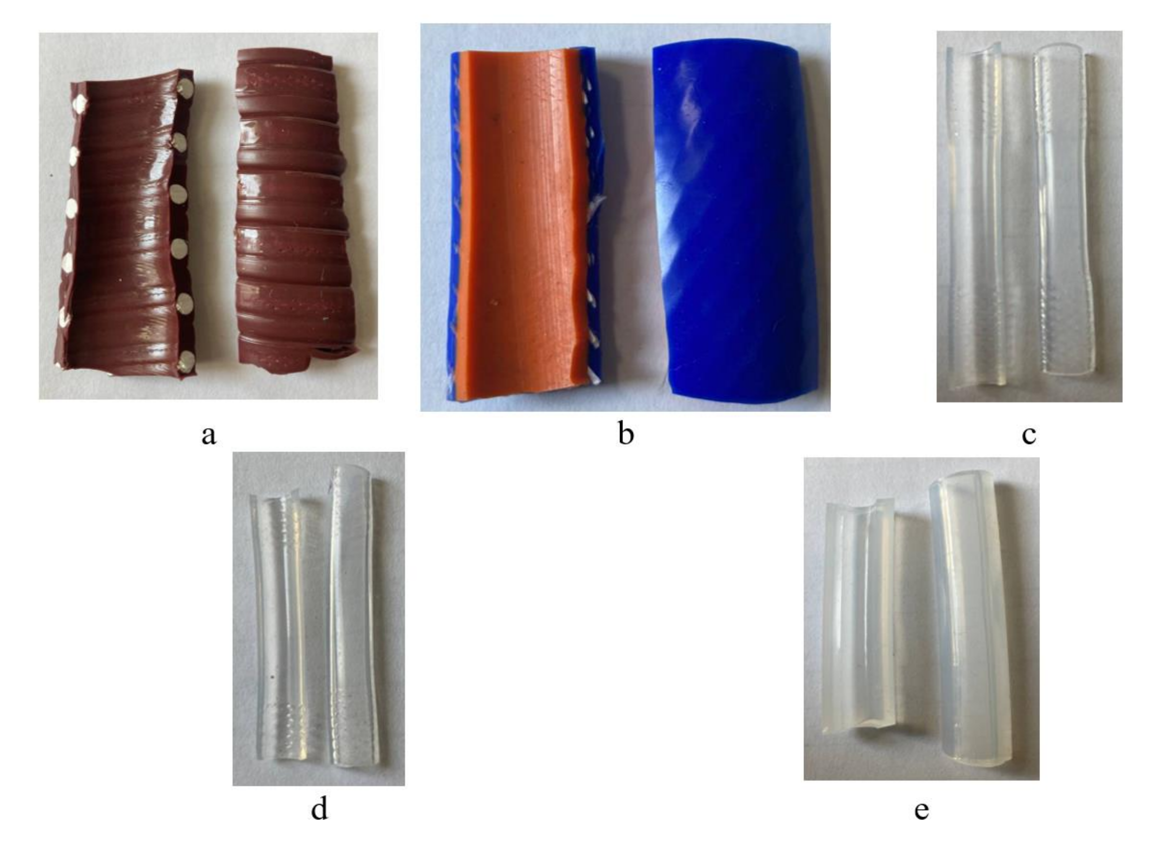


The Raman spectra of the pristine and irradiated Polyurethane.

Mechanical Test

The Test-metric M350 10 CT was used to measure the impact of neutron irradiation on the mechanical characteristics of hose pipe samples (Young's modulus, limit of proportionality).

The apparatus can accurately measure the sample's elongation to within 0.5%. A strain gauge was used to record the mechanical stress that developed during tensile elongation of the specimen under investigation, which was clamped in mechanical clamps .



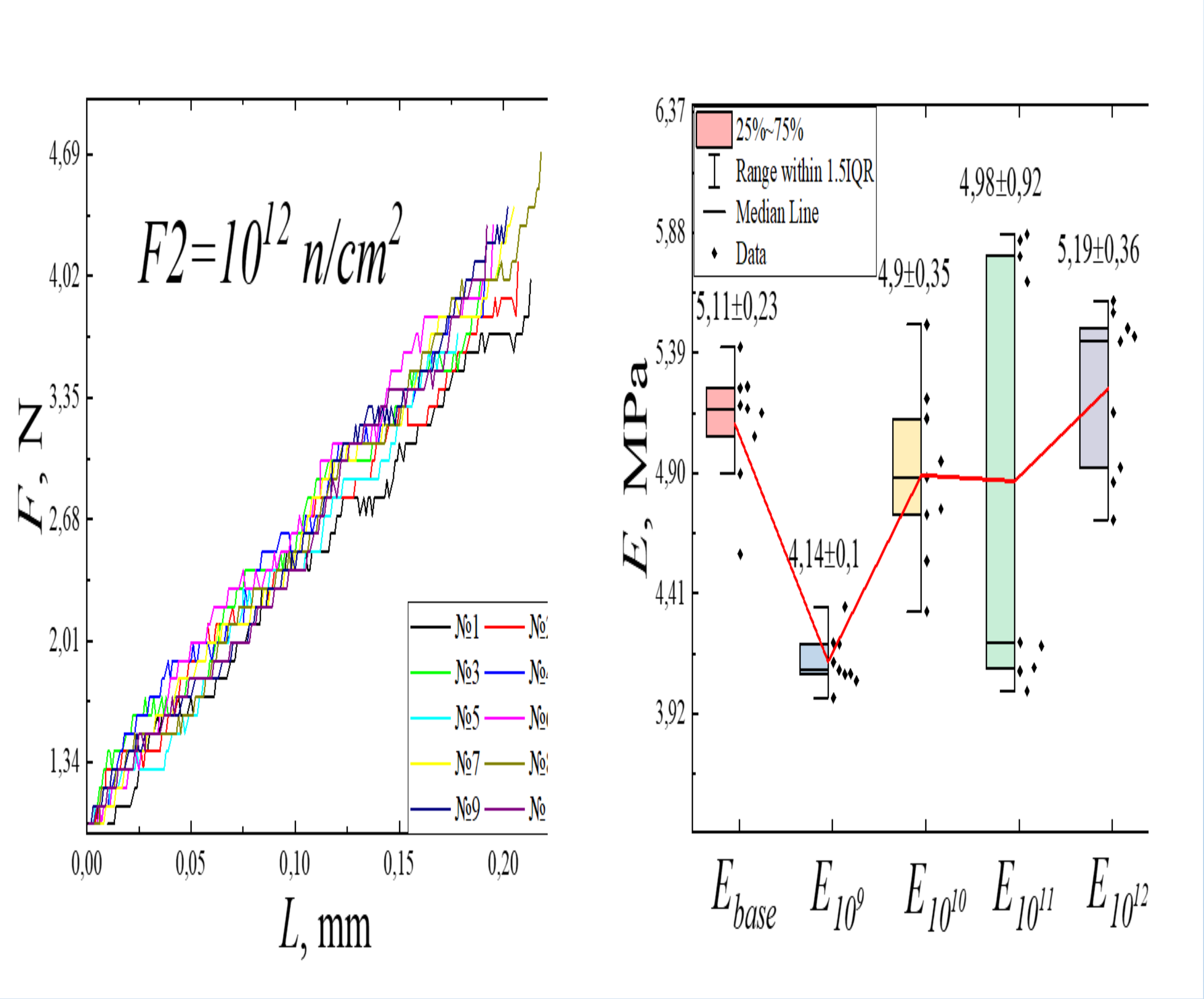
Cross-section photos of the studied hose pipes

Mechanical Test *Sample #1 Reinforced Polyvinyl chloride*

A) Dependences of the elongation on the mechanical load of the initial and irradiated PVC samples with various fluences including fluence 10^{12} n/cm^2,

B) Chart Box for all initial and irradiated PVC samples.

According to the results of the cyclic application of the load in the region of elastic deformation, "reinforced PVC" does not show a statistically significant deterioration in mechanical characteristics under the influence of neutrons irradiation with various fluences.

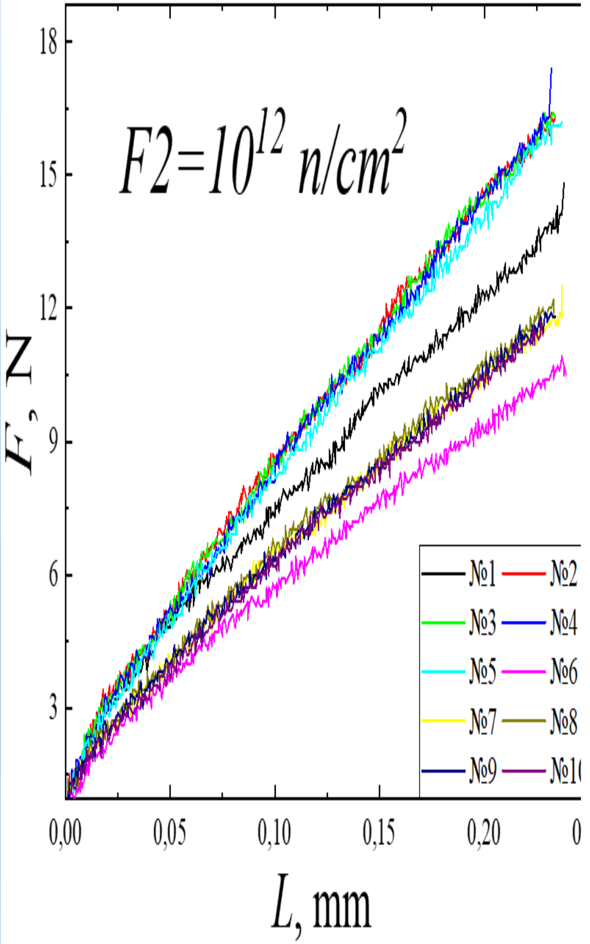


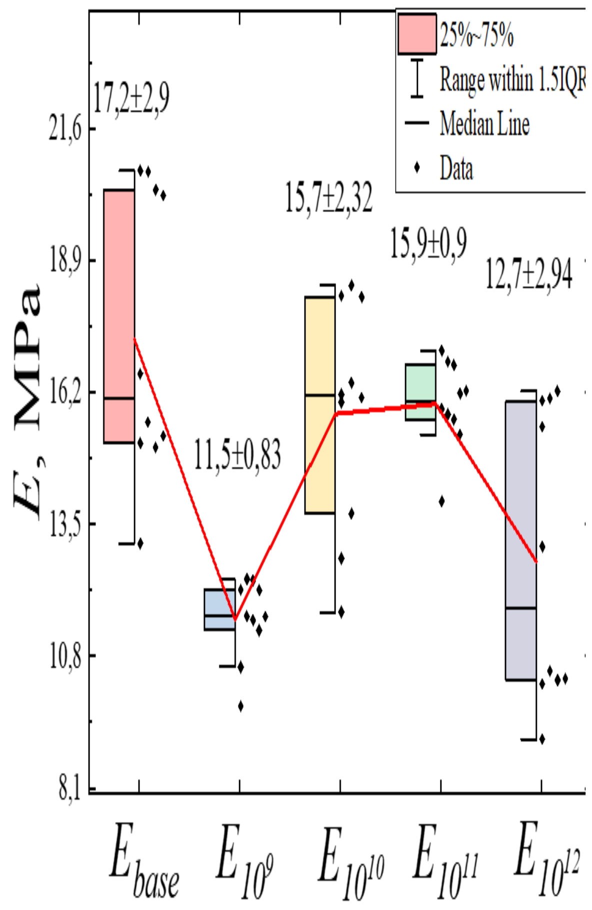
Mechanical Test Sample #2 Reinforced Silicone

A) Dependences of the elongation on the mechanical load of the initial and irradiated reinforced silicone samples with various fluences including fluence 10^{12} n/cm^2,

B) Chart Box for all initial and irradiated reinforced silicone samples.

According to the results of the cyclic application of the load in the field of elastic deformations, "reinforced silicone" does not show a deterioration in mechanical characteristics under the influence of neutrons with various doses.



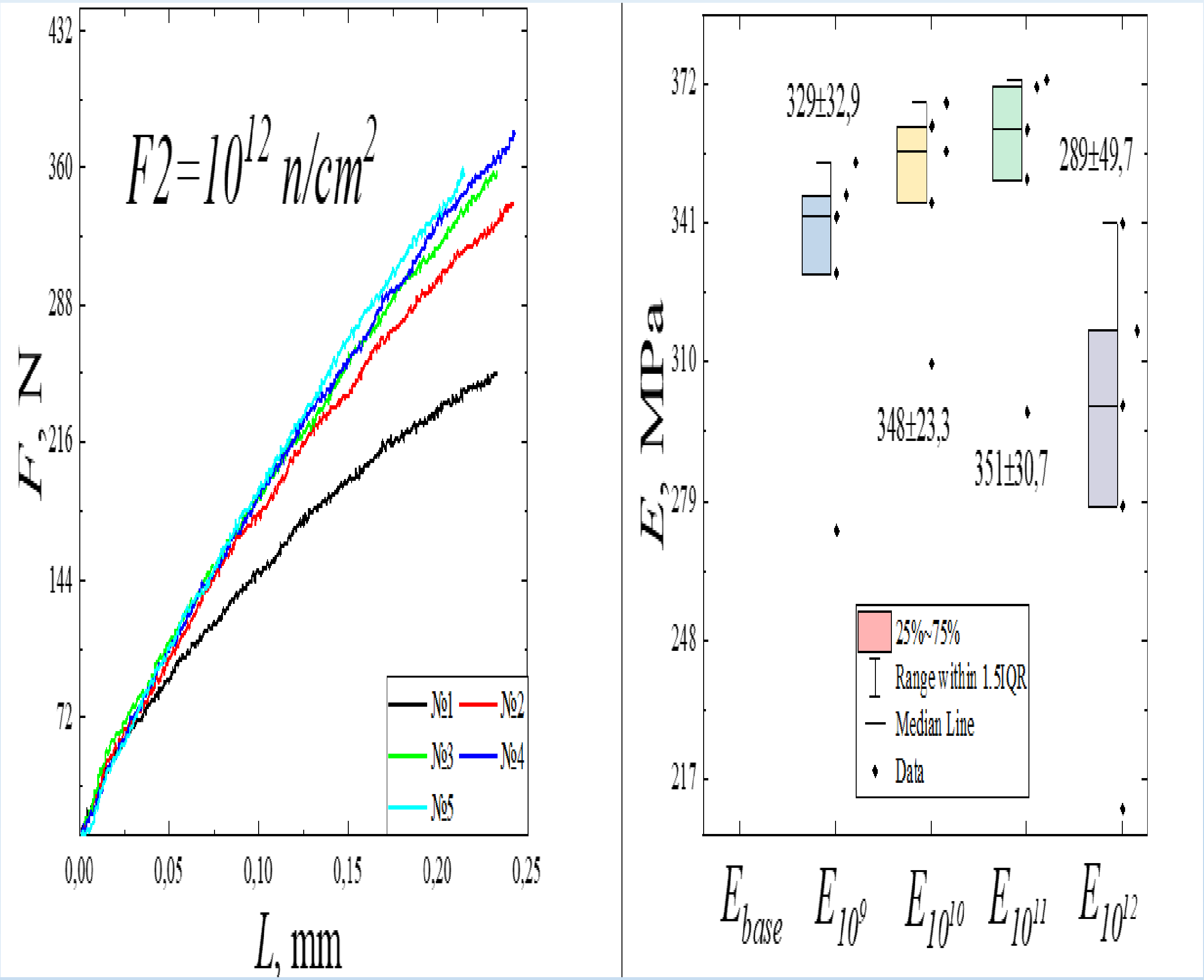


Mechanical Test Sample #3
Polytetrafluoroethylene (PTFE) “Teflon”

A) Dependences of the elongation on the mechanical load of the initial and irradiated (PTFE) samples with various fluences including fluence 10^{12} n/cm^2,

B) Chart Box for all initial and irradiated (PTFE) samples.

According to the results of the cyclic application of the load in the region of elastic deformations, (PTFE) sample No. 3 "Corresponds to Figure 8 d" does not show a deterioration in mechanical characteristics under the influence of neutron irradiation in the studied dose range.

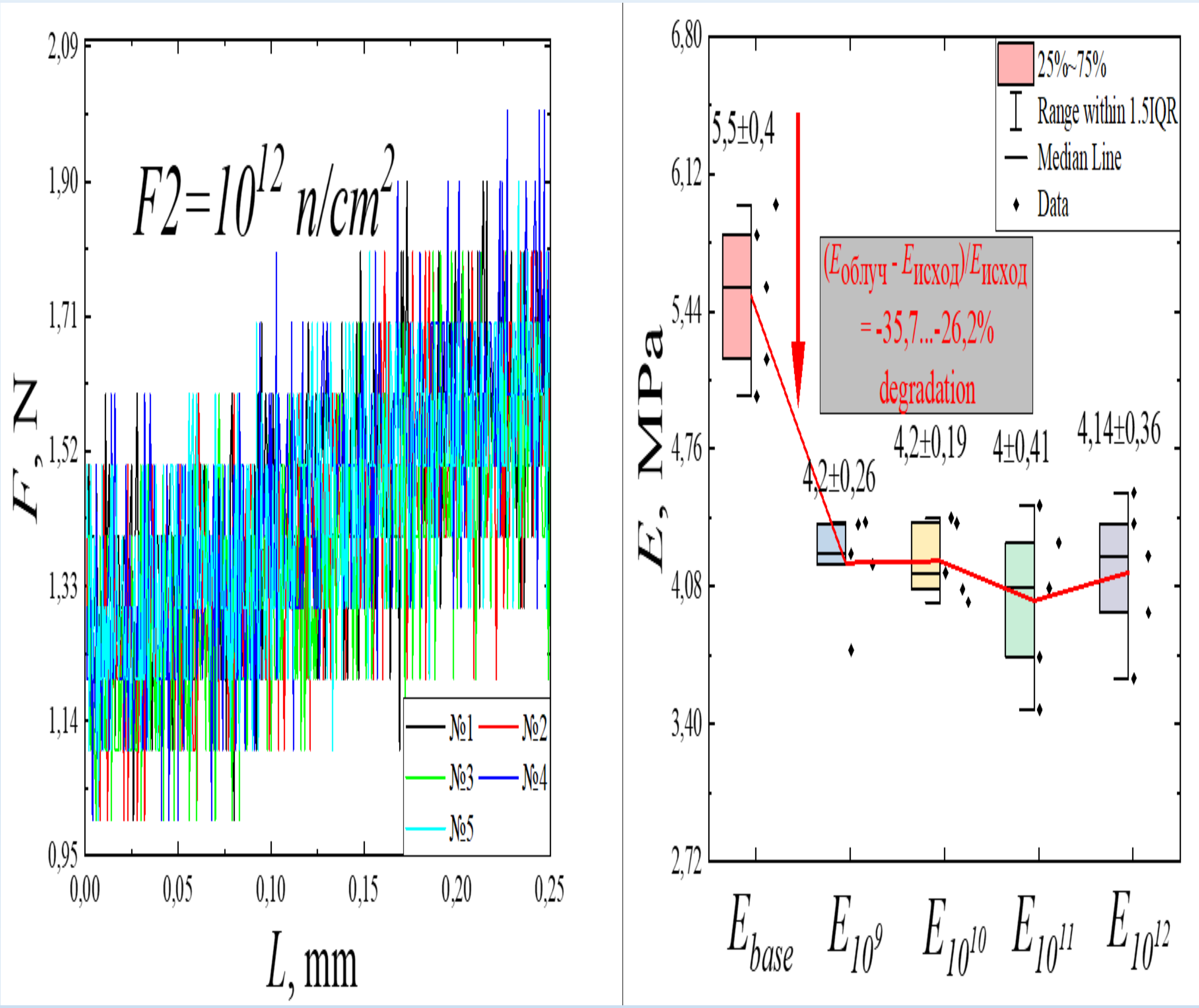


Mechanical Test Sample #4 Polydimethylsiloxane (PDMS) “Silicone”

A) Dependences of the elongation on the mechanical load of the initial and irradiated (PDMS) samples with various fluences including fluence 10^{12} n/cm^2,

B) Chart Box for all initial and irradiated (PDMS) samples.

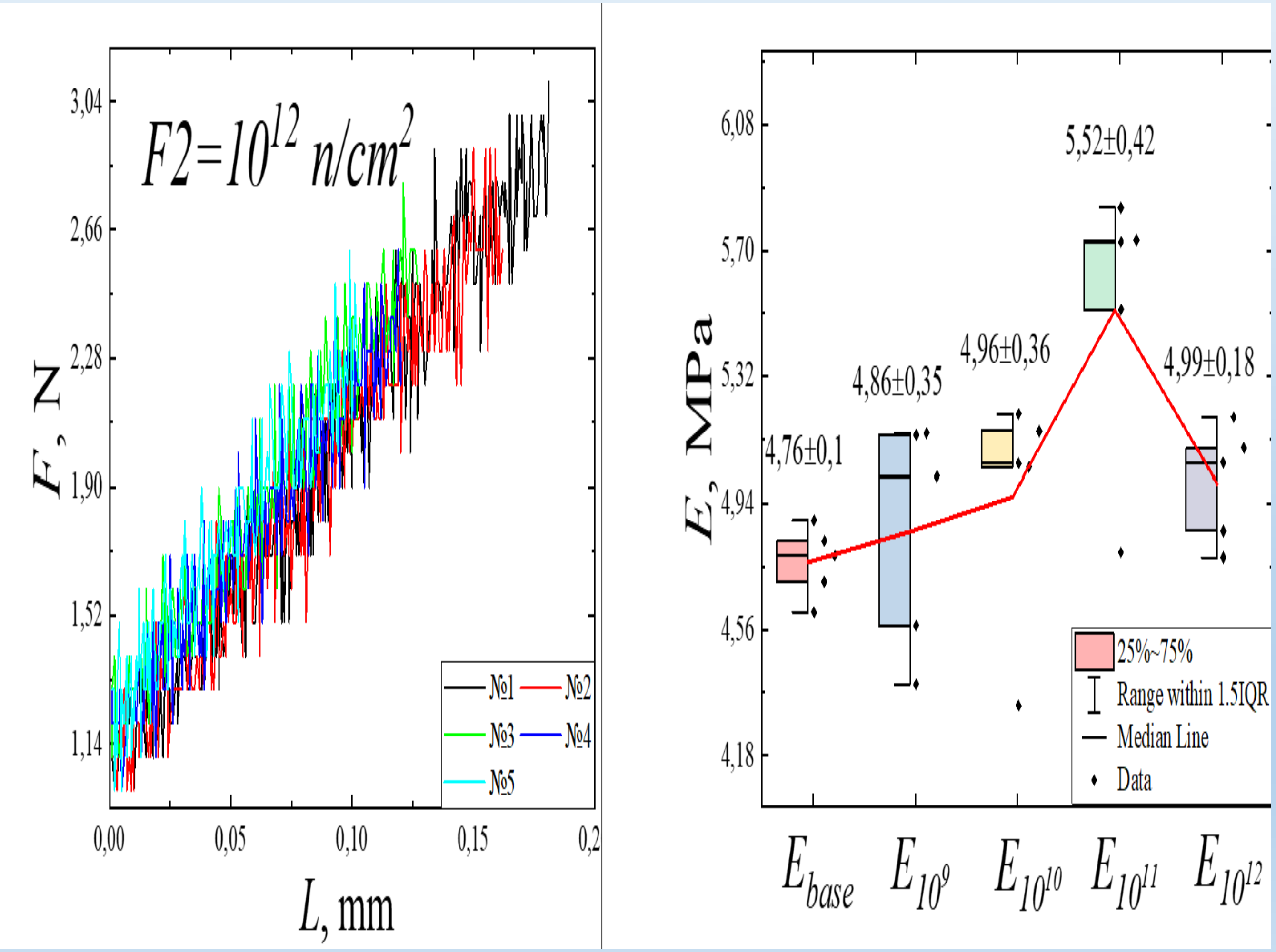
According to the results of the cyclic application of elastic deformations, (PDMS) sample No. 4 "Corresponds to Figure 8 d" shows deterioration of mechanical characteristics under the influence of neutrons irradiation from 26 to 37%.



Mechanical Test Sample #5, Transparent soft silicone hose pipe

A) Dependences of the elongation on the mechanical load of the initial and irradiated samples fluences including fluence 10^{12} n/cm^2,

B) Chart Box for all initial and irradiated samples.



According to the results of the cyclic application of the load in the region of elastic deformations-the sample No.5 "Corresponds to Figure 8 e, shows deterioration of mechanical characteristics under the influence of fast neutrons with various doses from +2.4 to +15.9%.

Leakage Test Analysis and Diffusion Analysis Through Polymer Membranes

- Leakage tests are the tests that are subjected to after the production of products that do not want to be leakage. Air leakage tests include air leakage tests of manufactured products. These tests are based on monitoring the pressure change as a result of air inflation of the products to be tested.

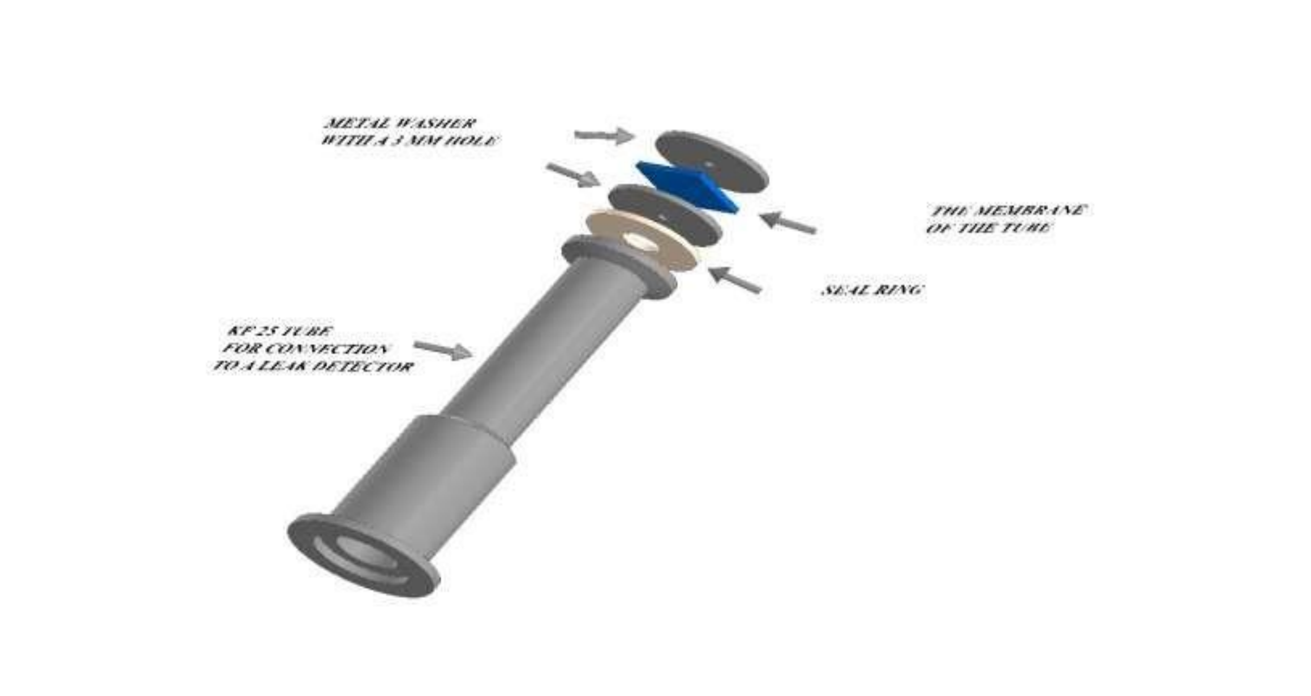
Measurement for air leakage (diffusivity) from the atmosphere into the inside of the hose pipe with the air pumped out inside; the pressure inside the air was measured by a pressure sensor .

- In the leakage analysis for the hose pipe analysis, the study based on two various leakage test devices to initiate more accurate results (Ley-bold Phoenix Quadro Dry and Pfeiffer Vacuum Device), which show the approximate same results analysis.

Diffusion Analysis Through Polymer Membranes

This test set-up is designed to fit several constraints, namely 1) to use a wide exchange surface area between gas and polymer membrane to maximize gas flowrates, 2) to measure very low gas flowrates.

Geometrical Stabilization for The Installation of Diffusion Analysis for The Polymer Membrane Using COMPUS solid mechanics software.



Diffusion Analysis Through Polymer Membranes Followed

Diffusion membrane analysis test for the silicone observed that there is a high leakage rate for both samples irradiated and non-irradiated when operated in fore vacuum pressure, which means that silicon can't be operated as a cooling hose pipe.

The diffusion membrane analysis for Polyurethane observed that there is approximately no leakage rate for both samples irradiated and non- irradiated, which operated in fore vacuum pressure, which means that Polyurethane is the best candidate for a cooling hose pipe used in thermal electronics with a fore vacuum pressure cooling system .

The irradiation influence on the PVC hosing pipe by checking the diffusion membrane test is quite the same influence for the two samples before and after irradiation.

Air Leakage Test

The Tracer Gas Method

The tracer gas method is a method based on measuring the change over time of a special gas that is filled homogeneously into the volume to be determined by the air leakage value.

Some tracer gas leakage test methods include helium mass spectrometry, hydrogen leakage testing and refrigerant gas leakage for cooling applications.

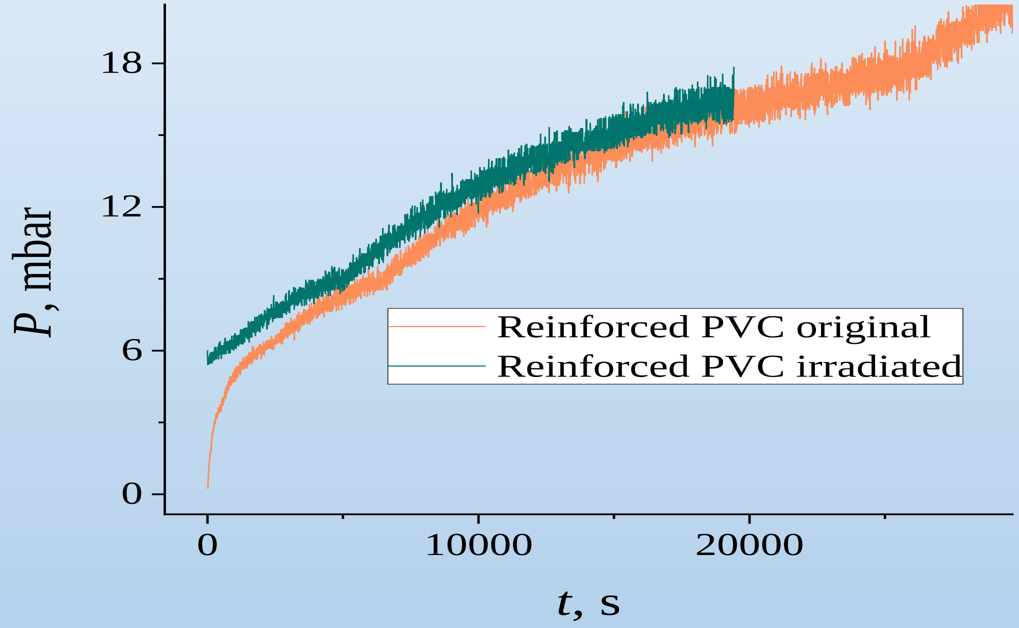
A) *B)*

A) analysis for Polyurethane based on (Ley-bold Phoenix Quadro Dry) test leakage device, B) leakage test analysis for reinforced silicone, which is directly squeezed once fore vacuum pressure is initiated.

Air Leakage Test
The Tracer Gas Method Followed

- Leakage analysis test for reinforced silicon shows that both irradiated and non-irradiated samples squeezed once operating at fore vacuum pressure, which means that the reinforced silicon can't be used for cooling of the thermal stabilization that is operated in a fore vacuum pressure cooling system.

- also analysis for polyurethane based on a Ley-bold Phoenix Quadro Dry test leakage device has been studied and indicates that polyurethane is the best candidate for a cooling hose pipe with no leakage.

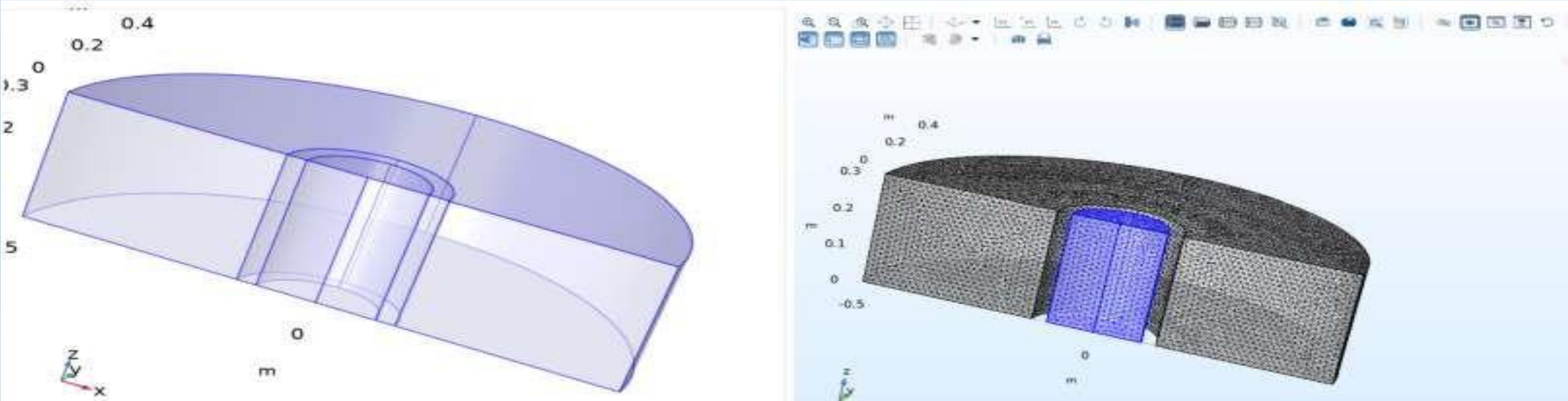


Leakage analysis test for the PVC observed that there is approximately no leakage rate for both samples irradiated and non-irradiated, which operated in fore vacuum pressure, which means that reinforced PVC is the best candidate for a cooling hose pipe .

COMSOL Multi-Physics Modelling

COMSOL Multi-Physics Software has been used to model for the Cooling process, based on the Reinforced PVC hose pipes with the coolant water, the Reinforced PVC pipes surrounded by air that exist in a radioactive environment of spectrum neutrons in range of 1 MeV neutrons.

A) Geometry, B) Mesh analysis used in COMSOL for three domains of coolant as a Domain one ,Reinforced PVC for the hose Pipe as a second domain, Air as third domain.



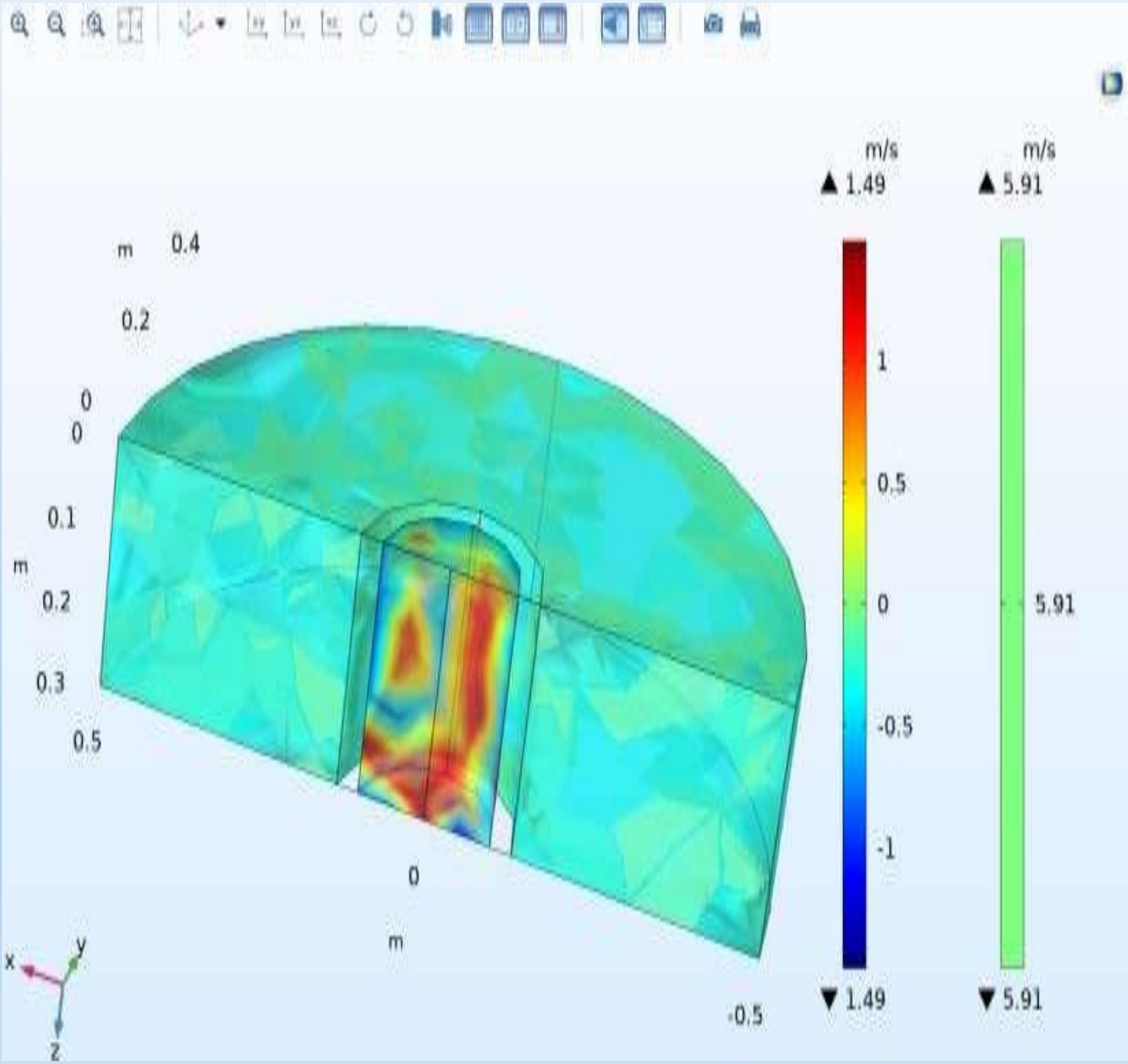
Laminar Flow for both the two fluids of the water Coolant and air surrounding the main Geometry.

$$\rho(u \cdot \nabla)u = \nabla \cdot [-pI + K] + F$$

$$\nabla(\rho.u) = 0$$

$$K = \mu(\nabla u + (\nabla u)^T) - \frac{2}{3}\mu(\nabla.u)I$$

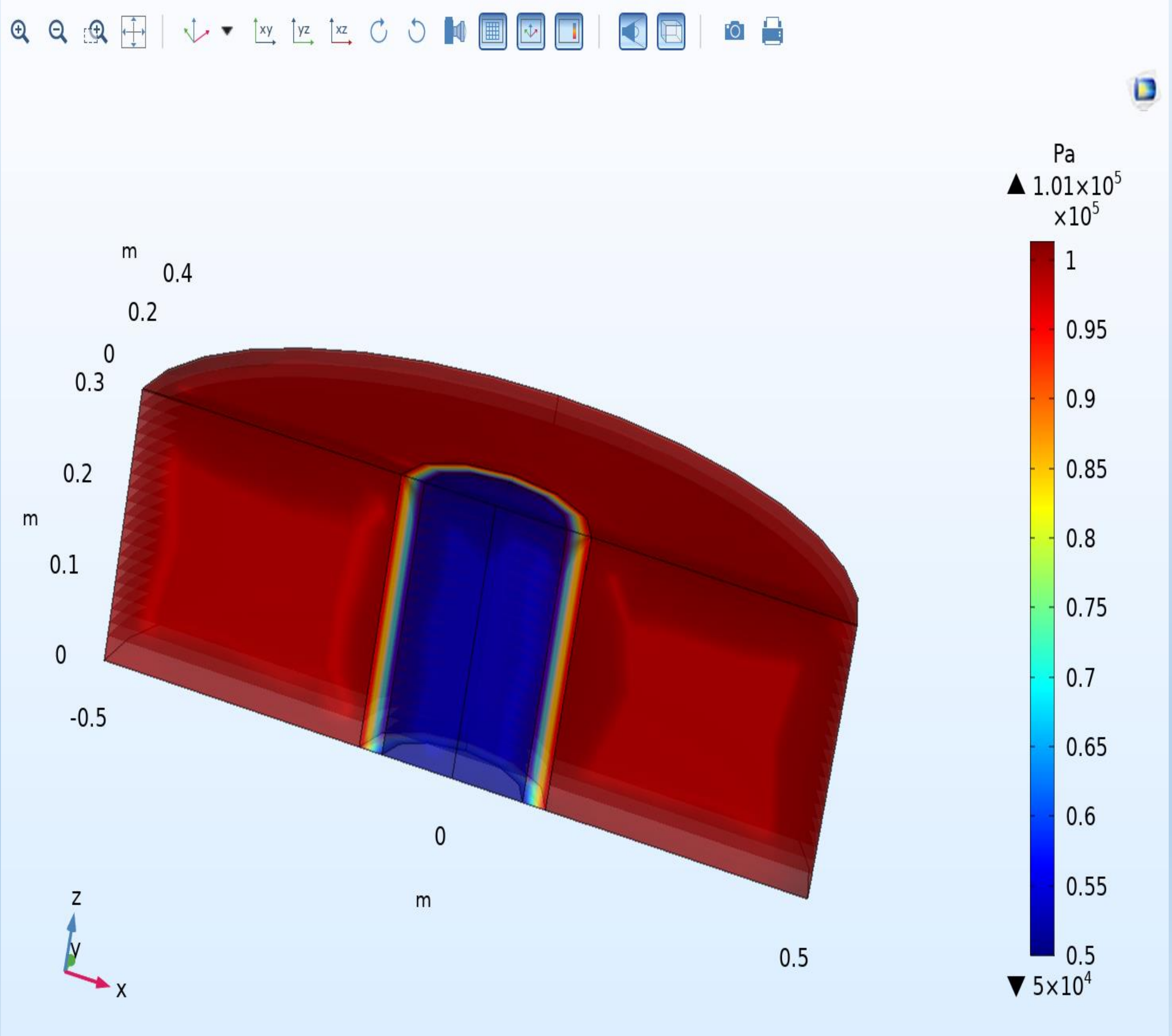
Here are the numerical results for the velocity model for both the two domains of the coolant and the air surrounding the reinforced PVC hose Pipe; based on COMSOL physics, as it is a laminar flow for semi- compressible liquid with a time-dependent study of physics.



Laminar flow for both the two fluids of the water coolant and air surrounding the main geometry.

- ρ is the density (SI unit: kg/m^3)
- I: is an Identity Tensor Matrix.
- u is the velocity vector (SI unit: m/s)
- p is pressure (SI unit: Pa)
- K is the viscous stress tensor (SI unit: Pa)
- F is the volume force vector (SI unit: N/m^3)
- µ is the dynamic viscosity, (SI unit: Pa ·s)

The numerical results for the Pressure Model for the three domains of the coolant, the air surrounding, and the reinforced PVC hose Pipe; based on the COMSOL physics, as it is a laminar flow for semi-compressible liquid with a time-dependent study of physics.

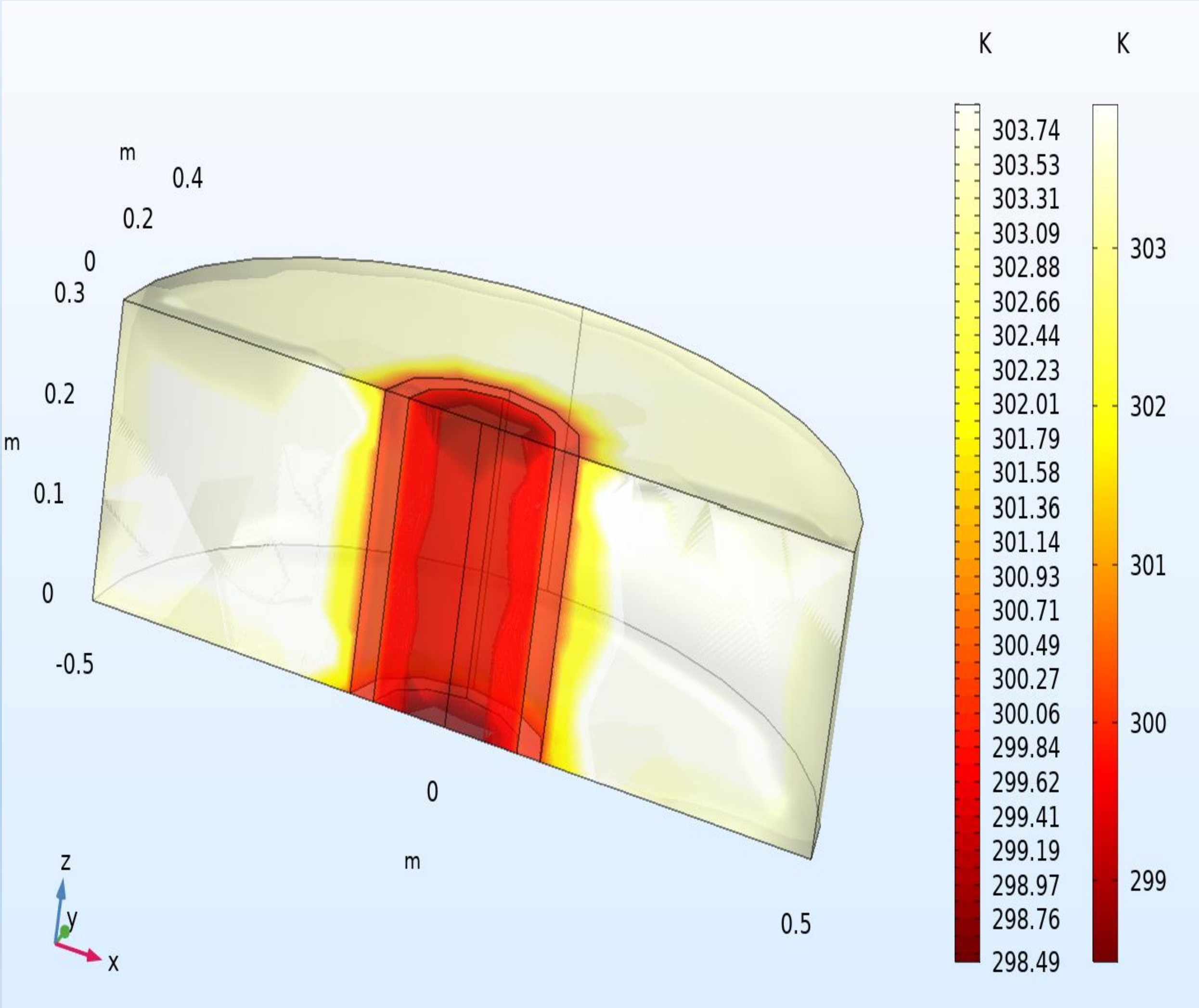


Heat transfer for both the two fluids of the water coolant and air surrounding the main geometry, added to the Reinforced PVC hose pipe.

$$\rho Cp\left(\left(\frac{\partial T}{\partial t}\right)+ u\,trans\,\cdot\,\nabla T\right)+\nabla.(qr+q)= -\alpha T\frac{dS}{dt}+Q$$

In the modeling of heat transfer, it is indicated that heat gradually decreased by convection from the outside domain of the air up to the PVC pipe using iso- surface temperature physics.

added to the temperature profile of the coolant, which decreased gradually from the edges of the coolant domain up to the center of the coolant domain.



The Magnetic Fields Interface

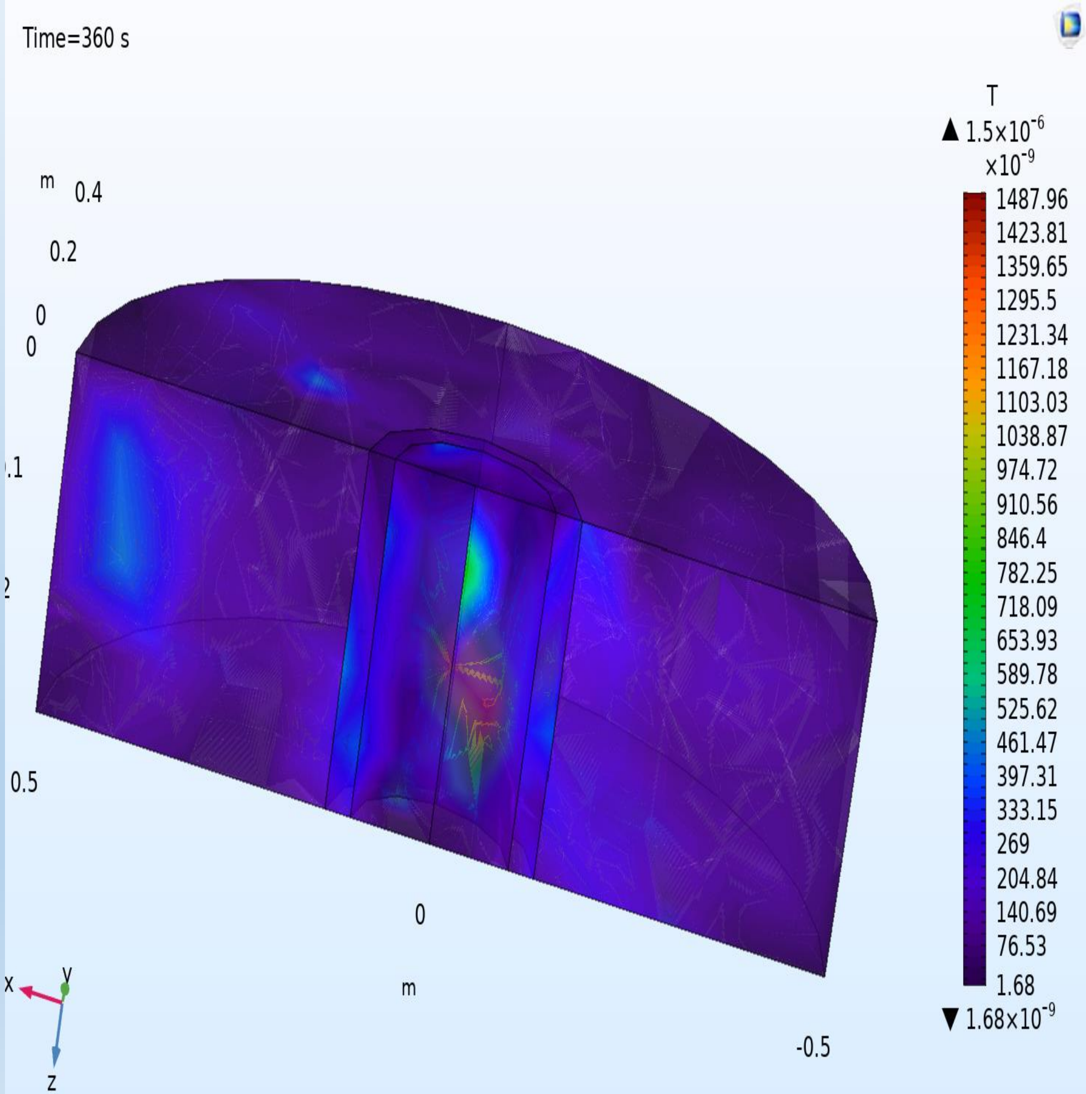
$$\nabla . H = J \ , (\text{VI.C.1}) B = \nabla . A,$$

$$J = \sigma E + J_e \ ,$$

$$E = -\frac{\partial A}{\partial t},$$

based on the electromagnetic equations used, because there is a detectable difference for relative permeability and electrical conductivity for the three domains of water coolant, air, and reinforced PVC hose pipe.

Considering the current analysis, it should be moved to the upcoming research to study the influence of magnetic field variation on the reinforced PVC hose pipe.

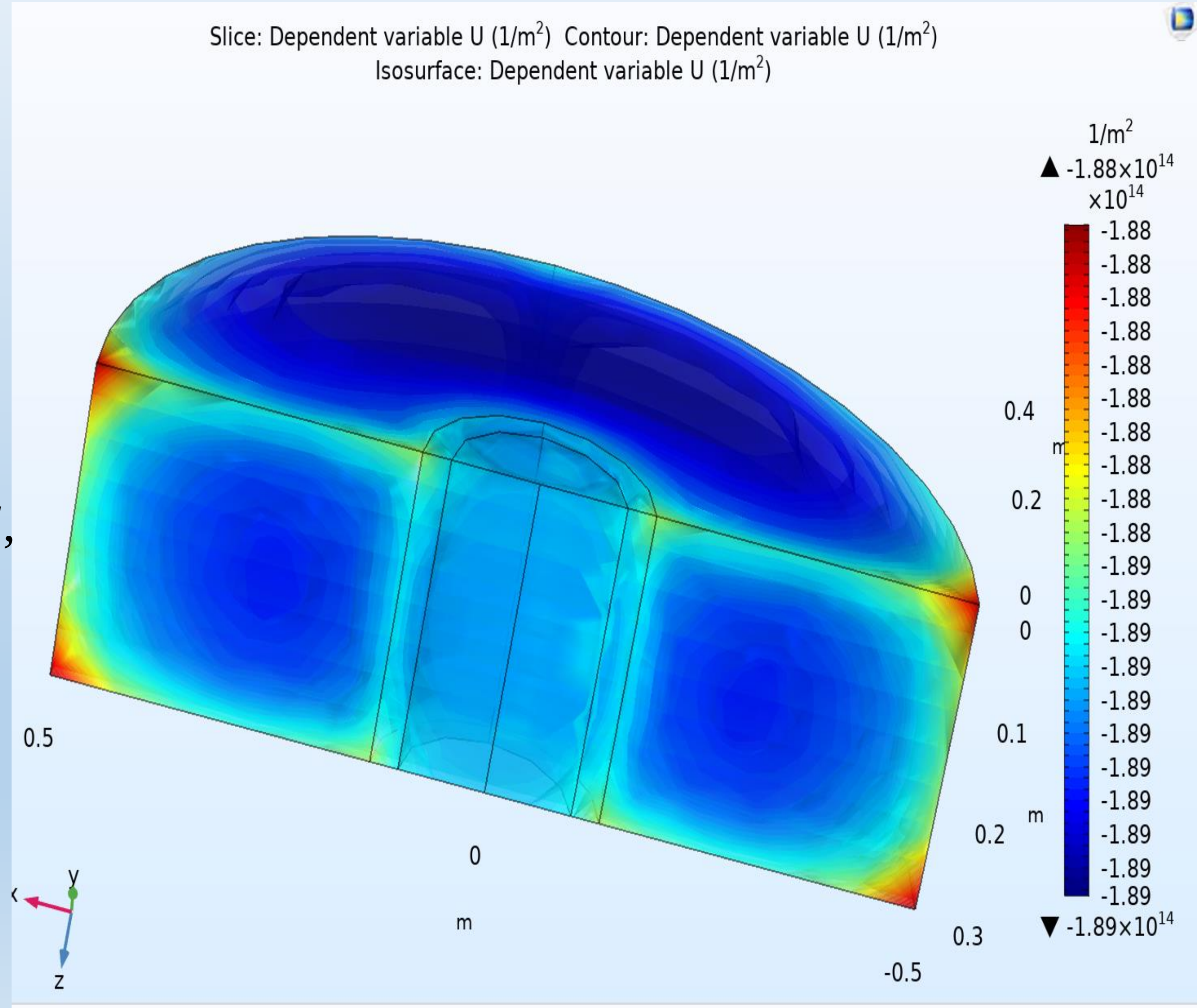


Neutron Fluence Distribution using the Coefficient of PDE Physics

Neutrons are distributed semi-uniformly, taking into account the distribution of neutrons will be impacted by changes in the absorption rate, scattering rate, and diffusion rate for the three domain materials—air, reinforced PVC, and water coolant—neutrons are dispersed semi-uniformly.

$$\lambda^2 e_a u - \lambda\, d_a u + \nabla.-(c\nabla u - \alpha u + \gamma) + \beta.\nabla\, u + au = f,$$

$$u = [U, U2]^T\,,\ \nabla = [\frac{\partial}{\partial X}, \frac{\partial}{\partial Y}, \frac{\partial}{\partial Z}]\,,$$



Conclusion

- The results of the leakage analysis test for “reinforced PVC” conducted on both irradiated and non-irradiated samples under vacuum pressure showed that there was almost no leakage rate.
- Polyurethane is a good option for cooling hose pipes. The leakage analysis test for polyurethan found that there is almost no leakage rate for both irradiated and non-irradiated samples that operated under vacuum pressure.
- The Estimation Leakage for All MPD System for irradiated reinforced PVC hose pipe is about 2.4 cm^3/min, and for non-irradiated reinforced PVC hose pipe is about 2.17 cm^3/minute.

Conclusion Followed

- COMSOL Studies have been done on a laminar flow for semi-compressible liquids used as water coolant. The modeling of heat transfer indicates that heat is progressively lost through convection from the air's exterior domain up to the PVC pipe and then to the water coolant domain; this information should be transferred to the next new study that will examine the impact of magnetic field variation on the reinforced PVC hose pipe.
- Silicone cannot be used as a cooling hose pipe because, according to the results of the leakage analysis test, there is a significant leakage rate for both irradiated and non-irradiated samples when operated at fore vacuum pressure. In addition, silicone samples are mechanically compressed once operating at vacuum pressure. Nevertheless, the small-diameter silicone hose pipes can be used only for electronics cooling in a limited quantity.

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Thanks for your Attention

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