

Thermo-Mechanical Performance Evaluation Of Mechanical Seal Materials in Fire Tender Pumps Using Ansys Finite Element Simulation

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Abstract: Mechanical seals are critical components of centrifugal fire tender pumps because excessive leakage or loss of sealing performance can reduce pump effectiveness during emergency firefighting operations. This study evaluated the predicted thermo-mechanical response of Carbon Graphite, Silicon Carbide (SiC), and Tungsten Carbide (WC) mechanical seal materials for a fire tender pump at Julius Nyerere International Airport (JNIA), Tanzania, using finite element analysis (FEA) in ANSYS Workbench. A three-dimensional seal assembly was modelled using field-measured geometry and operational information, supplemented by literature and manufacturer/reference data where direct measurement was not available. A sequential one-way thermo-mechanical procedure was used in which the steady-state thermal field was transferred to a structural analysis. The principal loading conditions were hydraulic pressure of 1.5 MPa, rotational speed of 4000 rpm, seal-face temperature of 180 °C, ambient temperature of 35 °C, friction coefficient of 0.12, contact pressure of 0.8 MPa and convection coefficient of 25 W/m²·K. The predicted results were 0.0330 mm deformation, 82.4 MPa equivalent stress and 0.74 MPa average contact pressure for Carbon Graphite; 0.0105 mm, 54.7 MPa and 0.82 MPa for SiC; and 0.0085 mm, 48.2 MPa and 0.84 MPa for WC, respectively. WC exhibited the lowest predicted deformation and equivalent stress among the investigated materials under the applied loading conditions, whereas sic showed a relatively balanced thermo-mechanical response. The results are numerical predictions and should not be interpreted as complete evidence of service reliability. Experimental testing, wear assessment and leakage measurements are required for complete material qualification.

Keywords: Mechanical seals; fire tender pumps; thermo-mechanical analysis; ANSYS; finite element analysis; Carbon Graphite; Silicon Carbide; Tungsten Carbide; deformation; stress; contact pressure.

I. INTRODUCTION

The reliability of fire tender pumps is essential to Aircraft Rescue and Firefighting (ARFF) operations because the pumps must deliver water at adequate pressure during emergency events. The mechanical seal is a critical component because it limits fluid leakage between the rotating shaft and stationary casing and supports reliable pump operation. During operation, mechanical seals are exposed to combined mechanical and thermal loading, including contact pressure, rotational speed, frictional heating and repeated operating conditions. These factors can influence temperature distribution, deformation, wear and sealing performance (Jin et al., 2024; Qiu et al., 2025; Yao et al., 2024).

The operating environment of tropical coastal locations such as Dar es Salaam may introduce additional thermal and environmental challenges. Consequently, seal-face material selection is important because properties such as elastic modulus, thermal conductivity and thermal expansion influence temperature and deformation behaviour. Recent numerical and experimental studies have examined thermo-mechanical deformation, friction and wear in mechanical seals, including analyses of seal-ring thermal deformation and dynamic thermo-mechanical response (Jin et al., 2024; Qiu et al., 2025; Yao et al., 2024).

Although previous studies have investigated mechanical seal materials and thermo-mechanical behaviors, limited studies have systematically compared Carbon Graphite, Silicon Carbide and Tungsten Carbide under identical thermo-

mechanical conditions representative of aircraft rescue firefighting pump applications. Many published investigations focus on particular seal pairs, lubrication conditions, slurry pumps, turbopumps or other operating environments, making direct comparison under fire tender pump conditions difficult. This study therefore addresses the gap by applying the same three-dimensional geometry, loading framework and performance indicators to the three candidate materials.

The objective of the present study was to compare the predicted thermo-mechanical response of Carbon Graphite, Silicon Carbide and Tungsten Carbide mechanical seal materials under representative fire tender pump operating conditions using ANSYS finite element simulation. The assessed indicators were total deformation, equivalent Von Mises stress and average contact pressure.

II. MATERIALS and METHODS

The study employed finite element analysis using ANSYS Workbench. The workflow comprised field-data collection, three-dimensional geometry development, material-property definition, mesh generation and convergence verification, sequential thermal-to-structural analysis, extraction of performance indicators, and comparative interpretation.

A. Field and Secondary Data Collection

Field and secondary information were used to define the operating and geometric conditions. To avoid treating reference values as direct measurements, the input classification is explicitly identified below.

TABLE I: PRIMARY AND SECONDARY DATA

Parameter	Value / Range	Source classification	Source / basis
Shaft diameter	35 mm	Measured	Field measurement
Seal-face outer diameter	52 mm	Measured	Field measurement
Seal-face inner diameter	35 mm	Measured	Field measurement
Seal-face width	8 mm	Measured	Field measurement
Spring length	24 mm	Measured	Field measurement
Pump rotational speed	1200–4000 rpm	Measured / specification	Tachometer measurements and pump specifications
Operating pressure	0.1–2.0 MPa	Measured / specification	Pressure readings and pump manual
Seal-interface temperature	120–180 °C	Reference value	Seal engineering references
Ambient temperature	30–40 °C	Site/environmental range	JNIA environmental conditions
Start-stop cycles	10–20 cycles/day	Operational record	ARFF operational records
Friction coefficient	0.10–0.15	Literature/reference	Mechanical seal literature
Contact pressure	≈0.8 MPa	Reference value	SKF seal manual

The simulation used the upper/representative operating conditions specified in the model: 1.5 MPa hydraulic pressure, 4000 rpm rotational speed, 180 °C seal-face temperature, 35 °C ambient temperature, friction coefficient of 0.12 and contact pressure of 0.8 MPa. These values define the numerical test condition and should not be interpreted as simultaneous continuous measurements unless independently instrumented during a test.

B. Three-Dimensional Model and Geometry Assumptions

A three-dimensional model of the mechanical seal assembly was developed in ANSYS Design Modeler using the measured shaft and seal dimensions. Small geometric features that were not expected to materially influence the global deformation and stress response were simplified. The model represented the principal seal components and contact region. The shaft diameter and seal-face dimensions were retained from field measurements. The model did not include detailed surface roughness, microscopic asperities or progressive wear because the objective was to compare initial thermo-mechanical response rather than long-term tribological degradation.

TABLE II: GEOMETRY AND MESH INFORMATION FOR MECHANICAL SEAL SIMULATION

Parameter	Value
Total model volume	6,280.3 mm ³
Bounding box (X × Y × Z)	82.500 × 36.200 × 34.800 mm
Total nodes	58,320
Total elements	29,870
Mesh type	Program Controlled; Mechanical Preference
Mesh quality	Passed

C. Mesh Verification

Mesh refinement was concentrated around the sealing contact region because stress and contact-pressure gradients are expected to be higher there. The final mesh contained 58,320 nodes and 29,870 elements. The original manuscript reported mesh-independence verification qualitatively but did not provide the numerical convergence sequence. Therefore, no unsupported convergence values are introduced here. The final mesh was retained for the reported results after the mesh-quality check passed. For full numerical reproducibility, future work should report at least three mesh levels with element count and the corresponding maximum equivalent stress or other selected response, together with the percentage change between successive refinements.

D. Material Properties

The candidate materials were represented using the property values in the study dataset. Because the manuscript does not identify commercial seal grades or provide certificates for the material batches, the values are treated as representative material-grade/reference properties rather than verified properties of a specific manufactured seal. This distinction limits direct claims about field-service performance.

TABLE III: THERMO-MECHANICAL PROPERTIES OF SELECTED SEAL MATERIALS.

Property	Carbon Graphite	Silicon Carbide	Tungsten Carbide	Source / status
Density (kg/m ³)	1800	3100	15000	Kim et al. (2024) / representative
Young's modulus (GPa)	12	410	550	Zhang et al. (2025) / representative
Poisson's ratio	0.22	0.17	0.23	Cui et al. (2024); Liu et al. (2024)
Thermal conductivity (W/m·K)	110	120	84	Material-grade/reference data
Thermal expansion coefficient (×10 ⁻⁶ /°C)	4.5	4.0	5.5	Material-grade/reference data
Maximum working temperature (°C)	450	1400	900	Material-grade/reference data

E. Boundary Conditions and Governing Formulation

TABLE IV: BOUNDARY CONDITIONS FOR THERMO-MECHANICAL SIMULATION.

Boundary parameter	Applied value
Pump pressure	1.5 MPa
Rotational speed	4000 rpm
Seal-face temperature	180 °C
Ambient temperature	35 °C
Friction coefficient	0.12
Contact pressure	0.8 MPa
Convection coefficient	25 W/m ² ·K

The thermal field was evaluated using the steady-state heat-conduction formulation $\nabla \cdot (k \nabla T) + Q = 0$, while frictional heat generation was represented by $Q = \mu PVA$. Thermal expansion was represented by $\Delta L = \alpha L_0 \Delta T$ and thermal stress by $\sigma = E \alpha \Delta T$. These formulations were used as engineering representations of the thermal and mechanical response under the specified boundary conditions.

F. Sequential One-Way Thermo-Mechanical Coupling

A sequential one-way coupling approach was used. First, the steady-state thermal analysis calculated the temperature field from the prescribed thermal and frictional conditions. The resulting temperature field was then transferred to the Static Structural analysis, where hydraulic pressure, contact pressure and rotational loading were applied. The outputs were total deformation, equivalent Von Mises stress and average contact pressure.

The one-way assumption means that the structural response was not iteratively returned to the thermal model to update the temperature field. This reduces computational complexity and is appropriate for a comparative screening analysis when the thermal field is treated as prescribed. However, it cannot fully represent two-way feedback between deformation, contact-area changes, frictional heat generation and temperature. Consequently, the results should be interpreted as predicted responses under the defined sequential model rather than a complete transient or fully coupled thermo-fluid-tribological solution.

G. Performance Indicators and Interpretation

Total deformation was used to indicate dimensional change under the applied loading. Equivalent Von Mises stress was used to compare the predicted intensity of the structural stress state. Average contact pressure was used to assess the predicted contact loading at the sealing interface. Lower deformation and stress were interpreted as lower predicted mechanical response under the selected loading case, while contact pressure was interpreted as a measure of the simulated interface loading. These indicators alone do not establish leakage rate, wear life, fatigue life or complete field reliability.

III. RESULTS

The ANSYS results showed clear differences among the three candidate materials.

TABLE V: SUMMARY OF RESULTS

Material	Total deformation (mm)	Equivalent stress (MPa)	Average contact pressure (MPa)
Carbon Graphite	0.0330	82.4	0.74
Silicon Carbide	0.0105	54.7	0.82
Tungsten Carbide	0.0085	48.2	0.84

A. Total Deformation

Tungsten Carbide produced the lowest predicted total deformation of 0.0085 mm, followed by Silicon Carbide at 0.0105 mm. Carbon Graphite produced the largest predicted deformation at 0.0330 mm. The difference is consistent with the large contrast in Young's modulus used in the model: the reported values were 550 GPa for WC, 410 GPa for SiC and 12 GPa for Carbon Graphite. Under comparable loading, the higher stiffness of WC and SiC therefore limits elastic dimensional response relative to Carbon Graphite.

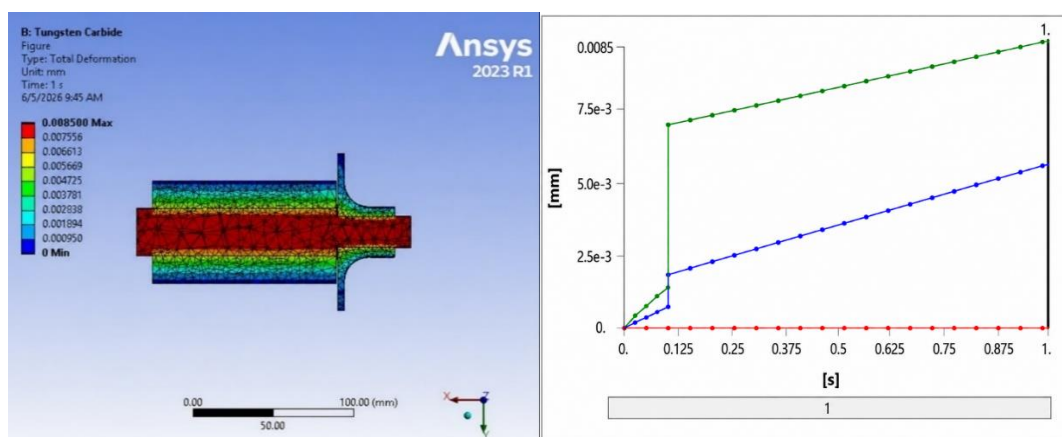


Figure. 1 Tungsten carbide deformation (ANSYS, 2023 R2)

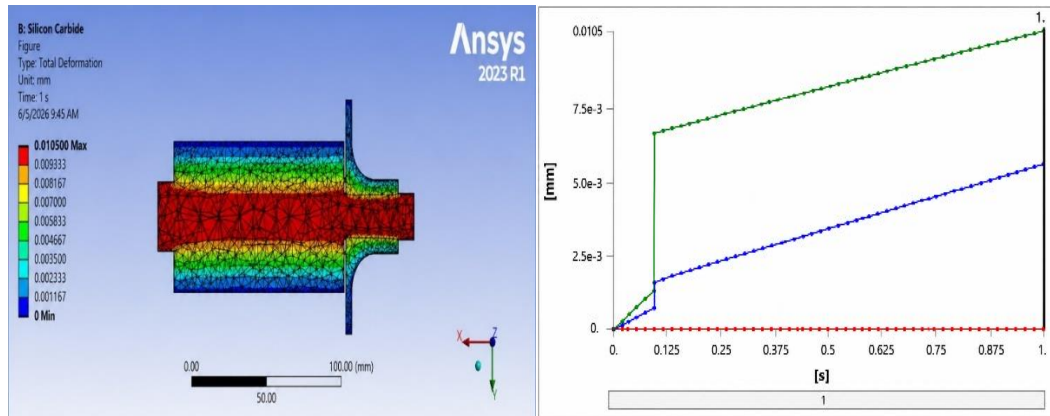


Figure. 2 Silicon Carbide deformation (ANSYS, 2023 R2)

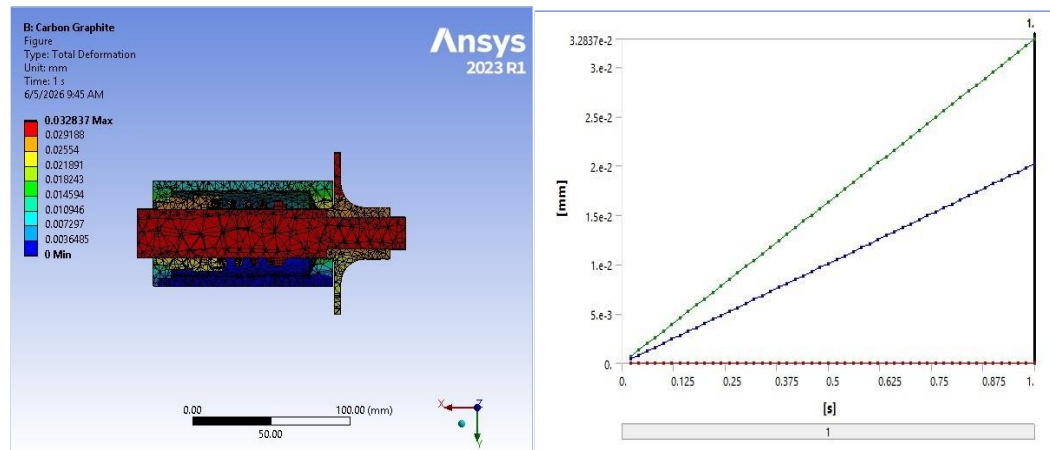


figure. 3 carbon graphite deformation (ANSYS, 2023 R2)

B. Equivalent Von Mises Stress

The lowest predicted equivalent stress was obtained for Tungsten Carbide at 48.2 MPa, followed by Silicon Carbide at 54.7 MPa. Carbon Graphite produced the highest value at 82.4 MPa. These results indicate that, within the numerical model, the two hard materials experienced lower predicted equivalent stress than Carbon Graphite under the selected loading condition. The values should not be interpreted directly as failure margins because the manuscript does not provide experimentally verified strength data for the specific seal grades.

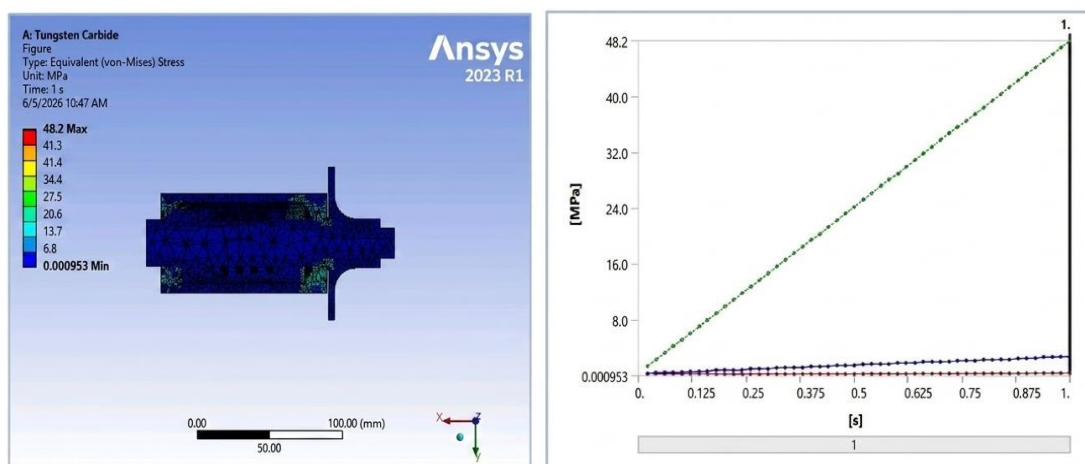


Figure. 4 Tungsten Carbide stress (ANSYS, 2023 R2)

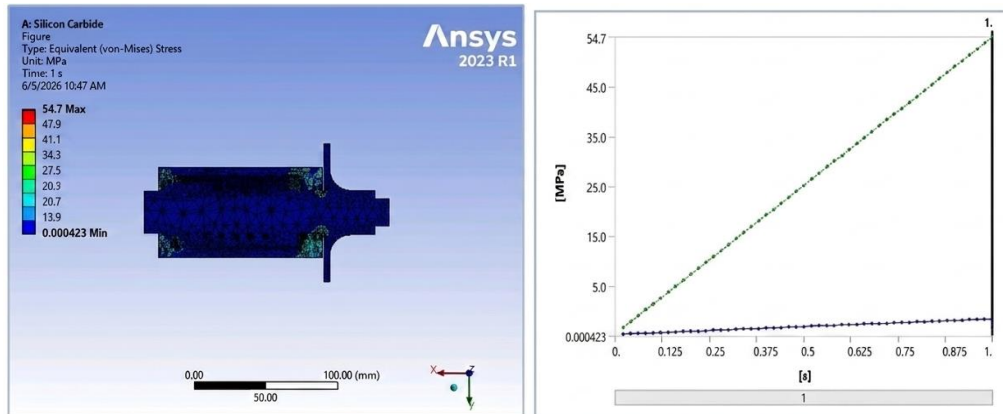


Figure. 5 Silicon Carbide stress (ANSYS, 2023 R2)

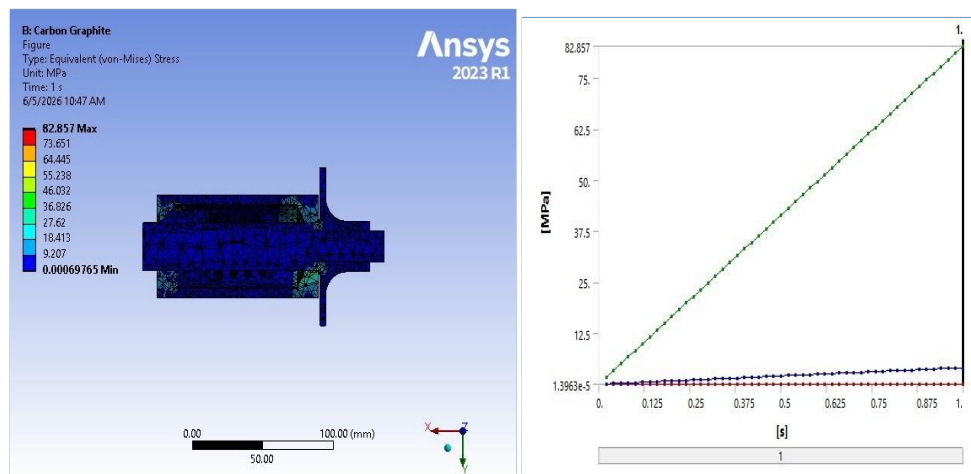


Figure. 6 Carbon Graphite stress (ANSYS, 2023 R2)

C. Contact Pressure

Average contact pressure values were 0.74 MPa for Carbon Graphite, 0.82 MPa for Silicon Carbide and 0.84 MPa for Tungsten Carbide. The increasing contact-pressure response from Carbon Graphite to WC is consistent with the greater structural stiffness represented in the model. Contact pressure is relevant to sealing, but its adequacy cannot be established from the present results alone because leakage depends on additional factors such as surface roughness, film formation, wear, alignment, fluid properties and operating history.

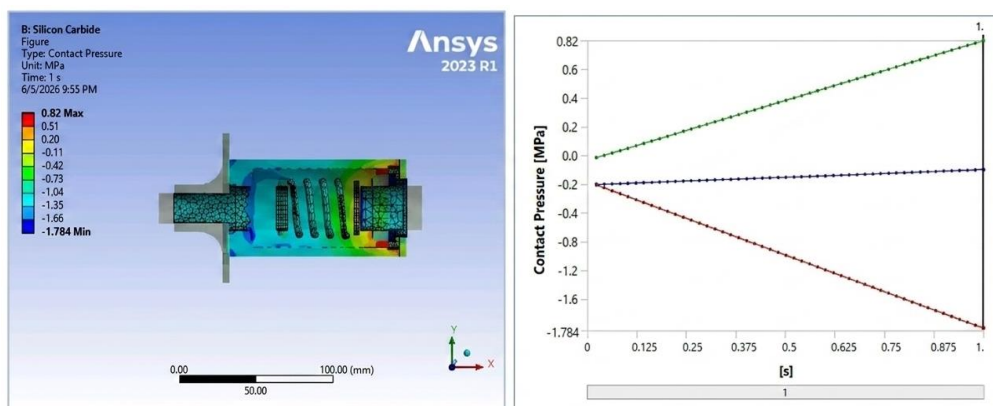


Figure. 7 Silicon Carbide pressure (ANSYS, 2023 R2)

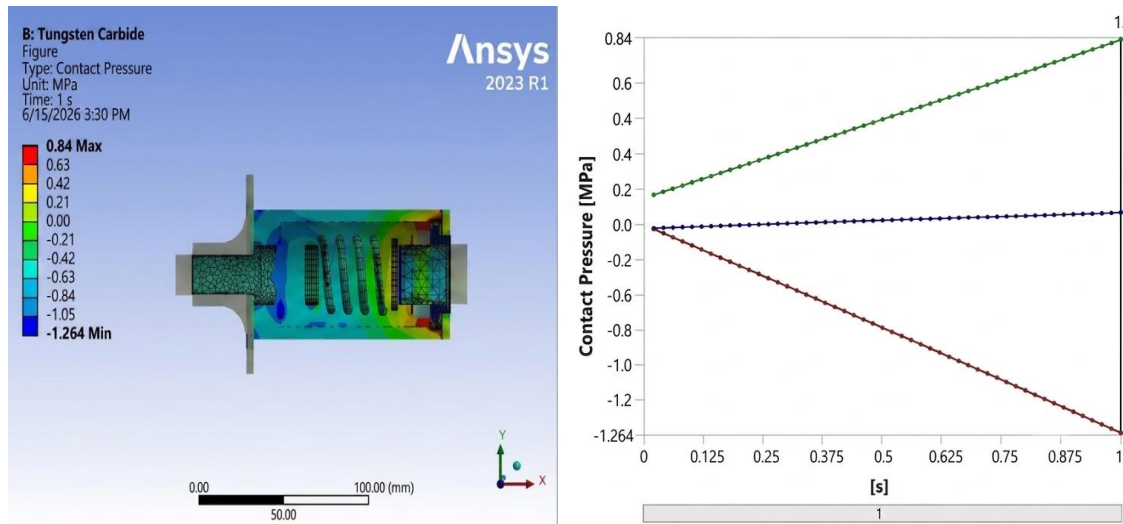


Figure. 8 Tungsten Carbide pressure (ANSYS, 2023 R2)

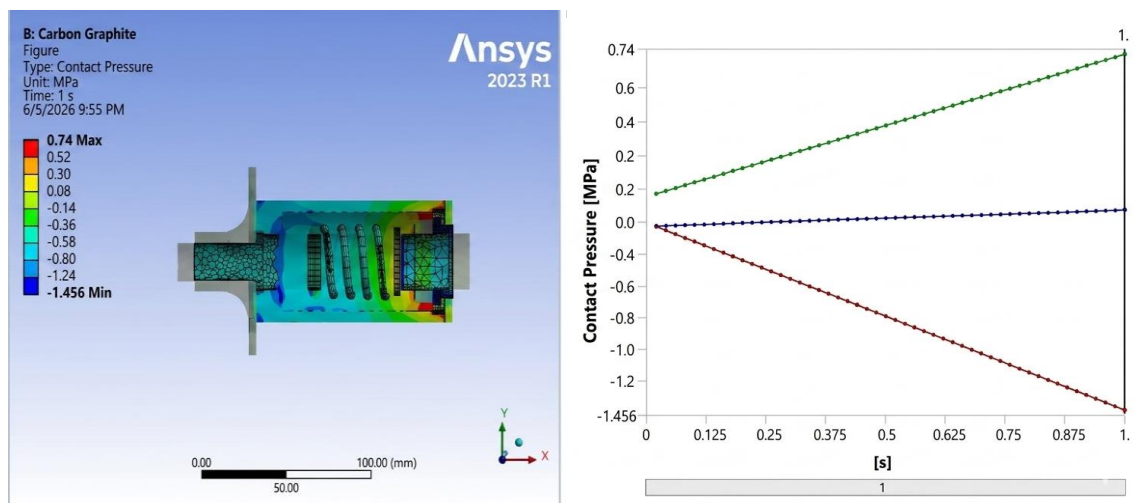


Figure. 9 Carbon Graphite pressure (ANSYS, 2023 R2)

IV. DISCUSSION

A. Carbon Graphite

Carbon Graphite produced the highest predicted deformation (0.0330 mm) and equivalent stress (82.4 MPa), with an average contact pressure of 0.74 MPa. Its lower Young's modulus in the model contributes to greater deformation under the combined thermal and mechanical loading. Carbon-based materials are nevertheless widely used in seal systems because of their tribological characteristics and thermal properties; therefore, the numerical deformation result should not be interpreted as evidence that Carbon Graphite is unsuitable for service. Its actual suitability would also depend on wear, lubrication and the mating-face material (Zhao et al., 2024).

B. Silicon Carbide

Silicon Carbide showed a relatively balanced predicted response, with 0.0105 mm deformation, 54.7 MPa equivalent stress and 0.82 MPa contact pressure. The model used a thermal conductivity of 120 W/m·K, a thermal expansion coefficient of $4.0 \times 10^{-6}/^{\circ}\text{C}$ and a maximum working temperature of 1400 °C. These properties are consistent with the relatively low deformation predicted in the simulation. The result supports considering SiC where both thermal and mechanical response are important, but it does not by itself establish long-term reliability or leakage performance.

C. Tungsten Carbide

Tungsten Carbide exhibited the lowest predicted deformation (0.0085 mm), lowest predicted equivalent stress (48.2 MPa) and highest predicted contact pressure (0.84 MPa). Its high Young's modulus of 550 GPa in the model contributes to high

dimensional rigidity under the applied structural loading. However, the model used a lower thermal conductivity for WC (84 W/m·K) than for SiC (120 W/m·K). Therefore, the mechanical response alone should not be used to infer that WC provides the best overall thermo-mechanical performance. The result demonstrates a strong predicted structural response within the specified numerical conditions.

D. Comparative Thermo-Mechanical Assessment

The results show that the three materials respond differently to the same numerical loading conditions. WC gives the lowest predicted deformation and equivalent stress, while SiC provides low deformation and stress together with the highest thermal conductivity among the three materials in the adopted property set. Carbon Graphite gives the largest predicted deformation and stress but has material characteristics that can be relevant to tribological applications. The comparison therefore demonstrates a trade-off among the selected numerical indicators rather than a universal material ranking.

E. Material Selection Interpretation

The earlier manuscript referred to a weighted multi-criteria assessment but did not document the weighting procedure or calculation. To avoid an unsupported selection claim, the present paper does not report a weighted score. Instead, it reports the numerical response transparently: WC had the lowest predicted deformation and stress, while SiC showed a comparatively balanced response across the adopted mechanical and thermal property set. A definitive material qualification would require a documented decision framework together with experimental leakage, wear and thermal testing.

F. Validation and Benchmarking

The simulation results were compared with published findings to assess numerical consistency of predicted thermo-mechanical behavior. The present dataset indicates that the predicted stresses were 82.4 MPa, 54.7 MPa and 48.2 MPa for Carbon Graphite, SiC and WC, respectively, and that the maximum predicted deformation was 0.0330 mm. However, the supplied manuscript does not provide directly comparable literature values for the same geometry, loading, material grade and boundary conditions. Therefore, a numerical error percentage or quantitative validation claim cannot be justified from the available evidence. The appropriate interpretation is numerical benchmarking rather than experimental validation. Future work should compare the model with measured seal temperature, deformation, contact pressure and leakage under controlled pump testing.

V. CONCLUSION

This study evaluated Carbon Graphite, Silicon Carbide and Tungsten Carbide mechanical seal materials using ANSYS finite element simulation under combined thermal and mechanical loading representative of a fire tender pump. Under the specified model conditions, WC exhibited the lowest predicted total deformation (0.0085 mm) and equivalent Von Mises stress (48.2 MPa), while SiC showed low predicted deformation (0.0105 mm), stress (54.7 MPa) and the highest thermal conductivity in the adopted material-property set. Carbon Graphite produced the highest predicted deformation and stress. The results therefore demonstrate different thermo-mechanical responses among the three materials under the selected loading conditions. They do not, by themselves, establish complete service reliability, leakage resistance, wear life or a universally preferred material. Experimental testing, wear analysis and leakage evaluation are required for complete material qualification.

VI. RECOMMENDATIONS

Future assessment should include controlled experimental testing of the actual pump/seal assembly, with simultaneous measurement of shaft speed, hydraulic pressure, seal temperature, contact behaviour and leakage. Material-specific wear and tribological testing should be conducted to complement the static thermo-mechanical simulation. Where data permit, transient start-up and shut-down simulations, overload conditions, thermal-mechanical two-way coupling and fluid-structure interaction should also be investigated. For practical material selection, the decision criteria and weights should be documented before applying a multi-criteria method.

VII. CONTRIBUTION TO KNOWLEDGE

The study provides comparative numerical data for Carbon Graphite, Silicon Carbide and Tungsten Carbide under a common set of representative fire tender pump conditions. It also demonstrates an ANSYS-based sequential thermo-mechanical framework that can be used to screen candidate seal materials before experimental testing. The contribution is primarily numerical and comparative; it does not replace physical qualification of mechanical seal materials.

Abbreviations

ARFF: Aircraft Rescue and Firefighting; ANSYS: Analysis System; FEA: Finite Element Analysis; FEM: Finite Element Method; JNIA: Julius Nyerere International Airport; MPa: Megapascal; rpm: revolutions per minute; SiC: Silicon Carbide; WC: Tungsten Carbide.

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BIOGRAPHY

Eng. Aloyce Waryoba is a Tanzanian Automobile Engineer professional with approximately four years of professional experience in Automobile engineering, facility maintenance and fire protection systems. He is currently working at Julius Nyerere International Airport (JNIA), Dar es Salaam, where his responsibilities involve the operation, inspection, maintenance and troubleshooting of mechanical systems and equipment, with particular focus on firefighting pump systems and associated mechanical infrastructure.

His areas of professional expertise include fire pump systems, mechanical equipment maintenance, preventive and corrective maintenance, pump troubleshooting, mechanical system inspection, equipment condition assessment, fault diagnosis and maintenance planning. He holds a Bachelor's degree in Automobile Engineering and is currently pursuing a Master of Mechanical Engineering with Transportation Machinery at the National Institute of Transport (NIT), Tanzania.