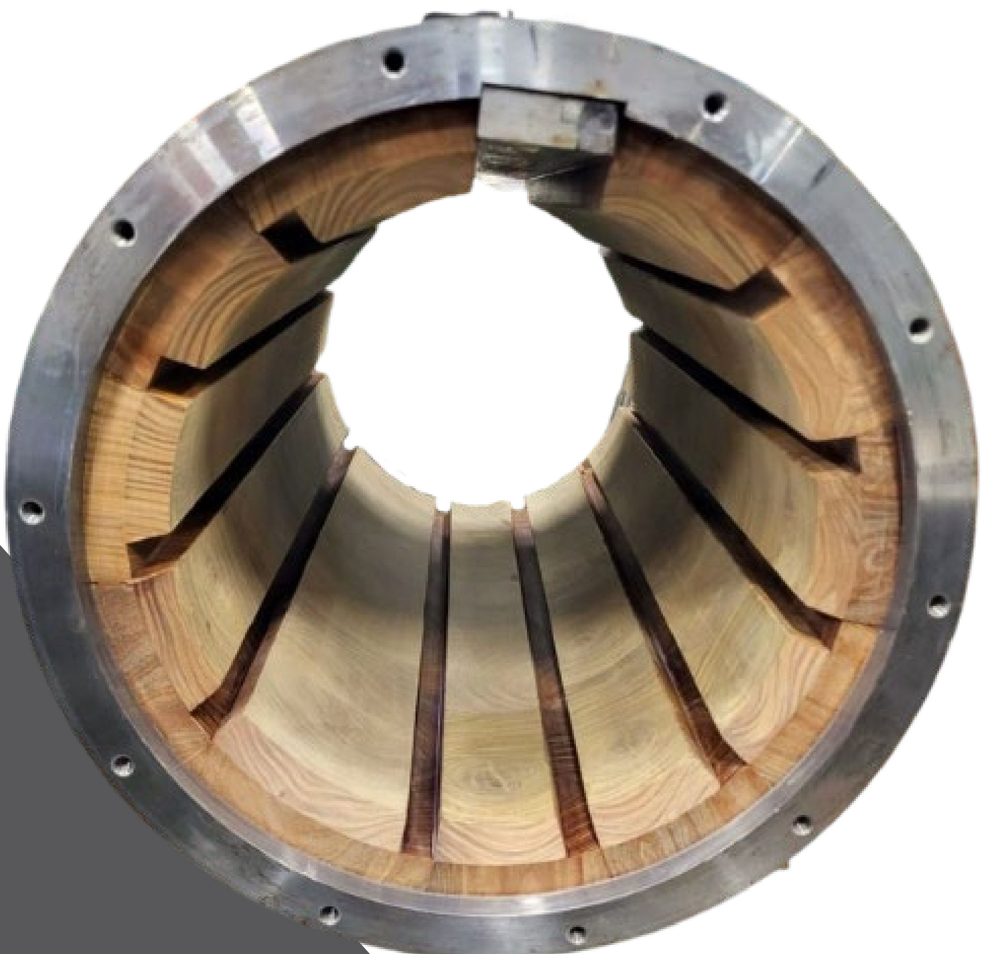
LIGNUM VITAE WATER BEARINGS



Maintenance,
Storage, and
Engineering
Manual

INDEX

INDEX

INDEX

GRAIN DIRECTIONS AND COMMONLY USED TERMS

End Grain – the grain which corresponds to the transverse surface of the tree's trunk. This grain grows normal to the radial-tangential plane.
Edge Grain – the grain formed parallel to the longitudinal axis and perpendicular to the annual growth rings
Face grain – the grain which is tangent to the annual growth rings and parallel to the longitudinal axis.
LRT Coordinate system – the coordinate system used to define a tree and its grains
Flatwise – see end grain
Edgewise – refers to edge grain, face grain or some combination thereof

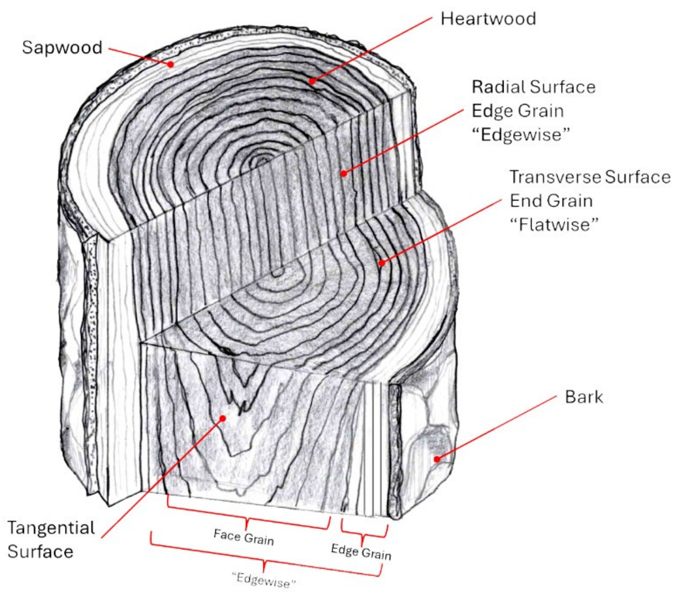


Figure 1. Illustration showing grain directions.

Global Service and Support

This information is provided as part of our customer service. The material provided here is intended for reference purposes only. Hydro Tech is equipped to analyze and offer guidance tailored to specific applications.

Hydro Tech:
Telephone: +1 705 946 3182
Fax: 1 705 946 8492
Email: info@hydtrotech-inc.ca
Web: www.HydroTech-inc.ca

Lignum Vitae North America:
Telephone: +1 804 372 6206
Email : Contact@Lignum-Vitae.com
Web: Lignumvitaesolutions.com

LIGNUM VITAE DEFINITION

The wood known as lignum vitae originates from the Guaiacum species. The two most common species identified as Lignum Vitae are Guaiacum Officinale and Guaiacum Sanctum. These are the woods which were historically used and selected for bearing applications. Guaiacum Officinale was historically favored over Guaiacum Sanctum due to the large log size and thinner sapwood layer of Guaiacum Officinale [1], [2], the heartwood from both trees were considered high quality regarding performance [1].

Qualitative Characteristics

The wood can be identified from its appearance and wood grain structure. Its dark green-brown coloured heartwood [3] [4] [5] which may appear black [2] [6] or be streaked black [4] [7]. The wood has a highly contrasting yellow [2] [3] [4] [7] or cream [6] [8] colored sapwood. It has an interlocked grain that is fine and uniform in appearance [3] [4] [7]. The growth rings are very fine and are viewed as either indefinite or untraceable bands [4] [7]

Small to minute pores that are just visible by the naked eye distributed throughout the heartwood [1] [2] [4] [7] with 16 to 43 pores per square **millimeter** [7]. Pores are circular or elliptical and are irregularly distributed with no definite arrangement occasionally echelon and in some cases ring-porous has been observed [1]. Pore size ranges from 0.08mm to 0.18 mm with pores being widely variable in size [1]. The pores are filled with a resin that gives the wood a characteristic oily [1] [6] or waxy [4] feel. This resin makes up to 30% of the trees mass [5].

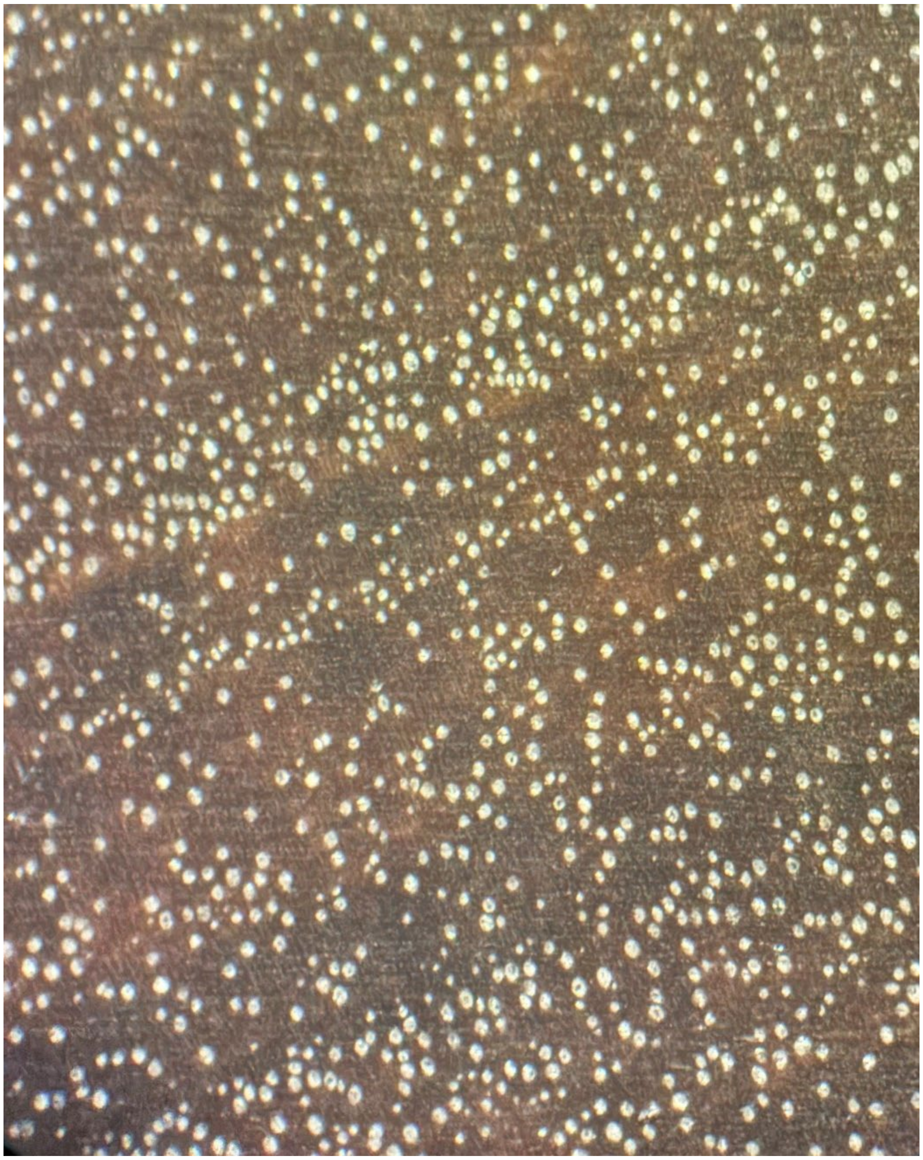


Figure 2. Image of Lignum Vitae material at 20x Magnification.

LIGNUM VITAE DEFINITION

Quantitative Characteristics

Specific Gravity/Density

Lignum Vitae wood suitable for bearing applications has an average specific gravity of ranging from 1.15 to 1.35 g/cm³ at a moisture content of 15%. The density of the wood is a function of its moisture content. Care must be taken when determining the specific gravity as exposure to high temperatures (such as those typically used when kiln drying wood) will lead to the excretion of the resin and give an overly low specific gravity.

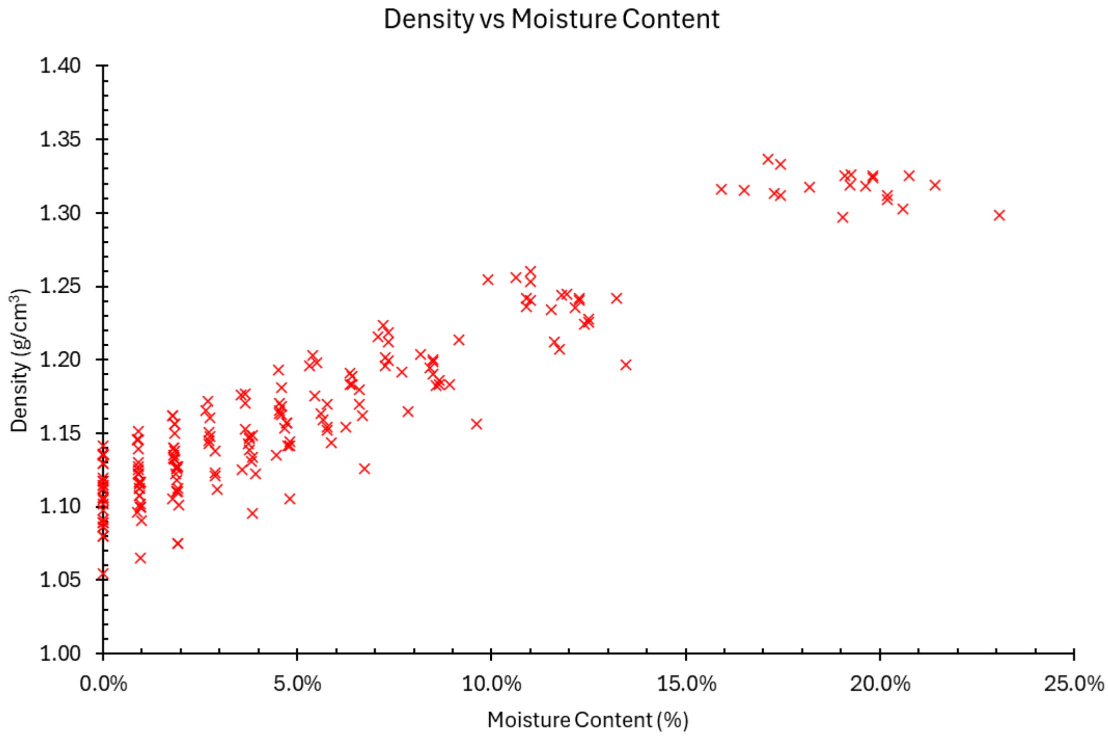


Figure 3. Lignum Vitae Density vs Moisture Content

Lignum vitae wood for use in stern tube bearing applications should maintain a moisture content of 12% or greater. If the wood dries beyond this 12 % limit, then cracks may form in the wood leading to a loss of dimensional tolerances and therefore poor fit up of the bearing.

To ensure a high moisture content is maintained during shipping and storage Hydro Tech has developed a storage system which seals the Lignum Vitae wood from the atmosphere. Staves are saturated in water prior to shipping and then sealed in the containment system. Upon receipt of the bearing water may be added to the storage system to protect the Lignum Vitae staves.

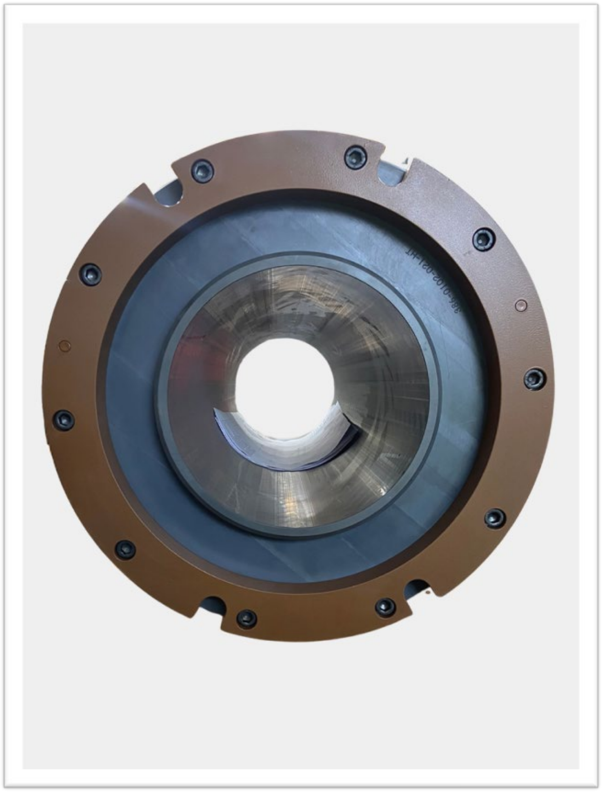


Figure 4. Left, image of STB with staves exposed.
Figure 5. Right image of staves protected by containment system.

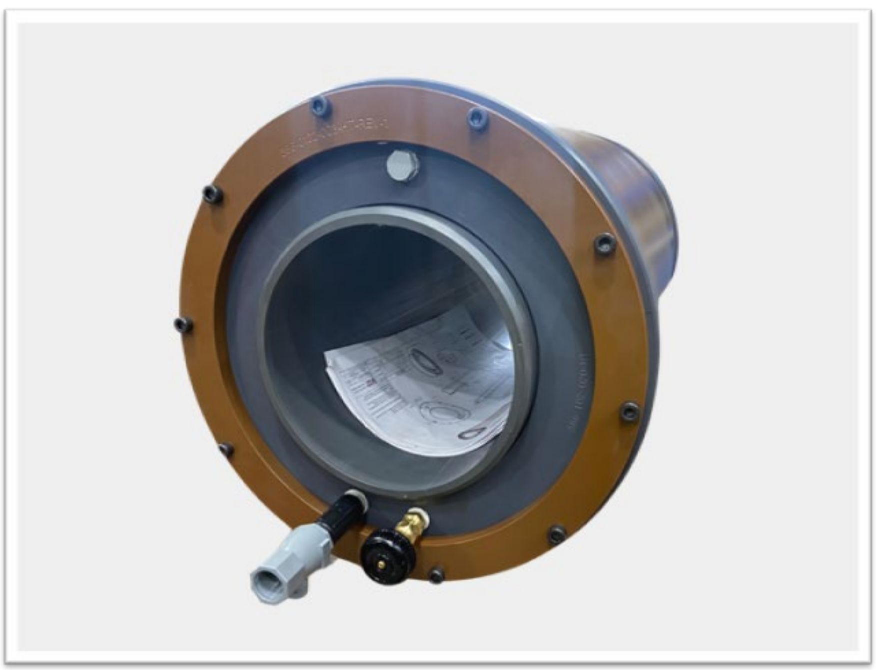


Figure 6. Image of drain and fill port on containment system.

Resin Content

The resin within the wood can act to reduce the coefficient of friction and provide a glazing to the shaft. This resin also gives the wood its waxy or when wet slippery feel. Lignum vitae wood suitable for bearing applications has a resin content of greater than or equal to 14% by mass. The resin content can be determined by examining the area of the pores present within the heartwood.

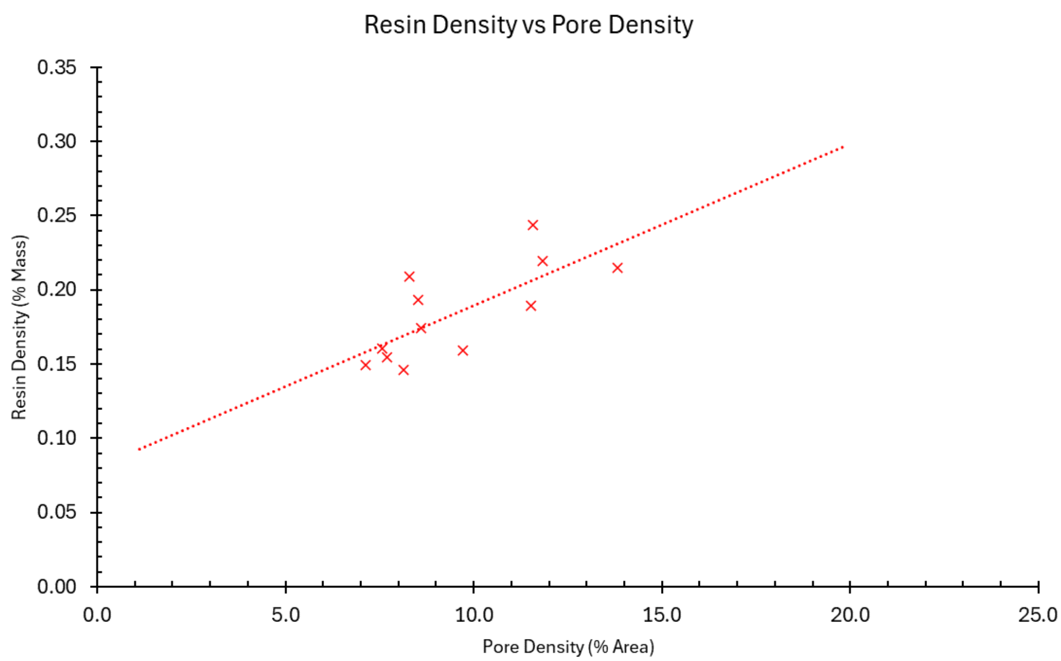


Figure 7. Lignum Vitae Resin Density vs Pore Density

Hardness

Lignum Vitae wood is known for its high hardness. Due to the orthotropic nature of lignum vitae, it is unadvisable to convert between different hardness values or infer hardness values from a different grain direction. Hardness values as tested on the end grain are presented for Rockwell M and the Janka hardness test. The Rockwell M scale (6.35mm (0.250") diameter ball with 100 kg load) yielded an average hardness of (267.5 MPa) 38800 psi corresponding to a Rockwell M hardness of 45 while the Janka hardness scale (11.27mm (0.444") ball pushed until full projection) required an average pressure of (113.4 MPa) 16450 psi to insert the ball to full projection which corresponds to a force of 10000 N (2550 lbf).

MACHINING AND MEASURING

General Machining

Lignum Vitae is a wooden material and, as such, behaves differently from metal or plastic. Unlike metal, which peels and makes chips, Lignum Vitae cuts and chips in thin shavings, typically 5 to 20mm ($^{3}/_{16}$ to $^{3}/_{4}$ inch) long, when machined properly. The feeds and speeds can vary greatly depending on the tooling and work holding potential. Solid carbide tooling and inserts provide the best tool in life. High-speed steel (HSS) and cobalt steel tooling can also be used and, in some cases, may be better for delicate parts since these tools are often sharper and create less resistance against the workpiece.

For boring operations, carbide insert tooling is typically used with a lead angle of 5° or less. Removing up to 2.5 mm (0.1") of material per pass is not uncommon with strong fixturing and a large boring bar. The depth of cut should be adjusted to match the capability of the setup and provide the best finish possible. To minimize chipping at the corners of water grooves, any sharp edges should be back beveled to prevent tear out.

While Lignum Vitae dissipates heat well, excessive milling speeds can cause resin to build up and harden on the tool due to excessive heat while cutting. Although this rarely affects tool performance negatively, as the resin can be scraped off between passes, it should signal the need to lessen the feed rate or depth of cut. It is recommended to make a spring pass as the final pass to account for any deflection of the boring bar.

Lignum Vitae should always be kept wet while machining. This can be accomplished by misting with a spray bottle filled with cooling fluid, as using water alone may damage machining equipment. Thin wall bearings, in particular, will dry out quickly while turning, which can result in unpredictable shrinkage.

Machining

- Use Sharp Tooling: Always machine lignum vitae with new, sharp tools to ensure clean cuts and minimize damage.
- Resin Properties: lignum vitae resin starts to melt at 80ºC (176°F), and acts as a natural lubricant. As a result, cooling or cutting fluids are generally not required during machining.
- Maintain Moisture: lignum vitae must always be kept moist. If it dries out, the end grain can catch on the cutting tool, especially when cutting across the grain. Over-wetting is not a concern. Submerge or flood large pieces as needed without risk of damage.

- Rough Out First: Rough out the part surfaces before finishing the machining process. This helps to reduce stress on the material and ensures a smoother finish.
- Re-wet During Machining: Keep the surface moist while cutting. For small to medium pieces, a spray bottle with plain water is effective. For larger pieces, ensure they are fully submerged or stored in water-filled containers.
- No Chemicals: Do not use chemicals or chemical treatments for the preparation, storage, preservation, or use of lignum vitae materials or products.

If the wood begins to split or separate, it may be irreparable and unsuitable for service. For further guidance, consult Hydro Tech.

Dimensional and Surface Finish Measurements

In most cases, Lignum Vitae bearings can be measured using the same instruments and methods as other materials. However, unlike metals, Lignum Vitae is susceptible to changes in moisture content. Therefore, measurements should ideally be taken while the material is wet or surface dry, but not after it has been allowed to dry out for longer than one hour. If the material has been out of water for several hours, it should be soaked for at least one hour before measurements are recorded.

For larger diameter bearings with relatively thin walls, it is common to observe ovality after machining and removal from the lathe. It is important to pay attention to the wall thickness of the tube being machined, as well as the diametric measurements taken across the part. After the staves are installed into the housing, the inside diameter can then be finished to a precise tolerance while maintaining the concentricity of the tube.

BONDING

A) Surface Preparation

Bedding epoxy can be used to improve the interface between a Lignum Vitae bearing and an uneven or out-of-round housing. Generally, Lignum Vitae does not bond well with any adhesive, so adhesives should not be used as the primary method of attachment. In our shop, we use West System products and urethane glues during the production of staves; however, final attachment should be achieved by other methods.

If adhesives are to be used, it is essential that the surface is dry and free of any oil or wax. The Lignum Vitae surface should be cleaned with denatured alcohol before the application of adhesives.

B) Storage

Lignum vitae bearings are most stable when wet. To ensure stability, it has been saturated before machining and shipped in a sealed bag with water. In this state, the bearing can be safely stored for up to 4 weeks in a cool place away from direct sunlight. For longer storage, it is recommended to keep the bearing in water. The bearing should not be allowed to dry out for more than 4 hours. Upon installation, the exposed end of the bearing should be coated with wax.

TRIBOLOGY

Friction

Friction can be dry or viscous. Dry friction occurs between solid bodies and "is generally defined as the force at their surface of contact which resists their sliding on one another. The friction force F is the force required to initiate or maintain motion" [11]. For a coefficient of friction μ and a normal reaction force N, $\mu = F/N$. There are static and kinetic coefficients of friction with the latter being typically smaller than the former.

Lubrication can produce a viscous friction that is much lower than solid-to-solid friction. If solid surfaces are in relative motion and a fluid wedge is established between them then no solid-to-solid contact is possible. Under ideal conditions, the hydrodynamic pressure of the lubricant film will support the normal force N and the solid surfaces will not wear [11].

Modes of Lubrication

Fluid film bearings operate under three primary lubrication regimes: hydrodynamic, mixed, and boundary lubrication. In the hydrodynamic regime, a thin fluid film completely separates the two surfaces, eliminating contact and resulting in negligible wear. In the boundary regime, surface asperities on the journal and bearing come into contact, with only minimal lubricant present between the surfaces. This condition leads to increased wear due to direct surface interaction. The mixed lubrication regime features both fluid film formation and areas where larger surface asperities from one material contact the asperities of the other material.

The changes in lubrication regime cause a significant change in the coefficient of friction observed. The coefficient of friction was computed for a lignum vitae bearing with a shaft diameter of 50mm, a 2:1 L/D ratio, an eccentricity of zero. This was completed for bearing loads of 0.4MPa and 0.6MPa.

Note, bearing eccentricity will change the transition point from boundary to mixed and full film lubrication.

The same graphs show the coefficients of friction observed for a polyurethane elastomer that is commonly used in stern tube bearing applications under the same operating and design parameters. In both cases the Lignum Vitae bearing demonstrates a lower coefficient of friction in the mixed mode lubrication due to the resin within the wood. As the asperities of the shaft and bearing make contact the was acts as an additional lubricant.

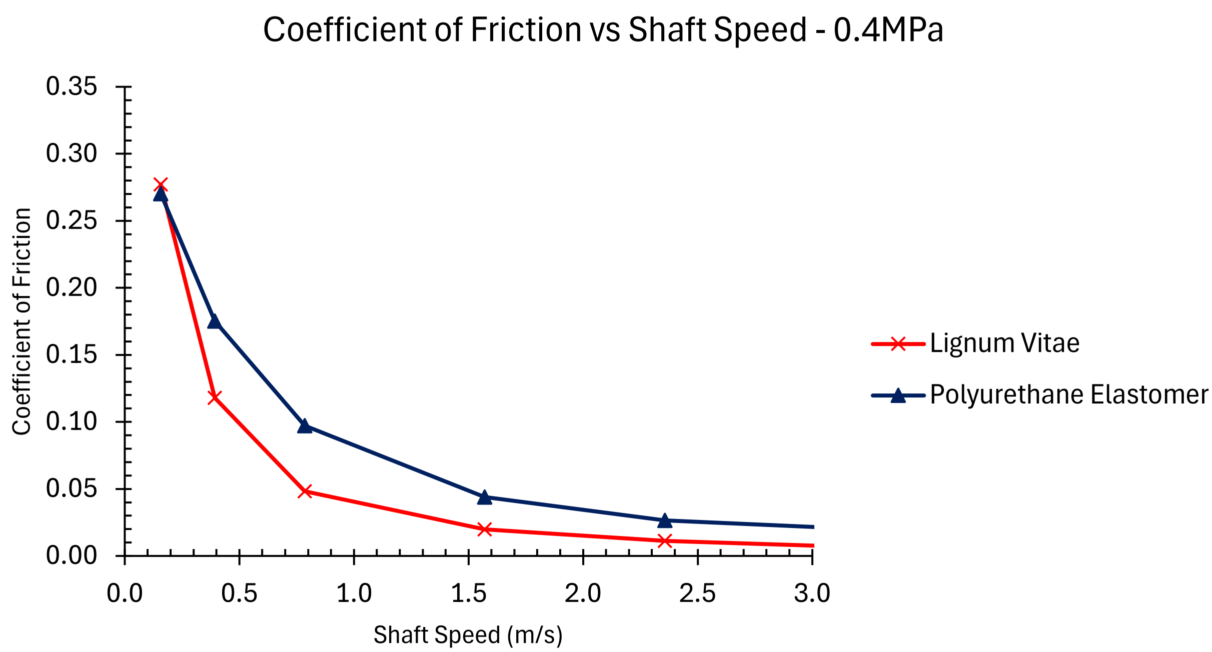


Figure 8. Comparison of Bearing Materials: Friction vs Shaft Speed at 0.4 MPa

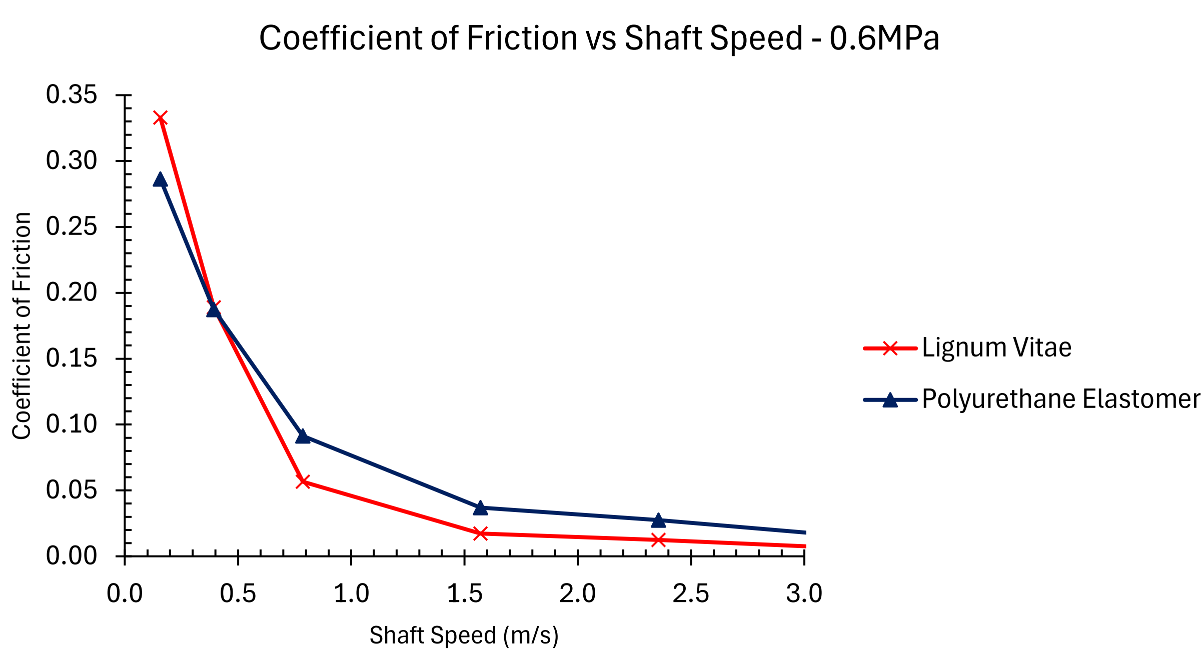


Figure 9. Comparing Bearing Materials: Friction vs Shaft Speed at 0.6 MPa

Wear of Water Lubricated Bearings

Wear testing was quantified by an accredited third-party laboratory using a Falex testing machine. Testing was completed in accordance with ASTM G77 Ranking resistance of materials to Sliding wear using Block-on-Ring wear test. The load was applied to the end grain. The samples were subject to a 10-minute break in period using 3.6 MPa at a shaft speed of 2.2m/s, after which the samples were tested at 5.1 MPa and a shaft speed of 4.4m/s for 1 hour. The wear was quantified by the mass lost as a percentage of the initial mass.

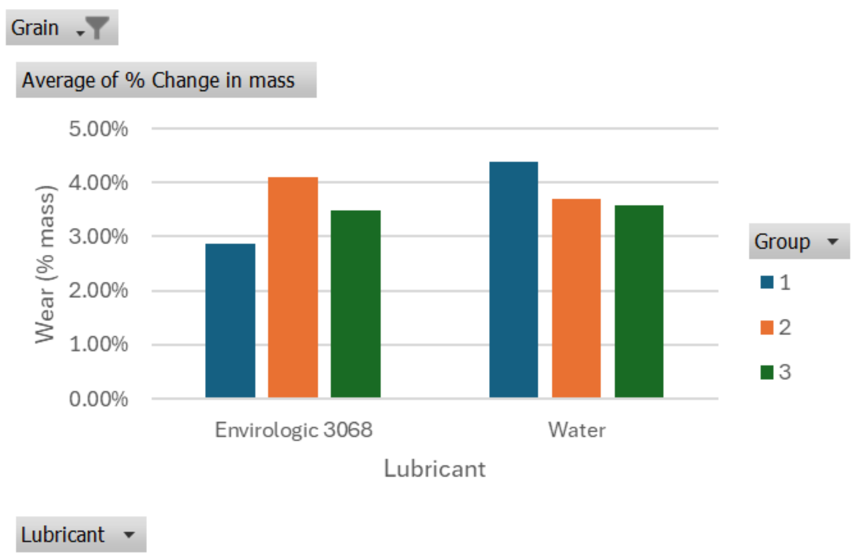


Figure 10. Wear vs Lubricant for Three Different Harvest Groups of Lignum Vitae

The wear results presented are for three groups of materials. Group 1 is a log harvested prior to World War 2, while group 2 is a log harvested around 1960, group 3 is a lignum vitae log that was harvested in the 2010's. The performance of the wood over time is consistent and the wood harvested today demonstrates the same performance as the wood used in the past.

Additional wear testing has been completed at speed-load combinations relevant to stern tube bearings on a machine built around the DNV-CP-0081 wear test standard. Wear is dependent on the lubricant properties (such as input temperature and cleanliness), shaft speed, and bearing load. A Lignum Vitae bearing was tested on a 50 mm shaft, with 0 eccentricity, lubricated with water at 25°C, and filtered at 100 microns at various speed and load combinations. The duration of testing was sufficiently long enough to demonstrate a steady state wear behavior after a running in period where surface discontinuities caused by machining were removed.

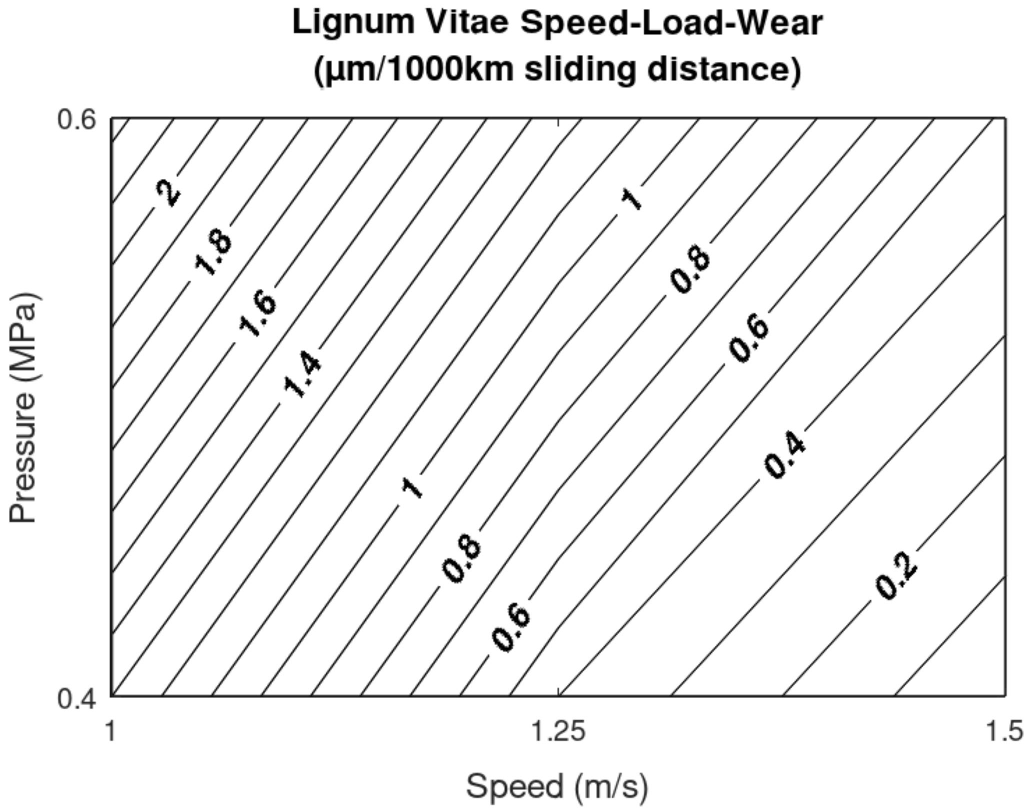


Figure 11. Image of wear map for lignum vitae wood; 0 eccentricity, 50 mm shaft, filtered water 100 microns.

It can be observed that increases in propulsion shaft speed and reductions in bearing load reduce the experienced wear while reducing the speed and increasing the load increased the wear experienced.

PHYSICAL PROPERTIES

During the operation of a bearing the friction forces will generate heat. Lignum vitae is a wood, it is an insulator with a low thermal conductivity. Typically, the lubricant flow is designed to remove the heat generated during operation. The maximum operating temperature for lignum vitae bearings operating in a wet environment is 80°C. This is because at this temperature the resin within the Lignum vitae begins to melt and be excreted by the material

Excretion of Lignum Vitae's Resin

An excretion was observed on the Lignum Vitae samples for temperatures at 60°C and 80°C. Images of the Lignum vitae are shown below. At temperatures of 50°C, a waxy film appeared on the surface, but no clumps of resin were present. The resin is denatured at temperatures equal to or above 60°C, becoming grit-like. At 40°C no film or grainy texture is observed on the Lignum Vitae samples. Images of the sample are shown.

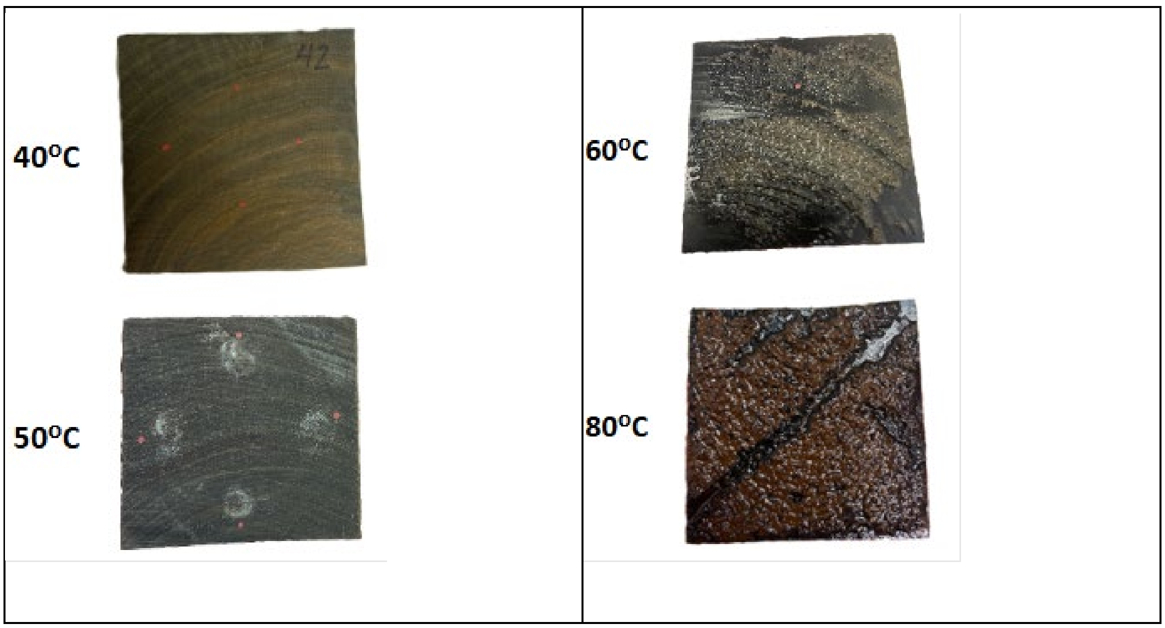


Figure 12. Lignum Vitae Samples at Four Different Temperatures

The resin may be extracted from the wood from heat alone, the wood does not need to be submerged in water. When extracted in atmosphere the resin has a hard feeling on cooling and appears black with a reddish tint.

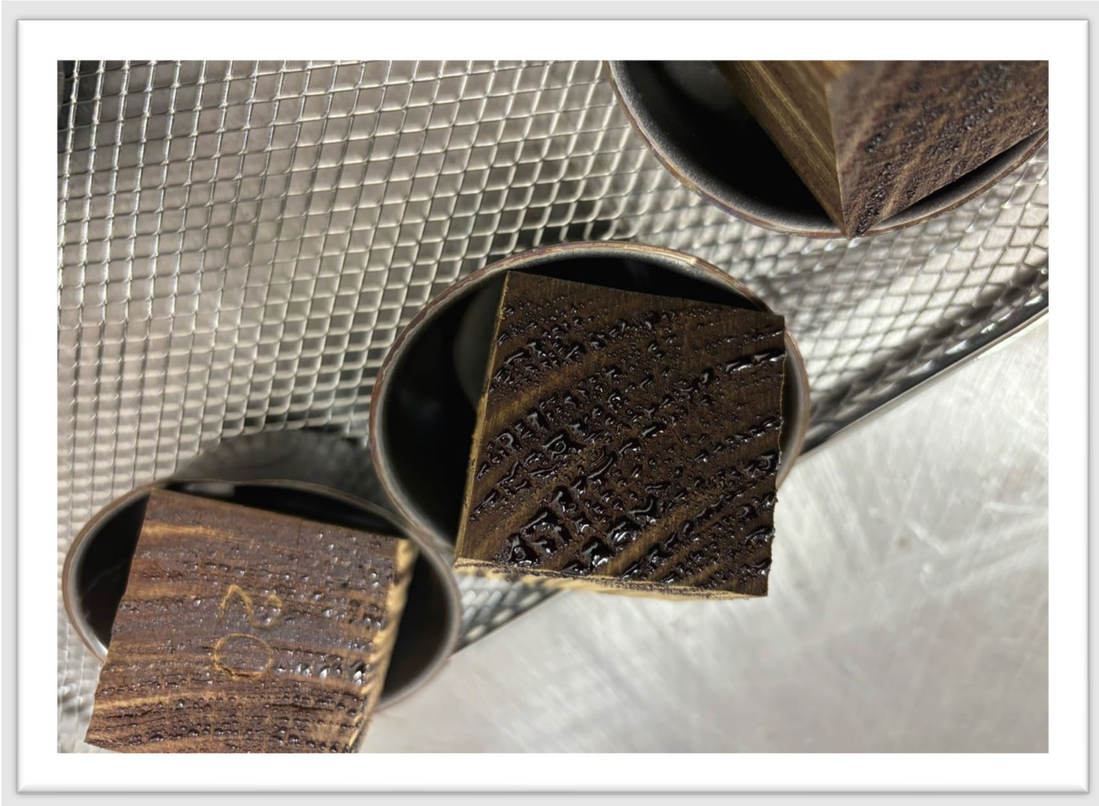


Figure 13. Image showing resin extracted from the wood after being subjected to temperatures greater than 120°C.

Operating Without Lubricant

It is highly advisable to use a lubricant when designing bearings from lignum vitae. Lignum vitae can endure brief periods of time with lubricant flow interruptions, however if the bearing is run dry for too long the material will char and crack after losing all the resin.

Figure 14. Charred Lignum Vitae Wear Samples

The maximum amount of time that lignum vitae can endure without proper lubrication is dependent on the shaft speed and the bearing load. For a specific application Hydro Tech can advise on the maximum allowable dry running period.

Effect of Water or Oil

Oil can be used as the lubricant for lignum vitae bearings. However, oil tends to cause lignum vitae wood to shrink instead of swell. Lignum vitae wood was immersed in various oils at 90psi and at atmospheric pressure.

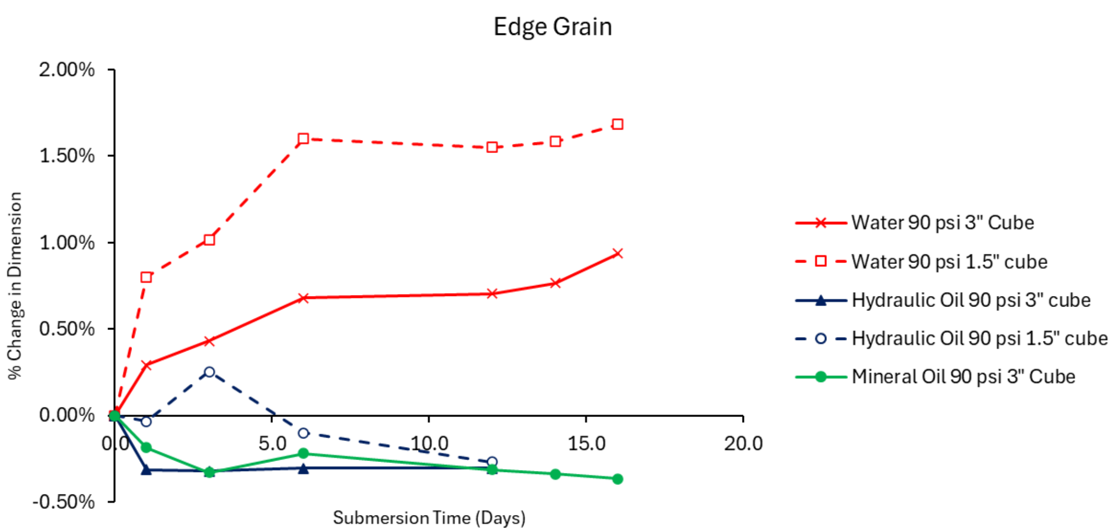


Figure 15. Edge Grain Dimensional Change of Lignum Vitae when Submerged in Water or Oil

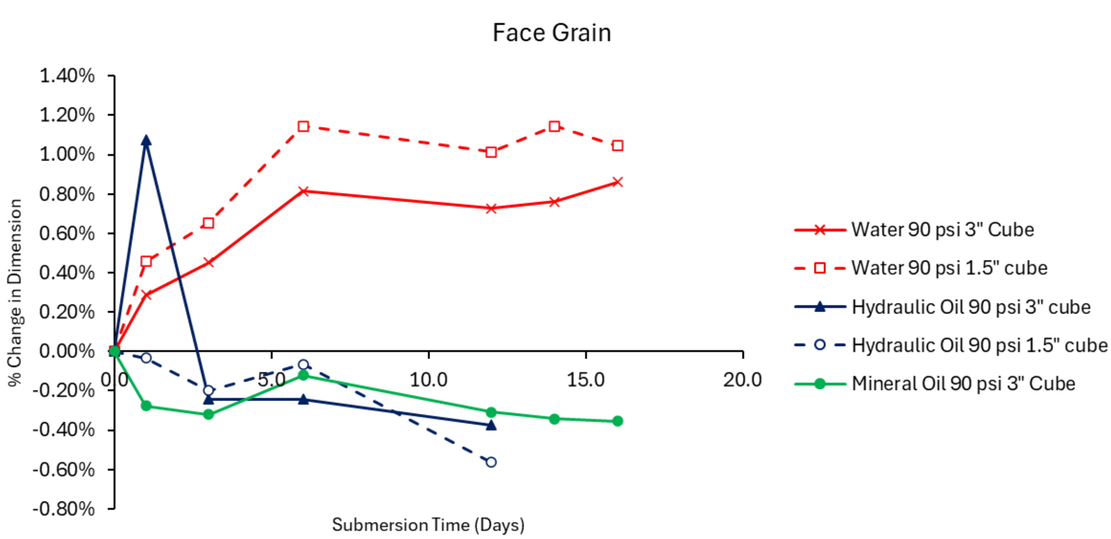


Figure 16. Face Grain Dimensional Change of Lignum Vitae when Submerged in Water or Oil

The results demonstrate that the oil causes a slight decrease in the face and edge grains whereas water causes the wood to swell. Thus, the chosen lubricant will impact the restraint design used to secure the bearing and the required amount of restraint to be applied.

It is important to note that different oils may contain additives and undergo transformations when exposed to seawater. These reactions may increase the acidity of the oil leading to damage of the bearing material. This is especially true of environmentally adoptable lubricants (EALs). Contact Hydro Tech to ensure the desired lubricant is suitable for the lignum vitae wood.

Stress Strain

Bearing materials are loaded in compression. As such compressive strength was evaluated using a compressive load applied by a tensile testing machine. This also provides the compressive modulus for the material. The bearing material is typically oriented so that the end grain aligns with the compressive load.

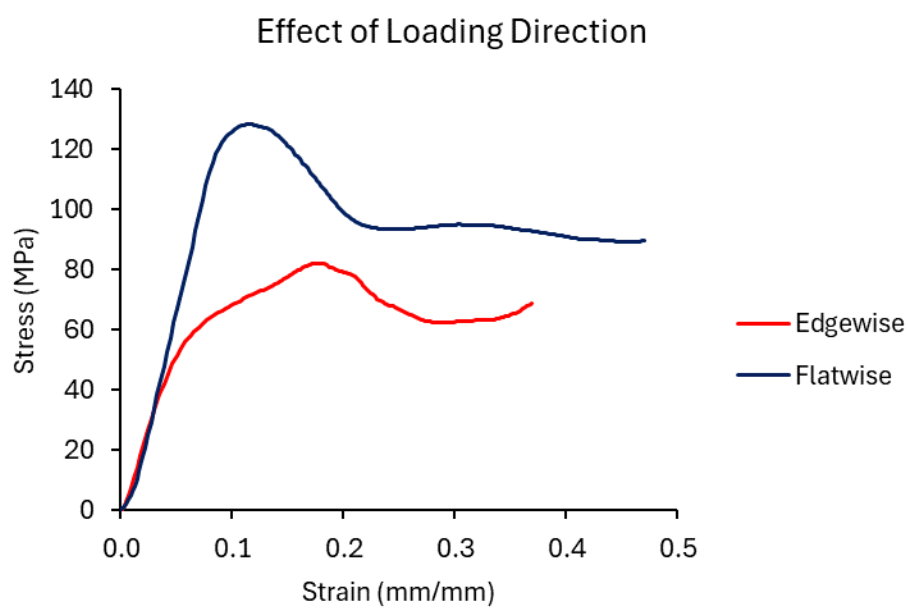


Figure 17. Stress vs Strain for Edgewise or Flatwise Loading of Lignum Vitae

The grain orientation will have a significant effect on the strength of the wood material. The average compression stress at yield for flatwise and edgewise samples were 121.3 ± 3.9 and 78.4 ± 7.1 MPa.

Effect of Water Saturation on Strength

The strength of wooden materials is proportional to the moisture content of the material. The lower the moisture content the higher the strength. The compressive strength of lignum vitae wood was tested in both the dry and saturated conditions in the flatwise direction. The average compressive strength and compressive modulus were 92.88 ± 3.82 MPa and 1228.76 ± 3.82 MPa for water immersed lignum vitae while air dried lignum vitae demonstrated an average compressive strength of 121.3 ± 3.9 MPa and compressive modulus of 1437.0 ± 165.1 MPa.

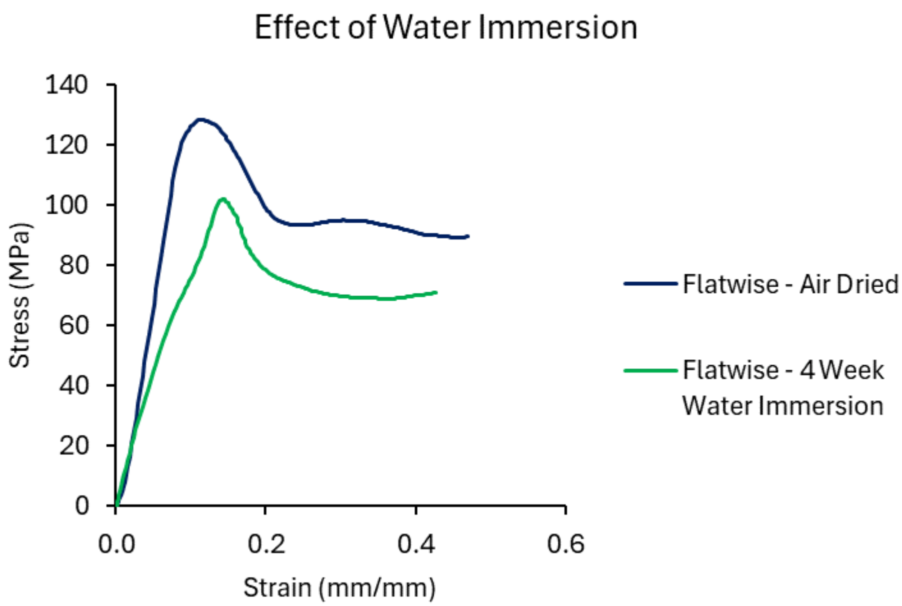


Figure 18. Effect of Water Immersion on Stress vs Strain for Flatwise Loading

The wood demonstrates an allowable design strength of 87.5 Mpa and 115.8 Mpa for saturated and dry respectively. Both values represent the lower tolerance limit using 5% rejection criteria – that is only 5% of lignum vitae wood demonstrates a lower strength than these values. The lower tolerance limit differs from the average value where 50% of the data would fall below the mean value.

Effect of Temperature on Strength

Lignum vitae wood shows little change in strength with increases in temperature up to 50oC. The material will not lose strength at typical operating temperatures. For elevated temperatures the average strength was 123.8 ± 21.9 Mpa while the dry was 121.3 ± 3.9 Mpa. Higher temperatures did lead to a higher variance in the result, but no significant deterioration in strength occurs. A change in the compressive modulus is observed as the wood becomes more pliable at elevated temperatures.

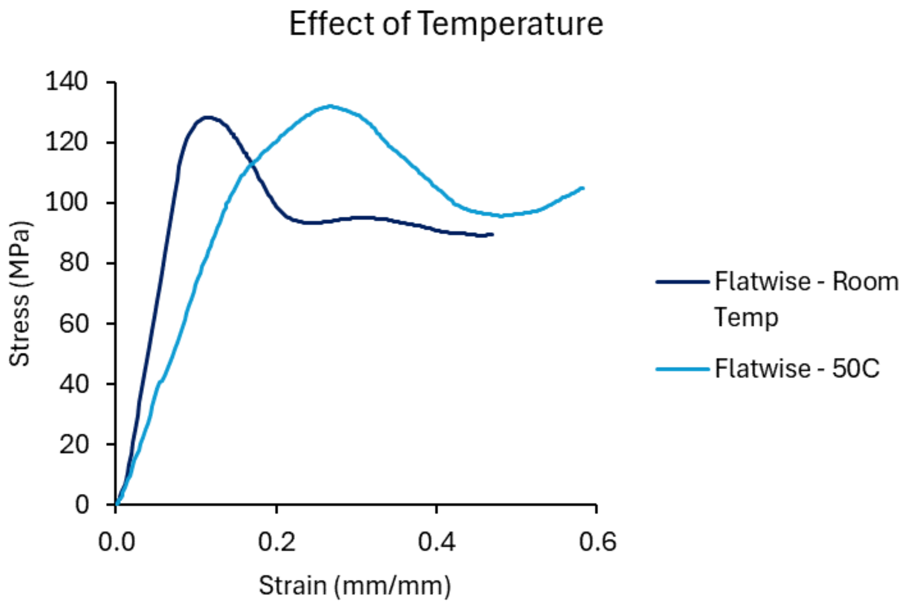


Figure 19. Effect of Temperature on Stress vs Strain for Flatwise Loading

Summary of Strength

Condition	Compressive Strength (MPa)	Compressive Modulus (Mpa)
Flatwise, dry, room temp	121.3 ± 3.9	1437.0 ± 165.1
Edgewise, dry, room temp	78.4 ± 7.1	-
Flatwise, water immersed, room temp	92.88 ± 3.82	1228.76 ± 3.82
Flatwise, dry, 50 C	123.8 ± 21.9	1156.4 ± 221.3

Compression Set, Creep and Stress Relaxation

Creep is the gradual deformation of a material when under an applied load. Lignum vitae wood will undergo creep if subjected to a significant load. Bearing loads are typically much less than the compressive strength even with adjustments made for temperature and water immersion. As such, the bearing is not greatly affected by the effects of creep. However, after installing the propulsion shafting small deflections (10 to 20 microns) in the bearing may occur over the first 48 hours. The amount of creep that will occur depends on the applied load, surface finish, temperature and moisture content of wood.

Lignum vitae wood was subject to a 1.0Mpa load and the change in thickness was measured over time. It was observed that the majority of the creep which is going to occur will happen within the first 48 hours of the load being applied.

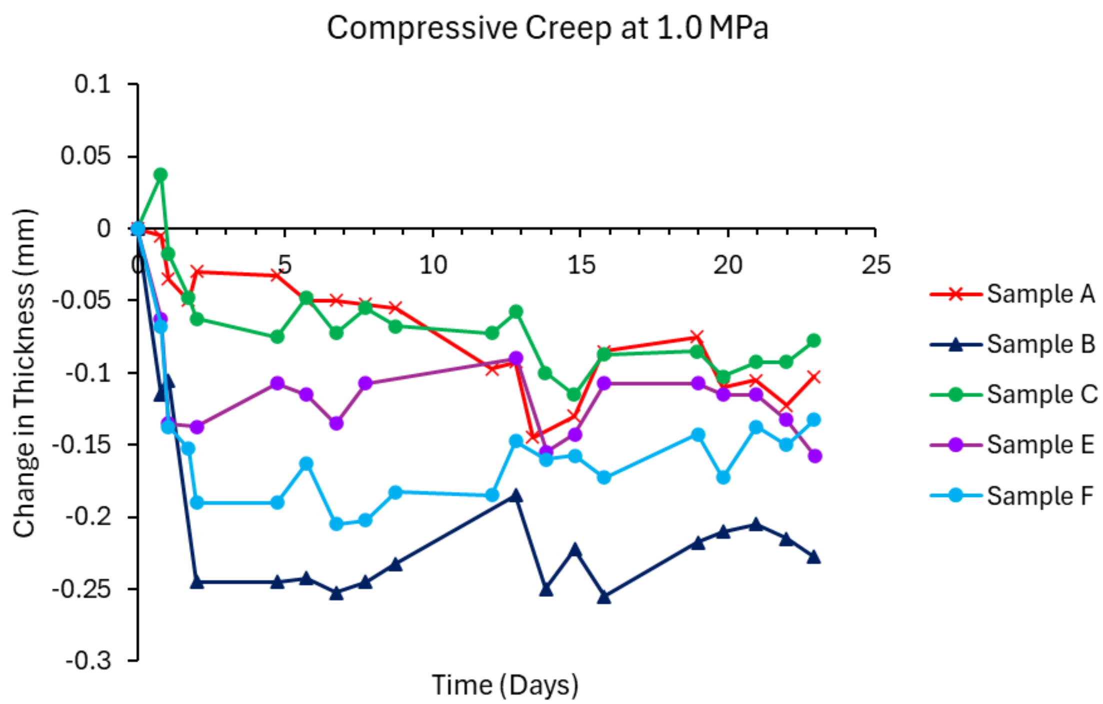


Figure 20. Compressive Creep of Five Lignum Vitae Samples

A portion of the compressive creep can be recovered after removing the applied load. Changes in thickness up to of a few microns can be observed 48 hours after the load is removed, beyond the first 48 hours there is not much further change in thickness.

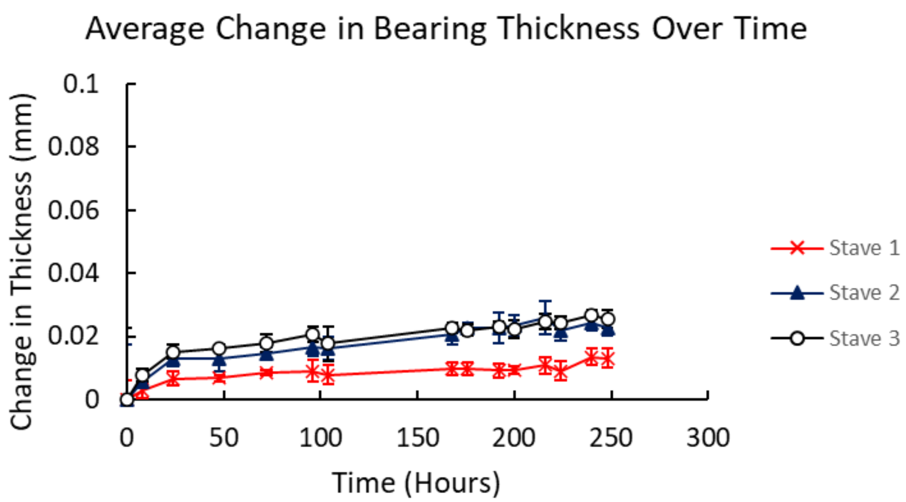


Figure 21. Change in Thickness vs Time for Three Staves

Impact Strength

Charpy impact strength was tested by an accredited laboratory. The impact strength was tested with the load oriented in both the edgewise and flatwise directions as the grain direction will affect the final strength.

Samples were prepared and tested as per ASTM D256. The average impact strength in the flatwise direction was 4.3 kJ/m^2 with a standard deviation of 0.5 while in the edgewise direction the impact strength was 3.4kJ/m^2 with a standard deviation of 0.6.

Chemical Resistance

Chemical	Rating
Salt Solutions	A
Seawater	A
Weak Acids	C-D
Strong Acids	C-D
Weak Bases	C-D
Hydrogen Peroxide 3%	A
Petroleum Jelly	B

Chemical	Rating
Sodium Silicate	C
Acetone	D
Isopropyl Alcohol	B
Detergents	B-C
Bar Soap	B-C
Vegetable Oil	A
Mineral Oil	A-B

A: Excellent – No Effect
B: Good – Little Effect
C: Fair – Moderate Effect
D: Unacceptable

PHYSICAL PROPERTIES

Mechanical Properties

LIGNUM VITAE
MATERIAL DATA SHEET

PROPERTY	UNIT		VALUE	
Compressive Strength (Dry)	Mpa	Psi	121.3	17590
Compressive Strength (Water Saturated)	Mpa	Psi	92.9	13470
Compressive Strength (50°C)	Mpa	Psi	123.8	17950
Compressive Modulus (Dry)	Gpa	Ksi	1.43	207.4
Compressive Modulus (Water Saturated)	Gpa	Ksi	1.23	178.4
Compressive Modulus (50°C)	Gpa	Ksi	1.16	168.2
Flexural Strength	Mpa	Psi	122.5	17770
Janka Hardness (11.27mm ball)	N	lbf	10000	2550
Rockwell Hardness (Rockwell M)	M Scale		45	
Maximum Temperature (ASTM D648)	°C	°F	100	212
Minimum Temperature	°C	°F	-45	-50
Poissons Ratio	Dimensionless		0.35	
Specific Gravity (Greenwood)	g/cm^3	lb/ft^3	1.35	84.3
Specific Gravity (Air Dried to 12% Moisture Content)	g/cm^3	lb/ft^3	1.15	71.8
Thermal Expansion	(mm/mm)/°C	(in/in)°F	4.7×10^{-5}	2.6×10^{-5}
Charpy Impact (Flatwise)	kJ/m^2	$ft\text{-}lbs/in^2$	4.3	2.0
Charpy Impact (Edgewise)	kJ/m^2	$ft\text{-}lbs/in^2$	3.4	1.6

ENGINEERING PROCESS

Identify the Problem

- Define the specific requirements and challenges for turbine bearings.
- Understand the operational conditions, including load, speed, and environmental factors.
- Establishing any additional requirements unique to the bearing application.

Research and Gather Information

- Conduct detailed research on existing water-bearing requirements.
- Gather information on materials, lubrication systems, and failure modes.

Specify Requirements

- Identify key performance criteria such as load capacity, lifespan, and thermal resistance.
- Define constraints such as size, weight, and compatibility with existing turbine components.

Brainstorm and Conceptualize

- Generate a range of potential bearing designs.
- Explore different geometries, space requirements, locations, and lubrication methods.

Develop and Evaluate Concepts

- Create preliminary sketches and models of the most promising bearing designs.
- Evaluate the feasibility of each concept based on performance requirements and constraints.

Select the Best Solution

Selecting the best solution from a range of design concepts is a critical step in the engineering design process. This step involves a thorough evaluation of each concept to ensure that the chosen solution meets all requirements and constraints. Here are the steps involved in selecting the best solution for an engineering design:

1. Define Evaluation Criteria

- Performance: Evaluate how well each concept meets the performance requirements.
- Cost: Consider both the initial development cost and long-term operational costs.
- Feasibility: Assess the technical feasibility of manufacturing and implementing each design.
- Reliability and Durability: Examine the expected lifespan and reliability of each design under operational conditions.

- Compliance: Ensure that each design adheres to industry standards and regulations.

2. Develop Evaluation Matrix

- Criteria Weighting: Assign weights to each criterion based on its importance.
- Scoring System: Develop a scoring system to rate each concept against the criteria.

3. Conduct Detailed Analysis

- Technical Analysis: Perform detailed technical analysis for each design, such as stress analysis, thermal analysis, and dynamic analysis.
- Cost-Benefit Analysis: Analyze the cost implications of each design, including manufacturing, maintenance, and lifecycle costs.
- Risk Assessment: Identify potential risks and uncertainties associated with each design and evaluate their impact.

4. Collect Feedback

- Stakeholder Input: Gather feedback from stakeholders, including engineers, customers, and end-users.
- Iterative Refinement: Use the feedback to refine and improve the designs.

5. Compare and Score

- Scoring: Use the evaluation matrix to score each design based on the defined criteria and collected data.
- Total Score Calculation: Calculate the total score for each design by summing the weighted scores.

6. Perform Sensitivity Analysis

- Assess Robustness: Conduct sensitivity analysis to determine how changes in criteria weights and assumptions affect the ranking of each design.
- Identify Critical Factors: Identify which criteria have the most significant impact on the decision.

7. Make Final Decision

- Review Scores: Review the total scores and sensitivity analysis results to identify the best overall solution.
- Consensus Building: Engage stakeholders in the decision-making process to build consensus and ensure support for the selected design.

- Final Selection: Choose the design that best meets the evaluation criteria and aligns with project goals.

8. Document the Decision

- Decision Rationale: Document the rationale for selecting the chosen design, including the evaluation process, scores, and feedback.
- Design Documentation: Update all design documentation to reflect the final selected design.

9. Plan for Implementation

- Implementation Strategy: Develop a detailed plan for implementing the selected design, including prototyping, testing, and production stages.
- Resource Allocation: Allocate resources and assign responsibilities for the next phases of the design process.

By following these steps, you can systematically evaluate and select the best solution for your engineering design, ensuring that it meets all requirements and constraints while optimizing performance, cost, and feasibility.

Develop Detailed Design

Developing the detailed design for bearings is a crucial phase that involves translating the selected conceptual design into comprehensive technical specifications and models. This phase ensures that the design is ready for prototyping, testing, and eventual production.

Here are the steps involved in developing a detailed design for turbine bearings:

1. Develop CAD Models

- 3D Modeling: Use Computer-Aided Design (CAD) software to create accurate 3D models of the turbine bearing. This helps in visualizing the design and performing various analyses.
- Part and Assembly Models: Develop separate models for individual parts and the overall assembly to ensure proper integration.

2. Create Detailed Drawings

- Engineering Drawings: Produce detailed engineering drawings with precise dimensions, tolerances, and annotations. These should include views and cross-sections to fully convey the geometry of the bearing.
- Assembly Drawings: Include assembly drawings showing how the bearing fits with other components of the turbine.

3. Material Selection

- Material Properties: Specify the materials for each component of the bearing, considering factors like load capacity, wear resistance, and thermal stability.
- Supplier Specifications: Include detailed material specifications and ensure compatibility with supplier capabilities.

4. Perform Detailed Analysis

- Finite Element Analysis (FEA): Conduct FEA to evaluate the structural integrity of the bearing under operational loads. Identify and address any areas of high stress.
- Computational Fluid Dynamics (CFD): Perform CFD analysis to optimize lubrication flow and minimize friction and heat generation.

5. Design for Manufacturability

- Manufacturing Processes: Specify the manufacturing processes required for each part, including machining, heat treatment, and surface finishing.
- Tolerances and Fits: Define precise tolerances and fits to ensure proper assembly and operation. Use geometric dimensioning and tolerancing (GD&T) standards.

6. Design for Assembly and Maintenance

- Ease of Assembly: Design the bearing for ease of assembly, considering factors such as alignment, fastening, and accessibility.
- Maintenance Requirements: Ensure that the bearing design facilitates easy maintenance, including lubrication, inspection, and replacement.

7. Documentation

- Technical Specifications: Prepare detailed technical specifications for each component and the overall bearing assembly.
- Bill of Materials (BOM): Create a comprehensive BOM listing all parts, materials, and quantities required for the bearing.

8. Quality Control Plans

- Inspection Criteria: Define inspection criteria and quality control procedures to ensure that each bearing meets the design specifications.
- Testing Protocols: Develop testing protocols to validate the performance and reliability of the bearing.

9. Review and Approval

- Design Reviews: Conduct formal design reviews with stakeholders to ensure that all requirements are met, and any potential issues are addressed.
- Approval: Obtain final approval from relevant authorities and stakeholders before proceeding to prototyping and testing.

By following these steps, the detailed design phase ensures that the turbine bearing is fully developed, documented, and ready for the next stages of prototyping and testing. This meticulous process helps in minimizing errors and ensuring the reliability and performance of the final product.

DESIGN GUIDELINES

A) Application Analysis

To conduct a thorough analysis of an application, it's essential to examine and accurately assess all relevant information. These factors include:

- Temperature: The operational temperature range within which the bearing will function, affecting material selection and performance characteristics.
- Environment: Whether the operational environment is abrasive, potentially leading to increased wear, or clean, which may reduce wear but still requires consideration for material compatibility.
- Pressure: The load or stress that will be applied to the bearing, influencing material strength and durability requirements.
- Sliding Velocity: The speed at which the bearing will move relative to its mating surface, impacting lubrication needs and wear rates.
- Lubrication Groove: To aid the flow of lubricant through the bearing. Facilitate abrasive to pass.
- Size: The dimensions of the bearing must be compatible with the space available and the operational requirements of the application.
- Historical Material Performance: Any issues or successes with previously used materials, guiding the selection of new materials for improved performance.
- Mating Surface Characteristics: The properties of the surface against which the bearing will operate, including hardness and finish, which affect wear and operational efficiency.
- Life Expectancy: The anticipated operational lifespan of the bearing, dictating material selection and design for durability.
- Operational Cycle: The frequency and pattern of use, including any cyclic loads or conditions that the bearing must withstand.
- Initial Clearance: The required space between the bearing and its housing or shaft at installation, ensuring proper fit and function

B) Bearing Pressure

Bearing pressure is calculated by dividing the radial load by the projected or cross-sectional area. The projected area is determined by multiplying the inside diameter of the bearing by the bearing length, as illustrated in Fig.1. Using the inside diameter multiplied by the bearing length is a standard method in the bearing industry for calculating the projected area for bearing pressure. By dividing the load by the projected area, we can obtain an approximate pressure value, assuming uniform pressure distribution across the bearing area.

However, in practice, the pressure distribution is not uniform. The pressure is highest at 270° and decreases in a parabolic curve to zero, where the shaft begins to have clearance with the bearing. Consequently, to optimize load-carrying capacity, it is advantageous to minimize running clearances.

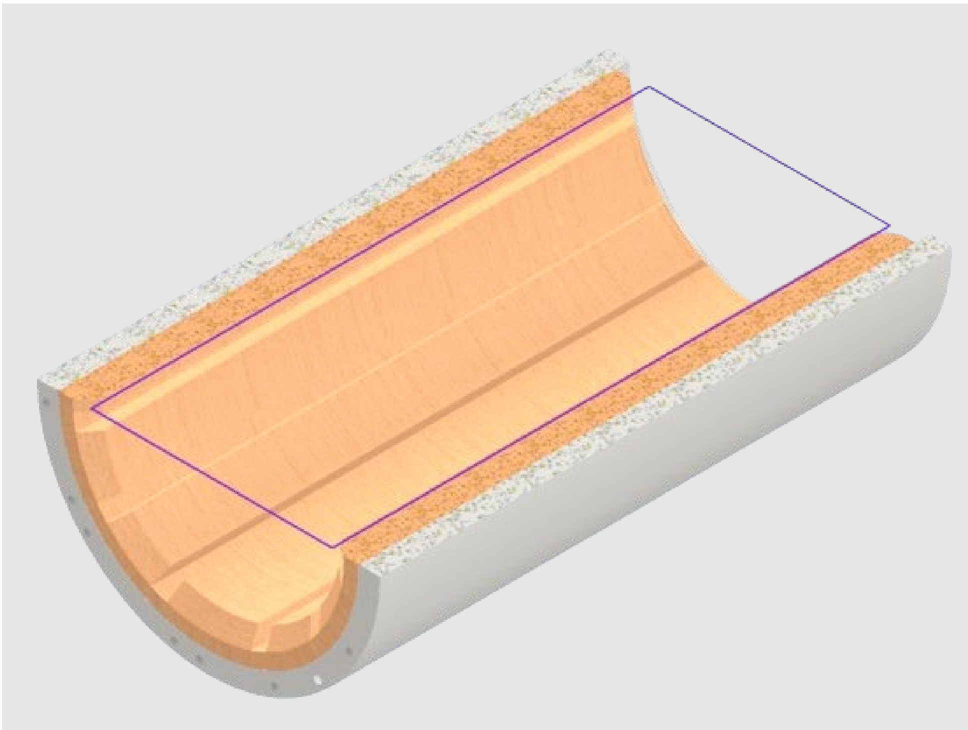


Figure 23: Projected Area of a Bearing Pressure = $\frac{\textbf{Radial Load}}{\textbf{Projected area/cross section } (L \times I.D.)}$

Where, the radial load is either the maximum load anticipated during design, the typical load encountered during regular operation, or a mix of both static and dynamic (impact) loads.

C) Velocity

The rate of sliding or circumferential speed of the shaft plays a crucial role in design considerations. This factor is pivotal when assessing the generation of heat due to friction. For rotating shafts, the calculation of this velocity is determined by the given formula.

$$V\ (\text{m/s}) = \frac{\pi dN}{60 \times 1000} \text{ or } \frac{dN}{19100} \qquad \text{(metric)}$$

$$V\ (\text{fpm}) = \frac{\pi dN}{12} \text{ or } .262\ dN \qquad \text{(imperial)}$$

where:

V = Sliding Velocity

d = Shaft Diameter (mm or in.)

N = Shaft RPM

π = constant 3.1416

D) Length/ Diameter Ratio (L/D)

L/D ratio is a fundamental design consideration that influences a bearing's performance, durability, and suitability for specific applications. For applications involving water-lubricated propeller shaft bearings, a traditional L/D ratio varies from 2:1 to 4:1 depending on the application, which has been preferred to maintain lower bearing pressures. Selecting an L/D goes beyond a set value, many factors need to be considered like heat dissipation, lubrication flow, friction and efficiency. Therefore, Hydro Tech determines the ratio by considering all these factors along with operating conditions and the pressure acting on the bearing surface.

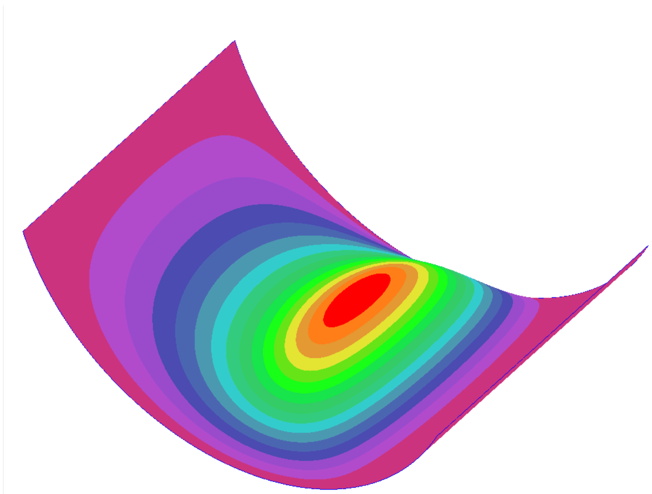


Figure 24: Hydro Tech performing CFD to determine optimal L/D ratio in an application.

E) Wall Thickness

As a general rule shaft sizes under 200 mm (8”) can have a wall thickness as thin as 12.7mm (0.5”). For larger bearings 19mm (0.75”) wall thickness is required. Bolted-in-place staves are easier to accomplish than solid tubes which are aided by extra wall thickness for ease of installation and manufacturing. To stay within practical manufacturing constraints, wall thickness should increase proportionately with shaft diameter.

F) Lubrication Grooves

In applications where liquid flows over the bearing surface, lubrication grooves are integrated into the bearing design by machining the staves. These grooves facilitate the distribution of lubricant across the bearing, enhancing lubrication efficiency. Additionally, they serve as conduits for the expulsion of abrasive particles, thereby protecting the bearing surface. The specifications of these grooves, including their number, depth, and width, are tailored according to the bearing's size, design, and the thickness of the material. While the width of these grooves is typically similar to their depth, adjustments can be made based on heat transfer and cooling requirements. LV bearings can be designed with solid bottom as well as grooved.

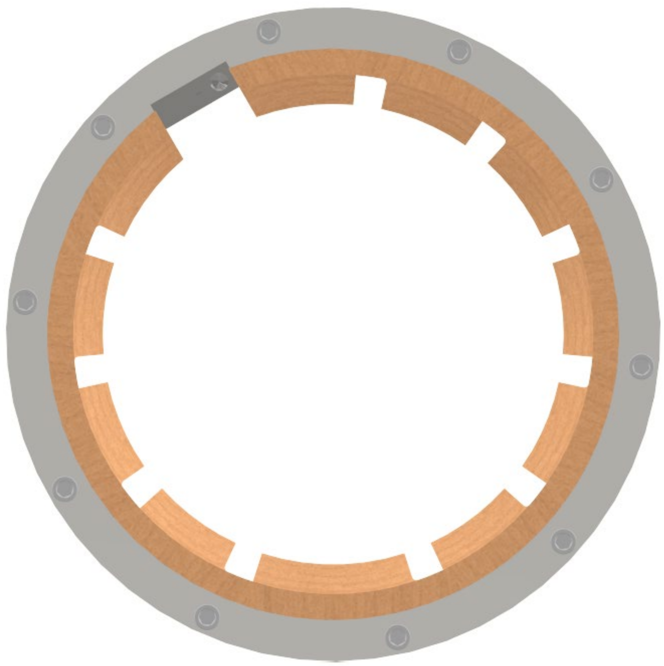


Figure 25: Lubrication groove in a Stern Tube Bearing designed by Hydo Tech.

G) Mating Surface Characteristics

For water-lubricated propeller shaft bearings, LV bearings have worked with all types of shaft material that Hydro Tech worked on so far. Stainless steel, aluminum bronze, or marine bronze remains a popular choice for shaft liners due to its corrosion resistance and compatibility with various bearing materials, including lignum vitae. However, in abrasive conditions, it is advisable to select harder or abrasive-resistant material steel grades, over softer ones like 304, to prevent excessive wear.

To minimize initial wear during the bedding-in period, the mating shaft's surface finish should be as smooth as feasible. A normal machined finish on the shaft is typically adequate for lignum vitae bearings to perform effectively. For optimal results, a final machined surface finish of the mating shaft between 0.4 to 0.8 micrometers (16 to 32 micro-inches) Ra is recommended.

H) Fitting

Bolting each stave individually is the most robust and preferred method for securing staves; however, this approach may not be practical for all applications. Therefore, when fitting LV bearings, the tapered key design is the most effective and reliable option as shown in Figure 4. Alternative methods, such as using low-viscosity epoxy to bed tubes, can work well, especially if the housing is out of round. However, these methods can make it impossible to remove the bearing from the housing without causing damage. Interference fits are challenging to achieve consistently due to the shrink-swell potential of LV materials.

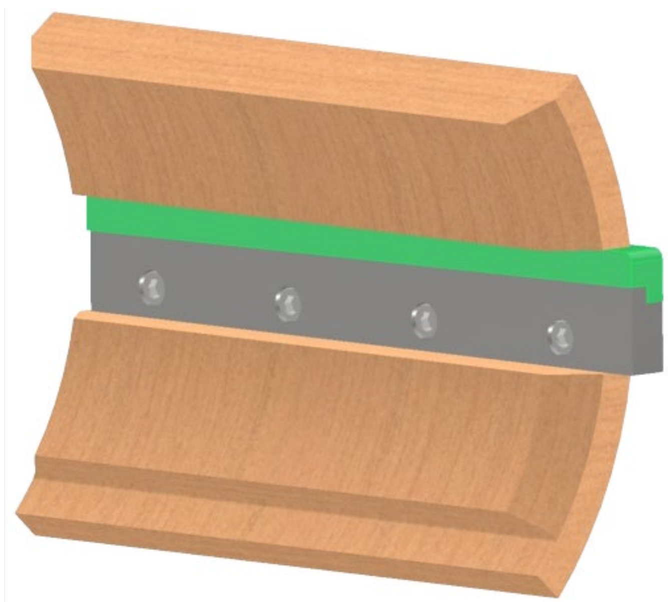
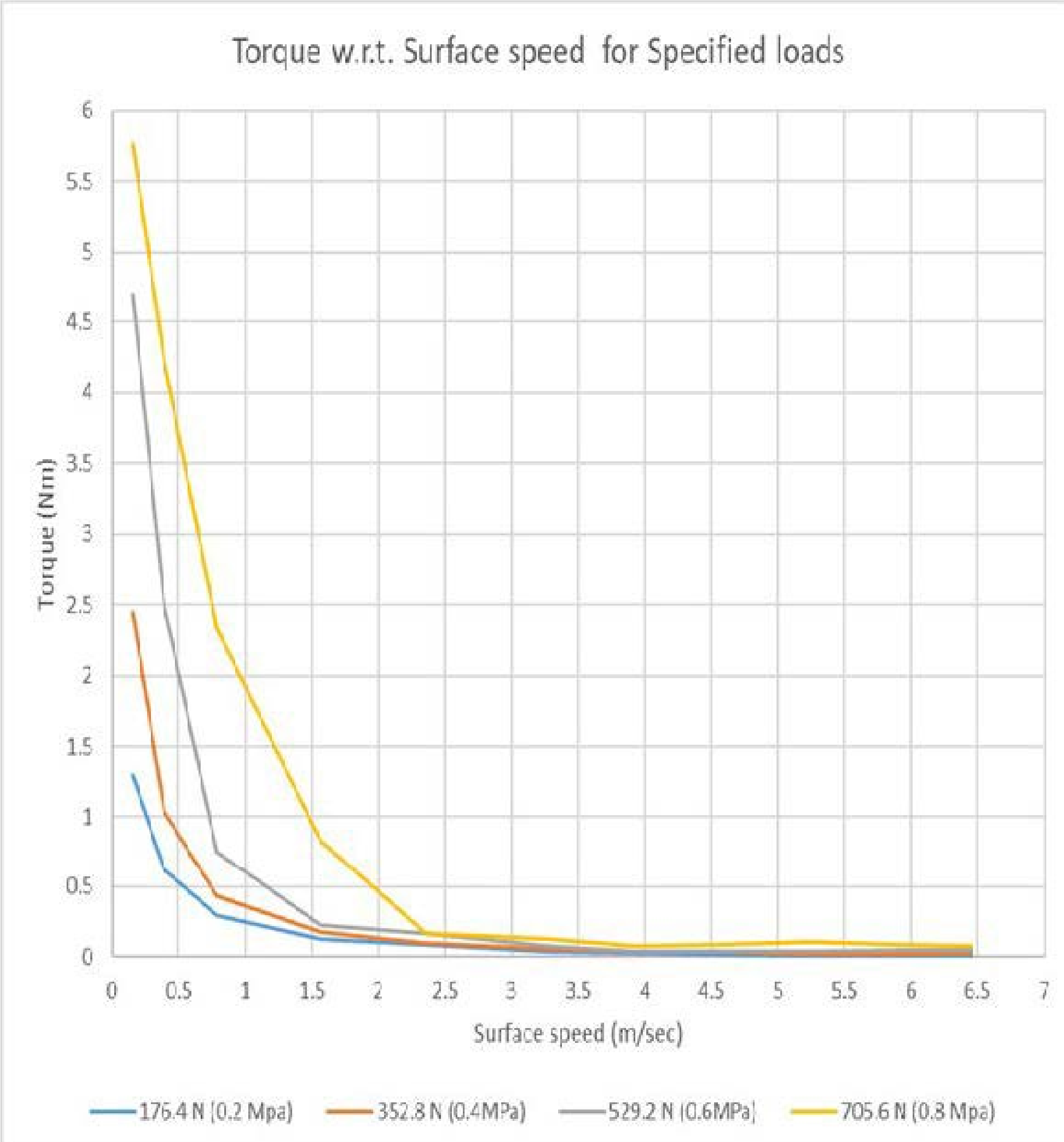


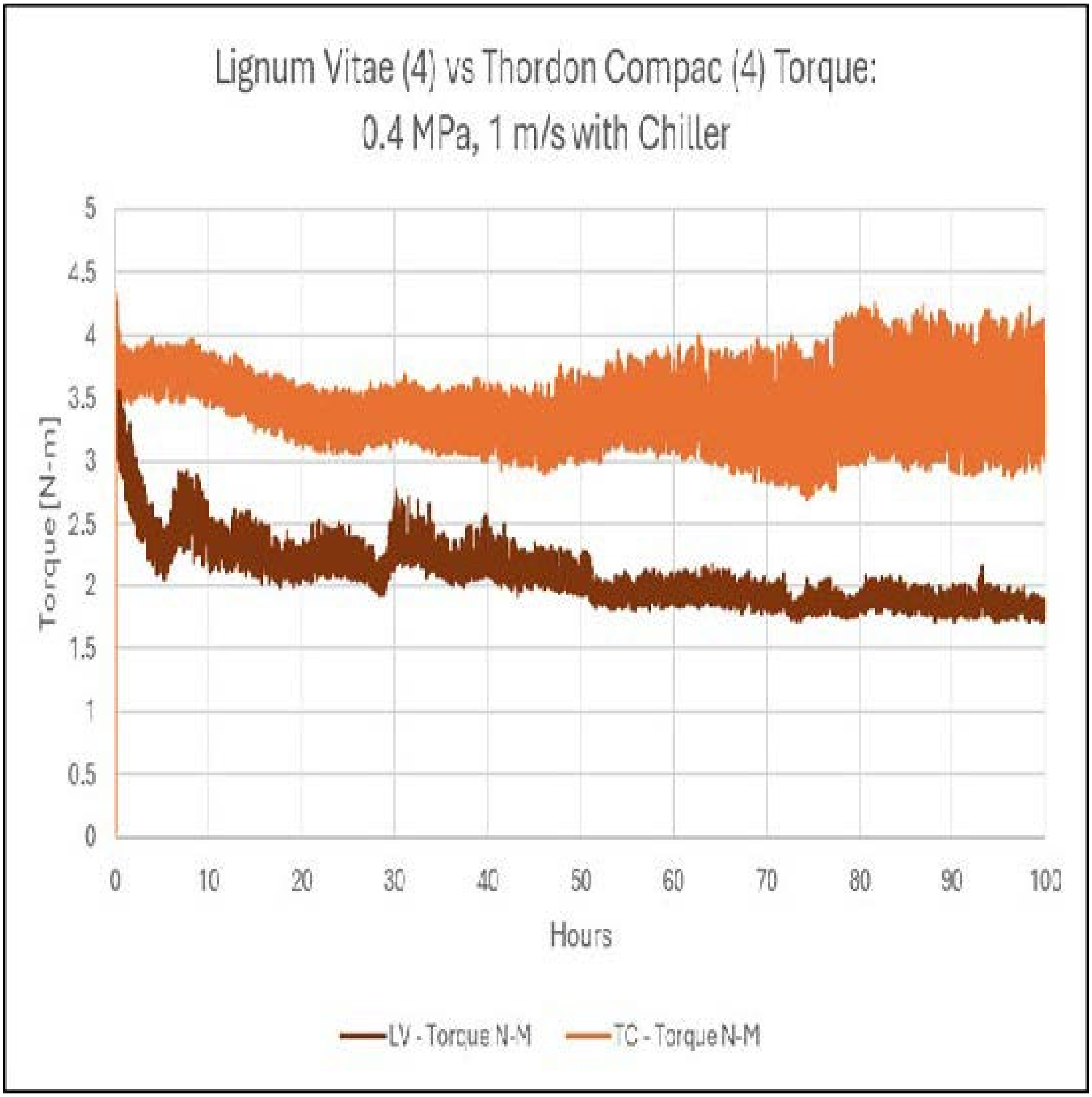
Figure 25: The tapered key is designed by Hydro Tech for optimal fitment.

If an anti-rotation bar is not installed, appropriately sized dowels should be used instead to prevent rotation. Bolting a single stave in place can also be an effective way to prevent the staves from rotating. Adhesive alone should not be used as the sole means of securing the bearing, as LV materials are resistant to bonding with glues and epoxies. Mechanical methods of securement are necessary for all applications.

I) Initial Clearance

By using end grain staves we eliminate changes to the bearing wall thickness due to shrinking and swelling of the wood. The staves will shrink and swell in width which may cause them to become loose in the housing if the housing is dewatered and allowed to dry. We recommend installing material that is not fully saturated (75% or below). This


Torque w.r.t. Surface speed for Specified loads
Torque (Nm)
0
0.5
1
1.5
2
2.5
3
3.5
4
4.5
5
5.5
6
0
0.5
1
1.5
2
2.5
3
3.5
4
4.5
5
5.5
6
6.5
7
Surface speed (m/sec)
176.4 N (0.2 Mpa)
352.8 N (0.4MPa)
529.2 N (0.6MPa)
705.6 N (0.8 Mpa)



Lignum Vitae (4) vs Thordon Compac (4) Torque:
0.4 MPa, 1 m/s with Chiller
Torque [N-m]
5
4.5
4
3.5
3
2.5
2
1.5
1
0.5
0
0
10
20
30
40
50
60
70
80
90
100
Hours
LV - Torque N-M
TC - Torque N-M

allows the remaining swell potential to aid in a tight fitment once the bearing is introduced to water. This also prolongs the time that the bearing can be kept dry without the loss of fitment.

J) Material Selection Process for Lignum Vitae Bearings

Selecting lignum vitae for bearings involves a thorough evaluation to ensure it meets the specific requirements of the application. Follow these steps to guide the material selection process:

1. Define Application Requirements
   - Operational Environment: Assess the conditions in which the bearings will be used, including exposure to moisture, chemicals, or extreme temperatures.
   - Load and Stress Factors: Determine the load-bearing capacity and shock loading conditions the bearings will need to withstand.
   - Performance Characteristics: Identify key performance attributes such as wear resistance, friction reduction, and self-lubrication needs.

2. Material Assessment
   - Physical Properties: Verify that the lignum vitae's density, hardness, and strength align with the application's demands.
   - Natural Lubrication: Ensure the self-lubricating properties of lignum vitae will enhance performance and longevity in the given environment.
   - Corrosion and Wear Resistance: Confirm that its resistance to corrosion and abrasion meets the application's requirements.

3. Environmental and Sustainability Considerations
   - Environmental Impact: Evaluate the environmental benefits of using lignum vitae, such as its renewable nature and lower environmental impact compared to synthetic alternatives.
   - Storage and Preservation: Follow proper storage procedures to maintain the material's properties and avoid deterioration.

By following this comprehensive selection process, you can ensure that lignum vitae bearings are appropriately chosen and will deliver optimal performance in your specific application.

Thermal Expansion

Lignum vitae is a wood and therefore an insulator. It is subject to some thermal expansion. When heated the wood will expand in the endgrain direction at an average value of $4.7 \times 10^{-5} \pm 6.8 \times 10^{-6}$/°C, however in the radial direction we observe an average expansion of $-6.83 \times 10^{-7} \pm 1.4 \times 10^{-6}$/°C. Note that the negative value indicates a contraction – that is the wood will shrink. It is worth pointing out that the coefficient is very small, and the effects of thermal expansion are not significant to the performance of lignum vitae.

Water Swelling

Wood swells when immersed in water. The amount of swelling is a function of the moisture content to which the wood was allowed to dry. Furthermore, at elevated temperature the wood may swell more.

To determine the effects of water absorption at elevated temperature lignum vitae wood was subjected to salt water at various temperatures. Due to the orthotropic nature of wood the changes the wood expands differently for different grain directions.
The effects of grain orientation were analyzed by calculating an expansion coefficient for a given grain direction.

$$C_e = \frac{Measurement_{final} - Measurement_{initial}}{Measurement_{initial}}$$

Where Ce is the coefficient of expansion in mm/mm.

The results were compiled for wood which was properly stored "wet shipped" having a moisture content of greater than15% and for wood which was permitted "dry shipped" having a moisture content of less than 8%.

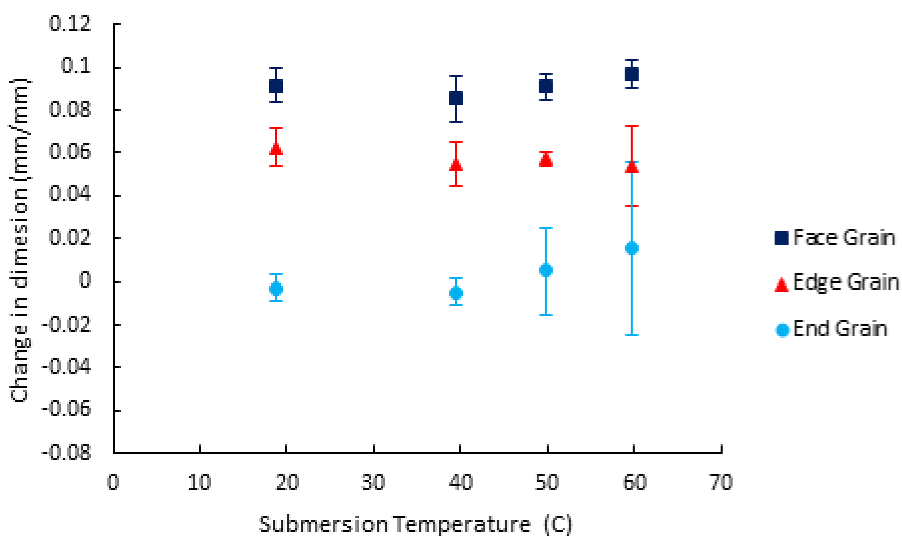


Figure 26. Change in Dimension vs Submersion Temperature for Each Grain Direction

Coefficient of expansion vs. submersion temperature for various grain directions of dried lignum vitae (less than 8% Moisture content). Error bars show 95% confidence interval.

Finally, the volumetric change in the wood was compared to polyurethane elastomers.

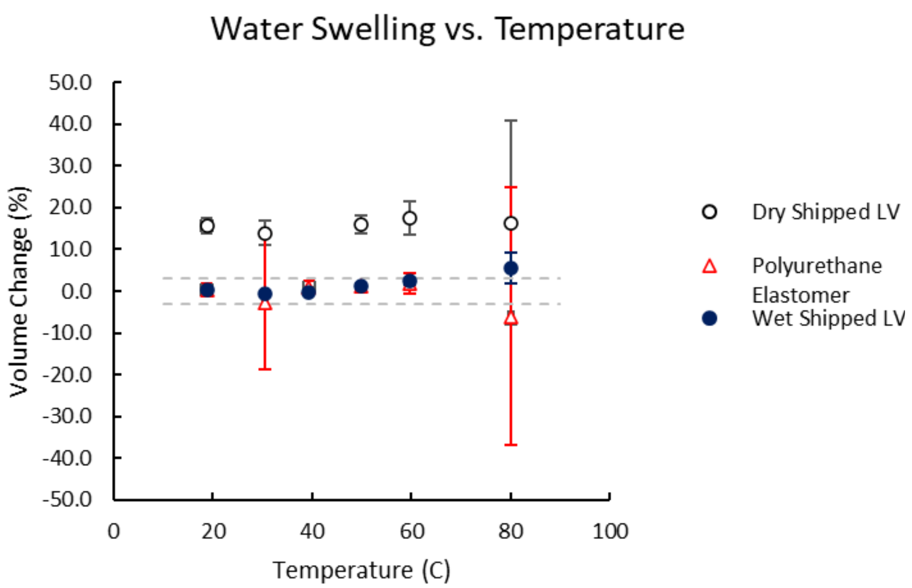


Figure 27. Comparing Bearing Materials: Water Swelling vs Temperature

The dry shipped Lignum Vitae demonstrated volumetric swelling ranging from 13.9% to 17.4% for the temperatures studied. The dry shipped Lignum Vitae also demonstrated a larger variance compared to wet shipped Lignum Vitae.

Above 60°C, the wet shipped lignum vitae begins to expand beyond 3%. Similarly, the Polyurethane elastomer also swells beyond 3% at 60°C. It is worth noting that the polyurethane elastomer is not recommended for use above 60°C. At high temperatures (80°C), all bearing materials experienced large volumetric changes and a large variation within the results.

APPLICATION DESIGN

A) Application Design

Lignum vitae bearings can be installed mostly using mechanical aids like keeper strips/ tapered keys or in some cases low-viscosity epoxy to bed tubes in out-of-round housings. When opting for mechanical aids, considerations such as interference, bore closure, running clearance, water absorption, and swelling must be considered.

To aid in the precise dimensioning of Lignum vitae bearings, Hydro Tech performs engineering calculations and uses specialized software programs to streamline the process of calculating the necessary dimensions.

Hydro Tech considers the following key parameters when sizing Lignum vitae bearings:

Housing Size and Tolerance: Ensure that the housing can accommodate the bearing and allow for any necessary clearances.

Shaft Diameter and Tolerances: The shaft must be compatible with the bearing's internal diameter, considering any swelling of LV. (a slight change due to swelling gets compensated during bedding period)

Length of Bearing: The bearing length should match application requirements, ensuring adequate support and load distribution,

Operating Temperatures: Account for the potential expansion or contraction due to temperature fluctuations.

Machine Shop: Consider the ambient temperature and moisture content of LV during installation, as it may affect the initial fitting of the bearing.

Retention Method: To secure the bearing in its housing mostly by mechanical aids like keeper strips or keys.

B) Bore Closure

This phenomenon occurs due to the volumetric displacement of the bearing material caused by the pressure exerted from the housing during installation. Hydro Tech calculates bore closure considering material properties of LV like the modulus of Elasticity and based on the operating condition of each application due to variable factors like temperature, wall thickness, and fit. Lignum vitae has a relatively low modulus of elasticity compared to bearing materials, which affects how much it compresses under load. It is typically around 1100 to 1500 MPa.
Bore closure can be calculated using the formula for radial deformation due to interference:

$$\Delta \text{Bore} = \frac{D_i \times P}{E}$$

Where:

- ΔBore= Change in bore diameter (bore closure)
- D_i= Initial inside diameter of the bearing
- P = Pressure exerted on the bearing material due to interference
- E = Modulus of elasticity of lignum vitae

C) Running Clearance

Diametrical running clearance is crucial for ensuring proper operation of the bearing within its application. It accounts for the necessary space between the shaft and the bearings inside diameter once the bearing is installed and operational, considering factors that could cause the bearing to expand or contract. These factors include temperature changes and variable speed, which are particularly relevant for bearings made from materials susceptible to dimensional changes due to these external conditions. Hydro Tech calculates running clearance by considering the operating conditions like speed and load, and environmental conditions like temperature. To effectively design a bearing application, Hydro Tech utilizes CFD to include all critical design parameters and simulate with different running clearance and compare the bearing performance to find the optimal clearance.

D) Minimum Installed Clearance

Referencing figure 28. Lignum Vitae wants to run a tighter clearance as low as 75% of the industrial chart. Too tight of a clearance would present issues with shaft installation but not affect the functionality of the bearing.

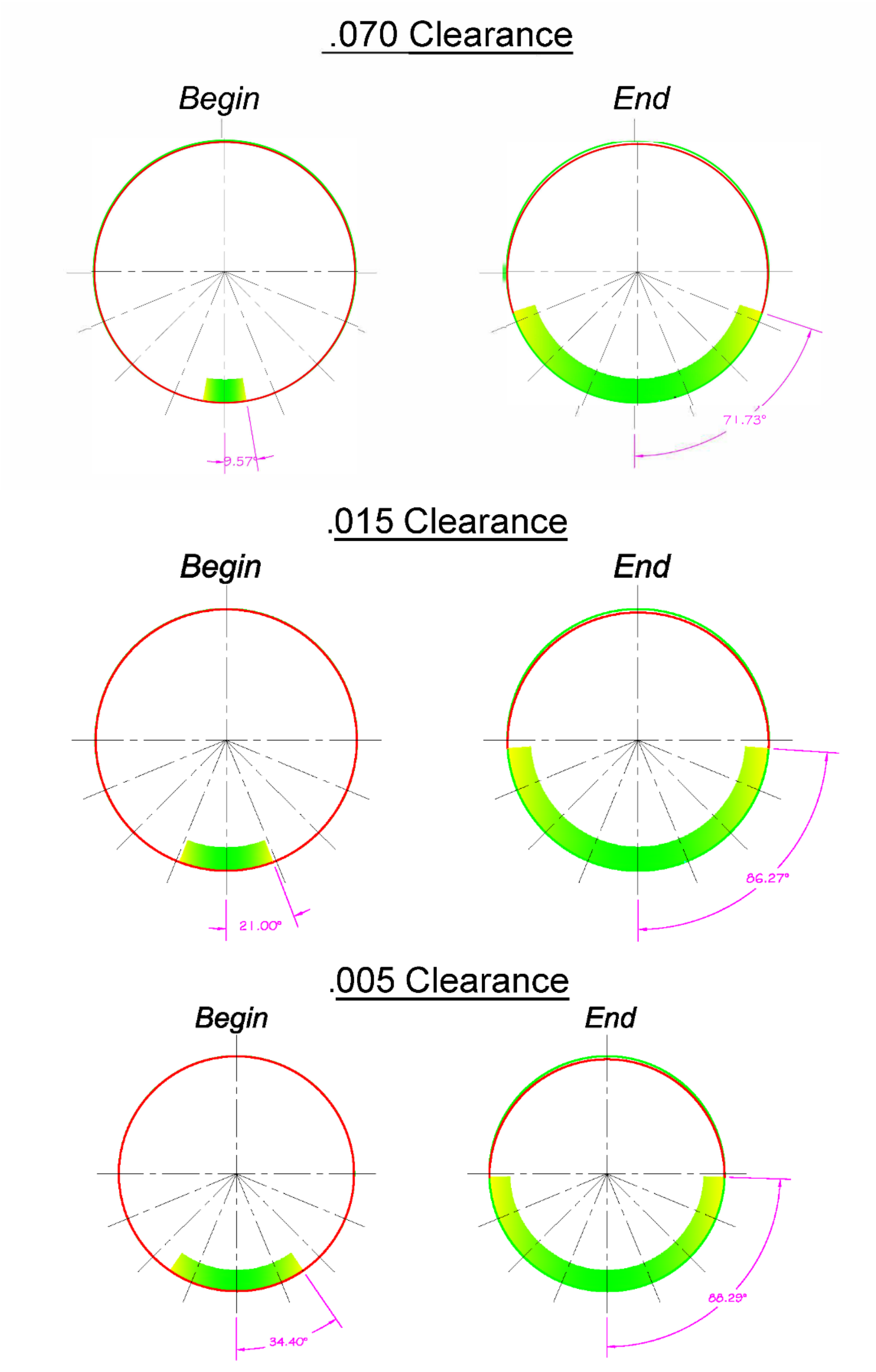

.070 Clearance
Begin
End
9.57°
71.73°
.015 Clearance
Begin
End
21.00°
86.27°
.005 Clearance
Begin
End
34.40°
88.29°

Figure 28.

BIBLIOGRAPHY

[1] S. J. Record, "Lignum-Vitae: A Study of the Woods of the Zygophyllaceae with Reference to the True Lignum-Vitae of Commerce - Its Sources, Properties, Uses and Substitutes," *Yale University School of Forestry Bulletin No 6,* 1921.

[2] C. S. Sargent, Silva of North America, Cambridge: The Riverside Press, 1890.

[3] Department of Scientific and Industrial Research - Forest Products Research, A Handbook of Empire Timbers, London: His Majesty's Stationary Office, 1939.

[4] S. J. Record and R. W. Hess, Timbers of the New World, New Haven: Yale University Press, 1943.

[5] A. Galletly, "Wood of Certain Resin Producing Trees," *Trans. Bot. Soc. Edin,* vol. 16, pp. 381-388, 1889.

[6] M. Chudnoff, Tropical Timbers of the World, Madison: USDA Forest Products Laboratory, 1980.

[7] H. Stone, The Timbers of Commerce and Their Identification, New York: D Van Nostrand Company, 1918.

[8] F. R. Longwood, Agricultural Handbook No. 207 - Present and Potential Commercial Timbers of the Caribbean, Washington, D.C.: USDA Forest Service, 1962.

[9] R. W. H. Samuel J Record, Timbers of the New World, New Haven: Yale University Press, 1943.

[10] S. Greene, "An Investigation of Certain Physical and Mechanical Properties of Lignum Vitae," *Forest Products Journal,* pp. 303-307, 1958.

[11] D. Tabor, Mechanial Design Handbook, 2 ed., J. Shigley and C. Mishcke, Eds., New York: McGraw-Hill, 2006.