BEARING TESTING IN LIQUID SODIUM FOR FAST REACTOR TECHNOLOGY

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INTRODUCTION: When compared to traditional light water reactors, sodium fast reactors (SFRs) have the potential to lower capital costs, provide inherent safety, and close the nuclear fuel cycle. These three benefits are connected to the use of liquid sodium as the primary coolant, which has a much higher thermal conductivity and boiling point than water and is a weak neutron moderator. However, sodium metal is very reactive, requiring an inert environment and limiting the materials that can be used within the reactor vessel and piping. Due to the high temperature environment and material incompatibility with sodium, no lubrication can be used within the reactor vessel for mechanical components such as bearings. Bearings are a key load-bearing component for SFR in-vessel fuel handling machines (FHMs), systems to remove core assemblies from the reactor, and mechanical pumps. Bearings within these systems will require long service lifetimes and reliability despite the high temperature sodium environment and lack of conventional lubrication. Development of technology for an in-vessel FHM for SFRs at Argonne National Laboratory (ANL) has illuminated a gap in testing for bearings submerged in liquid sodium. The paper details the challenges associated with sodium-lubricated bearings and the design of a Bearing Test Article (BTA) for versatile testing of bearings submerged in liquid sodium under prototypic reactor conditions and loading requirements to help fill the gap in performance data for these bearings.

1. BEARING OPERATION IN LIQUID SODIUM

Liquid metal, including sodium, tends to have a much lower viscosity than conventional lubricants, resulting in very thin lubricating films and higher chance of contact between surfaces. In liquid sodium metal, surface films, such as oxides, that would normally provide some amount of lubrication are stripped away by the sodium resulting in metal-on-metal contact. Furthermore, materials used in sodium bearings need to have complete compatibility with sodium, as any corrosion will accelerate bearing wear and failure. For rolling element bearings, these challenges are amplified by the high contact pressure between the rolling element and the race, increasing material transfer, wear, and eventually leading to bearing failure [1]. Similarly, sodium-lubricated hydrodynamic bearings have much less tolerance for instability than conventionally lubricated hydrodynamic bearings due to the tight tolerances required to maintain the lubricating film in liquid metal.

Testing in the past has shown successful operation of hydrodynamic bearings [1] and rolling element bearings [2, 3] submerged in molten sodium for extended periods of time. However, the testing is usually limited to a few selected materials and under limited loading conditions that do not represent the loading of advanced SFR systems. Wear of mechanical elements, such as bearings, is heavily affected by situation-specific variables such as material, loading, relative surface speed, geometric clearances, and temperature [4]. An experimental study for the Japan Experimental Fast Reactor (1970) demonstrated successful operation of deep-groove ball bearings for hundreds of thousands of shaft revolutions submerged in liquid sodium [3]. However, loading in this study was lower than many bearings would experience in in-vessel FHMs for SFRs and was limited to only thrust loading; no radial loading was applied. Likewise, testing conducted in the Mechanisms Engineering Test Loop (METL) facility at ANL with the Gear Test Assembly (GTA) for development of fuel handling technology has also shown successful operation of roller bearings for thousands of shaft revolutions, however, the roller bearings in this testing were consistently the point of failure, loading conditions of the bearings in the GTA were not directly measured, the size of the bearings being tested were very limited, and as expected, materials of construction had a large role in bearing performance. Further testing is needed for a wider range of bearing sizes, types, and materials submerged in sodium with specified and measured loading conditions representative of use cases in SFRs.

2. BEARING TEST ARTICLE

2.1. Overview of the METL facility

The METL facility is a 2,840-liter (750-gallon) sodium testing facility located at the Argonne National Laboratory Lemont campus. METL supplies reactor grade, purified, liquid sodium to three 46-centimeter (18-inch) test vessels and two 71-centimeter (28-inch) test vessels with 151-liter (40-gallon) and 643-liter (170-gallon) capacities respectively. Within the test vessels, sodium experiments can be performed within a prototypical sodium fast reactor environment up to a maximum temperature of 648°C in the larger vessels. The test vessels can be isolated from the rest of the loop to allow for individual test conditions in each vessel or connected to the loop for continuous flow of sodium. Research conducted in the METL facility contributes to the development and advancement of instrumentation, components, fuel handling systems, thermal hydraulic testing, and health monitoring systems for SFRs.

Sodium purity is controlled with a cold trap system within the METL facility. Sodium is pumped through the cold trap and cooled below the saturation temperature of hydride and oxide impurities in the sodium, which precipitate out and are collected in the cold trap. Sodium purity is an important consideration for bearing testing as higher impurity concentrations lead to increased rates of corrosion and accelerated bearing wear.

2.2. Bearing test article design

The Bearing Test Article has been designed for use in the METL facility at Argonne National Laboratory to fill the need for further testing of sodium bearings and support the development of technologies for advanced SFRs such as in-vessel FHMs, core-assembly removal systems, and mechanical pumps. The design of the BTA, shown in Fig. 1, emphasizes control of loading conditions and versatility in the size, types, and materials of bearings that can be tested.

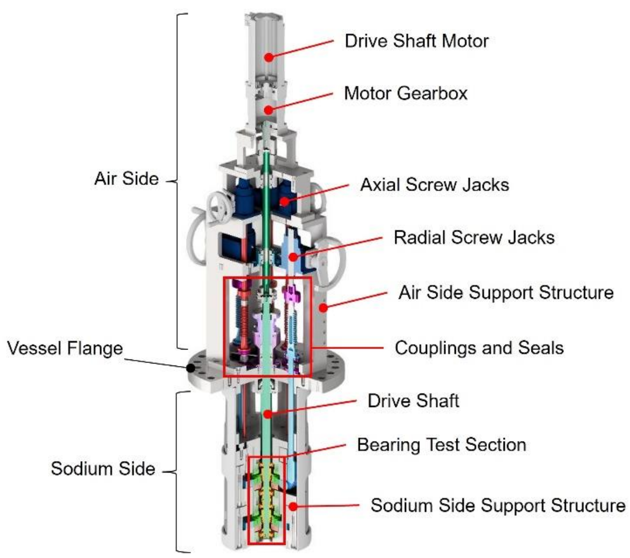

Fig. 1. CAD model of the bearing test article design.

Test bearings in the BTA can be loaded both axially and radially in combination loading, or isolated loading of just axial or just radial loads. The BTA can apply radial loads from 0-44.4 kilonewtons (10,000 pounds-force) and axial loads from 0-26.6 kilonewtons (6,000 pounds-force). The design can accommodate bearings up to 152 millimetres (6 inches) in outer diameter and a variety of bearing types from radial ball or roller bearings to pure thrust bearings or hydrodynamic bearings with minimal modification needed. Rolling element bearings are the initial focus for testing in the BTA since sodium-lubricated hydrodynamic bearings are not advisable for high-load, low-speed, systems such as FHMs due to their low load carrying capacity at low speeds.

The BTA will be built off a standard ANSI flange so that it can be installed easily in one of the METL facility's smaller vessels (46-centimeter or 18-inch). Above the vessel flange–on the air side outside of the test vessel–are the drive shaft motor, motor gearbox, axial and radial screw jacks, couplings and seals for the bearing loading mechanisms and ports, and the air side support structure. The screw jacks on the air side generate the force of the radial and axial loading mechanisms. The force is measured by in-line load cells on the air side.

The drive shaft and loading mechanisms extend through the vessel flange to the sodium side within the test vessel. On the drive shaft, fully submerged in liquid sodium, is the bearing test section. Fig. 2 shows the three main structures of the sodium side of the BTA: the drive shaft and bearings, the loading mechanisms, and the support structure. The sodium side of the BTA is designed to operate at temperatures up to 350°C while under load, and up to a maximum 538°C while static.

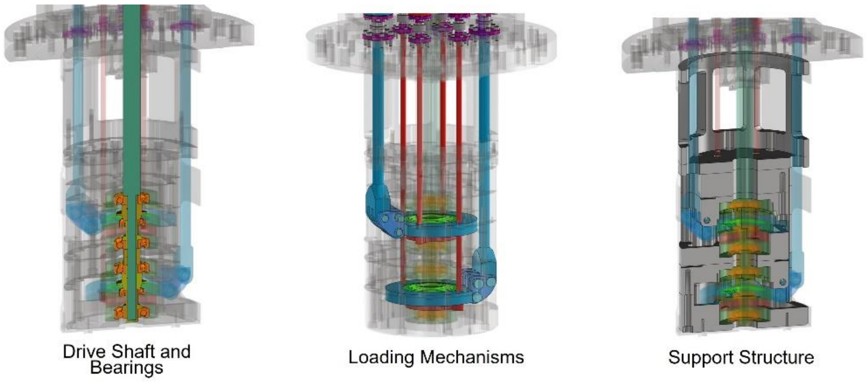

Fig. 2. Sodium side structures of the bearing test article.

Bearings are mounted to the drive shaft with shaft sleeves that can be swapped out to accommodate bearings with various bore sizes. In total there are six submerged bearing locations: two test bearings, and four support bearings. The support bearings, located above and below each test bearing, are mounted in the support structure to provide rigidity and keep the deflection of the shaft low at the maximum loading conditions of the BTA (142 kilonewtons). Each test bearing has individual loading mechanisms–both radial and axial–to reduce uncertainty in the measurement of the loads on each test bearing. Fig. 3 shows the radial and axial loading mechanisms in more detail.

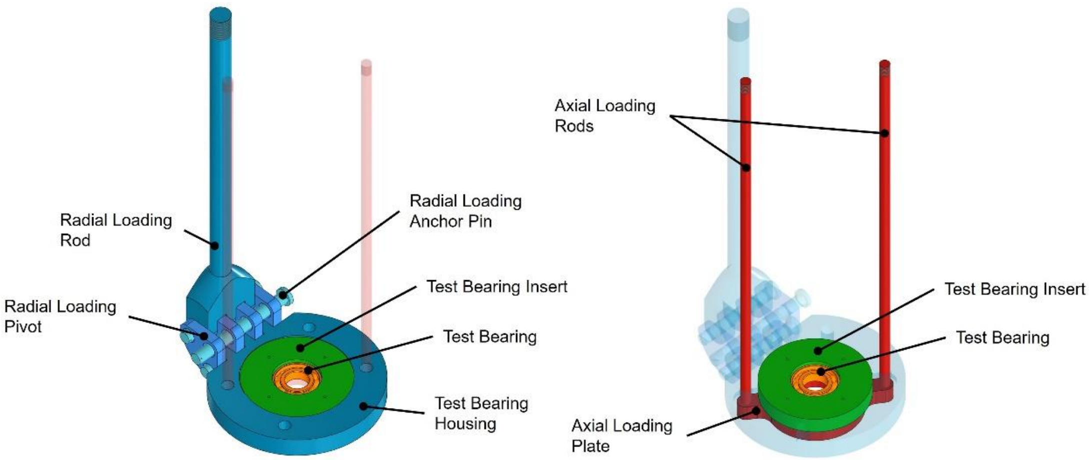

Fig. 3. Bearing test article loading mechanisms.

The radial loading mechanisms, shown in blue, and axial loading mechanisms, shown in red, are designed to act independently of one another. The radial and axial load rods are coupled to the screw jacks on the air side. In the radial loading mechanism, force is transferred from the loading rod through a pivot–secured to the support structure with an anchor pin–to change the direction of the force from axial force to radial force on the bearing. In the axial loading mechanism, two loading rods attached to screw jacks pull upward on a loading plate below the test bearing insert to generate the axial load on the test bearing. Like the shaft sleeves, bearing inserts within the bearing housings can be swapped out to accommodate test bearings and support bearings of different geometries.

2.3. Evaluation of bearing performance

Bearing performance can be evaluated in several ways. First, the number of drive shaft revolutions will be monitored throughout testing with the BTA; if a bearing fails during the testing, the shaft revolutions to failure give a measure of bearing operational lifetime for the loading and temperature conditions of the test. These shaft revolutions can be correlated to fuel handling maneuvers completed, core removal operations, or hours of pump operation depending on the application. Accelerometers attached to the bearing housings will determine when bearing failure occurs and collect data throughout operation. The second method of bearing evaluation involves pre-test and post-test inspection of the bearings. Several inspection techniques can be used including visual inspection, scanning of the bearing surfaces for dimensional change, hardness testing, profilometry, and other non-destructive evaluation methods to compare the bearings before and after testing.

3. CONCLUSION

Development of liquid sodium bearing technology for systems such as fuel handling machines, core removal systems, and mechanical pumps in advanced SFRs require further testing in a prototypical SFR environment and with representative bearing loading for the intended use to overcome the challenges presented by the liquid sodium coolant. The BTA will help fill this gap by providing valuable performance data for sodium-lubricated bearings in a wide variety of geometries, types, and materials. During testing, the sodium conditions, including temperature and purity, will be representative of a typical SFR environment and loading will be adjusted to match the intended use case for the bearing.

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