ANL-ART-248
ANL-METL-39

Gear Test Assembly – Experimental Testing and Gear Analysis – FY2022

Nuclear Science and Engineering Division

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I. Executive Summary

The Gear Test Assembly (GTA) is an experimental test apparatus built for use in the Mechanisms Engineering Test Loop (METL) at Argonne National Laboratory (ANL). The purpose of the GTA is to test mechanical components used in advanced fuel handling mechanisms built for pool-type sodium fast reactors. Radial spur gears in Inconel 718 and mechanical roller bearings in 52100 bearing steel are currently under investigation. After four experimental campaigns, the Inconel 718 gears have completed 14,018 simulated fuel assembly maneuvers (removal from core and insertion back into core) while experiencing negligible mechanical wear. The tapered roller bearings and cylindrical pin thrust bearings have experienced failures after completing a range of simulated fuel assembly maneuvers, as early as 1,266 to as high as 9,800[1]. Summaries of all experimental campaigns completed to-date are provided, along with gear analysis in the form of over-pin dimensions. Testing will continue until the original gears experience a failure. Following this, gears in a different material will be tested. Bearing development is underway to increase the lifetime of this component. This report covers the results of Experimental Campaign #4 that tested the original Inconel 718 spur gears and fresh tapered roller bearings in heat treated 52100 steel. The previous three experimental campaigns are summarized in this report as well, with gear analysis in the form of over-pin dimensions presented for each campaign. Finally, details regarding Experimental Campaign #5 are presented.

[1] As a reference, for PRISM Mod A the number of core assemblies handled each cycle is about 26-27 and for PRISM Mod B the number is 48-57 depending upon the core. If those core assemblies are handled 4 times for in-vessel decay, then the 1,266 maneuver to 9,800 maneuvers equates to handling 316 to 2,450 core assemblies before the IVTM would experience an issue due to bearing failure.

II. Introduction

The Gear Test Assembly (GTA) is an experimental test article built for use in the Mechanisms Engineering Test Loop (METL) at Argonne National Laboratory (ANL). The GTA was the first test article to operate in METL, with the initial experimental campaign beginning in early 2019. A total of four experimental campaigns have been completed to-date, and the fifth is currently underway. This report will discuss the results of the four completed campaigns with gear analysis in the form of over-pin dimensions. Finally, information regarding Experimental Campaign #5 will be discussed. All over-pin measurements of the gears tested in sodium will be available in the Appendix.

1. Motivation for Gear Test Assembly

The purpose of the GTA is to evaluate the performance of mechanical components intended for use in an ANL designed advanced fuel handling mechanism (FHM). The ANL FHM will be used in pool-type sodium fast reactors and is designed such that all fuel assemblies can be reached using a single rotatable plug. This is compared with the more traditional use of multiple eccentric rotatable plugs that allow for a single point on the smallest plug to cover the whole of the reactor core. This allows for a reduction in the diameter of the reactor vessel which translates into a smaller containment facility overall, reducing the overall capital costs of the reactor plant. To accomplish this, the FHM requires mechanically driven components to be fully submerged in the primary coolant. These components include radial spur gears, roller bearings, ball screws, bushings, and universal joints. At the initiation of this project, limited literature could be found regarding the performance of such mechanical components in liquid sodium. Therefore, it is necessary to test some of the components before proceeding to the full FHM design and testing campaigns.

The GTA is the first step in the process of component development leading up to the FHM. As mentioned, the GTA is currently equipped to test radial spur gears up to 6” in diameter and mechanical roller bearings with an internal bore of 2.5”. The GTA can be modified to test bushings, helical spur gears, worm gears, and straight or spiral bevel gears as well as hydrostatic or hydrodynamic bearings with minimal replacement of parts inside the liquid sodium testing area.

The performance of the gears and bearings in the GTA has informed the design of the Gripper Test Assembly (GrTA). The GrTA is an experimental assembly that will evaluate the performance of a fuel assembly gripper head that is driven using mechanical components that are submerged in liquid sodium. The GrTA design has been completed and the project is currently in the fabrication phase. Figure 1 shows CAD representations of the GTA, the GrTA, and the final ANL FHM.

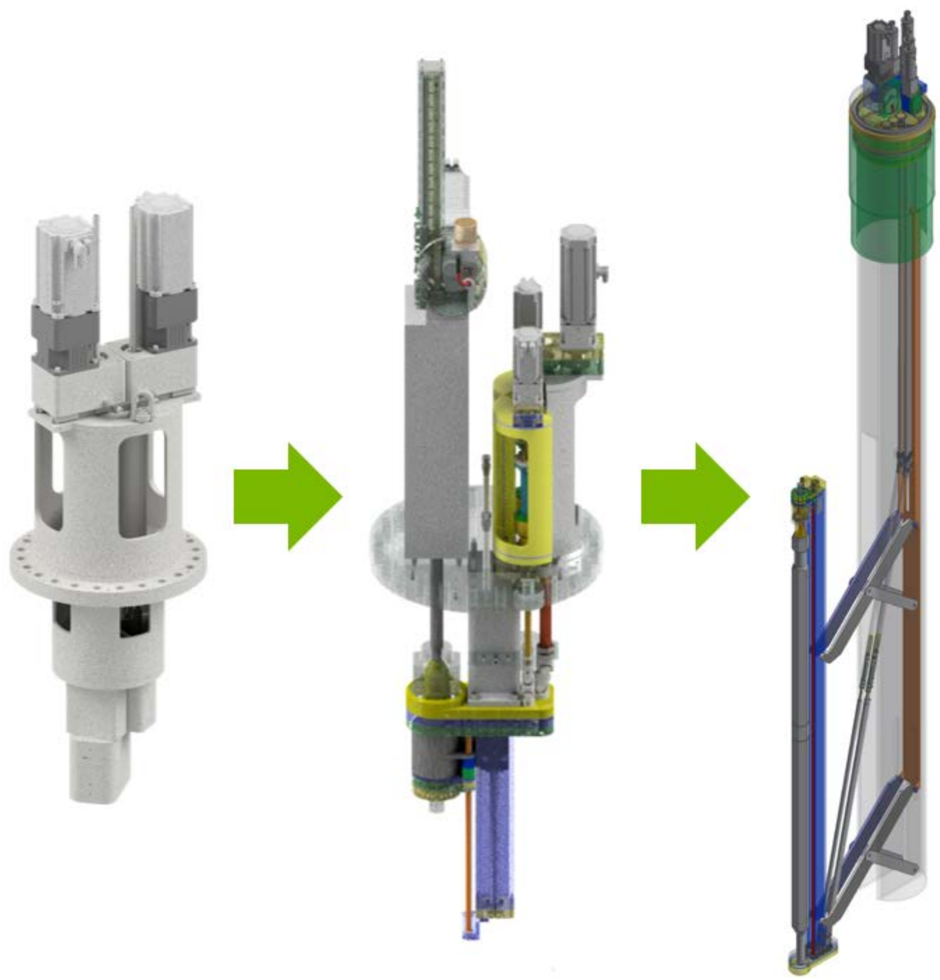


Figure 1: Progressive experimental plan for the development of a compact fuel handling mechanism. Gear Test Assembly (left), Gripper Test Assembly (mid), Fuel Handling Mechanism (right)

2. Gear Test Assembly Overview

The GTA was designed to operate in the smaller 18” test vessels at the METL facility. Therefore, the design of the GTA is incorporated into a blank 18” 150# ANSI flange. Two drive shafts penetrate the flange to provide the prescribed torque to the tested gears and bearings. An internal support structure is used to position the test gearboxes in the liquid sodium pool, past the argon cover-gas space. Two test gearboxes house two sets of radial spur gears custom made for this project, one large pair with 15-teeth and one small pair with 22-teeth. These gears are supported with tapered roller bearings and the shafts are supported axially with cylindrical pin thrust bearings. Essentially all submerged components are manufactured from 316 stainless steel to ensure known material compatibility with the liquid sodium test environment. The 316 stainless steel also provides sufficient strength for the load bearing components to operate in this environment at elevated temperatures. The only submerged components not made from 316 stainless steel are the gears and bearings under investigation. Figure 2 provides an overview of the GTA system, both sodium side and non-sodium side. Figure 3 provides a view inside the test gearboxes to show the tested components.

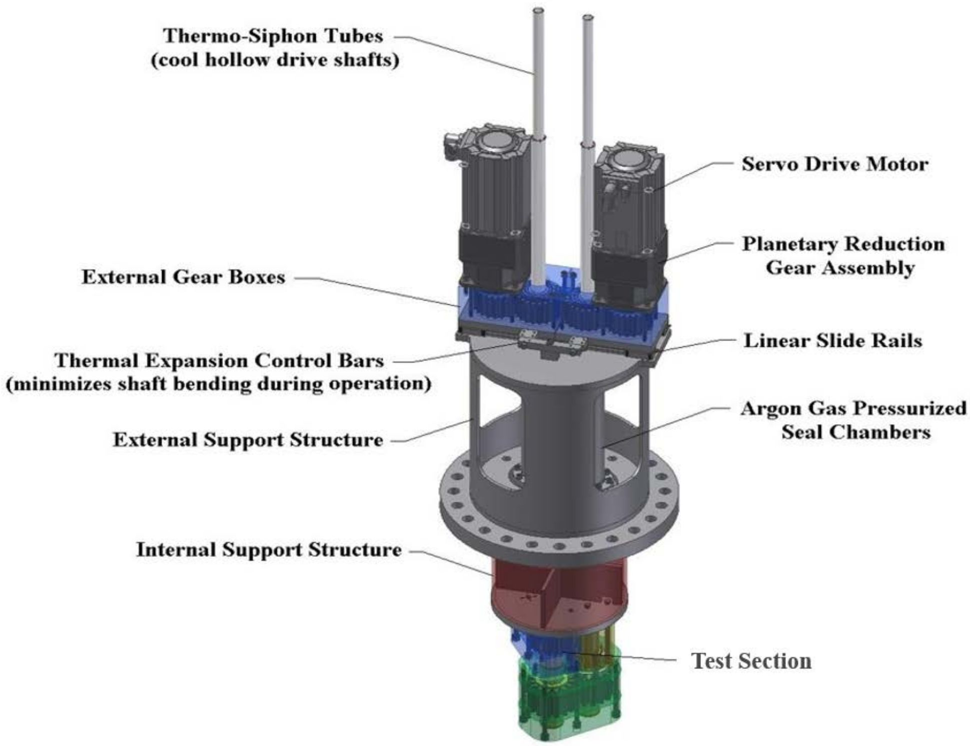


Figure 2: Overview of the Gear Test Assembly

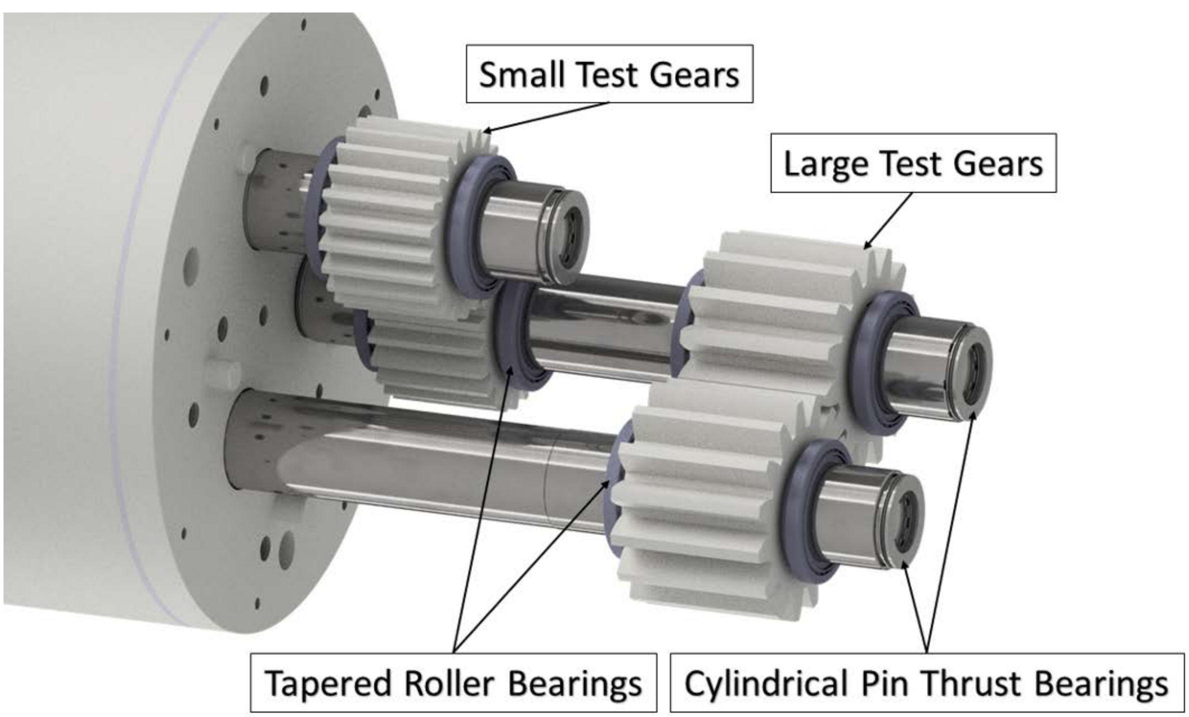


Figure 3: Overview of the submerged mechanical components tested in the GTA.

III. <u>Experimental Operations</u>

Four experimental campaigns have been completed to-date, and the fifth is currently in operation. An experimental campaign begins with the sodium fill in Test Vessel 1 where the GTA is installed after the build is complete. Sodium is filled to the overflow line of the vessel to ensure the test section of the GTA is fully submerged. Then the sodium in Test Vessel 1, along with the rest of the online sodium inventory, is purified using the Cold Trap to bring the oxygen content down to <5wppm. This purification process significantly reduces the chemical activity of the sodium and prevents excess corrosion and wear from taking place. Once purification is complete, Test Vessel 1 is isolated from the rest of the loop and testing can begin. The testing is monitored using vibration sensors and torque sensors that can indicate if an internal component has been damaged or failed. If a failure is detected, testing is stopped, and the cleaning and disassembly phase will begin. Cleaning and disassembly of the GTA is described in a previous report [1]. Testing was paused twice mid- campaign due to external factors. Experimental Campaign #2 was paused due to the lab shutdown for COVID19. Experimental Campaign #4 was paused when a line in the Cold Trap loop became plugged and the sodium inventory could not be purified. Table 1 presents the timelines for each experimental campaign.

Table 1: Timelines for each experimental campaign.

Activity	*Campaign 1*	*Campaign 2*	*Campaign 3*	*Campaign 4*	*Campaign 5*
Sodium Fill	2/1/2019	3/3/2020	2/9/2021	11/22/2021	6/15/2022
Testing Start	2/5/2019	3/18/2020	2/16/2021	11/23/2021	6/21/2022
Standby	-	3/20/2020	-	12/6/2021	-
Restart	-	5/28/2020	-	1/12/2022	-
Fault	3/7/2019	6/15/2020	3/4/2021	1/27/2022	-
Removal	8/6/2019	8/7/2020	3/18/2021	2/21/2022	-
Carbonation Start	8/6/2019	8/10/2020	3/19/2021	2/22/2022	-
Carbonation End	9/17/2019	8/18/2020	4/2/2021	3/21/2022	-
Cleaned & Disassembled	11/7/2019	9/2/2020	5/5/2021	4/29/2022	-

The torque profile applied to the shafts during testing is designed to mimic the removal and insertion of an SFR fuel assembly. An initial high torque period simulates the fuel assembly being freed from the core grid basket, where growth and bowing will often cause the fuel assembly to become stuck. Once the fuel assembly is freed, the torque required is associated with the free-weight of the fuel assembly under gravity. The high torque period is short (2-10 seconds) and the low torque period is longer (30+ seconds). There is a pause after the low torque period to simulate other operations taking place with the FHM, and then the process is reversed to simulate more movement of the fuel assembly followed by its insertion back into the core grid basket. Table 2 presents data regarding the loads applied to the gears, their time under load, their time soaking in high temperature sodium, and the total number of handling maneuvers. One handling maneuver refers to a core assembly being removed from the core, the assembly being moved around the core, then an insertion back into the core.

Table 2: Data regarding the performance of the gears and the sodium exposure time.

	Campaign #1	*Campaign #2*	*Campaign #3*	*Campaign #4*	*Total*
Time in Sodium [h]	4344.00	3528.00	576.00	864.00	9312.00
Time at High Torque [h]	16.33	7.69	8.71	7.03	39.77
Time at Low Torque [h]	163.33	21.53	24.39	19.69	228.95
Time Active [h]	179.67	29.22	33.10	26.73	268.71
Time Idle [h]	4164.33	3498.78	542.90	837.27	9043.29
Handling Maneuvers[2]	9800	1384	1568	1266	14018
High torque [Nm]	400	450	450	450	-
Low Torque [Nm]	150	150	150	150	-

[2] A core assembly handling maneuver is comprised of removing and then inserting a core assembly. For reactors with in-vessel storage, a core assembly is handled 4 times by the in-vessel transfer machine during its life within the vessel. For example, for PRISM Mod B – there are 192 core assemblies and about 48 core assemblies are handled during refueling. Thus, for the lowest GTA campaign cycle of 1,266 handling maneuvers, this would equate to handling 316 core assemblies – assuming that each of the core assemblies require in-storage decay (which some core assemblies such as reflectors and shield will not require in-storage decay). The ability to handle 316 core assemblies with this configuration greatly exceeds the performance of the current requirements for one PRISM Mod B refueling campaign.

1. Results from Experimental Campaign #1

Experimental Campaign #1 tested two sets of Inconel 718 (ASM 5664) spur gears that were fabricated using electrical discharge machining. The Inconel 718 was annealed and aged to reach a hardness of 36 HRC. Commercially available tapered roller bearings in 52100 bearing steel were used to provide radial support to the shafts. These tapered roller bearings received heat treatment to maintain a hardness of >58 HRC at temperatures up to 350°C. The shafts were supported using cylindrical pin thrust bearings in 52100 bearing steel, but these did not receive a heat treatment, as the loads are manageably small (no applied load, only the weight of the shafts).

Testing took place in nuclear-grade liquid sodium with an oxide content below 5-wppm. The liquid sodium was maintained at a temperature of 250°C. The shafts were rotated at a speed of 250 rpm during operation. The torque profile for Experimental Campaign #1 had a high torque of 400 Nm that lasted for 3-seconds, and a low torque of 150 Nm that lasted for 30-seconds. The testing took place continuously until a failure occurred on the sodium side of the assembly that prevented the shafts from rotating. A total of 9,800 simulated fuel assembly maneuvers were completed prior to the failure.

Following cleaning and disassembly of the GTA, a failed tapered roller bearing was found above gear L1IT (Figure 4). Cross-sections of the inner race, outer race, and cage of the failed bearing were prepared, and microhardness profiles were generated to examine the material property of the bearing (Figure 5). The profiles revealed that the races did receive the heat treatment (indicated by the elevated surface hardness), but the cage appeared to be fabricated in a lower alloy steel.

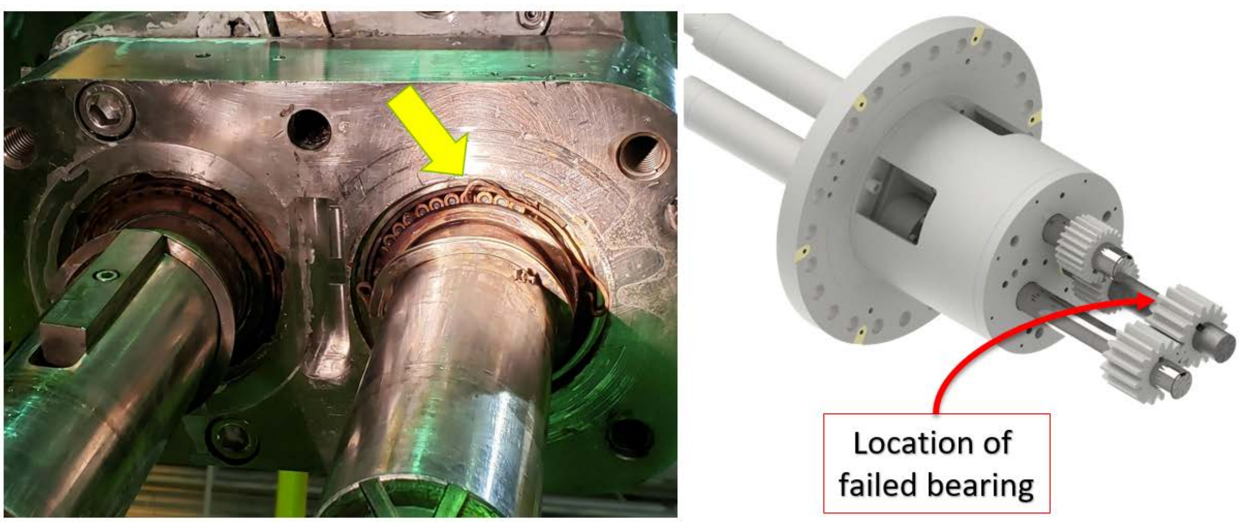


Figure 4: View of the tapered roller bearing that failed in Experimental Campaign #1.

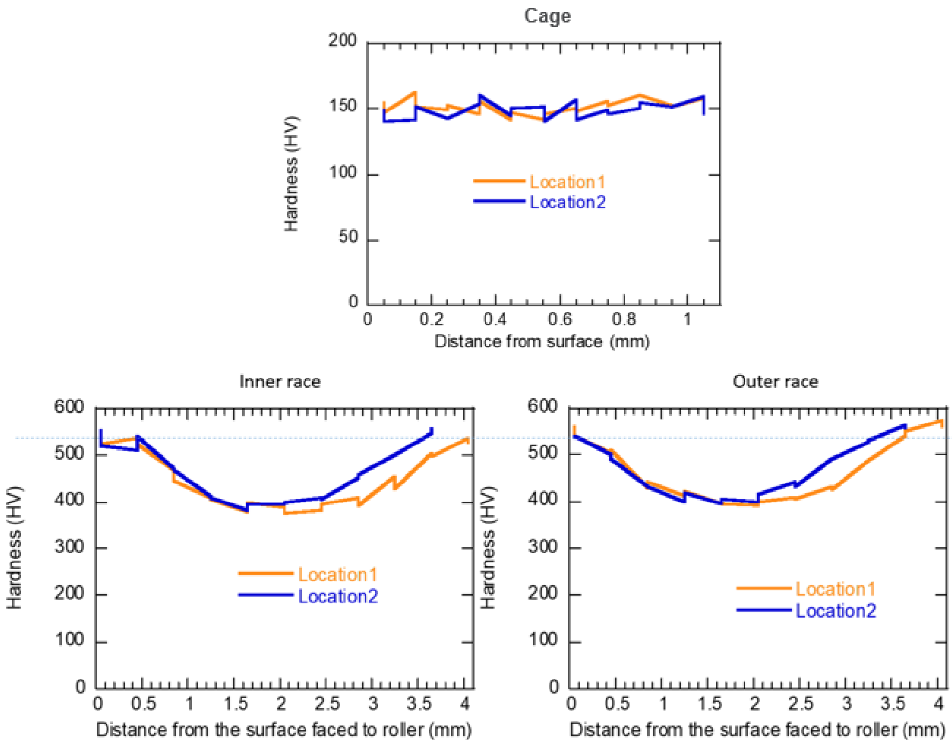


Figure 5: Hardness data taken from the failed tapered roller bearing.

2. Results from Experimental Campaign #2

Experimental Campaign #2 tested the original two sets of Inconel 718 (ASM 5664) spur gears, as they showed no obvious signs of failure [2]. Commercially available tapered roller bearings in 52100 bearing steel were used to provide radial support to the shafts. These tapered roller bearings did not receive the same heat treatment as the previous test. The heat treatment requires a significant lead-time and incurs a 10-x increase in cost, so it was of interest to see how the off-the-shelf variant performed. The shafts were supported using the same cylindrical pin thrust bearings in 52100 bearing steel as the original test.

Testing took place in nuclear-grade liquid sodium with an oxide content below 5-wppm. The liquid sodium was maintained at a temperature of 250°C. The shafts were rotated at a speed of 250 rpm during operation. The torque profile for Experimental Campaign #2 had a high torque of 450 Nm that lasted for 10-seconds, and a low torque of 150 Nm that lasted for 30-seconds. New planetary gearboxes were purchased to increase the available torque, and the motor programming was changed to provide a more gradual change in torque. The testing took place during regular work hours until a failure occurred on the sodium side of the assembly caused significant (audible) vibrations. Operations were paused due the COVID19 pandemic that caused the lab to shut down. During this period, the GTA sat in Test Vessel1 that remained filled with sodium at 250°C. A total of 1,384 simulated fuel assembly maneuvers were completed prior to the failure.

Following cleaning and disassembly of the GTA, a failed tapered roller bearing was found below gear T1BT (Figure 6). The bearing fragmented in the gearbox, causing visible damage to both the gearbox and the shaft (Figure 7). The shaft collar on which the gear and bearings were located was damaged so significantly that it needed to be cut off and replaced (Figure 8).

Figure 6: Remains of failed tapered roller bearing (left) and location of failed bearing (right) from Experimental Campaign #2.

Figure 7: Remains of bearing in gearbox (left) and on shaft (right).

Figure 8: Damaged shaft sleeve following Experimental Campaign #2.

3. Results from Experimental Campaign #3

Experimental Campaign #3 tested the original two sets of Inconel 718 (ASM 5664) spur gears, as they showed no obvious signs of failure [3]. Commercially available tapered roller bearings in 52100 bearing steel were used to provide radial support to the shafts. These tapered roller bearings were identical to those used in Experimental Campaign #2 to examine the influence the extended soak at temperature had on the performance of the bearings. The shafts were supported using the same cylindrical pin thrust bearings in 52100 bearing steel as the original test.

Testing took place in nuclear-grade liquid sodium with an oxide content below 5-wppm. The liquid sodium was maintained at a temperature of 250°C. The shafts were rotated at a speed of 250 rpm during operation. The torque profile for Experimental Campaign #3 had a high torque of 450 Nm that lasted for 10-seconds, and a low torque of 150 Nm that lasted for 30-seconds. The testing took place during normal work hours until a failure occurred on the sodium side of the assembly caused significant (audible) vibrations. A total of 1,568 simulated fuel assembly maneuvers were completed prior to the failure.

Following cleaning and disassembly of the GTA, a failed thrust roller bearing was found above gear T1IT. The bearing seized in the gearbox and the friction from the rotating shaft wore material away. This also wore down the end of the shaft in this location (Figure 9).

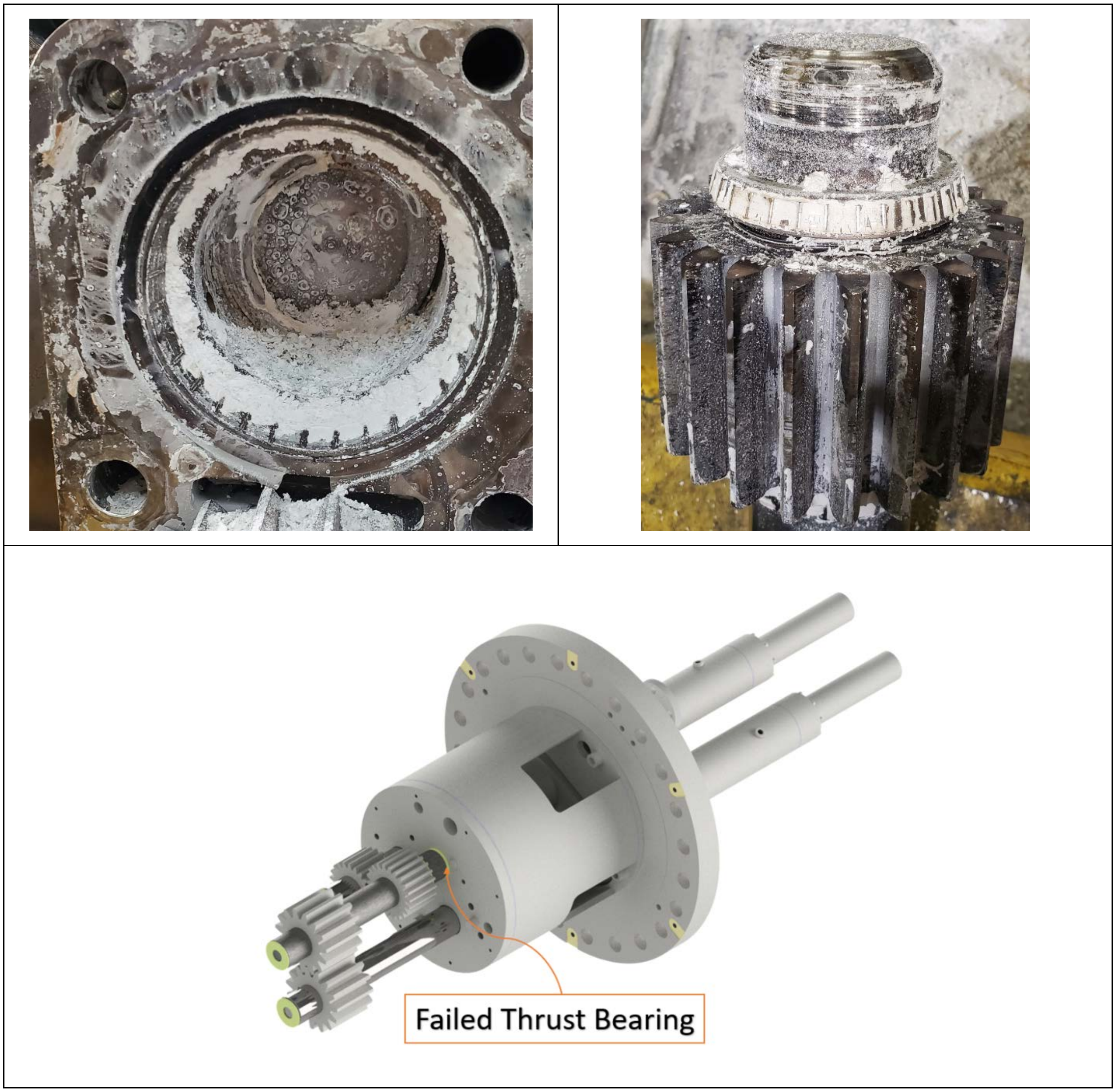


Figure 9: Remains of failed thrust bearing in gearbox (left) and on shaft (right) from Experimental Campaign #3. Location of failed thrust bearing (bottom).

4. Results from Experimental Campaign #4

Experimental Campaign #4 tested the original two sets of Inconel 718 (ASM 5664) spur gears, as they showed no obvious signs of failure [4]. Commercially available tapered roller bearings in 52100 bearing steel were used to provide radial support to the shafts. These tapered roller bearings received heat treatment to maintain a hardness >58 HRC at temperatures up to 350°C (identical to Experimental Campaign #1). The thrust bearing assemblies were not included in this build, as the tapered roller bearings also provide axial support, and the thrust bearing was seen as an unnecessary failure point.

Testing took place in nuclear-grade liquid sodium with an oxide content below 5-wppm. The liquid sodium was maintained at a temperature of 250°C. The shafts were rotated at a speed of 250 rpm during operation. The torque profile for Experimental Campaign #4 had a high torque of 450 Nm that lasted for 10-seconds, and a low torque of 150 Nm that lasted for 30-seconds. The testing took place during normal work hours until a failure occurred on the sodium side of the assembly caused significant (audible) vibrations. A total of 1,266 simulated fuel assembly maneuvers were completed prior to the failure.

Following cleaning and disassembly of the GTA, a failed tapered roller bearing was found above gear L1IT that had fragmented significantly (Figure 10). An additional failure was found above gear T1BT, but the failure was much less severe (Figure 11). The locations of these failures are indicated in Figure 12.

Figure 10: Remains of the fragmented tapered roller bearing from Experimental Campaign #4.


Figure 11: Damaged tapered roller bearing from Experimental Campaign #4.

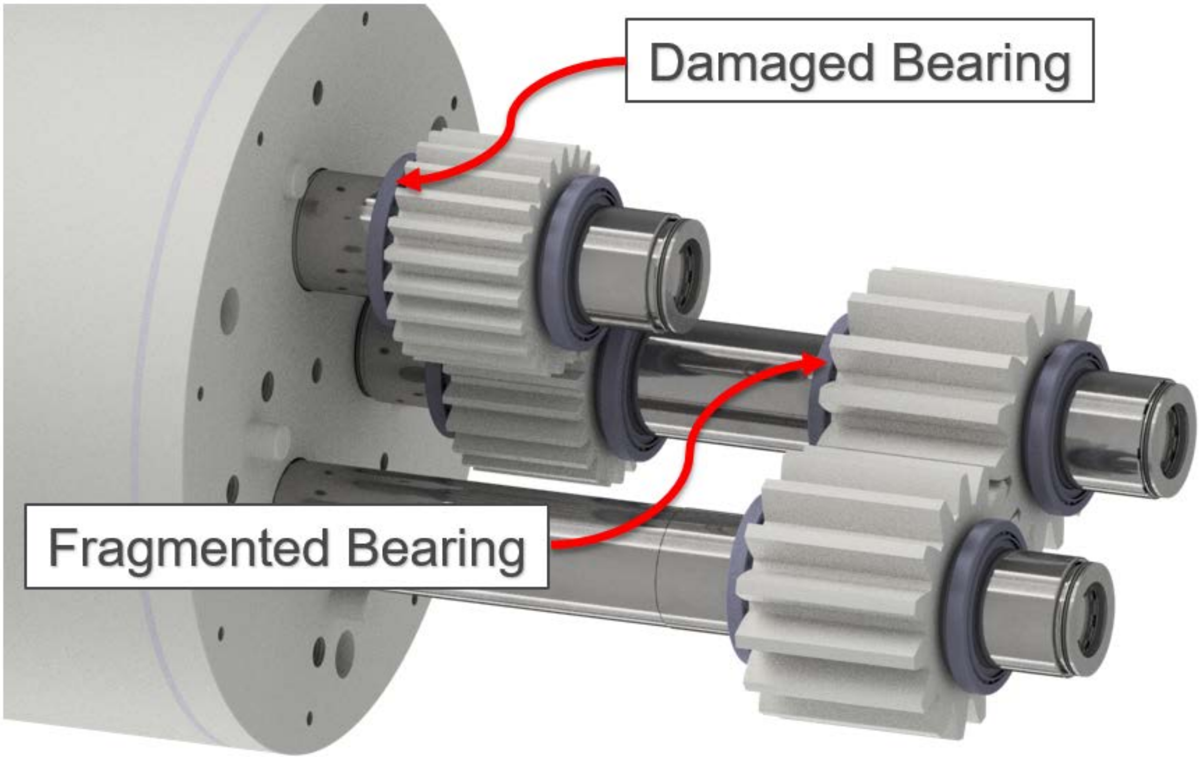


Figure 12: Locations of bearing failures from Experimental Campaign #4.

5. Gear Analysis

Following each experimental campaign, the gear analysis is performed on each of the gears that are submerged in liquid sodium. Novel ultrasonic and electromagnetic techniques have been developed at Argonne National Laboratory and have been used to monitor the health of the over the course of testing [4]. Following Experimental Campaign #4, these analyses were skipped to expedite the rebuild for Experimental Campaign #5. Experimental Campaign #4 had the shortest operational life, and the gears did not show visible signs of wear, so skipping these methods was deemed reasonable.

Gear analysis in the form of over-pin dimensions have been recorded after every campaign to-date. Over-pin dimensions are taken by placing dowel pins in opposite gear teeth roots and measuring the distance between. Figure 13 shows how the measurements are taken for each gear, and their ideal measurements. Figure 14 shows the tooth numbering and meshing system for the large gears (L1AT and L1IT). Figure 15 shows the tooth numbering and meshing system for the small gears (T1BT and T1IT).

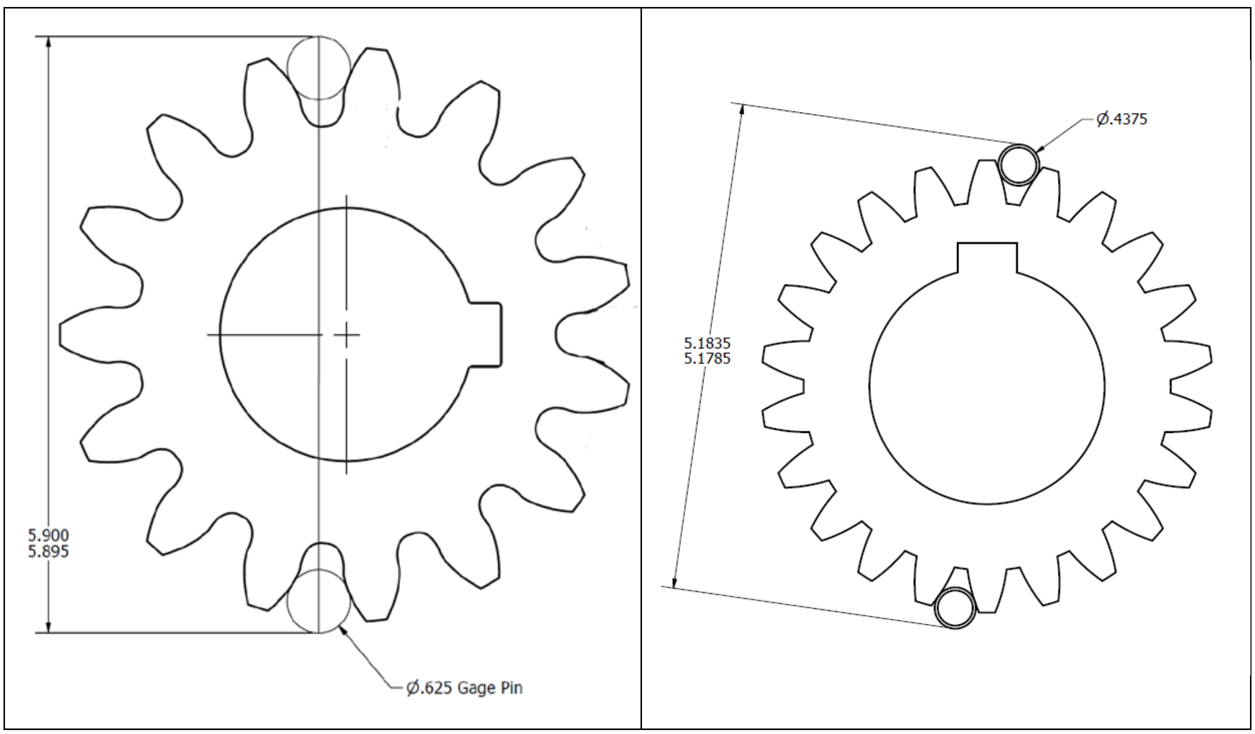


Figure 13: Ideal over-pin dimensions for gears L1AT/L1IT (left) and T1BT/T1IT (right).

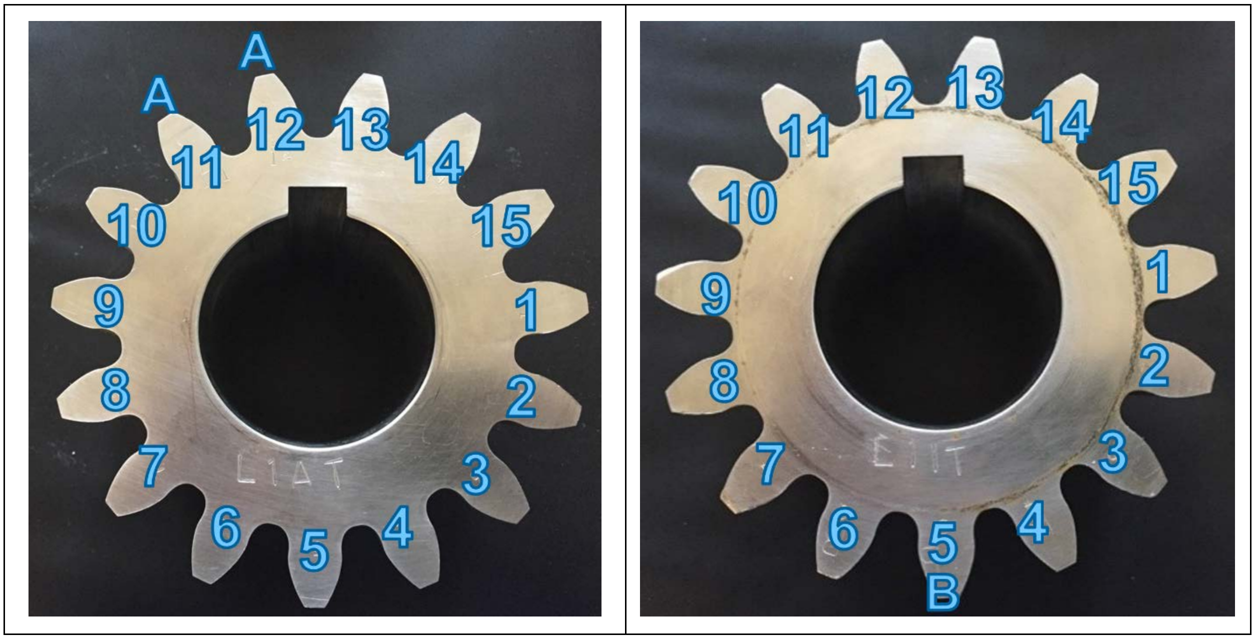


Figure 14: Pictures of the L1AT and L1IT gears with the gear teeth numbering labelled. The "A" and "B" notation are used to indicate where the gears mesh.

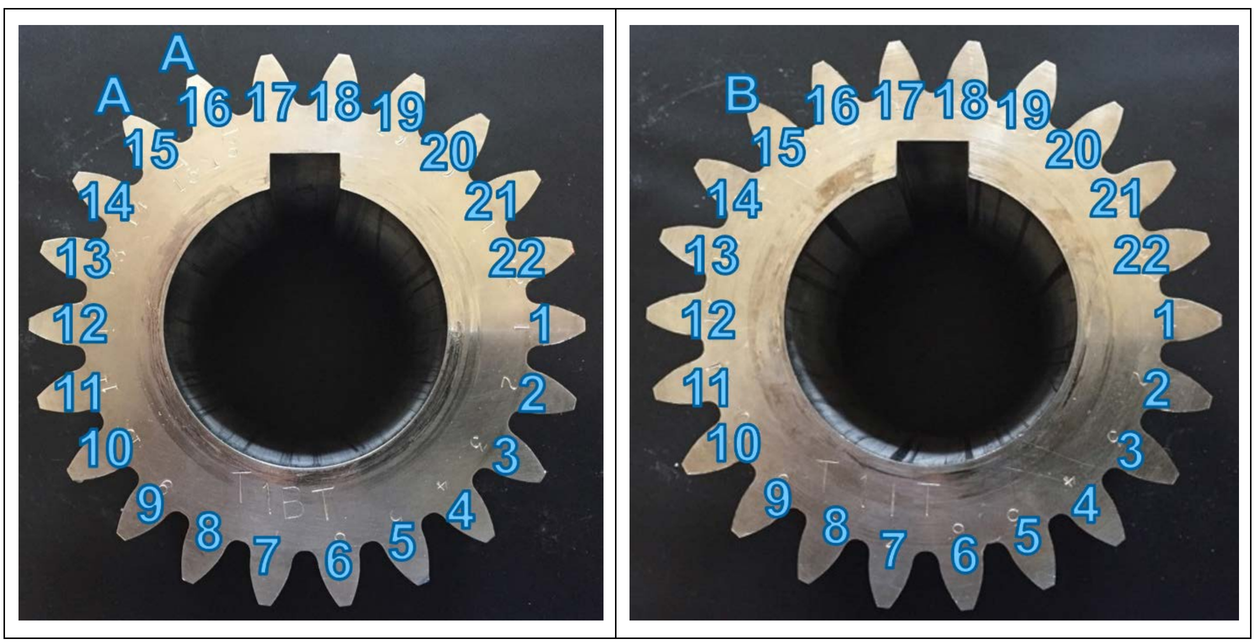


Figure 15: Pictures of the T1BT and T1IT gears with the gear teeth numbering labelled. The "A" and "B" notation are used to indicate where the gears mesh.

Table 3 presents the average over-pin measurements for all four gears after each experimental campaign. Each value in Table 3 is generated by averaging all the measurements taken for each gear. This provides a high-level measurement of the overall gear health. Table 4 provides the change in average over-pin dimensions following each experimental campaign. This provides a high-level measurement of the amount of wear each gear is experiencing following each experimental campaign. Note that some of the values for "Δ2" (change in average over-pin dimension following Experimental Campaign #2) are negative. This was likely due to the use of a digital caliper with an accuracy of ±0.001", where the changes in measurement were smaller than this accuracy. Measurements for the following experimental campaigns were made using a manual micrometer with an accuracy of ±0.00015". The results of this analysis show that the gear are experiencing measurable wear, but this wear is minor.

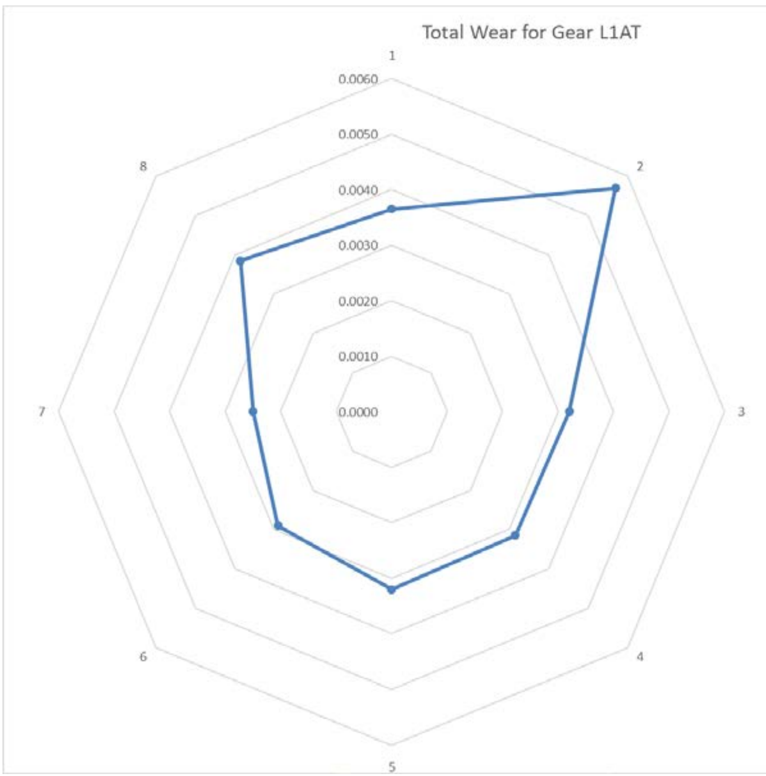
Table 3: Average over-pin dimensions collected for sodium-wetted gears, taken after the listed campaign [inches].

Gear	*Campaign*				
-	Initial	#1	#2	#3	#4
L1AT	5.8968	5.8935	5.8942	5.8941	5.8933
L1IT	5.8991	5.8955	5.8969	5.8962	5.8942
T1BT	5.1831	5.1804	5.1802	5.1802	5.1784
T1IT	5.1800	5.1780	5.1780	5.1777	5.1763

Table 4: Change in average over-pin dimensions following each campaign [inches].

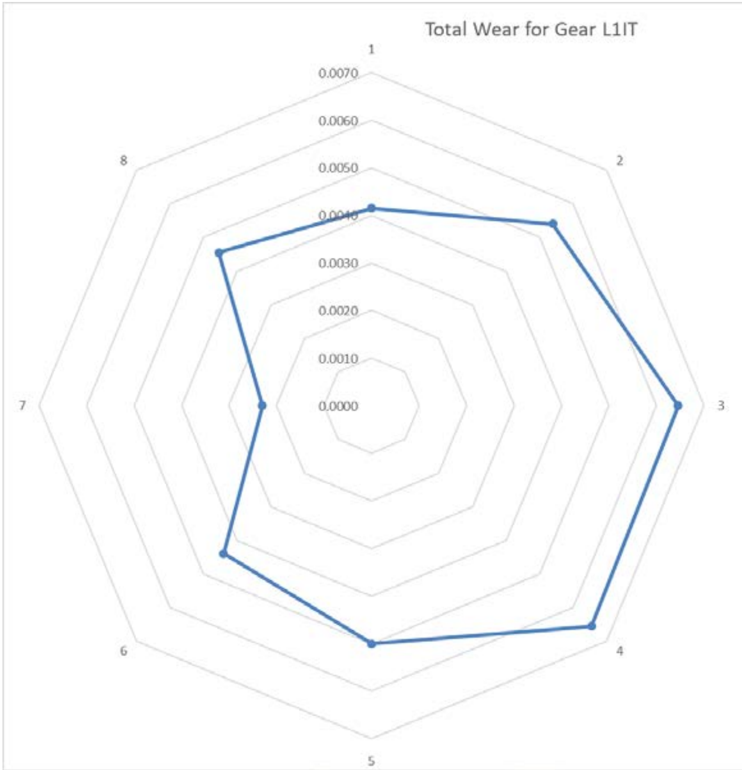
Gear	*Δ1*	*Δ2*	*Δ3*	*Δ4*	*Total Wear*
L1AT	0.0033	-0.0006	0.0001	0.0008	0.0035
L1IT	0.0036	-0.0014	0.0008	0.0019	0.0049
T1BT	0.0027	0.0001	0.0000	0.0018	0.0047
T1IT	0.0020	0.0001	0.0003	0.0014	0.0037

Figure 16, Figure 17, Figure 18, and Figure 19 present polar plots of the change in over-pin dimensions between the initial measurement and the most recent measurement following Experimental Campaign #4. This provides a view of how the gears are wearing across each individual tooth. Gears L1AT, L1IT, and T1IT show fairly uniform wear across all teeth, as what would be expected. Gear T1BT shows rather non-uniform wear, with low changes at Identifier #2, #9, #10, and #11, then large changes at Identifier #1, #4, and #5. One possible explanation is the presence of burrs on the gear teeth that would provide high spots that were not previously measured. Further measurements are needed to determine the cause. A complete record of all over-pin dimensions is provided in the Appendix of this report.



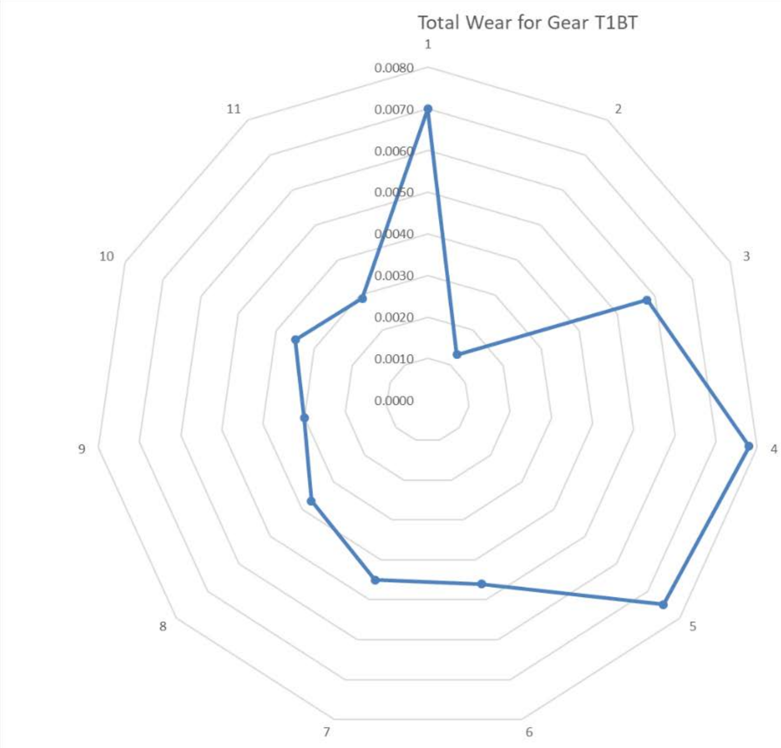
Identifier	*Pin Locations*	
1	1,2	8,9
2	2,3	9,10
3	3,4	10,11
4	4,5	11,12
5	5,6	12,13
6	6,7	13,14
7	7,8	14,15

Figure 16: Total wear measurements for gear L1AT made by taking the difference in over-pin dimensions [inches].



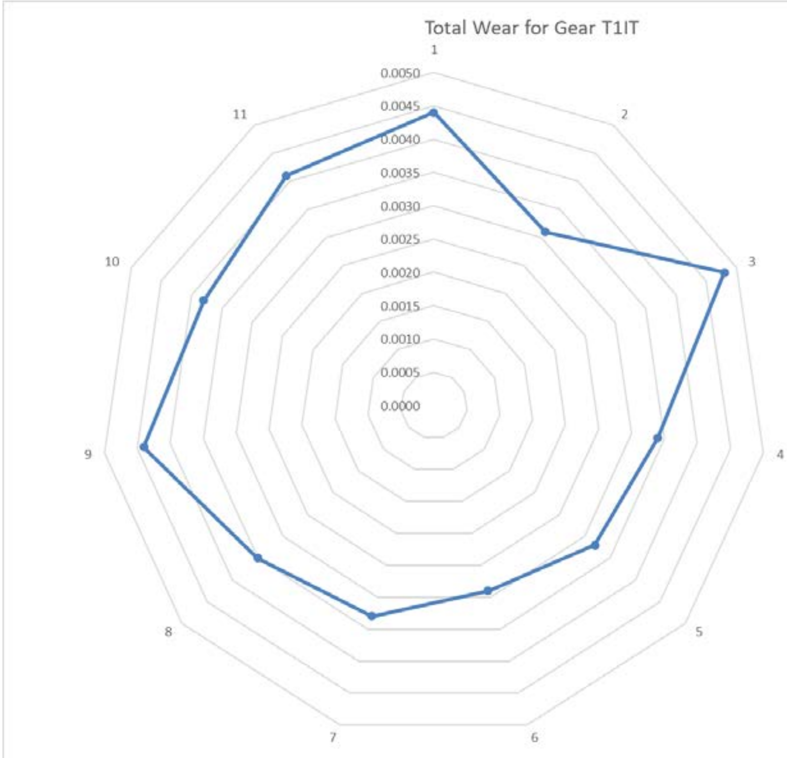
Identifier	*Pin Locations*	
1	1,2	8,9
2	2,3	9,10
3	3,4	10,11
4	4,5	11,12
5	5,6	12,13
6	6,7	13,14
7	7,8	14,15

Figure 17: Total wear measurements for gear L1IT made by taking the difference in over-pin dimensions [inches].



Identifier	*Pin Locations*	
1	1,2	12,13
2	2,3	13,14
3	3,4	14,15
4	4,5	15,16
5	5,6	16,17
6	6,7	17,18
7	7,8	18,19
8	8,9	19,20
9	9,10	20,21
10	10,11	21,22
11	11,12	22,1

Figure 18: Total wear measurements for gear T1BT made by taking the difference in over-pin dimensions [inches].



Identifier	*Pin Locations*	
1	1,2	12,13
2	2,3	13,14
3	3,4	14,15
4	4,5	15,16
5	5,6	16,17
6	6,7	17,18
7	7,8	18,19
8	8,9	19,20
9	9,10	20,21
10	10,11	21,22
11	11,12	22,1

Figure 19: Total wear measurements for gear T1IT made by taking the difference in over-pin dimensions [inches].

IV. Path Forward

The GTA has been fully cleaned and disassembled following the Experimental Campaign #4. The rebuild for Experimental Campaign #5 includes the original Inconel 718 gears, as they have shown no signs of failure and only marginal wear according to over-pin dimensions. The same commercially available tapered roller bearings without heat treatment will be used in this build. The thrust bearing assemblies originally included in the build will be reintroduced, as their absence in Experimental Campaign #4 may have been a factor in the early failure of the heat-treated bearings. Figure 20 shows two pictures of the bottom of the GTA test section, one where the thrust bearing assemblies are not installed (left), and one where the thrust bearing assemblies are being installed (right). The GTA has been fully rebuilt, installed in Test Vessel 1, and testing has commenced.

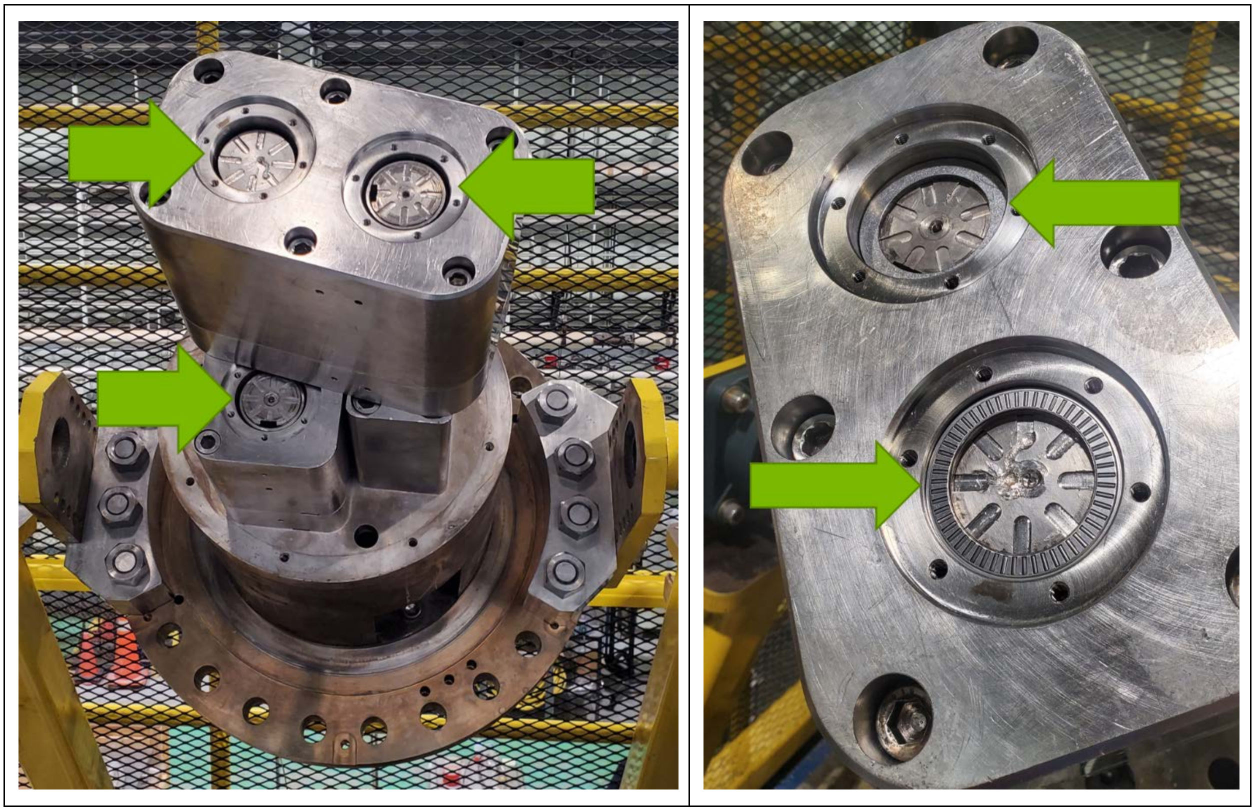


Figure 20: The bottom of the GTA with no thrust bearing assemblies, indicated by green arrows (left). The bottom of the GTA with the thrust bearings included (right). The right-top arrow shows the bottom of a shaft with the thrust race in place. The right-bottom arrow shows the bottom of a shaft with the thrust race and bearing in place.

V. <u>Appendix</u>

1. Over-Pin Dimensions Following Water Testing

Gear	Pin location		Measurement
L1AT	#1	#2	[in.]
	1,2	8,9	5.8980
	2,3	9,10	5.9005
	3,4	10,11	5.8975
	4,5	11,12	5.8960
	5,6	12,13	5.8950
	6,7	13,14	5.8940
	7,8	14,15	5.8950
	8,9	15,1	5.8985
	AVERAGE		5.8968
L1IT			
	1,2	8,9	5.9000
	2,3	9,10	5.9030
	3,4	10,11	5.9015
	4,5	11,12	5.8995
	5,6	12,13	5.8970
	6,7	13,14	5.8960
	7,8	14,15	5.8950
	8,9	15,1	5.9005
	AVERAGE		5.8991
T1BT			

	1,2	12,13	5.1830
	2,3	13,14	5.1780
	3,4	14,15	5.1835
	4,5	15,16	5.1860
	5,6	16,17	5.1865
	6,7	17,18	5.1840
	7,8	18,19	5.1835
	8,9	19,20	5.1835
	9,10	20,21	5.1820
	10,11	21,22	5.1830
	11,12	22,1	5.1810
	AVERAGE		5.1831
T1IT			
	1,2	12,13	5.1820
	2,3	13,14	5.1800
	3,4	14,15	5.1815
	4,5	15,16	5.1800
	5,6	16,17	5.1795
	6,7	17,18	5.1795
	7,8	18,19	5.1790
	8,9	19,20	5.1790
	9,10	20,21	5.1800
	10,11	21,22	5.1800
	11,12	22,1	5.1800

	AVERAGE	5.1800

2. Over-Pin Dimensions Following Experimental Campaign #1

(Including measurements of both sides of large gears to find discrepancies)

Gear	**Pin location**		**Measurement**	**Measurement**
L1AT	#1	#2	[in.]	[in.]
			Side L1AT	Side AA
	1,2	8,9	5.8955	5.8935
	2,3	9,10	5.8970	5.8930
	3,4	10,11	5.8960	5.8920
	4,5	11,12	5.8925	5.8925
	5,6	12,13	5.8920	5.8930
	6,7	13,14	5.8910	5.8935
	7,8	14,15	5.8915	5.8940
	8,9	15,1	5.8955	5.8940
			5.8939	5.8932
	AVERAGE		5.8935	
L1IT			Side L1IT	Side BB
	1,2	8,9	5.8980	5.8980
	2,3	9,10	5.8985	5.9000
	3,4	10,11	5.8965	5.8965
	4,5	11,12	5.8940	5.8945
	5,6	12,13	5.8920	5.8940
	6,7	13,14	5.8925	5.8935

	7,8	14,15	5.8925	5.8940
	8,9	15,1	5.8965	5.8965
			5.8951	5.8959
	AVERAGE		5.8955	
T1BT				
	1,2	12,13	5.1785	
	2,3	13,14	5.1785	
	3,4	14,15	5.1795	
	4,5	15,16	5.1810	
	5,6	16,17	5.1815	
	6,7	17,18	5.1800	
	7,8	18,19	5.1815	
	8,9	19,20	5.1815	
	9,10	20,21	5.1810	
	10,11	21,22	5.1805	
	11,12	22,1	5.1810	
	AVERAGE		5.1804	
T1IT				
	1,2	12,13	5.1785	
	2,3	13,14	5.1785	
	3,4	14,15	5.1775	
	4,5	15,16	5.1785	
	5,6	16,17	5.1775	
	6,7	17,18	5.1785	

	7,8	18,19	5.1775	
	8,9	19,20	5.1780	
	9,10	20,21	5.1775	
	10,11	21,22	5.1780	
	11,12	22,1	5.1775	
	AVERAGE		5.1780	

3. Over-Pin Dimensions Following Experimental Campaign #2

(Including measurements of both sides of large gears to find discrepancies)

Gear	**Pin location**		**Measurement**	**Measurement**
L1AT	#1	#2	[in.]	[in.]
			Side L1AT	Side AA
	1,2	8,9	5.8950	5.8955
	2,3	9,10	5.8965	5.8965
	3,4	10,11	5.8950	5.8950
	4,5	11,12	5.8920	5.8940
	5,6	12,13	5.8910	5.8935
	6,7	13,14	5.8910	5.8940
	7,8	14,15	5.8925	5.8940
	8,9	15,1	5.8960	5.8950
			5.8936	5.8947
	AVERAGE		5.8942	
L1IT			Side L1IT	Side BB
	1,2	8,9	5.8975	5.8975
	2,3	9,10	5.9010	5.8990

	3,4	10,11	5.8980	5.8965
	4,5	11,12	5.9000	5.8950
	5,6	12,13	5.8930	5.8940
	6,7	13,14	5.8930	5.8945
	7,8	14,15	5.9010	5.8950
	8,9	15,1	5.8975	5.8980
			5.8976	5.8962
	AVERAGE		5.8969	
T1BT				
	1,2	12,13	5.1780	
	2,3	13,14	5.1780	
	3,4	14,15	5.1790	
	4,5	15,16	5.1810	
	5,6	16,17	5.1810	
	6,7	17,18	5.1810	
	7,8	18,19	5.1810	
	8,9	19,20	5.1810	
	9,10	20,21	5.1810	
	10,11	21,22	5.1805	
	11,12	22,1	5.1810	
	AVERAGE		5.1802	
T1IT				
	1,2	12,13	5.1790	
	2,3	13,14	5.1780	

	3,4	14,15	5.1780	
	4,5	15,16	5.1780	
	5,6	16,17	5.1780	
	6,7	17,18	5.1780	
	7,8	18,19	5.1780	
	8,9	19,20	5.1770	
	9,10	20,21	5.1775	
	10,11	21,22	5.1780	
	11,12	22,1	5.1780	
	AVERAGE		5.1780	

4. Over-Pin Dimensions Following Experimental Campaign #3

(Including measurements of both sides of large gears to find discrepancies)

(Now using micrometer with ±0.00015” accuracy, replacing caliper with ±0.001” accuracy)

Gear	**Pin location**		**Measurement**	**Measurement**
L1AT	#1	#2	[in.]	[in.]
			Side L1AT	Side AA
	1,2	8,9	5.8952	5.8948
	2,3	9,10	5.8963	5.8958
	3,4	10,11	5.8946	5.8941
	4,5	11,12	5.8930	5.8935
	5,6	12,13	5.8922	5.8934
	6,7	13,14	5.8911	5.8940
	7,8	14,15	5.8925	5.8940
	8,9	15,1	5.8953	5.8952

			5.8938	5.8944
	AVERAGE		5.8941	
L1IT			Side L1IT	Side BB
	1,2	8,9	5.8973	5.8975
	2,3	9,10	5.9004	5.8983
	3,4	10,11	5.8973	5.8958
	4,5	11,12	5.8985	5.8943
	5,6	12,13	5.8928	5.8937
	6,7	13,14	5.8927	5.8934
	7,8	14,15	5.8982	5.8941
	8,9	15,1	5.8970	5.8972
			5.8968	5.8955
	AVERAGE		5.8962	
T1BT				
	1,2	12,13	5.1779	
	2,3	13,14	5.1779	
	3,4	14,15	5.1780	
	4,5	15,16	5.1805	
	5,6	16,17	5.1806	
	6,7	17,18	5.1803	
	7,8	18,19	5.1812	
	8,9	19,20	5.1816	
	9,10	20,21	5.1810	
	10,11	21,22	5.1817	

	11,12	22,1	5.1815	
	AVERAGE		5.1802	
T1IT				
	1,2	12,13	5.1790	
	2,3	13,14	5.1781	
	3,4	14,15	5.1783	
	4,5	15,16	5.1779	
	5,6	16,17	5.1775	
	6,7	17,18	5.1778	
	7,8	18,19	5.1770	
	8,9	19,20	5.1769	
	9,10	20,21	5.1770	
	10,11	21,22	5.1777	
	11,12	22,1	5.1773	
	AVERAGE		5.1777	

5. Over-Pin Dimensions Following Experimental Campaign #4

(Including measurements of both sides of large gears to find discrepancies)

(Now using micrometer with ±0.00015” accuracy, replacing caliper with ±0.001” accuracy)

Gear	**Pin location**		**Measurement**	**Measurement**
L1AT	#1	#2	[in.]	[in.]
			Side L1AT	Side AA
	1,2	8,9	5.8954	5.8933
	2,3	9,10	5.8961	5.8935
	3,4	10,11	5.8946	5.8940

	4,5	11,12	5.8929	5.8928
	5,6	12,13	5.8916	5.8920
	6,7	13,14	5.8897	5.8925
	7,8	14,15	5.8917	5.8933
	8,9	15,1	5.8950	5.8943
			5.8934	5.8932
	AVERAGE		5.8933	
L1IT			Side L1IT	Side BB
	1,2	8,9	5.8961	5.8956
	2,3	9,10	5.8977	5.8975
	3,4	10,11	5.8957	5.8944
	4,5	11,12	5.8933	5.8926
	5,6	12,13	5.8918	5.8922
	6,7	13,14	5.8908	5.8924
	7,8	14,15	5.8921	5.8933
	8,9	15,1	5.8960	5.8959
			5.8942	5.8942
	AVERAGE		5.8942	
T1BT				
	1,2	12,13	5.1760	
	2,3	13,14	5.1767	
	3,4	14,15	5.1777	
	4,5	15,16	5.1782	
	5,6	16,17	5.1790	

	6,7	17,18	5.1794	
	7,8	18,19	5.1790	
	8,9	19,20	5.1798	
	9,10	20,21	5.1790	
	10,11	21,22	5.1795	
	11,12	22,1	5.1781	
	AVERAGE		5.1784	
T1IT				
	1,2	12,13	5.1776	
	2,3	13,14	5.1769	
	3,4	14,15	5.1767	
	4,5	15,16	5.1766	
	5,6	16,17	5.1763	
	6,7	17,18	5.1766	
	7,8	18,19	5.1757	
	8,9	19,20	5.1755	
	9,10	20,21	5.1756	
	10,11	21,22	5.1762	
	11,12	22,1	5.1759	
	AVERAGE		5.1763	

VI. References

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