Status of GTA Gear Inspection after Testing in Sodium

Nuclear Science & Engineering Division

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March 2020

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Introduction

The Mechanisms Engineering Test Loop (METL) is an intermediate-scale liquid metal experimental facility that provides purified reactor-grade (R-grade) sodium to various experimental test vessels (Figure 1). In these test vessels, components that are required to operate in an advanced fast reactor can be tested in a prototypical sodium environment. Experiments conducted in METL significantly assist in the development and maturation of systems and components for advanced reactors. The METL facility consists of multiple test segments including: a purification and diagnostic loop (cold trap was designed after EBR-II), two 18" diameter test vessels with 150 L capacities capable of operating in static or dynamic flow at 538°C, two 28" diameter test vessels with 644 L capacities capable of operating in static or dynamic flow at 650°C, a 3,180 L dump tank with 21 instrumentation ports, and the infrastructure to expand capacity in the future.

Control of METL is handled by a fully automated Labview/Eurotherm I&C system. The components and instrumentation this system controls include: 52 Swagelok diaphragm valves, 12 Kammer diaphragm valves, three electromagnetic pumps, three electromagnetic flow meters, over 150 resistive heater zones, over 1000 thermocouples, a 1000 L Airgas argon supply, and two VFD blowers.

METL has been fully operational since early 2018 when sodium was transferred into the dump tank and then into the main loop. The initial experimental campaign of the first test article, the Gear Test Assembly, was completed in the spring of 2019.

Figure 1: Overhead View of METL Facility.

The Gear Test Assembly (GTA) is an experimental apparatus designed to test mechanical components used in advanced fuel handling systems of liquid-sodium cooled fast-spectrum nuclear reactors (Figure 2). The need for METL was identified during a component and infrastructure technology gap analysis for advanced reactors that was performed for the DOE-NE Advanced Reactor Concept (ARC) program in 2009. Reviews of existing documentation indicated a lack of testing for specific mechanical components used in the construction of advanced fuel handling systems. Most historical dynamic testing performed to-date uses a pin rubbing on a plate to test various materials for friction, wear, and self-welding. The existing data is insufficient for proper lifetime calculations of gearing components which operate under load in a high temperature flowing liquid sodium environment. The loads applied to the components in the GTA are based upon maximum design loading conditions calculated for a fuel handling system under conservative operating conditions.

The GTA system is designed for maximum testing flexibility and can accommodate various sizes of normal and parallel helical spur gears and mechanical roller bearings. The system can also be modified to test worm gears and straight or spiral bevel gears as well as other bearing geometries with minimal replacement of parts inside the liquid sodium testing environment. Resulting data are taken using vibration probes, torque sensors, tachometers, thermocouples, etc. and compared with data recorded by the METL system on sodium flow rates, purity, and temperatures. There is considerable reserve capacity in the system for additional measurements devices. There was extensive pre- and post-test non-destructive evaluation (NDE) analysis of the gears to determine the onset and evolution of mechanical failure.

Figure 2: Overview of GTA System.

Figure 3 - Exploded View of GTA - showing test gears and primary drive gears

The GTA was designed to accommodate spur gear sizes in the range of six-inch diameter and smaller. The design maximum torque applied to the input shaft is approximately 6,000 inch-pounds and is applied by a pair of Parker DC servo motors through a 7:1 Stober reducing gearhead. This type of peak force may be required to release a stuck core assembly during refueling operations. The weight of a commercial size core assembly can be approximately 1,000 pounds. Continuous loads are applied during GTA operations simulating the entire removal process of the core assembly. The duty cycle for testing is shown in Table 1, the gears will be subjected to the following forces which simulate a potential maximum load with margin.

The loading procedure (Table 1) starts at step 1 at the maximum load expected for 2 seconds (to simulate core assembly being released from the grid plate structure and surrounding core assemblies). While continuing to turn, the resisting load is suddenly reduced to simulate handling the weight of a typical commercial-size fuel assembly in step 2 for 58 seconds. At the final step in removing the core assembly, the loading proceeds to step 3 where the motion pauses for 30 seconds (to simulate time during other motions of the fuel handling system) and the control system reverses the motor directions and motor operation modes from driving to resisting (and vice versa).

With the direction reversed, the simulated core assembly weight is lowered in step 5 for 58 seconds. The load is suddenly increased in step 5 to simulate contact of the core assembly nose piece into the inlet plenum for 2 seconds. The motion is paused again for 30 seconds (to simulate other motions of the fuel handling system) in step 6 while the control system reverses the motor directions and motor operation modes from resisting to driving (and vice versa). The test duty cycle then begins again at step 1 and continues until testing completes or interim inspections and measurements are required or component failure occurs.

Table 1: GTA Designed Torque Profile.

Load Step	Torque at Gear [in-lbs.]	Time [s]	Motor A Operation Mode	Motor B Operation Mode	Equivalent Process in Core Assembly Handling Procedure
1	6,000	2.0	Driving	Resisting	Lifting core assembly with resistance due to adjacent core assembly load pads and nose piece to grid plate removal
2	1,000	58.0	Driving	Resisting	Lifting core assembly weight
3	0	30.0	Dwell	Dwell	Core assembly vertical position unchanged during horizontal traverse (motor direction and operation reverses)
4	1,000	58.0	Resisting	Driving	Lowering core assembly weight
5	6,000	2.0	Resisting	Driving	Lowering core assembly with resistance due to adjacent core assembly load pads and nose piece to grid plate insertion
6	0	30.0	Dwell	Dwell	Core assembly vertical position unchanged during horizontal traverse (motor direction and operation reverses)

In early October 2018, all necessary pre-sodium commissioning work was completed in Building 206 and the GTA was moved to Building 308. The GTA was assembled in the experimental test assembly workstation on the METL Mezzanine to ready the system for insertion into METL (Figure 4). All supporting electrical hardware and support instrumentation needed to be moved and installed in 308 to properly operate the GTA. This hardware included:

- 2x 480 VAC Transformers
- 480 VAC Disconnect Panel for Motor Power
- 240 VAC Disconnect Panel for Heater Power
- 2x Parker Compax3 Motor Controllers with Braking Resistors
- Argon Gas Supply Manifold
- Instrumentation and Control Panel including:
 - Parker ACR Programmable Motor Controller
 - Parker EPX2 HMI
 - NI cDAQ-9188XT
 - NI9428 Analog Output Card –SSR and Solenoid Valve Control
 - NI9208 4-20mA Input Card – Pressure Transducer and Torque Sensor Input
 - NI9213 Thermocouple Card – Temperature Input
 - NI9234 Voltage Input Card – Vibration Sensor Input
 - Watlow EZ-Zone RM Integrated Controllers
 - Watlow EZ-Zone Remote User Interface Modules.
 - Futek Torque Sensor Amplifier
 - 24VDC SSRs
 - Ethernet Switch

Figure 4: The GTA During Qualification in Building 308.

The final qualification of the GTA was completed once the system was assembled in Building 308 and all the above hardware was installed and made operational. The motor control system, the heaters, the thermocouples, the vibration sensors, the pressure transducers, the various gas seals, and the Labview Control VI were all confirmed to be in working order prior to installing the GTA in METL. Following this final qualification, the GTA was thoroughly cleaned to remove any potential contaminants that would otherwise end up in METL's sodium.

The GTA was installed and sealed in Test Vessel 1 in early January 2019. Leak testing was performed to confirm the performance of the main flange seal, the dynamic shaft seals, and the instrument port seal. This was accomplished by pressurizing Test Vessel 1 with 10 psig of helium via the sample port on the METL Valve Manifold. A helium leak detector with sniffer wand was used to probe the various seals and confirmed all three were operating satisfactorily. The GTA was again fully instrumented now that the test article installation had been completed.

A final in-vessel commissioning was performed to confirm the operation of the various supporting instrumentation. The GTA was insulated using Cerablanket and prepared for heat-up. Test Vessel 1 and the GTA began the gradual heat-up and bake-out process on January 10, 2019 when the system was commanded to go to 250°C at 1.5°C/hour. After reaching the operating temperature of 250°C, Test Vessel 1 and the GTA sat for roughly 2 weeks to bake-out any moisture that would cause problems during sodium fill. On February 1, 2019, Test Vessel 1 was filled to the overflow line with sodium from METL's dump tank.

The first round of testing of the GTA started February 5th, 2019 after the sodium in Test Vessel 1 was purified using METL's cold trap. The torque profile described in Table 1 was modified such that the high torque value of 6000 in-lbs. was reduced to 4000 in-lbs. This was required because the available motor controllers could not supply enough current to the motors. Future tests will use a gearbox with a higher torque ratio to reach the desired 6000 in-lbs.

Figure 5: Example Torque Data from the GTA.

The GTA operated continuously until March 7, 2019 when the automated system reported an over current fault coming from the motor controllers. The operator made attempts to restart the system, but found that the shafts would not rotate in either direction. An attempt to free the shafts was made by maximizing the allowed current the motors could draw and slowly jogging them, but the shafts would not rotate. First, the upper gearboxes were disassembled to determine if something failed in that location, but the gears and bearings looked healthy. The motors were tested free from the system and found to be in working order. Finally, an aluminum rod was

inserted in the upper gearboxes and a large pipe wrench was used to try to manually turn the shafts, but the system was found to be seized. This suggested there was a failure on the sodium side of the GTA and that a shutdown was required. METL remained in hot standby with the GTA isolated from the loop in Test Vessel 1. The GTA operated for 19,600 cycles (equivalent to 9,800 removal and insertion cycles for a core assembly). Test Vessel 1 was drained, the GTA was removed using the Flexicask System, and the GTA was cleaned and disassembled to properly inspect the gears.

Gear Design

The required lifetimes of the gears have been sized based upon 20,000 hours of continuous use in a high temperature (air) environment. The calculations for the gears were performed in accordance with the requirements of ANSI/ AGMA 2001-D04:2005 and have determined acceptable lifetime rating safety factors for fatigue bending and pitting of the gear teeth based on the Inconel 718 material and the selected heat treatment process. Other materials and heat treatments may be selected based on subsequent findings. The equations used to determine the AGMA evaluated bending and contact stresses are based upon several aspects of their loading and environmental conditions, safety factor equations for contact and bending fatigue (for gear 1 to gear 2 contact) are expressed below for reference. The American Gear Manufacturers Association has developed these methodologies for designing gearing components by calculating the lifetime of gearing components using lifetime reduction factors for various loading and environmental considerations. Equations for safety factors of contact and bending fatigue are utilized to evaluate the lifetimes of the designed gearing components and provide a method for assuring the gears perform for their intended lifetime within the applicable ranges of validity of the design lifetime reduction factors. Factors for lifetime reduction for operation in an elevated temperature flowing liquid sodium environment have not been developed.

$$\text{Safety Factor of Contact Fatigue: } S_{H12} := \frac{s_{ac} \cdot Z_{n12} \cdot C_{H12}}{C_p \cdot K_T \cdot K_R \cdot \sqrt{F_t \cdot K_o \cdot K_v \cdot K_{s12} \cdot \frac{K_{m12}}{d_{w1} \cdot b_w} \cdot \frac{C_{f12}}{I}}}$$

$$\text{Safety Factor of Bending Fatigue: } S_{F12} := \frac{s_{at12} \cdot Y_{N12} \cdot Y_{A12}}{K_T \cdot K_R \cdot F_t \cdot K_o \cdot K_v \cdot K_{s12} \cdot \frac{P}{b_{wF12}} \cdot \frac{K_{m12} \cdot K_{B12}}{J_{12}}}$$

The variables used in the AGMA safety factor equations include;

- s_{ac} – Allowable contact stress number
- s_{at12} – Allowable bending stress number
- F_t – Nominal tangential force acting on teeth
- d_{w1} – Operating pitch diameter of gear
- b_w – Operating tooth width
- P – Normal pitch
- b_{wF12} – Operating tooth width
- I – Geometry factors for pitting resistance
- Z_{n12} – Stress cycle factor for pitting resistance
- C_{H12} – Hardness ratio factor
- K_O – Overload factor
- K_V – Dynamic Factor
- K_{S12} – Size factor
- K_{m12} – Load distribution factor
- J_{12} – Geometry factor for bending strength
- Y_{N12} – Stress cycle factor for bending strength
- Y_{A12} – Reverse loading factor
- C_{f12} – Surface condition factor
- K_{B12} – Rim thickness factor
- K_R – Reliability factor
- K_T – Temperature factor
- C_P – Material factor

NDE Techniques and Results

In-Service Inspection of Advance Reactor Components

The METL user facility at ANL serves as a platform for the evaluation of various advanced reactor systems and components. In support of those activities, nondestructive evaluation (NDE) methods are being developed for detection and characterization of damage and degradation in parts that operate in liquid metal environment. Following the initial studies conducted earlier at ANL, two NDE techniques were identified as viable methods for in-service inspection of metal alloy components. They included eddy current testing (ECT) and ultrasonic testing (UT). The ECT method, in its various forms, is generally employed for detection of surface and near-surface flaws in electrically conducting and semi-conducting materials. Ultrasonic testing methods, on the other hand, allow volumetric examination of a broad range of materials. Other NDE methods such as radiographic testing (RT), thermal imaging, and optical methods may be used as supplementary or validation methods for volumetric or surface examination of advance reactor components.

Pre-operation inspections of a set of the four spur gears used in the GTA system were conducted prior to the GTA testing in METL. Post-operation inspections of the gears were conducted recently following the removal and cleaning of the parts. Any sodium that was adhered to the surface of the gears was removed by a chemical cleaning process. The gears were then inspected by employing the same ECT and UT methods employed for the acquisition of the baseline data. In addition, supplementary examinations were performed this time by using a specialized eddy current (EC) array probe technique that was developed more recently at ANL to allow rapid inspection of advanced reactor components with complex geometries. The NDE methods used for inspecting the spur gears of the manipulator test assembly are initially described below. Subsequently, representative data are presented on comparison of the baseline with the post-operation examination of the parts. **The NDE results generally indicate that further volumetric wall loss has been introduced as a result of in-service operation. The damage mechanism affecting the gear teeth in all cases is in the form of mechanical wear. Based on the analysis of NDE data, no detectable indications of cracking have so far been observed in any of the gear parts.**

Over Pin Measurement Comparison

Collecting over pin dimensions is a typical method to monitor the health of mechanical spur gears. This is accomplished by placing two identical dowel pins in the roots opposite each other on a gear. A caliper or micrometer is then used to measure the distance between the outer diameter of both dowel pins. As the gear operates and experiences wear, this dimension will reduce in size indicating that the gear teeth are experiencing mechanical wear. Figure 6 shows how this measurement would be made for the larger test gears in the GTA. Over pin measurements were made before the sodium testing and after the sodium testing. The difference in these measurements represents the gross mechanical wear the gears experienced over the course of the first experimental campaign. This data is presented in Table 2.

Gear L1AT wore 0.0033", or 4.62% of estimated life. Gear L1IT wore 0.0036", or 5.06% of estimated life. Gear T1BT wore 0.0026", or 3.68% of life. Gear T1IT wore 0.0020", or 2.88% life. This gross measurement method indicates mechanical wear occurred, but the amount of wear is minimal and testing of these gears should continue.

Figure 6: Example Over Pin Dimension for GTA Gear.

Table 2: Over Pin Data

	Gear	Pin location		Pre-Experiment	Post-Experiment			Average Wear
		#1	#2	Measurement [in]	Measurement (in)	Measurement (in)	Average Measurement	
	L1AT				Side L1AT	Side AA		
		1,2	8,9	5.8980	5.8955	5.8935	5.8945	
		2,3	9,10	5.9005	5.8970	5.8930	5.8950	
		3,4	10,11	5.8975	5.8960	5.8920	5.8940	
		4,5	11,12	5.8960	5.8925	5.8925	5.8925	
		5,6	12,13	5.8950	5.8920	5.8930	5.8925	
		6,7	13,14	5.8940	5.8910	5.8935	5.8923	
		7,8	14,15	5.8950	5.8915	5.8940	5.8928	
		8,9	15,1	5.8985	5.8955	5.8940	5.8948	
Average Measurement				5.8968	5.8939	5.8932	5.8935	
Average Wear								0.003281
	L1IT				Side L1IT	Side BB		
		1,2	8,9	5.9000	5.8980	5.8980	5.8980	
		2,3	9,10	5.9030	5.8985	5.9000	5.8993	
		3,4	10,11	5.9015	5.8965	5.8965	5.8965	
		4,5	11,12	5.8995	5.8940	5.8945	5.8943	
		5,6	12,13	5.8970	5.8920	5.8940	5.8930	
		6,7	13,14	5.8960	5.8925	5.8935	5.8930	
		7,8	14,15	5.8950	5.8925	5.8940	5.8933	
		8,9	15,1	5.9005	5.8965	5.8965	5.8965	
Average Measurement				5.8991	5.8951	5.8959	5.8955	
Average Wear								0.003594
Large Gear Average Wear								0.003437
	T1BT							
		1,2	12,13	5.1830	5.1785	5.1770	5.1778	
		2,3	13,14	5.1780	5.1785	5.1790	5.1788	
		3,4	14,15	5.1835	5.1795	5.1785	5.1790	
		4,5	15,16	5.1860	5.1810	5.1805	5.1808	
		5,6	16,17	5.1865	5.1815	5.1810	5.1813	
		6,7	17,18	5.1840	5.1800	5.1815	5.1808	
		7,8	18,19	5.1835	5.1815	5.1820	5.1818	
		8,9	19,20	5.1835	5.1815	5.1820	5.1818	
		9,10	20,21	5.1820	5.1810	5.1815	5.1813	
		10,11	21,22	5.1830	5.1805	5.1815	5.1810	
		11,12	22,1	5.1810	5.1810	5.1815	5.1813	
Average Measurement				5.1831	5.1804	5.1803	5.1805	
Average Wear								0.002614
	T1IT							
		1,2	12,13	5.1820	5.1785	5.1785	5.1785	
		2,3	13,14	5.1800	5.1785	5.1785	5.1785	
		3,4	14,15	5.1815	5.1775	5.1785	5.1780	
		4,5	15,16	5.1800	5.1785	5.1780	5.1783	
		5,6	16,17	5.1795	5.1775	5.1780	5.1778	
		6,7	17,18	5.1795	5.1785	5.1780	5.1783	
		7,8	18,19	5.1790	5.1775	5.1775	5.1775	
		8,9	19,20	5.1790	5.1780	5.1775	5.1778	
		9,10	20,21	5.1800	5.1775	5.1780	5.1778	
		10,11	21,22	5.1800	5.1780	5.1780	5.1780	
		11,12	22,1	5.1800	5.1775	5.1780	5.1778	
Average Measurement				5.1800	5.1780	5.1781	5.1780	
Average Wear								0.002045
Small Gear Average Wear								0.002330

Eddy Current Inspection of Spur Gears

An eddy current (EC) inspection system has been assembled at ANL for NDE of advanced reactor components. For the sake of completeness, the inspection system including the added features that have been incorporated since baseline examinations were performed, is briefly described next. The NDE results from post-operation inspection of the spur gears of the manipulator test assembly are discussed afterwards.

The EC inspection system is composed of three main blocks that include the EC tester and probe assembly, a four-axis translation/rotation stage, and a PC based motion control and acquisition hardware with the associated software. The same PC is also used for running a number of algorithms that have been integrated under a common user interface for the processing and displaying of the data. The software based tools were developed in-house and adapted to the application at hand. The ECT instrument, displayed in Figure 7(a) is a MIZ-200 (Zetec, Inc.) multi-frequency acquisition system that is designed for a broad range of balance-of-plant inspection applications. The instrument operates under the PC-based Velocity software platform, which includes an acquisition and an analysis module. The MIZ-200 unit available at ANL is capable of handling many probe types with absolute or differential configurations such as bobbin, rotating, array (64 channels) and pencil type probes. The photos of a spur gear mounted on the translation/rotation stage with a pencil probe positioned over the in-line calibration block and over the part under test are displayed in Figure 7(b) and Figure 7(c), respectively. It should be noted that the parts associated with the probe and the gear holders were all manufactured at ANL by using an additive manufacturing (3D printing) process. This approach allows manufacturing of probe holders for inspecting parts with arbitrary shapes and dimensions. A photo of the four-axis motion stage is displayed in Figure 7(d). The screen shots of the user interfaces implanted using C# software programming language for the motion control system are displayed in Figure 8. These software tools have been refined and updated since the initial NDE assessments to further accommodate inspections with array probes. A more detailed description of the motion control software was provided in a previous report.

Figure 7: Eddy current inspection system consisting of a (a) MIZ-200 acquisition unit, probes, and a four axis translation/rotation stage. Shown in the figure are photos of a gear mounted on the stage with the probe scanning over (b) the in-line calibration block (c) the gear tooth. The entire four-axis stage is displayed in (d).

Figure 9(a) shows the drawings of the calibration block made of Alloy 718 material that was machined in-house and used as the reference standard. The block contains three flat bottom holes of different depths. To closely emulate the probe response from subsurface volumetric flaws, tightly fitted pins made of the same alloy material were inserted into the holes. Figure 9(b) shows the back side of the calibration block before the pins were inserted. As with the baseline EC data,

the calibration block is scanned prior to inspecting each spur gear. The signals from known machined flaws in the reference standard are then used to normalize the amplitude and adjust the phase angle of the EC data collected on the gears. Figure 9(c) shows the EC data associated with the calibration block, which is displayed in strip chart, lissajous curve and terrain plot formats. The presence of three subsurface machined flaws are clearly visible in the data associated with the 500 kHz frequency channel. In agreement with the EC skin depth attenuation, the intensity of flaw signals is inversely proportional to the thickness of the remaining conductor material over the machined holes on the calibration standard block. The ANL computer aided data analysis tool was used in all cases to process and display the EC inspection data. The user interface, which was developed under MATLAB environment, allows processing and visualization of the NDE data by using various signal processing and data analysis algorithms adapted to the application at hand.

(a)

(b)

(c)

Figure 8: Screen shots of the user interfaces implemented at ANL in C# for controlling the four-axis translation/rotation stage. Shown in (a)-(c) are the main scan configuration panel, the manual control panel, and the raster scan control panel, respectively.

Figure 9: (a) Drawings of the Alloy 718 calibration block with three machined subsurface flat-bottom holes, (b) a photograph of the back side of the sample manufactured at ANL and the three cylindrical inserts that fill the holes and (c) the EC inspection data associated with the calibration block in strip chart, lissajous, image and terrain plot formats displayed using the ANL computer aided data analysis tool.

A new capability to handle array type probes for in-situ examination of advanced reactor components has been added to the EC inspection system at ANL. As noted earlier, the primary motive behind this R&D effort was to increase the speed of inspection for parts with arbitrary geometries. To this end, hardware and software modifications were incorporated recently to allow acquisition of data with EC array probes with up to 64 elements. The 64-channel array probe design used in this work takes advantage of thin-film printed circuit technology. As such, the flexible probe can conform to the surface of parts with complex geometries. The increase in speed of inspection offered by array probes is a direct result of increased spatial coverage of the probe. An additional capability of the array probe used in this work is its directional sensitivity. This is achieved by incorporating two rows of transmit-receive (T-R) coils, thus allowing the orientation of discontinuities to be identified by sensing the outputs of orthogonal elements.

Figure 10(a) shows a photo of one of the array probe holders made of soft plastic material, which was manufactured at ANL by utilizing 3D printing technology. Separate probe holders were manufactured to allow inspection of gears of two different sizes. A photo of the 64-element flexible thin-film EC array probe, prior to being fully mounted on the holder, is displayed in Figure 10(b).

The two rows of T-R elements are visible in that photo. Finally, Figure 10(c) shows a photo of the probe mounted on the translation/rotation stage and positioned over the part under examination. For inspecting the gears, the surface conforming EC array probe sequentially traverses individual gear teeth in an automated manner. The entire surface of each tooth, which includes top and bottom flanks, top land, and root, is examined in this manner via a single linear scan of the array probe along the tooth's length.

Figure 10: (a) Array probe holder made of soft plastic material that was manufactured at ANL by a 3D printing process, hat forms a contour over a gear tooth, (b) 64-element flexible EC array probe prior to full mounting on the holder and (c) the probe mounted on the stage and placed over a gear tooth.

Figure 11 shows the drawings and the photos of two different size Alloy 718 spur gears of the gear test assembly examined in this work. Eddy current inspections were performed on a total of four gears (two of each size). The drawings of the parts are shown in Figure 11(a) and (b). The photos of the front surface of the parts associated with the drawings in Figure 11(a) and (b) are displayed in Figure 11(c) and (d), respectively. Numbering of the gear teeth was etched at the METL facility on the front surface of each gear. However, to be consistent with the baseline NDE data, a different numbering scheme was used for scanning the parts. Except for one gear, labeled as L1AT, the teeth numbering for EC inspections is in counterclockwise (CCW) direction with the rotation of the stage being in the clockwise (CW) direction. Raster scan data with the pencil probe were collected on the top and the bottom surface of all teeth by acquiring data once with the front side and once with the back side of the gear facing outward. The numbering of the teeth starts with the one that is closest to a horizontal surface when the gear is mounted on the rotational stage and with

the notch being in vertical position. For this latest set of tests, red markers were placed on tooth #1 of each gear for the purpose of position identification during the scanning process.

Figure 11: Drawings of the (a) small and (b) large spur gears made of Inconel 718 material on which post operation NDE was performed. Photos of the gears (two for each size) associated with the drawings in (a) and (b) are shown in (c) and (d), respectively. The teeth numbering is etched on each part.

EC examinations were performed on the four spur gears supplied for NDE assessments following their removal from testing and service. EC data were simultaneously collected at multiple frequencies (multiplexed channels) ranging from 50 kHz to 500 kHz. The highest test frequency for EC inspection of the spur gears was determined based on the electrical properties of Alloy 718 material ($\rho=127 \mu\Omega\cdot\text{cm}$ at 20°C) and the expected depth of service-induced flaws in the parts under examination. As a tradeoff, while the lower test frequencies provide larger depth of penetration, the higher test frequencies provide finer spatial resolution and higher sensitivity to near-surface flaws. Representative EC inspection data associated with the 500 kHz frequency channel are presented next that exhibit the range of variation in the level of service-induced damage to the gears since the baseline inspections were performed. The examples include comparison of pre- and post-service EC data acquired with a pencil probe, data from gear teeth with more significant surface-initiated volumetric damage and comparison of data collected on the same tooth with the pencil probe and with the array probe. The NDE data in all cases are processed and displayed using the ANL data analysis tool. **As noted previously, the observed damage in all cases are indicative of normal mechanical wear, that includes some more severe damage occurring near the edges of the teeth.**

As the first example, Figure 12 shows a comparison of EC inspection results between the pre-service (2018) and post-service (2019) data collected on a gear tooth that exhibits a more extensive

newly induced degradation. The data in both cases were collected on the front side of tooth #3 of the gear identified as L1AT (see Figure 11). In this case, the horizontal component of the calibrated data is displayed in image format. The pre- and post-service data are displayed in the top and middle images of Figure 12, respectively. Also shown in the bottom pane of that figure is a photo of the front surface of the tooth #3. Based on comparison of the NDE results, the extent of mechanical wear is more apparent, over the entire surface of the tooth, in the most recent data. The area where new degradation has been introduced since the baseline examinations were conducted are marked on the two images in Figure 12. Analysis of EC data in this case suggests that the flaw signals are all indicative of shallow volumetric indications.

Representative EC inspection data collected with the pencil probe on different gears are presented in the next three figures. The data represents the range of variation in the degree of service-induced volumetric degradation. Figure 13 shows the EC data collected on the back side of tooth #1 of the gear identified as L1AT. Shown in that figure are the vertical and horizontal components of the data that was processed and displayed with the ANL data analysis tool. Also shown as inset is the corresponding photo of the gear tooth. As observed in other cases, a more extensive degree of wear is detectable over the surface of the tooth. A relatively large signal, indicative of a volumetric flaw, is visible near the center of the top edge of the tooth. This dominant feature detected in the EC data, clearly visible in the images in Figure 13, is where visible corrosion was later observed following immersion of the part in water to conduct ultrasonic testing.

Representative EC data collected with the pencil probe on the back side of tooth #1 of the gear identified as T1BT is shown in Figure 14. Once again, the vertical and horizontal components of the processed data are displayed with the ANL data analysis tool. Also shown as inset is the corresponding photo of the gear tooth. Analysis of the EC inspection results indicate the presence of an extensive degree of wear in the center part of the tooth. As in the previous example, a dominant volumetric indication is visible in that region. The flaw-like signals have a larger horizontal component and are indicative of shallow volumetric degradation.

Figure 15 shows another example of EC data collected with the pencil probe on the back side of tooth #13 of the gear identified as L1AT. The vertical and horizontal components of the processed data are displayed with the ANL data analysis tool. The corresponding photo of the gear tooth is displayed as inset. Analysis of the EC inspection results indicate a moderate degree of wear that is mostly present on one side of the tooth. As in the previous example, a dominant volumetric indication is visible in center region of the tooth. The flaw-like signals in this case are also indicative of shallow volumetric degradation.

Finally, comparison of representative EC data collected with two different probes is presented in Figure 16. The NDE results are associated with tooth #11 of the spur gear identified as L1IT. Figure 16(a) displays the vertical component of the data in image format that was constructed from a single linear scan with the array probe. The image in Figure 16(a) encompasses the entire surface of the tooth (top and bottom flank). The corresponding image obtained by raster scanning of the pencil probe and covering only the back side of the same tooth is displayed in Figure 16(b). Comparison of the data collected with the two probes shows good overall consistency between the two probe types. A dominant feature on the back side of the tooth, indicative of wear type flaw, is

present in the same location in the data acquired with both probes. Scanning of the sample with the array probe, however, was performed over a significantly shorter period of time in comparison to the raster scan method used for acquiring data with the pencil probe.

Conclusions and Discussions of Eddy Current Testing

An eddy current inspection system has been developed at ANL for NDE of advanced reactor components. A number of hardware and software modifications have been incorporated into the system since it was originally designed. The latest improvements include the ability to interface the EC acquisition unit with array probes and the refinement of the software to process data acquired with high resolution probes. A surface conforming array probe that takes advantage of flexible thin-film technology was adapted more recently for use with the EC inspection system. The latest performance tests conducted on a set of manipulator spur gears have clearly demonstrated the advantage of flexible array probe technology over conventional single-element EC probes. The primary advantage is the significant increase in the speed of inspection. An extensive NDE database has so far been assembled at ANL, which includes pre- and post-service NDE data on the spur gears of the GTA assembly at the METL facility. While the available NDE to date has been analyzed using conventional methods, planned activities include evaluation of alternative schemes for automated analysis of the available EC inspection data. Future plans also include acquisition and analysis of additional data on samples before and after exposure to realistic operating environments. Although the R&D efforts at ANL have demonstrated the utility flexible array probe technology for more rapid inspection of parts with complex geometry, further improvements could be made in the future to increase the resolution of such probes. Numerical electromagnetic modeling, utilized extensively at ANL, can be employed to not only optimize the design of EC probes but also help with interpretation of the probe response under challenging conditions. Radiography and computerized tomography are routinely used as validation techniques for evaluation other NDE methods. As such, future plans in connection with NDE of advanced reactor components at ANL include further evaluation of the X-ray radiography and CT methods including the use of a new CMOS linear array and area detectors that can provide higher spatial resolution than conventional detectors.

Figure 12: Comparison of EC inspection 2018 data (top) with 2019 data (middle) collected on gear L1AT, tooth #3, front side. Also displayed is the photo of the gear tooth (bottom). While the increased degree of wear is apparent over the entire surface of the tooth, new areas of wear are also detectable in recent data (delineated in red).

Figure 13: Representative EC data collected with a pencil probe on the back side of tooth #1 of gear L1AT. Shown above are the vertical and horizontal components of the processed data that is displayed with ANL data analysis tool. Also shown (inset) is the corresponding photo of the gear tooth. The dominant signal in the EC data (top center of the images) is where corrosion was later observed following immersion of the part in water for ultrasonic testing.

Figure 14: Representative EC data collected with a pencil probe on the back side of tooth #1 of gear T1BT. Shown above are the vertical and horizontal components of the processed data that displayed with ANL data analysis tool. Also shown (inset) is the corresponding photo of the gear tooth. The NDE results indicate a more extensive degree of wear in the center region of the tooth.

Figure 15: Representative EC data collected with a pencil probe on the back side of tooth #13 of gear LIAT. Shown above are the vertical and horizontal components of the processed data that displayed with ANL data analysis tool. Also shown (inset) is the corresponding photo of the gear tooth. The NDE results indicate a more moderate degree of wear in the center region of the tooth.

(a)

(b)

Figure 16: Representative EC data collected on tooth #11 of gear LIIT. The vertical components of the data displayed in image format were obtained from (a) array probe scan of the entire surface of the tooth (top and bottom flank) and from (b) pencil probe scan of the back side of the same tooth. The corresponding dominant feature on the back side of the tooth, indicative of wear type flaw, is present in the data acquired with both probes.

Ultrasonic Inspection of Spur Gears

Ultrasonic testing (UT) is an NDE technique used for in-situ examination of complex parts for detection and volumetric sizing of defects. An ultrasonic inspection system (Figure 17) is assembled to collect baseline NDE data on four manipulator spur gears that had been tested in liquid sodium at METL. The system consists of an ultrasonic pulser/receiver (Imaginant DPR-300), a submersible ultrasonic transducer, a water tank, a gain-pass filter (Krohn-Hite Model 3944), a three-axes scanning translation module, and a scanning and data acquisition (S&DAQ) unit.

Two UT techniques, pulse-echo and through-transmission, have been commonly used for UT inspection. The choice between them is based on both accessibility and defect types. To detect internal defects, rather than surface defects as for EC technique, of the manipulator spur gears, the pulse-echo technique was selected. An ultrasonic transducer is held by a mounting unit that is mounted on a three-axes scanning translation module. Each linear translation stage is driven by a step motor with a minimum moving resolution of 2 micrometers. Through an XY-scanning, both the 2D intensity and time-of-flight (TOF) images are generated to locate and size any internal defects between the front and back mounting surfaces. However, limited by the travel distances of the XY-translation stages, the UT inspection system can only scan an area less than 3" x 3". Figure 18 shows the setup of UT inspection of a manipulator spur gear in water. The gear and transducer were submerged in water and the placement and distance between them was fixed. To completely scan a gear as well as keep the same scanning dimension, the gear was manually rotated clockwise by several teeth or ~45 degrees after each scan and totally eight scans were taken for the gear.

Figure 17: Ultrasonic inspection system consisting of an ultrasonic pulser, a submersible ultrasonic transducer, a water tank, a three-axes scanning translation module, and a scanning and data acquisition (S&DAQ) unit.

Figure 18: UT inspection setup of a manipulator spur gear in water.

The improved S&DAQ unit, developed for the under-sodium viewing project, was improved to reduce scanning time and enhance real-time intensity images generated from raw data. The system automatically calculates an optimal scanning speed based on the moving average number and scanning resolution set by an operator. The real-time ultrasonic intensity image is generated from results of the total energy of the moving average of ultrasonic A-scan signals while scanning. Figure 19 shows the S&DAQ control panel on a LabVIEW platform and a real-time intensity image of gear teeth of Gear A-T1IT.

Figure 19: Improved S&DAQ control panel and a real-time intensity image of gear teeth.

Due to the relatively large thicknesses of the gears, it is important to select an ultrasonic transducer with optimal operation frequency, output power, beam size and focal distance such that a clean ultrasonic reflection signals from both sides of the gear mounting surfaces could be received and better detection resolution can be achieved. Different focused and unfocused ultrasonic transducers were tested to evaluate the effect of beam size. For a better comparison of the UT inspection results of the gears before and after sodium test, the same focused transducer (Panametrics A309R, series # 2911425) was used. The transducer has an operation frequency of 5 MHz, a diameter of 0.5", and a focal distance of 2". The gear being tested was placed at the focal distance. Figure 20 shows a typical real-time ultrasonic RF signal received by the focused transducer from a pulse-echo test of the GTA spur gear. Any internal defects could produce a reflection echo in between the front and back surfaces depending on its orientation and size.

Figure 20: Typical real-time ultrasonic RF signal of from a pulse-echo test of a GTA spur gear.

Ultrasonic NDE of Gear B-T1BT after in-sodium test was conducted by using the selected focused ultrasonic transducer and the results before and after in-sodium test were then compared. The gear was manually rotated clockwise by three teeth after each scan, which is 2.4" x 2.4" in dimension and 100x100 pixel in resolution. To inspect the whole gear, eight images were generated. Figure 21 shows the real-time ultrasonic intensity images of Gear B-T1BT after sodium test. Figure 22 shows the composite ultrasonic intensity images of Gear B-T1BT generated by ultrasonic NDE before and after in-sodium test, as well as photos before and after teeth number punched.

Figure 21: Ultrasonic intensity images of Gear B-T1BT after sodium test.

Figure 22: Composite ultrasonic intensity images of Gear B-T1BT a) before and b) after sodium test, and photos c) before and d) after teeth number punched.

Location and size of any internal defects in the gear can be determined by using a MATLAB based image processing package, named imagingGUI, developed at Argonne for advanced data image processing and 2D/3D data visualization. Toolboxes and plug-in features have been developed and embedded in the imagingGUI for various NDE techniques, such as millimeter wave (mmW), ultrasonics, eddy current (EC), and photoacoustic spectroscopy (PAS). It contains plug-ins to convert existing data generated from different platforms into proper formats. It can process, analyze, and display different data types acquired from various NDT techniques or different layouts of one particular sample. Various user-generated filters and functions are also available for different data types and NDT techniques. Figure 23, for example, shows the signal processing

results of the ultrasonic intensity of tooth #16-17-18-19 of Gear B-T1BT. Figure 23(top) shows the ultrasonic A-scan signal at the cursor (i.e. at the cross point) in the ultrasonic images. Figure 23(left) and (right) shows the TOF and intensity images of the gated area, respectively. Profiles of the TOF and intensity at the cursor along X and Y axes are also displayed on the left and the top of each image accordingly. The intensity profiles directly show the defect dimensions along the X and Y axes respectively.

Figure 23: (top) Ultrasonic RF signal at the cursor, (left) TOF image, and (right) intensity image of Gear B-T1BT.

Before in-sodium test, there were extra reflection signals found at the location around 1/4 to 1/3 of the gear thickness underneath the front surface and along the edge of the gear's shaft key. A narrow digital gate then was set and covered the area of the extra reflections such that only the data within the gate (i.e. the cross-section of the gear within the gate) were then analyzed and displayed. Further evaluation shows that the reflections are the multiple reflections between teeth wall. With better positioning and alignment of the gear and the ultrasonic transducer, the multiple reflections disappear. Figure 24 shows the intensity of at corner of gear key of Gear B-T1BT before and after in-sodium test, respectively.

Figure 24: Intensity images of Gear B-T1BT a) before and b) after in-sodium test with a narrow digital gate.

Figure 25 shows the real-time ultrasonic intensity images of Gear A-T1IT after in-sodium test by using the selected focused ultrasonic transducer. Each image is 2.4" x 2.4" in dimension and 100x100 pixel in resolution. The gear was manually rotated clockwise by three teeth after each scan. Figure 26 shows the composite ultrasonic intensity images of Gear A-T1IT generated by ultrasonic NDE before and after in-sodium test, and photo after teeth number punched. Figure 27 shows the ultrasonic intensity images of Gear A-T1IT before and after in-sodium test, respectively.

Figure 25: Ultrasonic intensity images of Gear A-T1IT after sodium test.

Figure 26: Composited ultrasonic intensity images a) before and b) after sodium test, and c) photo of Gear A-TIIT.

Figure 27: Intensity images of Gear A-TIIT a) before and b) after in-sodium test.

Figure 28 shows the real-time ultrasonic intensity images of Gear AA-L1AT by using the selected focused ultrasonic transducer. Each image is 2.0" x 2.0" in dimension and 100x100 pixel in resolution. The gear was manually rotated clockwise by two teeth after each scan. Figure 29 shows the composite ultrasonic intensity image generated from the images in Figure 28, and a photo of the gear after teeth number punched. Figure 30 shows the ultrasonic intensity images of Gear AA-L1AT before and after in-sodium test, respectively. With better positioning and alignment of the gear and the ultrasonic transducer, the gear tooth number of each tooth and the gear name can be observed.

Figure 28: Ultrasonic intensity images of Gear AA-LIAT after sodium test.

Figure 29: Composite ultrasonic intensity images of Gear AA-LIAT a) before and b) after sodium test, and photos c) before and d) after teeth number punched.

Figure 30: Intensity images of Gear AA-LIAT a) before and b) after in-sodium test.

Figure 31 shows the real-time ultrasonic intensity images of Gear BB-LIIT by using the selected focused ultrasonic transducer. Each image is 2.0" x 2.0" in dimension and 100x100 pixel in resolution. The gear was manually rotated clockwise by two teeth after each scan. Figure 32 shows the composite ultrasonic intensity image generated from the images in Figure 31, and a photo of the gear after teeth number punched. Figure 33 shows the ultrasonic intensity images of Gear BB-LIIT before and after in-sodium test, respectively. With better positioning and alignment of the gear and the ultrasonic transducer, the gear tooth number of each tooth and the gear name can be observed.

Figure 31: Ultrasonic intensity images of Gear BB-LIIT after sodium test.

Figure 32: *Composited ultrasonic intensity images a) before and b) after sodium test, and c) photo of Gear BB-LIIT. Note that image a) and b) are composite images of the gear teeth, leading to a jagged center hole depiction.*

Figure 33: *Intensity images of Gear BB-LIIT a) before and b) after in-sodium test.*

Conclusions and Discussions of Ultrasonic Testing

We have demonstrated that the ultrasonic energy is strong enough to penetrate through the GTA spur gears made of Inconel 718 with thickness greater than 4 inches. The UT technique has also demonstrated that it is capable of detecting and sizing defects inside a component or at a location that is difficult to be reached. The UT technique, with better positioning and alignment of the gear and the ultrasonic transducer, clearly shows the gear tooth number of each tooth and the gear label that were punched on the gear's mounting surfaces, as shown in Figure 28 and Figure 30. **By analyzing the images taken before and after in-sodium test, no crack-like defect has been found in all four gears.**

Bearing Failure

The preceding sections of this report described the methods used to examine the health of the gears after the first experimental campaign. All methods showed that the gears experienced wear, but they are still in good condition after operations in sodium. It is therefore important to describe why the first testing campaign was halted and the system disassembled. As mentioned earlier, after a month of continuous operation the GTA control system experienced multiple faults associated with the drive motor. All indications were that the shafts has seized inside the GTA. After removal and disassembly, it was discovered that the cause of the seizure was a bearing failure in the test gearbox. A tapered roller bearing failed such that the cage holding the rollers to the inner race broke, allowing the rollers to become lodged between the teeth of the gears. Figure 34 shows images of the broken bearing alongside an unused bearing.

Figure 34: (Left) Broken Bearing Cage. (Middle) Inner Bearing Race with a few Rollers. (Right) Untested Bearing for reference.

The bearings used in this test were Timken brand tapered roller bearings made of 52100 bearing steel that was heat treated to raise the maximum operating temperature from 150°C to 350°C. 52100 bearing steel is a low alloy steel, and it was suspected that these bearings would fail before the gears due to the fact that they were not engineered specifically for longevity in a high temperature sodium application. Efforts to source high alloy or exotic alloy bearings have been underway but so far unsuccessful due to the specialty nature of these bearing materials. Therefore, the project moved forward with these bearings as the best available choice. Nonetheless, it was desirable to examine the bearings to understand the cause of their failure. Cross sections of the inner race, outer race, and cage material were made to perform optical analysis, SEM analysis, micro-hardness testing, and to determine chemical composition. This revealed that the inner and outer race were manufactured from 52100 steel, and that the outer surfaces of these races were hardened, likely during the heat treatment process, but the cage material was standard carbon steel. Hardness profiles for each of the components is presented in Figure 35. This data, along with the physical appearance of the bearing after disassembly, suggests the failure occurred at the bearing cage and allowed the rollers to fall from the bearing and into the gears. Future bearing development will be needed to extend the duration of the testing the GTA can complete in one campaign with the ultimate goal of deploying these advanced systems in an advanced reactor.

Figure 35: (Left) Inner Race Hardness Profile. (Right) Outer Race Hardness Profile. (Bottom) Cage Hardness Profile.

Acknowledgement

This research was sponsored by the U.S. Department of Energy, Office of Nuclear Energy, for the Advanced Reactor Technologies (ART) Research and Development Program under Contract DE-AC02-06CH11357. We gratefully acknowledge the support provided by Tim Beville of DOE-NE, Advanced Reactor Technologies, R&D Program Manager; Brian Robinson of DOE-NE, Advanced Reactor Technologies, Fast Reactor Manager; and Robert Hill of Argonne National Laboratory, ART R&D Fast Reactor National Technical Director.

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