Gear Test Assembly – Experimental Testing and Gear Analysis - FY2021 Year End Report

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Gear Test Assembly – Experimental Testing and Gear Analysis - FY2021 Year End Report

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1. Introduction

The Gear Test Assembly (GTA) is an experimental apparatus designed to test mechanical components used in fuel handling systems of liquid-sodium cooled fast-spectrum nuclear reactors (Figure 1). The performance and lifetime of gears, bearings, and dynamic seals are the primary focus of study. Three experimental campaigns have been completed since the start of operation in 2019, and the GTA is currently assembled and ready to begin the fourth experimental campaign. Sodium operations at the Mechanisms Engineering Test Loop (METL) have been paused while repairs are made to the Building 308 Alkali Metal Scrubber. This work is nearly complete, and once METL is brought back into operation the GTA will begin sodium testing immediately.

![Figure 1: The GTA fully assembled (left), a CAD view of the GTA with components removed to show the tested gears (right).](image)

2. Experimental Testing History

Three experimental campaigns have been completed to date, with details on each campaign available in previous DOE-ART reports [1,2]. The first campaign tested radial spur gears of Inconel 718, tapered roller bearings of heat-treated 52100 bearing steel, and a dynamic shaft seal using composite graphite. The first campaign completed 9,800 simulated fuel assembly maneuvers before a tapered roller bearing failed requiring shutdown (Figure 2). The second campaign tested the original Inconel 718 radial spur gears, tapered roller bearings of standard 52100 bearing steel with no heat-treatment, and a lantern ring seal with graphite cord. The second campaign completed
1,384 simulated fuel assembly maneuvers before a tapered roller bearing failed requiring shutdown (Figure 3). The third campaign tested the original Inconel 718 radial spur gears, tapered roller bearings of standard 52100 bearing steel, and a spring loaded lantern ring seal. The third campaign completed 1,568 simulated fuel assembly maneuvers before a thrust bearing assembly failed requiring shutdown (Figure 4 & Figure 5). Table 1 gives an overview of the operation and maintenance times for each of the previous three campaigns.

Table 1: GTA Experimental Operation Time Table

<table>
<thead>
<tr>
<th>Activity</th>
<th>Campaign 1</th>
<th>Campaign 2&lt;sup&gt;1&lt;/sup&gt;</th>
<th>Campaign 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Testing Start</td>
<td>2/5/2019</td>
<td>3/18/2020</td>
<td>2/16/2021</td>
</tr>
<tr>
<td>Hot Standby</td>
<td>-</td>
<td>3/20/2020</td>
<td>-</td>
</tr>
<tr>
<td>Restart</td>
<td>-</td>
<td>5/28/2020</td>
<td>-</td>
</tr>
<tr>
<td>Removal</td>
<td>8/6/2019</td>
<td>8/7/2020</td>
<td>3/18/2021</td>
</tr>
<tr>
<td>Carbonation Start</td>
<td>8/6/2019</td>
<td>8/10/2020</td>
<td>3/19/2021</td>
</tr>
<tr>
<td>Carbonation End</td>
<td>9/17/2019</td>
<td>8/18/2020</td>
<td>4/2/2021</td>
</tr>
<tr>
<td>Cleaned &amp; Disassembled</td>
<td>11/7/2019</td>
<td>9/2/2020</td>
<td>5/5/2021</td>
</tr>
</tbody>
</table>

<sup>1</sup> Campaign 2 was impacted by the shutdown of Argonne during the COVID19 pandemic. The GTA test article soaked in the sodium at 250°C for 69 days before testing could resume.
Figure 3: Fragmented remains of tapered roller bearing from Campaign 2.

Figure 4: Remains of thrust bearing assembly in gearbox from Campaign 3.
3. Gear Analysis Following Campaign #3

Nondestructive examination (NDE) of a set of four spur gears used in the GTA system of the METL facility was performed following the third experimental campaign of in-sodium operation. Consistent with the previous examinations, two complementary NDE techniques were employed for this purpose. The techniques included eddy current testing (ECT) and ultrasonic testing (UT). The eddy current (EC) data were acquired by using a specialized surface-conforming array probe developed at Argonne for the inspection of GTA gears of different size. Volumetric examination of the gears by the UT method was performed using an imaging system assembled for this purpose.

In what follows, a brief description is provided first of the NDE systems and procedures used for the inspection of spur gears of the manipulator test assembly. Representative data and results from this latest round of inspections are subsequently presented. Comparative assessments based on the NDE results indicate that the gear teeth experienced some additional wall loss since the parts were
last inspected. However, the ECT results generally indicate that the rate of damage during the last period of operation is lower than that experienced during the previous period of operation. Consistent with past observations, mechanical wear was identified as the primary degradation mechanism affecting the gear teeth. The degree of wear, on the other hand, did not occur in a uniform fashion. Damage in the form of nicks located along the edges of the gear teeth was also observed in this latest round of inspections. No significant increase was observed with regard to the number and the extent of nicks. It is worth noting that, in comparison with the previous inspection results, the latest EC data indicate a slight overall reduction in the surface roughness of the gears’ teeth. This points to a more systematic wearing of the teeth over the last period of in-sodium operation. Finally, consistent with previous observations, the ECT results did not exhibit any detectable indications of surface cracking in any of the parts.

3.1 Eddy Current Inspection of Spur Gears

The EC inspection system assembled earlier at ANL for NDE of advanced reactor components is being utilized for examination of the spur gears of GTA at the METL facility. The main parts of the system include the EC tester and probe assembly, a four-axis translation/rotation stage and a PC based motion control acquisition hardware and the associated software. Software based tools including a number of algorithms for processing and visualization of EC inspection data have been developed and integrated into a common user interface under MATLAB environment. The EC inspection system is shown in Figure 6. The acquisition unit is a MIZ-200 (Zetec, Inc.) multi-frequency instrument that can be interfaced with a broad range of impedance, transmit-receive and remote field probes. The 64-channel ECT instrument at ANL is capable of handling both rotating and array probes operating in either absolute or differential configuration. The instrument operates under the PC-based Velocity software platform, which includes an acquisition and an analysis module. A photo of the computer controlled MIZ-200 acquisition unit is shown in Figure 6(a). Photos of a gear mounted on the stage with the array probe in disengaged and engaged positions are shown in Figure 6(b).

Hardware and software modifications have been incorporated into the EC inspection system at ANL to further enable acquisition of data with EC array probes. A major advantage of multiple element array probes over conventional single element probes is the higher inspection speed through increased spatial coverage. In comparison to single element probes that require multi-dimensional scanning of components with nonplanar geometries, surface-conforming array probes allow inspection of the entire surface of a component using a single linear scan, which in turn leads to longer operating life for array probes. The 64-channel array probe design used in this work takes advantage of thin-film printed circuit technology. A number of probe holders have been fabricated at ANL by using an additive manufacturing (3D printing) process. This approach allows rapid development of application-specific surface conforming array probes for inspection of components with complex geometries. The directional array probes utilized at ANL further allow for identification of the orientation of material discontinuities. This capability is of great importance to many NDE applications for which proper assessment of component integrity depends on the availability of information about flaw orientation. The array probe design used in this work incorporates two rows of transmit-receive (T-R) coils that allow orientation of
discontinuities to be identified through sensing the outputs of diagonal elements. The photos in Figure 7 show a 3D printed flexible EC probe holder on which a flexible coil array is mounted and the front side of an array probe head assembly that was modified to interface with different probe holders. The entire surface of a tooth, which includes bottom lands, flanks, faces and top land is inspected by means of a single linear scan of the array probe.

Figure 8 shows the motion control user interfaces implemented in-house for the four-axis rotation/translation system. The software based tools have been refined and updated over time to accommodate inspections with different probe types including array probes. Shown in Figure 8 are the main scan configuration panel and the manual control panel that is used in conjunction with surface conforming array probes. Other configuration panels, not shown here, such as that used for raster scanning have also been integrated into the motion control interface.

The EC data in this latest round of post operation inspections were all acquired by using the array probes developed specifically for NDE of the GTA spur gears. This approach was deemed acceptable in view of the assessments conducted earlier, which showed comparable sensitivity of the array probe to that of single-element probe employed in the previous tests. Calibration of raw EC data acquired with single-element probe was performed by using a reference block made of Inconel 718 material containing machined flaws in the form of flat bottom holes. The procedure was described in previous reports on this subject [3].
Figure 6: Eddy current inspection system consisting of an acquisition unit, array probe, and a four-axis translation/rotation stage used for NDE of GTA gears. Shown above are (a) computer-controlled MIZ-200 acquisition unit with 64-channel array probe capability (b) photos of a gear mounted on the stage, with the array probe in disengaged (top) and engaged (bottom) position.

Figure 7: Photos of a 3D printed flexible EC probe holder (top) and the array probe head assembly (bottom).
A different approach was adopted for the calibration of EC data acquired with array probes. A detailed description of the calibration procedure was presented in a previous report [3]. For the sake of completeness, a brief description of the procedure is provided here. The calibration of array probe data was done by using a relatively undamaged gear tooth as the reference test piece. Consistent with the conventional approach, adjustment of the signal phase angle is based on minimizing the vertical component of probe response to lift-off. Scaling of the signal amplitude on the other hand is in reference to the probe response to a pre-determined lift-off distance. Figure 9 displays the horizontal component of the baseline array probe data with different levels of probe lift-off at 50 kHz after the calibration process. The data are displayed in image format using the data analysis software developed at ANL. Also shown in Figure 9 is a linear trace which represents a cross section of the 2D data. The regions associated with different levels of lift-off, ranging from 0.01 in. to 1.0 in., are marked on the figure. The inset in Figure 9 displays a photo of the array probe with an arrow pointing in the direction of motion for the measurement of lift-off. Following the initial measurements, the calibration coefficients are automatically calculated and applied to all the frequency channels, which include 50 kHz, 250 kHz and 500 kHz.

Because array probes are comprised of a number of T-R elements, each pair of coils must be calibrated independently in order to compensate for any signal variations caused by uneven probe
lift-off across all the elements. Furthermore, the effect of signal drift over time, exhibited as low-frequency baseline fluctuations, needs to be suppressed. A series of algorithms have been implemented for suppression of signal drift and for lift-off compensation. The processing of raw data from all 64 elements of the array probe are performed in an automated manner by using the software based tools developed for this purpose.

The flexible array probes used for inspection of the GTA spur gears have a fixed number of elements, thus providing unequal coverage of the two different size gears. For the larger gears, the 64-element probe encompasses the surface area between the centers of the bottom lands on opposite sides of each tooth. For the smaller gears, the coil coverage extends beyond the surface of individual teeth. To avoid overlapping of data from adjacent teeth on the smaller gear, a simple procedure has been developed for identifying the limits in array probe data. This is done by moving a conducting object along the array probe in order to determine the position of successive bottom land center points in EC data. An algorithm has been implemented for automatic cropping of the array probe data acquired on the smaller gears.

![Figure 9: Calibration of array probe signal phase angle based on the lift-off signal. The horizontal component of the data with different levels of probe lift-off is shown in image format. The linear trace presents a cross section of the 2D data. The inset is a photo of the array probe with an arrow pointing in the direction of motion for the measurement of lift-off.](image)

The drawings and photos of two different size Inconel 718 spur gears of the manipulator test assembly examined in this work are displayed in Figure 10. Eddy current inspections were performed on a total of four gears (two of each size). The drawings of the parts are shown in Figure 10(a) and 10(b). Photos of the gears associated with Figure 10(a) and 10(b) are displayed in Figure 10(c) and 10(d), respectively. The arrows on these figures show the direction of gear rotation during the data acquisition process. Numbering of the gear teeth was etched at the METL facility on the front surface of each part. However, to be consistent with the baseline NDE data, a different numbering scheme was used for EC measurements. Except for one gear, labeled L1AT, the teeth numbering for EC inspections is in counterclockwise direction with the rotation of the stage being
in clockwise direction. 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. Markers were placed on tooth #1 of each gear for the purpose of position identification during the scanning process. Array probe data covering the entire surface of each tooth (bottom lands, flanks, faces and top land) were acquired by means of a single linear scan. Complete inspection of every tooth on all four gears using two different probe holders were performed in this manner.

Figure 10: Drawings of the (a) small and (b) large spur gears made of Inconel 718 material. Also shown are post operation photos of the (c) small (T1BT and T1IT) and (d) large (L1AT and L1IT) gears.
Following the latest period of in-sodium operation, EC examinations were performed on four spur gears of the GTA system. Multiple frequency EC data were acquired with array probes over the range of 50 kHz to 500 kHz by multiplexing a large number of channels. The highest and the lowest EC test frequency were determined based on the electrical properties of Inconel 718 material ($\rho=127 \mu\Omega\cdot\text{cm}$ at $20^\circ\text{C}$) and the expected depth of service-induced flaws in the parts under examination. It is worth noting that the selection of optimum test frequency is always a tradeoff between penetration depth and sensitivity. While lower test frequencies provide larger depth of penetration, higher test frequencies provide finer spatial resolution and increased sensitivity to near-surface flaws.

An extensive NDE database has been assembled to date comprising of pre- and post-operation EC inspection data collected on the GTA spur gears. Presented next are representative ECT data acquired with array probes that exhibit the range of service-induced damage to the gears. The examples from this latest round of inspections are intended to mainly illustrate the evolution of damage since the parts were last examined. The EC inspection data in all cases were processed and displayed by using the data analysis tool implemented at ANL. Consistent with previous NDE results, the primary degradation mechanism in all cases is mechanical wear, with the more severe wall loss occurring near the edges of the teeth. A second damage mechanism, mostly affecting the larger gears, is in the form of nicks located along the edges of the teeth. The nicks became readily detectable by ECT only during the last two rounds of inspections. Improved detection of this particular form of damage can be attributed to the larger coverage provided by array probes, in comparison with single-element probes used in previous inspections.

Figure 11 displays representative EC inspection data collected with an array probe on tooth #5 of the gear labeled L1AT, which is one of the two larger GTA spur gears. The vertical and the horizontal components of the processed data at 500 kHz in image, strip chart and lissajous formats, are displayed in Figure 11(a) using the ANL data analysis tool. A photomontage of the top surface, the top land and the bottom surface of the gear tooth is shown in Figure 11(b). The corresponding regions of the EC image and the gear tooth are marked on Figure 11(a) and 11(b). The signals associated with discontinuities over the surface of the tooth are discernible in the data displayed in Figure 11(a). While the dominant features in the EC data are associated with nicks, more detailed analysis of the data indicates the presence of mechanical wear over the entire surface of the gear tooth. The results also indicate that the more severe damage is present near the edges of the tooth.

The EC image of tooth #6 of the gear labeled L1AT is shown in Figure 12(a). The corresponding photomontage of the tooth is shown in Figure 12(b). As in the previous example, the dominant features in EC data are associated with a series of nicks along the edges of the gear tooth. Circles drawn on Figure 12(a) and 12(b) delineate the location of more prominent nicks along the edges of the top land region. Comparison of the data in Figure 12(a) with its counterpart in 11(a) suggests that the extent of damage to these teeth is comparable. The ECT results once again indicate the presence of mechanical wear over the entire surface of the gear tooth in Figure 12, with the more severe damage present near the edges of the tooth.

Figure 13 shows EC array probe data collected on tooth #10 of the gear labeled L1AT. Processed data in image format at 500 kHz are displayed in Figure 13(a). A photomontage of the top surface,
top land and bottom surface of the gear tooth is shown in Figure 13(b). A large number of nicks are detectable in the EC data associated with the highest test frequency. Once again, the more prominent features in the EC images in Figure 13 are associated with a series of nicks located along the edges of the tooth’s top land. In comparison with the EC data in Figure 12(a), a larger number of nicks are detectable in the data displayed in Figure 13(a). The EC data also indicates the presence of wall loss in the form of mechanical wear over the surface of the gear tooth, with the more severe damage being present near the edges of the tooth.

As another example, representative data collected with an EC array probe on tooth #14 of the gear labeled L1AT are shown in Figure 14. The processed data in image format at 500 kHz are displayed in Figure 14(a). A photomontage of the gear tooth is shown in Figure 14(b). The more dominant signals in the EC images are once again associated with a series of nicks located along the edges of the tooth’s top land. However, in comparison to the cases shown in Figure 13, a fewer number of nicks are detectable in the EC data in Figure 14. Indications of mechanical wear are also observed in the EC data in this case, with the more severe damage being present near the edges of the gear tooth.

![Figure 11: Representative EC inspection data collected with an array probe on tooth #5 of gear L1AT. Shown above are (a) the EC data at 500 kHz displayed in various formats using the ANL data analysis tool, and (b) photomontage of the top surface (T), middle surface/top land (M) and bottom surface (B) of the gear tooth. The markings show the corresponding regions of the EC data in (a) and the photo in (b).](image_url)
Figure 12: Representative EC inspection data collected with an array probe on tooth #6 of gear L1AT. Shown above are (a) the vertical and horizontal components of the processed EC data at 500 kHz, displayed using ANL data analysis tool and (b) photomontage of the top surface, top land and bottom surface of the gear tooth. Circles delineate the location of more prominent nicks on the edges of the tooth’s top land.

Figure 13: Representative EC inspection data collected with an array probe on tooth #10 of gear L1AT. Shown above are (a) the vertical and horizontal components of the processed EC data at 500 kHz, displayed using ANL data analysis tool and (b) photomontage of the top surface, top land and bottom surface of the gear tooth.
Figure 14: Representative EC inspection data collected with an array probe on tooth #14 of gear L1AT. Shown above are (a) the vertical and horizontal components of the processed EC data at 500 kHz, displayed using ANL data analysis tool and (b) photomontage of the top surface, top land and bottom surface of the gear tooth.

Figure 15 through 17 display representative EC inspection data collected with an array probe on the second large gear labeled L1IT. In each figure the vertical and the horizontal components of the processed data are displayed in image format for the 500 kHz channel. Also displayed in each figure is the photomontage of the top surface, the top land and the bottom surface of the corresponding gear tooth. As with the EC data from the first large gear shown in Figure 11 through 14, the more prominent features in Figure 15 through 17 are associated with a series of nicks located along the edges of the top land of each tooth. For the cases shown here, there is a notable variability in the extent of damage to the teeth on the L1IT gear. Comparison of the analysis results in Figure 15 through 17 with those in Figure 11 through 14 generally indicates that the overall severity of damage in the form of nicks is lower for the gear L1IT than that for L1AT. Once again, in all cases volumetric wall loss in the form of mechanical wear is observed in the EC data, with the more severe damage being present near the edges of the gear teeth. Some observations were made through comparative assessments of data from the last two inspections. In most cases, such as that in Figure 16, a lower level of surface roughness is exhibited in the EC data from the latest inspections. This could be attributed to a more uniform wearing of the gear teeth during the last period of operation. Furthermore, the extent of damage associated with nicks in this latest round of inspection is somewhat lower than that seen in the EC data from the previous inspection.

Representative EC inspection data collected with an array probe on the gear labeled T1BT, which is one of the two small gears examined in this round of inspections, are presented in the next four figures. The data represent the range of variation in service-induced damage to the gear following the last period of in-sodium operation. Figure 18 shows the EC data collected on tooth #1 of T1BT gear. The vertical and horizontal components of the data at a test frequency of 500 kHz are shown.
in Figure 18(a). A photomontage of the top surface, top land and bottom surface of the gear tooth is shown in Figure 18(b). Unlike the NDE results for the two large gears, the EC data analysis results for this small gear do not indicate any significant damage associated with nicks. The primary mode of degradation in this case is volumetric wall loss in the form of mechanical wear that is detectable over the entire surface of the tooth, with the more severe damage being present near the edges of the tooth. Comparison of the EC data from the current and the previous inspection suggest a slight increase in the degree of wear at the two ends of the gear tooth.

Figure 19 and 20 show two more examples of EC inspection data collected with an array probe on the gear labeled T1BT. In both cases the processed data are displayed at a test frequency of 500 kHz along with the photomontage of the top surface, top land and bottom surface of the gear tooth also provided in each figure. The NDE results in Figure 19 and 20 suggest the presence of minor damage associated with nicks at the edges of top land on tooth #6 and tooth #12, respectively. Once again, the results indicate that the primary mode of degradation is mechanical wear that is detectable over the entire surface of the tooth. The more severe wall loss is present near the edges of each tooth. In reference to Figure 19 and 20, a large volumetric indication located on the top land region is clearly visible in the EC images of both tooth #6 and tooth #12. These volumetric degradations are marked on the EC images as well as the corresponding photos of the gear tooth in Figure 19 and 20. These prominent features were also readily detectable in the data collected during the previous round of inspections. Similar features were also detected in data from a number of other teeth on T1BT gear. The NDE results also indicate a more systematic wearing of the surface along the edge on one end of the gear teeth. However, comparison of the EC data from the current and the previous inspection in general do not show a measurable increase in the overall extent of damage to T1BT.

Figure 15: Representative data collected with an EC array probe on tooth #5 of gear L1IT. Shown above are (a) the vertical and horizontal components of the processed EC data at 500 kHz, displayed using ANL data analysis tool and (b) photomontage of the top surface, top land and bottom surface of the gear tooth.
Figure 16: Representative data collected with an EC array probe on tooth #11 of gear L1IT. Shown above are (a) the vertical and horizontal components of the processed EC data at 500 kHz, displayed using ANL data analysis tool and (b) photomontage of the top surface, top land and bottom surface of the gear tooth.

Figure 17: Representative data collected with an EC array probe on tooth #12 of gear L1IT. Shown above are (a) the vertical and horizontal components of the processed EC data at 500 kHz, displayed using ANL data analysis tool and (b) photomontage of the top surface, top land and bottom surface of the gear tooth.
Figure 18: Representative data collected with an EC array probe on tooth #01 of gear T1BT. Shown above are (a) the vertical and horizontal components of the processed EC data at 500 kHz, displayed using ANL data analysis tool and (b) photomontage of the top surface, top land and bottom surface of the gear tooth.

Figure 19: Representative data collected with an EC array probe on tooth #06 of gear T1BT. Shown above are (a) the vertical and horizontal components of the processed EC data at 500 kHz, displayed using ANL data analysis tool and (b) photomontage of the top surface, top land and bottom surface of the gear tooth.
Figure 20: Representative data collected with an EC array probe on tooth #12 of gear T1BT. Shown above are (a) the vertical and horizontal components of the processed EC data at 500 kHz, displayed using ANL data analysis tool and (b) photomontage of the top surface, top land and bottom surface of the gear tooth.

Finally, representative EC inspection data are presented for the second small gear labeled T1IT. Processed data are shown in Figure 21 through 24 for tooth #02, #04, #07 and #22, respectively. Once again, in each case the data are displayed at a test frequency of 500 kHz along with the photomontage of the corresponding gear tooth. Comparison of the data in Figure 21 with that obtained on the same tooth during the prior inspection indicates a measurable increase in damage along the top land region. In reference to Figure 22, indications of small nicks initiating along the edges of the top land are detectable on tooth #4. However, as with the NDE results for the other small gear, no significant increase in damage associated with nicks were readily detectable in EC data from gear T1IT. The EC data analysis results in all cases once again indicate that the primary mode of degradation is mechanical wear that is detectable to different degrees over the entire surface of the tooth. Consistent with the observations made on all the other gears, the more severe wall loss is present near the edges of each tooth. A more non-uniform wearing of the surface on one side of the gear tooth was also observed on several teeth of T1IT gear. In reference to Figure 23 and 24, some dominant features indicative of volumetric wall loss on the top land of both teeth are visible in the EC images. For all the cases shown here, shallow volumetric signals indicative of minor corrosion spots on the top land of each tooth are also detectable in the EC data. These damage indications were also detected during the prior inspection of T1IT gear, with no measurable increase in their size and extent over the last operating period.
Figure 21: Representative data collected with an EC array probe on tooth #02 of gear T1IT. Shown above are (a) the vertical and horizontal components of the processed EC data at 500 kHz, displayed using ANL data analysis tool and (b) photomontage of the top surface, top land and bottom surface of the gear tooth.

Figure 22: Representative data collected with an EC array probe on tooth #04 of gear T1IT. Shown above are (a) the vertical and horizontal components of the processed EC data at 500 kHz, displayed using ANL data analysis tool and (b) photomontage of the top surface, top land and bottom surface of the gear tooth.
3.2 Conclusions and Discussions of Eddy Current Testing Results

An eddy current inspection system assembled at ANL for NDE of advanced reactor components was utilized for examination of GTA spur gears following the third experimental campaign of in-sodium operation. Hardware and software modifications and refinements have been incorporated over time to improve the system performance. More recent hardware modifications included development of improved surface conforming array probes through utilization of additive
manufacturing process at ANL. The directional array utilized this work to take advantage of flexible thin-film technology that can be efficiently adapted to different test conditions. In comparison to single-element probes, a major advantage of the array probe technology is the significant gain in the speed of inspection through incorporation of a large number elements (increased probe coverage). More recent software modifications included refinement of data acquisition firmware for more efficient multiplexing of array probe channels.

Representative ECT data acquired with array probes were presented from this latest round of inspections to illustrate the evolution of damage since the parts were last examined. Comparative assessments based on the NDE results indicate that the gear teeth experienced some additional wall loss since the parts were last inspected. However, the ECT results generally indicate that the rate of damage during the last period of operation is lower than that experienced during the previous period of operation. Consistent with past observations, mechanical wear was identified as the primary degradation mechanism affecting the gear teeth. The degree of wear, on the other hand, did not occur in a uniform fashion. Damage in the form of nicks located along the edges of the gear teeth was also observed in this latest round of inspections. No significant increase was observed with regard to the number and the extent of nicks. It is worth noting that, in comparison with the previous inspection results, the latest ECT data indicate a slight overall reduction in the surface roughness of the gears’ teeth. This points to a more systematic wearing of the teeth over the last period of in-sodium operation. Finally, consistent with previous observations, the ECT results did not exhibit any detectable indications of surface cracking in any of the parts.

To date, an extensive NDE database has been assembled at ANL, which includes pre- and post-service NDE data on the spur gears of the GTA system at the METL facility. Planned activities in this work include inspection of the parts following each period of exposure to realistic operating environments. The NDE related R&D efforts at ANL to date have demonstrated the utility surface conforming EC array probe technology for efficient inspection of parts with complex geometries. However, applied research on both hardware and software side are needed to further improve the performance and utility 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. The software based tools implemented at ANL could be further developed to fully automate analyses of large amounts of data generated by array probes. Finally, the existing NDE facilities at ANL, such as X-ray computed tomography, could be utilized in the future for confirmatory volumetric examination of advanced reactor components.

### 3.3 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. Two UT techniques, pulse-echo and through-transmission, have been commonly used for UT inspection. The selection between the two is based on accessibility and defect type. To detect internal defects, rather than surface defects as for EC technique, of the manipulator spur gears, the pulse-echo technique was selected. A UT imaging system was assembled for nondestructive inspection of four manipulator spur gears before and after in-manipulator tests in sodium. Figure 25 shows the setup of the UT imaging system that
consists of an ultrasonic pulser/receiver (Imaginant DPR-300), an immersible 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. The immersible ultrasonic transducer is held by a mounting unit that is mounted on the three-axes scanning translation module. Each linear translation stage is driven by a step motor with a minimum moving resolution of 2 micrometers. Through XY-scanning, both the 2D intensity and time-of-flight (TOF) images are generated to locate and size any defects on and 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 of 3” x 3”. To completely scan a gear as well as keep the same scanning dimension, the gear was manually rotated clockwise by several teeth, three for small gears or two for large gears, after each scan. A total of eight C-scans were taken for each gear and a complete C-scan image of the gear is then generated from the composite of the eight images. Figure 26 shows the setup of UT imaging of a manipulator spur gear in water. The gear and transducer were submerged in water and separated by a distance equal to the focal distance (2 inches) of the transducer.

Figure 25: UT imaging system consisting of an ultrasonic pulser/receiver, an immersible ultrasonic transducer, a water tank, a three-axes scanning module, a gain-pass filter, and a DAQ system.
Figure 26: Setup of UT imaging of a manipulator spur gear in water.

The improved S&DAQ unit, developed for the under-sodium viewing project, was used for C-scan imaging of the gears to reduce scanning time and enhance real-time intensity images generated from raw data. The S&DAQ unit automatically calculated an optimal scanning speed based on the moving average number and 2D scanning resolutions set by an operator. The real-time ultrasonic intensity C-scan image was generated from results of the total energy of the moving average of ultrasonic A-scan signals in real-time while scanning. Figure 27 shows the S&DAQ control panel running on a LabView platform and a real-time intensity C-scan image of gear teeth #16-#19 of spur gear T1BT. The top-right shows the real-time ultrasonic A-scan signal of the scanning location; the bottom-right the setup of scanning parameters, including scanning size and resolutions; the top-right the setup of data acquisition parameters, including time delay and acquisition rate; the bottom-right the real-time C-scan image.
Due to the relatively large gear thicknesses (3” and 4”), 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 mounting surfaces of a gear could be received and better detection resolution could be achieved. Different focused and unfocused ultrasonic transducers were tested to evaluate their effect of beam size and output energy. An immersible ultrasonic transducer (Panametrics A309R, series # 2911425) was selected. The transducer has an operation frequency of 5.0 MHz with diameter of 0.5” and focal distance of 2”. The gear being tested was placed at the focal distance. Figure 28 shows a typical real-time ultrasonic RF signal received by the focused transducer from a pulse-echo test of a manipulator spur gear. Reflection echo from any internal defects or edge effect could be produced in between the echoes of the front and back surfaces. The time of the echo shows the location of the defect underneath the front surface and the intensity is depending on the orientation and size of the defect.
Figure 28: Typical real-time ultrasonic RF signal of from a pulse-echo test of a manipulator spur gear.

3.4 Ultrasonic NDE Inspection of Gear T1IT

Ultrasonic NDE of Gear T1IT after the third in-sodium test was conducted by using the selected focused ultrasonic transducer and the results before and after the first and second in-sodium tests were then compared. Each scan produced a C-scan image with 2.4” x 2.4” in dimension and 120 x 120 pixels in resolution. The gear was manually rotated clockwise by three teeth after each scan and a total of eight images were produced. Figure 29 shows real-time ultrasonic intensity images, with a peak detector covering the whole thickness of Gear T1IT, i.e., within a gated window between front and back surfaces of Figure 28, after the third in-sodium test. To evaluate the whole gear, a composite intensity image was generated from the eight images shown in Figure 29. Figure 30 shows a photo and the composite ultrasonic intensity images of Gear T1IT before and after the second and third in-sodium tests, respectively. By closely evaluating and comparing the photos and images of Gear T1IT, no noticeable defects or dents were identified.
Figure 29: Real-time ultrasonic intensity images of Gear T11T after the third in-sodium test.
Argonne developed a MATLAB based image process package, named ImagingGUI, for advanced data image processing and 2D/3D data visualization and has been used to determine the location and size of any internal defects in the gear. Toolboxes and plug-in features have also been developed and embedded in the ImagingGUI for various NDE techniques, such as millimeter wave (mmW), ultrasonics, eddy current (EC), and photoacoustic spectroscope (PAS). The package contains plug-ins that are capable of converting raw data generated from different platforms into designated MATLAB formats. Different data types acquired from various NDT techniques or different layouts of one particular data type can be processed, analyzed, and displayed with
ImagingGUI. Various user-generated filters and functions are also available for different data types and NDT techniques. Figure 31, for example, shows the signal processing results of the ultrasonic intensity of tooth #16-17-18-19. Figure 31(top) shows the ultrasonic A-scan signal at the cursor (i.e. at the cross point) in the ultrasonic images. Figure 31(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 images accordingly. The intensity profiles directly show the defect sizes along the X and Y axes respectively. Figure 32 shows the ultrasonic intensity images after post-processing of Gear T11T before and after in-sodium tests, respectively. The dimensions of the images were adjusted to provide similar sizes of teeth.

Figure 31: (top) Ultrasonic RF signal at the cursor, (left) TOF image, and (right) intensity image of Gear T11T after third in-sodium test.

Figure 32: Intensity images after post-processing of Gear T11T before and after in-sodium tests.
Figure 33 shows the ultrasonic RF signal at the cursor, TOF image, and intensity image after post-processing with a moving gate along the TOF set between the reflection signals of the front and back surfaces of tooth #16-17-18-19 of Gear T1IT. The RF signal, ultrasonic A-scan, shows the ultrasonic scattering generated at the location of the cursor (intersection of the two cross-lines). The moving gate is shown by the blue region inside the RF signal. By knowing the sound velocity of the gear, the time history between the reflection signals of the front and back surfaces can be converted to be the thickness of the gear. The RF signals at different times after the reflection signals of the front surface represent the ultrasonic scatterings caused by wearing of the gear tooth at the corresponding depths into the thickness of the gear. The intensity image shows the peak signals within the moving gate of the gear. By changing leading time and the width of the gate, an image of ultrasonic scatterings at the designated depth can be generated. Figure 34 shows intensity images of peak ultrasonic scatterings of the full depth of Gear T1IT, with a moving gate set between the reflection signals the front and back surfaces after the third in-sodium test. Figure 35 shows the composite intensity images of peak ultrasonic scattering of the full depth of Gear T1IT after the second and third in-sodium tests, respectively. Without proper intensity calibration, the image shows qualitative, rather than quantitative, measurements of the wearing of the gear teeth. From theoretical and experimental experiences, beside tooth wearing, a tooth defect is most likely to happen at the root of the tooth. By evaluating and comparing these two composite images, there was not much change of teeth wearing, nor any internal defects.
3.5 Ultrasonic NDE Inspection of Gear T1BT

Ultrasonic NDE of Gear T1BT after the third in-sodium test was then conducted by using the selected focused ultrasonic transducer. Each scan also produced an image with 2.4” x 2.4” in dimension and 120 x 120 pixels in resolution. The gear was manually rotated clockwise by three
teeth after each scan and a total of eight images were produced. Figure 36 shows a real-time ultrasonic intensity images, with a peak detector covering the whole thickness of Gear T1BT after the third in-sodium test. To evaluate and compare the whole gear wear, a composite intensity image was also generated from these eight images. Figure 37 shows a photo and the composite ultrasonic intensity images of Gear T1BT before and after the second and third in-sodium tests, respectively.

Figure 36: Real-time ultrasonic intensity images of Gear T1BT after third in-sodium test.
By closely evaluating and comparing the photos and images of Gear T1BT, there are defects or dents on some of the teeth close to the gear’s top mounting surface. Figure 38 shows photos after the second and third in-sodium tests and the real-time intensity images of teeth #11-12-13 before and after the three in-sodium tests. Defects (circled in red) were found on the both sides of teeth #11 and #12 after the second in-sodium test. The defects were not shown before and after the first in-sodium test and stayed about the same after the third in-sodium test. A defect (circled in red) was also found on the left side of tooth #22, shown in Figure 39, after the second in-sodium test. The defect was not shown before and after the first in-sodium test and did not get any worse after
the third in-sodium test. The photo shows very small dents on the right side of tooth #22 and the left side of tooth #1 that were not detected. Like most of the NDE techniques, depending upon the size and orientation of a defect as well as detecting resolution, some defects might not be detected. The problems might be resolved by using angle beam technique, higher detecting resolution, or other NDE techniques.

Figure 38: Photos and real-time ultrasonic intensity images of tooth #11-12-13 of Gear T1BT before and after in-sodium tests.
By setting a moving gate between the reflection signals of the front and back surfaces, Figure 40 shows intensity images of peak ultrasonic scatterings of the full depth of Gear T1BT after the third in-sodium test. Figure 41 shows the composite intensity images of peak ultrasonic scattering of the full depth of Gear T1BT after the second and third in-sodium tests, respectively. By evaluating and comparing these two composite images, it does not appear that the teeth wearing is getting any worse, nor are there any internal defects.
3.6 Ultrasonic NDE Inspection of Gear L1AT

Figure 42 shows the real-time ultrasonic intensity images of Gear L1AT and each image is 2.4” x 2.4” in dimension and 120x120 pixels in resolution. The gear was manually rotated clockwise by two teeth after each scan. The intensity of the image of Teeth #10-11 was much less than the
others. It might be caused by the dissolved gas in the water that was accumulated and trapped in the focus lens of the transducer overnight. Figure 43 shows a photo and the composite ultrasonic intensity images of Gear L1AT before and after three in-sodium tests. By closely evaluate and compare the photos and images of Gear L1AT, no noticeable defects or dents were identified.

Figure 42: Ultrasonic intensity images of Gear L1AT after third in-sodium test.
By setting a moving gate between the reflection signals of the front and back surfaces, Figure 44 shows intensity images of peak ultrasonic scatterings of the full depth of Gear L1AT after the third in-sodium test. Figure 45 shows the composite intensity images of peak ultrasonic scattering of the full depth of Gear L1AT after the second and third in-sodium tests, respectively.
3.7 Ultrasonic NDE Inspection of Gear L1IT

Figure 46 shows the real-time ultrasonic intensity images of Gear L1IT after the third in-sodium test with 2.4” x 2.4” in dimension and 120x120 pixels in scanning resolution. The gear was manually rotated clockwise by two teeth after each scan. Figure 47 shows a photo and the
composite ultrasonic intensity images of Gear L1IT before and after each of the three in-sodium tests.

Figure 46: Ultrasonic intensity images of Gear L1IT after third in-sodium test.
By closely evaluating and comparing the photos and images of Gear L1IT, defects or dents are found on most of the teeth of the gear’s top mounting surface. Figure 48, as an example, shows photos of teeth #6-7 after the second and third in-sodium tests and the real-time intensity images of the two teeth before and after in-sodium tests. Defects (circled in red) are found on the top of teeth #6 and top and right sides of teeth #7 after the second in-sodium test. The defects were not shown before in-sodium test, become worse after the second in-sodium test, and did not change much after the third in-sodium test.
By setting a moving gate between the signals of the front and back surfaces of Gear L1IT, Figure 49 shows intensity images of peak ultrasonic scatterings of the full depth of the gear after the third in-sodium test. Figure 50 shows the composite intensity images of peak ultrasonic scattering of the full depth of Gear L1IT after the second and third in-sodium tests. No internal defects were detected. By comparing the two images, there is an additional ultrasonic scattering, shown in Figure 51, at the center shaft key-hole between teeth #8 and #9. After visual inspection of the shaft key-hole, no defect was found. A more thorough ultrasonic inspection is needed to evaluate the cause of the ultrasonic scattering. Without proper intensity calibration, the image shows qualitative, rather than quantitative, measurements of the wearing of the gear teeth.
Figure 49: Intensity images of ultrasonic scatterings of Gear L1IT after third in-sodium test.

Figure 50: Composite intensity images of ultrasonic scattering of Gear L1IT after in-sodium tests.
3.8 Ultrasonic NDE Conclusions and Discussions

To optimize beam size and output energy, a focused transducer that has an operation frequency of 5.0 MHz with diameter of 0.5” and focal distance of 2” was selected. We demonstrated that the ultrasonic energy is strong enough to penetrate through the manipulator spur gears made of Inconel 718 with thickness greater than 4 inches. The UT technique, with better positioning and alignment of the gear and the ultrasonic transducer, demonstrated that it is capable of detecting and sizing defects inside a component or at a location that is difficult to be reached. By analyzing the images taken before and after in-sodium tests, defects or dents were found on some of the teeth close to the top mounting surface of Gear T1BT and L1IT. Defects or dents on teeth of Gear T1BT were found only after the second in-sodium test and are not propagating or enlarged after the third in-sodium test. Defects or dents on teeth of Gear L1IT found after the first in-sodium test were getting worse after the second in-sodium test and had worsen after the third in-sodium test. No internal defect was found for all of the four gears. To accurately size the defects, as a standardized practice and requirement, it is necessary to generate a calibrated sizing database/images using a calibration block made of the same material and consisting of premised holes or designed defects with different dimensions and orientations.

By setting a moving gate between the scattering signals of the front and back surfaces of a gear, intensity image of peak ultrasonic scatterings of the full depth of the gear can be generated. Composite intensity images of peak ultrasonic scattering of the full depth then were generated for all of the four gears after the second and third in-sodium tests. Without proper intensity calibration, the ultrasonic scattering images show just qualitative, rather than quantitative, measurements of the wearing of the gear teeth. By comparing the composite images of Gear L1IT generated after
the second and third in-sodium tests, an additional ultrasonic scattering at the center shaft key-hole between teeth #8 and #9. After visual inspection of the shaft key-hole, no defect was found. A more thorough ultrasonic inspection is needed to evaluate the cause of the ultrasonic scattering. Depending upon the size and orientation of a defect as well as detecting resolution, some defects might not be detectable by the UT spectroscopy technique. The problems might be resolved by using angle beam technique, higher detecting resolution, or other NDE techniques.

4. Sodium Passivation and Decontamination

The GTA must be removed from METL following each experimental campaign to repair any components damaged during the testing. The reactive nature of sodium means that any exposure to air or water will lead to significant oxidation, and high oxide levels lead to increased corrosion and plugging. The Flexicask System is used to remove test articles from METL while maintaining an inert environment inside the Test Vessel and around the test article. The Flexicask System is a collapsible assembly that can mate and seal to the Test Vessel and the GTA. Using the Flexicask System, oxygen concentrations inside the Test Vessel have been maintained below 100ppm during all removal and insertion operations. Figure 52 shows an overview of the operation of the Flexicask, and more details can be found in DOE report ANL-ART-187 [4]. Figure 53 is a picture of the Flexicask moving the GTA from the Test Vessel.

![Figure 52: General operation of the Flexicask System.](image-url)
Once the GTA is removed from METL, the residual sodium that is adhered to the assembly must be treated. The treatment must be benign to ensure no additional damage is done to the components as this would obfuscate the results of the experiment. The Carbonation System was designed to react the residual sodium with moist carbon-dioxide to produce sodium-bicarbonate and hydrogen gas. This process is much lower energy than the typical treatment of superheated steam, thereby
maintaining the integrity of the components during cleaning. Figure 54 shows a system diagram of the Carbonation System to explain how the moist carbon-dioxide is introduced to the test article.

![Carbonation System diagram](image)

**Figure 54: Carbonation System diagram.**

The Carbonation Process is most effective when moisture levels are high and exposed sodium surface area is large. One improvement to the operation of this system was the addition of vessel heaters to the Reaction Chamber. This has improved carbonation by preventing the moisture in the incoming carbon-dioxide from condensing on a cold vessel wall. Significant improvements in carbonation were seen after the addition of these heaters (Figure 55). Another method to improve carbonation is to disassemble the component as much as possible to expose raw sodium, but this is not always possible.
Following effective carbonation, most of the components are ready to be disassembled. The exception to this are the components that have tight clearances, such as the gears installed on the shafts. The thin gap between gear and shaft is large enough to allow for sodium to penetrate, but not large enough to allow for effective carbonation. Additionally, the sodium-bicarbonate reaction product expands in volume and can pack an enclosed space easily. The result is a gear that is “glued” to the shaft (Figure 56). The current solution for this is to soak the glued components in an alcohol bath followed by a DI water bath. The alcohol bath reacts away any residual raw sodium that is present in the problem area. If this step is skipped, this sodium can react violently with the DI water. The alcohol-sodium reaction process can be monitored by the presence of bubbles (hydrogen gas) emerging from the problem areas. It is best to soak the components in alcohol for a few hours after the last bubble is observed. Once there is confidence that no raw sodium is present, the DI bath can be used to dissolve any remaining reaction products. Figure 57 shows a gear and bearing assembly after carbonation, but before both baths. Figure 58 shows a gear and bearing assembly after carbonation and both baths. Both baths are typically given in an ultrasonic bath with heating to promote solubility (Figure 59).
Figure 56: Example of a gear stuck to a shaft following carbonation. The white material emerging from the keyway is sodium bicarbonate.
Figure 57: A gear and bearing assembly following carbonation but preceding the alcohol and water baths.
Figure 58: A gear and bearing assembly following carbonation and the alcohol and water baths.
5. Path Forward
METL is currently in a cold-standby state while repairs to the Building 308 Scrubber System are completed. The thaw and restart of METL operations will take place in Fall 2021. The GTA has been fully cleaned, disassembled, repaired, and re-assembled. The gears are the original Inconel
718 radial spur gears. The bearings are heat-treated 52100 bearing steel tapered roller bearings, identical to the bearings used in the first campaign. The spring loaded lantern ring seal will be used for both shafts this campaign. A final change in this assembly is the removal of all thrust bearing assemblies. Each shaft that has an end terminate inside a gearbox originally had a stainless steel needle thrust bearing located between the shaft and the gearbox. While these did not see any torque loading, they did help to position the shafts during assembly while still allowing for rotation. Following the thrust bearing failure in the third experimental campaign, it was decided to remove all thrust bearings of this type to remove a potential failure point. The current assembly (for the fourth experimental campaign) does not include these thrust bearings, along with the gearbox plates that were used to install these bearings. Figure 60 shows the GTA rotated in the test stand to highlight the removal of these bearings and plates. The removal of these plates may also provide better drainage for sodium following the upcoming campaign. The GTA is ready for install in METL and to begin sodium operations once the facility has been restarted.

Figure 60: GTA rotated to view the bottom side of the gearboxes where the thrust bearings and gearbox plates have been removed.
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7. References


