Advanced Reactor Safeguards & Security

Pebble Bed Reactor Fuel Monitoring with Eddy Current Imaging

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Executive Summary

Conducted in the latter half of FY24 and all of FY25, this project explores the potential utility of eddy current (EC) imaging as a practical tool for acquiring structural and potentially identifiable images of fuel pebbles in advanced pebble bed reactor (PBR) systems for both safeguards and operational safety purposes. The results detailed herein convey a novel capability for EC imaging being successfully able to identify a range of surface and subsurface artefacts on the graphite surface of (surrogate) fuel pebbles, including small surface cracks, scratches, dents, and other dislocations. Voids at depths of 2 mm and 5 mm were also detected thus confirming the ability of EC imaging techniques to locate and identify artefacts anywhere within the 5mm graphite layer common in fuel pebble designs of US-designed PBRs. The ability to monitor for the formation of dents, cracks, and other small artefacts indicates a strong potential for early identification of structural degradation before pebble breakage, and thus, potential flow blockages at core discharge.

The capability of EC imaging being able to detect fine surface and subsurface features supports the concept of using naturally-occurring or even engineered artefacts as “fingerprints” for individual pebbles or types of pebbles. The initial idea for this project began on the concept of incorporating embedded features in the 5mm-thick graphite matrix shell and evaluating the ability of an existing (not yet determined) imaging technique to distinguish types of pebbles. Through industry engagement on the infeasibility of altering the fuel fabrication process, the imaging techniques shifted to inspecting pebbles for non-engineered features that would occur during normal operations. Due to the normal inner-core environment of high temperatures, high radiation, and high abrasion, Argonne researchers posited that dislocations would form within pebbles commensurate with in-core residence times and that those resulting dislocations could assist as an identifying measure for types of pebbles. With the assessed capability of EC imaging (not susceptible to a pebble’s radiation emitted) and a well-conceived design, even the high throughput a PBR would conceptually exhibit at core discharge would not overwhelm an EC-based imaging system. The combination of pebble tracking monitoring and burnup information could enhance material control and accounting by allowing operators to sort pebbles by batch (e.g., core-introduction date, initial enrichment, etc.) without relying solely on radiological methods (which also would require ex-core cooling down time that would prove wasteful for a PBR’s operational schedule).

Results discussed here in this report convey how EC measurements can adequately (A) distinguish between solid and annular (surrogate) graphite pebbles (provided by Kairos Power), (B) scan a high-throughput of pebble, and (C) do so in a high temperature environment. Taken together, the results validate the core premise of this project: eddy current imaging is an adaptable and relatively high-throughput technology that can be repurposed from its established roles in nuclear plant inspection to meet the unique needs of PBR designs.

While additional work is warranted - in particular, extended high-temperature testing in realistic geometries, refinement of probe designs for in-situ deployment, and integration with plant-scale handling systems – the present study provides a strong basis for continued development. EC imaging emerges as a credible candidate technology to support both advanced reactor safeguards and the reliable, efficient operation of future PBR systems.

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1 Introduction

Researchers at Argonne National Laboratory (ANL) investigated the utility of eddy current (EC) imaging for monitoring the structural integrity of pebble fuel in pebble bed reactors (PBR). Initially planned to only track types of pebbles as a contributor for material control and accounting methods, the monitoring of pebble health became the primary interest of PBR designers later in this study. A prototype device for identifying batches of pebbles was initially designed but the focus of this project was refined to test various non-destructive evaluation (NDE) techniques including thermal imaging and electromagnetic imaging. Positive experimental results, specifically with eddy current (EC) imaging (electromagnetic imaging) led researchers to focus on this technology for presenting to industry partners who agreed on the value of this technique for use in pebble defect monitoring in the primary loop system of a PBR design. Researchers still support the value such imaging techniques provide for material control and accounting but do not refute the value for monitoring pebble structural integrity – an accepted operational safety concern for PBR designs.

This report details experimental results yielded by the ANL research team on applying EC imaging techniques to properly and quickly characterize surrogate graphite pebbles using existing artefacts like surface and subliminal dislocations that would occur during normal operations of such reactors. The intent is to eventually leverage the orientations and locations of such artefacts as identifiable characteristics for pebble monitoring (a key safeguards element for secure PBR operation) as well as monitor their formation on the pebbles to assist operators in anticipating structural breakdowns before they become catastrophic to the system. Herein, researchers took on 3 tasks to fully evaluate the utility of such imaging techniques. First, a reassessment of a comparable imaging technique based on thermal energy was used to gauge the benefit of eddy current imaging. Leveraging many years of experience with eddy current imaging by ANL research staff, applicability of electromagnetic imaging on a non-metallic medium proved adequate enough to assess pebble dislocations as they would occur in a PBR system. Second, characterizing the feasibility of eddy current imaging techniques on subliminal artefacts was necessary to test the limits of applicability of eddy currents in imaging dislocations that may occur within the 5-mm thick graphite layer of each pebble. Third, an eddy current point probe designed for high-temperature analysis was developed and procured by ANL researchers to test efficacy of EC imaging in elevated temperature environments (which, as designed, would be characteristic of pebbles assessed upon immediate reactor core discharge). The advantage researchers tried to prove was that a non-radiological measurement system could be used to characterize radioactively hot pebbles without requiring a cooling time (such as in conventional, radiologically-based nondestructive analytical techniques). These results are included in later sections of this report with a culminating discussion and conclusion for the benefit of the reader.

2 Motivation

The motivation for this project is to develop and demonstrate a pebble sorting system that supports a material control and accounting (MC&A) approach. The goal is to support safeguards and MC&A by categorizing and potentially tracking pebble types into batches using a non-radiological, high-throughput method. The developed approach enhances operational safety and efficiency by detecting surface and subsurface degradation before the pebble begins to break apart (which may lead to flow obstruction). A system entailing this approach could serve a dual purpose by monitoring structural health as well as assess pebble identity (type/batch). This hypothetically could reduce cooling time for a radiological assessment through high-temperature-capable, non-radiological inspection of pebbles shortly after core discharge.

As the project evolved, industry partners recognized that the same capabilities that would support safeguards categorization could also provide real-time insight into pebble health. This led to a shift in emphasis from primarily supporting MC&A by sorting and tagging pebbles, to a dual-purpose system that monitors structural integrity (cracks, voids, and other defects), and leverages such artefacts, where appropriate, as identifiers or signatures.

Early collaboration with Kairos Power led to the provision of twelve 4-cm diameter surrogate graphite pebbles for experimental validation (*Figure 1*). These pebbles served as a basis for testing the ability of eddy current (EC) technology to identify recognizable surface and subsurface artefacts and eventually associate them with varying pebble characteristics such as initial uranium enrichment levels and other criteria. The goal is to enable rapid sorting and inspection, reducing pebble ex-core time, and enhance overall reactor efficiency.

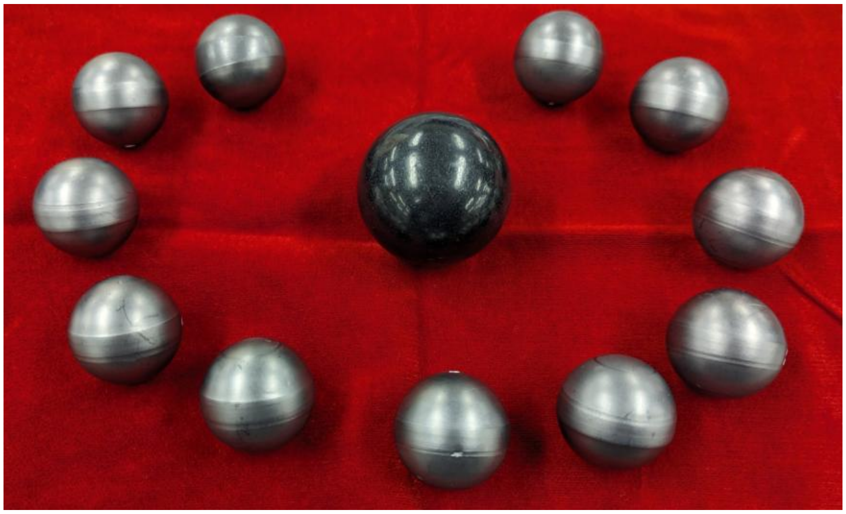


Figure 1. 4-cm graphite pebbles acquired from Kairos (center pebble representing 6-cm diameter HTR pebble fuel for comparison).

Pebble fuel in a pebble bed reactor (PBR) consists of a graphite matrix surrounding an inner core of uranium fuel kernels (i.e., TRISO fuel particles) embedded within a graphite-fuel medium. The 5-mm thick graphite shell provides good thermal conductivity while maintaining the structural integrity of the fuel core within. Unfortunately, exposure to radiation and an elevated thermal environment over time leads to increased brittleness in the graphite and may lead to structural failures like cracks or other dislocations occurring on the pebble's surface or underneath. Not just limited to fuel pebbles, in some designs, such structural degradation also occurs in moderating, non-fuel pebbles comprised of pure graphite. Though a small hazard exists in structural degradation leading fuel pebbles to crack and release unintended radiation upon reactor core discharge, the larger concern is the potential for pieces of cracked pebbles to impede the flow of pebbles through the reactor system thus affecting the operation of the entire plant. Pebbles are discharged from the reactor core through a mechanical singulizer system where pebbles individually flow to a burnup measurement location. The path for pebbles to traverse should not be impeded by any obstruction of broken pebbles and therefore, insight an operator can gain before that occurs would be highly appreciated by the designer – especially when the designer wants to maximize the number of passes a pebble traverses the core to harness the most energy from each pebble. Herein lies the optimization of the system: maximizing time within the core while minimizing the risk of pebble breakdown.

This particular work began as an attempt to assist operators meet their safeguards needs by providing a non-radiological manner to track pebble types through a PBR. Operators will eventually report material quantities to a domestic and/or international inspectorate. Without the ability for precisely quantifying the fissile content inside each pebble, the intent of this work was to be able to categorize types of pebbles so that, at the minimum, an operator can track the number of pebbles that were introduced into the system on a given date or by what the initial enrichment was. This was to assist operators in categorizing types of pebbles as a way to discretize the hundreds of thousands of pebbles in a given PBR system into more digestible collections for reporting purposes. Discussions with industry led to how the formation of artefacts (i.e., surface and subliminal dislocations) could serve as an identifiable characteristic that could potentially be used as tracking pebbles: "Pebble A with a gash 3.7mm long in the equatorial region of the 4th quadrant has been identified twice through the discharge point and therefore can be reinserted into the core for a third pass because it was introduced into the system only 9 months ago with an initial enrichment of 15.5% 235U." Upon further consideration, industry began to contemplate the ability of such system to be used for monitoring pebble health – i.e., operational safety. The ability of monitoring pebbles began to be considered to serve dual purposes: monitoring for pebble health and for pebble identity.

3 Background

Two imaging techniques were assessed early on in the project to evaluate effectiveness and adequacy for meeting defined objectives: thermal imaging and electromagnetic imaging. Thermal imaging uses infrared cameras to detect energy at stand-off distances. While it offers near-instantaneous acquisition, it lacks the subsurface detection capabilities of EC technology. Though results will be shown of thermal imaging scans, the majority of the remaining work focuses on the assessment and applicability of electromagnetic imaging techniques (specifically, using eddy current technology).

3.1 Eddy Current Technology

Eddy Current (EC) inspection is a mature non-destructive examination (NDE) technology that is fast and economical. The concept of applying EC technology was to use an EC sensor to sort pebbles by batch at higher temperatures (and unaffected by radiation) which could improve the turn-around/ex-core time of a pebble considerably. Initially, pebble batches were thought to have engineered artefacts on surfaces to identify each pebble by various criteria, including initial uranium enrichment and first date of introduction. With this knowledge quickly available upon pebble discharge, newer batches of pebbles could be returned into circulation immediately with random samples pulled out for complete inspection while older batches could be separated out for more complete inspection or removed entirely. EC probes are adaptable for a broad range of in-situ inspection applications – Argonne has extensive experience with the design and development of advanced EC probes, both hardware and software.

EC inspection operates by inducing eddy currents in a material using alternating current applied to a coil, as shown in *Figure 2*. A secondary field is in turn created by the induced currents in the material. The resulting secondary field is detected by the same coil or a neighboring coil, enabling the identification of surface and subsurface features. EC technology is fast, economical, and adaptable for in-situ applications. While traditionally limited to temperatures below 200 °C, advancements are pushing the limits to 600 °C and beyond.

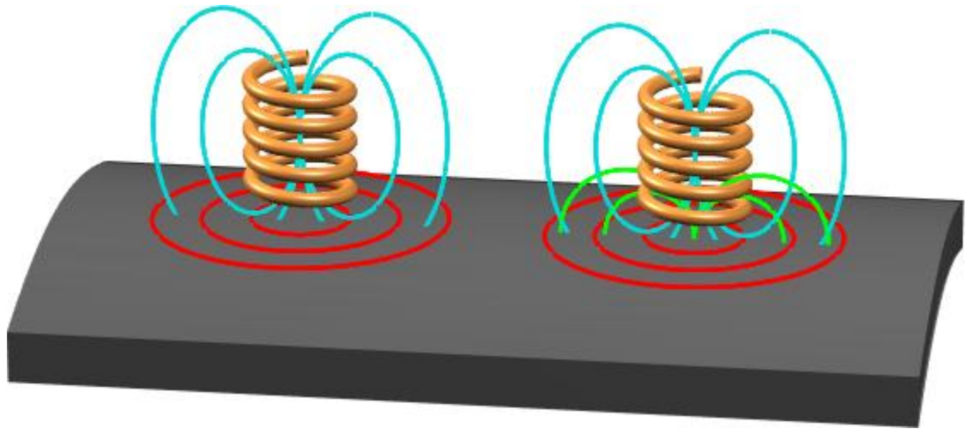


Figure 2. Illustration of how Eddy Current works.

Applying EC imaging to graphite was an initial challenge considering EC has been traditionally applied to metallic media for capitalizing on the material's conductivity. Compared to metals, graphite has less conductivity and therefore, the ability of EC providing adequate results was evaluated. Based on Volume Integral Method simulations, Argonne researchers made several observations that aided toward optimization of EC test parameters. Depending on the type of graphite within the pebble's makeup, sensor frequency would have to be adjusted. For example, if researchers assessed the conductivity of the pebble's graphite matrix was high within the graphite range, a scanning frequency below 1000 kHz would be optimal. However, if the conductivity of the pebble was in the lower range for graphite, higher frequencies would be more advantageous. Experimental data showed that the pebbles provided by Kairos were in the lower conductivity regime. This led to the use of higher frequencies around 1000 kHz and seeking probe designs which induce higher current density. Lower frequencies may still be desired for greater depth of penetration (at the cost of reduced sensitivity and spatial resolution). Simulations also showed that while a 6 mm diameter coil may produce a stronger signal, the difference of a single order of magnitude between 6 mm and 3 mm coils at 4.5 mm depth may be an acceptable tradeoff to achieve higher resolution. Though available probes at Argonne were sufficient for proof-of-concept testing, due to their smaller diameter, future probe designs should consider the use of larger coils if detections at greater depths are desired.

3.2 EC Application in Nuclear Industry

EC inspection technology was selected for this application due to its maturity, adaptability, and potential for high-temperature applications. Furthermore, nuclear industry adoption of EC technology is already widespread – particularly in nuclear energy for In-Service Inspections (ISIs) of steam generators, feedwater heaters, and other components. Based on conversations with Zetec, Inc., a provider of EC equipment and services to the nuclear industry for steam generator inspection, it was determined that near-term EC probes supporting up to 500°C were in current development. With the ability of an EC sensor being applied to high surface temperature pebbles, the ability of sorting pebbles by batch was posited to reduce ex-core time considerably.

Moreover, EC technologies are just now being applied within the advanced reactor design community. Based on presentations by Kairos Power, a non-imaging eddy current probe is being adapted for pebble counting and possible sorting. This type of "encircling probe" is proven technology but it is a simpler design than an imaging probe. While it can support higher temperatures due to being a simpler probe, since it would not be in direct contact with the pebbles the maximum temperatures necessary are likely reduced as well (contrary to a direct contact probe needed for imaging). While this type of probe will not be able to detect features in the surface of the pebbles, it may be able to sort pebbles as discussed later. Since this will be measured through the wall of a stronger conductor, it may not be an easy task, but in theory it should be possible.

4 Experimental setup

Experimental work was conducted in FY25 consisted of three primary tasks:

1. Compare imaging techniques in potential customized scanning setups for thermal and eddy current imaging. This task included an evaluation of sampling speed rates with assessing results to confirm the ability of electromagnetic imaging.
2. Validate NDE technologies in ambient conditions and report on the limits of both superficial and subsurface artefacts of pebbles. This task consisted of analyzing surface penetration of eddy currents by creating standards for depth scanning.
3. Evaluating the ability of EC technology to be used in a high temperature environment using a high-temperature probe and testing its performance on Kairos-provided pebbles. This task includes initial tests made with a single-element high-temperature probe to evaluate potential damage to the probe from elevated operational temperatures.

4.1 Sampling Speed rates

Task 1 was to evaluate the timing question of both EC and thermal imaging. Thermal imaging has a near instantaneous acquisition time due to having a 2D array of elements (i.e. an IR camera) to detect the infrared energy, which can be collected at stand-off distances. Despite its instant data acquisition, the data is insufficient to assess any artefacts on or under the pebble's surface.

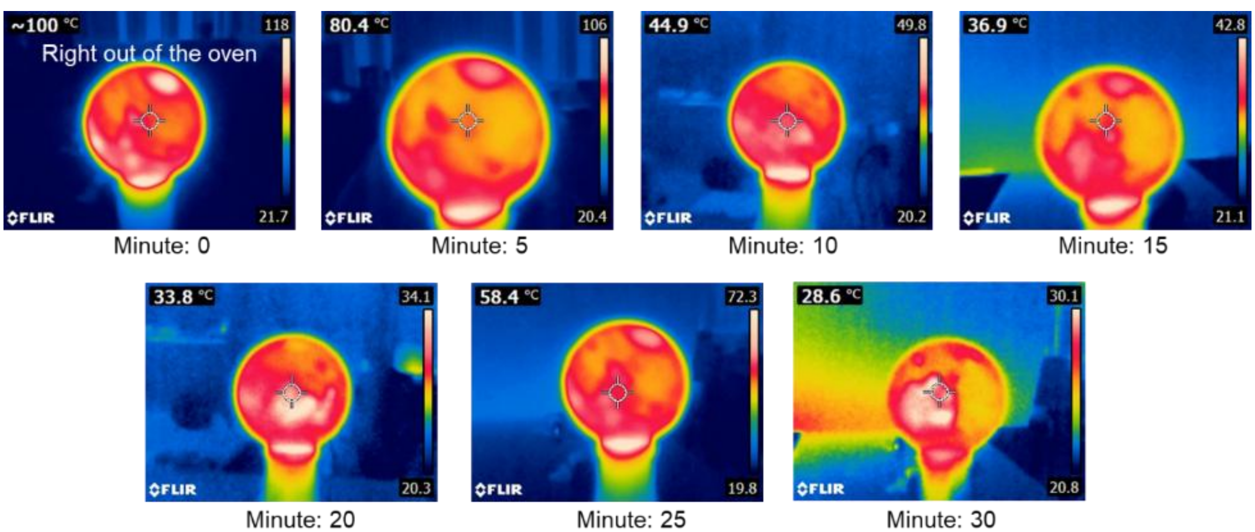


Figure 3. Thermal images of a pebble with time snapshots.

Eddy current, however, is a technology that requires close proximity to establish the eddy currents in the material. An eddy current sensor that would give similarly timed results as that of thermal imaging would be a sensor made of an array of coils in two hemispheres which could be placed over the pebble and acquire near instantaneous results. This, however, would be a complicated system to design and develop. A simpler system would be an array through which the pebble rotates allowing collection of data on all sides, for example an array of coils embedded in the pebble chute. The ensuing question then is the operational scanning speed of such a system.

Proof-of-concept data on samples was collected in a laboratory situation in which the user had to operate two separate programs to move the pebble and to acquire data respectively. To facilitate this, the pebble was rotated through multiple rotations, allowing the user to switch to the acquisition program and manually time when to start / stop data collection. To this end, the rotation had to be slow enough for the operator to respond to. For these samples, the rotation rate was set to 17.8 sec/rotation. The data acquisition rate was set at the system's minimum: 1,000 Hz. With the low rotational speed, copious data was collected and then down-sampled afterwards by a factor of 5 for ease of processing. With an estimated circumference of 12.6 cm, the spatial sampling rate is calculated at 0.71 cm/s. In the X direction, this gives a resolution of 280 samples/cm. The Y resolution, defined by the coil spacing, is 11.5 samples/cm. The ratio between the two dimensions leads to a considerable over-sampling in the X direction. Therefore, to get a 1:1 X to Y aspect ratio, the rotation speed of the pebble could be theoretically increased to approximately 7 rotations/sec (i.e. pebbles/sec), at 0.15 sec per scan (see *Figure* 4).

Comparing surface sampling speeds of eddy current inspections within steam generator tubing in nuclear power plants can give a better idea of real-world values for scanning pebble surfaces. Due to the relative slowness of the sampling rate in relation to the speed of electromagnetic propagation in both materials, the material type should not appreciably affect the acquisition speeds between these two materials. The example Eddy Current Data Sheet shown in Figure 5 shows a typical recording speed for an array probe of 40 in/s (101.6 cm/s) sampled at 1,300 Hz. The target resolution is approximately 30 samples/in (11.8 samples/cm). Extrapolating from that recording speed, this would lead to a pebble rate of approximately 8 pebbles/sec – i.e., 100,000 pebbles every 3.4 hours theoretically. Eddy current acquisitions in steam generators are also sometimes performed at 100 in/s (254 cm/s) yielding 20 pebbles/sec or 100,000 pebbles every 1.4 hours. Zetec's MIZ-200 instrument used in the current project claims a sample rate up to 40,000 Hz in its specifications, which could conceptually allow a recording speed of 3127 cm/s and, thus, provide a scan rate of just under 250 pebbles/sec or 100,000 pebbles every 6.7 minutes.

At this point, the question is not about the speed capability of the eddy current acquisition itself, but rather it is about the hardware needed to support that acquisition. If pebbles need to be manipulated to be placed or rotated in a sensor assembly, this becomes the bottleneck. However, if the pebbles can pass through an in-situ sensor assembly, the inspection rates can be made much faster.

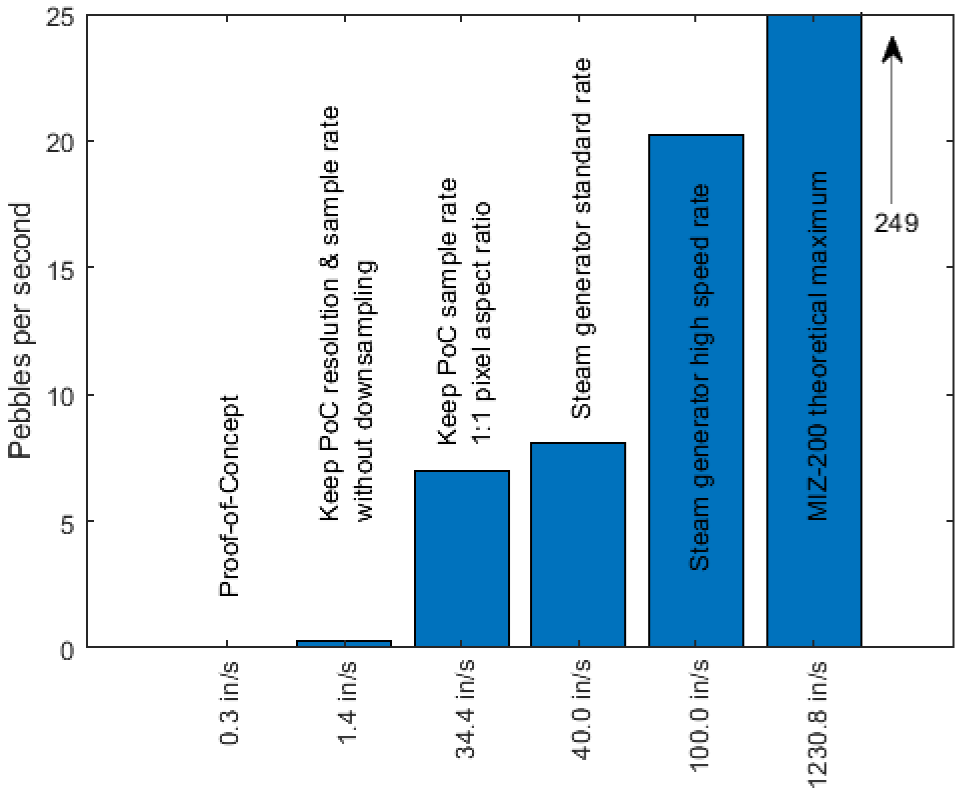


Figure 4. Graph of theoretical pebble scanning rates

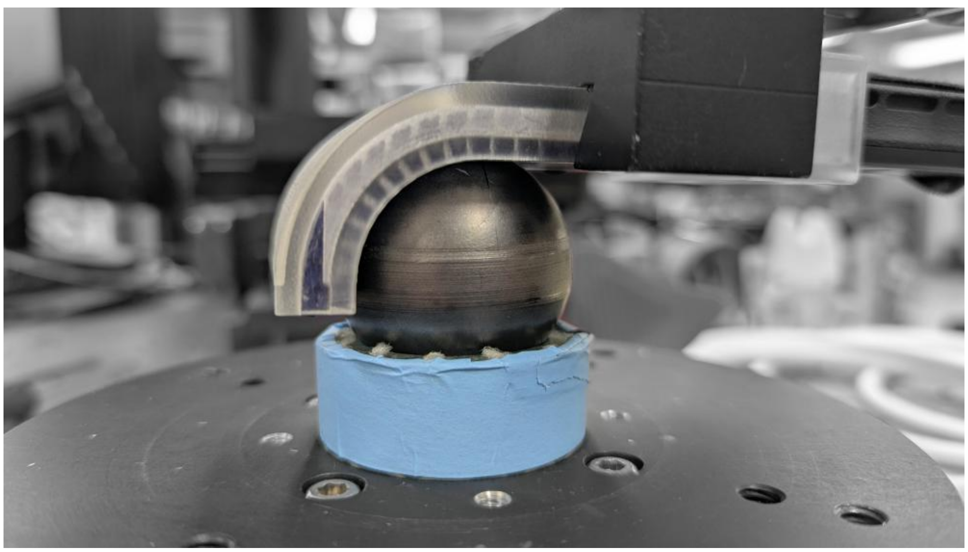
	Cal Freq	Option 1	Option 2	Option 3	Calculated Freq	kHz	Test Freq
Probe Dia.	0.610						
Tube O.D.	0.7500				2x Prime	1060	
Tube Wall	0.0430				1.5x Prime	795	600
Tube I.D.	0.6640				Optimum Freq.	530	550
Resistivity (µΩcm)	[illegible]				3/4 Prime	398	400
Sample Rate (Hz)	1300				1/2 Prime	265	300
Record Speed	40.00				F90 (Detection)	246	270
Samples/Inch	32.5	0.0	0.0	0.0	One Std Depth	206	200
Fill Factor	84.40%	0.00%	0.00%	0.00%	1/4 Prime	132.5	130.0
Rotating Coil RPM					1/8 Prime	66.25	100.00
Axial Samples/Inch	0.0	0.0	0.0	0.0	20% F90	49.29	
OD Circ Samples/Inch	0.0	0.0	0.0	0.0	10% F90	24.65	

Figure 5. Example from an Eddy Current Data Sheet used by industry

4.2 Surface Penetration of Eddy Currents

Data acquisition for Task 2 involved the use of pencil probes and array probes. Pencil probes provided spot measurements, while array probes enabled rapid inspection of whole pebbles. Early validation data was acquired with an array probe from Waygate (formerly GE), which has stopped making the probe. After simulations were performed, a newly developed Surf-X array probe from Zetec was believed to give better capabilities at the 5mm depth in graphite (Figure 6). This probe was purchased previously and was tested in this program. A custom handle was additively manufactured to conform the probe to the surface of the pebbles and data were acquired at six frequencies between 50 kHz and 1000 kHz. The setup for this probe also allowed for the collection of data sensitive to flaws that were parallel to and perpendicular to the direction of scans.

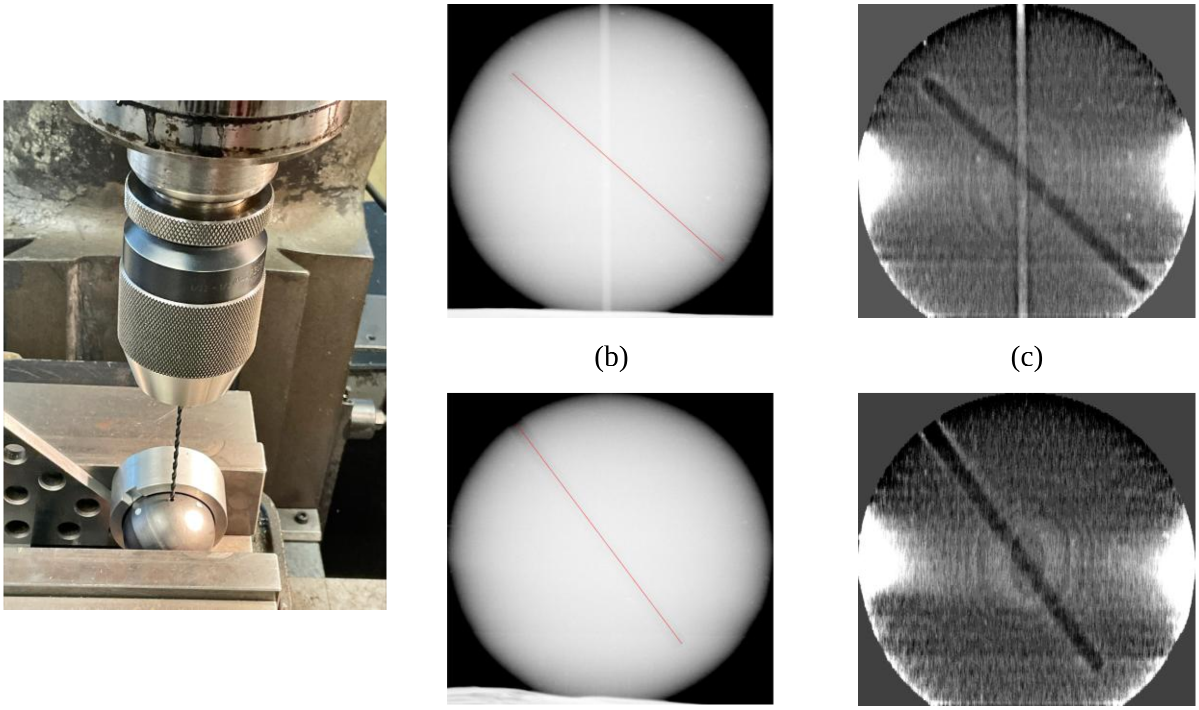
(a)



(b)

Figure 6. (a) A new Surf-X eddy current array probe was purchased from Zetec. (b) An additively manufactured handle was created to conform the probe to the pebble surface.

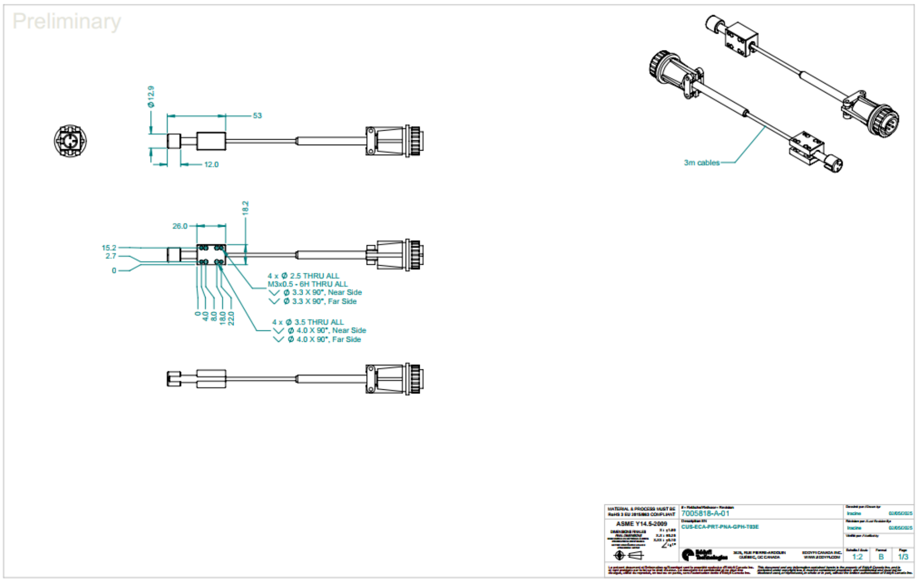
To experimentally validate the NDE technologies in ambient conditions and report on the limits of both superficial and subsurface artefacts of pebbles, two pebbles (chosen as the most pristine) were selected as depth standards: PGP-3 and PGP-6. Holes were drilled from one side of the pebbles to depths of 2mm and 5mm below the opposite surface of the pebbles, shown in *Figure 7*(a). Measurements from X-ray radiographs, *Figure 7*(b) - *Figure 7*(e), confirm that depths are within ±0.1mm of target.



(a) (b) (c) (d) (e)

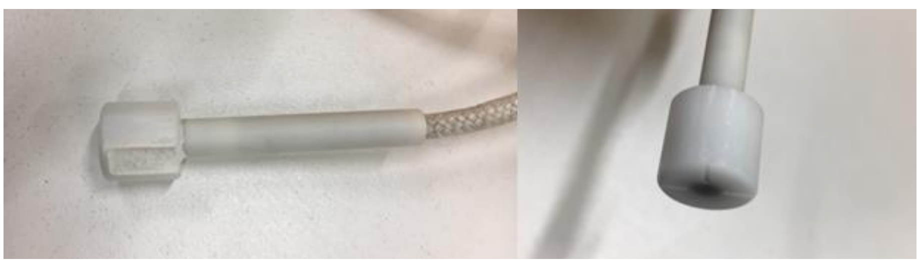
Figure 7. (a) Depth standards were created using two PGP samples. X-ray radiographs collected on samples with voids (b),(c) 2mm below the surface and (d),(e) 5mm below the surface. Radiographs are shown (b),(d) unfiltered, and (c),(e) filtered to enhance contrast

The goal was to procure a high-temperature eddy current probe to test its performance in a thermally-elevated environment on the Kairos-provided pebbles. This probe would be a single-element probe in case of damage from the elevated temperatures. Based on previous experience with a probe manufacturer, Zetec, Inc. of Washington, USA, an arrangement was pursued where they were provided with sensor requirements for the pebble scan in a high-temperature environment. Zetec probe developers collaborated with the experimental team at Argonne to design and develop a high-temperature probe by an original target date for delivery of June – finally delivered in November due to numerous logistical, legal, and supply chain delays.



(a)

(b)



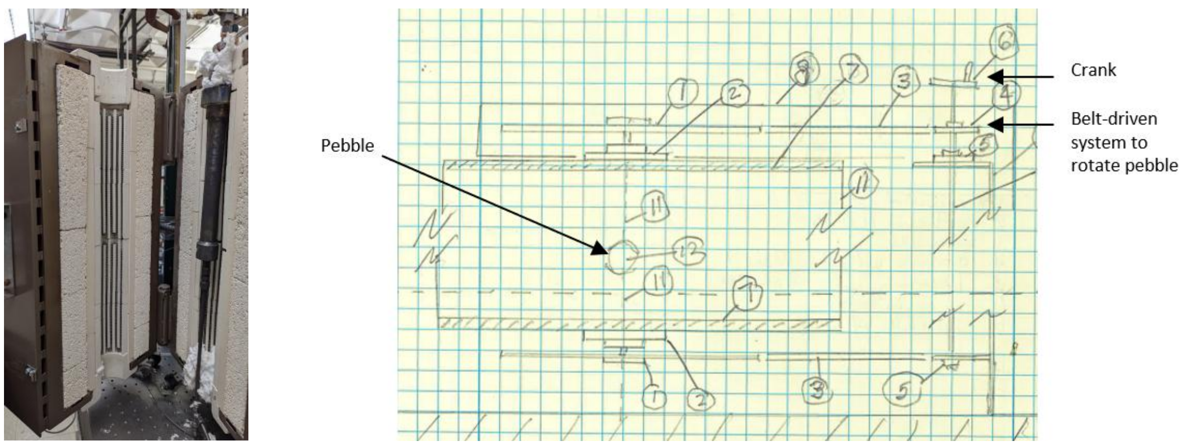
(c)

Figure 8. High temperature probe purchased from EddyFi through Zetec. Shown are (a) the design of the probe, (b) an additively manufactured mock-up to aid in lab setup, and (c) photos of the actual probe in development at EddyFi.

The final probe design as shown in *Figure 8*(a) was provided to Argonne for approval. The section between the mounting bracket and the instrument connector is a 3m cable designed to withstand the elevated operating temperatures. The probe head is encased in ceramic for temperature resistance. A surrogate probe model was 3D printed to complete the experimental setup in the laboratory – as shown in *Figure 8*(b). Unfortunately, the mounting bracket in the original design tended to crack the ceramic probe head. The probe head as-created is shown in *Figure 8*(c). A new method to mount the probe has been designed using a fiberglass cloth as padding and a different bracket type (not pictured).

4.3 High temperature scanning

A furnace was procured in which to conduct the elevated temperature tests of Task 3 (*Figure 9*). This furnace, with a 6cm-diameter cylindrical shaft, was ideal for testing 4cm-diameter Kairos pebbles. The maximum operating temperature of the furnace (1000°C) exceeded experimental needs of this particular project. An additively manufactured surrogate probe (*Figure 8*(b)) was created based on initial probe designs from the vendor to mock-up the setup while awaiting the probe. However, the initial probe design was modified due to fragility of the ceramic probe sheath, and a new configuration will have to be implemented once the probe arrives.



(a) (b)

Figure 9. Furnace for elevated temperature tests and diagram of the setup to be used.

This task was originally intended to explore the limitations of eddy current probes in an elevated temperature environment – similar to a pebble downstream from its core discharge point. Once the high temperature probe would have been received, the experimental setup would have consisted of a pebble within the furnace oriented in a configuration to easily identify and characterize a recognized artefact on the surface of the pebble when rotated within the furnace. Moreover, data would be collected at room temperature so that a direct comparison can be made to the high temperature readings. The pebble would have been heated with an Overtemp Protection Controller limited to a maximum vessel temperature during experiment of 527°C - 560°C, setting the Main Temperature Controller to 500°C. Once the intended furnace temperature is achieved, the pebble would have been given sufficient time to come to temperature (estimated for 1 hour). Once at temperature, the furnace opening would allow the placement of the probe and a hand-cranked jig which would allow one to rotate the pebble under the probe. The signal is anticipated to be relatively flat as the pebble is rotated until the known artefact comes under the probe coil, resulting in a trace similar to the simulated trace in *Figure 10*.

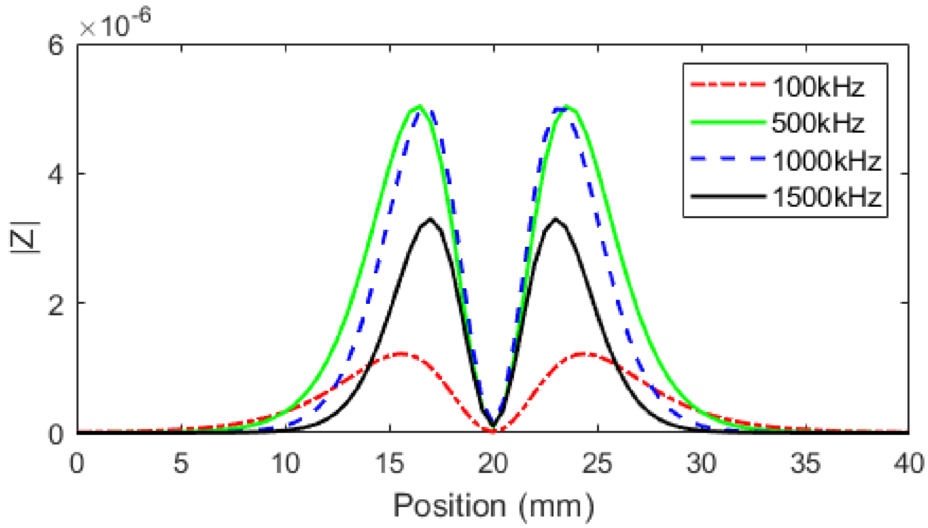


Figure 10. Simulation of a 1mm³ flaw 4.5mm below the surface.

5 Data Collection and Analysis

Data acquisition involved a variety of probes. Pencil probes provided spot measurements, while array probes enabled rapid inspection of whole pebbles. Filtering techniques, such as median-subtraction and resampling filters, were applied to align and reduce the size of datasets for efficient analysis.

The spot measurements with the pencil probe were conducted on Kairos-provided ASP (annular with surrogate particles pebbles) and PGP (pressed graphite pebbles). As shown in *Figure 11*, EC can readily distinguish between these two types of pebbles using K-means clustering, which is a technique used to group *n* data points into *k* clusters. Potentially due to the difference in annealing, this analytical technique was able to differentiate between the two pebble types. Informal discussion at a recent program review has confirmed that, in operational experience, solid graphite pebbles are still manufactured differently from fuel pebbles.

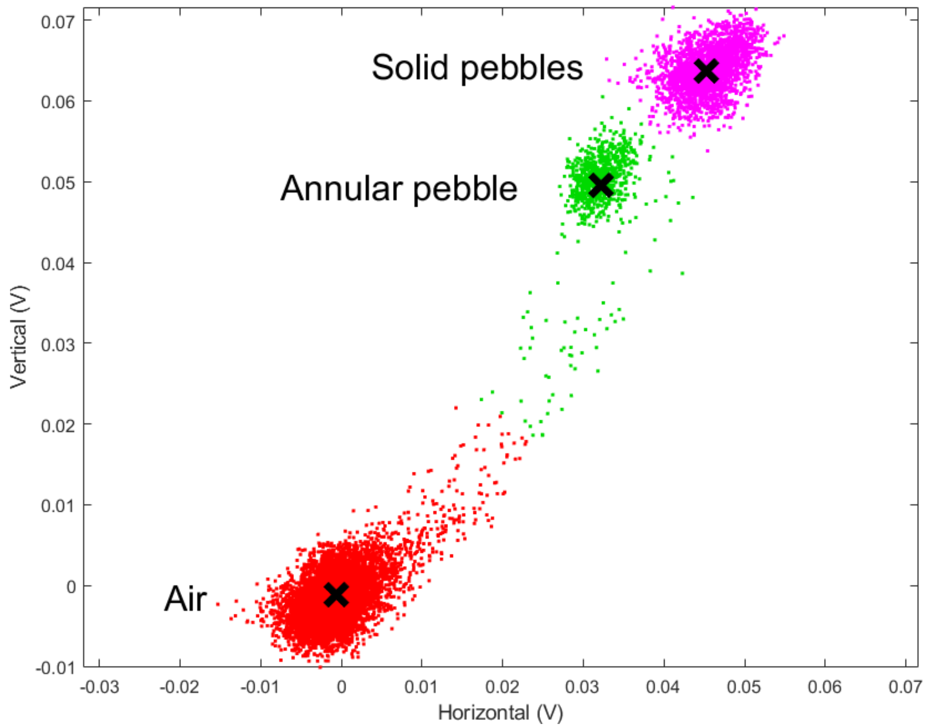


Figure 11. Eddy current can readily distinguish between these two types of pebbles using K-means clustering

Comparison of EC amplitude data collected with the old array probe versus the new array probe in *Figure 12* shows that the new probe has the ability to detect East-West oriented flaws (marked in yellow) as well as the North-South oriented flaws detected with the previous probe (marked in blue). Comparison of *Figure 12* (a) and *Figure 12* (c) shows that the new probe has a better signal-to-noise ratio for detected cracks. However, this better sensitivity comes with a trade-off in that the flaws are not as sharply defined in the new probe images due to the increased coil size of the new probe, leading to apparently wider flaws. Photographs of the pebble confirm the presence of the newly detected East-West flaw, along with the previous confirmation of the North-South flaw (*Figure 13*). This pebble also exhibits a dent on the right side of the pebble, not shown in the photograph here, but shown in previous reports (available upon request by the reader).

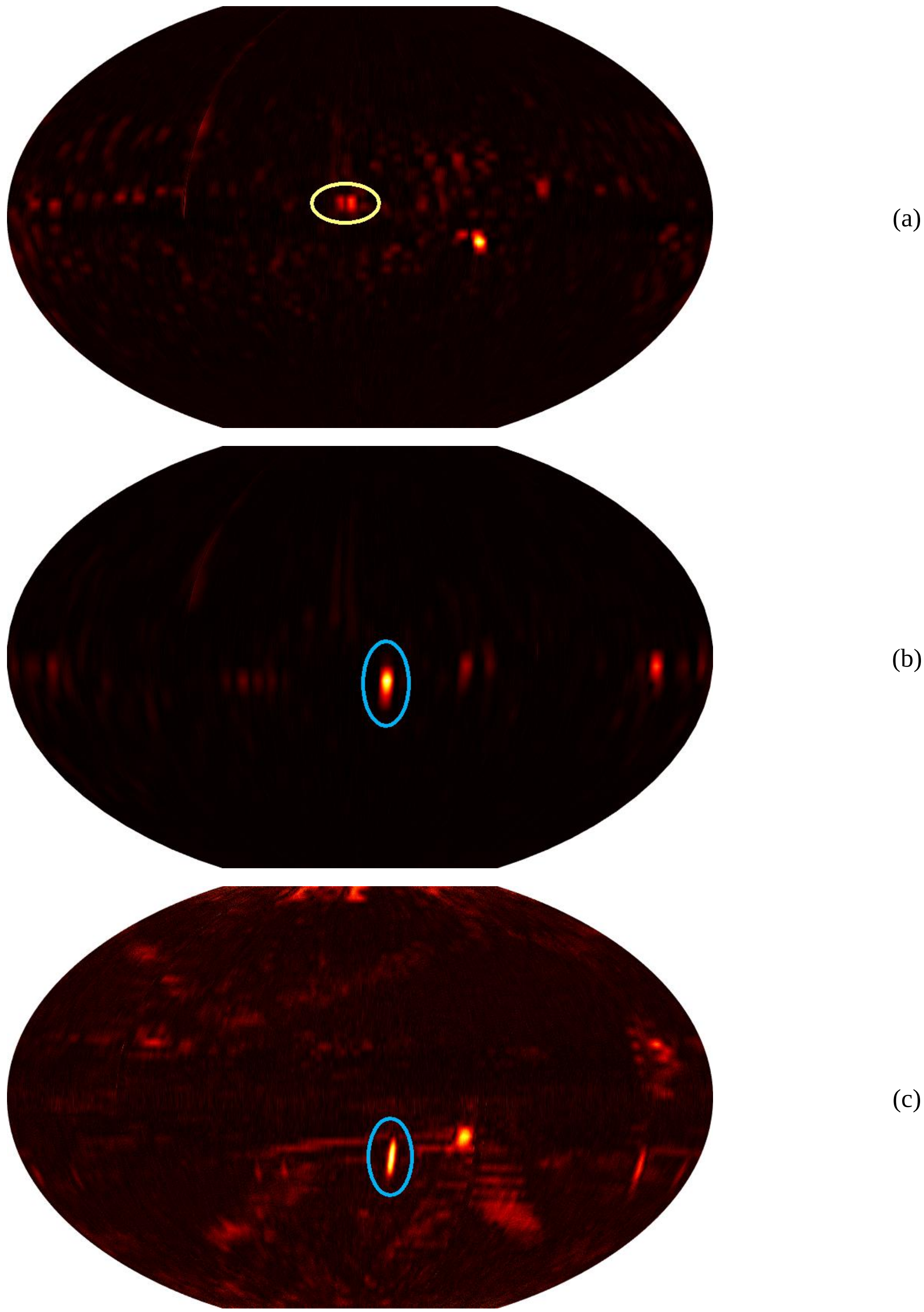


Figure 12. Comparison of EC amplitude data collected with the new array probe vs the old array probe. The new probe (a,b) shows ability to detect (a) east-west flaws and (b) north-south flaws, similar to (c) data previously collected from the earlier probe.

Figure 13. Photographic confirmation of flaws in Figure 12

Two PGP pebbles were selected as depth standards and holes drilled from the back side to within 2mm and 5mm of the upper surfaces to simulate the formation of subsurface voids. When collecting data on these samples, gain had to be increased from the 23dB, used in previous tests, to 36dB in order to detect the voids at 5mm depth. At this gain, the horizontal (lift-off) component dominates the amplitude signal. Even so, the subsurface voids are detectable at both 2mm (*Figure 14*) and 5mm (*Figure 15*) below the surface in the vertical component of the data. Using this map projection, one can also see the entrance holes on the back side of the pebbles at the lower edges of the figures.

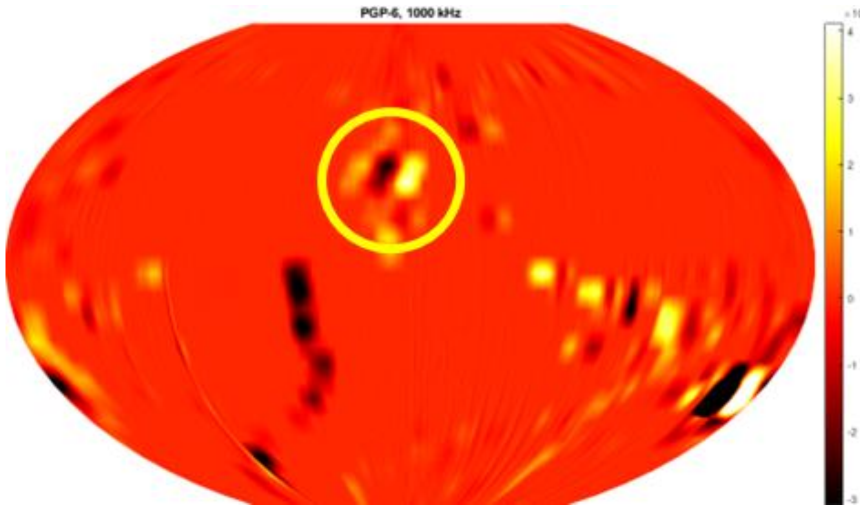


Figure 14. Vertical component of 1000 kHz EC scan of depth standard with void 2mm below the surface

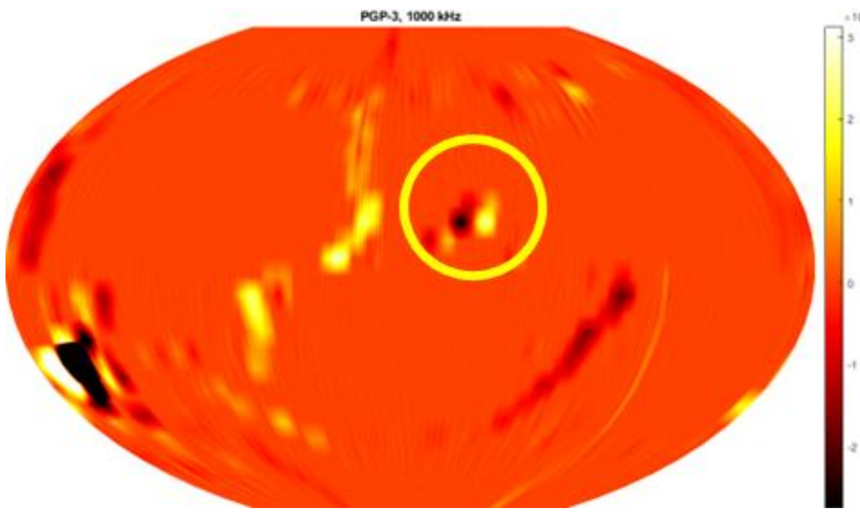


Figure 15. Vertical component of 1000 kHz EC scan of depth standard with void 5mm below the surface

As mentioned earlier, though a high-temperature EC probe was ordered from EddyFi, it did not arrive early enough to conduct the full elevated temperature experiment. However, developers at EddyFi did provide preliminary scanning/response results of the new probe to the Argonne team (up to 400°C) to prove its ability for the experimental setup (the probe was tested up to 500°C but data was not collected at the 500°C). EC data, is shown in *Figure 16*atthe latter 400°C, with measurable contrast between regions of differing properties (e.g. SS 400°C to Air 400°C).

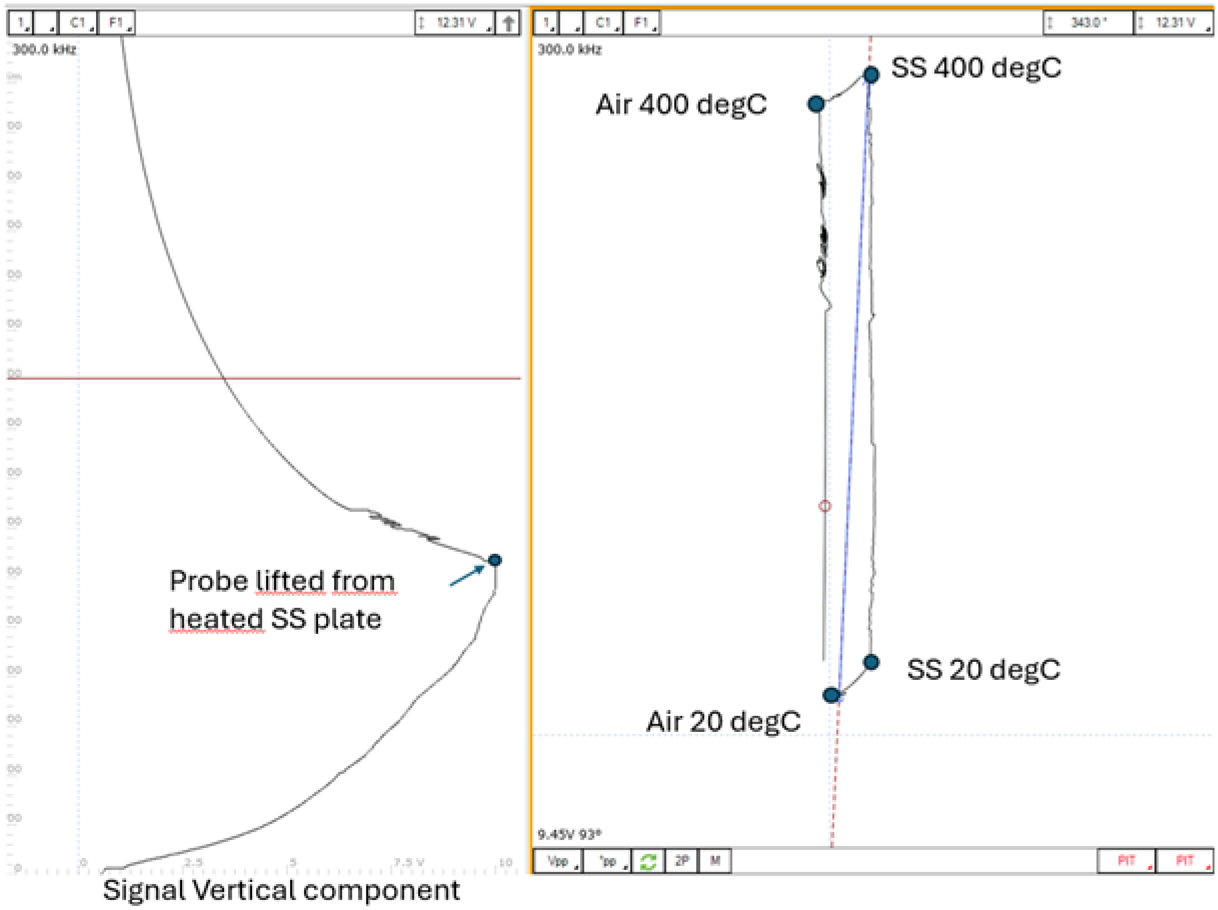


Figure 16. Data from high temperature probe collected at 400°C.

6 Results

EC responses from dented regions and cracked regions showed distinct signatures, enabling differentiation between dents and surface-breaking cracks. This distinction is important for operational decisions, as cracks are more likely than dents to propagate, shed material, or lead to pebble fragmentation. Vertical cracks were consistently located at the equatorial band, suggesting manufacturing origins. Small defects were easily detected, supporting the feasibility of embedding batch identifiers in pebble shells. The earlier GE array probe primarily detected cracks oriented in one dominant direction (e.g., North–South). The new Surf-X array probe enabled detection of both North–South oriented flaws and East–West oriented flaws, that were not clearly resolved with the earlier probe. The new probe provides a better signal-to-noise ratio for crack detection; flaws appear more prominent relative to background noise. However, due to its larger coil size, flaw images appear somewhat wider and less sharply defined compared to data from the earlier probe.

EC scans at 1000 kHz were performed on the newly prepared depth samples using the new array probe. For consistency with earlier tests, an initial gain of 23 dB was used but was insufficient to clearly detect the 5-mm-deep void. Increasing the gain to 36 dB allowed both 2-mm and 5-mm voids to be detected. At this higher gain, the horizontal (lift-off) component of the signal became dominant in the amplitude; however, the vertical component still provided clear contrast for the subsurface features. At 2 mm depth (*Figure 14*), the void is clearly visible in the vertical component image, confirming strong sensitivity to shallow subsurface defects. At 5 mm depth (*Figure 15*), the void remains detectable. Although the signal is slightly weaker and more susceptible to noise, as expected, it was stronger than the order of magnitude fall-off from the signal at 2 mm depth which was expected from simulations.

Measurements using an EC pencil probe on ASP and PGP pebbles showed that EC technology can reliably distinguish between different pebble types based on their electromagnetic response. Using amplitude and phase information from the EC signals as inputs, K-means clustering was applied to the dataset (*Figure 11*). The clustering clearly separated ASP and PGP pebbles into distinct groups, demonstrating that their effective conductivities differ in a way that EC can resolve.

Due to supply chain and contractual delays, the prototype high temperature probe did not arrive at Argonne in time for in-house elevated-temperature testing. However, EddyFi tested the completed probe at their facility at 20°C and 400°C. Results (*Figure 16*) show that the probe maintained functional EC response at 400°C, with measurable contrast between regions of differing properties. Signal characteristics shift with temperature, as expected due to changes in material conductivity and probe characteristics, but remain usable for inspection.

7 Conclusions

This work demonstrates that eddy current (EC) imaging is a promising tool for acquiring structural and potentially identifiable images of graphite pebble fuel in advanced pebble bed reactor (PBR) systems for both safeguards and operational safety purposes. EC imaging successfully identified a range of flaws on surrogate graphite pebbles, including small surface cracks, and dents. Voids at depths of 2 mm and 5 mm were detected, confirming that EC techniques can sense artefacts within the 5 mm graphite layer rather than just superficial damage. The ability to distinguish between denting and cracking, and to detect relatively small features, indicates strong potential for early identification of structural degradation before it leads to pebble breakage or flow blockages in the primary loop.

More than 80% of the pebbles examined exhibited vertical cracks concentrated near the edge of the equatorial band. The alignment and repeatability of these features strongly suggest that many cracks originate from the manufacturing process. This observation highlights a potential feedback pathway: EC imaging could support quality assurance for pebble fabrication and help industry partners refine manufacturing processes to minimize initial defect populations.

The consistency with which EC imaging detects fine surface and subsurface features supports the concept of using naturally occurring or engineered artefacts as "fingerprints" for individual pebbles or pebble batches. Small, intentionally embedded features in the outer shell could be used as batch identifiers that are detectable by EC, even at high throughput (until this concept has full concurrence with fuel fabricators and PBR designers, this will not be pursued). Combined with pebble monitoring and burnup information, such identifiers could enhance material control and accounting by allowing operators to sort pebbles by batch, introduction date, and initial enrichment without relying solely on radiological methods.

EC measurements, combined with K-means clustering, readily distinguished between different pebble types (e.g., ASP vs. PGP) based on conductivity differences. In this campaign, the separation is likely linked to annealing differences. However, even if future pebbles are processed identically, EC operation at suitable frequencies should still distinguish pebble types due to the presence or absence of embedded fuel particles, which modify the effective conductivity of the annular region. This capability supports rapid, non-radiological sorting of pebbles by type and function, which is valuable for both safeguards reporting and core management.

By drawing on existing industrial practice (e.g., EC inspection of steam generator tubing) and considering realistic sampling rates and probe speeds, the study shows that pebble inspection rates of tens of pebbles per second are achievable using commercially-available EC hardware. With optimized sampling and handling, inspection rates on the order of hundreds of pebbles per second are theoretically feasible, shifting the primary bottleneck from EC instrumentation to mechanical handling and pebble manipulation. These results indicate that EC imaging can be integrated into online or near-online inspection stations without creating significant operational delays.

A custom high-temperature EC probe, designed for operation up to approximately 500 °C, was successfully fabricated and tested by the vendor. Preliminary data collected at 20 °C and 400 °C demonstrate that EC response remains usable at elevated temperatures characteristic of recently discharged pebbles. Although the probe did not arrive in time for in-house testing at Argonne, these vendor-provided results support the technical feasibility of using EC to inspect "hot" pebbles with minimal or no cooling time, reducing dependence on traditional radiologically based nondestructive testing methods that require extended delays.

Taken together, these results validate the core premise of this project: eddy current imaging is an adaptable, and relatively high-throughput technology that can be repurposed from its established roles in nuclear plant inspection to meet the unique needs of pebble bed reactor designs.

While additional work is warranted - in particular, extended high-temperature testing in realistic geometries, refinement of probe designs for in-situ deployment, and integration with plant-scale handling systems - the present study provides a strong basis for continued development. EC imaging emerges as a credible candidate technology to support both advanced reactor safeguards and the reliable, efficient operation of future pebble bed reactor systems.

8 Acknowledgement

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