Electropotential Verification for Nuclear Facility Design Information Verification

Phoenix Baldez, Christine Downs, Chester Weiss, Rachel Helguero, Jesse Bland, Michael Hamel

Sandia National Laboratories[1]

Submitted to the INMM/ESARDA 2023 Joint Annual Meeting, May 22-26, Vienna, Austria.

ABSTRACT

Verifying that a nuclear facility's infrastructure matches the declared design is vital to the continued success of international safeguards regimes. Electropotential verification (EPV) is a newly proposed verification method that could provide real-time online monitoring of a facility's infrastructure design. EPV works by passing a low-voltage current through a conductive infrastructure such as pipes in a uranium enrichment plant and taking voltage readings from various probing locations throughout the infrastructure network to establish baseline values. Deviations from the baseline readings would point toward changes made to the system configuration, which could indicate possible undeclared activities. EPV has two large advantages over DIV methods that rely on line-of-sight approaches such as visual inspection or 3D laser scanning. First, because the low electrical current will interrogate and detect changes throughout the entire infrastructure network, portions of the facility deemed sensitive or proprietary do not have to be visually inspected. Second, significant alterations to the system can be detected and flagged instantaneously instead of during periodic inspections. To show the viability of this technique, a laboratory-scale tabletop network of stainless-steel pipes was constructed, which is analogous to the complex piping infrastructure present in a facility. Measurements of this mockup have shown successful detection of system alterations, including the addition, removal, or change in the location of grounded elements. Additionally, the software Hi-FEM, which uses hierarchal finite element modeling to simulate electrostatics, was used to model the laboratory measurements. The models showed good agreement in relative potential differences throughout the network. This model validation is important to show that the simulation tool is viable to use in further study of EPV. Future efforts will work to show concept viability on a larger scale and create conceptual instrumentation designs for concept implementation.

INTRODUCTION

EPV is a novel method proposed for performing continuous design verification monitoring of complex facility infrastructure and verification of spent nuclear fuel submerged in a cooling pond. EPV relies on the electrical conductivity of facility infrastructure and the unique circuit properties exhibited when the infrastructure is energized. The infrastructure materials, configuration, and paths to electrical ground play a large role in how an electric current propagates throughout the system. In an implementation of EPV, the infrastructure is energized

---

[1] *Sandia National Laboratories is a multimission laboratory managed and operated by National Technology and Engineering Solutions of Sandia, LLC, a wholly owned subsidiary of Honeywell International Inc., for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-NA0003525 SAND2022-16964 A.*

with a power supply that maintains a constant current. Voltage readings are taken throughout the system in order to establish baseline values. Later readings are then compared to these baseline values to determine if the current infrastructure deviates from the prior configuration [1].

The application of EPV technology has the possibility to extending into many safeguards applications but for now work in DIV has shown to give promising results. Success in application would improve the International Atomic Energy Agency's (IAEA) capability for timely detection of undeclared activities. For example, a uranium enrichment facility could be monitored using EPV, and critical points in a cascade could be subjected to continuous monitoring of the low-voltage current. Subsequent changes to the cascade, which could be indicative of diversion or enrichment beyond normal limits, would show up as significant readings on the EPV measurements. This method would provide continuous monitoring of a system, as opposed to only being investigated when IAEA inspectors are on-site. This method would also inherently protect proprietary information because the only information being gathered is changes in voltage; no visual inspection would be used to detect changes to the infrastructure.

The laboratory-scale experiments have proved that the concept of EPV works; it can be used to detect a change in conductive infrastructure with both instantaneous and continuous measurements. The results from the laboratory experiments also reflect the outputs from the Hi-FEM simulations, opening doors for further research in application spaces for EPV without experimental testing. As of now, field-scale EPV tests are ongoing, but the initial results show that signals can be detected through 100s of feet of large-bore cast-iron drilling machinery. With the ability to detect signals through facility-scale amounts of conductive material, the next step will be to apply EPV to a complex and possibly noisy system that would be found in such a facility.

DIV EXPERIMENTS

Experimental Setup

The laboratory-scale experiments were designed to offer a range of possible facility-like layouts to study with relative ease and freedom to change the parameters. The experimental structure consisted of a series of 304 stainless steel pipes with a ¾ in. nominal diameter, each with a 12 in. length. The elbows and tees used to connect the pipes with threading were also ¾ in. 304 stainless steel. In order to achieve consistent results, the measurement location and contact needed to be standardized, so copper connectors that fit around the pipes were used to hold a wire in place that would travel to centralize measurement location. The wire used was standard 10 AWG insulated copper wire, there were no measurable effects on the measurements because copper's conductivity is about 40 times higher than that of stainless steel. This copper wire was additionally used as a "pipe 15" used to create a loop due to the inability to screw a threaded rod in two directions at once and as a low resistance path for the grounding points. Figure 1 shows a schematic of the pipe system layout with measurement points, pipes and grounds all labeled, the numbering will be used consistently to refer to results for the rest of this paper.

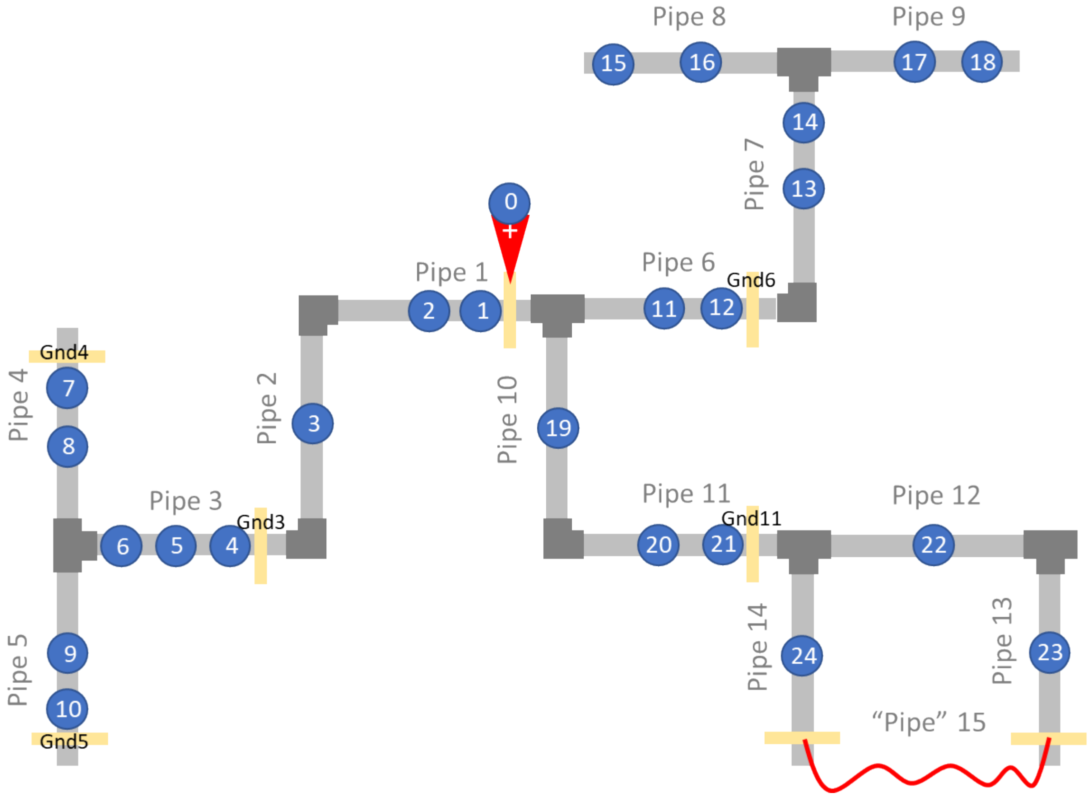

Figure 1: Pipe fixture layout with the measurement points labeled in blue circles.

To provide power to the system a Kepco MBT 55-7M was used in constant current operating mode. For all the experiments that will be shown and discussed a current of 7 A was used, producing voltages from the power supply from 0.78 to 0.84 V. The positive lead from the power supply was attached to the system at a central location while the negative lead was attached to a busbar. The grounding bar was used for the power supply, the multimeter and all the system grounds, which was then secured to a conductive part the structure of the building where the experiments were taking place. To take the measurements a Fluke 289 RMS Logging Multimeter was used with the negative lead grounded, and the positive lead applied to each of the measurement wires. Figure 2 shows the experimental setup, at the top of the figure is the power supply and grounding busbar while the bottom has the centralized measurement location and multi meter.

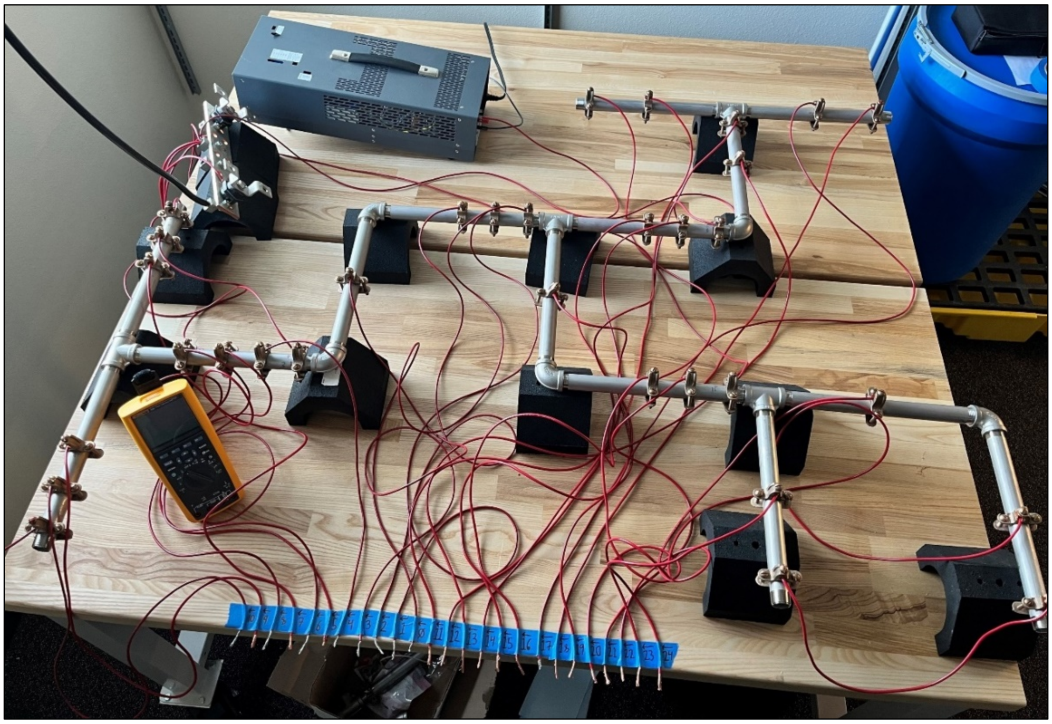

Figure 2: Experimental lab pipe system setup.

Instantaneous Measurements

The most important fact in acquiring measurements is establishing a baseline or the measurements before changes are made to the system. This was done at the start and end of every experimental change to the system, often including measurements throughout the experiment as well. This led to a large number of data points, collected over a long period of time. Figure 3 is a summary of all 33 baseline measurements, there is some spread in the data, which is proportional to the proximity of the measurement point to the voltage source but still not well quantified. For the purposes of data visualization once the baseline is compared to changes in the system, the data will be represented by the average point with error bars.

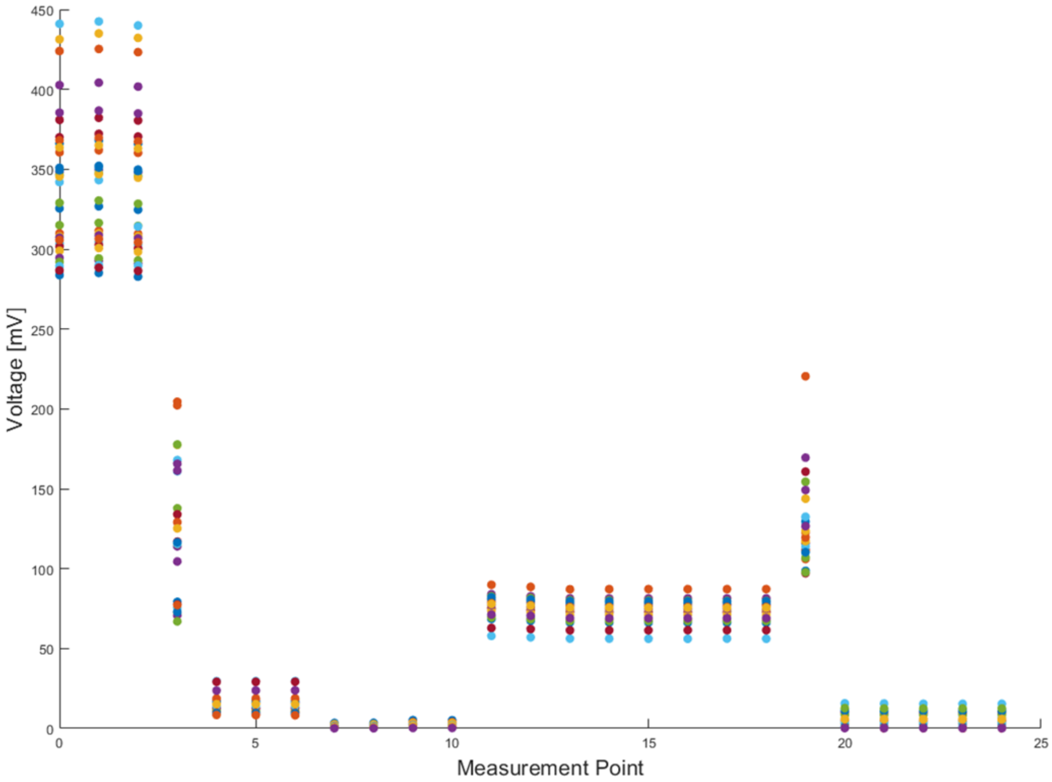

Figure 3: Summary of all baseline voltage measurements at each point. The various colors represent a different data set.

While current measurements were not recorded as a part of the normal experiment it was necessary to get a current seen flowing through each one of the grounding locations for use in the simulation code. This is presented in Table 1 as an average of all the current measurements. This measurement was taken with a handheld device, the HIOKI 3287. While a constant 7 A is applied there is slightly more current flow through the sum of all of the grounds due to the difficulty in measuring low current low accurately with a handheld device. It is consistent that ground 11, the grounding point closest to the voltage source had the most current, this makes sense given that current will find the path of least resistance to flow. Grounds 4 and 5 had very low, but still measurable, current due to being “behind” ground 3 from the voltage source.

Table 1: Current measured flowing through each of the grounding wires.

Ground Number	Current (A)
3	0.80
4	0.15
5	0.20
6	1.09
11	5.51

There were numerous experiments done in reconfiguring the system, but for the sake of brevity the measurement that provides the most insight to the reaction of the system to a change is the removal of ground 3, shown in Figure 4. It might be necessary to refer to Figure 1 for the numbers and locations of the grounds and measurement points. Almost the entire system showed an increase in voltage, except for the loop portion which was within bounds of the baseline measurement. The increase was most significant nearer to ground 3, with points 3-10 all showing a statistically significant difference from the baseline measurement. This trend was repeated throughout other changes to the system, as grounds were removed the voltage when increase significantly in close proximity to the change and less so the further away the measurement point was.

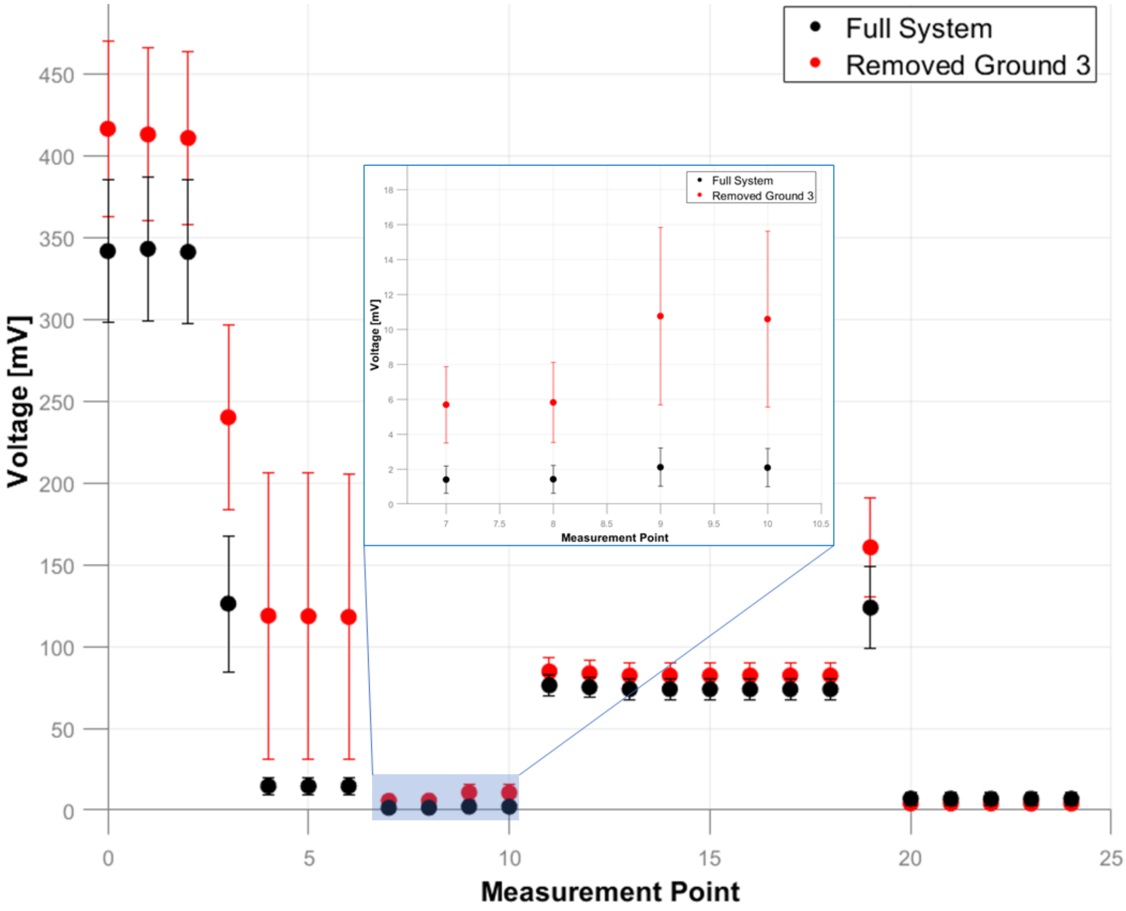

Figure 4: Baseline measurements compared to the measurements when ground 3 was removed.

The addition of a ground had a similar, yet opposite effect, the most significant was the introduction of a ground at point 15. The usually isolated section of the system experienced a drastic drop off in voltage while the rest of the system experienced little to no changes. A ground was also added "behind" measurement point 10, this had no effect on the system due to the small amount of current that was present after passing by two other paths to ground.

Hi-FEM Modeling

These measurements were all compared to the Hi-FEM modeling software which had the dimensions, material properties and factors such as the current at ground locations as inputs [2]. The properties are defined within a volumetric cell in an unstructured tetrahedral mesh, accurately representing the pipe as the connected edges. The generation of the mesh is done by a secondary program CUBIT where the most important segments of the modeled problem are more finely represented to better reflect the experimental setup [3]. Factors such as the conductivity of the air, and supports for the structure are all modeled as accurately as possible, but to reduce strain on the program, grounds are modeled converging on a floating point above the system, this should have no effect on the output. Figure 5 shows the visualization of the Hi-FEM model color coded to show voltage on the pipe as well as electric field generated around the pipe.

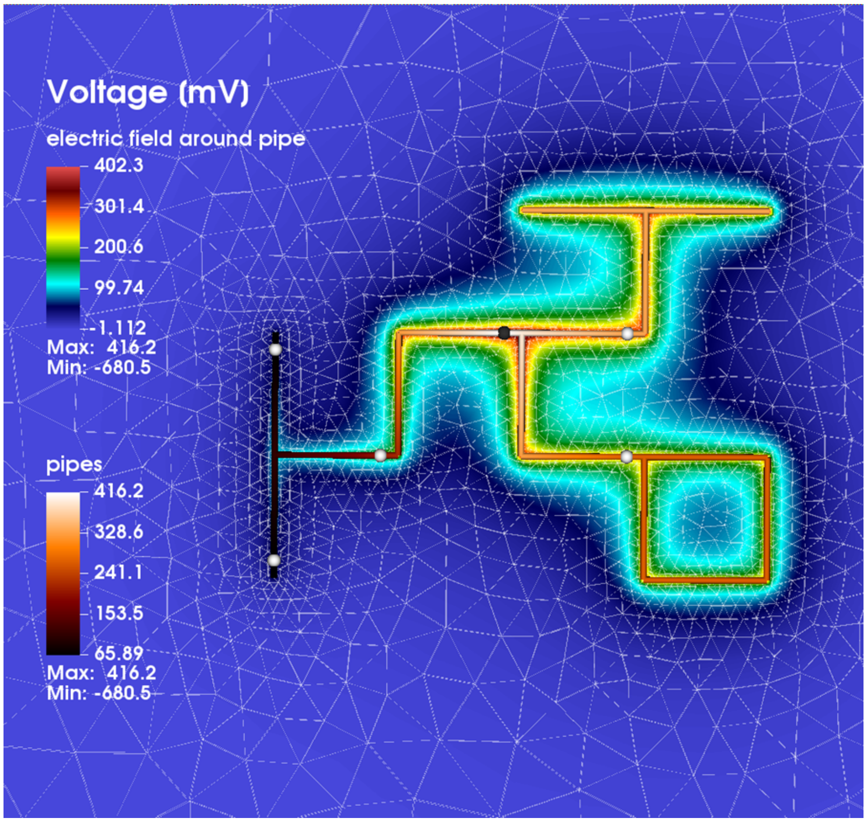

Figure 5: The pipe network modeled in Fi-FEM to generate the data we compare our experimental output to.

Figure 6 shows the comparison of two data sets, experimental and simulation for the baseline system as well as the removal of ground 3. Overall, the simulation results have a higher voltage than the experimental results, this is probably due to inefficiencies it is not possible to easily capture in a simulation, such as good contact between the threads of the pipes and joints. The structure and relation between points is very similar between the simulation and the experimental data. Outliers such as point 3 and 19 are clearly seen in both while there are also the same groupings of points giving similar voltages.

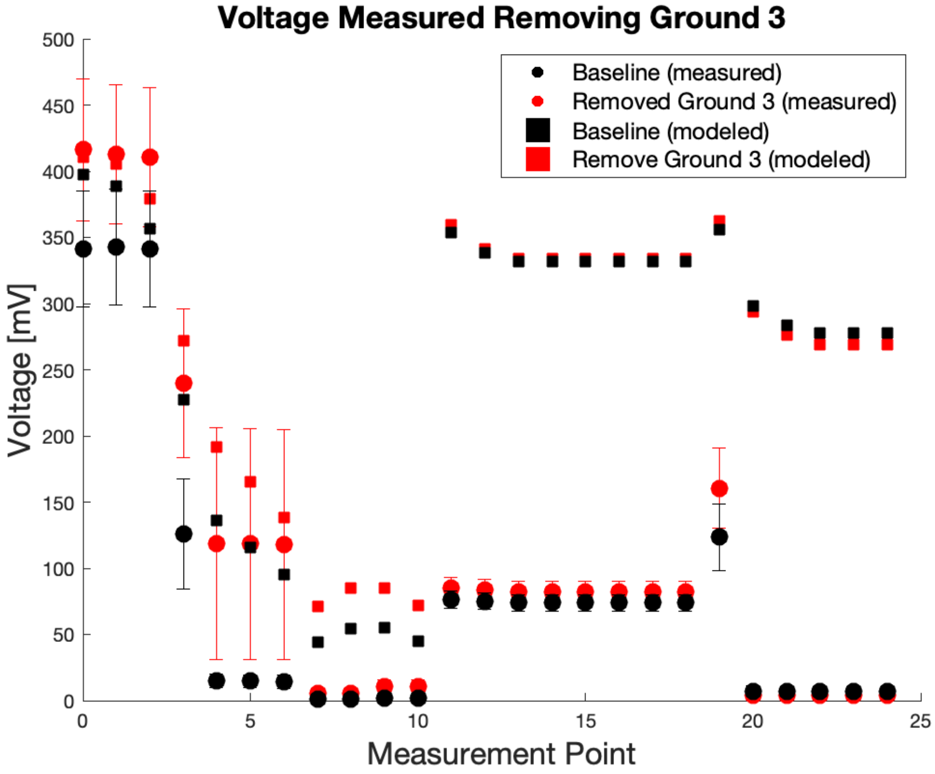

Figure 6: Comparison of baseline simulations results to the experimental system. Additionally, a comparison between simulation and experiment when ground 3 is removed.

Continual Measurements

With EPV technology there is the option for continuous monitoring of voltages at any location. For every point measured a full logging system is needed so it would be important to determine the continuous monitoring locations with forethought. While no giving the most significant changes, point 0 had the most consistency in having a response no matter where the change in the system took place. Figure 7 shows how the voltage at point 0 changes over the measurement period of 94 hours. At the start of the measurement there is the sharp rise in voltage that the slowly decays, only reaching a plateau about 15 hours after being energized. This is more than likely the cause of much of the variation in the instantaneous measurements, which were done minutes after the system was energized. There are slight variations in the voltage over the measurement that are probably due to environmental factors. At hour 90 a purpose change to the system is made, this is clearly visible and shows a sharp deviation from the rest of the data.

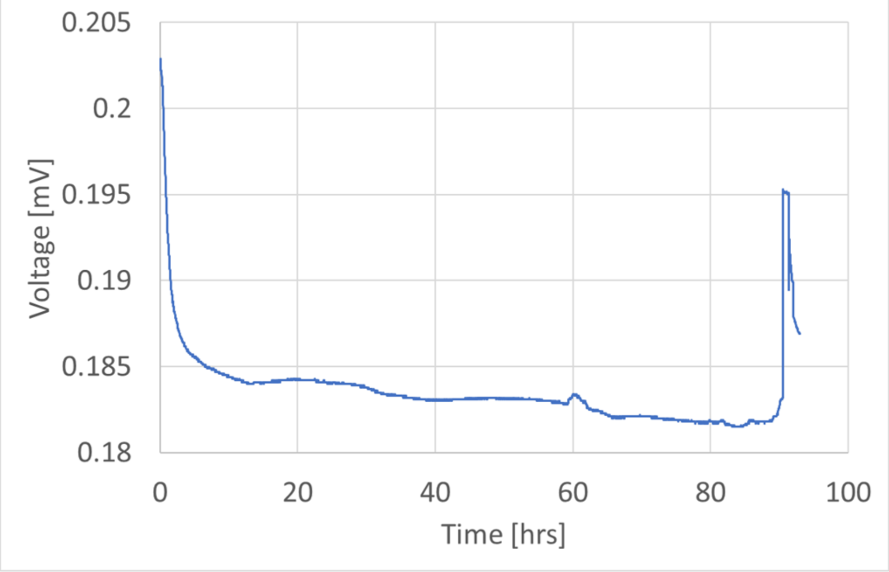

Figure 7: Voltage at point 0 measured continuously for 94 hours.

Figure 8 is finer view of the changes made near hour 90, this includes the removal of ground 3, its reattachment and then the subsequent removal of ground. Each of these changes are clearly seen in the voltage measurement, however, the magnitude of the change, baseline and even direction of voltage change is not consistent. To negate most of the effects, including the slow drift seen in Figure 7, the voltage differential can be taken. This results in a very steady baseline with large spikes that indicate changes being made to the system and would be the alarm to which trigger a more detailed inspection to ensure the integrity of the facility.

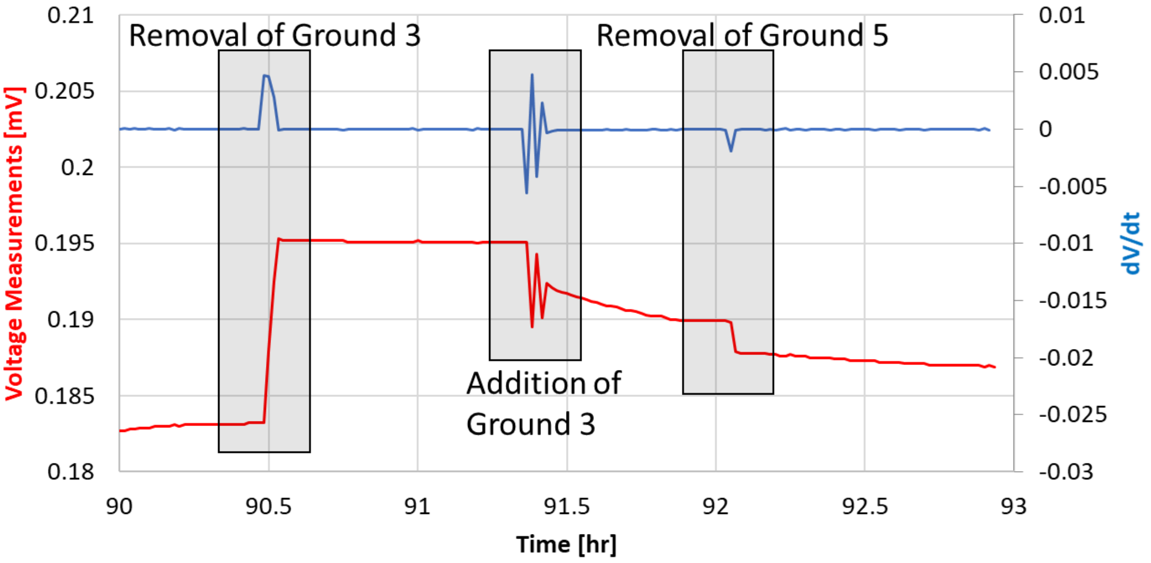

Figure 8: Changes to the system over time.

Field Measurements

More recently field measurements have begun. There are being done with abandoned drilling infrastructure, providing a significant amount of material to test. As of April 2023, significant signals were seen approximately 100 ft from the application point with as little as 0.3 A at 0.1 V. With these promising results, testing the addition of grounds and possible diversion scenarios along with continuous monitoring with environmental noise will take place soon.

SUMMARY

The laboratory-scale experiments that have been done show a proof of concept for EPV as a DIV technology. The more recent field-scale tests show that EPV is scalable and shows promise for facility scale implementation in the future. The long range of the EPV signal through a large quantity of conductive material with relatively low current and voltage gives hope that safety concerns could be mitigated using minimal power. Both instantaneous and continuous measurement modes have shown to be successful in showing changes to the system, each with a slightly different application space for inspectors performing DIV.

REFERENCES

[1] M. D. Hamel, P. Baldez, C. Downs, C. Weiss, R. Helguero and J. Bland, "Electropotential Verification for Nuclear Safegaurds," Sandia National Laboratories , Albuquerque, 2023.

[2] C. J. Weiss, "Finite-element analysis for model parameters distributed on a hierarchy of geometric simplices," *Geophysics,* vol. 82, no. 4, pp. E155-E167, 2017.

[3] T. Blacker, W. Bohnhoff and T. Edwards, "CUBIT mesh generation environment. Volume 1: User's manual," United States, 1994.