ORNL/SPR-2023/3205

Results from the First Field Test of a Ruggedized Continuous Holdup Monitor

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November 30, 2023

Oak Ridge National Laboratory

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Nuclear Energy and Fuel Cycle Division and Electrification and Energy Infrastructures Division

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Prepared by
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managed by
UT-BATTELLE LLC
for the
US DEPARTMENT OF ENERGY
under contract DE-AC05-00OR22725

CONTENTS

LIST OF FIGURES

LIST OF TABLES

LIST OF ABBREVIATIONS

DC	direct current
MCA	Multichannel Analyzer
NaI	sodium iodide
NFS	Nuclear Fuel Services
ORNL	Oak Ridge National Laboratory
PoE	Power over Ethernet
SiPM	silicon photomultiplier

ABSTRACT

A first field test of the inexpensive and ruggedized online holdup monitor under development at the US Department of Energy's Oak Ridge National Laboratory (ORNL) was performed in September of 2023 with highly successful results. ORNL staff collaborated with personnel at the National Fuel Services (NFS) to place two battery-powered detector units at the facility, one on a fuel processing line and the other on a HEPA filter. Both units collected gamma-ray counts per second, temperature, humidity, and battery power data every 5 s seconds over the course of 19 days. Analyzed results from the measurements were discussed with NFS personnel after the units were removed. Vendor feedback on the units was overwhelmingly positive with an expressed desire to deploy finished units at the facility and an open invitation for testing future prototypes.

1. BACKGROUND

1.1 PROJECT GOALS

Holdup monitoring is an essential part of the material accountancy necessary for any work with special nuclear material [1], [2]. In FY 2021, Oak Ridge National Laboratory (ORNL) completed an industry survey on holdup monitoring approaches currently in use [ORNL/TM-2021/2197]. That survey determined that the largest return on investment and potential process improvement would be to pursue the design of instrumentation that could replace periodic monitoring of the ventilation systems and ductwork. Such a system could reduce maintenance costs to facilities because the maintenance of HEPA filters and other ductwork would only need to be performed when sufficient holdup had accumulated to require remediation, instead of on a schedule. Furthermore, personnel safety could be improved because some measurement points are hazardous to reach. Additionally, a permanent system would significantly reduce systematic errors in measurements.

Typical facilities monitor 200 or more points that are each measured for 10–20 s using a collimated sodium iodide (NaI) detector on the end of a pole. Of the positions monitored, the priority for continuous monitoring would be (1) positions that historically acquire holdup more readily, (2) positions that are difficult to reach, and (3) remaining positions.

Researchers at ORNL are developing an inexpensive distributed holdup monitor to alleviate the burden on facilities [3]. The final holdup monitors will be ruggedized to survive exposure to the elements and will work together to enable real-time, low-error measurements with automated reporting on unit health and alarm status.

1.2 SYSTEM DESCRIPTION

Each detector unit is independent and encased inside light-tight 3D-printed housing. The unit diagram, shown in Fig. 1, describes the battery-powered units used in this first field test. The unit is constructed of a scintillator, a silicon photomultiplier (SiPM), a printed circuit board with custom counting electronics, a battery, and a 3D printed tungsten grit collimator all housed in a 3D printed housing. There is a hub model with power and communications over Ethernet is currently under development.

The current version of the electronics and detector without the housing are shown in Fig. 2 with the assembled unit shown in Fig. 3. Each unit is collimated; the collimator is cast from epoxy and tungsten grit on-site at ORNL.

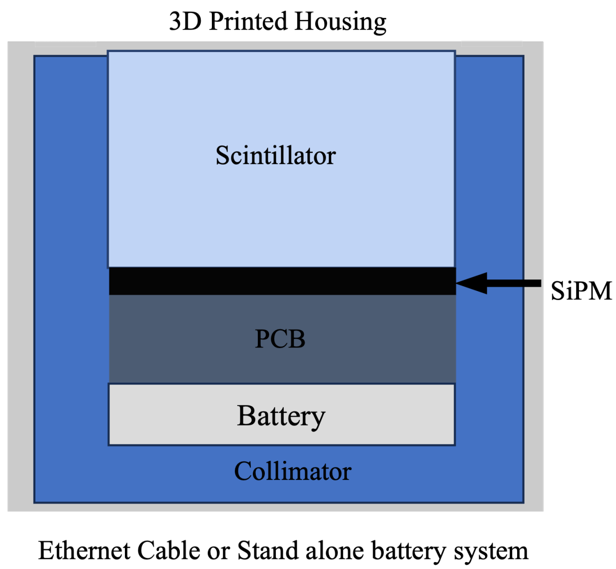


Figure 1. Rough diagram of a detector single unit showing a scintillator optically coupled to a silicon photomultiplier (SiPM). A printed circuit board contains the counting electronics and processing unit, data storage and battery.

Figure 2. Sodium iodide detector with integrated silicon photomultiplier, battery, printed circuit board, and system indicators. These components are necessary for a stand-alone detector. Note quarter for scale.

Figure 3. Prototype detection system in printed housing.

2. NFS COLLABORATION

Two prototype units were provided to Nuclear Fuel Services (NFS) on September 19, 2023, and retrieved on October 24, 2023. Both units contained NaI crystals packaged with SiPMs by Luxium Solutions and with data acquired by the electronics discussed in Section 1.2. The units were delivered to NFS with cinch straps for easy attachment.

2.1 UNIT QUALIFICATION PREDEPLOYMENT

To ensure unit functionality before deployment, both units underwent significant benchtop testing both with and without radioactive sources. One necessary test checks that the threshold is set to an appropriate level. A threshold that is too high would miss the desired sources entirely, a threshold that is too low would place the detector operating within the noise floor of SiPM, providing a noisy detector that could be incapable of measuring the desired signal above the noise. The threshold for this deployment was set to a minimum range of 100 keV. To determine this appropriate threshold, a range of radioactive sources were measured. First, the lowest energy source, ^{241}Am with primary γ-ray energy of 56 keV, was brought closer to and further away from each unit while the threshold value was set in software to verify detection. Then ^{241}Am, ^{133}Ba, ^{137}Cs, ^{166}Ho, and ^{152}Am, were measured at a fixed distance from each unit for consistency to provide a rough efficiency curve shown in Fig. 4. The unit with the smaller detector, the 1.5-in. NaI, was less efficient at

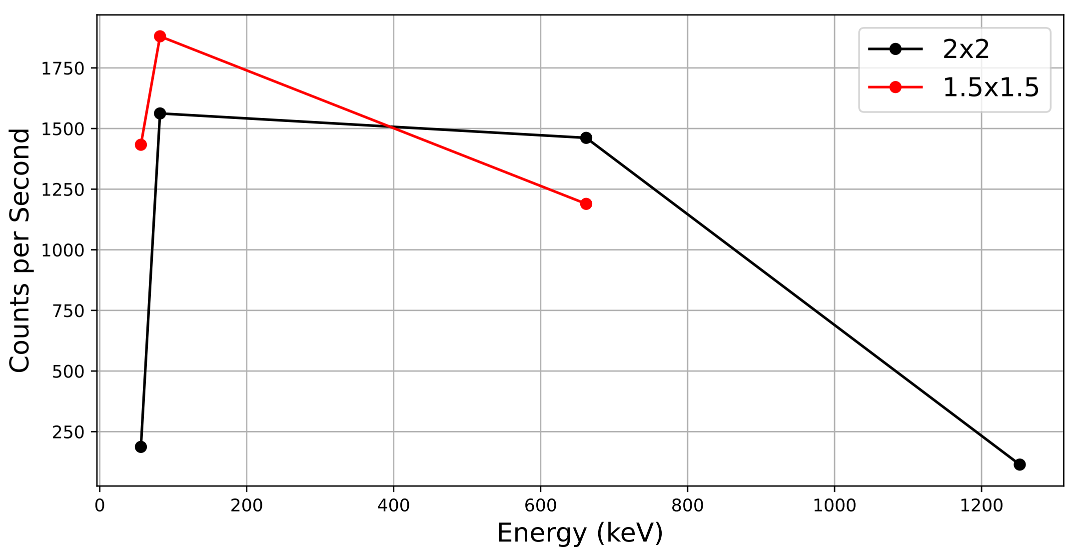


Figure 4. Counts per second versus energy for both units with sources placed at 3 cm from the detector.

higher energies than the other unit with the larger 2-in. NaI, as expected. The efficiency curve verifies that the desired γ-ray energy detection range is within the detector's maximum efficiency area.

The counting system was checked for unexpected statistical fluctuation by collecting several minutes of counts from several sources to induce moderate to high count rates in the detector. The counts were checked for Poisson statistics by comparing the empirical mean and variance, which should be equal for a Poisson process [4]. During testing some non-Poisson statistics were observed in the counts when compared with a commercial digital Multichannel Analyzer (MCA) and the same detector. For a first prototype without the additional signal processing of a digital MCA this was not unexpected. New electronics are being developed for the future custom SiPM detector and this test will be an essential feature of the qualification.

In addition to testing with radioactive sources, the counting electronics were tested with generated waveforms of known amplitude, frequency, and timing characteristics. These tests were designed to test the comparator and counting electronics without the commercial detector. We intend to automate and extended these to a range of operating conditions including different supply voltages and temperatures.

The comparator and digital counter were tested to support over 1 Mcps. Some incorrect counting was observed when using the low-power clocks for the counter integrated into the microcontroller, and the software was modified to use the high-power clock for now. The threshold values for the energies of interest were lower than expected and approached the limits of the comparator and data acquisition system. This issue will be investigated further as we develop the new design.

2.2 PROTOTYPE PLACEMENT

NFS personnel attached one unit to a HEPA filter and the second unit to a 4-in. fuel processing line. The units were approximately 4 ft apart during the count. Data was collected until the battery ran out of power, for both units this occurred after 19 days of collection.

3. SYSTEM PERFORMANCE

During the deployment, the units were programmed to run continuously and accumulate counts for periods of 5-s. After each 5-s counting period, a time stamp, the counts per second, temperature, humidity, and battery voltage were recorded to the onboard nonremovable storage. The result was a list-mode style dataset recording the device history throughout the 19 days of operation. Device lifetime could be extended by counting discontinuously, putting the device to “sleep" between 5-s counting periods. Onboard firmware already supports such functionality.

3.1 GROSS COUNTS ANALYSIS

The count rate versus date for both devices, showing the counting history of the devices from installation until battery depletion are shown in Fig. 5. The unit on the HEPA filter recorded in the 400–600 cps range,

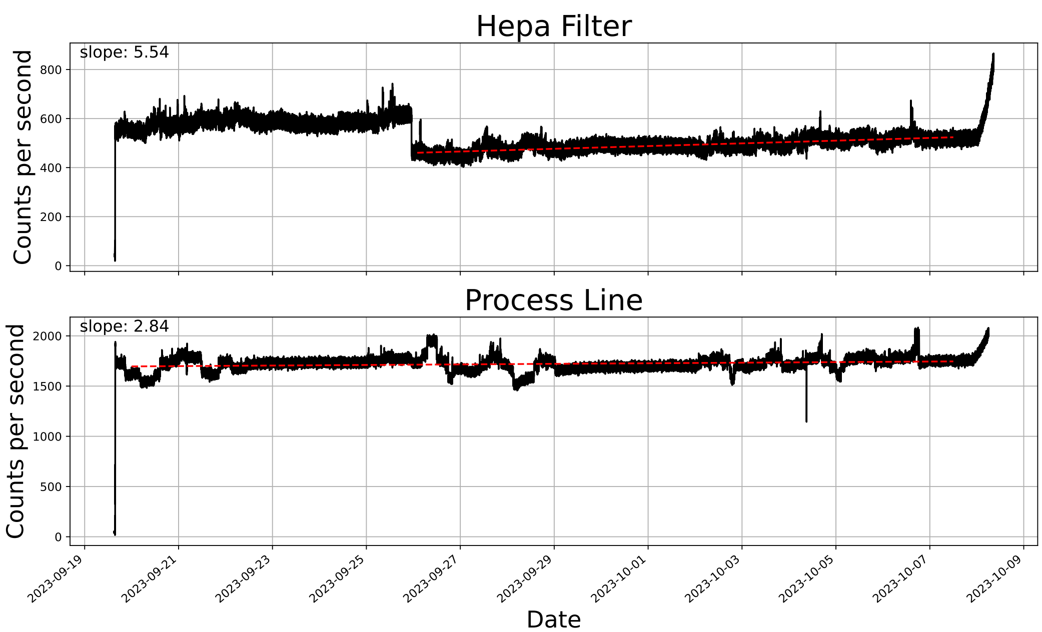


Figure 5. Counts per second per 5 s counting period versus time for both units. A trend line (red) has been fit to both, and the slope of the line is displayed in the top left.

and the unit on the fuel processing line recorded a much higher count rate at 1,500–2,000 cps. This behavior is expected because the fuel processing line will have more radioactive material flowing through it at any given time than the HEPA filter. However, the unit on the fuel processing line had the smaller crystal—the 1.5 × 1.5 in. cylinder of NaI—and therefore will have a slightly lower efficiency than the larger 2 × 2 in. crystal on the HEPA filter. An efficiency correction is easily achievable using the data obtained during the predeployment qualification procedure but was not deemed necessary for this report.

3.1.1 TRENDS

Both units indicate a positive trend in count rates, as shown by the slope of the fitted trend line in the top left of Fig. 5. The unit on the HEPA filter shows a stronger positive trend. This result is expected because the HEPA filter is designed to collect material, preventing escape out into the greater ductwork beyond.

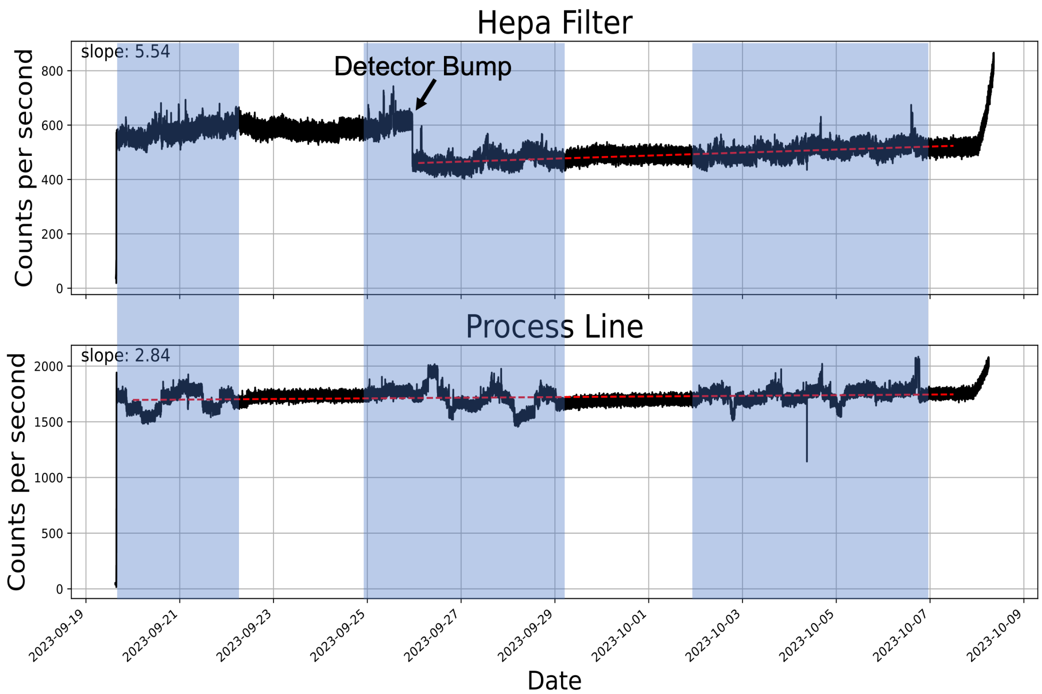


Figure 6. Counts per second versus time for both units. A trend line (red) has been fit to both, and the slope of the line is displayed in the top left. The periods that fuel was actively being processed are highlighted in blue and the time that we believe the detector on the HEPA filter was bumped is annotated.

3.1.2 COUNT VARIATIONS

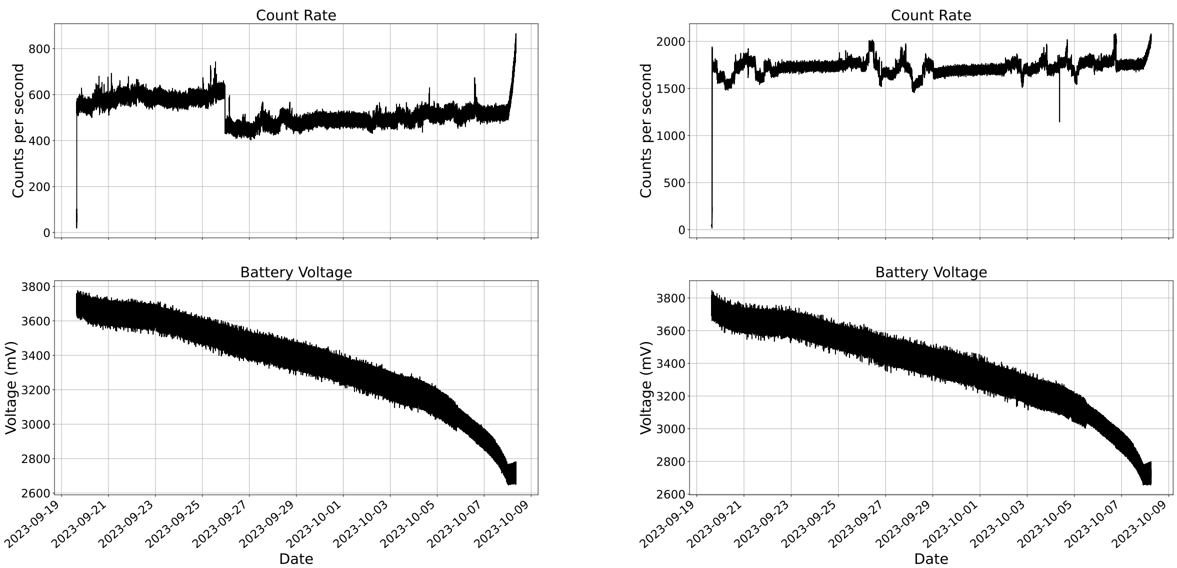
Although count rates generally followed a positive trend, fuel was only processed periodically throughout the measurement period. Three multiday stints of processing were observed in the count rates and confirmed by the facility. These periods are highlighted in blue in Fig. 6. The background outside of the facility is in the range of 12 cps; inside the facility it is much higher, making up most of the count rate with a relatively smaller proportion—on the order of 10% of the total count rate—because of active fuel processing.

The cause of the drop in counts in the HEPA filter plot shown in Fig. 5 on September 26 is unknown. The HEPA filter was not replaced during this time, as confirmed by the facility. Because a similar change was not observed in the fuel processing line and small changes in orientation to a collimated detector would produce this type of behavior, it is likely that the unit on the HEPA filter was bumped, resulting in the ~120 cps drop in count rate. Future units will contain a low-power accelerometer to detect these issues.

3.2 POWER ANALYSIS

The battery power and measured count rates versus time are shown in Fig. 7. The battery power is a typical lithium-ion discharge curve. The system includes significant voltage regulation and includes an internal voltage reference that is accurate over a range of environmental conditions. Therefore, until the battery approaches complete depletion, count rates should not be affected. Indeed, no effect was observed until the battery power hit critically low levels, in this case below 2.8 V.

The possible effects of voltage regulation or an inaccurate voltage reference on the count rate are related to the threshold voltage and other discrimination circuitry that determine whether an event has occurred. A loss in voltage regulation is expected when the battery voltage approaches the dropout voltage of the linear regulators used for the analog power supply. This effect is demonstrated in Fig. 8, where the battery voltage drops below the configured analog power supply voltage. The digital electronics continue to function at the reduced voltage, but the analog power supply is not correctly regulated and the generated threshold voltage is no longer at the desired set point. A major feature of the upcoming version of the electronics is a more accurate voltage reference. However, as a standard practice, data should be excluded once battery power has dropped below critical levels.



(a) HEPA filter **(b) Fuel processing line**

Figure 7. Count rates and battery voltage for both units versus date.

The analog supply and reference voltage require a complex trade-off between electronics' requirements, signal-to-noise ratio, and power consumption. Tests are being performed to evaluate whether some other direct current (DC) offset is somehow being introduced that affects the discrimination threshold. This issue might already be addressed in the design changes for the next revision of the electronics.

3.3 TEMPERATURE ANALYSIS

Temperature and count rates versus time are shown in Fig. 9. SiPMs, which are used in these detectors, are known to be very temperature-sensitive devices. Although count-rate changes caused by temperature fluctuations could be a concern, Luxium includes temperature compensation in all of their SiPM units, a feature that was enabled for this deployment. Furthermore, detectors were located indoors, and temperature fluctuations were small—on the order of 2°C. A comparison of the temperature and count rates versus time does not indicate any observable correlation between the two. As we move away from Luxium-packaged units for cost-effectiveness, future circuit designs will have required temperature compensation such that the units are deployable in outdoor locations.

To further examine any possible temperature effects, the count rates and temperatures for a single day were plotted, as shown in Fig. 10. The chosen date, October 1, 2023, was selected because no processing occurred that day, and therefore "real" changes to count rates, owing to facility operations, were not expected. The count rate appeared very uniform, and the temperature variations appeared to be entirely due to the HVAC

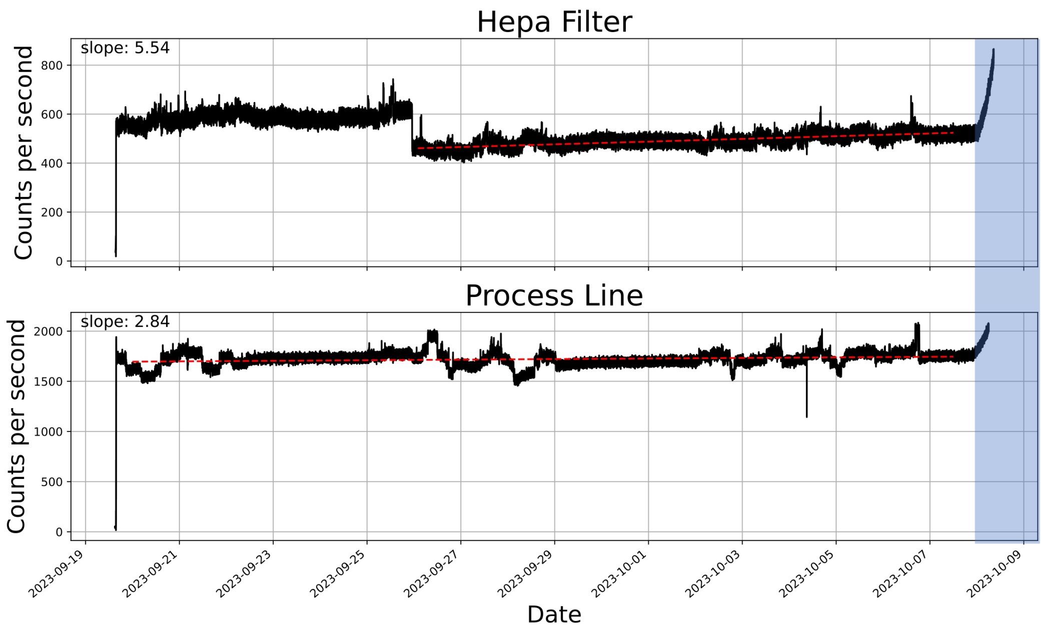
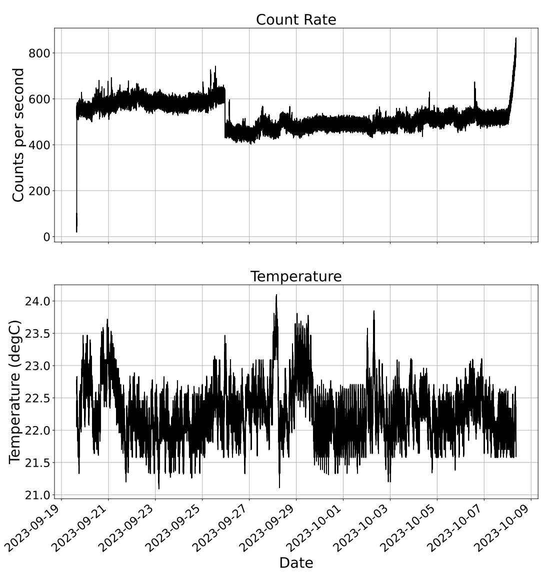
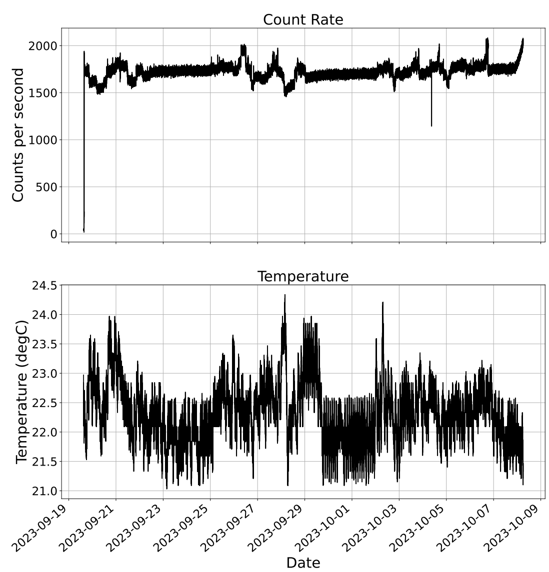


Figure 8. Counts per second versus time for both units. A trend line (red) has been fit to both, and the slope of the line is displayed in the top left. Blue highlights the region in which it is believed that battery voltage had a major effect on count rates.



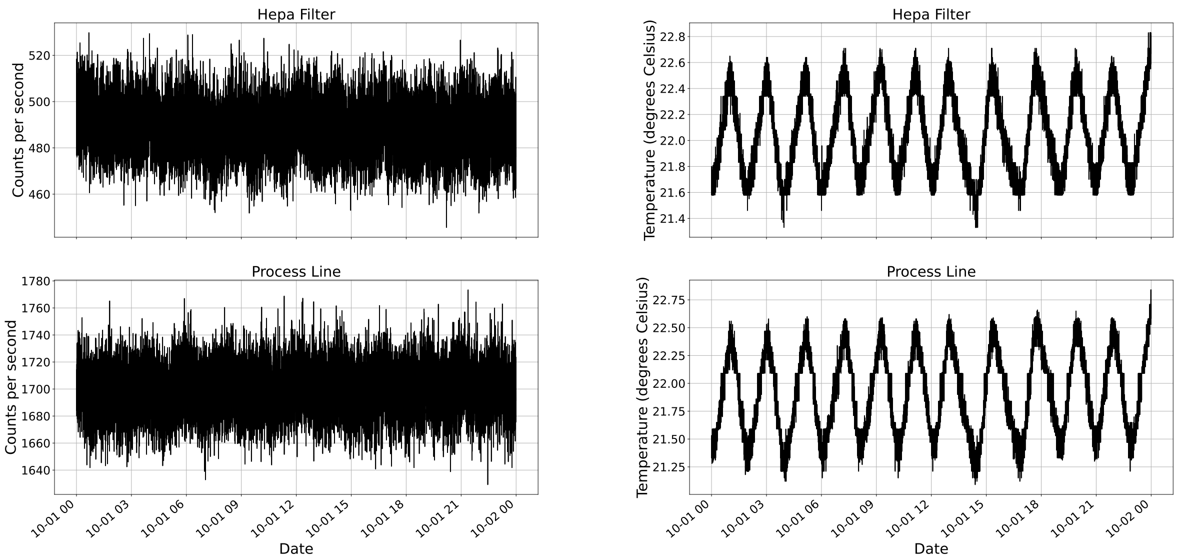
(a) HEPA filter



(b) Fuel processing line

Figure 9. Count rates and onboard temperature for both units versus date.

system at the facility. Although this is a null result, it is nevertheless an excellent example of the sensitivity of the acquisition to all environmental parameters.



(a) Count rate **(b) Temperature**

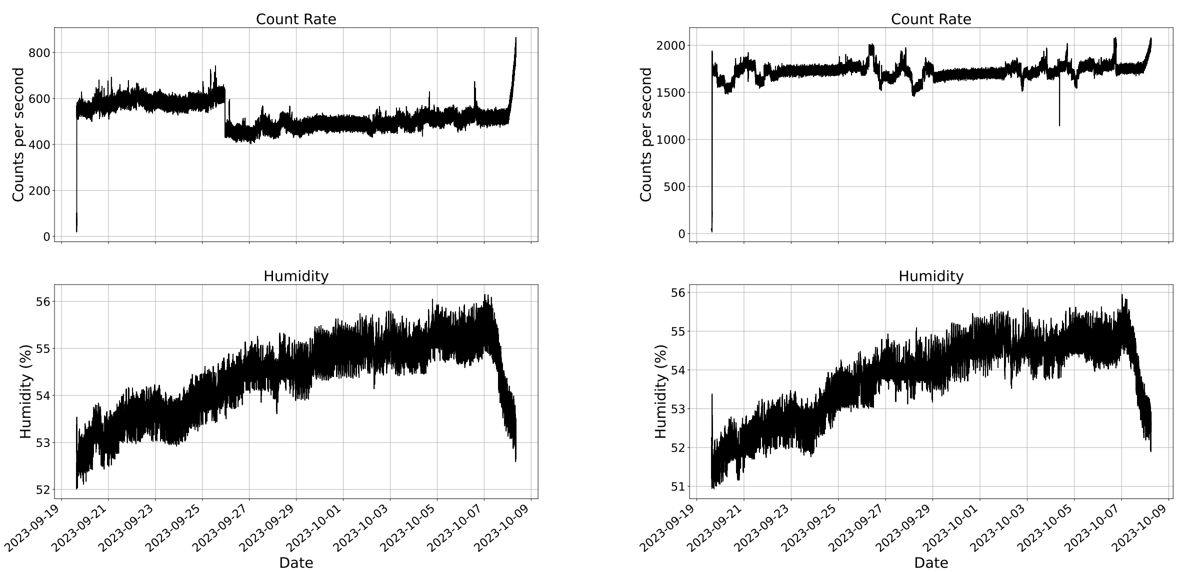
Figure 10. Count rates and onboard temperature for both units versus time for the date of October 1, 2023.

3.4 HUMIDITY ANALYSIS

The final variable, for completeness, is humidity, plotted versus time along with count rate in Fig. 11. In this case, humidity is not expected to affect the measured count rates, only serving as an indication that the electronics have not become inundated. Both units were mounted directly to the pipes to minimize space between the measurement location and the unit. Close placement reduces any interference from humidity in the air. Furthermore, measured humidity changes were small, on the order of 4% throughout the measurement period. The results confirm this supposition with no apparent correlation between count rates and humidity for these experimental conditions.

3.5 MEASUREMENT SUMMARY

Daily averages for each measurement from both units are shown in Fig. 12 and Fig. 13.



(a) HEPA filter **(b) Fuel processing line**

Figure 11. Count rates and onboard humidity for both units versus date.

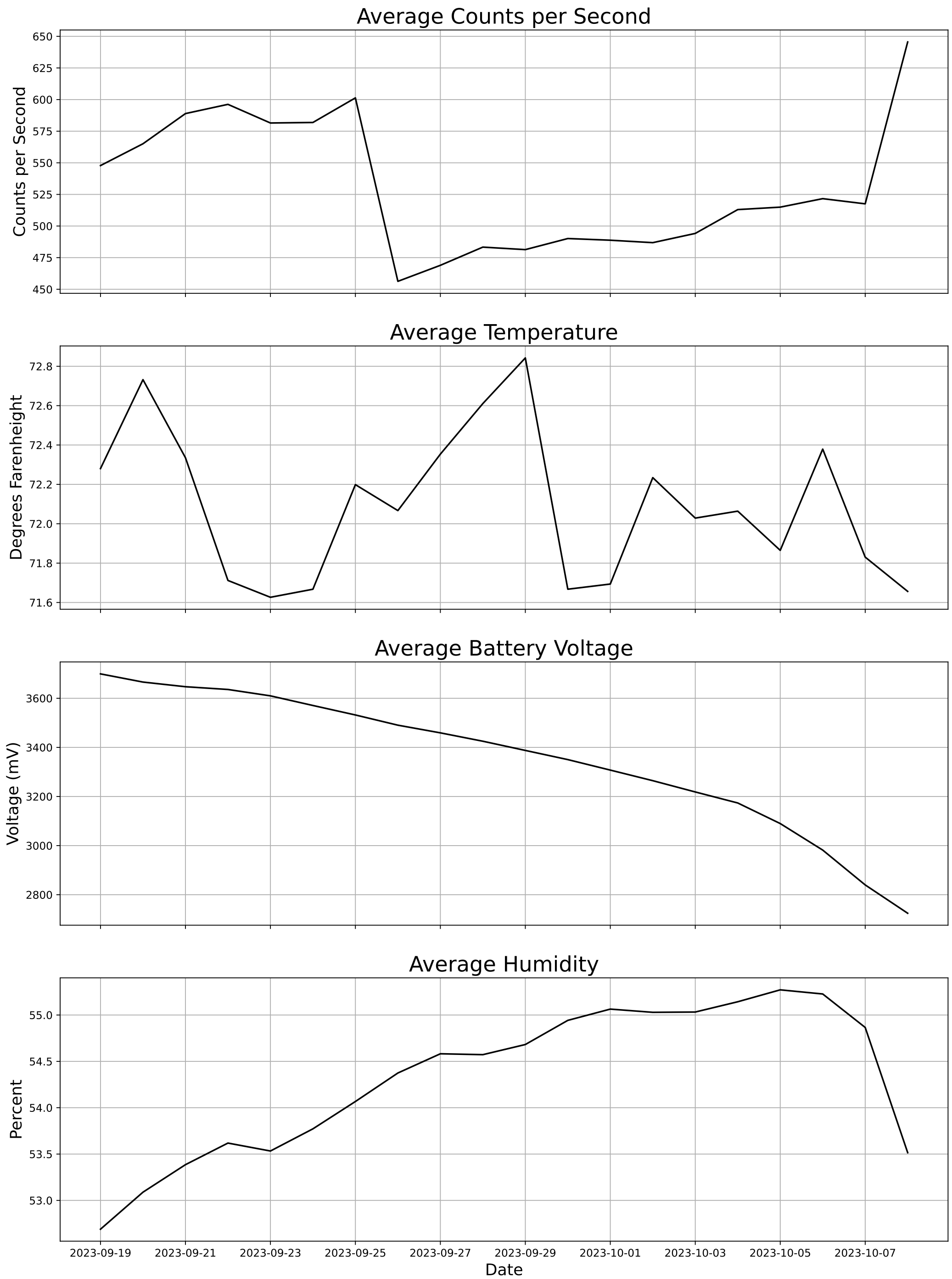


Figure 12. Daily averages for each measurement for the unit on the HEPA filter.

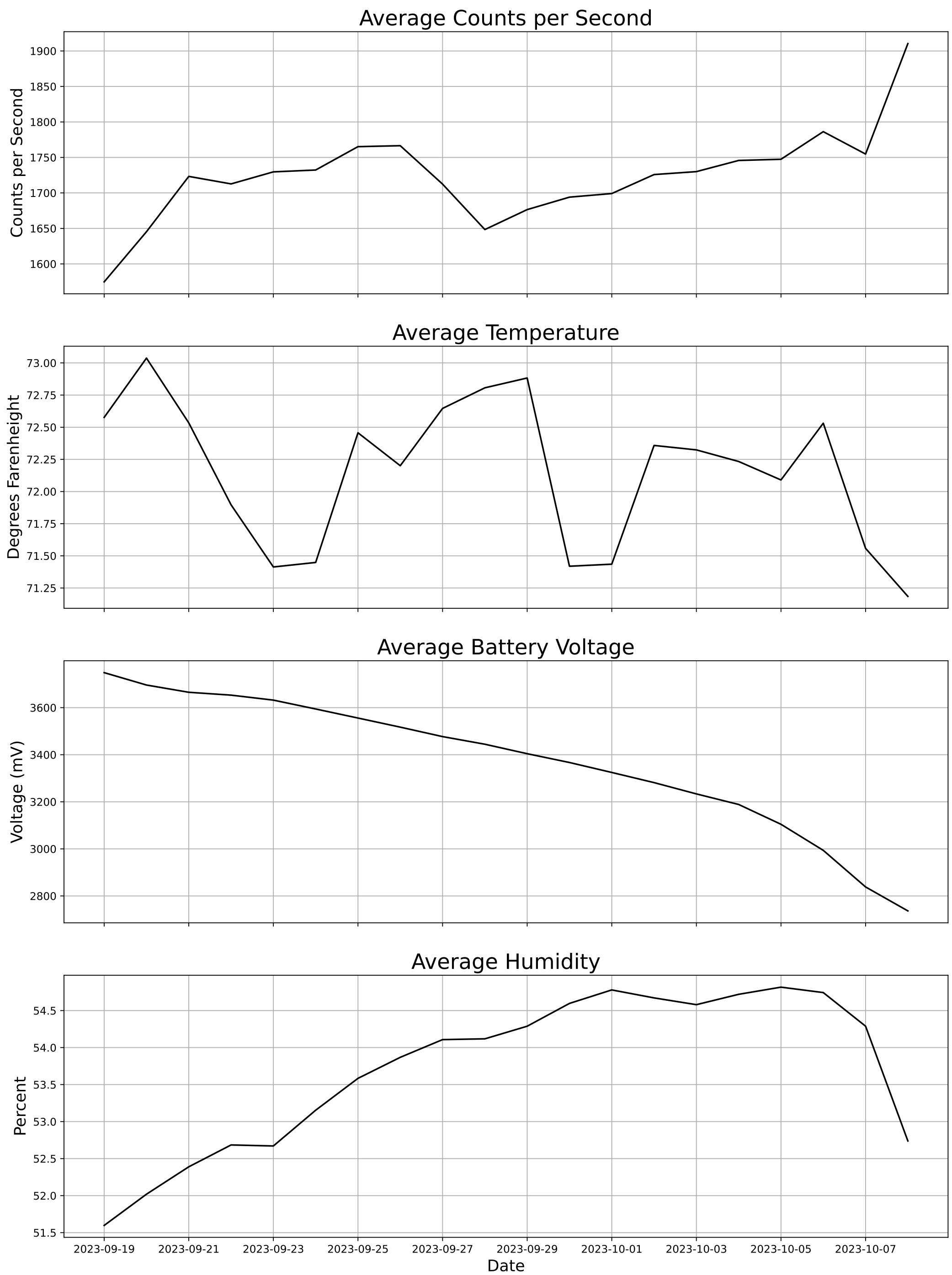


Figure 13. Daily averages for each measurement for the unit on the fuel processing line.

4. NEXT STEPS

These same systems will be deployed at Savanah River National Laboratory in future tests. Additional software support will be added to demonstrate the networking capabilities and collect data on a stand-alone single-board computer for multiple detectors simultaneously. This revision will continue to use USB for networking and power but will closely resemble the Power over Ethernet (PoE) design that is expected to be completed later this year. These data will be very useful for further calibrating detection-alarm algorithms. Additionally, work is ongoing to better optimize and demonstrate SiPM arrays with plastic scintillators, desirable for their cost-effectiveness. This milestone will be crucial in moving toward low-cost, effective systems.

5. VENDOR FEEDBACK

An NFS staff member participated in discussions to review the data for insights and feedback. He was very supportive of our approach, and the response was overwhelmingly positive. The vendor indicated two issues with their current method of holdup monitoring that he feels the ORNL monitors address. The first is that NFS currently uses a detector attached to a pole to reach some difficult measurement locations. This detector must be lifted high, posing a safety risk to those who are working below. The second major issue with the current holdup monitoring approach is variability in measured count rates owing to each worker's training and experience. The NFS staff member felt that the ORNL approach was an excellent solution to both issues: the compact, self-contained, and mountable design addresses the first, and the ability to leave the detectors collecting in place addresses the second. Furthermore, he appreciated the flexibility in the design in that the same detector could be used in different areas with only small modifications. He also liked the power efficiency of the detector units. In this case, data were collected for three weeks continuously, but he liked the fact that this time could be extended for the battery-powered units by conducting periodic collections. In terms of requests for future detectors, the staff member asked that the units be easy to open for inspections upon initial entry into the facility for security reasons. This factor is being considered for future models.

The NFS staff member indicated that he would be interested in further efforts for the power-over-Ethernet system. He could envision a handful of areas within his facility where a dedicated system that provides automated and consistent measurements would be very welcome. He mentioned that unit cost is important, but they would be willing to invest for consistency: a price per unit of approximately $1,000 would be well within a reasonable region for them.

The discussions about the results from the measurements indicated that knowing how much material is at the measurement location is crucial. The HEPA filters are replaced when they reach 50 g of holdup; this figure represents months of accumulation. NFS's current method uses computational models to set a threshold of detector counts above which an area must be cleaned; current procedures set this threshold at 30,000 cps. Although different detectors will count somewhat differently based on their internal efficiencies, no concerning holdup occurred during the ORNL measurement period. The staffer indicated that the observed holdup seemed reasonable, indicating good detector performance.

In summary, the response was highly positive, and the NFS staff member indicated that he sees a strong need in industry for these holdup monitors. He liked the design and asked for only small changes to accommodate safety inspections. He liked that the design is compact and self-contained, feeling that it is excellent for monitoring inaccessible areas. He also liked its measurement flexibility and power efficiency and finds the more consistent automated approach highly appealing. He indicated that he might like to employ the hub model within several areas in his facility. Finally and most importantly, he extended an invitation to host more prototype systems as they are developed under this program.

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