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Performance Evaluation of the Starfire nGen-350 DD Neutron Generator for Use with the Fast Neutron Coincidence Collar

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Nuclear Nonproliferation Division

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ABBREVIATIONS

FNCL	Fast Neutron Coincidence Collar
HDPE	high-density polyethylene
HHMR	handheld multiplicity shift register
IAEA	International Atomic Energy Agency
INCC	IAEA Neutron Coincidence Counting (software)
ORNL	Oak Ridge National Laboratory
UNCL	Uranium Neutron Coincidence Collar

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ABSTRACT

The Starfire Industries nGen-350 [1] DD neutron generator has been developed for use with the Fast Neutron Coincidence Collar (FNCL). The generator was adapted from the nGen-310 model generator by Starfire to accommodate an International Atomic Energy Agency (IAEA) request to incorporate a neutron yield stabilization mechanism. An nGen-350 generator was obtained by Oak Ridge National Laboratory (ORNL)for evaluation as a potential neutron interrogation source replacement for Am(Li) in the FNCL. This report provides a summary of the performance of the nGen-350.

1. INTRODUCTION

The Fast Neutron Coincidence Collar (FNCL) [2], [3], [4] is a liquid scintillation detector–based active neutron collar developed as a potential alternative to the traditional ^{3}He-based Uranium Neutron Coincidence Collar (UNCL). The FNCL, developed by the International Atomic Energy Agency (IAEA) in cooperation with CAEN Technologies and initial testing of the collar with Am(Li) neutron sources, has demonstrated potential performance gains in terms of measurement precision and reduced sensitivity to gadolinium poison rods. Replacement of the Am(Li) neutron sources by a neutron generator addresses the current unavailability of Am(Li) sources and can potentially provide improvement of the measurement precision as the fast liquid scintillator is not rate limited in the same way that the ^{3}He systems are. The overall project objectives examined the performance of the FNCL, using both isotopic Am(Li) neutron sources and steady-state DD neutron generator. However, this report focuses on the performance of the Starfire Industries nGen-350 neutron generator.

Ideally use of the neutron generator as replacement of the Am(Li) neutron interrogation sources would require no modifications to the FNCL software or operating procedures. That is, the neutron generator should serve as a “drop-in” replacement for the Am(Li) sources. The output from most commercial neutron generators is not stable and can vary several percent from run to run or within a single irradiation cycle. To address this limitation, the Starfire nGen-350, incorporates a feedback circuit to stabilize the neutron yield. This feature was added at the request of the IAEA for use with the FNCL.

The nGen-350, manufactured by Starfire Industries, is a DD neutron generator capable of emitting up to 1E7 n/s. The model employed in the Safeguards Extension Laboratory at ORNL is equipped with an internal neutron flux monitor that provides continuous feedback during use for neutron yield stabilization. It is currently being used to examine the viability of neutron generators as the interrogating neutron source for nondestructive assay of fresh fuel assemblies by a Fast Neutron Collar (the FNCL). The generator has been run collectively for more than 48 hours and spread across the equivalent of more than 400 hypothetical FNCL runs over the course of 2 years during this investigation. The device has proven to be highly reliable thus far. The only challenge faced with the generator has been a communication error with the operating software, likely caused by cable malfunctions unrelated to the generator itself.

The following sections present the results of the evaluation of the stability, predictability, reliability, and utility of the nGen-350. The nGen-350 neutron generator used in this evaluation is shown in Figure 1.

Figure 1. Photograph of the nGen-350 neutron generator at ORNL.

2. THE NGEN-350 NEUTRON GENERATOR

The nGen-350 was modified from the Starfire nGen-310-DD steady state DD neutron generator. The nGen-310 [5] is a light weight, sealed fusion neutron generator with a compact form factor with maximum yield of 1E7 n/s. Most other neutron generator tubes of similar yield place the neutron generation point (the accelerator target-line) several centimeters from the end of the tube. The Starfire design places the neutron generation point within 0.5 cm of the tube end, providing additional flexibility when integrating the tube into the measurement system. A photograph of the nGen-310 is shown in Figure 2. The nGen-310 generator tube is used as the core of the nGen-350 and is mounted within the nGen-350 cooling duct/generator housing.

Figure 2. Photograph of the nGen-310 neutron generator tube (without the required control electronics module) from the Starfire data sheet [5].

An important and distinguishing capability of the nGen-350 is the neutron yield stabilization provided by the continuous feedback monitor installed in the unit. The stabilization mechanism consists of 6 RDT Domino® solid-state tile detectors [6] arranged in an approximate "C" configuration about the generator tube and embedded in a 13 × 16 × 16 cm block of high-density polyethylene (HDPE) which is, in turn, surrounded by a layer of flex boron. The neutron detectors use a "micro-structured semiconductor neutron detector (MSND®) technology with ^{6}Li converter. [6]" A sketch of the detector assembly is shown in Figure 3, and an example of the Domino neutron detectors is shown in Figure 4. The count rate from these detectors is monitored, and the accelerator beam current and high voltage (HV) settings are adjusted to achieve a user-selected neutron emission rate. The detectors were calibrated at the Starfire factory. A count rate of 1 cps corresponds to 857 n/s yield.

A comparison of the nGen-350 generator with a traditional DD neutron generator (the ThermoFisher MP320 [7]) is provided in Table 1. Photographs of the two generators are shown in Figures 5 and 6.

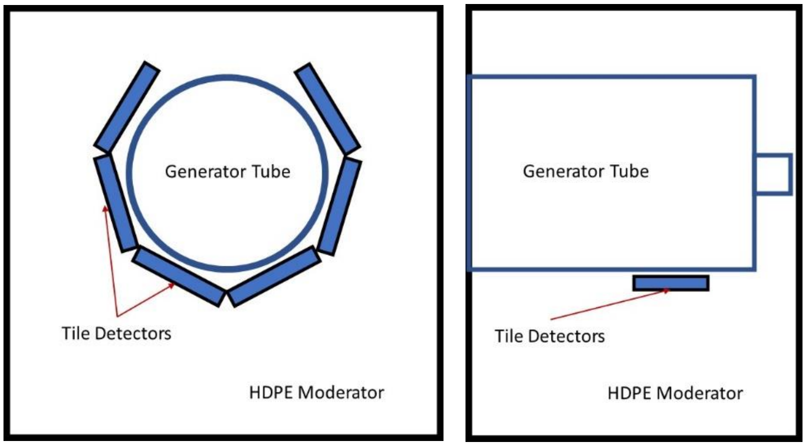

Figure 3. Sketches showing the arrangement of the tile detectors about the neutron generator.

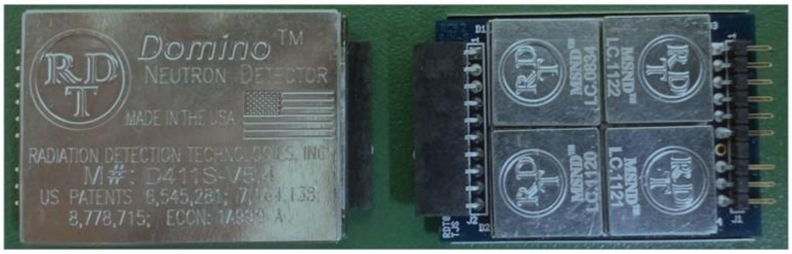

Figure 4. Photograph of the front and back of the Domino neutron detector (each module is approximately 0.50 × 2.72 × 3.82 cm) [6].

Table 1. DD Neutron Generator Vendor Stated Characteristics

Generator Make/Model	ThermoFisher Scientific MP320 [7]	Starfire nGen350 [1]
Type of generator:	DD	DD
Maximum emission rate:	2×10^6 n/s	~1×10^6 n/s
Neutron energy:	2.48 MeV	2.48 MeV
Output Stabilizer	NA	Active Feedback (with external detector)
Stability		< 0.1% variation after warmup
Steady state/pulsed:	Both	Steady State Only
Pulsed mode		
Frequency range:	250 Hz to 20 kHz	N/A
Duty cycle:	5%–100%, 5 μs minimum pulse width	N/A
Generator tube dimensions		
Diameter:	12.06 cm	9.0 cm
Length:	55.88 cm	50.0 cm
Target line:	13.97 cm	~1.5 cm
Weight	11.3 kg	11.45 kg

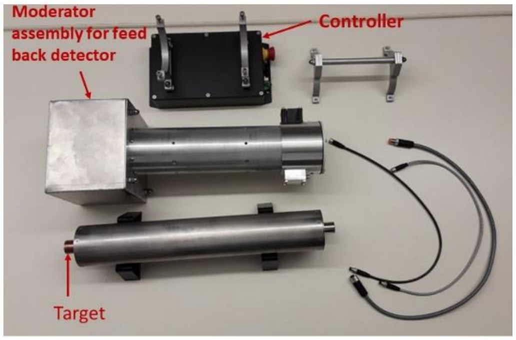

Figure 5. Photograph of the assembled nGen-350 steady-state DD neutron generator (*left*) and disassembled (*right*).

Figure 6. Photograph of the MP320 controller (*left*) and the detached MP320 DD neutron generator tube (*right*).

3. GENERATOR PERFORMANCE

3.1 GENERATOR YIELD

The nGen-350 feedback circuit was calibrated at the factory using a REM ball and should be considered only approximate. To examine the actual yield, the nGen-350 was placed inside a 200 L drum ^{252}Cf shuffler system. The ^{252}Cf shuffler provides a 4π neutron detection efficiency of 17.6% for ^{252}Cf neutrons located in the center of the assay cavity. The shuffler count rate as a function of the requested neutron yield is shown in Figure 7. Overlain on the shuffler measurements are the observed rates obtained 2 years later using a small ^{3}He tube embedded in HDPE located 5 cm from the side of the neutron generator detector block. The data from the two different counter configurations demonstrates that the nonlinearity is a function of the neutron generator, not the test measurements. From the shuffler measurement results, we also see that the actual neutron yield from the nGen-350 is only 9.6E5 n/s when the output is set for 2E6 n/s, or about half the expected value.

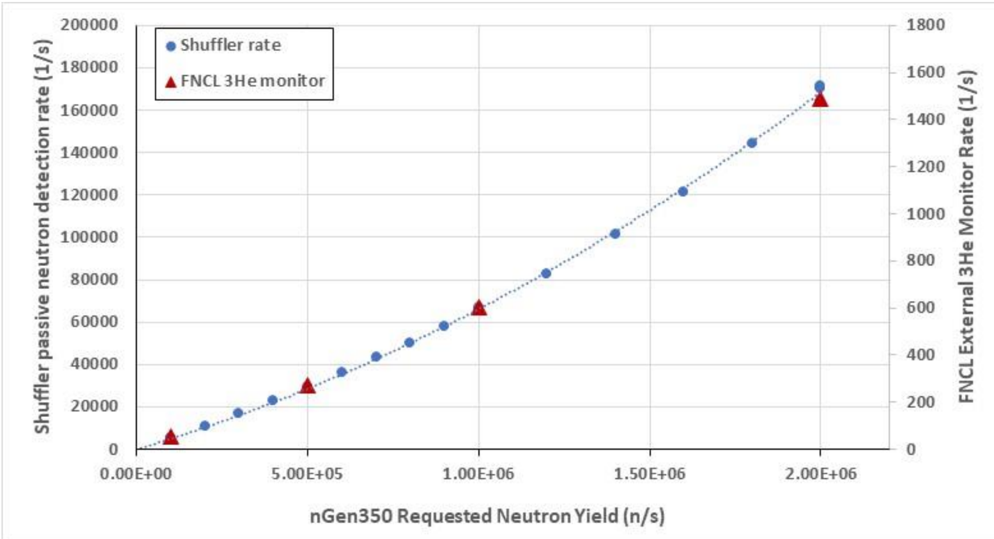

Figure 7. Plot of the observed passive neutron rate as a function of the neutron yield setpoint in the nGen-350 controller software.

This behavior is likely due to inaccurate or missing deadtime correction in the nGen-350 feedback circuit. As the count rate and deadtime increase, the feedback detector loses a greater fraction of the counts and so that it raises the yield at a greater rate to compensate. The stated deadtime of the Domino Tile detector is 150 µs. The documentation provided by Starfire with the nGen-350 indicates that yield as a function of detection rate, *R*, is

$$Yield\ (nps) = 857 \cdot R\ (cps).$$

Therefore, a setting of 2E6 n/s corresponds to a detection rate of 2,333 cps.

The shuffler measurement indicates that the actual yield for our nGen-350 is much lower than the requested value and that the actual yield is not linear as a function of the selected value. The data suggests that the deadtime for the collection of tile detectors is 197 µs and the correct equation for the yield, *Y*, is

$$Y = a \cdot R \cdot e^{b \cdot R},$$

where *a* = 258.7 and *b* = 1.97E-4 s.

The current Starfire software does not support the exponential deadtime correction. Additionally, the conversion factor (857) is not accessible from the Starfire GUI. Instead, an external command must be sent to the controller before each use. A plot of the ratio of the actual to requested yield is provided in Figure 8. Because the GUI limits the yield setting to a maximum value of 2E6, our generator has an effective maximum yield setting of 1E6 n/s. In its present form, to run at a yield of 2E6 n/s, a command would have to be sent with each use to change the conversion factor to a value of 411.

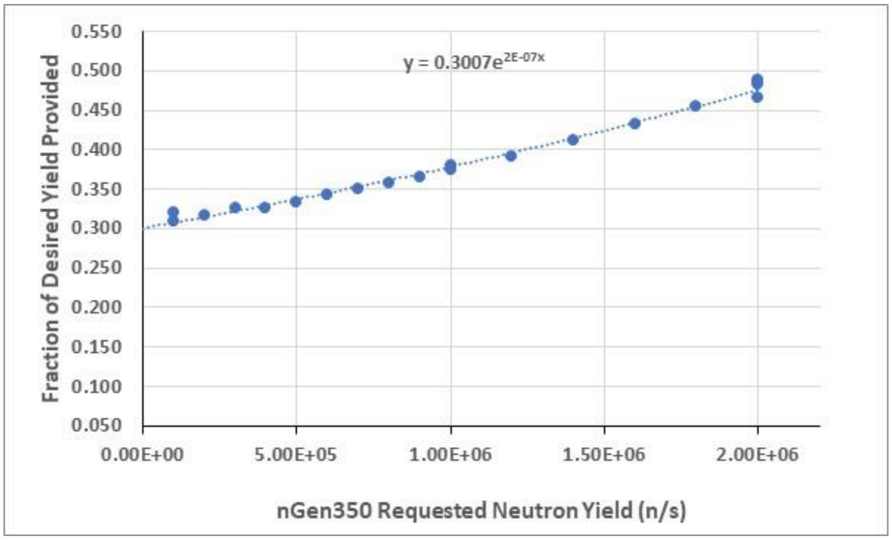

Figure 8. Plot of the ratio of actual yield to selected yield as a function of requested value.

3.2 GENERATOR STABILITY

The nGen-350 relies on the feedback detector to provide a stable neutron yield. The stabilization mechanism is intended not only to provide a stable neutron output but also to allow the desired yield to be selected by the operator. To investigate the stability of the system, a series of repeat empty chamber FNCL assays were performed. To avoid potential complications from drift in the FNCL detectors, the neutron emission rate was monitored using an external ^{3}He detector embedded in HDPE using a handheld multiplicity shift register (the HHMR) and the Los Alamos INCC [7] neutron counting software.

First, to illustrate the basic function of the stabilizer, a short measurement was performed with the stabilizer turned off. (The generator HV was set to 65 kV.) The measured count rates are shown in Figure 9 and illustrate the extreme variation in neutron yield as a function of time. This can be compared with the response from a stabilized run as shown in Figure 10. When using the stabilization routine (called the Auto function in the Starfire generator interface software), the desired neutron yield is selected and the software modifies the operating parameters, such as the HV setting, until the desired yield is achieved. The variation in count rate is reduced from more than 1,000 cps without stabilization to approximately 10 cps over the course of a 5 minute interrogation with the stabilizer in use.

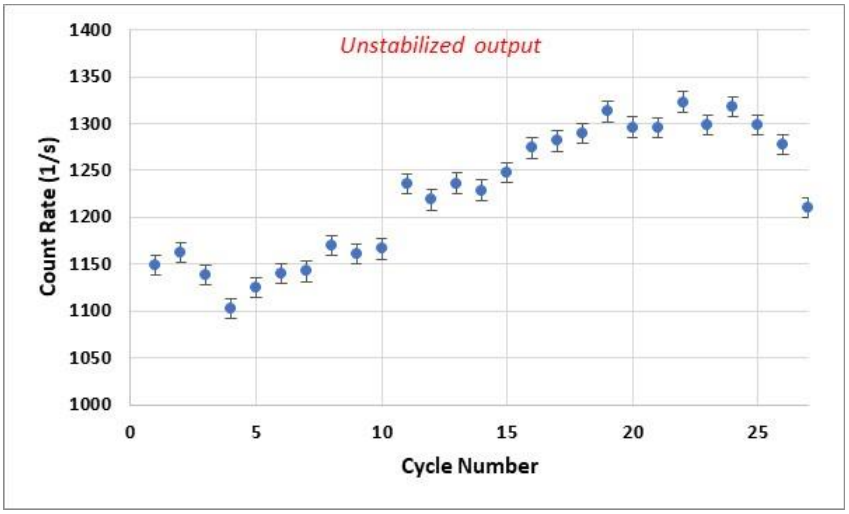

Figure 9. Plot of the neutron count rate from the nGen-350 in an external moderated ^{3}He tube for the FNCL assay cavity empty with using the stabilizer. The measurement was divided into 10 second counting intervals.

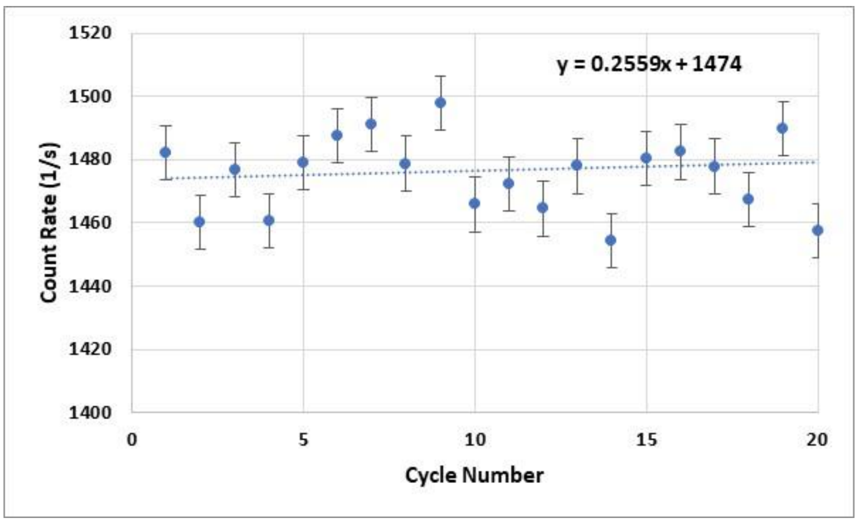

Figure 10. Plot of the neutron count rate from the nGen-350 in an external moderated ^{3}He tube for a single 400 second run with the FNCL assay cavity empty. The measurement was divided into twenty 20-second intervals.

Based on the results of many measurements, the internal detector response appears to have a temperature dependence. To investigate the stability of the neutron yield over the course of a typical inspection campaign, two sequences of nine assays each were performed. An assay sequence was assumed to involve a passive background measurement requiring approximately 10 minutes to execute. Following this, a neutron generator would be turned on, 2–3 minutes would be allowed for the generator output to stabilize, then a 400 second active interrogation count would be performed so that the generator would be producing neutrons for a total 600 seconds. Nine repeats were performed within a 3 hour interval. The sequence was then repeated later in the day following a 2 hour pause. The neutron yield from the generator was monitored using a small (20 cm active length, 2.54 cm diameter) 4 atm ^{3}He tube embedded in an HDPE moderator located approximately 5 cm from the side of the nGen-350 detector block.

The observed detection rates for the full sequences are plotted in Figure 11. The data show a statistically significant increase in the neutron yield with each run. It was noted that as the measurements progressed, the nGen-350 detector housing grew noticeably warm to the touch (room temperatures varied by less than 1°C during each 3 hour campaign). Since the feedback mechanism should adjust for any changes in the neutron generation mechanism, it is likely that the cause of the variation is a temperature effect on the neutron detection properties of the Domino Tile detectors. The average rate of increase in count rate was approximately 2% per hour. However, over the course of 3 hours of measurements, the neutron yield increased by 6%. Without implementation of a correction factor, this drift would introduce a corresponding 6% drift in the assay result. There were indications that the yield may stabilize when operated for longer periods than 3 hours, however, such a long warm up period would be impractical during an inspection.

A long, continuous measurement was also performed to confirm that the change in count rate was not a firmware or software issue. In this case 120 cycles of 30-second measurement time were performed with the generator operating continuously with selected yield of 2E6 n/s. The results are plotted in Figure 12 and shows the same time dependence with approximately 2% increase in yield per hour.

A potential solution would be to implement either a temperature compensation mechanism in the detector or implement an empirical temperature correction.

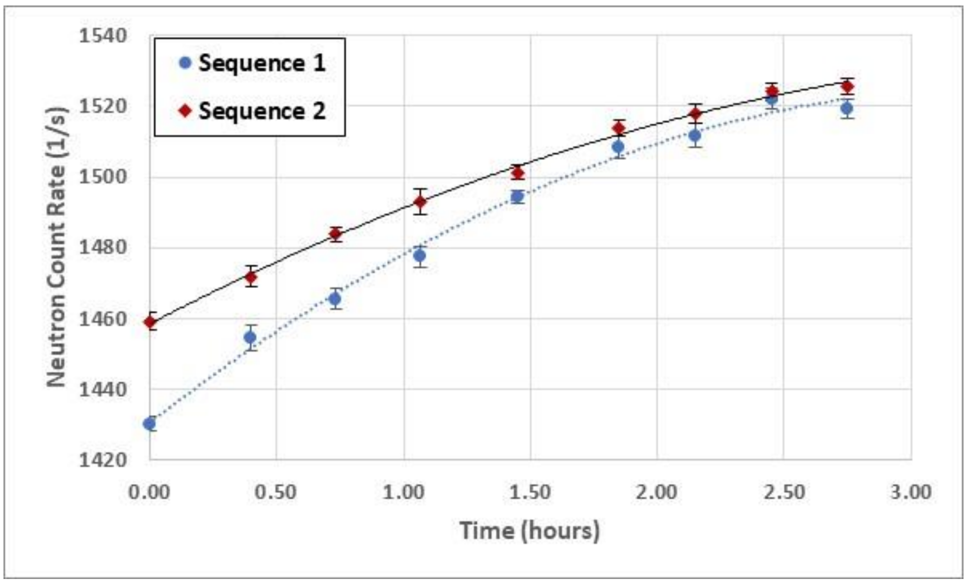

Figure 11. Plot of the neutron count rate in an external ^{3}He tube for a sequence of repeat measurements of the empty FNCL assay cavity. The irradiation time (neutron beam on) was approximately 7 minutes per measurement repeated at roughly 20 minute intervals.

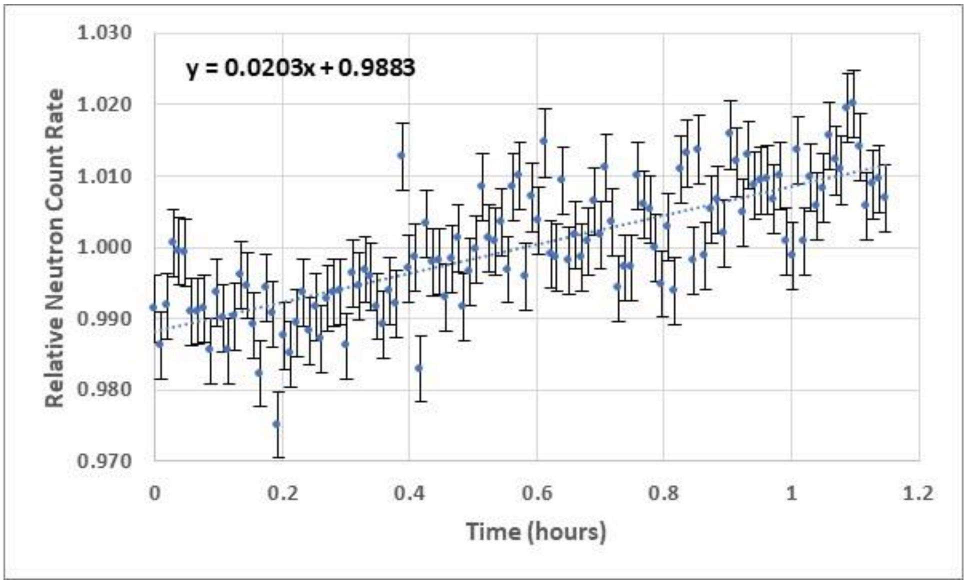

Figure 12. Plot of the neutron count rate from the nGen-350 in an external moderated ^{3}He tube for a 70-minute continuous run with the FNCL assay cavity empty. The measurement was divided into one hundred twenty 30 second intervals (a communications burden between each cycle extended the total count time).

To evaluate the benefit of the stabilization method, a similar test was performed using an existing MP320 DD neutron generator. (The MP320 generator used was approximately 8 years old with 205 hours of run time. The generator is run only intermittently and may sit unused for longer than 2 years between measurement campaigns. No effort was made to condition the generator prior to these measurements.) The measurements consisted of a 40 minute run followed by a 15 minute cooling off then a 70 minute run using the same ^{3}He tube and moderator discussed previously, although the geometry was more favorable for the MP320 measurement.

For comparison, a plot of the neutron output over a 2.25 hour measurement period is provided in

Figure 13 for the MP320 neutron generator. The approximate yield for these measurements was 1E6 n/s. As can be seen in the plot, this non-stabilized generator performs equally as well as the stabilized nGen-350, although the output tends to decrease with “on time” rather than increase. However, the plot shows the impact of a 15 minute beam-off interval on the neutron yield. In this case the yield is reduced at a rate of 0.5% per hour.

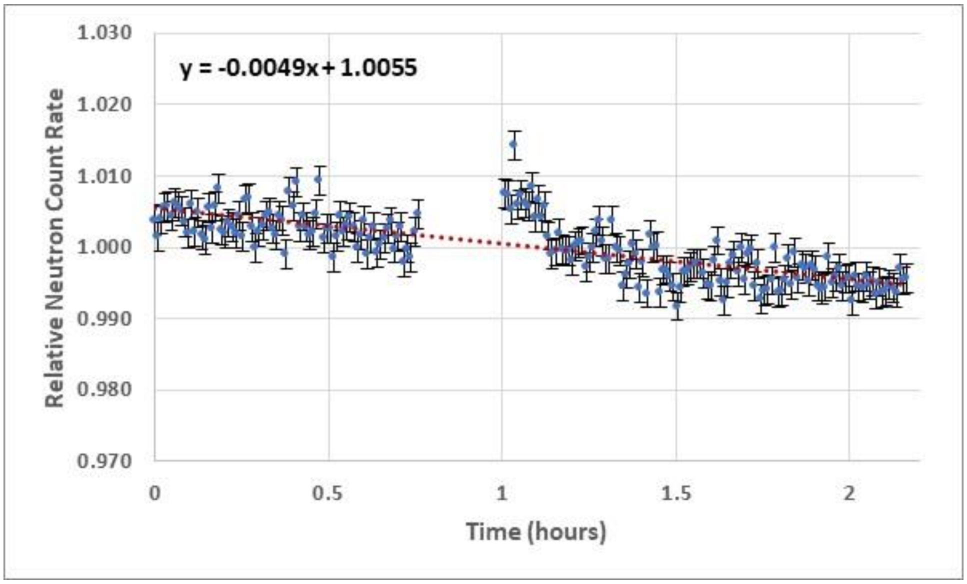

Figure 13. Plot of the neutron count rate from the MP320 generator in an external moderated ^{3}He tube for a single long run with the FNCL empty assay cavity. Measurement duration was 30 seconds.

These results suggest that the traditional generator provides better short-term stability than the stabilized nGen-350 detector. However, the yield in the traditional system can be expected to vary over the long term, requiring a normalization run using either a reference source or reference detector to determine the yield. Although the short-term stability of the nGen-350 appears to be poorer than the traditional generator, the feedback mechanism does allow the yield to be selected in a simple manner and ensures that the yield is within 2% or 3% of the desired value without the need for additional measurement reference measurements.

4. FNCL MEASUREMENTS

The stability of the generator yield was also examined using the FNCL to monitor the relative changes in emission rate. Assessing the performance of this system is crucial to understanding its reliability for use in the field. Measurements with the FNCL were taken in 5-minute intervals over the course of several months. The neutron singles rates in the liquid scintillators of the FNCL for empty chamber measurements can provide data to inform the performance of the neutron yield stabilization. Figure 15 shows the 1 second averaged singles rate as a function of measurement time for a single measurement (5 minutes) detected in the liquid scintillators of the FNCL. This plot was fit with a line to reveal any systematic drift in the average rate. The slope of the line shown in Figure 15 is $-0.14(9)\ s^{-2}$. Figure 16 shows the distribution of 1 second averaged singles rates over this 5-minute measurement. The spectrum is fit with a Gaussian distribution that gives an average rate value of about 18,400(500) 1/s. Both results are typical values for a variety of measurements made at different times with the same setup.

Given that the slope of the linear fit from Figure 15 indicates a smaller overall rate shift during a 5-minute measurement than the standard deviation of the distribution in Figure 16, we conclude that the continuous feedback monitor does provide some yield stabilization. However, the standard deviation of the fit from Figure 16 is roughly four times the value we would expect from statistical variation alone (543 vs. 134). To put this into context, we can observe the distribution of average rates (the constant value in the linear fit from Figure 15) from 16 runs with an empty chamber (note these 16 runs were performed on different days and would not necessarily show the same effects seen in Figure 11 above). The distribution here gives a value of 18,400(200). This means that the 1 second averaged rate detected in the FNCL for a single run has a greater variance than the distribution of average rates between runs. Finally, to further bolster the claim that there is no systematic neutron yield drift with the continuous feedback monitor, we looked at the distribution of the slopes from the linear fits of 16 runs with an empty chamber. The distribution is Gaussian and gives a value of 0.1(4). Since this value is statistically consistent with 0, we conclude that the continuous feedback monitoring eliminates any systematic drift of the neutron yield during a run. The distributions mentioned above for the 16 empty chamber runs are shown in Figure 16 and Figure 17, respectively.

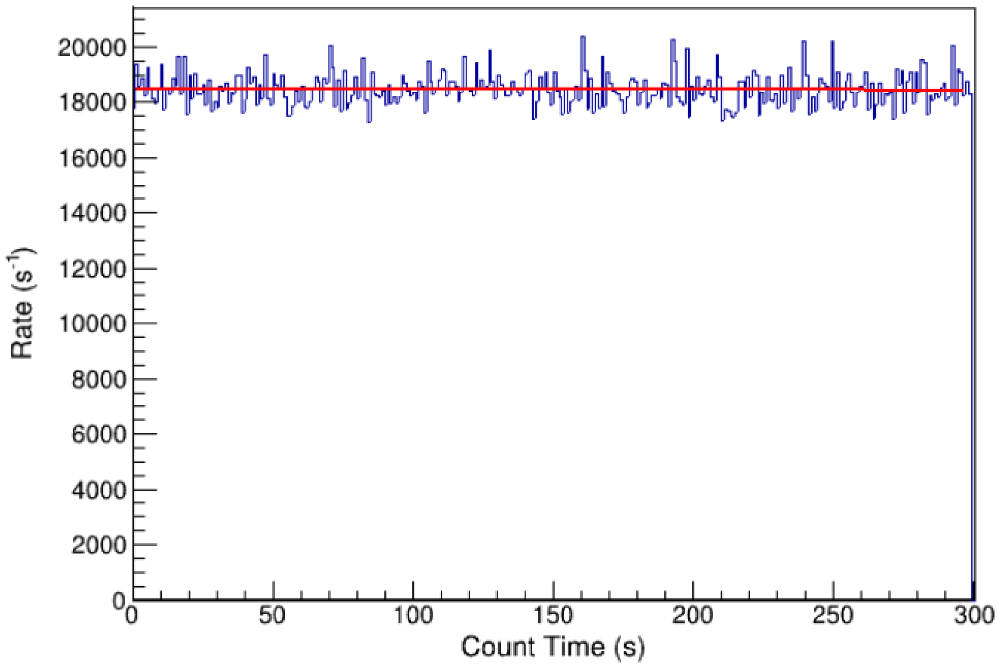

Figure 14. Singles rate in the FNCL over time. The slope of the linear fit is −0.14(9) indicating little change in the count rate over the 5 minute measurement.

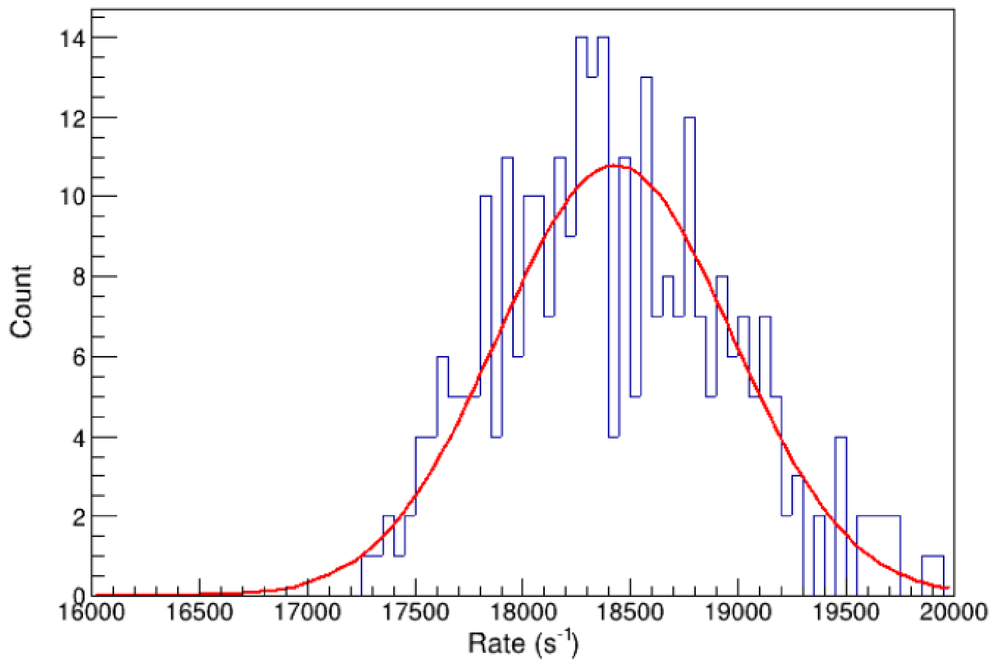

Figure 15. Distribution of singles rates (averaged over 1-second intervals) in the FNCL during a single measurement. The mean for this fit is 18,428(15) and the standard deviation is 543(23).

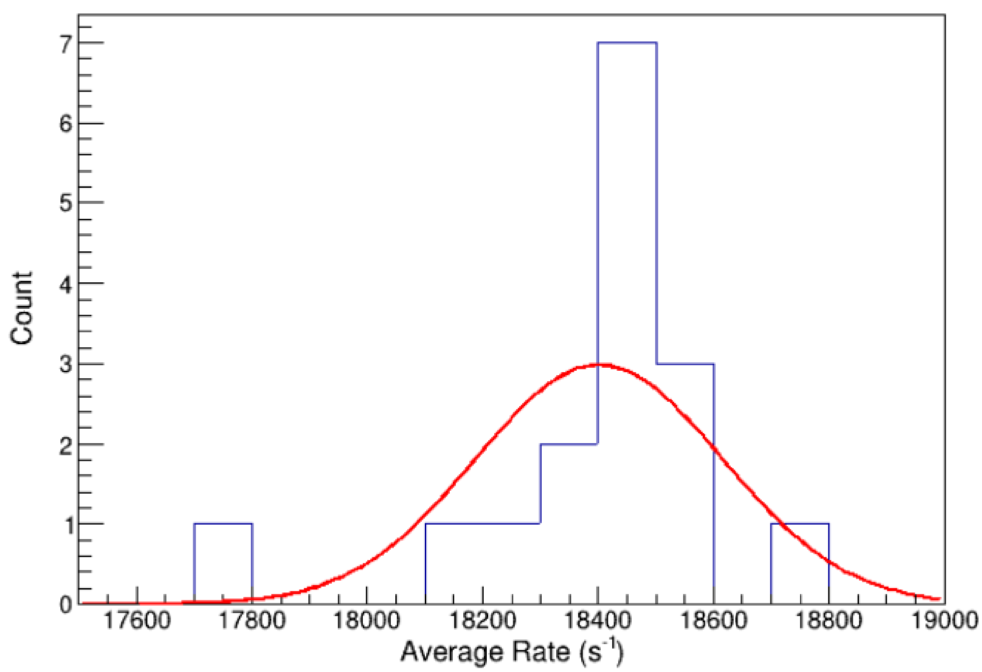

Figure 16. Distribution of average neutron singles rates in the FNCL from 16 runs with an empty chamber.

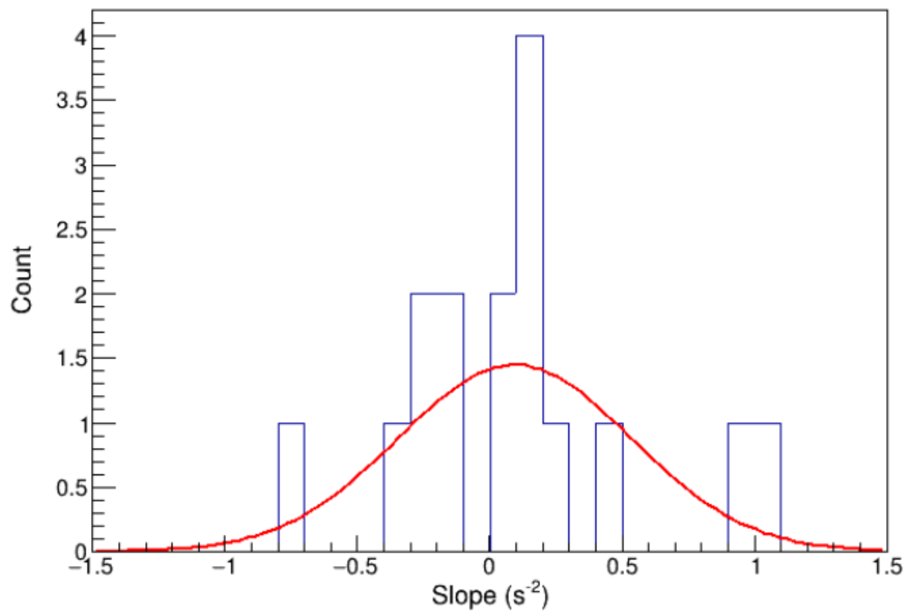

Figure 17. Distribution of slopes for linear fit to the rate of 16 runs with an empty chamber. The distribution having such overlap with 0 implies that the feedback monitoring system eliminates much of the neutron yield drift.

Finally, the FNCL rates obtained in parallel with the measurement sequences used to create Figure 11 were analyzed. The plots in Figure 18 show the same general trend and magnitudes of drift as seen with the ^{3}He detector. However, the response of sequence 2 is more linear than observed for the ^{3}He data. Additionally, the rates from the two sets of data converge at opposite ends of the curve (i.e., the FNCL rates for the two sequences agree at time = 0, whereas for the ^{3}He data they converge at the 2.5 hour mark). This effect has not yet been explained.

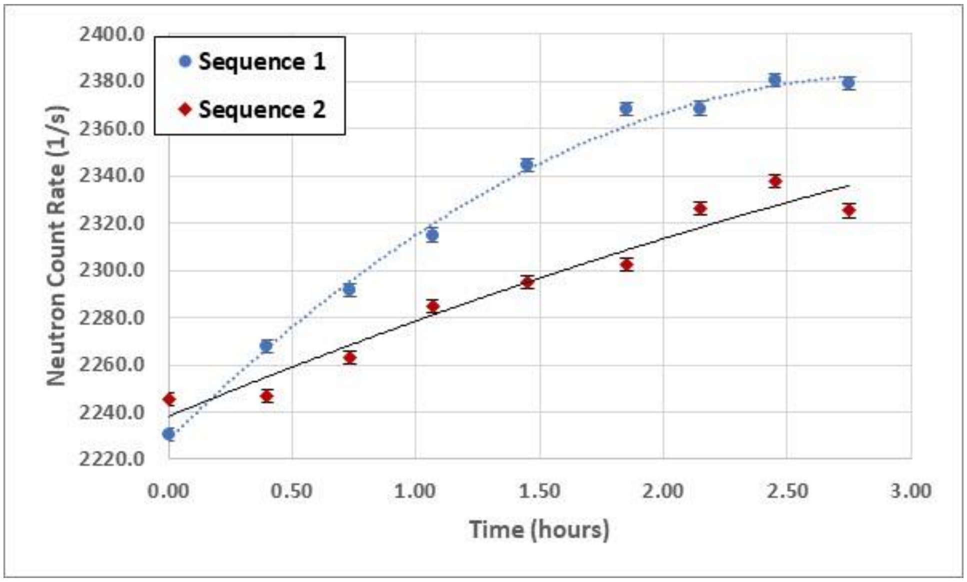

Figure 18. Plot of the FNCL nonpileup event rates for a sequence of repeat measurements of the empty FNCL assay cavity. The irradiation time (neutron beam on) was approximately 7 minutes per measurement repeated at roughly 20 minute intervals.

5. RELIABILITY

During testing the generator has operated (produced neutrons) for approximately 48 hours. The 48 hours run time is equivalent to more than 350 fuel assembly measurements. During this time, no failures directly attributed to the generator have been observed; availability has been nearly 100%. Failures noted include:

- Communication Failure: We have noted a handful (<5) of communications errors that can be attributed to the host PC and communications cable.

- Mechanical: One minor mechanical issue was also noted: he screws holding the controller to the frame worked loose from inside the controller housing. The loss of tension on the screws resulted in the cap nuts holding the frame to work free and the generator tube separating from the controller (Figure 19).

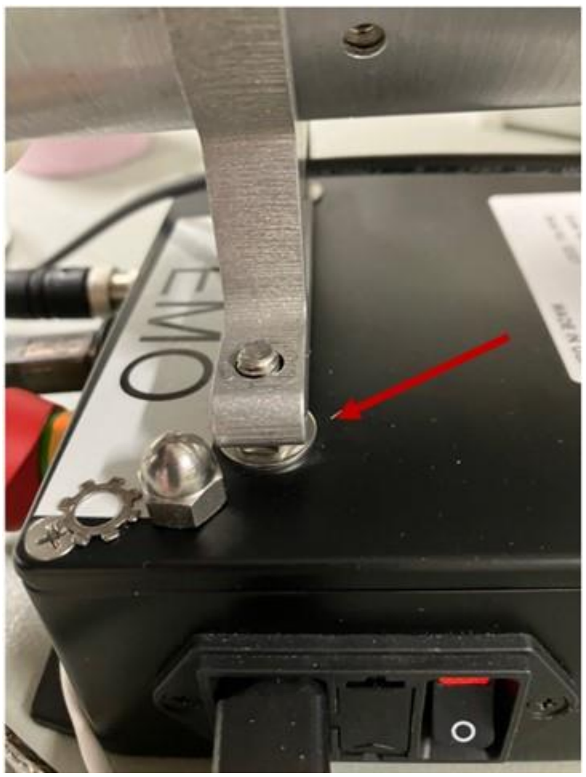

Figure 19. Photograph showing one of the loose screws. The problem is in the contact with the controller casing. The lower contact loosens first, causing the upper cap nut to loosen and fall off.

6. SUITABILITY OF THE GENERATOR FOR USE WITH THE FNCL

The nGen-350 DD neutron generator has been reliable, simple to setup and has been relatively straightforward to integrate the generator with the FNCL. However, we conclude that without modification the Starfire nGen-350 is not suitable for the intended FNCL application. This is due to the significant systematic drift of the neutron yield with use. The results of the testing performed suggest biases of 6% or more can be expected if no correction for the instability is made. Without modification, use of the nGen-350 will require implementation of an external flux monitor to allow normalization of the variation in yield.

We suggest the following potential solutions to the instability/drift of the neutron yield:

- Replacement of the Domino Tile Detectors
  Within the bounds of the existing feedback detector housing, one or two short ^{3}He proportional tubes could provide equivalent detection efficiency without the temperature or deadtime effects observed during this testing. This would provide improved stability of the neutron yield and accuracy of the neutron output relative to the desired values.

- Improved Cooling System
  As mentioned, the feedback detector assembly appears to warm with operation of the generator. This may be the root cause of the observed neutron yield instability. Modification of the cooling fan and ducting could reduce heating of the feedback detectors and potentially eliminate or reduce the yield instability.

We also make the following observations and suggestions:

- Yield Calibration
  The yield calibration parameter is not readily accessible from the controller software. Since the factory calibration of the generator output would seem be significantly biased, it would be beneficial to make this parameter available from the interface. Additionally, the feedback detector count rate shows significant deadtime losses resulting in a very nonlinear relationship between the selected yield value and the actual yield. A deadtime correction should be added to the calibration. The deadtime parameter should also be accessible from the software interface.

- Computer Operating System
  It would be convenient if the FNCL and the nGen-350 could be operated from a single computer. However, the FNCL operates on a Debian 9, a GNU/Linux-based operating platform while the Starfire software requires a Windows operating system. Operating the nGen controller software from the FNCL computer will require installation of .NET on the FNCL computer. This may be problematic because Debian 9 reached end of life in June 2022 (Microsoft does not support end of life products).

- Placement of the Feedback Detectors
  Placement of the feedback (Domino Tile) detectors at the front face of the generator opens the potential for interference from both the fuel and FNCL detector assemblies. That neutron emitted in the assay cavity could be detected by the feedback detectors, causing the system to produce fewer neutrons. Alternately the presence of moderator or reflector materials could raise the neutron detection efficiency again, causing the generator to produce fewer neutrons. Relocation of the feedback detectors should be examined through testing or simulations.

- Form Factor
  One of the better features of the nGen generator series is the compact form factor and location of the neutron generation point (target line). It is unfortunate that the feedback detector assembly (essentially a shoebox of HDPE) eliminates this benefit. Alternate methods for stabilization should be investigated to regain that benefit.

- Stability
  The short-term stability of the non-stabilized MP320 neutron generator outperforms the stabilized nGen-350. The design of the traditional neutron generators may offer insight into improved stability of the nGen-350.
  Without the Auto mode (use of the feedback mechanism), the nGen-350 yield is highly variable. We

have not determined whether this is due to limitations of the nGen control software or if is it inherent in the nGen concept. Performing safeguards or accountability measurements with the nGen-350 without using the stabilizer would be impractical.

7. CONCLUSION

The nGen-350 is an easy-to-use, easy-to-set-up neutron generator with adequate neutron emission rates to perform active neutron interrogation measurements in safeguards applications. Software features, such as the Auto mode, are innovative and commendable, though they need some improvement. The inherent instability or drift of the neutron yield of the Starfire nGen-350 makes it unsuitable for quantitative assay at this time without modification to the generator or the addition of an external flux monitor to correct for the drift. However, the observed shortcomings of the unit are addressable, and the potential solutions should be presented to the vendor.

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