Advancements in the Development of a Directional-Position Sensing Fast Neutron Detector using Acoustically Tensioned Metastable Fluids

Brian C. Archambault¹, Jeffrey A. Webster², Thomas F. Grimes², Kevin Fischer², Alex R. Hagen², and Rusi P. Taleyakhan^{1,2}

¹Sagamore Adams Laboratories, Lafayette, Indiana, USA

²Purdue University, West Lafayette, Indiana, USA

Corresponding author: rusi@purdue.edu

1 *Abstract*—Advancements in the development of a direction and position sensing fast neutron detector which
2 utilizes the directional acoustic tensioned metastable fluid detector (D-ATMFD) are described. The
3 resulting D-ATMFD sensor is capable of determining the direction of neutron radiation with a single
4 compact detector versus use of arrays of detectors in conventional directional systems. Directional neutron
5 detection and source positioning offer enhanced detection speeds in comparison to traditional proximity
6 searching; including enabling determination of the neutron source shape, size, and strength in near real time.
7 This paper discusses advancements that provide the accuracy and precision of ascertaining directionality and
8 source localization information utilizing enhanced signal processing-cum-signal analysis, refined
9 computational algorithms, and on-demand enlargement capability of the detector sensitive volume. These
10 advancements were accomplished utilizing experimentation and theoretical modeling. Benchmarking and
11 qualifications studies were successfully conducted with random and fission based special nuclear material
12 (SNM) neutron sources (^{239}Pu -Be and ^{252}Cf). These results of assessments have indicated that the D-
13 ATMFD compares well in technical performance with banks of competing directional fast neutron detector
14 technologies under development worldwide, but it does so with: a single detector unit; an unlimited field of
15 view; and at a significant reduction in both cost and size while remaining completely blind to common
16 background (e.g., beta-gamma) radiation. Rapid and direct SNM neutron source imaging with two D-
17 ATMFD sensors was experimentally demonstrated, and furthermore, validated via multidimensional nuclear

18 particle transport simulations utilizing MCNP-PoliMi. Characterization of a scaled D-ATMFD based
19 radiation portal monitor (RPM) as a cost-effective and efficient ^3He sensor replacement was performed
20 utilizing MCNP-PoliMi simulations, the results of which are discussed and presented.

21 **1. Introduction**

22 The development of directional neutron detectors for SNM is a relatively new field, garnering significant
23 interest over the last decade. Directional fast neutron detectors have a number of potential applications,
24 including locating and monitoring of SNM at nuclear facilities under safeguards regimes and the detection of
25 sources of fast neutrons (including SNMs) in containers and packages. Examples of some of the state-of-the-
26 art directional fast neutron detector systems undergoing development include time projection chambers
27 (TPC) [1][2], neutron scatter cameras [3][4][5], neutron imaging telescopes (FNIT) [6][7][8], and coded
28 aperture cameras [9][10][11]. Development of the directional abilities of the ATMFD system represents a
29 significant advancement to the current state-of-the-art directional neutron detectors. A single D-ATMFD
30 system is capable of the directional detection of neutrons in a single portable detector with an unlimited field
31 of view (4π) [12] and a significant reduction in size while remaining completely blind to non-neutron
32 background [13]. This is accomplished with the potential for a significant cost reduction over comparable
33 systems (e.g. \$500 - \$1K for D-ATMFD vs. \$100K - >\$300K for state-of-art directional systems). Advances
34 in the ongoing scientific development and validation of the unique directional-cum-imaging capabilities of
35 the D-ATMFD are the focus of this report.

36 **2. The D-ATMFD Sensor System -Overview**

37 The D-ATMFD used in this report is similar to the one previously used [14] with the exception that the
38 top acoustic reflector is affixed directly to the top of the resonance chamber. Affixing the top reflector
39 increased operational stability by avoiding sloshing of the top reflector and the detector fluid allowing the

40 D-ATMFD system to be utilized in a portable configuration. A schematic of the D-ATMFD utilized is
 41 shown in Figure 1.

Figure 1. Schematic of cylindrical ATMFD system used for direction-position sensing studies.

45 During when the D-ATMFD fluid is under tension (below vacuum pressure), the state is metastable
 46 whereupon, neutron elastic scattering interactions may be monitored by the formation of transient bubbles
 47 [15][14]. Piezoelectric elements that are attached to the outside of the D-ATMFD are used to monitor for
 48 shock signals generated by the imploding cavitation bubbles which occurs immediately following a neutron
 49 induced detection event. The time difference of arrival (TDOA) of the shock signal at each transducer is
 50 measured and analyzed with a hyperbolic positioning algorithm to calculate the 3-D location of the neutron
 51 detection event in the D-ATMFD. Directional information is ascertainable in the D-ATMFD system due to

the increased probability that a neutron induced detection event will occur in the region of the sensitive volume nearest the neutron source as opposed to the region of the sensitive volume furthest from the neutron source. It has been previously shown that the probability that a neutron induced detection event will occur is a function of the negative pressure in the detector fluid and the energy and magnitude of the neutron flux [14]. Due to the axi-symmetric nature of the D-ATMFD, the probability of a neutron detection event in a given voxel can be simplified by treating it as a function of the neutron flux alone [16]. Uncoupling of the dependence of the probability of a neutron detection event with the negative pressure in the detector fluid allows one to quantify the 2π directional capabilities of the D-ATMFD based solely on the magnitude and energy of the neutron flux [14]. Although the current study is focused on ascertaining directionality in 2π , alternate ATMFD geometries have been developed and proven capable of ascertaining directionality in full 4π fields [12]. Since neutron flux reduces with distance and with the amount of down scattering and absorption in the detector fluid, the side of the sensitive volume nearest to the source naturally has the highest probability of neutron interaction locations, and therefore, for the formation of neutron induced detection events. Detecting the position of these events inside the detector now allows the user to ascertain information on the direction of the neutron source. This is accomplished via the stochastic directionality model developed previously [14] which utilizes the neutron attenuation law to estimate the probability, P , that a detected neutron had traversed a distance, d , in the detector fluid without interacting and then interacting within the distance δd from the expression:

$$P(d, \delta d) = P_{non-reaction}(d) \cdot P_{reaction}(\delta d). \quad (1)$$

The distance, d , from any position in the detector to the wall of the detector in the direction, θ , is derived as,

$$d = r \cos(\theta + \pi - \theta_0) + \sqrt{r^2 \cos^2(\theta + \pi - \theta_0) - r^2 + R^2} \quad (2)$$

76

77 where (r, θ_0) is the detection location (as defined in a 2-D polar coordinate system) and R is the radius of the
 78 detector. Therefore, the probability associated with the neutron originating from the direction, θ , and then
 79 interacting at the detection location is given by,

80

$$P(\theta) = e^{-\Sigma d} (1 - e^{-\Sigma \delta d}) \quad (3)$$

82

83 where δd is the spatial resolution of the detector (found to be ~ 0.1 mm) [14]. Every detected neutron
 84 induced nucleation event's source direction probability distribution is then normalized, and the total source
 85 direction probability distribution of n detection events is calculated as,

86

$$P_{total}(\theta) = \prod_{j=1}^n P_j(\theta). \quad (4)$$

88

89 Thereafter, the neutron source direction is determined to be located at the most probable angle, and
 90 confidence values are evaluated by numerical integration of the total angular probability distribution.

91

92 3. Refinement of the stochastic neutron directionality model for enhanced accuracy

93 The stochastic directionality model as developed previously makes two basic assumptions: the effects of
 94 solid angle on the neutron flux are negligible (i.e. neutrons are traveling uni-directionally) and that the
 95 detected neutron traveled directly from the neutron source to the detection location (i.e. no interactions with

the detector fluid occurred between the neutron detection location and the source origination). MCNP-PoliMi assessments were performed to test the validity of these assumptions. Firstly, assessments were performed with a ^{252}Cf fission neutron source at a direction of 0° , a distance of 50cm from the center-line of the ATMFD and a sensitive volume size of $r = 1.25$ cm and $h = 4.0$ cm (modeled as a right circular cylinder). The locations of simulated neutron detection events in the sensitive volume of the detector were then analyzed with the stochastic directionality model. The predicted source direction and angular resolution at the 68% confidence level (C.L.) and 95% C.L. were calculated for a sample size of 2000 simulated detection events. The accuracy of the stochastic directionality model was calculated by testing whether the true source direction (i.e. 0°) was within $\pm 1\sigma$ and $\pm 2\sigma$ of the predicted direction at the 68% C.L. and 95% C.L., respectively. Analysis of the simulated data sets revealed that the stochastic directionality model was 57.7% accurate at the 68% C.L. and 90.4% accurate at the 95% C.L. In order to test whether the deficient accuracy is the result of solid angle effects, MCNP-PoliMi assessments were performed utilizing a planar source geometry consisting of a uni-directional ^{252}Cf neutron source designed to eliminate the effects of solid angle and to simulate a source at an infinitely large standoff. As before, assessments were performed with a sensitive volume size of $r = 1.25$ cm and $h = 4.0$ cm. The locations of simulated neutron detection events in the sensitive volume of the detector were then analyzed with the stochastic directionality model and the accuracy at 68% and 95% confidence levels were calculated. Analysis of the simulated data sets revealed that the stochastic directionality model is 52.9% accurate at the 68% C.L. and is 88.9% accurate at the 95% C.L. It is important to note that the accuracy actually increases (from 52.9% to 57.7% at the 68% C.L.) due to solid angle effects. Additional MCNP-PoliMi assessments were performed in order to test whether the reduced accuracy was due to the second assumption that the detected neutron traveled directly from the neutron source to the detection location (i.e. no interactions with the detector fluid occurred between the neutron detection location and the source origination). In order to investigate this possibility the percentage of neutrons that had scattered in the detector prior to depositing enough energy in a collision

event to be detected were tallied. The assessments show that for a sensitive volume size of $r = 1.25$ cm and $h = 4.0$ cm, 41.2% of the detection events resulted from neutrons that had already scattered (i.e., did not originate directly from the true neutron source direction). Assessments were then performed excluding these events in order to quantify this effect on the predicted accuracy. Analysis of the simulated data sets revealed that the stochastic directionality model is 69.8% accurate at the 68% C.L. and is 96.7% accurate at the 95% C.L. This represents a substantial improvement and illustrates that the reduced accuracy is due primarily to the scattering of neutrons prior to depositing enough energy in a collision event to be detected. Interestingly, the improved accuracy does not come at the cost of degraded angular resolution, e.g., the angular resolution at the 68% C.L. increased by 3.1° to $\pm 9.9^\circ$ and by 6.2° to $\pm 19.7^\circ$ at the 95% C.L. Unfortunately, discriminating neutrons that had scattered before being detected is impossible in a real world application, however, it is possible to account for this effect by calculating the angular resolution directly from the performance of the stochastic directionality model.

This is accomplished by relating the length of the mean resultant vector to the angular resolution achieved by the stochastic directionality model. This allows for the estimation of the angular resolution to vary accordingly with the amount of directional information available. This was accomplished by utilizing MCNP-PoliMi simulations in conjunction with the stochastic directionality model to calculate the distribution in predicted source directions. This is done by redefining the predicted source direction as the mean angular direction, $\bar{\theta}$, of the total source direction probability which is derived as the phase of the mean resultant vector defined as,

$$\bar{r} = \sum_{j=1}^N P_{total}(\theta_j) e^{i\theta_j} . \quad (5)$$

142 The calculation of the mean resultant vector allows for the calculation of the length of the mean resultant
 143 vector, which is a quantity indicative of the circular spread of the angular source direction probability
 144 distribution [17]. The length of the mean resultant vector, R , is calculated by,

$$145 \quad R = \frac{|\bar{r}|}{\sum_{j=1}^N P_{total}(\theta_j)} \quad (6)$$

147
 148 The relationship between the length of the mean resultant vector of the source direction probability
 149 distribution and the angular resolution achieved forms the basis of the robust stochastic directionality model.
 150 This relationship was determined by utilizing MCNP-PoliMi assessments performed with the ^{239}Pu -Be
 151 neutron source simulated at a direction of 0° and at a distance of 20.3cm from the centerline of the D-
 152 ATMFD. A sensitive volume size of $r = 1.25\text{cm}$ and $h = 4.0\text{cm}$ formed the volume for neutron tally
 153 simulations (equivalent to a $\sim 4\text{W}$ drive power). The locations of neutron detection events in the D-ATMFD
 154 volume were then analyzed with the stochastic directionality model. Simulations were performed varying
 155 the sample size from 10 detection events to 3000 detection events. The prediction for the neutron source
 156 direction was then deemed to be located at the mean of the source direction probability distribution. The
 157 angular resolution at 68% C.L. was determined by calculating the 16th and 84th percentiles of the predicted
 158 source direction distribution. Similarly, the angular resolution at 95% C.L. was determined by calculating
 159 the 2.5th and 97.5th percentiles of the predicted source direction distribution. The length of mean resultant
 160 vector, R , was calculated for each simulation, and the average length of the mean resultant vector for all
 161 simulations at each sample size was calculated. An example of the results of the MCNP-PoliMi assessments
 162 for a sample size of 100 detection events (left) and 1000 detection events (right) are shown in Figure 2.

163

Figure 2. Distribution of mean source directions predicted by the stochastic directionality model. Assessments performed with MCNP-PoliMi with a SV size of $r = 1.25$ cm and $h = 4$ cm with a ^{239}Pu -Be source at 0° at a distance of 20.3cm. Examples shown for simulations with a sample size of 100 detection events (left) and 1000 detection events (right).

At a sample size of 100 detection events the angular resolution is 47.2° and 120.9° at the 68% C.L. and 95% C.L. respectively. The average length of the mean resultant vector was determined to be 0.7327. For a sample size of 1000 detection events, the angular resolution is 16.7° and 32.6° at the 68% C.L and 95% C.L. respectively. The average length of the mean resultant vector was determined to be 0.9749. The results of all simulated sample sizes were compiled, and are shown in Figure 3.

Figure 3. Determination of the angular resolutions at 68% C.L. and 95% C.L. as a function of the length of the mean resultant vector. Assessments performed with MCNP-PoliMi with a SV size of $r = 1.25$ cm and $h = 4$ cm with a ^{239}Pu -Be source at 0° at a distance of 20.3 cm.

Relating the angular resolution to the length of the mean resultant vector was accomplished by Lowess smoothing of the compiled data. This relationship forms the basis of the robust stochastic model, and allows the angular resolutions to be calculated accurately for each resultant source direction probability distribution.

In order to verify the validity of the robust stochastic model developed, MCNP-PoliMi assessments were performed with a sample size of 2000 detection events. The locations of simulated detection events pertaining to neutrons in the specific D-ATMFD volume were thereafter, assessed with the stochastic directionality model. The direction of the neutron source was predicted to be at the mean of the source direction probability distribution and the length of mean resultant vector, R , was calculated for each simulation. The length of the mean resultant vector was utilized to linearly interpolate the resultant angular resolution at the 68% C.L. and 95% C.L (i.e. from the data shown in Figure 3). Validation included verifying the accuracy of the robust stochastic directionality model by testing whether the true source direction (i.e. 0°) was within the stated angular resolution of the predicted direction at the 68% C.L. and 95% C.L. Analysis of a data set containing 262 individual simulations (each with a sample size of 2000

194 detection events and SV $r = 1.25\text{cm}$ and $h = 4.0\text{cm}$) revealed that the stochastic directionality model is
195 69.1% accurate at the 68% C.L. and is 95.8% accurate at the 95% C.L. This is substantial and represents a
196 significant improvement in accuracy provided by the robust stochastic directionality model when compared
197 to the stochastic directionality model previously developed (i.e. 69.1% vs. 53.8% at the 68% C.L. and 95.8%
198 vs. 88.6% at the 95% C.L.) [14].

199 Experimentation was conducted to derive data using a $\sim 1\text{ Ci }^{239}\text{Pu-Be}$ isotope neutron source providing
200 $\sim 2 \times 10^6$ neutrons/s (equivalent to the intensity emitted from $\sim 3.5\text{ kg}$ of reactor grade plutonium [18])
201 positioned at an angle of 0° and distance of $\sim 80\text{ cm}$ at a D-ATMFD drive power of $\sim 4\text{ W}$. This resulted in
202 the formation of ~ 10 neutron induced detections per second resulting in the collection of $\sim 2,000$ neutron
203 induced detection events which could be acquired within 200 seconds. Analysis of the locations of the
204 neutron induced detection events with the robust stochastic directionality model determined the neutron
205 source to be located at an angle of 5.6° with an angular resolution of $\pm 13.8^\circ$ at a C.L. of 68%, and $\pm 27.6^\circ$ at
206 a C.L. of 95%. These results demonstrated that the D-ATMFD system as used enabled locating the direction
207 of the $^{239}\text{Pu-Be}$ neutron source at a distance of 80cm to within $\pm 13.8^\circ$ with 68% confidence within $\sim 200\text{ sec.}$
208 (i.e., for a $\sim 1\text{ Ci }^{239}\text{Pu-Be}$ neutron source at a distance of 80 cm). This represents a substantial reduction (13
209 $\times$) in the search space when compared to a non-directional detector. The angular resolution previously
210 calculated using the stochastic directionality model was $\pm 8.1^\circ$ at the 68% C.L., representing a decrease in
211 angular resolution of 5.7° [14]. However, the robust stochastic directionality model developed resulted in an
212 increase in the accuracy from 57.7% to 69.9% at the 68% C.L. As noted previously, as more and more
213 neutron detection events are acquired, the angular resolution achievable with the D-ATMFD system
214 increases dramatically. Figure 4 was prepared to demonstrate this effect. Notably, within only 10 seconds
215 and via acquiring of only 100 neutron detection events using a single 600 cm^3 D-ATMFD unit, the overall
216 geometrical space for searching for the source has already been brought down by a factor of ~ 6 .

217

Figure 4. Depiction of precision for determining neutron radiation from a 1 Ci ^{239}Pu -Be neutron source located 80 cm from detector at 0° improving dramatically with increased counts. Error bars pertain to 68% confidence. Time for acquisition was based on a detection rate of ~ 10 per second in the D-ATMFD.

Additionally, we also conducted experiments in which we acquired with a $\sim 45 \mu\text{Ci}$ ^{252}Cf isotope fission spectrum neutron source emitting $\sim 1.9 \times 10^5$ neutrons/s (equivalent to the intensity emitted from ~ 2.5 kg of WGP [19]) positioned at 0° and at about 20 cm away using a D-ATMFD drive power of ~ 4 W. This resulted in the formation of ~ 5 neutron induced detections per second subsequently resulting in $\sim 1,500$ neutron induced detection events which could be acquired within 300 seconds. Analysis of the experimental data with the robust stochastic directionality model determined the neutron source to be located at an angle of 0.4° with data resolved to $\pm 11.4^\circ$ at a C.L. of 68%, and $\pm 21.4^\circ$ at a C.L. of 95%. This represents an improvement in the angular resolution (i.e. 2.4° better at the 68% C.L. and 6.2° better at the 95% C.L.) achievable with the robust stochastic directionality model when ascertaining the direction of a ^{252}Cf isotope fission spectrum neutron source and required $\sim 25\%$ fewer detection events. This is substantial and represents a corresponding $\sim 25\%$ decrease in the time to detect the direction of a SNM neutron source. The increased directional precision is due to the higher elastic scattering cross section (and consequently

increased down scattering and absorption in the detector fluid) for neutrons from the spontaneous fission of ^{252}Cf .

4. Scaling of D-ATMFDs for optimization of directionality information

As mentioned previously, the neutron flux as measured by the D-ATMFD is a function of the distance from the source, and the level of scattering and absorption occurring in the detector fluid. Therefore, a detector with a larger sensitive volume is sensitive to a greater amount of neutron down scattering and absorption and consequently an increased amount of directional information is available. Previous work has shown via COMSOL multi-physics based assessments and direct experimental measurements of the distribution density of neutron-induced bubble nucleation sites that the size of the sensitive volume (and consequently the radius) is directly related to the input power of the D-ATMFD resonant chamber. For example, a relatively small (~40%) rise in the input power from 4 W to 5.5 W resulted in significant increase of the sensitive volume (by ~75%), i.e., from ~20 cm³ to ~35 cm³ [14][15]. This is based on the principle that the higher the negative pressure amplitude in the detection fluid is, the higher the probability that a neutron induced detection event will occur. The increase in the amount of directionality information attainable with the robust stochastic directionality model was assessed via MCNP-PoliMi simulations. Several simulations were performed with various detector sensitive volume sizes ranging from a radius of 0.5 cm to 3.0 cm with a fixed height of 4.0 cm (sensitive volume approximated as a right circular cylinder tally volume). The locations of simulated neutron detection events occurring were then analyzed with the robust stochastic directionality model and the accuracy at 68% and 95% confidence levels were calculated. The results are shown in Figure 5. These results illustrate that as the drive power and subsequently the radius of the sensitive volume increase, the resolution that may be achieved increases significantly due to not only an increased sensitive volume size, but also simultaneously due to improved detection efficiency. These results provide proof that the D-ATMFD capabilities are amenable for enhancement and possible to

tailor via the scaling of the size of the detection sensitive volume, which is attainable either by increasing the drive power and/or physically scaling the D-ATMFD unit.

Figure 5. Pointing accuracy of the D-ATMFD increases with the increased sensitive volume radius and increased detection efficiency. MCNP-PoliMi simulations of D-ATMFD were performed until 500 neutron detection events were recorded for $R = 1.25\text{cm}$ case. Number of detection events used for other cases are scaled appropriately. All cases used a SV height of 4.0 cm.

5. The D-ATMFD used for localizing the neutron source -- experiments and analysis

An example of one of the applications of a directional-capable neutron detector system is the ability to image a neutron source which allows for the determination of the neutron source shape, size and strength. Neutron imaging detectors thus have the potential to play an important role in non-proliferation type applications. Localization of the neutron source is accomplished by utilizing multiple detectors that are located such that the angle subtended by the detector and the direction of the source is distinct for each detector. Experimentation was performed to investigate capabilities of the D-ATMFD system for this type of application. Two D-ATMFD detectors (each operated at a drive power of $\sim 4\text{ W}$) were placed 25 cm apart (as measured from the centerline of each D-ATMFD). The XY coordinate system was defined such that the detectors were located at (0 cm, 0 cm) and (25 cm, 0 cm) and a 2D mesh was created covering an

276 experimental area of 1 m². A ~1 Ci ²³⁹Pu-Be neutron source was placed at (15 cm, -20 cm) and data were
 277 recorded. This enabled collecting ~2,000 neutron induced detection events within ~200 seconds.

278

279 **Figure 6.** Experimentally measured and calculated neutron source location probability. ²³⁹Pu-
 280 Be neutron source located at (15 cm, -20 cm). The contour scale is in units of source location
 281 probability density per unit area (mm²).

282 The locations of simulated neutron detection events were thereafter, assessed using the robust stochastic
 283 directionality model to evaluate the total source direction probability distribution function for each detector
 284 and then the corresponding total source location probability was calculated. The results are shown in Figure
 285 6. The neutron source was determined to be located at the most probable location of (16.6 cm, -15.6 cm) and
 286 the confidence level was calculated by directly integrating the area under the surface and was found to cover
 287 an area of 750 cm² at a 68% confidence level. Additionally, a MCNP-PoliMi model was developed to
 288 simulate the experimental conditions. The experimental conditions were replicated in the model, and
 289 simulations were run until a total of 2000 neutron detection events occurred in the D-ATMFDs. The neutron
 290 source was determined to be located at the most probable location at (18 cm, -17.4 cm). The confidence

level was calculated by integrating the area under the surface and was found to cover an area of 1020 cm^2 at 68% confidence. Importantly, both MCNP-PoliMi simulations and experimental data resulted in very similar neutron source locations, and the true source location was well within the predicted 68% confidence level for both cases. Comparing these results to the previously published values for a similar experiment performed indicate that the assumptions previously made neglecting multiple scattering and solid angle effects resulted in an overestimation of the confidence. This was expected as the neutron source was located at a distance that was sufficiently close enough that the effects of solid angle were not negligible.

6. D-ATMFD based ANSI Cat. E RPM Simulations

Another example for demonstrating one of many unique applications of the D-ATMFD neutron detector is the external non-intrusive monitoring and imaging of moving neutron sources, including special nuclear material, in containers and packages being scanned. The design of one such D-ATMFD based radiation detection portal monitor was assessed following ANSI standard N42.35-2006 which is intended to provide the testing and evaluation criteria for installed radiation detection portal monitors that detect radioactive materials (without identification capabilities) [21]. The standard outlines performance criteria and test methods used to evaluate installed radiation detection portal monitors (RPM) for use in U.S. Homeland Security. The standard states that the source shall be moved at a specified speed dependent on the type of monitor. The setup or evaluation distances vary for different applications, in which the distances are measured from the face of the detector case or assembly. The baseline case we studied was targeted for a category E configuration representing a multiple-sided pedestrian or package monitor. The D-ATMFD based RPM simulated consists of 4 separate panels (20 cm x 20 cm x 60 cm), each with 6 individual D-ATMFD elements with a sensitive volume of $r = 3.0 \text{ cm}$ and $h = 5.0 \text{ cm}$. The spacing between D-ATMFD panels along the axis of the conveyer was 1 m as measured from the center-line of each panel. The detectors are separated 1 m apart as measured from the external face of the detector assembly. The detector fluid simulated was acetone. An illustration of the simulated D-ATMFD based RPM is shown in Figure 7.

Figure 7. Schematic of D-ATMFD based ANSI Cat. E. RPM system consisting of 24 D-ATMFD elements.

The source speed was set at 1.2 m/s. Preliminary assessments simulated a ^{252}Cf based neutron source with an activity equivalent to an 4 kg mass of weapons grade plutonium in a metallic sphere ($\sim 1 \times 10^6$ n/s) [19]. The simulation is started with the SNM source located at the center of the conveyor and 3 m away from the center-line of the D-ATMFD RPM assembly. The locations of simulated neutron detection events are analyzed as they occur in the simulation with the robust stochastic directionality model in order to calculate the source location probability distribution. An example of the source location probability distribution 2 seconds into a simulation is shown in Figure 8. The location of the SNM source was correctly identified to within 0.2 m^2 with 68% confidence within 2 seconds. The acquisition of additional neutron detection events allows for further refinement of the location of the SNM source. After 4.75 seconds, the location of the SNM source was correctly identified to within an area of 0.06 m^2 (see Figure 9).

Figure 8. Simulation of the passage of an 4 kg mass of WGP thru the D-ATMFD based RPM. Figure shown taken at T=2 seconds. The contour scale is in units of source location probability density per unit area (cm²).

Figure 9. Simulation of the passage of an 4 kg mass of WGP thru the D-ATMFD based RPM. Figure shown at T=4.75 seconds. The contour scale is in units of source location probability density per unit area (cm²).

336 Additional assessments included a ^{252}Cf based neutron source with an activity equivalent to a 2 kg of
337 weapons grade plutonium ($\sim 1.2 \times 10^5$ n/s) [19]. As before, the simulation is started with the SNM source
338 located at the center of the conveyer and 3 m away from the center-line of the D-ATMFD RPM assembly.
339 The locations of simulated neutron detection events are analyzed as they occur in the simulation with the
340 robust stochastic directionality model in order to calculate the source location probability distribution. The
341 location of the SNM source was correctly identified to within an area of 0.3 m^2 with 68% confidence within
342 5 seconds.

343 7. Conclusions and Future Work

344 The directionality model previously developed for the D-ATMFD made two basic assumptions: the
345 effects of solid angle on the neutron flux are negligible (i.e. neutrons are traveling uni-directionally) and that
346 the detected neutron traveled directly from the neutron source to the detection location (i.e. no interactions
347 with the detector fluid occurred between the neutron detection location and the source origination). The
348 robust stochastic directionality model for the D-ATMFD developed and described herein analyzed the
349 effects these assumptions had on the resultant precision and accuracy and provided a means of increasing
350 the accuracy of the determination of the SNM source direction. From direct experimentation it has been
351 shown that the D-ATMFD system as presently configured and with the newly developed robust stochastic
352 directionality model is capable of locating the direction of ~ 3.5 kg of RGP (represented by use of a ~ 1 Ci
353 ^{239}Pu -Be neutron source) to within 13.8° with 68% confidence; this required $\sim 2,000$ detection events which
354 could be collected within ~ 200 sec. at a detection rate of ~ 10 per second. Additional experimentation has
355 shown that the D-ATMFD system is capable of locating the direction of ~ 2.5 kg of WGP (simulated by a
356 $\sim 45 \text{ } \mu\text{Ci}$ ^{252}Cf isotope fission neutron source) to within 11.4° with 68% confidence; this required $\sim 1,500$
357 detection events which were acquired within ~ 300 sec. at a rate of ~ 5 per second. This is indicative of the
358 potential for a noteworthy reduction ($16\times$) in the search space when compared to a non-directional detector.
359 Additionally, two D-ATMFD systems were shown to be capable of ascertaining the location of a neutron

source, an aspect which was validated via experimentation, and also successfully simulated with a MCNP-PoliMi modeling scheme. A D-ATMFD based RPM capable of the external non-intrusive monitoring and imaging of sources of fast neutrons, including SNM, in containers and packages was developed and characterized. The D-ATMFD based RPM developed was shown to be capable of ascertaining the location of a 4 kg mass of WGP moving at a speed of 1.2 m/s to within 0.06 m² in less than 5 seconds. Planned work includes assessing the possibility of further enhancing directional and positional information via higher drive powers, higher sensitivity detection fluids, and potential physical scaling of the detector size, and to investigate additional nuclear security safeguards applications.

Acknowledgment

The reported work for this paper was sponsored by Sagamore Adams Laboratories, LLC and is gratefully acknowledged. This work builds upon past work supported in part by funds from other sponsors such as the U.S. Department of Defense, the U.S. Department of Energy, the U.S. National Science Foundation, and the Department of Homeland Security. This work also benefited from assistance from Purdue University's REM and several other Purdue staff and are acknowledged.

References

- [1] S. Ahlen, D. Dujmic, P. Fisher, A. Inglis, H. Tomita, and H. Wellenstein, "A Background-Free Direction-Sensitive Neutron Detector," *IEEE Trans. Nucl. Sci.*, vol. 57, no. 5, pp. 2740–2746, Oct. 2010.
- [2] N. S. Bowden, M. Heffner, G. Carosi, D. Carter, P. O'Malley, J. Mintz, M. Foxe, I. Jovanovic, and P. O'Malley, "Directional fast neutron detection using a time projection chamber," *Nucl. Instruments Methods Phys. Res. Sect. A Accel. Spectrometers, Detect. Assoc. Equip.*, vol. 624, no. 1, pp. 153–161, Dec. 2010.
- [3] N. Mascarenhas, W. Mengesha, J. Peel, and D. Sunnarborg, "Directional Neutron Detectors For Use with 14 MeV Neutrons," 2005.
- [4] W. Mengesha, N. Mascarenhas, J. Peel, D. Sunnarborg, A. The, and G. Monte, "Modeling of a Directional Scintillating Fiber Detector for 14 MeV Neutrons," vol. 53, no. 4, pp. 2233–2237, 2006.
- [5] N. Mascarenhas, J. Brennan, K. Krenz, P. Marleau, and S. Mrowka, "Results With the Neutron Scatter Camera," *IEEE Trans. Nucl. Sci.*, vol. 56, no. 3, pp. 1269–1273, Jun. 2009.
- [6] U. Bravar and P. Bruillard, "Design and testing of a position-sensitive plastic scintillator detector for fast neutron imaging," *Nucl. Sci. ...*, vol. 53, no. 6, pp. 3894–3903, 2006.

- 388 [7] G. a. de Nolfo, S. D. Hunter, J. T. Link, and N. a. Guardala, "Neutron Imaging Camera," *2009 IEEE Conf. Technol.*
389 *Homel. Secur.*, pp. 282–286, May 2009.
- 390 [8] R. S. Woolf, P. F. Bloser, U. Bravar, J. S. Legere, M. L. McConnell, J. R. Macri, P. C. Mallik, B. Pirard, J. M. Ryan, and
391 J. R. Wood, "Imaging and spectroscopy of fission neutrons with the FNIT experiment," *2009 IEEE Conf. Technol. Homel.*
392 *Secur.*, pp. 274–281, May 2009.
- 393 [9] E. Fenimore and T. Cannon, "Coded aperture imaging with uniformly redundant arrays," *Appl. Opt.*, pp. 1–9, 1978.
- 394 [10] P. Marleau, J. Brennan, E. Brubaker, and J. Steele, "Results from the coded aperture neutron imaging system," *IEEE*
395 *Nucl. Sci. Symp. Med. Imaging Conf.*, pp. 1640–1646, Oct. 2010.
- 396 [11] R. S. Woolf, B. F. Philips, A. L. Hutcheson, L. J. Mitchell, and E. a. Wulf, "An active interrogation detection system
397 (ACTINIDES) based on a dual fast neutron/gamma-ray coded aperture imager," *2012 IEEE Conf. Technol. Homel.*
398 *Secur.*, pp. 30–35, Nov. 2012.
- 399 [12] B. Archambault, T. F. Grimes, J. A. Webster, N. W. Wilson, A. Hagen, K. Fischer, and R. P. Taleyarkhan, "Development
400 of a 4π directional fast neutron detector using tensioned metastable fluids," *2012 IEEE Conf. Technol. Homel. Secur.*, pp.
401 423–428, 2012.
- 402 [13] T. F. Grimes, B. Archambault, J. a. Webster, A. Sansone, and R. P. Taleyarkhan, "Gamma-blind transformational nuclear
403 particle sensors," *2012 IEEE Conf. Technol. Homel. Secur.*, no. 1, pp. 417–422, Nov. 2012.
- 404 [14] B. C. Archambault, J. A. Webster, J. R. Lapinskas, T. F. Grimes, and R. Taleyarkhan, "Development of a novel direction-
405 position sensing fast neutron detector using tensioned metastable fluids," *Nucl. Instruments Methods Phys. Res. Sect. A*
406 *Accel. Spectrometers, Detect. Assoc. Equip.*, vol. 673, pp. 89–97, May 2012.
- 407 [15] R. Taleyarkhan, J. Lapinskas, and Y. Xu, "Tensioned metastable fluids and nanoscale interactions with external stimuli—
408 Theoretical-cum-experimental assessments and nuclear engineering applications," *Nucl. Eng. Des.*, vol. 238, no. 7, pp.
409 1820–1827, Jul. 2008.
- 410 [16] J. Wang and B. C. Archambault, "Numerical simulation and experimental study on Resonant Acoustic Chambers - For
411 novel, high-efficiency nuclear particle detectors," in *Proceedings of the 17th International Conference on Nuclear*
412 *Engineering*, 2010, pp. 1–11.
- 413 [17] J. Zar, *Biostatistical Analysis*, 5th ed. Prentice Hall, Inc., 2009.
- 414 [18] V. Bom, "Fast Neutron Imaging for SNM Detection," in *Proceedings of the International Topical Meeting on ...*, 2009,
415 no. table 1, pp. 1–7.
- 416 [19] R. T. Kouzes, E. R. Siciliano, J. H. Ely, P. E. Keller, and R. J. McConn, "Passive neutron detection for interdiction of
417 nuclear material at borders," *Nucl. Instruments Methods Phys. Res. Sect. A Accel. Spectrometers, Detect. Assoc. Equip.*,
418 vol. 584, no. 2–3, pp. 383–400, Jan. 2008.
- 419 [20] R. C. Runkle, "Neutron sensors and their role in nuclear nonproliferation," *Nucl. Instruments Methods Phys. Res. Sect. A*
420 *Accel. Spectrometers, Detect. Assoc. Equip.*, vol. 652, no. 1, pp. 37–40, Oct. 2011.
- 421 [21] ANSI, "American National Standard for Evaluation and Performance of Radiation Detection Portal Monitors for Use in
422 Homeland Security Accredited by the American National Standards Institute," Washington, D.C., 2006.