

This document was prepared in conjunction with work accomplished under Contract No. DE-AC09-96SR18500 with the U. S. Department of Energy.

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Ultra-wide Range Gamma Detector System for Search and Locate Operations

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Abstract – *Collecting debris samples following a nuclear event requires that operations be conducted from a considerable stand-off distance. An ultra-wide range gamma detector system has been constructed to accomplish both long range radiation search and close range hot sample collection functions. Constructed and tested on a REMOTEC Andros platform, the system has demonstrated reliable operation over six orders of magnitude of gamma dose from 100's of uR/hr to over 100 R/hr. Functional elements include a remotely controlled variable collimator assembly, a NaI(Tl)/photomultiplier tube detector, a proprietary digital radiation instrument, a coaxially mounted video camera, a digital compass, and both local and remote control computers with a user interface designed for long range operations. Long range sensitivity and target location, as well as close range sample selection performance are presented.*

I. INTRODUCTION

Operating a sample collection robot in a nuclear debris field presents two distinctly different challenges for a gamma radiation detection system. The first is simply navigating from a cold deployment zone to the area of interest, transitioning from navigation by compass heading to navigation by radiation levels indicative of good sample collection points. The second challenge is actually selecting which objects to retrieve when both the background and the objects themselves are all radiologically hot. The development task was to meet these disparate detection needs with a single detection system that could be deployed on an Andros platform.

II. EARLY DEVELOPMENT AND TESTING

In FY03, the Defense Threat Reduction Agency (DTRA) requested that a sample collection system be designed to fit an Andros Mark V bomb disposal robot. SRNL's response included a single nuclear detector capable of locating a hot area for sampling, as well as discriminating between closely spaced samples. Normally, these two capabilities result in significantly different nuclear detectors. A good candidate for long range search and locate operations is a large scintillating detector because volume and efficiency are the overwhelming factors in a low dose rate environment. To examine multiple, hot samples in close proximity to each other, a smaller detector with lower efficiency and directional shielding would normally be selected. Since the mission requirements were not yet well defined, a single detector was implemented, its size and shielding dictated by its mounting location atop the Andros' mast camera. This location was chosen to allow the most maneuverable

camera to be used for sample selection and because the additional height of the mast would allow better detection at long distances over uneven terrain.

To avoid overstressing the pan and tilt motors on the mast, the machinable tungsten shield needed to be as small as possible to reduce weight. This drove the detector selection process which resulted in a ½ by 1 inch Cesium Iodide detector with an ultra-miniature Hamamatsu photomultiplier tube. Initially, a two inch diameter, machinable tungsten shield was designed with screw-in collimators to allow testing in both low and high radiation fields. A remotely controlled, variable collimator assembly was not implemented at this point because the maximum radiation field for sample collection operations had not yet been specified.

II.A. Initial Test Results

Initial testing was conducted at Argonne National Laboratory - West (ANL-W, now INL) because of the availability of suitable facilities and gamma sources. The goals were threefold: (1) to determine the maximum distance at which a significant source could be detected; (2) to determine how well closely spaced sources could be discriminated from one another; and (3) to test the ability to discriminate between sources in the presence of high background radiation. A two axis grid was used with the sources located along the X axis, equidistant from the Y axis, while the robot traversed the Y axis toward the origin. Distances shown in all of the tables do not reflect actual source-to-detector (S-to-D) range, but from the front of the robot mast to the origin. There were also issues with the offset between the camera's field of view and the radiation detector's field of view (see figure 1) in the proof-of-concept prototype, particularly when the

0.200 and 0.100 collimators were used. Precise aiming of the radiation detector was not



Fig. 1. Proof-of-concept collimated gamma detector. generally possible, aggravated by the tilt motor’s inability to smoothly manipulate the mass of the shielded assembly and its moment as well. The significance of the Table 1 data is in the last row where the smaller source, A (0.8Ci 137Cs), seemingly produces a higher count rate than source B (2.5Ci 137Cs). This anomaly was immediately attributed to insufficient shielding on the sides and bottom of the detector and the testing was halted.

Table 1. Initial collimator test data.

S-to-D, yds	Coll. Dia.	Src Sep, yds	Src A Kcpm	Ctrline, Kcpm	Src B Kcpm
10	0.50	4	314	220	282
10	0.20	4	32	14.5	41
10	0.20	2	25	-	48
10	0.10	2	14	10.5	18
2	0.1	2	408	-	150

II.B. Shield Evolution Test Results

To prepare for a second round of testing, additional shielding was added in a box configuration, surrounding the original cylindrical shield and increasing its overall thickness to approximately 0.9 inch of tungsten on the sides and bottom of the detector. Data from this second configuration indicated that the 0.200 inch diameter collimator could be used somewhat effectively, but the 0.100 diameter could not because more counts were still reaching the detector than through the shield than through

the collimator hole. Table 2 contains selected data points that illustrate the improvement gained by the additional shielding alone.

Table 2. Collimator test data with revised shield and 0.200 collimator.

S-to-D, feet	Source A mR/hr	Centerline, mR/hr	Source B mR/hr
16	8	4	22
14	11	5	26
8	26	7	59
4	45	15	108
2	43	23	145

The mounting system to hold both the shielded collimator and the standard Andros mast lamp (Fig. 1) was modified for this second phase of testing, raising the lamp and lowering the collimator in an attempt to maintain reasonable control in the pan and tilt axes. The original problems with axial differences between the camera and the detector remained, but were compensated for by judicious use of the joystick for the tilt control to optimize radiation readings.

Additional tests with three sources gave some indication of sample selection capability in the presence of high background radiation. A 4.6 Ci 60Cobalt source was used to simulate high background, but of course was actually another point source, not a distributed one. Table 3 illustrates the effect of the cobalt (Source C) on the dose rate readings from the cesium sources (A and B). The “Centerline” reading was taken at the (0, 0) origin of the test grid; source C was located above the X axis at (0, 16).

Table 3. Simulated high background results with revised shield and 0.200 collimator.

S-to-D, feet	Source A mR/hr	Centerline, mR/hr	Source B mR/hr	Source C mR/hr
12	28	15	45	30
10	34	20	57	36
8	39	29	76	44
6	45	43	95	52

III. ADJUSTABLE COLLIMATOR CONFIGURATION

III.A. Collimator Development

After testing with the thicker tungsten shielding, a new specification was written to develop a remotely adjustable collimator system. The following constraints were applied:

1. The detector must be mounted directly behind and coaxial to the camera to eliminate the parallax problem.
2. All components will be mounted inside the camera housing for waterproof operation.
3. The mast assembly itself cannot be modified except to change the pan and tilt rates for slower scanning speeds.
4. The pan and tilt range of the standard Andros camera must be maintained.
5. The center of mass must permit the proper operation of the pan and tilt functions.

The prohibition against modifying the mast head, as well as the need to maintain the camera tilt range drove the design of the collimator assembly itself. Configurations involving rotating and sliding members were evaluated, but the result was basically a four inch diameter cylindrical shield, bored to accept a CsI/PMT detector 19mm in diameter. The forward portion of the shield was machined to accept a dovetail slide containing two collimation holes, 0.200 and 0.150 inch, respectively. Monte Carlo simulation had indicated that even at a forward shield thickness of 1.5 inches, a collimation hole below 0.150 inch in diameter would still be overwhelmed by counts passing through the shield. The 1.5 inch deep slide is 0.5 inch wide at the front edge and 1.0 inch wide nearer the detector so that the mating surfaces do not provide a slit directly into the detector itself. It rides vertically and permits a total of three collimations settings, 0.5, 0.2, and 0.15 inches. Even in the “wide open” position the horizontal acceptance angle is only 28 degrees, a good compromise between maximizing count rate at long distances and maintaining some directionality when scanning for hot spots at shorter ranges.

Having selected the overall design configuration, the next step was to select the slide actuation and position sensing mechanisms. A rack-and-pinion drive was implemented using a nylon rack on the face of the slide since it was effectively transparent to gamma radiation. The originally implemented microswitches were later replaced by magnetic sensors which improved the repeatability of the slide positioning and successfully withstood the violent shaking and vibration of off-pavement operations. Figure 2 is a 3D rendering of the adjustable collimator assembly in its final form.

III.B. Field Test Results

In the January, 2005, testing, the same nuclear detector and instrument were used as in the FY04 tests but with the fully automated, adjustable collimator shield

arrangement. The maximum shield thickness had increased to 1.5 inches, and the minimum collimator diameter had been revised to 0.150 inch. The earlier

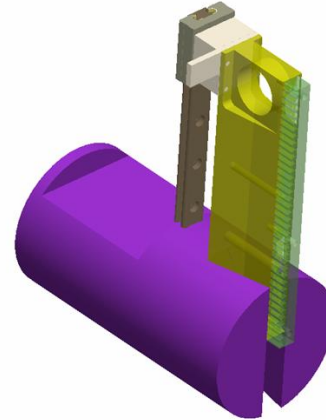


Fig. 2. Adjustable collimator assembly with slide drive and supporting structure removed.

testing had yielded a more realistic assessment of actual field operating conditions, and that data was fed into the modeling analysis of the shield. Particular attention was paid to the angle of the detector when doing close-up sample selection. This resulted in increased shielding over the top of the detector itself, with a relief over the PMT and PMT base to minimize weight. The resulting assembly with the slide and its drive included was nearly 30 pounds. The pan and tilt drives were modified to decrease speed and increase torque to handle the additional load. The mast assembly itself, however, was not modified after Remotec confirmed a vertical lift rating of 100 pounds.

The January tests were conducted using the same test plan and grid arrangement that had been successfully used in FY04. The test goals remained substantially the same, but were focused on the close range portion only where the limitations of the previous design had been most evident. Early on, some vertical mismatch between camera view and detector view was noted; however, aiming offsets were quickly empirically determined for all three collimator settings, Long Range, Short Range, and Sample Selection. These represent, respectively, 1/2 inch, 0.200 inch and 0.150 inch collimator settings, all with an effective length of 1.50 inches. The data shown in Table 4 was taken in the Long Range (0.5 inch collimator) mode. Again, distances are from the front of the robot to the X axis upon which the sources are placed at a separation distance of twelve feet. The usual expectation of inverse square law readings is not displayed in the data because the detector is approximately eight feet above ground level.

Table 4. Long Range setting results with two sources.

S-to-D, feet	Source A mR/hr	Centerline, mR/hr	Source B mR/hr
20	19	18	59
18	19	16	73
16	25	15	83
14	28	14	98
12	35	13	126
10	40	12	141
8	47	12	186
6	61	12	240
4	68	14	313
2	83	15	364
0	96	17	417

This performance with a 28 degree acceptance angle was so encouraging that the source separation was reduced to four feet and the following readings were taken (Table 5).

Table 5. Short Range and Sample Select performance.

S-to-D, feet	Source A mR/hr	Centerline, mR/hr	Source B mR/hr	Coll. Setting
0	109	212	645	LR
0	200	64	532	SR
2	187	75	614	SR
4	174	73	718	SR
6	130	73	452	SR
10	105	112	302	SR
10	83	49	275	SS
12	70	66	234	SS
14	60	58	193	SS
16	48	66	145	SS

Note that when the Long Range (LR) collimator had too wide a field of view at zero distance to target, switching to the Short Range (SR) collimator restored the capability to discriminate between the two sources. When the SR collimator could no longer distinguish Source A (0.8 Ci) at a distance of 10 feet, changing to the Sample Select (SS) collimator restored that capability and extended it to 14 feet. When deciding which item to collect from a cluttered debris field, this capability is enormously important to selecting good samples and to conserving battery power for the robot.

Three source testing was conducted to add background effects and was even extended to four sources by the addition of 30 Ci of 192Iridium. 137Cesium sources A and B were spaced four feet apart at (0, -2) and (0, +2) for Tables 6, 7, and 8; source C is the 4.6 Ci 60Cobalt. The selected collimator aperture is SS.

Table 6. Co60 background test; source C at (0, +12 feet).

S-to-D, feet	Source A mR/hr	Centerline, mR/hr	Source B mR/hr	Source C mR/hr
16	100	123	170	160
10	138	106	360	242
8	154	121	420	252
6	211	131	477	316
4	270	140	840	419

Compare Table 6 with Table 5 and the effects of the stronger gamma rays from 60Co (1.17 and 1.31 MeV) become apparent. Even with the narrow acceptance angle of the 0.150 SS collimator, at 16 feet Source A is indistinguishable; moving in to 10 feet, it is clearly visible.

Table 7 displays the shield's effectiveness against the 60Cobalt gammas, even at high dose rates. Note the relative contribution of the 60Cobalt to the centerline reading in comparison to that of the 137Cesium sources. Even though sources A and B are closer to the detector, the higher energy gammas from source C are significantly more penetrating.

Table 7. Co60 background test; source C at (0, +6 feet).

S-to-D, feet	Source A mR/hr	Centerline, mR/hr	Source B mR/hr	Source C mR/hr
4	370	294	980	940
2	550	360	1390	1340
2	-	38*	-	-

*Source C removed; A and B at (0, -2) and (0, +2).

Table 8's results appear counterintuitive at first, since the Source A and B readings are lower when the Ir192 is closer than when it is farther away. The reason for this is the tilt angle on the camera/detector assembly in relation to the distance to the Iridium source. With the Ir192 placed 12 feet beyond the test source line (x-axis), the direct line thickness of the shielding to the detector is actually less than when the Ir192 is placed 6 feet beyond the line. The tungsten shield's effectiveness is much more dramatically affected by thickness changes at 300 keV than it is at 1+ MeV. Table 7, row 3 and Table 8, row 4 confirm that 30 Curies of 192Ir produces very little more background than 4.6 Curies of 60Co at the same distance.

Table 8. Ir192 background test; source C still at (0, +6).

S-to-D, feet	Source A mR/hr	Centerline, mR/hr	Source B mR/hr	Source C mR/hr
4*	205	100	990	4105

4*	-	49	-	-
4**	170	110	880	8000
4**	-	47	-	-

*Ir192 located at (0, +12); ** Ir192 located at (0, +6)

III.C. Field Exercise Observations

A September, 2005, exercise provided the opportunity to assess the effectiveness of the final version of the adjustable collimator in a more realistic setting. As can be seen in the 3D rendering in figure 3, the collimator assembly is a simple dovetail slide, driven by a rack and pinion arrangement. The rack is mounted on the front face of the slide but it does not interfere with radiation readings since it is made of nylon and has comparatively low density. In the front view shown in figure 3, the slide is in the topmost position, providing a half inch wide access to the detector face. Since the front of the dovetail is one half inch wide and the detector face is set back somewhat more than 1.5 inches from the face of the shield, an effective collimator “hole” exists which restricts the field of view in the horizontal and upper vertical directions. The field of view is much wider in the down vertical direction which is helpful in short range scanning for samples. The two collimator holes in the slide are also evident in figure 4, while figure 3 displays the magnetic position sensors that ensure coaxial alignment of the collimator holes with the detector centerline. Although that alignment is not critical for the radiation dose rate readings, it is essential to precision aiming of the detector at potential samples.

During this exercise, the ambient background ranged from less than 1 milliRem per hour to as much as 20 Rem per hour. Individual sources up to hundred’s of R/hr were placed in unknown and disguised locations in a cluttered environment, requiring the Andros’ operator to survey the scene for gamma content and establish course headings to hot spots for source retrieval. Systematically, these sources were pinpointed using only the radiation information provided by the gamma search and locate system. With the addition of the gamma search and locate system and other system improvements, the Andros can be used to collect samples in environments in which humans could not operate for the requisite amount of time.

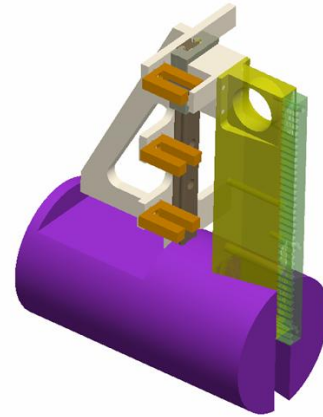


Figure 3. 3D rendering of the adjustable collimator assembly with slide drive removed.

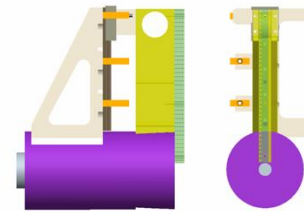


Figure 4. Side and front rendering of the adjustable collimator assembly, shown in the Long Range position.

IV. CONCLUSIONS

The addition of the remotely controlled, ultra-wide range, gamma search and locate system to the Andros platform produces a versatile sample collection platform for radiologically hot environments. With the adjustable collimator, a gamma detector with sufficient sensitivity for long range detection can also be used in very high background situations to locate and identify individual samples for retrieval.

ACKNOWLEDGMENTS

This work was performed for the Defense Threat Reduction Agency under contract with the Savannah River National Laboratory.

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