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*Monte Carlo Investigation of
Through-Casing γ - γ Density Logging*

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Monte Carlo Investigation of Through-Casing γ - γ Density Logging

by

Henry Lichtenstein

ABSTRACT

This report documents research I performed, employing Monte Carlo parametric simulations. I investigated the concept of utilizing high-energy γ rays for through-casing density logging. The research exploits the findings of my previously accomplished proof-of-concept, the present goal having been to characterize a generic γ - γ tool in various scenarios. In the process, I generated a database of tool-design information. My analysis of the computed results identified a novel design-evaluation technique, a natural extension of my earlier concept to use the *formation* signal as a quality gauge for the detected signal:

Analysis of the *formation* signal determines, *a priori*, whether a specific combination of design parameters is, *intrinsically*, compatible or mismatched.

It must be noted that the new technique is only possible in simulations of the present kind. But it is not limited to the set of parameters investigated in the present studies. Hence, any effort to design a prototype tool can benefit significantly from its application. The technique amplifies the power of simulation, which is an inherently cost effective adjunct to 'cutting metal.'

I. INTRODUCTION

This report documents research that I performed as a staff member in the Radiation Transport Group (X-6) at Los Alamos National Laboratory (LANL). This research was a follow-on to a proof-of-concept study that I accomplished previously for the Gas Research Institute of Chicago (GRI).^{1, 2}

The project, of which this research was a principal component, involved the investigation of a GRI idea to use accelerator-generated γ rays for density logging cased boreholes. The intent is to utilize the greater interrogation depth provided by these γ sources (as confirmed by my proof-of-concept study), which offer higher energies than chemical sources, such as Cesium (662-keV γ 's).

My computing system was the LANL MCNPTM code,³ a Monte Carlo radiation transport code that is used extensively for diverse applications, including many in the well-logging industry. Its role in these investigations was to provide the Monte Carlo simulation capability for what evolved into a multi-dimensional parametric design study. My parametric computations sought to characterize optimal design characteristics of a high-energy γ - γ density-logging tool, producing a tool-design data base in the process.

In addition to MCNP's abundant standard capabilities, I relied heavily on a conceptual device that I developed and implemented previously (see Appendix A). The latter allows me to analyze the detected signal by identifying the contributions originating from specific domains of the simulated borehole/formation environment. In particular, I can vary the parameters of a postulated source/detection scenario and determine, individually, the signal fractions attributable to the borehole, casing, cement, and formation, as well as the total signal. In this manner, I attempted to find optimal circumstances whereby the signal fraction due to the formation can be isolated to some degree.

Recognizing that the plethora of available parameters could have exhausted even a generous allocation of computing funds, I investigated in greater or lesser detail those parameters that had a greater or lesser effect on the detected signal, respectively. My general approach was to define (and redefine) dynamically a manageable ensemble of computations for the generation of a useful design data base — the results presented in this report.

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II. BACKGROUND

In order to place my current research in perspective, it is useful to summarize the research that preceded it; the first subsection below serves that purpose. The subsections that follow specify the objectives of the current research, describe my general approach, and specify the default physical scenario.

A. Previous Investigation

In the proof-of-concept study, I computed several cased-borehole scenarios, the results of which are summarized in Table 1. For each choice of scenario, this table has a corresponding set of percentile criteria for determining the ‘depth-of-interrogation’ or ‘penetrability’ of the source (and progeny) photons. Corresponding to each combination of scenario and percentile-criterion, there are 2 entries of computed information:

formation depth The indicated result in inches corresponds to the cumulative depth of formation that accounts for the corresponding percentile of signal.

% improvement The indicated percent improvement (for the unfiltered/iron-cased scenarios only) is computed relative to the 662- keV iron-cased scenario, which merely serves as a benchmark.

These results place the anticipated scenario of choice ($\sim 4\text{ MeV}$) into perspective, providing a practical upper limit via the 20- MeV source and an intermediate situation via the 2- MeV source. The 4- MeV “filtered” case provides specific information about the signal coming from the formation, the presumption being that the casing signal can somehow be filtered-out in practice.

If we acknowledge the 90-percentile results to be the principal measure of penetrability, then the 4- MeV source produces an unfiltered penetrability equivalent to the penetrability of the uncased 662- keV source. This finding supports the feasibility of utilizing a higher-energy γ - γ tool for density logging through casing. Moreover, if filtering-out the signal deriving from the iron casing is practicable, then it can be noted that significant relative improvement in depth-of-interrogation of the formation can be realized beyond that produced by the higher-energy source.

Table 1: Depth-of-Interrogation for Various Percentile Criteria and Source/Borehole Scenarios

Scenario	50%-ile	67%-ile	75%-ile	90%-ile	95%-ile
662ke V uncased	1.5in	2.3in	2.8in	4.5in	5.6in
662ke V cased	—	—	—	—	—
2Me V cased	0.8in 14%	1.7in 6%	2.3in 10%	4.3in 13%	5.7in 14%
4Me V cased	0.8in 14%	1.8in 13%	2.4in 14%	4.5in 18%	5.9in 18%
20Me V cased	0.8in 14%	1.8in 13%	2.5in 19%	4.6in 21%	6.1in 22%
4Me V filtered	1.7in	2.6in	3.2in	5.2in	6.7in

Figure 1: Comparison of signal spectra for the collimated generic tool in a cased borehole. The error bars have been suppressed for clarity.

Figure 1 presents a plot of the signal spectra corresponding to the summary results of Table 1. Specifically, these curves are the fraction of cumulative signal, gated about $[200,510] \text{ keV}$, as a function of formation depth in inches. These curves serve to characterize the detected signal, within the normal energy gating, in terms of the interrogation depth in a sandstone formation, as parameterized by the source energy of the γ rays. The simulation that yielded these results assumed a collimated and shielded generic tool in a cased water-filled borehole (with the single exception of the *uncased* Cesium-source benchmark).

In summary, I have previously accomplished a Monte Carlo simulation study as a proof-of-concept for a GRI idea. That idea envisions the utilization of higher-energy γ rays for density logging through cased boreholes. My principal findings were that:

- For a collimated generic tool, a 4-MeV γ source effects an interrogation depth through a *cased* borehole of ~ 4.5 inches, which is equivalent to the depth effected by Cesium γ rays (662 keV) in an *uncased* borehole.
- If the detector can somehow filter-out the portion of the signal originating from the casing, the resulting interrogation depth will be further enhanced.

B. Objectives and Approach

The current research exploits my preliminary positive findings. My goal was to characterize a generic γ - γ tool for density logging through casing in various scenarios.

In the context of this research, a ‘generic tool’ is one in which the principal components are implemented with a fair degree of conceptual integrity, albeit with liberal simplification of material and geometric detail. Such an implementation affords adequate realism, since I compare relative results in these parametric studies, with the advantages that simple point source and detector offer in MCNP calculations.

My idea of masking-out the ‘casing signal’ can be generalized to masking-out all signal contributions not attributable to the formation. Stated alternatively, my objective was to seek ways to emphasize, or isolate to some degree, the formation component of the detected signal, thereby enhancing the efficacy of its information content.

My computation system of choice (MCNP), augmented by my special tally (see Appendix A) allows me to analyze the detected signal by identifying the contributions originating from specific domains of the simulated borehole/formation environment. In particular, I can vary the parameters of the source/detection scenario and determine, individually, the signal fractions due to the borehole, casing, cement, and formation, as well as the total signal.

In this manner, my goal of finding optimal circumstances whereby the signal fraction due to the formation can be isolated to some degree, would, in the process, lead to the general objective of generating a database of tool design information.

C. Physical Scenario

The default specifications for the environment in this research were:

- a 35pu sandstone formation: SiO_2 (35%-porosity H_2O);
- a 3.937in-radius borehole filled with water;
- an iron casing having a thickness of 0.315in;
- a generic tool comprising a point source and point detector, both on the axis-of-symmetry in the borehole, separated by 19.685in;
- a varying thickness cement barrier, beyond the casing, was introduced in the later investigations of this project.

Both of the principal tool components are isolated in a void cell. A black absorber simulates a tungsten density pad above, between, and below the source and detector cells. This isolation effected a collimated and shielded tool. The void cells for source and detector provided a compromise between a more realistic eccentric placement of the tool near the borehole/casing boundary, and the computing efficiency that obtains from the centered placement on axis.

The seemingly odd choices for the dimensions of borehole radius and source-detector separation translate to 10cm and 50cm, respectively, when input to the MCNP code. As described in later sections, the source-detector separation, as well as the formation porosity, were among the variable parameters of the problem.

III. DETECTOR GATING

My basic characterization effort focused on ways and means for masking-out the casing signal, as well as other spurious components of the detected signal. My first attempt was to characterize the behavior of the detected signal, as a function of the detector energy gating, for a γ -source energy of $4M\epsilon V$. The specifications for the environment in this particular study were those described in Subsection C of Section II, excluding the cement barrier, which I did not introduce until the latter stages of my investigations.

I chose the energy interval of $200\text{--}500k\epsilon V$ to investigate the detected signal's dependence on energy gating. Using a $50k\epsilon V$ granularity, I computed all the possible combinations for detector gating, as shown in Table 2.

A. Computed Results

The corresponding set of results was computed in 10 individual runs, which I submitted concurrently, using 10 individual units (i.e., nodes) of the LANL IBM cluster. Each run completed 1 million histories, and, in this manner, I accomplished $7.5hrs$ of IBM cpu (roughly equivalent to $3.3hrs$ of Cray cpu) in about $2hrs$ of elapsed time.

The computed values of casing, formation, and total signal are presented in Tables 3–5, respectively. The computed relative standard errors (shown in parentheses) are satisfactory for all the formations, all the totals, and most of the casings, with just the 3 values in the lower right for the casing being of marginal quality. The latter values, however, are consistent with the general trends for these signals in the horizontal, vertical, and diagonal tabular directions.

B. Analysis of Results

If we consider the ratios of formation to total signal, we can construct the contents of Table 6. It would have been desirable for our purpose if the contents of Table 6 displayed some striking features, which would have suggested a strong benefit or penalty associated with certain energy intervals of our generic detector.

Table 2: Detector Energy Gates

	← Ceiling →					
↓Threshold↓	250keV	300keV	350keV	400keV	450keV	500keV
200keV	[200,250]	[200,300]	[200,350]	[200,400]	[200,450]	[200,500]
250keV		[250,300]	[250,350]	[250,400]	[250,450]	[250,500]
300keV			[300,350]	[300,400]	[300,450]	[300,500]
350keV				[350,400]	[350,450]	[350,500]
400keV					[400,450]	[400,500]
450keV						[450,500]

Table 3: Computed Casing Signal

	← Ceiling →					
↓Threshold↓	250keV	300keV	350keV	400keV	450keV	500keV
200keV	1.301E-09 (.0211)	2.309E-09 (.0196)	2.985E-09 (.0195)	3.411E-09 (.0197)	3.637E-09 (.0200)	3.766E-09 (.0204)
250keV		1.008E-09 (.0266)	1.699E-09 (.0247)	2.122E-09 (.0243)	2.341E-09 (.0246)	2.456E-09 (.0248)
300keV			6.756E-10 (.0342)	1.102E-09 (.0316)	1.322E-09 (.0307)	1.450E-09 (.0306)
350keV				4.269E-10 (.0459)	6.421E-10 (.0435)	7.812E-10 (.0426)
400keV					2.253E-10 (.0680)	3.338E-10 (.0627)
450keV						1.277E-10 (.0863)

Table 4: Computed Formation Signal

	← Ceiling →					
↓Threshold↓	250keV	300keV	350keV	400keV	450keV	500keV
200keV	2.626E-09 (.0124)	4.820E-09 (.0119)	6.499E-09 (.0120)	7.649E-09 (.0121)	8.329E-09 (.0123)	8.691E-09 (.0124)
250keV		2.195E-09 (.0145)	3.842E-09 (.0135)	5.018E-09 (.0136)	5.731E-09 (.0138)	6.097E-09 (.0140)
300keV			1.679E-09 (.0167)	2.829E-09 (.0161)	3.602E-09 (.0161)	3.984E-09 (.0162)
350keV				1.150E-09 (.0207)	1.889E-09 (.0198)	2.192E-10 (.0203)
400keV					6.797E-10 (.0275)	1.079E-09 (.0263)
450keV						3.820E-10 (.0374)

Table 5: Computed Total Signal

	← Ceiling →					
↓Threshold↓	250keV	300keV	350keV	400keV	450keV	500keV
200keV	3.926E-09 (.0133)	7.129E-09 (.0129)	9.483E-09 (.0129)	1.106E-08 (.0131)	1.197E-08 (.0133)	1.246E-08 (.0135)
250keV		3.203E-09 (.0157)	5.540E-09 (.0149)	7.141E-09 (.0149)	8.072E-09 (.0152)	8.554E-09 (.0154)
300keV			2.354E-09 (.0183)	3.931E-09 (.0178)	4.924E-09 (.0176)	5.434E-09 (.0178)
350keV				1.577E-09 (.0228)	2.531E-09 (.0223)	2.973E-09 (.0225)
400keV					9.050E-10 (.0309)	1.413E-09 (.0292)
450keV						5.096E-10 (.0403)

Table 6: Formation Signal Fraction

	← Ceiling →					
↓Threshold↓	250keV	300keV	350keV	400keV	450keV	500keV
200keV	0.66876	0.67613	0.68529	0.69157	0.69607	0.69769
250keV		0.68517	0.69340	0.70277	0.71000	0.71284
300keV			0.71301	0.71957	0.73155	0.73324
350keV				0.72935	0.74634	0.73726
400keV					0.75105	0.76374
450keV						0.74951

Table 7: Relative Total Signal

	← Ceiling →					
↓Threshold↓	250keV	300keV	350keV	400keV	450keV	500keV
200keV	0.31519	0.57232	0.76130	0.88792	0.96058	1.0
250keV		0.25713	0.44477	0.57323	0.64797	0.68666
300keV			0.18898	0.31561	0.39532	0.43623
350keV				0.12662	0.20319	0.23870
400keV					0.07265	0.11343
450keV						0.04091

But the information in Table 6 is largely characterized by the *absence* of striking features. The only noticeable deviation from the observed monotonic trends along the horizontals, verticals, and diagonals, occurs in the lower right corner of the table; the signal fraction in the $[450,500]\text{-}\text{keV}$ gate is seen to deviate from the monotonic increase both down the column and down the diagonal on which it lies. This exception could very well be statistical. The general trends in Table 6, however, suggest that the higher energy intervals are more important in characterizing the formation, and, perhaps, the $[400,450]\text{-}\text{keV}$ interval is most important.

The formation fraction is a measure of signal *quality* in the context of this project. As such, it is seen to be best in the “lower right” domain of the detector energy gates, as formatted by Table 2. Another signal property of interest, however, is signal *amplitude*, which we can examine by considering the relative fractions of total signal (normalized by the maximum value in the $[200,500]\text{-}\text{keV}$ gate). This variation is depicted in Table 7.

Although the monotonic increase along the horizontal rows is the same as for the signal “quality” in Table 6, the monotonic variations along the vertical columns and the diagonals for the signal amplitude in Table 7 are opposite to the general variations of the signal quality in Table 6. Thus, the highest quality signals are seen to correspond, unfortunately, to the lowest amplitudes.

IV. SOURCE-DETECTOR SPACING

After reporting my detector gating findings (see Section III) to GRI,⁴ I received feed-back concerning the extent of the energy range I chose for my investigation. It was suggested that energies below my chosen threshold of 200keV (i.e., $\sim 40\text{--}85\text{keV}$), in the photoelectric regime, are useful in characterizing the lithology of a formation.⁵ I, therefore, adopted $[40,500]\text{keV}$ as the total detector energy range for the remainder of my investigations.

My aim for this study was to characterize the behavior of the detected signal, as a function of the source-detector spacing, for a γ source energy of 4MeV . The specifications for the environment in this study were the same as for the gating study (see Section III).

A. Computed Results

Since some logging tools are designed with shorter spacing than my original choice of 50cm , I decided to compare spacings in the range $[20,50]\text{cm}$. I computed the detected signals for spacings of: 20, 30, 40, and 50cm , all other problem parameters being held constant, except for number of histories per production run. For each run, I chose a sufficient number of histories so that formation signals (in terms of flux at the point detector) were computed to within $\sim 5\%$ relative standard error. The computed results are presented in Tables 8–11, with computed relative standard errors shown in parentheses.

B. Analysis of Results

The computed relative standard errors are satisfactory (i.e., < 0.05) for most of the energy-binned results, and marginally acceptable (i.e., $0.05 - 0.10$) for a few. Only three values of casing signal have computed errors exceeding 0.10, which makes these values questionable. Despite the relative inadequacy of the latter three tabular entries, we can derive some useful information from the bulk of these results.

Table 8: Detected Signal [flux] for Source–Detector Spacing of 20cm
(computed relative standard error in parenthesis)

Gate [keV]	Casing Signal	Formation Signal	Total Signal
[50,100]	6.92906E-08 (.0136)	7.60601E-08 (.0067)	1.45351E-07 (.0081)
[100,150]	2.38636E-07 (.0115)	3.28822E-07 (.0063)	5.67458E-07 (.0070)
[150,200]	1.94858E-07 (.0150)	3.31781E-07 (.0077)	5.26639E-07 (.0084)
[200,250]	1.41144E-07 (.0192)	2.95033E-07 (.0086)	4.36177E-07 (.0095)
[250,300]	1.02959E-07 (.0239)	2.62320E-07 (.0092)	3.65279E-07 (.0104)
[300,350]	6.51586E-08 (.0313)	1.65911E-07 (.0121)	2.31069E-07 (.0135)
[350,400]	3.34904E-08 (.0470)	8.03010E-08 (.0188)	1.13791E-07 (.0206)
[400,450]	1.39950E-08 (.0739)	3.50743E-08 (.0325)	4.90692E-08 (.0340)
[450,500]	4.16902E-09 (.1365)	1.58786E-08 (.0560)	2.00477E-08 (.0563)
[40,500]	8.63768E-07 (.0102)	1.59118E-06 (.0052)	2.45495E-06 (.0060)

Table 9: Detected Signal [flux] for Source–Detector Spacing of 30cm
(computed relative standard error in parenthesis)

Gate [keV]	Casing Signal	Formation Signal	Total Signal
[50,100]	1.35905E-08 (.0184)	1.52820E-08 (.0094)	2.88725E-08 (.0115)
[100,150]	4.71527E-08 (.0159)	6.46518E-08 (.0097)	1.11804E-07 (.0107)
[150,200]	3.71100E-08 (.0205)	6.31284E-08 (.0114)	1.00238E-07 (.0126)
[200,250]	2.71254E-08 (.0264)	5.49999E-08 (.0135)	8.21253E-08 (.0149)
[250,300]	2.10915E-08 (.0342)	4.66989E-08 (.0154)	6.77904E-08 (.0176)
[300,350]	1.30834E-08 (.0480)	3.35806E-08 (.0186)	4.66640E-08 (.0218)
[350,400]	7.00473E-09 (.0646)	2.05580E-08 (.0252)	2.75627E-08 (.0279)
[400,450]	3.28124E-09 (.0979)	9.35671E-09 (.0382)	1.26380E-08 (.0428)
[450,500]	1.40131E-09 (.1691)	4.56661E-09 (.0618)	5.96793E-09 (.0668)
[40,500]	1.70861E-07 (.0161)	3.12823E-07 (.0093)	4.83684E-07 (.0106)

Table 10: Detected Signal [flux] for Source–Detector Spacing of 40cm
(computed relative standard error in parenthesis)

Gate [keV]	Casing Signal	Formation Signal	Total Signal
[50,100]	2.86323E-09 (.0174)	3.23748E-09 (.0110)	6.10071E-09 (.0123)
[100,150]	9.77831E-09 (.0161)	1.37486E-08 (.0110)	2.35269E-08 (.0119)
[150,200]	8.03219E-09 (.0201)	1.35119E-08 (.0128)	2.15441E-08 (.0137)
[200,250]	5.93830E-09 (.0259)	1.17393E-08 (.0148)	1.76776E-08 (.0160)
[250,300]	4.24300E-09 (.0328)	9.84928E-09 (.0173)	1.40923E-08 (.0186)
[300,350]	2.78342E-09 (.0447)	7.42469E-09 (.0206)	1.02081E-08 (.0225)
[350,400]	1.61492E-09 (.0648)	4.78364E-09 (.0272)	6.39856E-09 (.0298)
[400,450]	8.99328E-10 (.0888)	2.47025E-09 (.0383)	3.36958E-09 (.0420)
[450,500]	4.42697E-10 (.1362)	1.26122E-09 (.0625)	1.70392E-09 (.0652)
[40,500]	3.65972E-08 (.0177)	6.80263E-08 (.0116)	1.04624E-07 (.0128)

Table 11: Detected Signal [flux] for Source–Detector Spacing of 50cm
(computed relative standard error in parenthesis)

Gate [keV]	Casing Signal	Formation Signal	Total Signal
[50,100]	6.20554E-10 (.0160)	7.12801E-10 (.0106)	1.33335E-09 (.0113)
[100,150]	2.16304E-09 (.0143)	3.04605E-09 (.0099)	5.20909E-09 (.0107)
[150,200]	1.77847E-09 (.0175)	2.99043E-09 (.0110)	4.76890E-09 (.0119)
[200,250]	1.26700E-09 (.0217)	2.56073E-09 (.0125)	3.82772E-09 (.0135)
[250,300]	9.61323E-10 (.0272)	2.13332E-09 (.0144)	3.09464E-09 (.0157)
[300,350]	6.69328E-10 (.0355)	1.64474E-09 (.0172)	2.31406E-09 (.0189)
[350,400]	4.08880E-10 (.0507)	1.12212E-09 (.0211)	1.53100E-09 (.0236)
[400,450]	2.16963E-10 (.0736)	6.77862E-10 (.0282)	8.94825E-10 (.0321)
[450,500]	1.26972E-10 (.0932)	3.59735E-10 (.0381)	4.86707E-10 (.0422)
[40,500]	8.21348E-09 (.0152)	1.52478E-08 (.0104)	2.34613E-08 (.0113)

One general observation is that the formation signal is negligible below 50 keV , and the casing signal is insignificant, at best, in the implicit $[40,50]\text{ keV}$ gate or bin. This observation can be verified by summing the individual contributions in the 50-keV -spaced bins and comparing to the corresponding total values in the $[40,500]\text{-keV}$ bins. The obvious explanation is that at $\sim 40\text{ keV}$, the 0.315 in -thick iron casing represents ~ 16 photon mean free paths.

If we consider the ratios of formation to total signal, we can construct the contents of Table 12. As noted in the detector gating study (see Section III), the formation fraction is a measure of signal quality in the context of this project. Hence, it is of considerable interest that this measure appears to be largely *insensitive* to source detector separation, at least in the $[20,50]\text{ cm}$ range of this study. I believe such a result contradicts conventional wisdom, which holds that greater source–detector separation yields “purer” characterization of formation density (but see Section VII for clarification of this observation).

As before, let us also examine the dependence of “signal amplitude” on source–detector separation. The contents of Table 13 present the formation signals, normalized to the total computed value for the 20 cm separation, which represents the maximum computed in this study. Here we observe a significant, inversely-proportional, dependence on source–detector separation. This finding is in complete agreement with conventional wisdom.

As a consequence of this observed behavior of formation fraction and amplitude, these results appear to refute the traditionally held belief in the trade-off between quality and quantity of signal (but, again, see the clarification in Section VII). This result, therefore, seems to be very positive in support of the objectives for this project.

Table 12: Formation Signal Fraction for Varying Source-Detector Spacing

Gate[keV]	20cm	30cm	40cm	50cm
[50,100]	0.523	0.529	0.531	0.535
[100,150]	0.579	0.578	0.584	0.585
[150,200]	0.630	0.630	0.627	0.627
[200,250]	0.676	0.670	0.664	0.669
[250,300]	0.718	0.689	0.699	0.689
[300,350]	0.718	0.720	0.727	0.711
[350,400]	0.706	0.746	0.748	0.733
[400,450]	0.715	0.740	0.733	0.758
[450,500]	0.792	0.765	0.740	0.739
[40,500]	0.648	0.647	0.650	0.650

Table 13: Formation Signal Amplitude for Varying Source-Detector Spacing

Gate[keV]	20cm	30cm	40cm	50cm
[50,100]	0.048	0.010	0.002	0.000
[100,150]	0.207	0.041	0.009	0.002
[150,200]	0.209	0.040	0.008	0.002
[200,250]	0.185	0.035	0.007	0.002
[250,300]	0.165	0.029	0.006	0.001
[300,350]	0.104	0.021	0.005	0.001
[350,400]	0.050	0.013	0.003	0.001
[400,450]	0.022	0.006	0.002	0.000
[450,500]	0.010	0.003	0.001	0.000
[40,500]	1.0	0.197	0.043	0.010

V. TOOL STANDOFF

In a typical well-logging operation, provision is made to ensure contact between tool and casing, but contact is not guaranteed. The present parametric study gauged the effect of imperfect contact (i.e., tool 'standoff') on the detected signal.

My aim for this study was to characterize the behavior of the detected signal, as a function of the tool standoff, for a γ source energy of 4 MeV . The specifications for the environment in this study were the same as for the gating study (see Section III). The overall detector energy gate was $[40,500]\text{ keV}$, and, as a result of the spacing study (see Section IV), I specified a source-detector spacing of 20 cm , to take advantage of the much higher signal amplitude at the shorter spacing.

I simulated tool standoff by reducing the tool outer diameter from the inner diameter of the casing, which corresponds to zero standoff. I kept the cone of emission for the source photons constant and equal to the value of the opening for the default zero standoff case, thereby maintaining constant source collimation. By reducing the value of tool diameter, I introduced a sheath of borehole water between the outer surface of the tool and the inner surface of the casing. The resulting environment became a 3-regime material domain and the detected signal comprised three components: borehole, casing, and formation.

A. Computed Results

I computed gated signals for a series of measured standoffs: 0, 1, 2, 3, 4, and 5 cm . The computed results are presented in Tables 14–19. My computing strategy was to ensure better than 1% computed relative standard error for the total signal (flux) in the overall energy gate $[40,500]\text{ keV}$. In fact, I succeeded in computing all but one of the component signals to better than 1% in the overall gate, the lone exception being 1.02% for the zero-standoff casing signal.

My strategy produced an ensemble of computed signals, which is largely of satisfactory precision (i.e., $<5\%$ relative standard error for flux-at-a-point estimation). Only a few high-energy-gate results are marginally acceptable (5–10% relative standard error) and a handful are unreliable ($>10\%$). The fine precision for the bulk of these results makes them useful for the analysis that follows.

Table 14: Detected Signal Components for zero Tool Standoff
(computed relative standard error in parenthesis)

Gate [keV]	Borehole Signal [flux]	Casing Signal [flux]	Formation Signal [flux]	Total Signal [flux]
50,100	0.0	6.92906E-08 (.0136)	7.60601E-08 (.0067)	1.45351E-07 (.0081)
100,150	0.0	2.38636E-07 (.0115)	3.28822E-07 (.0063)	5.67458E-07 (.0070)
150,200	0.0	1.94858E-07 (.0150)	3.31781E-07 (.0077)	5.26639E-07 (.0084)
200,250	0.0	1.41144E-07 (.0192)	2.95033E-07 (.0086)	4.36177E-07 (.0095)
250,300	0.0	1.02959E-07 (.0239)	2.62320E-07 (.0092)	3.65279E-07 (.0104)
300,350	0.0	6.51586E-08 (.0313)	1.65911E-07 (.0121)	2.31069E-07 (.0135)
350,400	0.0	3.34904E-08 (.0470)	8.03010E-08 (.0188)	1.13791E-07 (.0206)
400,450	0.0	1.39950E-08 (.0739)	3.50743E-08 (.0325)	4.90692E-08 (.0340)
450,500	0.0	4.16902E-09 (.1365)	1.58786E-08 (.0560)	2.00477E-08 (.0563)
40,500	0.0	8.63768E-07 (.0102)	1.59118E-06 (.0052)	2.45495E-06 (.0060)

Table 15: Detected Signal Components for 1cm Tool Standoff
(computed relative standard error in parenthesis)

Gate [keV]	Borehole Signal [flux]	Casing Signal [flux]	Formation Signal [flux]	Total Signal [flux]
50,100	4.90005E-08 (.0209)	7.63697E-08 (.0124)	7.05924E-08 (.0061)	1.95963E-07 (.0090)
100,150	8.82420E-08 (.0150)	2.49127E-07 (.0104)	3.16722E-07 (.0058)	6.54090E-07 (.0067)
150,200	6.21530E-08 (.0192)	2.03202E-07 (.0136)	3.29725E-07 (.0069)	5.95080E-07 (.0078)
200,250	4.47127E-08 (.0241)	1.51337E-07 (.0174)	2.93623E-07 (.0080)	4.89673E-07 (.0090)
250,300	3.21787E-08 (.0288)	1.09579E-07 (.0225)	2.68651E-07 (.0085)	4.10409E-07 (.0099)
300,350	1.87561E-08 (.0385)	7.13037E-08 (.0297)	1.77450E-07 (.0106)	2.67510E-07 (.0124)
350,400	7.83120E-09 (.0648)	3.72807E-08 (.0431)	9.19418E-08 (.0160)	1.37054E-07 (.0186)
400,450	3.78607E-09 (.1002)	1.54355E-08 (.0710)	4.01944E-08 (.0275)	5.94160E-08 (.0306)
450,500	1.74893E-09 (.1546)	7.03618E-09 (.1197)	2.10935E-08 (.0543)	2.98786E-08 (.0547)
40,500	3.08958E-07 (.0118)	9.20757E-07 (.0094)	1.60999E-06 (.0049)	2.83971E-06 (.0058)

Table 16: Detected Signal Components for 2cm Tool Standoff
(computed relative standard error in parenthesis)

Gate [keV]	Borehole Signal [flux]	Casing Signal [flux]	Formation Signal [flux]	Total Signal [flux]
50,100	1.86177E-07 (.0148)	9.78740E-08 (.0111)	6.85347E-08 (.0058)	3.52586E-07 (.0096)
100,150	2.66398E-07 (.0118)	2.92137E-07 (.0092)	3.17759E-07 (.0054)	8.76293E-07 (.0065)
150,200	1.69432E-07 (.0145)	2.33165E-07 (.0119)	3.35889E-07 (.0064)	7.38486E-07 (.0072)
200,250	1.28322E-07 (.0174)	1.79859E-07 (.0153)	3.07124E-07 (.0076)	6.15304E-07 (.0083)
250,300	9.14716E-08 (.0216)	1.24710E-07 (.0200)	2.82562E-07 (.0082)	4.98743E-07 (.0093)
300,350	5.43980E-08 (.0290)	8.07739E-08 (.0276)	1.97842E-07 (.0096)	3.33014E-07 (.0115)
350,400	2.58201E-08 (.0435)	4.18462E-08 (.0399)	1.05044E-07 (.0143)	1.72711E-07 (.0163)
400,450	1.08143E-08 (.0732)	1.89366E-08 (.0647)	5.36980E-08 (.0237)	8.34489E-08 (.0267)
450,500	4.74443E-09 (.1251)	1.08606E-08 (.0992)	2.52428E-08 (.0437)	4.08478E-08 (.0464)
40,500	9.42917E-07 (.0094)	1.08051E-06 (.0084)	1.69370E-06 (.0047)	3.71622E-06 (.0055)

Table 17: Detected Signal Components for 3cm Tool Standoff
(computed relative standard error in parenthesis)

Gate [keV]	Borehole Signal [flux]	Casing Signal [flux]	Formation Signal [flux]	Total Signal [flux]
50,100	4.77794E-07 (.0105)	1.25679E-07 (.0093)	6.49006E-08 (.0059)	6.68373E-07 (.0085)
100,150	5.64552E-07 (.0093)	3.41938E-07 (.0083)	3.18057E-07 (.0055)	1.22455E-06 (.0062)
150,200	3.55769E-07 (.0113)	2.74113E-07 (.0110)	3.47026E-07 (.0066)	9.76908E-07 (.0070)
200,250	2.55271E-07 (.0137)	2.01676E-07 (.0146)	3.18685E-07 (.0078)	7.75633E-07 (.0081)
250,300	1.77118E-07 (.0172)	1.38797E-07 (.0199)	2.94754E-07 (.0083)	6.10670E-07 (.0093)
300,350	1.13462E-07 (.0229)	8.95963E-08 (.0278)	2.23696E-07 (.0096)	4.26754E-07 (.0113)
350,400	6.23596E-08 (.0327)	4.90600E-08 (.0390)	1.23216E-07 (.0149)	2.34635E-07 (.0164)
400,450	2.59056E-08 (.0520)	2.56304E-08 (.0565)	6.69069E-08 (.0231)	1.18443E-07 (.0238)
450,500	1.13067E-08 (.0933)	1.41804E-08 (.0892)	3.30769E-08 (.0388)	5.85640E-08 (.0405)
40,500	2.06458E-06 (.0077)	1.26141E-06 (.0078)	1.79032E-06 (.0046)	5.11630E-06 (.0053)

Table 18: Detected Signal Components for 4cm Tool Standoff
(computed relative standard error in parenthesis)

Gate [keV]	Borehole Signal [flux]	Casing Signal [flux]	Formation Signal [flux]	Total Signal [flux]
50,100	1.06806E-06 (.0078)	1.59545E-07 (.0075)	6.29035E-08 (.0059)	1.29051E-06 (.0070)
100,150	1.06802E-06 (.0073)	4.11925E-07 (.0068)	3.29902E-07 (.0054)	1.80985E-06 (.0056)
150,200	6.60894E-07 (.0089)	3.32940E-07 (.0091)	3.67942E-07 (.0063)	1.36178E-06 (.0063)
200,250	4.57327E-07 (.0108)	2.36476E-07 (.0123)	3.42413E-07 (.0073)	1.03622E-06 (.0072)
250,300	3.14107E-07 (.0134)	1.71238E-07 (.0163)	3.24118E-07 (.0080)	8.09463E-07 (.0084)
300,350	2.02329E-07 (.0174)	1.06689E-07 (.0219)	2.71276E-07 (.0084)	5.80294E-07 (.0095)
350,400	1.23637E-07 (.0234)	6.25945E-08 (.0307)	1.47325E-07 (.0126)	3.33557E-07 (.0132)
400,450	6.24025E-08 (.0340)	3.72236E-08 (.0425)	8.28543E-08 (.0183)	1.82480E-07 (.0186)
450,500	2.59286E-08 (.0592)	2.16454E-08 (.0664)	4.82460E-08 (.0311)	9.58200E-08 (.0314)
40,500	4.05504E-06 (.0063)	1.54178E-06 (.0066)	1.97698E-06 (.0045)	7.57380E-06 (.0049)

Table 19: Detected Signal Components for 5cm Tool Standoff
(computed relative standard error in parenthesis)

Gate [keV]	Borehole Signal [flux]	Casing Signal [flux]	Formation Signal [flux]	Total Signal [flux]
50,100	2.11024E-06 (.0063)	1.91986E-07 (.0061)	5.88893E-08 (.0055)	2.36111E-06 (.0059)
100,150	1.83984E-06 (.0061)	4.81810E-07 (.0055)	3.29359E-07 (.0048)	2.65101E-06 (.0050)
150,200	1.11021E-06 (.0074)	3.86172E-07 (.0072)	3.82349E-07 (.0054)	1.87873E-06 (.0054)
200,250	7.31584E-07 (.0091)	2.83472E-07 (.0097)	3.65106E-07 (.0062)	1.38016E-06 (.0063)
250,300	5.04267E-07 (.0113)	2.04687E-07 (.0125)	3.51455E-07 (.0065)	1.06041E-06 (.0071)
300,350	3.44627E-07 (.0141)	1.34027E-07 (.0161)	3.21991E-07 (.0063)	8.00645E-07 (.0079)
350,400	2.22434E-07 (.0184)	8.85729E-08 (.0213)	1.94602E-07 (.0087)	5.05609E-07 (.0104)
400,450	1.36048E-07 (.0255)	5.94257E-08 (.0264)	1.05646E-07 (.0133)	3.01119E-07 (.0143)
450,500	6.59107E-08 (.0364)	3.98330E-08 (.0354)	6.30958E-08 (.0213)	1.68840E-07 (.0206)
40,500	7.25139E-06 (.0051)	1.87218E-06 (.0051)	2.17249E-06 (.0036)	1.12961E-05 (.0041)

B. Analysis of Results

If we normalize the component signals of Tables 14–19 by their corresponding totals, and group the resulting signal fractions by specific energy gates, we produce the contents of Tables 20–29. As noted previously, the formation fraction is a measure of detected signal quality.

It is not surprising that increasing tool standoff effects a degradation of formation signal fraction, which I have defined to be the detected signal quality. What is perhaps startling, however, is the degree to which tool standoff effects the degradation of detected signal quality. Note that for the lowest gate considered (i.e., $[50,100] \text{ keV}$ of Table 20) a mere 2cm standoff reduces the formation fraction from 52% to 19% and enhances the borehole fraction from zero to 53%. At 5cm, the formation fraction has virtually vanished and the borehole fraction comprises 89% of the detected signal.

The formation fraction fares somewhat better in the higher-energy gates. In the highest gate (i.e., $[450,500] \text{ keV}$ of Table 28), the formation signal still dominates for a 2cm standoff; at 5cm, formation and borehole effect equivalent signal fractions.

It is convenient to summarize these findings by considering the influence of tool standoff on the overall energy gate, as described by Table 29. At zero standoff, the formation accounts for 65% of the detected signal, a relatively good quality. At 1cm, the formation fraction is still a “majority” of 57%. At 2cm, the quality has fallen to less than a majority 46%. At 3cm, the quality is lower than the borehole fraction. At 4cm, the borehole fraction has reached a majority of 54%. And at 5cm, the formation fraction is virtually indistinguishable from the casing fraction, with 64% of the detected signal characteristic of the borehole. Thus, within 5cm of standoff, the detected signal has degraded from a formation “characteristic” to a borehole characteristic.

Table 20: Signal Fractions for the (50,100)- keV Gate

Standoff	Borehole	Casing	Formation
0cm	0.0	0.477	0.523
1cm	0.250	0.390	0.360
2cm	0.528	0.278	0.194
3cm	0.715	0.188	0.097
4cm	0.828	0.124	0.049
5cm	0.894	0.081	0.025

Table 21: Signal Fractions for the (100,150)- keV Gate

Standoff	Borehole	Casing	Formation
0cm	0.0	0.421	0.579
1cm	0.135	0.381	0.360
2cm	0.304	0.333	0.363
3cm	0.461	0.279	0.260
4cm	0.590	0.228	0.182
5cm	0.694	0.182	0.124

Table 22: Signal Fractions for the (150,200)- keV Gate

Standoff	Borehole	Casing	Formation
0cm	0.0	0.370	0.630
1cm	0.194	0.341	0.554
2cm	0.229	0.316	0.455
3cm	0.364	0.281	0.355
4cm	0.485	0.244	0.270
5cm	0.591	0.206	0.204

Table 23: Signal Fractions for the (200,250)- keV Gate

Standoff	Borehole	Casing	Formation
0cm	0.0	0.324	0.676
1cm	0.091	0.309	0.600
2cm	0.209	0.292	0.499
3cm	0.329	0.260	0.411
4cm	0.441	0.228	0.330
5cm	0.530	0.205	0.265

Table 24: Signal Fractions for the (250,300)- keV Gate

Standoff	Borehole	Casing	Formation
0cm	0.0	0.282	0.718
1cm	0.078	0.267	0.655
2cm	0.183	0.250	0.567
3cm	0.290	0.227	0.483
4cm	0.388	0.212	0.400
5cm	0.476	0.193	0.331

Table 25: Signal Fractions for the (300,350)- keV Gate

Standoff	Borehole	Casing	Formation
0cm	0.0	0.282	0.718
1cm	0.070	0.267	0.663
2cm	0.163	0.243	0.594
3cm	0.266	0.210	0.524
4cm	0.349	0.184	0.467
5cm	0.591	0.206	0.204

Table 26: Signal Fractions for the (350,400)- keV Gate

Standoff	Borehole	Casing	Formation
0cm	0.0	0.294	0.706
1cm	0.057	0.272	0.671
2cm	0.149	0.242	0.608
3cm	0.266	0.209	0.525
4cm	0.371	0.188	0.442
5cm	0.440	0.175	0.385

Table 27: Signal Fractions for the (400,450)- keV Gate

Standoff	Borehole	Casing	Formation
0cm	0.0	0.285	0.715
1cm	0.064	0.260	0.676
2cm	0.130	0.227	0.643
3cm	0.219	0.216	0.565
4cm	0.342	0.204	0.454
5cm	0.452	0.197	0.351

Table 28: Signal Fractions for the (450,500)-keV Gate

Standoff	Borehole	Casing	Formation
0cm	0.0	0.208	0.792
1cm	0.059	0.235	0.706
2cm	0.116	0.266	0.618
3cm	0.193	0.242	0.565
4cm	0.271	0.226	0.504
5cm	0.390	0.236	0.374

Table 29: Signal Fractions for the (40,500)-keV Gate

Standoff	Borehole	Casing	Formation
0cm	0.0	0.352	0.648
1cm	0.109	0.324	0.567
2cm	0.253	0.291	0.456
3cm	0.404	0.247	0.350
4cm	0.535	0.204	0.261
5cm	0.642	0.166	0.192

VI. EFFECTS OF CONTAINING BARRIER

The tool must be capable of identifying the formation density, not only beyond the borehole casing but also beyond its surrounding cement barrier. My initial effort, in the context of this more complicated environment, did not (for simplicity) distinguish between the material content of the formation and the ‘cement’ barrier. Subsequently, after gauging its effect to be significant, I introduced a realistic cement specification (see following sections).

My aim for this initial investigation was to characterize the behavior of the detected signal, as a function of source energy and barrier thickness. The default specifications for the environment (see Subsection C of Section II) applied, except that the source–detector spacing was 20cm . The overall detector energy gate was $[40,500]\text{keV}$.

A. Computed Results

I performed a broad survey involving:

- 4 source energies —
 662keV ; 1.33MeV ; 4MeV ; 20MeV ;
- 13 barrier thicknesses —
 $0\text{--}12\text{cm}$, in 1cm increments.

This 52-production-run survey led to an intensive usage of the LANL IBM cluster in the open computing partition. In one afternoon, I was able to complete a total of 18cpu-hrs of single-node computing. Several days later, I accomplished more than 45cpu-hrs of single-node computing overnight.

The computed results are presented in Tables 30–33. My computing strategy was to ensure better than 2% computed relative standard error for the total signal (flux) in the overall energy gate $[40,500]\text{keV}$. In fact, I succeeded in computing all the component signals to better than 2% in the overall gate.

Table 30: Detected Signal Components for the (40,500)-keV Gate
Source Energy = 662keV
(computed relative standard error in parenthesis)

Barrier [cm]	Casing Signal [flux]	Barrier Signal [flux]	Formation Signal [flux]	Total Signal [flux]
0	5.63983E-07 (.0175)	0.0	1.06496E-06 (.0086)	1.62894E-06 (.0102)
1	5.63983E-07 (.0175)	2.04138E-07 (.0192)	8.60818E-07 (.0082)	1.62894E-06 (.0102)
2	5.63983E-07 (.0175)	3.78211E-07 (.0152)	6.86744E-07 (.0078)	1.62894E-06 (.0102)
3	5.63983E-07 (.0175)	5.28691E-07 (.0131)	5.36265E-07 (.0076)	1.62894E-06 (.0102)
4	5.63983E-07 (.0175)	6.50513E-07 (.0118)	4.14442E-07 (.0076)	1.62894E-06 (.0102)
5	5.63983E-07 (.0175)	7.47345E-07 (.0109)	3.17610E-07 (.0076)	1.62894E-06 (.0102)
6	5.63983E-07 (.0175)	8.23990E-07 (.0103)	2.40965E-07 (.0079)	1.62894E-06 (.0102)
7	5.63983E-07 (.0175)	8.84371E-07 (.0098)	1.80585E-07 (.0082)	1.62894E-06 (.0102)
8	5.63983E-07 (.0175)	9.30408E-07 (.0095)	1.34547E-07 (.0088)	1.62894E-06 (.0102)
9	5.63983E-07 (.0175)	9.65740E-07 (.0092)	9.92152E-08 (.0096)	1.62894E-06 (.0102)
10	5.63983E-07 (.0175)	9.93475E-07 (.0091)	7.14803E-08 (.0109)	1.62894E-06 (.0102)
11	5.63983E-07 (.0175)	1.01394E-06 (.0089)	5.10181E-08 (.0113)	1.62894E-06 (.0102)
12	5.63983E-07 (.0175)	1.02940E-06 (.0088)	3.55590E-08 (.0121)	1.62894E-06 (.0102)

Table 31: Detected Signal Components for the (40,500)-keV Gate
Source Energy = 1.33MeV
(computed relative standard error in parenthesis)

Barrier [cm]	Casing Signal [flux]	Barrier Signal [flux]	Formation Signal [flux]	Total Signal [flux]
0	7.91708E-07 (.0160)	0.0	1.46233E-06 (.0080)	2.25404E-06 (.0094)
1	7.91708E-07 (.0160)	2.66512E-07 (.0176)	1.19582E-06 (.0076)	2.25404E-06 (.0094)
2	7.91708E-07 (.0160)	5.03114E-07 (.0140)	9.59214E-07 (.0074)	2.25404E-06 (.0094)
3	7.91708E-07 (.0160)	6.95571E-07 (.0122)	7.66757E-07 (.0072)	2.25404E-06 (.0094)
4	7.91708E-07 (.0160)	8.55277E-07 (.0110)	6.07052E-07 (.0072)	2.25404E-06 (.0094)
5	7.91708E-07 (.0160)	9.84231E-07 (.0102)	4.78097E-07 (.0072)	2.25404E-06 (.0094)
6	7.91708E-07 (.0160)	1.08966E-06 (.0097)	3.72673E-07 (.0073)	2.25404E-06 (.0094)
7	7.91708E-07 (.0160)	1.17463E-06 (.0092)	2.87701E-07 (.0076)	2.25404E-06 (.0094)
8	7.91708E-07 (.0160)	1.24171E-06 (.0089)	2.20621E-07 (.0079)	2.25404E-06 (.0094)
9	7.91708E-07 (.0160)	1.29464E-06 (.0087)	1.67686E-07 (.0084)	2.25404E-06 (.0094)
10	7.91708E-07 (.0160)	1.33714E-06 (.0086)	1.25188E-07 (.0092)	2.25404E-06 (.0094)
11	7.91708E-07 (.0160)	1.36975E-06 (.0084)	9.25791E-08 (.0095)	2.25404E-06 (.0094)
12	7.91708E-07 (.0160)	1.39487E-06 (.0083)	6.74618E-08 (.0098)	2.25404E-06 (.0094)

Table 32: Detected Signal Components for the (40,500)-keV Gate
Source Energy = 4.0 MeV
(computed relative standard error in parenthesis)

Barrier [cm]	Casing Signal [flux]	Barrier Signal [flux]	Formation Signal [flux]	Total Signal [flux]
0	8.64544E-07 (.0137)	0.0	1.58852E-06 (.0069)	2.45307E-06 (.0079)
1	8.64544E-07 (.0137)	2.78886E-07 (.0161)	1.30964E-06 (.0066)	2.45307E-06 (.0079)
2	8.64544E-07 (.0137)	5.20372E-07 (.0123)	1.06815E-06 (.0065)	2.45307E-06 (.0079)
3	8.64544E-07 (.0137)	7.27769E-07 (.0106)	8.60755E-07 (.0063)	2.45307E-06 (.0079)
4	8.64544E-07 (.0137)	8.94244E-07 (.0096)	6.94279E-07 (.0063)	2.45307E-06 (.0079)
5	8.64544E-07 (.0137)	1.03296E-06 (.0089)	5.55564E-07 (.0063)	2.45307E-06 (.0079)
6	8.64544E-07 (.0137)	1.14695E-06 (.0084)	4.41572E-07 (.0064)	2.45307E-06 (.0079)
7	8.64544E-07 (.0137)	1.23916E-06 (.0081)	3.49363E-07 (.0065)	2.45307E-06 (.0079)
8	8.64544E-07 (.0137)	1.31298E-06 (.0078)	2.75547E-07 (.0067)	2.45307E-06 (.0079)
9	8.64544E-07 (.0137)	1.37366E-06 (.0076)	2.14866E-07 (.0070)	2.45307E-06 (.0079)
10	8.64544E-07 (.0137)	1.42327E-06 (.0075)	1.65255E-07 (.0076)	2.45307E-06 (.0079)
11	8.64544E-07 (.0137)	1.46323E-06 (.0073)	1.25292E-07 (.0079)	2.45307E-06 (.0079)
12	8.64544E-07 (.0137)	1.49366E-06 (.0072)	9.48665E-08 (.0084)	2.45307E-06 (.0079)

Table 33: Detected Signal Components for the (40,500)-keV Gate
Source Energy = 20.0 MeV
(computed relative standard error in parenthesis)

Barrier [cm]	Casing Signal [flux]	Barrier Signal [flux]	Formation Signal [flux]	Total Signal [flux]
0	1.49124E-06 (.0080)	0.0	2.72904E-06 (.0049)	4.22028E-06 (.0054)
1	1.49124E-06 (.0080)	4.86357E-07 (.0090)	2.24268E-06 (.0048)	4.22028E-06 (.0054)
2	1.49124E-06 (.0080)	9.03100E-07 (.0073)	1.82594E-06 (.0047)	4.22028E-06 (.0054)
3	1.49124E-06 (.0080)	1.25506E-06 (.0066)	1.47398E-06 (.0046)	4.22028E-06 (.0054)
4	1.49124E-06 (.0080)	1.54642E-06 (.0061)	1.18262E-06 (.0047)	4.22028E-06 (.0054)
5	1.49124E-06 (.0080)	1.78197E-06 (.0058)	9.47071E-07 (.0047)	4.22028E-06 (.0054)
6	1.49124E-06 (.0080)	1.97409E-06 (.0056)	7.54951E-07 (.0048)	4.22028E-06 (.0054)
7	1.49124E-06 (.0080)	2.12788E-06 (.0055)	6.01160E-07 (.0049)	4.22028E-06 (.0054)
8	1.49124E-06 (.0080)	2.25167E-06 (.0053)	4.77370E-07 (.0050)	4.22028E-06 (.0054)
9	1.49124E-06 (.0080)	2.35262E-06 (.0053)	3.76426E-07 (.0052)	4.22028E-06 (.0054)
10	1.49124E-06 (.0080)	2.43584E-06 (.0052)	2.93198E-07 (.0055)	4.22028E-06 (.0054)
11	1.49124E-06 (.0080)	2.50312E-06 (.0051)	2.25918E-07 (.0057)	4.22028E-06 (.0054)
12	1.49124E-06 (.0080)	2.55583E-06 (.0051)	1.73206E-07 (.0060)	4.22028E-06 (.0054)

Table 34: Formation-Signal Fractions for the (40,500)- $k\epsilon V$ Gate

Barrier	662 $k\epsilon V$	1.33 $M\epsilon V$	4.0 $M\epsilon V$	20.0 $M\epsilon V$
0 cm	0.654	0.649	0.648	0.647
1 cm	0.528	0.531	0.534	0.531
2 cm	0.422	0.426	0.435	0.433
3 cm	0.329	0.340	0.351	0.349
4 cm	0.254	0.269	0.283	0.280
5 cm	0.195	0.212	0.226	0.224
6 cm	0.148	0.165	0.180	0.179
7 cm	0.111	0.128	0.142	0.142
8 cm	0.083	0.098	0.112	0.113
9 cm	0.061	0.074	0.088	0.089
10 cm	0.044	0.056	0.067	0.069
11 cm	0.031	0.041	0.051	0.054
12 cm	0.022	0.030	0.039	0.041

B. Analysis of Results

If we normalize the formation signals of Tables 30–33 by their corresponding totals, and group the resulting signal fractions by source energy, we produce the contents of Table 34. As noted previously, the formation fraction is a measure of detected signal quality.

The 52-production-run survey indicates that the formation-signal fraction is relatively insensitive to source energy. Inspection of the Table-34 results indicates an absence of significant advantage for any of the source energies, based on signal quality alone. Nevertheless, a linac-produced 4- $M\epsilon V$ source would offer much higher source strength and an obvious safety advantage over the radioactive sources.

It is also evident that for typical barrier thicknesses, most of the detected signal is attributable to casing and barrier, which, in this context, is noise. The latter finding suggests that a detection scheme based on the absolute signal, at a 20 cm source-detector spacing, would be difficult to accomplish.

VII. DOUBLE-DETECTOR SCHEME

Since a single detector at 20cm is faced with the problem of an inferior signal-to-noise ratio (see Section VI), I proceeded to investigate the efficacy of a detection scheme that would rely on the relative signals detected at a pair of detector positions, one "near" the source and one "far" from the source. The near and far values that I chose were 20cm and 50cm, respectively. I also refined the investigation by including a real cement specification for the barrier beyond the borehole casing (see Appendix B).

A. Computed Results

The computed results for three source energies and three porosity values are presented in Tables 35-37. Inspection of the contents in these tables leads to several observations.

The near-detector signal is largely insensitive to variation in formation porosity, whereas the far-detector signal is quite sensitive to porosity. This porosity sensitivity becomes somewhat more pronounced as the source energy *decreases*, although the observed sensitivity is sufficient for discrimination at all three source energies examined. The marginal improvement in porosity sensitivity for the lowest energy, however, is outweighed by significant degradation in signal amplitude.

Table 35: Porosity Discrimination:
Total Flux in (40,500)- keV Gate
Near Detector @ 20cm; Far Detector @ 50cm;
7-cm Cement Barrier; 4.0-MeV Photon Source

Porosity	Near Signal	Far Signal	Far/Near
0%	1.19529E-06 (.0103)	3.18031E-09 (.0207)	0.00266
35%	1.24337E-06 (.0107)	7.05121E-09 (.0164)	0.00567
100%	1.20488E-06 (.0096)	3.42583E-08 (.0122)	0.02843

Table 36: Porosity Discrimination:
Total Flux in (40,500)- keV Gate
Near Detector @ 20cm; Far Detector @ 50cm;
7-cm Cement Barrier; 1.33-MeV Photon Source

Porosity	Near Signal	Far Signal	Far/Near
0%	9.31695E-07 (.0109)	9.99078E-10 (.0264)	0.00107
35%	9.75578E-07 (.0132)	2.52604E-09 (.0204)	0.00259
100%	9.95898E-07 (.0130)	1.82705E-08 (.0173)	0.01835

Table 37: Porosity Discrimination:
Total Flux in (40,500)- keV Gate
Near Detector @ 20cm; Far Detector @ 50cm;
7-cm Cement Barrier; 662- keV Photon Source

Porosity	Near Signal	Far Signal	Far/Near
0%	5.50424E-07 (.0123)	1.88591E-10 (.0329)	0.00034
35%	5.73070E-07 (.0122)	5.20762E-10 (.0258)	0.00091
100%	5.91291E-07 (.0153)	5.90386E-09 (.0179)	0.00998

B. Analysis of Results

Additional insight may obtain from my usual examination of the formation signal behavior. Tables 38–40 present the behavior of the formation signal and fraction of total signal, for both detectors and all three source energies.

We observe that the formation signal displays an increase in amplitude with increasing source energy, as observed for the total signal. Moreover, as for the total signal, the near-detector signal is relatively insensitive to porosity, while the far-detector signal is decidedly sensitive to porosity. What is interesting about these results, however, is that there is a marked sensitivity of the formation fraction (which, recall, is the measure of signal quality) to source–detector spacing! In my first spacing study (see Section IV), I did not observe such a sensitivity. In that earlier study, however, the scenario excluded any cement barrier between borehole casing and formation. That absence of a barrier effected a formation fraction that represented the majority fraction of the total detected signal. In the present scenario, the 7cm-cement barrier effects a formation signal that represents a minority fraction of the total detected signal. Thus, under normal cased-borehole conditions, which include a cement barrier, there appears to be an observable improvement in formation fraction with increased source–detector spacing.

The last finding is more in line with conventional wisdom. Moreover, I observe that this realistic “spacing sensitivity” is in the “desirable direction,” in that the higher signal quality coincides with the greater spacing, for which a sensitivity to formation porosity is detectable.

Table 38: Formation Flux and Fraction (of Total)
for the (40,500)-keV Gate
Near Detector @ 20cm; Far Detector @ 50cm;
7-cm Cement Barrier; 4.0-MeV Photon Source

Porosity	Near Signal	Fraction	Far Signal	Fraction
0%	9.37347E-08 (.0101)	0.07842	4.03521E-10 (.0204)	0.12688
35%	1.02976E-07 (.0085)	0.08282	1.05729E-09 (.0145)	0.14994
100%	1.06389E-07 (.0066)	0.08830	6.21061E-09 (.0082)	0.18129

Table 39: Formation Flux and Fraction (of Total)
for the (40,500)-keV Gate
Near Detector @ 20cm; Far Detector @ 50cm;
7-cm Cement Barrier; 1.33-MeV Photon Source

Porosity	Near Signal	Fraction	Far Signal	Fraction
0%	5.91035E-08 (.0094)	0.06344	1.16450E-10 (.0309)	0.11656
35%	6.74915E-08 (.0107)	0.06918	3.75956E-10 (.0194)	0.14883
100%	7.86741E-08 (.0074)	0.07900	3.33880E-09 (.0115)	0.18274

Table 40: Formation Flux and Fraction (of Total)
for the (40,500)-keV Gate
Near Detector @ 20cm; Far Detector @ 50cm;
7-cm Cement Barrier; 662-keV Photon Source

Porosity	Near Signal	Fraction	Far Signal	Fraction
0%	2.79038E-08 (.0110)	0.05070	2.09000E-11 (.0555)	0.11082
35%	3.27709E-08 (.0110)	0.05718	7.59000E-11 (.0331)	0.14574
100%	4.18449E-08 (.0091)	0.07077	1.12965E-09 (.0132)	0.19134

VIII. CEMENT THICKNESS VARIATION

As previously acknowledged, the tool must be capable of identifying the formation density beyond the borehole casing, as well as beyond a cement barrier. But, in addition, the cement barrier is likely to vary in thickness along the depth of the borehole. In my continuing investigation of the effects of a cement barrier, I, therefore, introduced the barrier thickness as yet another parameter to be varied.

In all but the preliminary calculations including a barrier (Section VI), I utilized a realistic cement specification (see Appendix B), based on information provided to me by an acknowledged expert consultant in these matters.⁶ After reporting my initial 'realistic cement' calculations⁷ (see Section VII), at a suggested density of 3.14g/cc, feed-back from GRI induced me to adopt a density of 1.8g/cc for cement.⁵ All of my remaining calculations reported herein are based on 1.8g/cc for the cement density.

A. Computed Results

My aim for the current investigation was to characterize the behavior of the detected signal due to a 4MeV-photon source, at *two source-detector spacings* ("near" and "far" from the source), as a function of detector gating (*two widely differing choices*), cement barrier thickness (*three values*), and formation porosity (*three values* spanning the theoretical range [0,100]%). As usual, I focused my attention on the computed total flux as well as the so-called "formation flux." The latter is that portion of the total (estimated) flux comprising estimates associated with collisions in the formation. As such, the formation flux serves as a measure of signal quality.

Thus, the present parametric study may be summarized in nested outline (or pseudo 'do-loop') form as follows:

1. Flux at "near" detector 20cm from the source;
 - (a) for a "wide open" [0.04,4.0]- $M\epsilon V$ gate;
 - i. given a 5-cm cement barrier;
 - A. with a formation porosity of 0% (pure rock);
 - B. with a formation porosity of 35%;
 - C. with a formation porosity of 100% (pure water).
 - ii. given a 6-cm cement barrier;
 - iii. given a 7-cm cement barrier.
 - (b) for a "narrow" [400,450]- $k\epsilon V$ gate.
2. Flux at "far" detector 50cm from the source.

Together with the distinction between formation flux and total flux, this comprises a 5-dimensional parameter space, having a total of 72 computed elements. These computed results are presented in Tables 41-44, along with their computed relative standard errors in parentheses. With but 5 marginal exceptions (all $< 6\%$), the computed errors are within accepted MCNP guidelines of $< 5\%$ for a flux-at-a-point detector.

Referring to Tables 41-44, we can make some general observations. The far signals are significantly more sensitive to porosity than the near signals. Moreover, at least for the wide-open gate, the total (far/near)-signal *ratio* is somewhat less sensitive to variation in cement-barrier thickness than its numerator alone (i.e., the total far signal). This observation identifies a useful formalism:

The (far/near)-signal ratio offers a normalized and dimensionless measure for porosity discrimination.

The situation for the narrow gate is less clear. The latter inconclusiveness tends to favor the wide-open gate for porosity discrimination, given the other parameter choices of this study.

Table 41: Porosity Discrimination:
4.0- $M\epsilon V$ Photon Source;
Far Detector @ 50cm; Near Detector @ 20cm;
Total Flux in the (0.04,4.0)- $M\epsilon V$ Gate

5-cm Cement Barrier			
Porosity	Far Signal	Near Signal	Far/Near
0%	1.36910E-08 (.0175)	2.44123E-06 (.0088)	0.00561
35%	2.78439E-08 (.0163)	2.64752E-06 (.0077)	0.01051
100%	1.35485E-07 (.0117)	2.74039E-06 (.0075)	0.04944

6-cm Cement Barrier			
Porosity	Far Signal	Near Signal	Far/Near
0%	1.60205E-08 (.0168)	2.56931E-06 (.0078)	0.00624
35%	2.85203E-08 (.0154)	2.68626E-06 (.0075)	0.01062
100%	1.20465E-07 (.0120)	2.63965E-06 (.0076)	0.04564

7-cm Cement Barrier			
Porosity	Far Signal	Near Signal	Far/Near
0%	1.79279E-08 (.0165)	2.60031E-06 (.0073)	0.00689
35%	2.96289E-08 (.0161)	2.66108E-06 (.0075)	0.01113
100%	1.08170E-07 (.0119)	2.58742E-06 (.0073)	0.04181

Table 42: Porosity Discrimination:
4.0- $M\epsilon V$ Photon Source;
Far Detector @ 50cm; Near Detector @ 20cm;
Total Flux in the (400,450)- keV Gate

5-cm Cement Barrier			
Porosity	Far Signal	Near Signal	Far/Near
0%	5.67710E-10 (.0479)	5.62386E-08 (.0438)	0.01009
35%	1.05349E-09 (.0429)	5.56486E-08 (.0444)	0.01893
100%	2.76992E-09 (.0502)	4.14592E-08 (.0492)	0.06681

6-cm Cement Barrier			
Porosity	Far Signal	Near Signal	Far/Near
0%	6.44925E-10 (.0437)	5.46764E-08 (.0420)	0.01180
35%	1.03002E-09 (.0423)	5.25148E-08 (.0413)	0.01961
100%	2.74342E-09 (.0481)	4.45201E-08 (.0558)	0.06162

7-cm Cement Barrier			
Porosity	Far Signal	Near Signal	Far/Near
0%	6.74591E-10 (.0438)	5.26247E-08 (.0379)	0.01282
35%	1.10760E-09 (.0437)	5.11247E-08 (.0435)	0.02166
100%	2.53137E-09 (.0464)	4.20020E-08 (.0475)	0.06027

Table 43: Porosity Discrimination:
4.0- $M\epsilon V$ Photon Source;
Far Detector @ 50cm; Near Detector @ 20cm;
Formation Flux in the (0.04,4.0)- $M\epsilon V$ Gate

5-cm Cement Barrier			
Porosity	Far Signal	Near Signal	Far/Near
0%	2.79536E-09 (.0181)	5.77655E-07 (.0078)	0.00484
35%	7.01458E-09 (.0143)	6.68545E-07 (.0063)	0.01049
100%	4.34823E-08 (.0090)	7.53876E-07 (.0056)	0.05768

6-cm Cement Barrier			
Porosity	Far Signal	Near Signal	Far/Near
0%	2.51201E-09 (.0178)	4.97580E-07 (.0073)	0.00505
35%	5.95565E-09 (.0142)	5.55100E-07 (.0066)	0.01073
100%	3.38570E-08 (.0091)	5.89395E-07 (.0056)	0.05744

7-cm Cement Barrier			
Porosity	Far Signal	Near Signal	Far/Near
0%	2.26963E-09 (.0181)	4.20130E-07 (.0064)	0.00540
35%	5.16163E-09 (.0160)	4.54114E-07 (.0065)	0.01137
100%	2.67423E-08 (.0087)	4.67371E-07 (.0052)	0.05722

Table 44: Porosity Discrimination:
4.0- $M\epsilon V$ Photon Source;
Far Detector @ 50cm; Near Detector @ 20cm;
Formation Flux in the (400,450)- $k\epsilon V$ Gate

5-cm Cement Barrier			
Porosity	Far Signal	Near Signal	Far/Near
0%	1.82834E-10 (.0466)	1.65860E-08 (.0416)	0.01102
35%	3.96527E-10 (.0386)	1.54463E-08 (.0438)	0.02567
100%	1.27913E-09 (.0367)	9.74456E-09 (.0547)	0.13127

6-cm Cement Barrier			
Porosity	Far Signal	Near Signal	Far/Near
0%	1.55060E-10 (.0485)	1.31730E-08 (.0442)	0.01177
35%	3.31454E-10 (.0377)	1.13723E-08 (.0460)	0.02915
100%	1.03045E-09 (.0346)	7.67081E-09 (.0571)	0.13433

7-cm Cement Barrier			
Porosity	Far Signal	Near Signal	Far/Near
0%	1.45444E-10 (.0480)	1.06985E-08 (.0408)	0.01359
35%	3.25916E-10 (.0437)	1.01476E-08 (.0476)	0.03212
100%	8.93786E-10 (.0354)	5.85810E-09 (.0512)	0.15257

B. Analysis of Results

If we examine the total signal ratio for the wide-open gate as a function of cement barrier thickness, we get the plots shown in Figure 2. What these plots indicate is that the total signal-ratio bandwidth is somewhat compressed with increasing thickness. Nevertheless, the situation is by no means hopeless; the 35%-porosity curve is amazingly flat.

As usual, an examination of the corresponding plots for the *formation* signal-ratio (refer to Figure 3) sheds some light on the foregoing considerations. Here we note another validation for using the formation signal as a measure of total signal quality. The plots spanning the theoretical range of formation porosity are virtually flat in this interval of cement barrier thickness. Such a flatness suggests that these particular choices of source energy, detector gating, and source-detector spacings are compatible, at least in principle. The observed deviation from a flat response in Figure 2 is probably due to the noise introduced by the barrier/casing/borehole contributions to the total signal. Aside from any signal processing techniques, which may mitigate such undesirable effects, it is clear that, given the controllable choices of tool design, this particular combination of choices is compatible for porosity discrimination.

Another view of the same information is shown in Figures 4–5. Here I have chosen the barrier thickness as the parametric constant for the plots of formation porosity as a function of detector signal ratio. Figure 4 displays the dispersion introduced by the undesirable contributions to the total signal (i.e., borehole/casing/barrier signals). Note that ~43% the porosity becomes totally insensitive to variations in barrier thickness (in the range investigated). The maximum dispersion is ~13% at the extrema. Figure 5 corroborates the above statements about the formation signal serving as an idealized guideline for the selection of compatible tool design parameters.

Figure 2: Total-signal ratio as a function of cement-barrier thickness, for the wide-open detector gate.

Figure 3: Formation-signal ratio as a function of cement-barrier thickness, for the wide-open detector gate.

Figure 5: Formation porosity as a function of formation-signal ratio, for the wide-open detector gate.

Figure 4: Formation porosity as a function of total-signal ratio, for the wide-open detector gate.

Figures 6–9 for the narrow $[400,450]\text{-keV}$ gate are analogous to their wide-open gate counterparts (Figures 2–5). Here is an example of poorly matched design parameters.

Figure 6 shows distortion of the signal-ratio bandwidth over the entire range of porosities, becoming non-monotonic at the upper end of the porosity range. Also, Figure 8 shows that at no point do all three plots converge (the absence of a porosity value insensitive to small variations in barrier thickness).

But the truly revealing evidence of tool-parameter mismatch is provided by Figures 7 and 9. The formation-signal ratio displays unsatisfactory behavior with respect to barrier thickness, as well as with respect to formation porosity. Such behavior implies that a tool based on these choices of tool-design parameters would be doomed to failure. My acquired insight leads me to suspect too small a source-to-far-detector spacing, for this choice of detector gate. Intuitively, my guess is that an increase of about a factor of $\sqrt{2}$ in spacing would result in an idealized compatibility for this set of design parameters.

Figure 6: Total-signal ratio as a function of cement-barrier thickness, for the narrow detector gate.

Figure 7: Formation-signal ratio as a function of cement-barrier thickness, for the narrow detector gate.

Figure 8: Formation porosity as a function of total-signal ratio, for the narrow detector gate.

Figure 9: Formation porosity as a function of formation-signal ratio, for the narrow detector gate.

C. A Novel Tool-design Concept

The present study was intended to expand my tool-design database, which it did. But, more importantly, it revealed a novel tool-design concept. This concept is an extension of my using the formation signal to gauge the quality of the detected total signal:

Analysis of the formation signal allows a tool designer to determine, *a priori*, if a specific combination of tool-design parameters is *intrinsically* either compatible or mismatched. This capability is only possible in simulations of the present kind.

As evidenced in the foregoing subsection, the parameter set for the wide-open gate is, *intrinsically*, compatible. The parameter set for the narrow gate is *intrinsically* mismatched. The implication of the latter conclusion is that signal processing aimed at mitigating the noise introduced by borehole/casing/barrier will be inadequate.

Computer simulations are inherently more cost effective than "cutting metal." With the added capability afforded by the analysis of the formation signal behavior, the already powerful simulation technique becomes significantly leveraged.

IX. IMPROVING PARAMETER COMPATIBILITY

My aim for the present investigation was to develop further the tool-design concept that was identified in the course of the preceding study (Section VIII). In the latter study, I estimated that an increase of $\sim\sqrt{2}$ in spacing, between source and far detector, would result in an idealized compatibility for the set of design parameters that specify a detector gate of $[400,450] \text{ keV}$. (The source energy is understood to be 4 MeV unless otherwise specified).

In the present study, I demonstrate how the analysis of the formation signal can provide guidance for an iterative process of tool design through simulation. Such an activity can benefit a more formal design process, which may include prototyping, by culling preliminary design parameters that show a promising self-consistency from the myriad of possible sets, most of which have mismatched parameters.

A. Computed Results

In order to demonstrate the efficacy of formation-signal analysis, I computed results for spacings of 60 cm and 70 cm and compared these with the original 50 cm set. Tables 45–48 summarize my computed results (which complement Tables 44 and 42 in the preceding section). As usual, the computed relative standard errors are provided in parentheses. Note that I recomputed the near detector results for the 100% porosity cases to insure that all the newly computed results (i.e., in Tables 45–48) are within accepted MCNP guidelines of $< 5\%$ for a flux-at-a-point detector.

Table 45: Porosity Discrimination:
4.0-MeV Photon Source;
Far Detector @ 60cm; Near Detector @ 20cm;
Formation Flux in the (400,450)-keV Gate

5-cm Cement Barrier			
Porosity	Far Signal	Near Signal	Far/Near
0%	3.69100E-11 (.0186)	1.65860E-08 (.0416)	0.002225
35%	1.14647E-10 (.0120)	1.54463E-08 (.0438)	0.007422
100%	6.89108E-10 (.0064)	9.42171E-09 (.0376)	0.073140

6-cm Cement Barrier			
Porosity	Far Signal	Near Signal	Far/Near
0%	3.43800E-11 (.0196)	1.31730E-08 (.0442)	0.002610
35%	1.02684E-10 (.0122)	1.13723E-08 (.0460)	0.009029
100%	5.76755E-10 (.0066)	7.51732E-09 (.0423)	0.076723

7-cm Cement Barrier			
Porosity	Far Signal	Near Signal	Far/Near
0%	3.23000E-11 (.0199)	1.06985E-08 (.0408)	0.003019
35%	9.54800E-11 (.0127)	1.01476E-08 (.0476)	0.009409
100%	4.83701E-10 (.0071)	5.91530E-09 (.0425)	0.081771

Table 46: Porosity Discrimination:
4.0- MeV Photon Source;
Far Detector @ 60cm; Near Detector @ 20cm;
Total Flux in the (400,450)-keV Gate

5-cm Cement Barrier			
Porosity	Far Signal	Near Signal	Far/Near
0%	1.21350E-10 (.0139)	5.62386E-08 (.0438)	0.002158
35%	2.99098E-10 (.0109)	5.56486E-08 (.0444)	0.005375
100%	1.49366E-09 (.0082)	4.17564E-08 (.0352)	0.035771

6-cm Cement Barrier			
Porosity	Far Signal	Near Signal	Far/Near
0%	1.43687E-10 (.0142)	5.46764E-08 (.0420)	0.002628
35%	3.07111E-10 (.0106)	5.25148E-08 (.0413)	0.005848
100%	1.36269E-09 (.0081)	4.37763E-08 (.0401)	0.031128

7-cm Cement Barrier			
Porosity	Far Signal	Near Signal	Far/Near
0%	1.57835E-10 (.0137)	5.26247E-08 (.0379)	0.002999
35%	3.19869E-10 (.0110)	5.11247E-08 (.0435)	0.006257
100%	1.24374E-09 (.0084)	4.19384E-08 (.0337)	0.029656

Table 47: Porosity Discrimination:
4.0- $M\epsilon V$ Photon Source;
Far Detector @ 70cm; Near Detector @ 20cm;
Formation Flux in the (400,450)- $k\epsilon V$ Gate

5-cm Cement Barrier			
Porosity	Far Signal	Near Signal	Far/Near
0%	7.58333E-12 (.0283)	1.65860E-08 (.0416)	0.000457
35%	3.17500E-11 (.0194)	1.54463E-08 (.0438)	0.002056
100%	3.54009E-10 (.0079)	9.42171E-09 (.0376)	0.037574

6-cm Cement Barrier			
Porosity	Far Signal	Near Signal	Far/Near
0%	7.22222E-12 (.0288)	1.31730E-08 (.0442)	0.000548
35%	2.93389E-11 (.0149)	1.13723E-08 (.0460)	0.002580
100%	2.99131E-10 (.0064)	7.51732E-09 (.0423)	0.039792

7-cm Cement Barrier			
Porosity	Far Signal	Near Signal	Far/Near
0%	7.35000E-12 (.0311)	1.06985E-08 (.0408)	0.000687
35%	2.61056E-11 (.0207)	1.01476E-08 (.0476)	0.002573
100%	2.46576E-10 (.0145)	5.91530E-09 (.0425)	0.041684

Table 48: Porosity Discrimination:
4.0- $M\epsilon V$ Photon Source;
Far Detector @ 70cm; Near Detector @ 20cm;
Total Flux in the (400,450)- $k\epsilon V$ Gate

5-cm Cement Barrier			
Porosity	Far Signal	Near Signal	Far/Near
0%	2.56000E-11 (.0176)	5.62386E-08 (.0438)	0.000455
35%	8.34522E-11 (.0148)	5.56486E-08 (.0444)	0.001500
100%	7.52218E-10 (.0088)	4.17564E-08 (.0352)	0.018014

6-cm Cement Barrier			
Porosity	Far Signal	Near Signal	Far/Near
0%	3.10667E-11 (.0168)	5.46764E-08 (.0420)	0.000568
35%	8.70111E-11 (.0108)	5.25148E-08 (.0413)	0.001657
100%	6.93386E-10 (.0068)	4.37763E-08 (.0401)	0.015839

7-cm Cement Barrier			
Porosity	Far Signal	Near Signal	Far/Near
0%	3.64277E-11 (.0192)	5.26247E-08 (.0379)	0.000692
35%	8.92450E-11 (.0158)	5.11247E-08 (.0435)	0.001746
100%	6.32914E-10 (.0193)	4.19384E-08 (.0337)	0.015092

B. Analysis of Results

Recall that, as seen in Section VIII, the narrow $[400,450]\text{-keV}$ gate, in conjunction with a source-to-far-detector spacing of 50cm , effects an unsatisfactory tool-design parameter set. My hunch was that this example of poorly matched parameters could be improved by increasing the spacing by $\sim\sqrt{2}$.

In Figure 10, the results for the 60cm and 70cm cases show how the parameter matching improves, with respect to the original choice of a 50cm spacing, for the formation-flux component of the total estimated flux. This compatibility improvement in principle (i.e., as demonstrated by the computed *formation-flux* ratios), is also manifested by a comparison of the corresponding results based on the *total-flux* ratios (see Figure 11).

Figures 12–15 present additional confirmation of the improvement in parameter matching with increasing source-to-far-detector spacing. The increasing flatness of signal ratio (with respect to small variations in cement barrier thickness) is observed both for the *ideal* case (as represented by the *formation-signal* ratio) and for the corresponding *real* case (as represented by the *total-signal* ratio). The same trends are observed over the entire theoretical range of formation porosity.

My concept of utilizing the *formation-flux ratio* to perform *intrinsic parameter-compatibility* checks is not necessarily limited to the set of parameters investigated in these studies. Nor is this concept limited to using the cement-barrier thickness as the independent parameter; the borehole-casing thickness, for example, could also serve as a valid independent parameter. Thus, another possible compatibility check would require stability in the *formation-flux* ratio for small variations in casing thickness.

Any significant effort to design a tool stands to benefit from these techniques. They enable *a priori* rejection of intrinsically poor design parameter sets. They also provide guidance in the refinement of intrinsically self-consistent sets of tool parameters.

Figure 10: Formation porosity as a function of formation-signal ratio. Parameter compatibility compared for 3 source-to-far-detector spacings.

Figure 11: Formation porosity as a function of total-signal ratio. Parameter compatibility compared for 3 source-to-far-detector spacings.

Figure 12: Formation-signal ratio as a function of cement-barrier thickness @0% porosity. Parameter compatibility compared.

Figure 13: Total-signal ratio as a function of cement-barrier thickness @0% porosity. Parameter compatibility compared.

Figure 14: Formation-signal ratio as a function of cement-barrier thickness @35% porosity. Parameter compatibility compared.

Figure 15: Total-signal ratio as a function of cement-barrier thickness @35% porosity. Parameter compatibility compared.

Figure 16: Formation-signal ratio as a function of cement-barrier thickness @100% porosity. Parameter compatibility compared.

Figure 17: Total-signal ratio as a function of cement-barrier thickness @100% porosity. Parameter compatibility compared.

X. SUMMARY AND CONCLUSIONS

I had previously accomplished a Monte Carlo simulation study as a proof-of-concept for a GRI idea. That idea envisions the utilization of higher-energy γ rays for density logging through cased boreholes. In that proof-of-concept, my principal findings were that:

- For a collimated generic tool, a 4-MeV γ source effects an interrogation depth through a cased borehole of ~ 4.5 inches. This depth is equivalent to the depth effected by Cesium γ rays (662keV) in an uncased borehole.
- If the detector can filter-out the portion of the signal originating from the casing, the resulting interrogation depth will be further enhanced.

In the present investigations, I exploited my preliminary positive findings. My goal was to characterize a generic γ - γ tool for density logging through casing in various scenarios. In the process, I would compile a database of tool-design information.

In the course of analyzing the computed results presented in this document, I identified a novel tool-design concept. This concept is a natural extension of my original concept to use the formation signal as a quality gauge for the detected signal:

Analysis of the formation signal allows a tool designer to determine, *a priori*, if a specific combination of tool-design parameters is *intrinsically* either compatible or mismatched. This capability is only possible in simulations of the present kind.

This concept is not necessarily limited to the set of parameters investigated in the present studies. Nor is this concept limited to using the cement-barrier thickness as the independent parameter; the borehole-casing thickness, for example, could also serve as a valid independent parameter. Thus, another potential compatibility check would require stability in the formation-flux ratio for small variations in casing thickness.

Any significant effort to design a tool stands to benefit from these techniques. They enable *a priori* rejection of intrinsically poor design parameter sets. They also provide guidance in the refinement of intrinsically self-consistent sets of tool parameters.

XI. ACKNOWLEDGMENTS

It has been observed that nobody works in a vacuum, and I am no exception. As noted in the references, Harvey Haines (GRI) and Dick Bramblett (Applied Physics Associates) provided useful information and feedback. My colleagues Bob Little and Pat Soran (both X-6) were generous with their time (and patience) whenever I needed a sounding board. And my colleague Grady Hughes (X-6) deserves special thanks for many stimulating conversations.

XII. REFERENCES

1. H. Lichtenstein, "Increasing Depth-of-Interrogation with Higher-Energy γ - γ Tools," Los Alamos National Laboratory Final Report X-6:HL-91-466 (August 12, 1991).
2. Henry Lichtenstein, "A Monte Carlo Simulation Study for γ - γ Density Logging," Los Alamos National Laboratory Report LA-12207 (October 1991).
3. Judith F. Briesmeister, Editor, "MCNPTTM — A General Monte Carlo N-Particle Transport Code," Los Alamos National Laboratory manual LA-12625-M, Version 4A (November 1993).
4. H. Lichtenstein, "GRI: Detector Gating Study," Los Alamos National Laboratory memorandum X-6:HL-93-408 (June 29, 1993).
5. H. H. Haines, GRI Senior Project Manager, private communications.
6. R. L. Bramblett, Applied Physics Associates letter, to Henry Lichtenstein (October 7, 1993).
7. H. Lichtenstein, "GRI: Barrier Study," LANL memorandum X-6:HL-93-737 (November 30, 1993).
8. H. G. Hughes, LANL Group X-6, private communications.

Appendix A. FORMATION-FLUX TALLY

Throughout this investigation, I relied on my ability to analyze the detected signal in terms of contributing fractions, attributable to collisions in specific domains of my simulated borehole/casing/cement/formation environment. In particular, I was able to vary the scenario parameters and determine, individually, the signal fractions due to the borehole, casing, cement barrier, and formation, as well as the total signal. My goal was to find optimal circumstances whereby the signal fraction due to the formation can be isolated to some degree.

The device that has enabled such an analysis of the detected signal is the special purpose tally routine, which I developed for my proof-of-concept study.^{1, 2} Stimulating discussions with a colleague⁸ helped me in the development of that software. For convenience, I present the description of that software "patch" for MCNP in this appendix.

My special tally routine accommodates two sets of user-defined tally bins, which are specified on input by two corresponding sets of squared radii (as measured from the axis-of-symmetry in the borehole). One of these sets defines differential user-tally bins in terms of cylindrical shells about the borehole axis-of-symmetry. The other set defines cumulative user-tally bins as coaxial cylinders of increasing depth from the axis-of-symmetry. If the user bins are properly defined, both the differential and cumulative set will span the range of all possible lateral locations with respect to the borehole axis (i.e., $[0, \infty]$).

Now, the MCNP point-detector tally is a normalized accumulation of contributions to the flux, as estimated at collision points. Hence, at every collision that leads to a tally, the flux-at-a-point estimation (which includes estimation of the associated standard relative error) is tallied within the appropriate differential user bin, as well as in the set of appropriate cumulative user bins (one or more), as determined by the coordinates of the collision point. The tally within the deepest cumulative bin corresponds to the total flux estimate at the detector.

This manner of estimating the flux at the detector point leads to a natural analysis of the flux tally in terms of fractions that correspond to depth-of-origination within the complex borehole/casing/cement/formation scenario. The differential tally bins correspond to fractions of the flux tally originating in the various regimes of the complex scenario. The cumulative bins provide the basis for characterizing the flux tally in terms of a percentile criterion that is linked to the penetration

```

*id patch
*d tx.8,tx.19
  ib=1
  r=xxx9(npb)**2+yyy9(npb)**2
  k=iptal(lipt+3,4,ital)-1
  l=iptal(lipt+3,1,ital)
  if(ntx.eq.1)then
    do 100 i=1,k
      if(r.le.tds(l+i))goto 200
100    continue
      i=k+1
200    ibu=i
  else
    n=k+2-ntx
    if(r.gt.tds(l+n).or.n.lt.1)then
      ibu=1
      ib=0
    else
      ibu=n
    endif
  endif
endif

```

Figure 18: Coding patch for special purpose tally routine.

depth in the formation. Thus, for instance, if 90% of the signal at the detector is chosen as the criterion for determining the source photon “penetrability” (i.e., ability of interrogating the formation), the cumulative bin tally can be used to find the corresponding depth in the formation that accounts for the specified fraction of signal.

This special-purpose tally routine is a technique that is accommodated by the TALLYX feature of MCNP. The coding patch for this routine is shown in Figure 18.

Appendix B. MIXING CEMENT

In the course of my investigations, it became necessary for me to specify an MCNP-material "card" for cement. I had received an "engineering-like" specification for a cement from Richard Bramblett.⁶ We know, however, that such specifications are not always ready to use by MCNP. Despite the mundane nature of the subject matter, I thought it useful, for future reference, to document the procedure that I used to convert the initial description to one usable by MCNP. This appendix can serve as a guide to other such preparations of homogenized materials.

To make cement, according to Bramblett, 0.58 pounds of water is added to each pound of solids, which are Described in Table 49.

The first thing I did was to arbitrarily add 0.04% to the CaO (yielding 64.25% for this component) to force the total to exactly 100%.

Next, I prepared an INP material card for each oxide so that MCNP would compute the requisite mass fractions for each component compound, viz.

c	cement component compounds
m1	14000 1.0 8016 2.0 \$ SiO2
m2	13000 2.0 8016 3.0 \$ Al2O3
m3	26000 2.0 8016 3.0 \$ Fe2O3
m4	20000 1.0 8016 1.0 \$ CaO
m5	12000 1.0 8016 1.0 \$ MgO
m6	16000 1.0 8016 3.0 \$ SO3
m7	11000 2.0 8016 1.0 \$ Na2O
m8	19000 2.0 8016 1.0 \$ K2O
m9	1001 2.0 8016 1.0 \$ H2O

Table 49: Class C Solids Composition, 1986 (Lone Star Cement Company)

Component Compound	Weight Percent
SiO_2	21.08
Al_2O_3	2.80
Fe_2O_3	4.76
CaO	64.21
MgO	3.13
SO_3	3.05
Na_2O	0.08
K_2O	0.33
H_2O of hydration	0.52
Total	99.96

From the resulting MCNP OUTP file, I retrieved the following mass fractions:

material

number	component nuclide, mass fraction			
1	14000,	.46750	8016,	.53250
2	13000,	.52932	8016,	.47068
3	26000,	.69949	8016,	.30051
4	20000,	.71475	8016,	.28525
5	12000,	.60310	8016,	.39690
6	16000,	.40056	8016,	.59944
7	11000,	.74191	8016,	.25809
8	19000,	.83019	8016,	.16981
9	1001,	.11191	8016,	.88809

warning. 9 of the materials had unnormalized fractions.

The warning is benign, since MCNP normalizes the atom fractions that I input based on the compound chemical formulas.

Using the weight percents from Table 49 and the MCNP-computed mass fractions, I calculated the following mass fractions for the component elements of the cement solids:

14000= 0.098549000 (Si)
13000= 0.014820960 (Al)
26000= 0.033295724 (Fe)
20000= 0.459226875 (Ca)
12000= 0.018877030 (Mg)
16000= 0.012217080 (S)
11000= 0.000593528 (Na)
19000= 0.002739627 (K)
1001= 0.000581932 (H)
8016= 0.359098244 (O)

Next, I scaled the above values by the ratio 1.0/1.58 to yield:

14000= 0.06237278481010 (Si)
13000= 0.00938035443038 (Al)
26000= 0.02107324303800 (Fe)
20000= 0.29064992088600 (Ca)
12000= 0.01194748734180 (Mg)
16000= 0.00773232911392 (S)
11000= 0.000375650632911 (Na)
19000= 0.00173394113924 (K)
1001= 0.000368311392405 (H)
8016= 0.22727736962000 (O)

Then, I added 0.58/1.58 of water fractions:

```
14000= 0.06237278481010 (Si)
13000= 0.00938035443038 (Al)
26000= 0.02107324303800 (Fe)
20000= 0.29064992088600 (Ca)
12000= 0.01194748734180 (Mg)
16000= 0.00773232911392 (S)
11000= 0.000375650632911 (Na)
19000= 0.00173394113924 (K)
 1001= 0.04144919746840 (H)
 8016= 0.55328509113900 (O)
-----
total= 0.99999999999751
```

Keeping 12 places of precision and forcing a total of exactly 1.0 yields:

```
14000= 0.062372784810 (Si)
13000= 0.009380354430 (Al)
26000= 0.021073243038 (Fe)
20000= 0.290649920886 (Ca)
12000= 0.011947487342 (Mg)
16000= 0.007732329114 (S)
11000= 0.000375650633 (Na)
19000= 0.001733941139 (K)
 1001= 0.041449197469 (H)
 8016= 0.553285091139 (O)
-----
total= 1.000000000000
```

Finally, the resulting material card for cement becomes:

c	Lone Star Cement			
m1	14000	-0.062372784810	13000	-0.009380354430
	26000	-0.021073243038	20000	-0.290649920886
	12000	-0.011947487342	16000	-0.007732329114
	11000	-0.000375650633	19000	-0.001733941139
	1001	-0.041449197469	8016	-0.553285091139

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