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SPECTRAL GAMMA-RAY LOG DATA ANALYSIS FOR
NTS BOREHOLE ER-20-6 #2

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SPECTRAL GAMMA-RAY LOG QUALITY REPORT FOR NTS BOREHOLE ER-20-6 #2

John Conaway
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SUMMARY

The Western Atlas spectral gamma-ray log curve plots from borehole ER20-6 #2 show one rather extensive anomaly from about 2027 ft to 2400 ft. In addition, small artificial nuclide anomalies not flagged as statistically significant are shown on the Atlas curve plots throughout much of the rest of the borehole, especially near the top and below 2550 ft. The most significant difference between the spectral gamma-ray log from this borehole and the one from ER20-6 #1 is that the zone of relatively high concentrations of artificial nuclides (mainly ^{137}Cs) found at around 1900 ft in ER20-6 #1 is not seen in ER20-6 #2.

According to the curve plots from borehole ER20-6 #2, the primary zone of artificial nuclides extending from about 2027 to 2400 ft contains (in order of decreasing effect on the total count rate) ^{106}Ru , ^{137}Cs , ^{125}Sb , ^{134}Cs , and ^{60}Co . Our analysis indicates that the anomaly can be largely attributed to ^{106}Ru and ^{137}Cs . These artificial nuclides appear to be in the borehole fluid (i.e., formation water) or to have been spread by the borehole fluid. We cannot confirm the presence of the other artificial gamma emitters indicated on the curve plots because the level of noise in the data precludes identification of trace quantities of nuclides. It is important to remember that the least-squares analysis technique used by Western Atlas to make the nuclide identifications will automatically identify coherent noise (as opposed to random statistical fluctuations) as some combination of the eight nuclide families (three natural and five artificial) for which spectral templates are available. Since several sources of coherent noise have been identified in the data, errors in nuclide identification are unavoidable. In addition to errors in concentrations reported for nuclides that are actually present, spurious anomalies corresponding to various nuclides not present can also be expected.

For this analysis, we divided the borehole into several zones based on spectral characteristics and analyzed the zones individually. As stated above, aside from the contaminated zone from about 2027 to 2400 ft, the curve plots show a variety of small artificial nuclide anomalies scattered through much of the borehole; none are flagged as statistically significant by Western Atlas. There is no clear evidence of other zones containing significant amounts of artificial nuclides. However, the data quality is not adequate for identifying relatively low concentrations of artificial gamma emitters unambiguously.

As in the case of spectral gamma-ray logs from borehole ER20-6 #1 discussed in an earlier report, the logs from borehole ER20-6 #2 seem to represent industry-standard technology. The computed artificial nuclide curves give a fairly reliable indication of zones where artificial gamma emitters are present but are not completely accurate in identifying *which* nuclides are present and which are not. In earlier data analysis efforts and experiments at the Atlas research facility in Houston, we identified a number of relatively minor deficiencies in the Atlas logging

system and software that contribute to this problem. To a large extent, data quality is limited by the low energy resolution inherent in the CsI detector used, and this cannot easily be changed.

The problem identified in our data analysis for borehole ER20-6 #1, the fact that photopeaks from artificial nuclides perturb the automatic spectral recalibration performed by Atlas in the post-processing stage, also was observed in the spectra from ER20-6 #2. This leads to degraded accuracy in the energy calibration and probably degraded accuracy in nuclide identification in the zones of greatest interest in the UGTA work, those contaminated by artificial gamma emitters. This problem can probably be fixed or improved with relatively little effort, and we have brought it to the attention of Western Atlas research personnel. Because we did not consider the energy calibration values for this log reliable, each summed field spectrum was individually recalibrated interactively during the analysis.

INTRODUCTION

Borehole ER20-6 #2 was drilled in Area 20 (Pahute Mesa) at the Nevada Test Site near the site of the Bullion underground nuclear test. Bullion was conducted in June, 1990, at a depth of 2211 ft. This report presents our interpretation of the Western Atlas spectral gamma-ray data from that borehole along with a quality analysis of the contractor's data and procedures. An analysis of the spectral gamma-ray logs from nearby ER20-6 #1 was given earlier.⁽¹⁾ A brief description of the spectral gamma-ray logging equipment used in the Underground Test Area work, including some of the deficiencies of the equipment and procedures, is given in Appendix A.

A water sample from ER20-6 #2 were analyzed by others⁽²⁾ for artificial gamma emitters (Table 1). Unlike ER20-6 #1, sidewall cores have not been obtained. Of the five artificial gamma emitters for which Western Atlas analyzes, one (^{134}Cs) was not found in the water samples and another (^{60}Co) was found at trace concentrations. A sixth artificial nuclide, $^{102\text{m}}\text{Rh}$, was found in the water sample at trace levels; the Western Atlas logging system has not been characterized for this nuclide. The presence of gamma emitters for which the logging system has not been characterized will introduce additional error into the results because the least-squares analysis technique used by Western Atlas to make the nuclide identifications will automatically identify including extra photopeaks from unknown nuclides as some combination of the eight nuclide families for which spectral templates are available. In this case the $^{102\text{m}}\text{Rh}$ will probably have little adverse effect because of its low concentration.

Table 1. Radionuclides detected in water pumped from ER20-6b #1 on 2-Apr-96⁽²⁾.

Nuclide	Activity (pCi/l)
^{106}Ru	120
^{125}Sb	54
^{137}Cs	13
$^{102\text{m}}\text{Rh}$	0.2
^{60}Co	0.1

DATA VALIDATION FOR BOREHOLE ER-20-6 #2

To provide an independent assessment of data quality, we have divided the spectral gamma-ray log from borehole ER20-6 #2 into regions based on the distribution of artificial nuclides indicated on the spectral gamma-ray log curve plots. For reference, the curve data are plotted here as Figures 1 - 5, in 500 ft sections. These plots have a logarithmic countrate axis to show detail at the low countrate end without clipping at the high countrate end.

The Western Atlas curve plots show one rather extensive anomaly from about 2027 ft to perhaps 2400 ft (Figure 4). In addition, small artificial nuclide anomalies not flagged as statistically significant are shown on the curve plots throughout much of the borehole, especially below 2550 ft (Figure 5). The zone of relatively high concentrations of artificial nuclides (mainly ^{137}Cs) found at around 1900 ft in the spectral gamma-ray log from ER20-6 #1 is not seen in ER20-6 #2. The spectral data are discussed in the sections of this report dealing with specific depth regions. The zone from 2027 to 2400 ft is considered first because it is the only significant artificial nuclide anomaly in this borehole. Other depth zones will be considered in order of increasing depth.

Quality control parameters for borehole ER-20-6 #2

In the Western Atlas spectral gamma-ray log post-processing, an initial calibration spectrum is summed over the first 50 ft of log. Quality control tests and calibration adjustments, if any, are based on that summed spectrum for a point centered in that 50 ft section. As processing proceeds, spectra from successive sample depths are added into the calibration spectrum and spectra are subtracted at the same rate from the other end of the 50 ft interval so the calibration spectrum always represents a spectrum accumulated over a 50 ft interval centered on the current depth.⁽³⁾ The quality control parameters are described briefly in Table 2.

Table 2. The Atlas spectral calibration and quality control parameters discussed in the text.

PARAMETER	DESCRIPTION
QMSL	Multiplicative energy calibration factor (gain, M).
QASL	Additive energy calibration factor (offset, A).
QPKS	Number of specified spectral reference peaks recognized by the calibration routine (out of a possible 5 peaks). Normally QPKS must be at least 4 for an automatic recalibration to be performed.
QCAL	Slope of the line obtained by performing linear regression on a plot of measured reference peak channels (y-axis) against expected reference peak channels (x-axis).
QSA	Chi-squared test describing goodness-of-fit of the reference peak channels versus energy plot. Normally, QSA must be less than 1 for an automatic recalibration to be performed

Figures 6 to 10 show plots of the Atlas quality control parameters for borehole ER20-6 #2 along with the artificial nuclide curves. Note that for most of the borehole, the criteria for an automatic

Figure 1. Western Atlas curve data for 500 - 1000 ft in borehole ER20-6 #2.

Figure 2. Western Atlas curve data for 1000 - 1500 ft in borehole ER20-6 #2.

Figure 3. Western Atlas curve data for 1500 - 2000 ft in borehole ER20-6 #2.

Figure 4. Western Atlas curve data for 2000 - 2500 ft in borehole ER20-6 #2.

Figure 5. Western Atlas curve data for 2500 - 3000 ft in borehole ER20-6 #2.

Figure 6. Western Atlas artificial nuclide data and quality control indicators for 500 - 1000 ft in borehole ER20-6 #2.

Figure 7. Western Atlas artificial nuclide data and quality control indicators for 1000-1500 ft in borehole ER20-6 #2.

Figure 8. Western Atlas artificial nuclide data and quality control indicators for 1500-2000 ft in borehole ER20-6 #2.

Figure 9. Western Atlas artificial nuclide data and quality control indicators for 2000-2500 ft in borehole ER20-6 #2.

Figure 10. Western Atlas artificial nuclide data and quality control indicators for 2500-3000 ft in borehole ER20-6 #2.

spectral calibration to take place are not met so the energy calibration factors QMSL and QASL remain fixed. However, in one significant zone from about 2000 to 2400 ft, the criteria are met ($QPKS = 4$ and $QSA < 1$); large shifts in QMSL and QASL are seen in that zone (Figure 9). It is probably not a coincidence that this is also the primary zone of artificial nuclides in the borehole. It is ironic that the only significant zone where automatic recalibration takes place is the zone where it is likely to be influenced adversely by interference from artificial gamma emitters. This erroneous spectral calibration reduces the chance that the Atlas automatic full-spectral processing software will correctly determine which artificial nuclides are actually present and which are not. Because we did not consider the energy calibration values for this log reliable, each summed field spectrum was individually recalibrated interactively during the analysis.

Zone from 2027 - 2400 ft

According to the Western Atlas curve plots, the primary zone of artificial nuclides in borehole ER20-6 #2 extends from about 2027 to 2400 ft (Figure 4). This zone is noted on the blue line as containing (in order of decreasing effect on the total count rate) ^{106}Ru , ^{137}Cs , ^{125}Sb , ^{134}Cs , and ^{60}Co . A somewhat similar anomaly was found in borehole ER20-6 #1 extending from about 2028 to 2566 ft. Figure 11a shows the field spectrum accumulated in that zone plotted on semi-log axes; the same information is plotted again in Figure 12a on a linear scale. Figure 11b shows the same accumulated field spectrum (solid curve) plotted along with the thorium spectral template (again, plotted on a linear scale in Figure 12b). The vertical lines represent the expected positions of three photopeaks representative of the thorium family spectrum and are shown for reference. The spectral template count rates have been scaled interactively to give a good fit over the prominent 2.614 MeV peak of ^{208}Tl (a daughter of ^{232}Th). Since no other significant photopeaks are expected in that energy range, we can confidently perform this fit and subtract the scaled spectral template from the accumulated field spectrum. It should be noted that ^{106}Rh , the daughter of ^{106}Ru , has gamma rays of energies up to 3.4 MeV but with negligible yields for our purposes.

The remaining field spectrum after the scaled thorium template has been subtracted is plotted as the solid curve in Figures 11c and 12c; the dashed curve in both plots is the uranium spectral template. The vertical lines represent the expected positions of three uranium family photopeaks, for reference. Again, the template has been interactively fitted to the higher-energy uranium peaks; since the contribution of thorium has been subtracted, uranium-family peaks in the range of 2.2 to 2.4 MeV should now be the only significant high-energy peaks.

Notice that there is some noise visible in the remaining field spectrum after subtracting the scaled thorium template, including a positive and negative excursion nearly centered on the expected position of the 2.614 MeV thorium (^{208}Tl) peak (because Figure 11c has a semi-log axis, negative count rates cannot be displayed and count rates below 0.01 counts/s/channel have been truncated). This error results largely from a small difference in energy calibration (gain and offset) between the field spectrum and the thorium spectral template (we recalibrated each summed field spectrum interactively before analysis but a perfect match with the templates was not attainable) along with differences in the shape of the two spectra because the calibration borehole environment was not the same as the field borehole environment. While negative count rates may seem troubling, they are simply an indication of imperfection in the data processing and they provide an indication of the noise level.

Figure 11. Field spectrum accumulated from 2027 to 2400 ft in borehole ER20-6 #2 plotted on semi-log axes. The various stages of data processing described in the text are shown.

Figure 12. Field spectrum accumulated from 2027 to 2400 ft in borehole ER20-6 #2 plotted on linear axes. The various stages of data processing described in the text are shown.

Subtracting the scaled uranium spectral template from the remaining field spectrum leads to the solid curve in Figures 11d and 12d. The vertical line represents the expected position of the single ^{40}K photopeak for reference. The dotted curve in both figures is the potassium spectral template with its count rate axis scaled interactively to fit over the single potassium photopeak in the field spectrum near 1.46 MeV. Several artificial gamma-emitters of interest at the NTS also produce photons in this energy range so some trial and error may be required at this stage. Note the pronounced difference in the amplitude of the low-energy part of the spectrum, below about 500 keV, between the remaining field spectrum and the potassium spectral template in Figure 12d, a clear indication of artificial nuclides.

Subtracting the scaled potassium spectral template from the remaining field spectrum produces the residual spectrum shown in Figures 11f and 12f. Since we have subtracted the scaled spectral templates corresponding to the known natural gamma-emitters, the residual spectrum includes any artificial nuclide components plus noise.

We can perform another check to see how well the natural spectral components explain the shape of the field spectrum. In Figures 11e and 12e, the original accumulated field spectrum is plotted as the solid curve while the dotted curve represents the sum of the scaled spectral templates corresponding to the natural gamma emitters, potassium and the uranium and thorium families. These plotted curves correspond fairly closely above about 0.7 MeV but the field spectrum shows a lot of gamma activity below that energy that is not accounted for by the weighted sum of the three spectral templates for the naturally-occurring gamma emitters, again, a clear indication of artificial nuclides.

In a case like this where artificial nuclides are present, the next stage in the analysis is to try to determine which nuclides they are. First, the residual spectrum is plotted alone (Figures 13a and 14a) and in combination with spectral templates corresponding to each of the five artificial gamma emitters for reference (Figures 13b - 13f and 14b - 14f). Based on these plots and the Western Atlas curve plots, we can try fitting the artificial nuclide templates interactively in the same way the natural nuclide templates were fitted in Figures 11 and 12 above. This procedure produces somewhat less satisfactory results in the case of the artificial nuclides than for the natural nuclide families for two reasons. First, the noise level of the field spectrum has been increased by the process of stripping out the natural spectral components. Second, the five artificial nuclides considered by Western Atlas have numerous overlapping photopeaks in a relatively narrow energy band between about 0.3 and 0.9 MeV (Figure 15), so any errors in energy calibration or other processing errors have a strong influence on the results.

Proceeding with the process of fitting the artificial nuclide templates, Figures 16f and 17f show the results assuming only ^{106}Ru and ^{137}Cs are present. The weighted sum of those two spectral templates explains most of the shape of the residual field spectrum except at lower energies where the residual spectrum falls below the weighted sum of the templates. A similar effect was observed in other sections of the borehole and is probably due to differences between field conditions and calibration conditions for this tool; the effect is discussed in those sections of this report.

The Western Atlas spectral gamma-ray log curve plots also show weaker anomalies from ^{125}Sb and ^{134}Cs that are flagged as statistically significant and a ^{60}Co anomaly that is not flagged as

Figure 13. Processed spectrum accumulated from 2027 to 2400 ft in borehole ER20-6 #2 plotted on semi-log axes showing the effect of artificial nuclides as described in the text.

Figure 14. Processed spectrum accumulated from 2027 to 2400 ft in borehole ER20-6 #2 plotted on linear axes showing the effect of artificial nuclides as described in the text.

Figure 15. Five artificial spectral templates plotted together. The many overlapping photopeaks between 0.3 and 0.9 MeV make the job of extracting artificial nuclide information difficult.

Figure 16. Processed residual spectrum from 2027 to 2400 ft in borehole ER20-6 #2 plotted on semi-log axes showing the fit with a weighted combination of the ^{106}Ru and ^{137}Cs templates.

Figure 17. Processed residual spectrum from 2027 to 2400 ft in borehole ER20-6 #2 plotted on linear axes showing the fit with a weighted combination of the ^{106}Ru and ^{137}Cs templates.

statistically significant. Although one or more of those artificial nuclides may be present, the quality of the field data and the Atlas spectral analysis software are not adequate to detect low concentrations of those materials in the presence of high concentrations of ^{137}Cs with any confidence. It is important to remember that the least-squares analysis technique used by Western Atlas to make the nuclide identifications will automatically identify coherent noise (as opposed to random statistical fluctuations) as some combination of the eight nuclide families for which spectral templates are available. Since several sources of coherent noise have been identified in the data, errors in nuclide identification are unavoidable. In addition to errors in concentrations reported for nuclides that are actually present, spurious indications of low concentrations of the various nuclides can also be expected.

In addition to this overall analysis of the zone from 2027 to 2400 ft, we also divided that zone into several sections based on relatively small differences in spectral characteristics and analyzed each section individually. The conclusions for the individual sections are basically the same as the conclusions for the entire zone – no significant differences were found among these sub-zones.

Our overall impression is that the extended artificial nuclide anomaly from 2027 to 2400 ft is probably contamination distributed in the borehole fluid or spread by the borehole fluid (note that the fluid level at the time of logging was noted on the blue line header as 2028 ft). Since the borehole fluid is identified as formation water in the log headers for both boreholes, the contamination may be carried by the formation water. In the case of borehole ER20-6 #1, one theory held that the source of this contamination may have been a relatively hot zone at 1900 ft, above the water level. However, the spectral gamma-ray log for that hole showed the anomaly at 1900 ft and the contamination below the water level to contain different nuclides, and our conclusion was that the entry point is probably below the water level.⁽¹⁾ Since there is no corresponding hot zone above the water level in ER20-6 #2 it seems likely that the entry point in both cases is below the water level if prompt-injection of contamination took place, or that the contamination has moved into the boreholes with the formation water since the test.

Zone from 771 - 802 ft

The uppermost zone of interest in borehole ER20-6 #2 is at the top of the log, from about 771 to 802 ft (Figure 1). This zone is noted on the blue line as containing ^{60}Co , but that result is not flagged as statistically significant. The field spectrum summed over that zone is plotted in Figure 18a on semi-log axes and on a linear scale in Figure 19a. Figures 18b and 19b show the same accumulated field spectrum (solid curve) plotted along with the thorium spectral template (dotted). The remaining field spectrum after the scaled thorium template has been subtracted is plotted as the solid curve in Figures 18c and 19c; the dotted curve in both plots is the uranium spectral template. Again, there is some noise visible in the remaining field spectrum; this noise results from an imperfect fit between the spectral template and the field spectrum.

Subtracting the scaled uranium spectral template from the remaining field spectrum leads to the solid curve in Figures 18d and 19d; the dotted curve is the potassium spectral template. Figure 19d shows that the potassium template explains most of the remaining information in the field spectrum – if artificial nuclides are present they are in trace quantities. There are several small peaks in the processed field data below 1.3 MeV that are not seen in the template (Figure 19d)

Figure 18. Processed spectrum accumulated from 771 to 802 ft in borehole ER20-6 #2 plotted on semi-log axes showing the effect of artificial nuclides as described in the text.

Figure 19. Processed spectrum accumulated from 771 to 802 ft in borehole ER20-6 #2 plotted on linear axes showing the effect of artificial nuclides as described in the text.

that could indicate some small amount of artificial nuclear material but more likely indicates the effect of small errors in the data processing. We expect that these peaks result from differences between the calibration conditions under which the templates were developed and the field conditions in ER20-6 #2.

Proceeding with the analysis of the zone from 810 to 2020 ft, we next subtracted the scaled potassium spectral template from the remaining field spectrum, producing the residual spectrum shown in Figures 18f and 19f. Since we have subtracted the scaled spectral templates corresponding to the known natural gamma-emitters, the residual spectrum includes any artificial components plus noise. The strong negative excursion at lower energies emphasizes the lack of significant quantities of artificial nuclides over this depth range, although trace quantities could be masked by the various errors in the data.

We perform another check to see how well the natural spectral components explain the shape of the field spectrum. In Figures 18e and 19e, the original accumulated field spectrum is plotted as the solid curve; the dotted curve represents the sum of the scaled spectral templates corresponding to the natural gamma emitters, potassium and the uranium and thorium families. These plotted curves correspond fairly closely except for the general deviation below about 1.3 MeV and we can conclude that the shape of the field spectrum is well explained by natural radiation – there is no sign of significant levels of artificial nuclides.

Zone from 810 - 2020 ft

On the curve plots (Figures 1-4), the zone from 810 ft to 2020 ft shows only occasional localized indications of artificial nuclides, and those are not flagged as statistically significant by Western Atlas. The field spectrum summed over that zone is plotted in Figure 20a on semi-log axes and on a linear scale in Figure 21a. Figures 20b and 21b show the same accumulated field spectrum (solid curve) plotted along with the thorium spectral template (dotted). The remaining field spectrum after the scaled thorium template has been subtracted is plotted as the solid curve in Figures 20c and 21c; the dotted curve in both plots is the uranium spectral template. Again, there is some noise visible in the remaining field spectrum, including the negative peak visible in Figure 21c around 2.6 - 2.7 MeV; this noise results from an imperfect fit between the spectral template and the field spectrum.

Subtracting the scaled uranium spectral template from the remaining field spectrum leads to the solid curve in Figures 20d and 21d; the dotted curve is the potassium spectral template. Figure 21d shows a rather substantial departure of the processed field spectrum from the potassium template below about 1.3 MeV. Since the potassium template curve is higher than the processed field spectrum, artificial gamma emitters are not responsible for this difference. Instead, this departure is due to differences between the calibration conditions under which the templates were developed and the field conditions in borehole ER20-6 #2. Note that this type of departure was less evident in the zone from 771 to 802 ft, discussed above. The steel casing lining the section of the borehole to 802 ft probably decreased the peak-to-Compton-continuum ratio of the spectra in that zone to more closely match that of the templates. (The Compton continuum is the lower-energy spectral region of scattered gamma rays associated with each primary photopeak.) In the case of the data from 810 to 2020 ft, that region of the borehole is uncased and the spectra have a higher peak-to-Compton continuum ratio. Ideally, separate spectral templates should be

Figure 20. Field spectrum accumulated from 810 to 2020 ft in borehole ER20-6 #2 plotted on semi-log axes. The various stages of data processing described in the text are shown.

Figure 21. Field spectrum accumulated from 810 to 2020 ft in borehole ER20-6 #2 plotted on linear axes. The various stages of data processing described in the text are shown.

available for these distinctly different borehole conditions, although that would represent a rather challenging calibration requirement.

Proceeding with the analysis of the zone from 810 to 2020 ft, we next subtracted the scaled potassium spectral template from the remaining field spectrum, producing the residual spectrum shown in Figures 20f and 21f. Since we have subtracted the scaled spectral templates corresponding to the known natural gamma-emitters, the residual spectrum includes any artificial components plus noise. The negative excursion at lower energies emphasizes the lack of significant quantities of artificial nuclides over this depth range, although trace quantities could be masked by the various errors in the data.

We perform another check to see how well the natural spectral components explain the shape of the field spectrum. In Figures 20e and 21e, the original accumulated field spectrum is plotted as the solid curve; the dotted curve represents the sum of the scaled spectral templates corresponding to the natural gamma emitters, potassium and the uranium and thorium families. These plotted curves correspond fairly closely and we can conclude that the shape of the field spectrum is well explained by natural radiation – there is no sign of significant levels of artificial nuclides.

Zone from 2400 - 2548 ft

Like the zone from 810 to 2020 ft discussed above, on the curve plots (Figures 4-5), the zone from 2400 ft to 2548 ft shows only occasional localized indications of artificial nuclides, and those are not flagged as statistically significant by Western Atlas. The field spectrum summed over the zone from 2400 to 2548 ft is plotted in Figure 22a on semi-log axes; the same information is plotted on a linear scale in Figure 23a. Figures 22b and 23b show the same accumulated field spectrum (solid curve) plotted along with the thorium spectral template (dotted). The remaining field spectrum after the scaled thorium template has been subtracted is plotted as the solid curve in Figures 22c and 23c; the dotted curve in both plots is the uranium spectral template.

Subtracting the scaled uranium spectral template from the remaining field spectrum leads to the solid curve in Figures 22 and 23d; the dotted curve is the potassium spectral template. Again, Figure 23d shows a rather substantial departure of the processed field spectrum from the potassium template below about 1.3 MeV. Since the potassium template curve is higher than the processed field spectrum, artificial gamma emitters are not responsible for this difference. Instead, this departure is due to differences between the calibration conditions under which the templates were developed and the field conditions in ER20-6 #2.

Proceeding with the analysis of the zone from 810 to 2020 ft, we next subtracted the scaled potassium spectral template from the remaining field spectrum, producing the residual spectrum shown in Figures 22f and 23f. Since we have subtracted the scaled spectral templates corresponding to the known natural gamma-emitters, the residual spectrum includes any artificial components plus noise. The strong negative excursion at lower energies emphasizes the lack of significant quantities of artificial nuclides over this depth range, although trace quantities could be masked by the various errors in the data.

Figure 22. Processed spectrum accumulated from 2400 to 2548 ft in borehole ER20-6 #2 plotted on semi-log axes showing the effect of artificial nuclides as described in the text.

Figure 23. Processed spectrum accumulated from 2400 to 2548 ft in borehole ER20-6 #2 plotted on linear axes showing the effect of artificial nuclides as described in the text.

At this point we can check to see how well the natural spectral components explain the shape of the field spectrum. In Figures 22e and 23e, the original accumulated field spectrum is plotted as the solid curve; the dotted curve represents the sum of the scaled spectral templates corresponding to the natural gamma emitters, potassium and the uranium and thorium families. These plotted curves correspond fairly closely except for the general deviation below about 1.3 MeV described above and we can conclude that the shape of the field spectrum is well explained by natural radiation – there is no sign of significant levels of artificial nuclides.

Zone from 2550 - 2935 ft

On the curve plots (Figure 5) this zone differs from the one immediately above it (1400 to 2548 ft) in that it indicates a roughly twofold increase in potassium concentration and more indications of artificial nuclides, particularly ^{60}Co (still not flagged as statistically significant by Western Atlas). According to the lithology log for this borehole, there is a transition at that depth from zeolitic pumiceous lava above 2550 ft, through a thin layer of silicic lava from 2550 to 2555 ft, to devitrified lava below 2555 ft. Zeolitic lavas have a much lower content of alkalis than devitrified lavas, so a large increase in potassium is consistent with the observed lithologic change.⁽⁴⁾

The field spectrum summed over the zone from 2550 to 2935 ft is plotted in Figure 24 on semi-log axes and on a linear scale in Figure 25a. Figures 24b and 25b show the same accumulated field spectrum (solid curve) plotted along with the thorium spectral template (dotted). The remaining field spectrum after the scaled thorium template has been subtracted is plotted as the solid curve in Figures 24c and 25c; the dotted curve in both plots is the uranium spectral template. Subtracting the scaled uranium spectral template from the remaining field spectrum leads to the solid curve in Figures 24d and 25d; the dotted curve is the potassium spectral template. Again, Figure 25d shows some departure of the processed field spectrum from the potassium template below about 1.3 MeV. Since the potassium template curve is higher than the processed field spectrum, artificial gamma emitters are not responsible for this difference, which can once again be ascribed to differences between the calibration conditions under which the templates were developed and the field conditions in ER20-6 #2.

Subtracting the scaled potassium spectral template from the remaining field spectrum gives the residual spectrum shown in Figures 24f and 25f. Since we have subtracted the scaled spectral templates corresponding to the known natural gamma-emitters, the residual spectrum includes any artificial components plus noise. The negative excursion at lower energies emphasizes the lack of significant quantities of artificial nuclides over this depth range, although trace quantities could be masked by the various errors in the data. In Figures 24e and 25e, the original accumulated field spectrum is plotted as the solid curve; the dotted curve represents the sum of the scaled spectral templates corresponding to the natural gamma emitters, potassium and the uranium and thorium families. These plotted curves correspond fairly closely except for the general deviation below about 1.3 MeV described above and we can conclude that the shape of the field spectrum is well explained by natural radiation – again there is no sign of significant levels of artificial nuclides.

Figure 24. Field spectrum summed over the zone from 2550 to 2935 ft in borehole ER20-6 #2 plotted on semi-log axes. The various stages of data processing described in the text are shown.

Figure 25. Field spectrum summed over the zone from 2550 to 2935 ft in borehole ER20-6 #2 plotted on linear axes. The various stages of data processing described in the text are shown.

CONCLUSIONS AND RECOMMENDATIONS

According to the Western Atlas spectral gamma-ray log curve plots from borehole ER20-6 #2, the primary zone of artificial nuclides extends from about 2027 to 2400 ft. Our analysis indicates that anomaly can be largely attributed to ^{106}Ru and ^{137}Cs ; this is consistent with the Atlas results. These artificial nuclides appear to be in the borehole fluid (i.e., formation water) or to have been spread by the borehole fluid. We cannot confirm the presence of the other artificial gamma emitters indicated on the curve plots at low concentrations because the level of noise in the data precludes identification of small quantities of nuclides. It is important to remember that the least-squares analysis technique used by Western Atlas to make the nuclide identifications will automatically identify coherent noise (as opposed to random statistical fluctuations) as some combination of the eight nuclide families (three natural and five artificial) for which spectral templates are available.

Aside from the contaminated zone from about 2027 to 2400 ft, the curve plots show a variety of small artificial nuclide anomalies scattered throughout much of the rest of the borehole; none are flagged as statistically significant by Western Atlas. We divided the borehole into several zones based on spectral characteristics and analyzed the zones individually. There is no statistically-significant evidence of other zones containing artificial nuclides; if they are present, they are below the detection limit for this logging system.

Several sources of coherent noise have been identified in the data, making some errors in nuclide identification unavoidable. For example, the spectral templates used in the processing were not as well matched to the data from ER20-6 #2 as they ideally should be. The calibration conditions under which the templates were produced were significantly different from the field conditions in this borehole and that is reflected in the mediocre fit between the spectral templates for the natural gamma emitters and the summed field spectra in uncontaminated sections of the borehole. In addition, the problem identified in our data analysis for borehole ER20-6 #1, the fact that photopeaks from artificial nuclides perturb the automatic spectral recalibration performed by Atlas in the post-processing stage, also was observed in the spectra from ER20-6 #2. This leads to degraded accuracy in the energy calibration and probably degraded accuracy in nuclide identification in the zones of greatest interest in the UGTA work, those contaminated by artificial gamma emitters. To help alleviate this problem, we individually calibrated each summed spectrum interactively before analysis. Finally, data quality is ultimately limited by the low energy resolution inherent in the CsI detector used, and this cannot easily be changed for this logging system.

REFERENCES

- {1} J. G. CONAWAY, "Spectral gamma-ray log quality report for NTS borehole ER-20-6 #1," Los Alamos Report LA-UR 97-xxx, (1997).
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- {4} R. G. WARREN, D.A. SAWYER, F.M. BYERS, Jr, and G. L. COLE, "A petrographic/geochemical database and stratigraphic and structural framework for the southwestern Nevada volcanic field," Los Alamos National Laboratory report (in preparation).

APPENDIX A

CHARACTERISTICS OF THE WESTERN ATLAS SPECTRAL GAMMA-RAY LOGGING SYSTEM USED IN THE UGTA WORK

The Western Atlas spectral gamma-ray tool used at the Nevada Test Site Underground Test Area has a 2 in by 12 in CsI(Na) (sodium-doped cesium iodide) scintillation detector. Cesium iodide has lower energy resolution than the better known sodium iodide scintillation material but is more rugged and is also more efficient, giving higher countrates especially at higher energies and potentially better counting statistics. Detected gamma rays are sorted into 256 energy bins using a pulse-height analyzer in the tool and the data are transmitted up the logging cable in digital form. Western Atlas personnel perform an energy calibration before and after each logging run using a calibration source. Atlas also performs a running adjustment of the spectral energy scale during the office post-processing based on the positions of known peaks in the naturally occurring spectral components; this will be discussed below.

The logging system has been characterized by Western Atlas so that, at least in theory, five artificial nuclides can be identified based on their gamma-ray signatures. Those nuclides are ^{60}Co (cobalt-60), ^{106}Ru (ruthenium-106), ^{125}Sb (antimony-125), ^{134}Cs (cesium-134), and ^{137}Cs (cesium-137). In the case of ^{106}Ru , which is not a gamma emitter, any detected gamma rays come from the daughter nuclide ^{106}Rh which can be considered to be in equilibrium with ^{106}Ru under most conditions. Atlas does not attempt to provide a quantitative radioelement concentration estimate for the artificial nuclides. Log curves are expressed in counts per second attributed to each nuclide and additionally, for the artificial nuclides, as a per cent of the total countrate attributed to K, U, and Th.

Spectral gamma-ray logging is potentially very sensitive, giving an estimated detection threshold better than 0.1 pCi/g for ^{137}Cs under good conditions. However, the conditions at the NTS are not ideal. At the NTS, the decision was made to use a scintillator-based logging system for operational reasons, in part because logging with high-resolution detectors would be much more expensive. With scintillator-based systems, much depends on the contractor's ability to extract subtle information from noisy, low-resolution gamma-ray spectra.

In a previous report^(A-1) we documented several problems with the Western Atlas equipment and procedures that are generally unimportant in the normal use of that system in petroleum logging, but can cause problems when searching for artificial gamma emitters. In 1996, we conducted joint experiments with Atlas at their research facility in Houston to see what effect these deficiencies might have on the results. We found that for experimental conditions that were essentially the same as the calibration conditions, the data processing worked well. As conditions departed from this ideal, errors increased. In general, the processing was able to identify the artificial nuclides that were actually present in any given experiment, but frequently also identified nuclides, sometimes indicating substantial quantities, that were not present. The system is able to recognize the presence of artificial nuclides fairly reliably, but sometimes misidentifies the specific constituents. Such errors are probably an unavoidable consequence of trying to extract small signals from noisy data but steps can be taken to reduce the errors. The contractor seems to be following generally accepted professional practice although some

improvements are possible. Some of the deficiencies are discussed briefly below; for more information see the earlier report mentioned above.⁽¹⁾

Energy calibration. While the energy calibrations of the spectral templates are not bad, there is room for improvement. Errors in peak position of a channel or two are common. We also have identified a separate problem with the Atlas automatic peak tracking where photopeaks from artificial nuclides interfere with the natural reference peaks used for post-processing calibration on the fly. Thus, the spectral calibration can be at its worst in zones of greatest interest in the UGTA work, zones that are contaminated by artificial gamma emitters.

Incorrect borehole environment. The borehole environments at the calibration facilities in which the Western Atlas spectral gamma-ray logging system was characterized differ significantly from the actual borehole environment in the Underground Test Area work. This results in different spectral shapes that can adversely affect the processing.

Missing templates. Artificial gamma emitters may be present in significant quantities that are not included in the data processing; this could lead to erroneous nuclide identifications.

Differential non-linearity. Pronounced differential non-linearity was observed in the Western Atlas spectra; in our experience, the differential non-linearity is unacceptably high for addressing the difficult problems at the NTS.

REFERENCES FOR APPENDIX B

- {A-1} J. G. CONAWAY, "Spectral gamma-ray log quality report for NTS borehole ER-20-6 #1," Los Alamos Report LA-UR 97-xxx, (1997).