

# High Temperature Spectral Gamma Well Logging

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CONF-971048-3

## Abstract

A high temperature spectral gamma tool has been designed and built for use in small-diameter geothermal exploration wells. Several engineering judgments are discussed regarding operating parameters, well model selection, and signal processing. An actual well log at elevated temperatures is given with spectral gamma reading showing repeatability.

## Introduction

Spectral gamma well logs can detect naturally occurring gamma emitting elements such as potassium, uranium, and thorium inside differing well lithologies. Potassium bearing deposits can be a byproduct of alterations. In SB-15, the spectral gamma tool measured high potassium presence in the production zone. Increased potassium maybe correlated to sericite found in fractures as seen in the core samples. Sericite contains 10% potassium by weight,  $K_2Al_4[Si_6Al_2O_{20}](OH,F)_4$ . Sericite is one example of material deposited in fractures.

A high quality spectral gamma log could, in some cases, map fractured areas. Spectral logs work with and without casing as potassium, uranium, and thorium all have gamma of sufficient energy to penetrate casing. Little is known about spectral gamma log data inside geothermal wells. There maybe correlations with uranium and thorium also. Sandia has the only known spectral gamma tool suitable for hot well applications.

## Mode of Operation

Below is a simplified block diagram of the Sandia spectral gamma tool. The tool uses a Bicron<sup>TM</sup> MWD (Measurement-While-Drilling) thallium-activated sodium iodide crystal optically coupled to a photo-multiplier. When a gamma ray hits the crystal, it surrenders some or all of its energy. The crystal produces a light (photons) proportional to the energy deposited by the incident gamma. The crystal is covered in a reflective coating with one end optically coupled to a photo-multiplier. The photo-multiplier captures the light, which causes electron flow from the high voltage supply (see Figure 1). The electron flow is also proportional to the amount of gamma ray energy deposited.

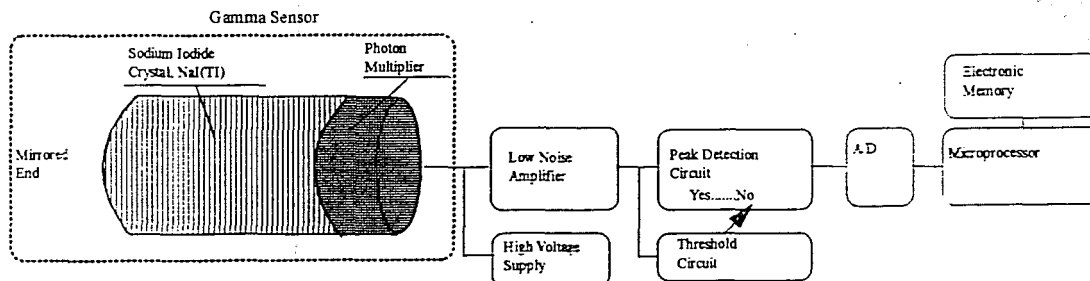


Figure 1. Simplified Block Diagram of the Sandia Spectral Gamma Logging Tool.

A low noise amplifier amplifies the small electron discharge large enough for the peak detection circuit to capture the peak signal. A threshold circuit tests the signal for sufficient amplitude. If too small, then the peak may only be electrical noise or very low energy gamma. Once a gamma ray of sufficient energy trips the threshold circuit, the peak value is recorded. For the Sandia spectral gamma instrument, the threshold

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is predetermined at  $\sim 0.35$  MeV (Million electron volts). The A/D (Analog to Digital converter) then reads the peak energy value returning an eight bit binary number. The energy levels are divided into 0 to 255 channels, with channel 255 being the greatest energy level. The upper energy limit is set at 2.8 MeV. Note: A simple total count gamma tool provides a count of gamma rays above a threshold. By calibrating the total count gamma against API (American Petroleum Institute) units, the spectral gamma tool can provide both spectral gamma and conventional gamma logs.

### Calibration

Gamma count rate is a relative measure of gamma flux within the well bore. This flux is proportional to the amount of radioactive material in the surrounding formation. Thus, the measured flux is converted to pCi/g by calibration coefficients derived from tool readings within calibration models. These models have known amounts of source material distributed in a large enough volume to appear infinitely large to traveling gamma rays. Infinitely large is approximately a two foot radius from well bore center.

The most commonly used calibration models are maintained for DOE's Grand Junction Projects Office in Grand Junction, Co. This office maintains a set of field calibration models at nearby Grants, New Mexico. These models contain three naturally occurring elements,  $K^{40}$ ,  $Ra^{226}$ , and  $Th^{232}$ , (KUT).

In working with subterranean gamma, there is a problem of higher energy gamma rays being counted in lower channels called down scattering. Stromswold (1981) uses gamma count windows centered about energy peaks of the three natural elements which unfold from highest energy to lowest. Table 1 shows his suggested windows.

Table 1 Spectral Energy Windows for Unfolding KUT

Element	Unique Gamma Ray (MeV)	Energy Window (MeV)
Potassium (K-40)	1.46	1.320-1.575
Uranium (Ra-226)	1.76 & 2.20	1.650-2.390
Thorium (Th-232)	2.61	2.475-2.765

By choosing the Thorium window about the 2.61 MeV gamma, Thorium can be solved for because potassium and uranium don't have any gamma rays that high in energy. The uranium window centers around 1.76 and 2.20 MeV for uranium ore excluding the potassium gamma at 1.46 MeV. Figure 2 shows the three energy windows given in Table 1 against spectrums taken at the Grants New Mexico facilities. The Grants calibration models are well suited for this unfolding process. The well model concentrations are listed in Table 2.

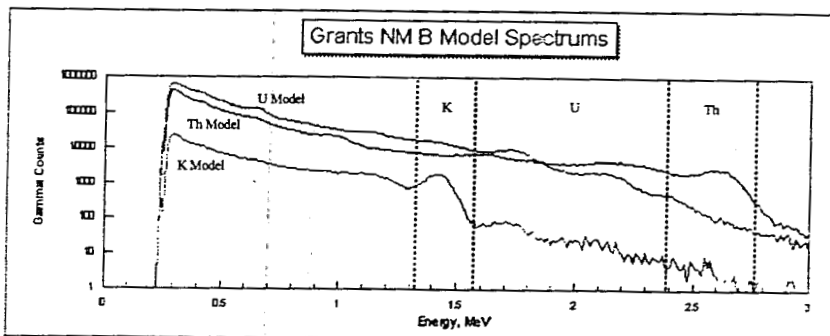


Figure 2. These are three spectral measurements made by the Sandia tool while in each of the three calibration wells at Grants, New Mexico. Sample period of one hour.

Table 2. Grants New Mexico B-Model Concentrations

Model	Concentration Th (pCi/g)	Concentration U (pCi/g)	Concentration K (pCi/g)
Th Model	68.06 ± 1.83	11.34 ± 0.58	9.71 ± 1.51
U Model	0.71 ± 0.06	178.18 ± 5.47	11.80 ± 0.84
K Model	0.10 ± 0.02	1.08 ± 0.10	52.16 ± 1.84

By placing the spectral gamma tool into each of the three models, subtracting electrical noise, and counting gamma for each of the three windows in Table 1, a rate matrix R is produced. Matrix R is guaranteed to be nonsingular because the window selection process assures an upper triangular form (an approximation, see Table 2). Using the concentrations of Table 2, a set of coefficients relating window count rates to concentrations (pCi/g) can be solved for using Eq1. Note: The statistical nature of gamma counting requires long counting periods to gain a meaningful count rate. The time period for Figure 2 spectrums was one hour.

$$A = CR^{-1} \quad (1)$$

Where as 'A' is a 3X3 matrix of calibration coefficients and R is a 3X3 matrix of count rate readings for each of the three windows shown in Figure 2. 'C' is a 3X3 matrix of known model concentrations from Table 2. Once 'A' is known, the system is tested against a fourth model which is a mix of all three elements. A properly calibrated spectrometer then solves for the concentration levels in the mixed well by using Equation 2.

$$C = AR \quad (2)$$

Where as 'R' is a 1X3 column vector containing window count readings, [T, U, K]<sup>T</sup> for the mixed (or unknown well) and 'C' is the resulting measured concentration of KUT for that well section in pCi/g. The measure of the gamma flux density is also dependent on well conditions such as diameter, casing, and fluid density. Also to be considered are tool electronics conversion rate and crystal size. The more complete Sandia research and development report will cover all of these topics; Expected release late summer 97.

### Geothermal Test Well

This test well was the first well where Sandia's spectral tool was used and the only well that had core data. Unfortunately, only a small portion of the well was logged due to time constraints. This section was logged three times at 2.25 ft/min and re-logged the following day at 5 ft/min. The slow logging rates are required to get some sense of statistical accuracy. At the time of this test, Sandia did not have a computerized depth correlation program. The data we have from this test was saved as an Excel<sup>TM</sup> file. The gamma readings were synchronized to depth readings manually and correlated within the Excel<sup>TM</sup> file. The tool takes readings every ten seconds and starts when the battery is installed. There is some uncertainty as to when the battery actually makes contact to start the tool. The Sandia tools now have computerized depth and measurement time correlation, thus eliminating uncertainties.

This test well provides some of our best results. The three passes created an ensemble of data. Ensemble averaging provides the best method for gaining consistent spectral gamma well bore readings. In the filtering section, two different ensemble filters are used to filter the three passes into one well log. Ruckbusch (1983) reports that a Kalman filter design provides highly repeatable spectral gamma logs. To filter spectral readings with only one pass, a Kalman filter was demonstrated. Before discussion about filtering, some basic understanding about the variance of spectral gamma well readings is needed.

## Basic Understanding of Well Bore Random Variables

As the tool moves down the well, spectral readings vary due to two random variables. First are differing rock/soil formations (lithology). As the tool moves between formations, different gamma signatures may be expected. Because the rock formations and mineral deposits are unknown at the start of a well logging run, the desired lithology information is a random variable. However, this information does not change (quickly) with respect to time. The well information is strict sense stationary for KUT concentrations versus well depth. In the ideal case, two logging runs done on two consecutive days will have identical readings.

The second random variable is the result of natural gamma count fluctuations. The gamma measurement data is best characterized as a non-zero mean, independent, normal, random process. The valued information is the non-zero mean relating to KUT concentrations. In other words, the well bore information desired is "What would the average gamma reading be if gamma readings could be sampled for all time." Eq 3 relates the window measured counts to the formation information and noise.

$$W_{\text{Count}} = F_{\text{KUT}} + N(0, \sigma) \quad (3)$$

Where  $W_{\text{count}}$  is the gamma count measured in any window.  $F_{\text{KUT}}$  is the average count rate for any window caused by KUT formation concentrations.  $N$  is a normal (Gaussian) random variable with zero mean and  $\sigma$  as the variance.

From these basic understandings, two assumptions can now be declared. First, ensemble averaging will eliminate zero mean noise and preserve the average  $F_{\text{KUT}}$  value. Thus, multiple passes through a well section can be averaged to reduce noise. Second, two consecutive readings within a common rock/soil formation will have a common variance,  $\sigma$ . As with any sample system, the ability to detect changes in formation must adhere to Nyquist criteria. Thus, the best possible formation resolution is 0.75 ft for a tool taking a reading every 10 seconds and logging at 2.25 ft/min. In practice, the best resolution maybe 4 to 6 times Nyquist or 3 to 4.5 ft.

## Filtering the Measurement to Improve Well Readings

### Unfiltered Data

The variation of individual samples is great within a ten second counting period. Ensemble averaging is used to reduce measurement variance. Figure 3, below is a plot of potassium window counts while the tool was stationary for ~3 minutes at a fixed depth of 1348.8 ft prior to each of the three passes within the test well.

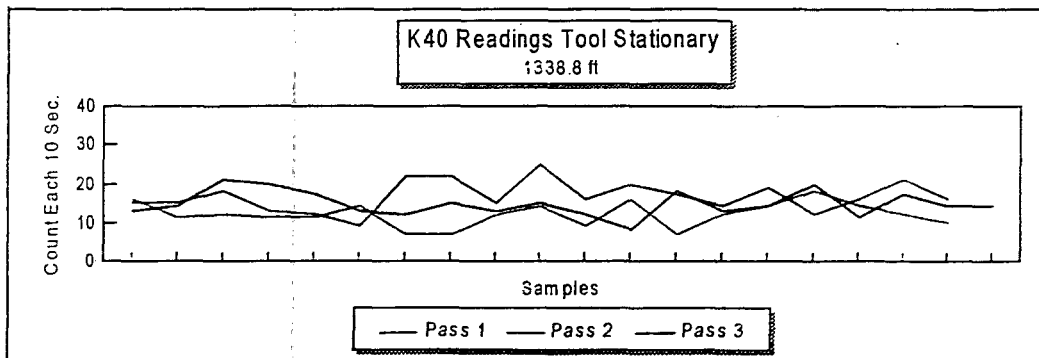


Figure 3.) Stationary readings. Note: The three stationary reads are constant at an average of 14.4 counts per period. This helps to show that the tool was not changing calibration while internal temperatures were increasing.

The mean value for the stationary reading is 14.4 counts per 10 second reading. The standard deviation is 3.8 counts per period. The expected range of readings for three standard deviations is 3 to 26. Note: Figure 3 readings do fall within this range. Also note: The three stationary reads are constant about an average of 14.4 counts per period. This implies that the tool was not changing calibration while internal temperatures were increasing with increased well bore exposure.

Because of the large variance in count readings, some sort of smoothing must be used so that the operator can detect slight changes occurring in the average gamma counts as the tool moves past varying lithology. Figure 4 is the potassium window count plot for the three passes. It is difficult to see anything useful about this data except some increase in all three passes at ~1370 ft.

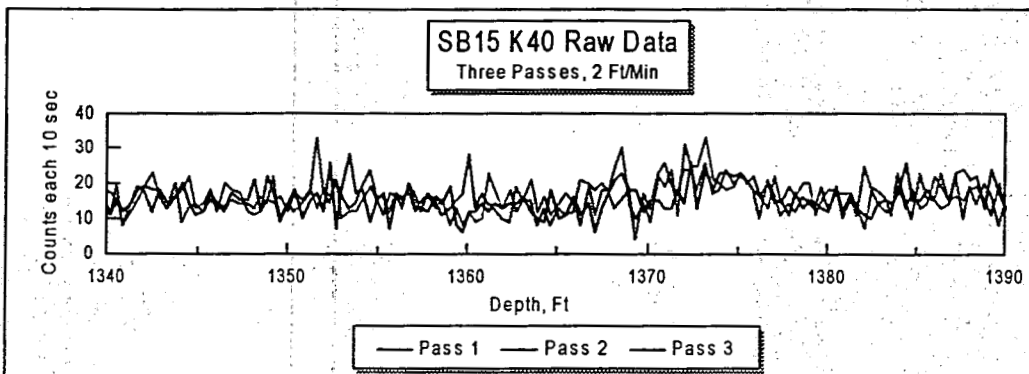


Figure 4.) Three Logs of the Same Well Section

#### Averaging Functions

There are a number of smoothing functions available for these problems. Linear digital filters as moving averages, FIR, IIR filters, and non-linear filters as median filters, and so on. After some experimentation, the median filter using only three points seems to provide the best overall results. Like the average value over infinite time, the median value approaches a constant value. The median value works by removing outlying sample points.

Using the stationary readings made at 1338.8 ft shown in Figure 3 both the moving three point average and three point median values were taken. Figure 5 demonstrates that the average value and the median filter result in smoothing the measured potassium window count to ~14 count per readings,  $F_{KUT}$  in Eq 3. If these readings are smoothed, then applying the same methods to the window reading while the tool is in motion should reduce the noise  $N$  in Eq 3 making lithology changes more apparent.

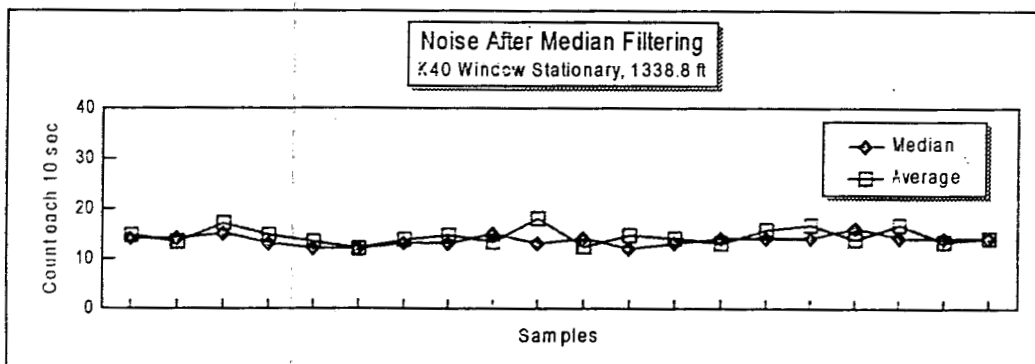


Figure 5. The median filter of the stationary gamma readings compared to taking the simple average.

The results of the three point median filter and the simple averaging of the three passes are shown in Figures 7 and 8, respectively. These resulted in a single set of readings for the 50 ft well section. For

completeness, Figure 6 shows the interim process of the median filter across each individual pass. The result shown in Figure 7 is the median value for each depth given the three passes in Figure 6. By filtering each pass first and then the ensemble, every point was compared to its neighbor in a two dimensional array.

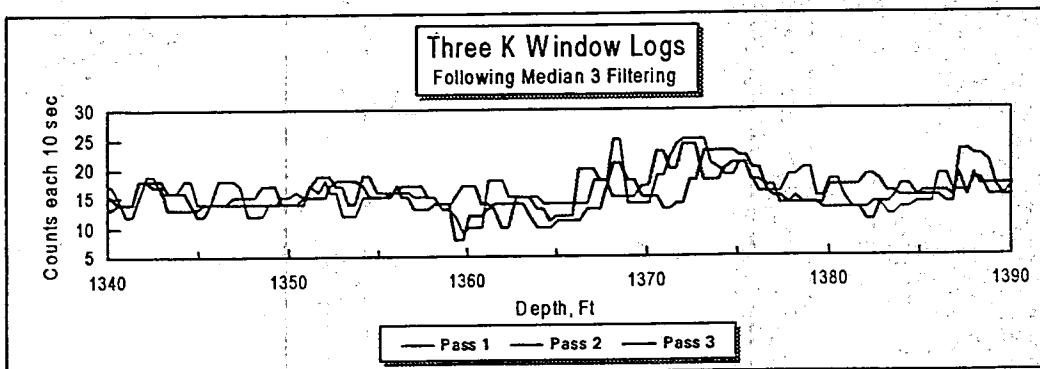


Figure 6. The median average for three points on each pass while logging at 2.25 ft/min

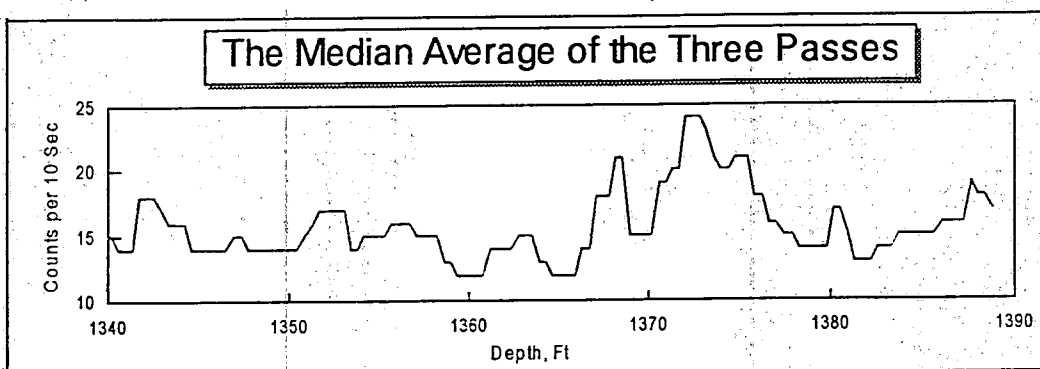


Figure 7. The median value of the three passes.

In Figure 7 the median filter reduces noise while preserving edges. Edges are important because they represent boundaries. The boundaries indicate formation changes or perhaps narrow veins of mineral deposits. More common linear filters or averaging restrict bandwidth to smooth signal readings. Reduced bandwidth rounds or smooths edges. Another slight advantage of the median filter is that it smooths signals while using actual readings. All of the data points in Figure 7 are actual potassium window count readings. For comparison, the three passes were filtered using a three point moving average, shown in Figure 8. Again, each signal was moving averaged and then the ensemble. One major limitation to ensemble filtering is the cost of increased logging time. Few well owners want to log multiple passes to gain one set of readings. For single pass measurements a Kalman filter was used.

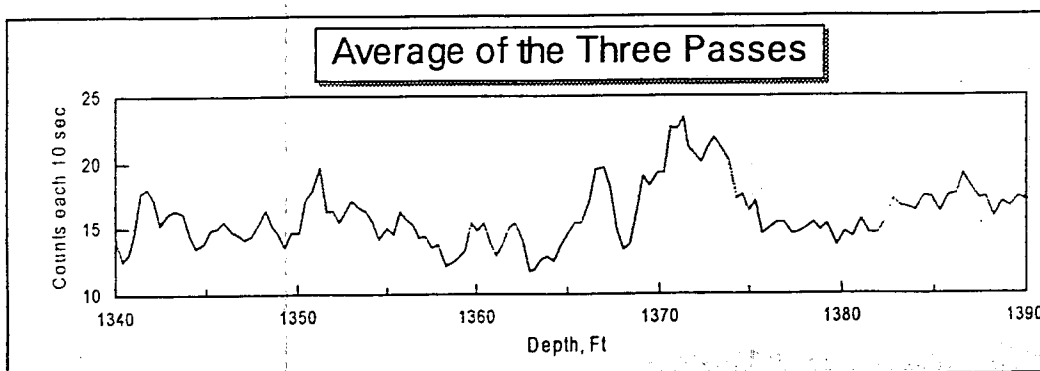


Figure 8. Using a three point moving average to filter the three passes.



### Kalman Filter for Spectral Filtering

Recursive digital filters based on estimators as Wiener and Kalman provide filtering through a statistical sense. The Kalman filter is well suited for filtering noisy measurements where both the noise and well lithology variances are known. For gamma count measurements, the standard deviation is equal to the square root of the expected value, Eq 4. For the stationary measurements at 1338.8 ft, the mean was 14.4 counts per period and the standard deviation is 3.8 counts per period. The standard deviation calculation is valid if the windowed count rate over the sample period is greater than five. At five and below, the count rate fails to look Gaussian and is, instead, Poisson, [4].

The variance of the well lithology is now needed. This is the unknown random variable discussed earlier. Ruckebusch [4] suggests a well model which assumes slowly varying well lithology with an occasional jump to an unknown value. These jumps are at the formation boundaries.

$$\text{Counting Variance (Noise): } \sigma_{K,U,T} = \sqrt{E[\text{Window Count}]} \quad (4)$$

$$\text{Well Model: } E[KUT_{n+1}] = E[KUT_n] + \epsilon + \delta_n \quad (5)$$

$$\text{Kalman Error: } K_e = KUT_{n+1} - E[KUT_{n+1}] \quad (6)$$

Equation 4 is the assumed standard deviation taken as the square root of the estimated count mean. This is the noise variance used in the Kalman filter. Equation 5 models well lithology as a sequence of gamma Kalman estimates for KUT,  $E[KUT]$ . The estimate is assumed constant with exception of a small errors  $\epsilon$  and jump  $\delta_n$  at unknown points within the sequence (lithology changes). The sequence is  $n$  samples which correlates to depth within the well. To account for small changes in the well lithology a small error,  $\epsilon$ , value is assumed based on priori information. Because of limited spectral log data in geothermal fields,  $\epsilon$  is a best guess at this time.

Now that the formal issues have been addressed, a simple explanation of the Kalman filter is in order. First, the filter will require establishing an estimated count rate mean for each of the KUT windows. This is done by holding the tool stationary at any point, even within the logging truck. The stationary time should be greater than 5 min, or long enough to let the tool's internal temperature stabilize. The value for  $\epsilon$  is preprogrammed. This value lets the filter follow slow changing lithology while not letting the filter react to transients. This clamping of the Kalman filter enforces well log repeatability. If the response is slowed then only major, hard-to-miss lithology changes are reported in the log.

Now that data is coming into the filter, the logging process begins. With each new measurement, the Kalman filter calculates its error,  $K_e$ . Here Equation 6 is taking the difference between the measured value and its estimated mean value. If the difference is less than three times  $\sigma_{kut}$ , the filter assumes a valid estimate and moves its next estimated mean value only slightly, by a factor of  $\epsilon$ . In short, if the measured value falls within the Gaussian distribution of the Kalman estimated gamma mean count rate: The Kalman estimated mean is kept with little change.

This process continues holding the filtered output centered within the statistical center of the readings. When a lithology changes quickly, the Kalman error is great. This is detected when the Kalman error,  $K_e$ , is more than three times  $\sigma_{kut}$ . The Kalman filter can no longer use its estimated mean value. There are several published methods on how to generate a new estimated mean while logging. The Sandia method takes advantage of the fact that all data samples are stored in memory. We simply start a new value by jumping ahead eleven samples and calculating the Kalman estimated mean moving backwards through the measured data. This method was first presented by Fraser and Potter [7] in 1969.

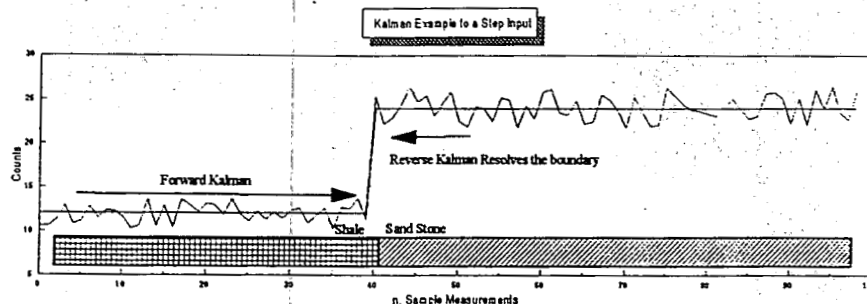


Figure 9. The Kalman smoother filter correcting for a lithology boundary condition.

By working backwards, the filter smooths out gamma readings but allows for detection of abrupt boundary conditions, see Figure 9. Starting back some 11 samples improves the filter rejection of formation widths which are too small to be repeatable subsequent log runs.

Using the data from the test well, the Kalman filter is applied to a single pass while logging at 5 ft/min. This rate does not provide the resolution of the three pass 2.25 ft/min, but the similarities of the two measurements are better than should normally be expected. The Sandia tool under present design (crystal size) should be logged at slower rates. The results are shown in Figures 10-13. Figure 10 contains the Kalman filtered values along with the actual potassium window counts. These data plots were produced by the Sandia tool software and copied into this Word<sup>TM</sup> document. This software was not available at the time the log was performed. This software is not fully developed and requires additional testing.

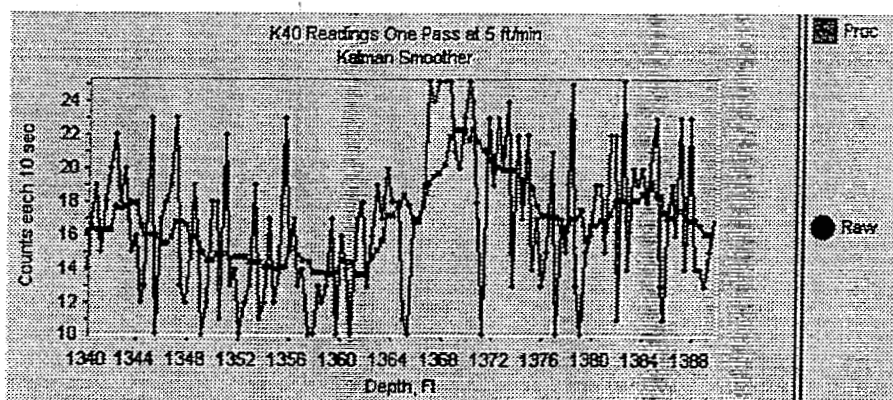


Figure 10. 50ft well section showing measured signal (blue, round) and Kalman filter response.

Figures 11-13 show the complete 160 ft run for all three windows following the Kalman filter.

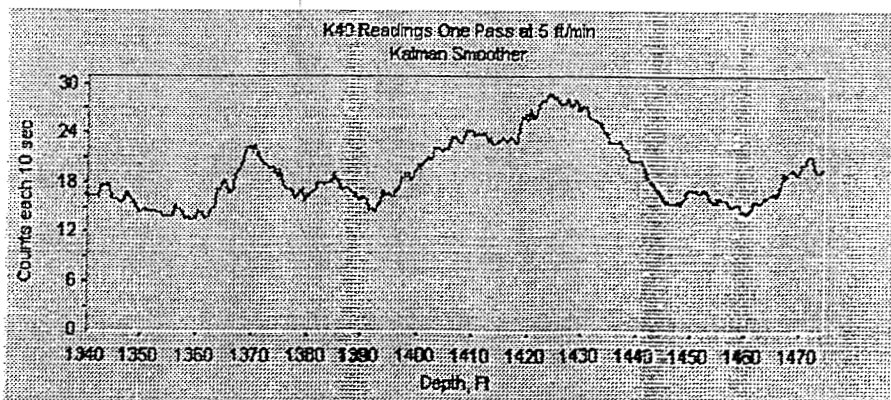


Figure 11. The complete 160 ft log showing potassium window counts.

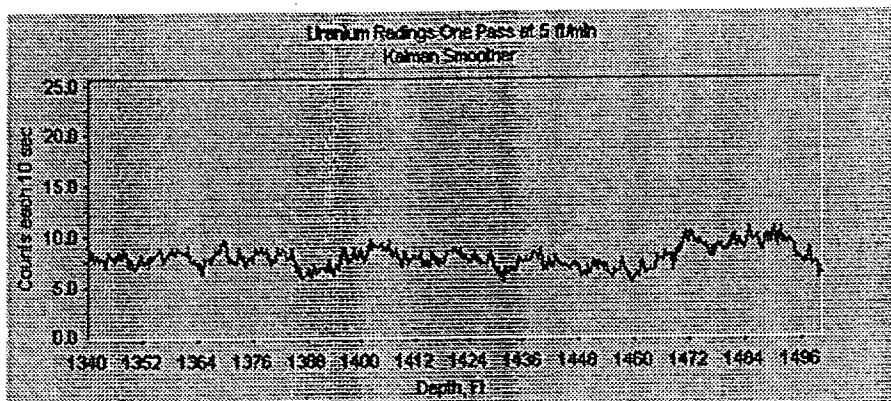


Figure 12. The complete 160 ft log showing uranium window counts.

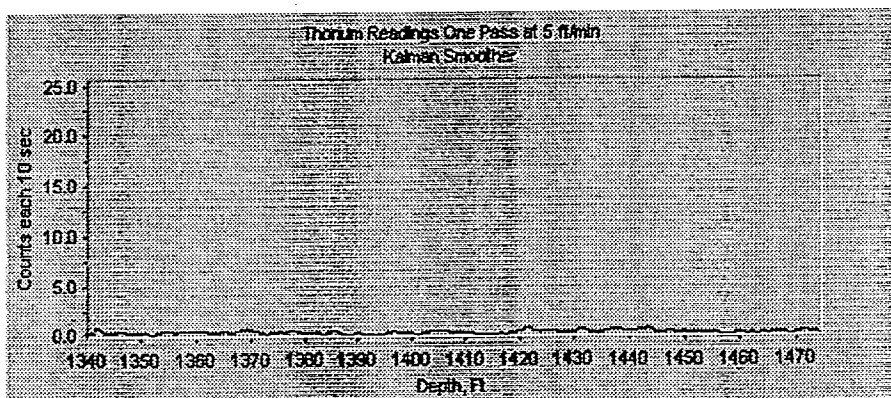


Figure 13. The complete 160 ft log showing the thorium window counts.

For window count readings within Figures 11 and 12 there are sufficient gamma counts to assume a Gaussian distribution. For Figure 13, the count rate was below an average of 5. There are insufficient gamma counts to assume a Gaussian distribution with the standard variance of Equation 4. Here the Kalman filter assumed a fixed variance giving the algorithm room to detect changes in count levels. The zero reading for the Thorium window indicates that the Thorium in the formation is well below that of the potassium.

### Conclusion

The Sandia spectral tool is capable of tracking potassium within uncased small diameter well bores. The detector is also well suited for gamma logs in API units while also measuring the gamma spectrum. Commercial spectral logging tools commonly use 2X8 and 2X12 crystals. These crystals provide a gamma count rate 8 to 12 times greater than the 1X6 used by the present slim hole spectral gamma tool. A second Sandia tool is being built using a 1.5X6 inch detector, which will increase the gamma count rate three times.

Slight changes in KUT lithology readings within the well are hidden by the large variance of gamma count readings. The natural variance in gamma count readings is large due to the small sample period needed for locating formation boundaries. Two methods for reducing gamma count variance were explored. One was the ensemble median filter and the other Kalman filter. The ensemble median filter provides excellent spatial resolution at the cost of multiple logging runs over the same well sections. Because ensemble filtering is not practical for consumer logging, the Kalman filter was also explored. Although the Kalman gave close representative readings to the ensemble, more filter testing is

recommended. More testing will lead to improvements in filter parameters, preserving spectral information that is most important to geothermal scientists and geologists.

### Acknowledgments

Sandia is a multiprogram laboratory operated by Sandia Corporation, a Lockheed Martin Company, for the United States Department of Energy under contract DE-ACO4-94AL85000.

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