**UOIT IEEE NPSS International Workshop**

**on**

**Real Time Measurements,
Instrumenation & Control**

**RTMIC**

**June 25 & 26, 2010**

# Hybrid Pulse Height/Integration Analysis Method For Portable TEPC Instrument

## By

## Dr. Thomas J Conroy

**University of Regina
Faculty of Engineering
Electronic Systems Engineering
Education Building, Room 409
Telephone: 1-306-585-4397
Email: Thomas.conroy@uregina.ca**

# ABSTRACT

Portable dosimeters typically use one of two methods for processing and analyzing data 1) total charge integration, which provides total absorbed dose, or 2) pulse height analysis, which provides both total absorbed dose and total dose equivalent. There are limitations of using each strategy with each method having both inherent advantages and disadvantages. For particular environments and applications, one method or the other may work well and have little or no disadvantages. However, for mixed varying fields this is not the case, researchers over the past 40 years have employed a number of methods, with limited success, to overcome the limitations. One such method is a hybrid that uses the integration method for low LET events, and pulse height for high LET events. For small-low powered instruments exposed to rough handling and noisy environments, the hybrid method of obtaining information from a single detector provides a number of benefits. Portable instruments constructed using the hybrid technique balance the inherit limitation of using either integration or pulse height analysis when also trying to achieve low power, small size, and operation in rugged environments.

# INTRODUCTION

Tissue Equivalent Proportional Counter instruments are a small part of the dosimeter market but of critical importance in a number of applications that require real-time assessment of total dose equivalent. TEPC's are one of only a few instruments that can be used to measure quality factors for varying radiation environments. The current selection of TEPC devices is fairly limited.

For the last 20 years, excluding, a small number of TEPC's built for research purposes, there have been two main sources of TEPC instruments. Though currently, there is only one source, Far West Technology – a number of R&D projects in different locations of the world could change this in the next few years. Far West makes two TEPC instruments for measuring total dose and dose equivalent exposure, the HAWK and REM500. These two instruments account for the majority of portable TEPC instruments that are currently in use worldwide. Additionally, there are a dozen or so instruments specially built for NASA and used on the space shuttle and space station. The NASA instrument designs were transferred to Far West in early 2000, and the HAWK is an enhancement of these earlier instruments.

The REM500, developed approximately 20 to 30 years earlier than the HAWK, differs in detector size, resolution, and range. Besides these, there are basic differences between the HAWK and REM500 in the definition of lineal energy, as well as different Q value tables for converting LET to dose equivalence (although recently the REM500 has been upgraded to provide an option to use the same methods as the Hawk). Lineal energy in the very early years of micro-dosimetry, somewhere prior to 1970 used the term Y (e.g. Bevan, 1966 [2]) which was defined as the energy deposited divided by the diameter, whereas the modern definition of lineal energy uses the variable y (e.g. Rossi 1970 [5]) which is defined as the energy deposited divided by the mean cord length. Despite the different decades when the two instruments were developed both instruments are very similar in operation, and use solely pulse height analysis for calculating dose and dose equivalent. The computation of the dose and dose equivalent values are fairly straightforward in principle (e.g. Assar;Waker 2010 [5]), but can in practice get a bit complicated, as detailed below for Far West Technologies Hawk instrument.

# HAWK SPECTRUM, Gy AND Sv COMPUTATIONS

The HAWK takes a full spectrum from 0 to 1535.5 keV/μm consisting of 1024 channels. In addition, an expanded spectrum of 256 channels is taken from 0 to 25.55 keV/μm, both spectrums are stored on a flash memory card once a minute. These two spectrums are used to compute dose, and dose equivalent. The raw data is downloaded from the instrument, allowing it to be stored and displayed, as well as, alternative methods to be used to convert the spectrum to dose and dose equivalence.

Unlike the REM500, the HAWK instrument provides a spectrum for both High LET and Low LET events. This capability is possible because of the low noise of the Hawk measurement electronics – approximately 0.1 to 0.2 keV/µm FWHM, and the inclusion of two pulse shaping circuits, one with 60 times greater gain than the other, and duplicate peak hold and A/D hardware to collect both spectrums. Two linear A/D converters (with range 0 to 2.048 volts) are used, one A/D provides 256 channels of pulse height (0.05 to 25.55 keV/µm with 0.1 keV/µm per channel) verses total counts, and the other provides 1024 channels (0.5 to 1535.5 keV/µm with 1.5 keV/µm per channel). Combining these two spectrums involves a few complications.

The HAWK instrument uses a spherical detector, who's inside diameter, **D= 4.95** inches, and is filled with 99.7% propane. K is calculated from first principles using pure propane at 7.0 Torr, and a 2-micron site size. For equation 1 and 2 below **K= 32.36 * $10^{-11}$**. In equation 1 and 2 below, D, is specified in inches.

$\text{HiGainSpect}_{\text{chn}}$ is array with each element being the total number of counts in each channel of the high gain spectrum (note: that the high gain corresponds to the low LET events), where chn=0 to 255. Similarly, $\text{LoGainSpect}_{\text{chn}}$ is the total number of counts in each channel of the low gain spectrum (High LET), where chn=0 to 1023. $\text{HawkHiQTable}_{\text{chn}}$ is the quality factor multiplier from the high gain (Low LET) quality factor conversion table for the specific channel, where chn=0 to 255. The values are shown graphically in figure 1, and correspond to the table in ICRP 60 [8]. $\text{HawkLoQTable}_{\text{chn}}$ is the quality factor multiplier from the low gain (High LET) quality factor conversion table for the specific channel, where chn=0 to 1023 -- As before the values are shown graphically in figure 1, and correspond to the table in ICRP 60 (for ICRP 60 the quality factor is 1.0 for all values in range 0 to 10 kev/ µm).

Threshold is the channel at which the discriminator is set to eliminate noise. Channels below the threshold have reduced or non-existent counts, and an extrapolation must be used to account for data in this region. The HAWK determines the threshold by finding the highest count value in the high gain (Low LET) spectrum channels 0 to 9 (0.05 keV/µm to 0.95 keV/µm), this channel is defined as the "threshold" channel. Using a cobalt-60 spectrum, extrapolation factors where calculated to account for the missing lower portion of the spectrum based on the threshold level. This approach was used to minimize the real-time computational requirements during data acquisition, and for simplicity was also used in all post analysis programs. For higher accuracy, a curve should be fit to the points above the threshold and extended down to 0 at 0 kev/µm.

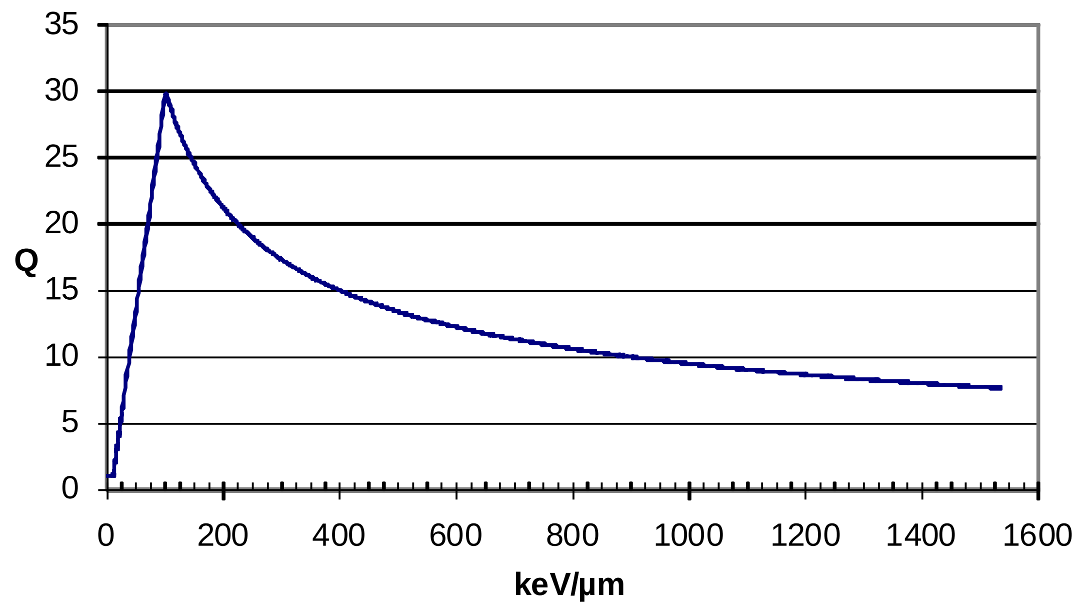


Figure 1 - HAWK Q TABLE from ICRP 60

The equation 1 and 2 below take a spectrum and convert it to Gy or Sv per time period, where the time period is equal to the elapsed time used to collect the spectrum. Additionally, the results have to be corrected for dead-time, equation 3.

HAWK INSTRUMENT EQUATIONS

[Equation 1]

$$\text{Dose (Gy)} = \frac{K}{D^2} * \left[ \begin{array}{l} ExtrapFactor_{threshold} * HiGainSpect_{threshold} * (0.1) keV/\mu m \\ + \sum_{chn=threshold+1}^{240} HiGainSpect_{chn} * (chn + 0.5) * (0.1) keV/\mu m \\ + \sum_{chn=transition}^{1023} LoGainSpect_{chn} * (chn + 0.5) * (1.5) keV/\mu m \end{array} \right]$$

[Equation 2]

$$\text{Dose Eq.(Sv)} = \frac{K}{D^2} * \left[ \begin{array}{l} ExtrapFactor_{threshold} * HiGainSpect_{threshold} * HawkHiQTable_{threshold} * (0.1) keV / \mu m \\ + \displaystyle\sum_{chn=threshold+1}^{240} HiGainSpect_{chn} * (chn + 0.5) * HawkHiQTable_{chn} * (0.1) keV / \mu m \\ + \displaystyle\sum_{chn=transition}^{1023} LoGainSpect_{chn} * (chn + 0.5) * HawkLoQTable_{chn} * (1.5) keV / \mu m \end{array} \right]$$

Where,
$\text{ExtrapFactor}_0 = 0.0$, $\text{ExtrapFactor}_1 = 1.0$, $\text{ExtrapFactor}_2 = 2.0$, $\text{ExtrapFactor}_3 = 3.89$, $\text{ExtrapFactor}_4 = 6.3$, $\text{ExtrapFactor}_5 = 8.9$, $\text{ExtrapFactor}_6 = 9.1$, $\text{ExtrapFactor}_7 = 12.2$, $\text{ExtrapFactor}_8 = 16.8$, $\text{ExtrapFactor}_9 = 18.2$

Equation 1 and 2 differ only in that equation 2 has a Quality factor multiplier. The first term in both equations is the dose or dose equivalence for the extrapolated region below the threshold. The second term is the dose or does equivalence for the region between the threshold and 24.0 keV/µm. The third term is for the dose and dose equivalence between 24.0 keV/µm and 1535.5 keV/µm. The split between term 2 and 3 is at approximately channel 16, and is referred to as the transition channel. Understanding the transition channel in equation 1 and 2 requires a detailed understanding of the raw spectrum data and how it is collected.

Each event in the TEPC detector is histogrammed in both the high and low gain (low LET and high LET) spectrum. For example, an event of pulse height 1.5 volts in the low gain channel produces a count in approximately channel 750 (or 1125 keV/µm); the same event the high gain channel would saturate (i.e. the voltage would be above 2.048 volts) producing a count in the maximum channel, or 255. As another example, an event of pulse height 1.5 volts in the high gain channel would produce a count in approximately channel 187 (or 18.75 keV/µm) of the high gain (Low LET) spectrum; for the same event in the low gain channel (High LET) the event would produce a count in approximately channel 12 (or 18 keV/µm). The electronics design results in the same total number of counts in both the high and low gain spectrums. For example, the data being used to calculate the dose and dose equivalence in the last region, approximately 24 to 1535.5 keV/µm of the low gain channel, will have a corresponding set of counts in channels 240 to 255 of the high gain (24 to 25.5 keV/µm), with most of the counts above 25 keV/µm saturated and appearing in channel 255.

The transition channel can best be understood by carefully following step-by-step the calculation of the dose and dose equivalence. The threshold is first found and the extrapolate portion is determined, followed by the addition of the second term summation from high gain (Low LET) channel 0 to 240 (0 to 24.05 keV/µm). At this point the total number of events (or counts) from high gain spectrum channel 0 to 240 are already included in the dose and dose equivalence partial totals. These events (or counts) will have a corresponding event (or count) in the low gain spectrum (0 to 24 keV/µm, high LET). These events (or counts) must be removed from the low gain spectrum prior to computing the last term in equation 1 and 2. The A/D converters and peak hold circuits are not particularly linear for very low voltage pulses; however, each channel is monotonic. Consequently, removal of events from the low gain spectrum is simple, just start at channel 0, and set the count value to zero and subtract the 0 channel count from the total number of events whose dose and dose equivalence has already been computed. Continue in this fashion until the required number of counts has been removed from the low gain spectrum. Likely the last channel, whose counts are reduced, will not be reduced to zero. The first non-zero low gain spectrum channel is called the transition channel. The third term sums the dose and dose equivalence from the transition channel (approximately channel 16 in low gain spectrum) to the last channel, 1023.

All the NASA TEPC instruments are precursors to the Hawk instrument, and work approximately the same. The Hawk is a nominally a 5-inch spherical detector, whereas the NASA instruments are cylindrical with the height equal to the diameter. They range in diameter from 0.7-inch to 2.0-inch.  The electronics designs and components and mechanical parts are different but fundamentally they produce the same type of data outputs, formats, etc.

# HAWK DEAD-TIME CORRECTION

Another potential source of error is dead-time. Neither the REM500 nor the HAWK provides dead-time correction (a later version of the HAWK provides a dead-time correction factor in the spreadsheet table it produces but doesn't correct any of the values. The correction has to be applied to the raw numbers). The REM500 detector is approximately 2” in diameter and the HAWKS 5”. Consequently, if the HAWK and REM500 are placed at the same measurement location (the same fluence), the count rate in the HAWK will be roughly 6 times greater. The HAWK as a consequence has dead-time induced errors at a much lower fluence than the REM500. Dead-time correction may be necessary for both instrument but is much more likely to be needed for the HAWK. The HAWK instrument provides total counts for each minute of data (CPM) and from this data the dead-time correction can be calculated for each minute [equation 3].  Dead-Time correction becomes significant for the Hawk above 1000 counts per second or roughly 60,000 counts per minute (correction factor for 60k cpm is 1.069).

Equation for Dead-Time Correction Factor in the Hawk instrument

[Equation 3]

$$DeadTimeFactor = \frac{1}{1-(1.07*10^{-6}*N)}$$

N= Total Counts in one minute

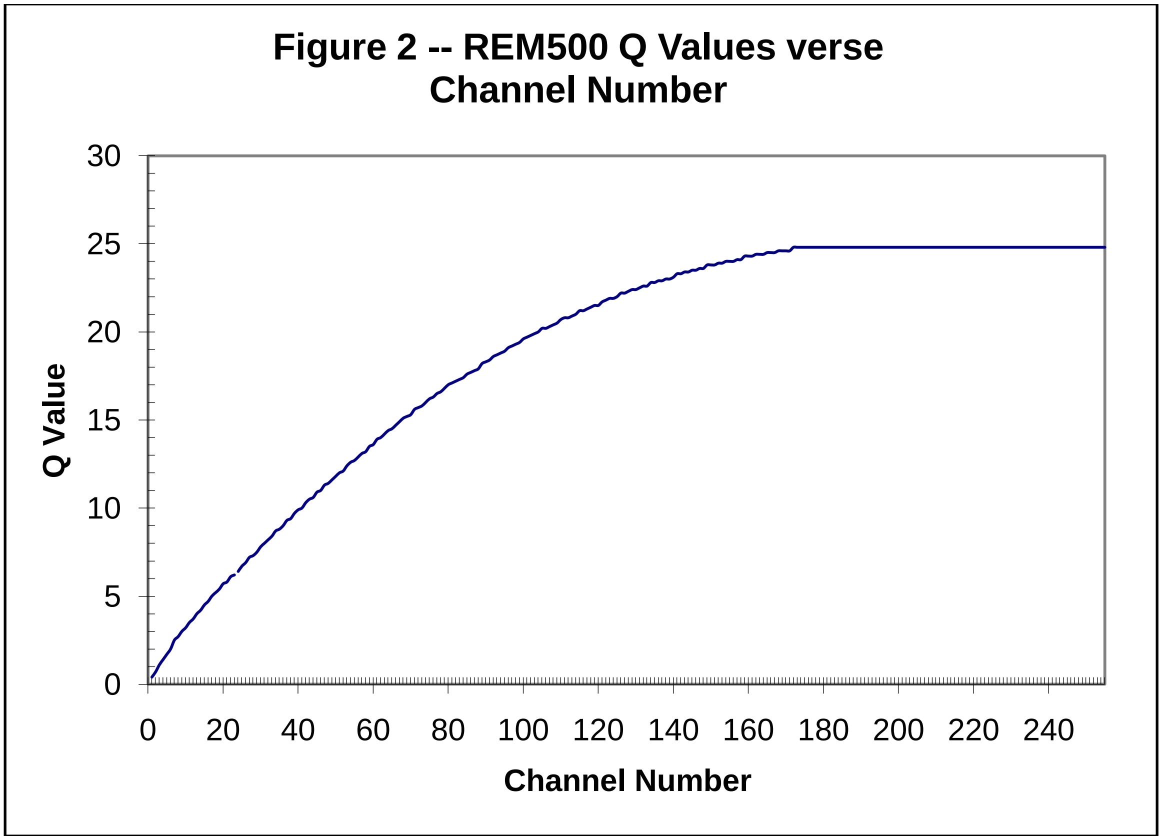
For example, if there are 330,000 counts in a one minute reading, and the unadjusted dose is 53.5 nSv/min then the correction factor is 1.55, and the adjusted Dose is 53.5*1.55 or 82.9 nSv.

# REM500 SPECTRUM, Rad AND REM COMPUTATIONS

As mentioned earlier the REM500 was designed at least 20 years earlier than the HAWK instrument, and many particulars of the historical record have been lost. In the late 1990's concern arose that the HAWK and REM500 were fundamentally different instruments and did not measure the same quantities. For example, measurements from bare Californium-252 were made with the REM500 and HAWK instrument in the same locations. When the researchers converted the REM500 REM values to Sv using the standard 100 Rad equals 1 Gy, they found that the HAWK value was between 1.5 and 1.7 higher than the REM 500 measured value – even after accounting for the gamma dose measured by the HAWK instrument that was below the REM500 threshold.

As shown in the analysis in this paper, the instruments are fundamentally the same, though there are a number of practical differences that make inter-comparison difficult. The two main differences are the weighting factors that are used in each instrument and the much higher threshold in the REM500. With proper application of the conversion process described below, readings from one instrument can be converted to comparable values in the other; thus, showing that the raw data acquired by both is basically the same – note that the raw spectrum is required for this conversion.

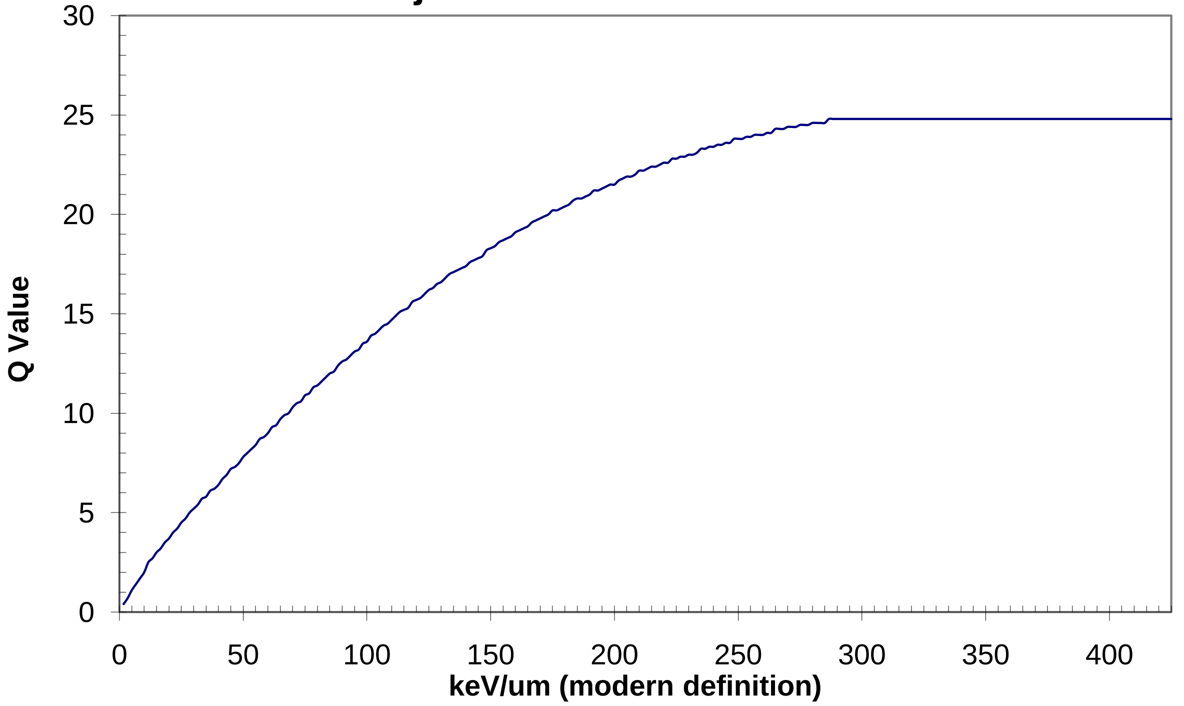
The REM500 takes a spectrum using an eight-bit A/D converter, providing 256 channels of data. Using the optional RS232 interface, the raw data from the REM500 can be downloaded from the instrument and the raw spectrum can be displayed as well as alternative methods used to convert the spectrum to dose and dose equivalence.



The REM500 spectrum, using the old definitions of lineal energy, corresponds to 1 keV/µm per channel. However, to compare the spectrum to the HAWK or to spectrums in recent literature, the REM500 values should be multiplied by 15/9 (each channel increases to 1.67 keV/µm not 1.0 keV/µm per channel). The REM500 calculates dose and dose equivalence using equations 4 and 5, with a threshold of channel 5, or about 8.2 keV/µm using the modern definition of lineal energy. The plot of channel number verse quality factor is shown in figure 2.

The REM500 places the proton edge (and the Cs244 alpha peak) in channel 90. According to the older definition of lineal energy this would correspond to 90 keV/um. However, the HAWK places the proton edge in channel 100, and this channel is 150 keV/um. Consequently, to provide a spectrum comparison from REM500 to Hawk, the REM500 channel numbers must be multiplied by 15/9, (i.e. channel 90 on REM500 is 150 keV/um). Shown in figure 3 is a plot of REM500 keV/um on the x-axis, and quality factor on the y-axis.

**Figure 3 -- REM500 Q Values verse Adjusted Values of LET**



The REM500 instrument uses a spherical detector, who's inside diameter, **D= 2.35** inches, and is filled with 13.3 Torr of pure propane, simulating a 2-micron site size. The equations below takes a REM500 spectrum and converts it to Rad or REM per time period, where the time period is equal to the elapsed time used to collect the spectrum. (The REM500 does not specify a method to correct for dead-time). **C** is the REM500 calibration constant and is nominally 100 – typically the calibration value for a specific instrument ranges from 90 to 100. The conversion of lineal energy to LET to dose equivalence for a specific channel is done using the quality factor in the REM500 table in appendix C. This table is significantly different than the one used by the HAWK instrument.

REM500 INSTRUMENT EQUATIONS
[Equation 4]

$$\text{Dose (Rad)} = \frac{C}{360 * 25.6} * 10^{-6} * \sum_{chn=5}^{255} Spect_{chn} * chn$$

[Equation 5]

$$\text{Dose Eq.(REM)} = \frac{C}{360*25.6}*10^{-6}*\sum_{chn=5}^{255} Spect_{chn}*REM500Table_{chn}*chn$$

These equations look significantly different than equation 1 and 2 used for the HAWK instruments; however, with a few minor re-arrangements, substituting a factor of 15/9 keV/µm per chn, an assumption that C is 90.03778 (for calibrated REM500 the value of C is typically close to 90), $D_{REM500}$ for the diameter of the detector, and 100 Rad = 1 Gy, and 100 REM = 1 Sv, and K from equation 1 and 2, we get equations 6 and 7.

RE-ARRANGED REM500 INSTRUMENT EQUATIONS
[Equation 6]

$$\text{Dose (Gy)} = \frac{K}{D^2_{\mathrm{Re}\,m500}}*\sum_{chn=5}^{255} \mathrm{Re}\,m500Spect_{chn}*chn*(15/9)keV/\mu m$$

[Equation 7]

$$\text{Dose Eq.(Sv)} = \frac{K}{D^2_{\mathrm{Re}\,m500}}*\sum_{chn=5}^{255} \mathrm{Re}\,m500Spect_{chn}*REM500Table_{chn}*chn*(15/9)keV/\mu m$$

K in equations 6 and 7 is exactly the same value that was previously calculated from first principles for the HAWK (equations 1 and 2). There is still one significant difference; the two equations differ by the reciprocal of the square of their diameters. Consequently for the same spectrum and total events the REM500 would read higher than the HAWK by the ratio of the square of their diameters.

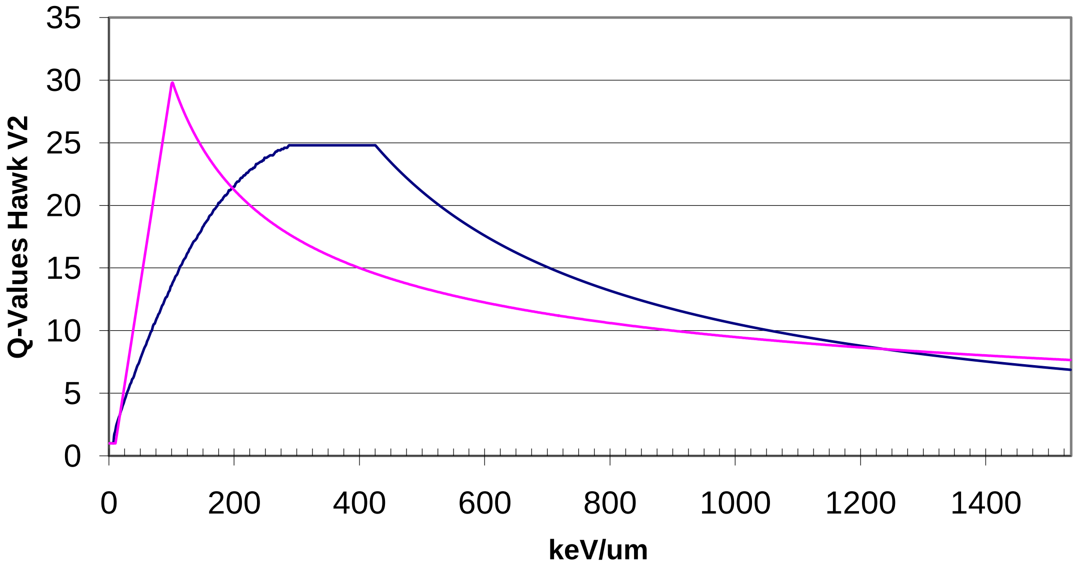
Spectrums of equal total counts would not occur if a HAWK and a REM500 were exposed at the same location, to the same source, for the same period of time. Instead, the REM500 would have the same basic spectrum, but with its total event count reduced by the ratio of the squares of the diameters, due to the smaller cross section of the REM500 compared to the HAWK. Consequently, the REM500 and Hawk (with the proper interpretation) measure the same quantities.

Equation 1 and 6 show that the HAWK and REM500 compute approximately the same dose value; the main difference being that the REM500 sums the dose from 8.2 to 425 keV/µm and the HAWK (with extrapolation) from 0.05 to 1535.5 keV/µm. The range of the REM500 is significantly less with a maximum value of approximately 425 keV/µm verse the HAWK's 1535.5 keV/µm. In most applications, there are few if any events above 425 keV/µm, and consequently the upper range difference usually do not affect the comparison between the two instruments. However, there usually is significant gamma radiation in the region from 0.05 to 8.2 keV/µm, resulting in the HAWK reading a higher dose value than the REM500 for the same exposure. This difference can be removed by setting the HAWK gamma/neutron split to 8 keV/µm and subtracting the gamma dose from the total dose – application software is available to recompute the HAWK raw data using a different split as well as a different quality factor table and units. Additionally, if the count rate is above about 1000 cps, the HAWK data should be corrected for dead time. Removing gamma dose and changing units for the HAWK is fairly simple, and allows a direct comparison between the HAWK and REM500 neutron dose measurements. On the other hand, neutron dose equivalence comparisons between the two are more difficult.

As can be seen in figure 1 and figure 3, the HAWK and REM500 have very different quality factor plots with significant variation in the region 50 to 200 keV/µm where the majority of the total dose equivalence is located for many common neutron exposures (bare Californium-252 is one of worst cases) . The HAWK spectrum is readily available, and using HAWK application software, the dose-equivalence can be re-computed using any quality factor table.

Figure 4 shows a comparison of the original HAWK quality factors (the curve with sharp peak) as compared to the new HAWK quality factor table used to mimic the REM500. The new HWK2R500 table (see appendix B for the complete numeric table used with the HAWK software) is exactly the same as the REM500 table up to the REM500's maximum of 425 keV/µm. In cases where an event is above 425 keV/µm, the REM500 saturates and the event is recorded in the highest spectrum channel or approximately 425 keV/µm. Above 425 keV/µm the HAWK_REM500 table is computed to mimic this saturation, and consequently Equation 6 can be used with this new table to compute a HAWK dose equivalence that can be compared to the REM500. For example, in the REM500 an event of 750 keV/µm saturates the electronics, and thus, is recorded as 425 keV/µm, i.e. in channel 255. Calculating dose equivalence from equation 7, the REM500 would use a quality factor multiplier that was the same as that for 425 keV/µm, or 24.8, and the ( 15/9*CHN)*Qfactor would be (15/9)*255*24.8 or approximately 10540. The Hawk on the other hand would record the event in channel 500. The HAWK quality factor table was carefully constructed so that the HawkChn*HawkQfactor (for events above the REM500 saturation, i.e. for hawk spectrum values above 425 keV/µm, or channel 425/1.5 or 283) when multiplied together will give approximately 10540. The HawkQfactor from the appendix B for 750.75 keV/µm is 14.05, 14.05*(750.75) is approximately 10548 (due to round off it isn't exactly 10540).

**Figure 4 - Hawk Q-Values From ICRP60 compared to Equivelant REM500 Hawk Q-Values**



# NEXT GENERATION TEPC ANALYSIS

There is a number of differences between the NASA instruments, TEPC HAWK and Rem500 instrument, as well as in their typical application area. Each works well for its particular application but a number of shortcomings have been found. For example, in low earth orbits the proton flux is directional. The NASA TEPC's cylindrical detectors are not optimal for directional fields. While likely this effect is small, NASA has identified the future desire for spherical detectors.

This papers purpose is not to enumerate all the shortcomings and desired improvements, nor to point out that many of them are conflicting and all cannot be satisfied simultaneously, but to describe a new TEPC data analysis design and the improvements that it would provide. Previous articles have described other improvements such as arrays or multi-element detectors that provide smaller lighter units (e.g. Aslam; Waker 2010 [1]).

The features that are desired in a new unit are smaller, lighter, lower power, handheld, or wearable, better measurement of total dose, and quality factor. The hybrid method can better achieve these results than the methodology used in the Hawk and Rem500. There are several important points to note about the hybrid analysis method and why it is preferred for small portable low powered units.

A whole set of problems occur when the desire is to lower the threshold in order to get more accurate dose and quality factors. First, one common method to lower noise is to use longer shaping times which increases dead-time. Second, as the threshold is lowered the count rate goes up (nearly exponentially), increasing dead-time even more. Even at the current configurations this is already a problem and will only get worse. Additionally, to get better statistics, a larger detector is desired; this would provide better results for the high LET particles, but again increase the number of counts for the low LET particles, which dominate. In fact, most of the current designs are carefully balanced between, power consumption, noise, threshold level, detector size, etc. -- getting better results in one area often means getting worse in another.

The hybrid method can better balance the opposing needs of the low LET high count rate verse the low count rate high LET region. In the low LET region (the weighting factor is always 1.0), and there is little concern for the spectrum shape but only a desire to measure the complete absorbed dose down to the lowest possible event. In the high LET region, the desire is to get high count rates, to get good statistics, and thereby an accurate weighting factor in a short period of time.

# HYBRID METHOD, Gy AND Sv COMPUTATION

The first reports of the use of the hybrid method appear to be from Kuehner, Chester, and Baum in 1972 [5]. From this report, the method appears to have worked well, but the concept does not seem to have been pursued. The reasons for this are not really clear; though historically, TEPC R&D instruments have rarely been replicated, except as noted above in the case of the REM500 and HAWK instruments. The methods and electronics are very outdated in this earlier instrument.

For clarity of explanation, and easy comparison, the hybrid method will be described by assuming the Hawk instrument is modified to use the hybrid method. The hybrid method requires that the high voltage by applied to the detector itself, and the anode be held at virtual group by directly connecting it to the preamp input (already done on the Hawk). For the hybrid method the preamp would need its gain reduced by a factor of approximately 10x to 20x, over a similar preamp design on the Hawk. PreampScaleFactor, Let the variable PreampScaleFactor, indicate the factor reduction. The Hawk uses a 1 pF feedback capacitor, requiring a change to a 10 pF or 20 pF (the current preamp would work fine with either value). In addition, the 100 M-ohm feedback resistor used to reset the HAWK preamp would have to be removed, allowing the charge to be integrated. The preamp would be periodically reset to zero by adding a transistor or optical reset circuit to the design. This would allow the preamp to be operated for at least 10x or 20x full-scale pulses, before it had to be reset. For sake of simplicity the preamp will be reset every 0.1 seconds, allowing approximately 100 to 200 full-scale pulses per second. The output of the preamp, through a buffer, would be directly connected to an A/D converter allowing the total integrated charge to be measured. Let the variable TotalAdDose represent this value. This A/D converter would be of the same range, 0 to

2.0 volts, and same accuracy, 12 bits, as the pulse height A/D, making it easy to convert the value to dose.

AC coupling the modified preamp output to the shaping amplifier will provide pulse analysis. The original Hawk pre-amplifier gain would be restored in the shaping circuit by increasing the gain by 10x to 20x. Thus, the resulting pulses would appear (with somewhat larger noise) to be nearly identical to the current Hawk instrument. The discriminator would be set much higher than the normal 0.3 to 0.5 keV/µm, somewhere around 5 to 10 keV/µm. The threshold is set as high as possible to reduce the count rate of the pulse analysis, and to reduce the effects of micro-phonics. The threshold cannot be set any higher then the value of where the quality factor table diverges from 1. Typically, quality factor tables apply a factor of 1.0 to all pulses as high as 5 to 10 keV/µm. The hybrid methods accuracy depends on this fact, and the threshold must be set no higher.

Similar to the HAWK, the hybrid method would provide a full spectrum from 0 to 1535.5 keV/µm, but not an expanded spectrum. Instead there would be a single total absorbed dose reading, TotalAdDose. The single spectrum and the total dose would be used to compute dose, and dose equivalence. Similar to the Hawk raw data can be downloaded from the instrument, allowing it to be stored and displayed, as well as, alternative methods to be used to convert the spectrum to dose and dose equivalence.

$HybridSpect_{chn}$ is the total number of counts in each channel of what use to be called the Hawk low gain spectrum (High LET), where chn=0 to 1023. $QTable_{chn}$ is the quality factor multiplier. The values are shown graphically in figure 1, and correspond to the table in ICRP 60 (same as Hawk).

Threshold is the channel at which the discriminator is set. Channels below the threshold have reduced or non-existent counts, and are ignored in the calculations. The equation 8 and 9 below take a spectrum and convert it to Gy or Sv per time period, where the time period is equal to the elapsed time used to collect the spectrum. Additionally, the results have to be corrected for dead-time.

## HYBRID INSTRUMENT EQUATIONS

[Equation 8]

$$\text{Dose (Gy)} = \frac{K}{D^2} * \left[ TotalAdDose * \mathrm{Pr}\,eampScaleFactor * (1.5 keV / \mu m) \right]$$

[Equation 9]

$$\text{Dose Eq.(Sv)} = \frac{K}{D^2} * \left[ \begin{array}{l} TotalAdDose * \mathrm{Pr}\,eampScaleFactor * (1.5keV/\mu m) \\ - \sum\limits_{chn=threshold}^{1023} Spect_{chn} * (chn + 0.5) * (1.5keV/\mu m) \\ + \sum\limits_{chn=threshold}^{1023} Spect_{chn} * (chn + 0.5) * QTable_{chn} * (1.5keV/\mu m) \end{array} \right]$$

$$= \frac{K}{D^2} * \left[ \begin{array}{l} TotalAdDose * \mathrm{Pr}\,eampScaleFactor * (1.5keV/\mu m) \\ + \sum\limits_{chn=threshold}^{1023} Spect_{chn} * (chn + 0.5) * (QTable_{chn} - 1) * (1.5keV/\mu m) \end{array} \right]$$

Equation 8 is straight forward, simply multiple the right constants times the measured preamp value to get total absorbed dose in Gy. Equation 9, has three terms which easily reduce to two terms ( Note that the Qtable is equal to or greater than 1 for all values). The first term in equation 9 is the same value that was calculated in equation 8, or the total absorbed dose. The second term is the total absorbed dose above the threshold; thus, if we subtract term 2 from term 1 we get the total absorbed dose below the threshold. By applying the Qtable factor of 1.0 for the region and adding the Qtable weighted values for all channels above the threshold we get the total dose equivalent.

Two additional equations are important for analyzing the behavior of the modified Hawk. These are the preamp voltage change with leakage current, and the total absorbed dose falsely indicated by the leakage current. With modern electronics, careful design techniques, and operational procedures, the leakage effects can be minimized to the point of making the hybrid technique useful for specific applications. For laboratory use in benign environments, lots of power, cooling of preamps, etc. The pulse height method still provides superior results. But, these techniques are infeasible in a small portable instrument.

The preamp output voltage due to leakage is given by the simple relationship that v=i/c, and the dose from this voltage is derived from noting that the full-scale voltage of the A/D converters is 2.048 volts.

[Equation 10]

$$\text{PreampVoltageLeakage (V)} = LeakageCurrent / FeedbackCapacitor$$

[Equation 11]

DoseLeakage (Gy) =

$$\frac{K}{D^2} * \left[ \frac{1024 * LeakageCurrent * PreampScaleFactor * (1.5)}{2.048 * FeedbackCapacitor} keV/\mu m \right]$$

## ANALYSIS AND CONCLUSIONS

The equations above were derived with little explanation or comparison being made to the hypothetical Hawk hybrid (with a 5-inch diameter spherical detector). In this section, the unpleasant aspects of the proposed hybrid method will be exposed. Previously, the statement was made that a laboratory instrument in a benign environment using straight pulse height analysis is superior. This also will be apparent given that a laboratory instrument can be constructed with a threshold of less than 0.1 keV/µm, and a high-count rate. In any case, the point is that the portable low power instrument niche requires different techniques to obtain the best possible results.

From the equations above a few simple results can be derived. The total absorbed dose for each 100 milli-seconds is given by equation 8 with TotalAdDose= 1024. Assuming, the same rate is maintained for one hour, the total absorbed dose would be 14.3 mGy/hr. This is high but may not be high enough. Obviously, if all of the events are from high LET particles with maximum Q factor the total dose equivalent could be as high as 429 mSv/hr. The current Hawk preamp design has a leakage current of roughly 1pA. Thus, from equation 10, the leakage current causes the preamp output to increase by 50 mV per second, or only 5 mV per 100 milli-seconds -- small enough that there wouldn't be any serious effect on either the operation of the pulse height analysis, nor the total absorbed dose measurement. However, the total dose caused by this leakage would be 9.7 nGy/sec or 35 uGy/hr. For comparison, background is on the order of 100 nGy/hr. The leakage induced false dose reading is an extremely high value.

The above worst case analysis is not exactly accurate because we can subtract off the average induced leakage dose. Consequently, if the leakage current stayed exactly 1pA and never changed, we could simply subtract out this contribution and it would not contribute any errors to our measurements. Thus, the variation in leakage current is actually more important. The average leakage current can be measured periodically with the high voltage turned off for a short period. Thus, instead of using the average leakage current for our calculation we should use value one or two orders of magnitude. This still gives roughly a few hundred nGy/hr, still high but nearly acceptable for our application. Remember, also that the calculations were based on a five inch detector, and that the effects are going to be much greater for smaller detectors. For example for 2-inch diameter it would be about 6x higher. To make use of this technique in low dose areas requires a high quality preamp design with a leakage current of roughly 100 fA and a variation of roughly 1fA – a difficult but not impossible task.

In summary, the practical aspects of using the hybrid approach mean that a very high quality preamp must be designed with low leakage, and instruments used to measure dose in low dose areas must use only large detectors, 2-inch or greater. Obviously, in a very intense region of radiation exposure the leakage current is of less importance, and a smaller detector could be used. The hybrid method by eliminating the high count rate from the low LET particles (by raising the threshold) allows longer shaping times, larger detectors, lower power, and hence better characterization of a mixed field environment. The higher threshold setting will reduce microphonic pickup in the pulse analysis, and won't be present in the integration data since microphonics is an AC signal. The combination of all these affords a better portable dosimeter.

# REFERENCES

[1] Aslam; Waker, A.J.; Performance of a High Sensitivity Multi-Element Tissue Equivalent Proportional Counter for Radiation Protection Neutron Monitoring Measurements. Health Physics, May 2010, volume 98, number 5. pp692-703

[2] Bevan, John S.; Parameters Describing the Microscopic Distribution of Radiation Dose. Phys. Med. Biol. 1966, Vol. 11, No. 3, 405-409.

[3] Booz, J.; Development of Dose Equivalent Meters Based on Microdosimetric Principles. Radiation and Environmental Biophysics. (1984) 23:pp155-170.

[4] Knoll, Glen F.; Radiation Detection and Measurements. Third Edition. John Wiley & Sons, Inc. 2000.

[5] Kuehner, Alan V.; Chester, John D.; Baum, John W.; Portable Mixed Radiation Dose Equivalent Meter. Health Physics and Safety Division, Brookhaven National Laboratory. Upton, New York. BNL 17298, informal report. October 26, 1972. pp1-19.

[6] Rossi, Harald H.; The Effects of Small Doses of Ionizing Radiation. Phys. Med. Biol., 1970, Vol. 15, No 2, 255-262.

[7] Shin, J.L.; Wilson, J.W.; Singleterry, R.C.; Xapsos, M.A.; Implication of Microdosimetry in Estimation of Radiation Quality in Space Environment. Health Physics, May 1999, Volume 76, Number 5. pp510-515.

[8] ICRP, 1990. Recommendations of the International Commission on Radiological Protection. Publication 60 (Oxford; Pergamon Press) (1991).