A NEW PARADIGM IN PERSONNEL DOSIMETRY USING LiF: Mg,Cu,P

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The United States Navy has been monitoring personnel for occupational exposure to ionizing radiation since 1947. Film was exclusively used until 1973 when thermoluminescent dosemeters were introduced and used to the present time. In 1994, a joint research project between the Naval Dosimetry Center, Georgetown University, and Saint Gobain Crystals and Detectors (formerly Bicron RMP formerly Harshaw TLD) began to develop a state of the art thermoluminescent dosimetry system. The study was conducted from a large-scale dosimetry processor point of view with emphasis on a systems approach. Significant improvements were realized by replacing the LiF:Mg,Ti with LiF:Mg,Cu,P TL elements due to the significant sensitivity increase, linearity, and negligible fade. Dosemeter filters were optimized for gamma and x-ray energy discrimination using Monte Carlo modeling (MCNP) resulting in significant improvement in accuracy and precision. Further improvements were achieved through the use of neural-network based dose calculation algorithms. Both back propagation and functional link methods were implemented and the data compared with essentially the same results. Several operational aspects of the system are discussed, including (1) background subtraction using control dosemeters, (2) selection criteria for control dosemeters, (3) optimization of the TLD readers, (4) calibration methodology, and (5) the optimization of the heating profile.

INTRODUCTION

The United States Navy (USN) has been using and actively involved in developing personnel dosimetry for occupational exposure to ionizing radiation for over 50 years. Although numerous research areas and technologies were developed or investigated over the years, the USN has used film dosimetry (1947 to 1987) and thermoluminescent dosemeters (TLD) (1973 to present) to monitor the exposure to the majority of its workers. USN Dosimetry has been accredited in the United States by the National Voluntary Laboratory Accreditation Program (NVLAP) since its inception in 1984 and was the first United States Department of Defense (DoD) organization to receive NVLAP accreditation for extremity dosimetry processing.

Currently the USN has three primary dosimetry systems using TLD technology. The first system consists of gamma TLD with a single element of CaF_2 in a glass bulb that fits into a cylindrical plastic holder with a thin lead shield. This TLD is readout with a manual reader that provides ohmic heating of a wire coil surrounding the crystal in the glass bulb. The height of the glow curve is proportional to the dose received.

The second and third systems are managed through the United States Navy Dosimetry Center (USNDC) in Bethesda, Maryland. The USNDC is a large-scale processor that mails TLDs to over 250 locations worldwide and processes about 240,000 whole body TLDs per year.

Both of the TLD systems at the USNDC use four-element lithium fluoride (LiF) chips mounted on an aluminium card and placed in a plastic holder with belt loops or a lanyard for hanging. Both of these TLDs measure beta, x-ray, gamma and albedo neutrons. Both are readout with hot gas heating to produce glow curves with areas proportional to the dose received.

One TLD system at the USNDC has been used since 1987[(1)]. Elements one, two, and four are 0.381 mm thick while element three is 0.0914 mm thick. Elements one and four are placed behind 600 mg/ cm^2 of ABS plastic. Element two is behind 91 mg/cm^2 of copper and 245 mg/ cm^2 of ABS plastic. Element three is behind a 7 mg/ cm^2 Mylar Window. Elements one, two, and three are made of TLD-700 (99.93% ^{7}Li and 0.07% ^{6}Li) and element four is made of TLD-600 (4.40% ^{7}Li and 95.60% ^{6}Li). In this paper, this TLD system will be referred to as the MT system because the TLD used in this system is LiF doped with magnesium and titanium elements (LiF:Mg,Ti).

The other TLD system at the USNDC is the focus of this paper and is the replacement for the MT system. The new system uses high sensitivity LiF doped with magnesium, copper and phosphorous elements (LiF:Mg,Cu,P). In this paper, the new TLD system will be referred to as the MCP system.

The MT system has proven to be cost effective, reliable, and accurate under a diverse set of operational settings[(2,3)]. However, in 1994, a new LiF: Mg, Cu, P material became available for commercial sale providing an opportunity to undertake a cost effective upgrade to the existing MT system. In 1995, the upgrade to the MT system was expanded to include a redesign of the holder for better photon energy discrimination. Also about this time, advances in dosimetry algorithms were being made through neural network technology and the USNDC realized the advantages of including this technology in the MT upgrade[(4)]. In 1996, the USNDC decided to do a critical review of all the MT system components to determine what else could be improved.

Upgrading the existing MT system was desirable over replacement. The USN had a great deal of expertise, experience, data, and equipment using this technology and desired to retain the best aspects of the MT system and build upon its success. Further, the planned upgrades to the MT system had little or no impact on the end user and changes at the USNDC were almost 100 percent transparent to them. Upgrading the MT system allowed the existing USNDC infrastructure to be retained and made the existing equipment forward compatible so that equipment, such as TLD readers, irradiators, calibrators, and Quality Assurance Shipping Machines, could still be used with the MCP dosemeter.

The remainder of the paper will describe the MCP system including dosimetry performance, dose algorithms, and operational aspects relevant to large volume dosimetry processors.

DOSIMETRIC PROPERTIES OF THE MCP SYSTEM

A high sensitivity LiF:Mg,Cu,P TL material, manufactured by Saint Gobain (Harshaw), was used for the MCP system. It is in the form of pressed pellets that are 3.6 mm in diameter. A four-element TLD card is again used in the new design. Element one is 0.381 mm thick of TLD-700H. Element two is 0.381 mm thick of TLD-700H used for the photon deep dose measurement. Element three is 0.254 mm thick of TLD-700H for beta and shallow dose measurements. Element four is 0.381 mm thick of TLD-600H used for the albedo neutron response. TLD-600H/700H have the same proportions of ^{6}Li and ^{7}Li as listed earlier for TLD-600/700.

For use in personnel dosimetry, the TLD pellets are encapsulated in clear thin 10 mg/cm^2 Teflon sheets. While this adversely adds to the filtration for beta measurements, its use has significant operational benefits. First, the Teflon keeps the TL element clean and protected. If the Teflon gets dirty it can be cleaned with a cotton swab dampened with methanol. Second, the Teflon encapsulation guarantees that no loss of TL mass occurs over the life of the TLD. The amount of mass is directly proportional to the output of light of the TL element for a given exposure. The loss of mass would result in a low measurement and necessitate recalibrating the element. A technical study done at the USNDC has shown that even if the TL element is broken into small pieces inside the Teflon no loss of sensitivity occurs. The Teflon encapsulation greatly increases the effective life of the TL element in the harsh military operational environment.

There are at least two types of Teflon used to encapsulate TL elements. The MT system uses PTFE Teflon, which requires 400 °C to be sealed. This Teflon can't be used in the MCP system because LiF:Mg,Cu,P loses its sensitivity at temperatures above about 270 °C. To overcome this problem FEP Teflon is used which can be sealed under pressure at temperatures below the desensitizing temperature of the LiF:Mg,Cu,P material. Teflon can be light sensitive and adversely contribute to the output signal of the TLD. To prevent this, each batch of Teflon used in production must be tested for light sensitivity and pass quality assurance limits to be accepted for dosimetry applications.

The dosimetric characteristics of the MCP material are promising for applications such as short issue personnel dosimetry (one-day) and low dose environmental dosimetry (typically measuring background radiation). The high sensitivity combined with its tissue equivalence are the main advantages of this material in personnel dosimetry applications.

The photon and beta sensitivity of LiF(MCP) in the form of bare chips is approximately 25 times higher than LiF:Mg,Ti (TLD-100). When encapsulated in a card the sensitivity is approximately a factor of 10 higher than TLD-100. A study at the USNDC irradiated MT and MCP cards to 10 μSv. The results of this study showed that the glow curves for the MCP cards were well shaped and consistent for both air and nitrogen heating.(5) Detection threshold levels using IEC 1066 evaluation criteria(6) are calculated to be 2.5 μSv for 0.381 mm thick MCP pellets encapsulated in FEP Teflon.

Both the MCP and MT material have the same effective atomic number (8.2), and could therefore be expected to have a similar photon energy response. In reality however, the photon energy dependence of the MCP material is considerably different as compared to MT material. Figure 1 shows that over the energy range of 20 keV to 1.25 MeV the MCP material has a maximum deviation in the photon deep and shallow dose equivalent response of +/- 22 and 21 percent respectively, while for the MT material it is +/- 100 and 45 percent. These numbers show that the MCP material is two to four times more tissue equivalent than the MT material and is capable of passing NVLAP proficiency testing criteria even without doing energy corrections. Doing energy corrections with neural networks resulted in an average value of absolute bias plus standard deviation (|B|+S) of 10.5% for all nine NVLAP proficiency categories(7).

The differences in photon energy response despite the same effective atomic energy can be explained as a microdosimetric ionization density effect. The decreased TL efficiency of the MCP material at the lower photon energies is a result of local saturation (decrease) of the TL efficiency in microscopic volumes along the tracks of the secondary electrons. The ability to trap electrons decreases as the energy deposition density increases. The decrease of efficiency of MCP at lower photon energies is an advantage for tissue equivalence since it counteracts the over response due to the increased probability of the photoelectric effect. This local saturation effect doesn't occur with MT material and only the increase in probability of the photoelectric effect at lower energies shows up in the photon energy response.

The local microdosimetric saturation of the MCP material explains the lack of supralinearity and early saturation in the dose response curve. The dose response curve of MCP material is linear-sublinear rather than linear-supralinear-sublinear as it is with MT material. The lack of supralinearity is a particular advantage in accident personnel dosimetry where the dose levels can exceed 1 Gy, reaching the supralinear region of LiF:Mg,Ti. Conservatively, the linearity range extends from 1 μGy up to 10 Gy where sublinearity starts. Bacci et al. reports linearity for LiF:Mg,Cu,P material out to 18 Gy.(8)

The sensitivity and glow curve shape are both dependent on the maximum readout temperature, and the pre-irradiation annealing parameters. The MCP time temperature profile is; linear heating at 15 °C/ second from ambient to 165 °C, pre-read annealing to remove the low temperature peaks at a constant temperature of 165 °C for 10 seconds, linear heating at 15 °C/ second from 165 °C to a maximum temperature of 260 °C for acquisition of data over a total time of 16.66 seconds, and post-read annealing for 10 seconds at 260 °C.

MCP material is linear heated at half the rate of MT material for two reasons. First, the maximum heating temperature for MCP is 40 °C lower and the preheat anneal temperature is 65 °C higher than that of MT leaving a temperature difference (ΔT) from preheat to maximum read temperature of 95°C for MCP and 200 °C for MT material. Reducing both the rate and ΔT by a factor of two yields approximately 6 seconds of linear heating and 10 seconds of constant temperature heating for both materials. Second, slower heating is more desirable to reduce thermal stresses, produce more even heating, and to separate the low temperature annealed peaks from the dosimetric peaks when using a pre-heat anneal.

The maximum temperature of the MCP material before it begins to lose sensitivity is approximately 265-270 °C. The Teflon encapsulation and short heating times allows heating to 260°C with 0.01% sensitivity loss per use over 1000 reads (10% total) which is comparable to the loss of sensitivity of the MT material. Figure 2 shows the results from one of the TLDs tested over the 1000 cycles and is representative of the others measured during this testing.

The pre-read annealing (heating) along with the lower inherent fade characteristics of MCP material result in negligible fading for up to at least 2 months at room temperature. The same effect can be obtained without pre-read annealing by oven annealing prior to exposure at 240 °C for 10 minutes[9]. Figure 3 shows the results of 120 day fade study for the MCP system using the heating profile discussed above. Data was taken at 2,4,8,16,24,30,60,90, and 120 day intervals with equal time between "annealing to exposure" (loss of sensitivity) and "exposure to reading" (loss of signal). The observed 0-2% increase in sensitivity over for the first 60 to 70 days was repeatable and unexpected. One hypothesis for this observation is that some energy from the decay of the low energy traps might have been reabsorbed by the higher dosimetry traps. The loss of energy from one peak to another would appear to be a zero sum gain. However, recall that the pre-heat anneal removes the lower temperature traps so they never contribute to the measured output. Therefore, a transfer of energy into the dosimetry peaks would appear as a net increase in the delivered dose over time. The possibility of a higher temperature trap contributing to the dosimetry measurement was tested by reading several MCP cards to temperatures of 300 °C with no observed increase in measurable output. Further study is needed and planned to understand this phenomenon better.

Other dosimetric properties such as batch homogeneity, repeatability, linearity, self-irradiation, residual signal, and light sensitivity for the MCP system were previous published by one of the authors of this paper[5] and will not be listed here.

OPTIMIZED PHOTON ENERGY DISCRIMINATOR

Part of the objective of a TLD holder is to provide various filters over each of the elements to (1) make the response more tissue equivalent (less energy dependent), (2) provide ratios of responses that can be used for energy discrimination, and (3) provide a mass thickness equal to the depth of measurement for shallow, deep, and eye dose equivalents. In theory, a greater number of elements on the TLD provides for more independent ratios of measurements, which should result in better energy discrimination. Faced with the constraint of having no more than four elements, one must seek to optimize the filters to provide the best dosimetric qualities in tissue equivalence, energy discrimination, and depth of measurement.

In 1997, a joint research project between the United States Naval Academy (USNA) and the USNDC began for the purpose of development of an optimized holder[10]. The results of this study led to the set of filters shown in Figure 4. Monte

Carlo N-Particle (MCNP) transport computer program (version 4B) was used to perform the optimization(11). The geometry and materials of the TLD card, holder, and phantom were input into the model along with various narrow beam x-ray spectra from 20 keV to 1.25 MeV(12). The energy deposited per photon emitted from the source was measured. It was assumed that the efficiency or conversion of light per energy unit absorbed was constant. It was later determined that the conversion was a function of photon energy but it didn't matter in this case since only ratios of measurements were sought. The conversion factors cancel in a ratio of element responses.

Three of the four filters were constrained by dosimetric considerations unrelated to photon energy discrimination as follows. One filter design objective was to make the filter mass thickness match the dose depth measurement requirements for deep (1000 mg/cm^2), eye (300 mg/ cm^2), and shallow (7 mg/ cm^2) doses. A second design objective was to retain or enhance the tissue equivalence of the deep, shallow, and eye dose photon responses. A third design objective was to avoid double valued functions in the photon response ratios over energy.

MCNP Optimization consisted of varying the fourth filter's composition and thickness. Aluminum ($_{13}$Al), Copper ($_{29}$Cu), zirconium ($_{40}$Zr), tin ($_{50}$Sn), tungsten ($_{74}$W), and lead ($_{82}$Pb) materials were modeled because of their range in atomic numbers from 13 to 82. The mass thickness for each of these materials was varied in the model as follows: 100, 300, 500, 1000, and 1400 mg/cm^2. For each trial case, response ratios between the fourth element and the other three elements were calculated. Of prime interest were the metal to plastic ratios since these are the ratios traditionally used for photon energy discrimination. A figure of merit was calculated based on an objective function. The objective function was a mathematical expression for quantifying the ability to energy discriminate. Two properties were scored. First, was the magnitude of the change in the response ratios. Large changes were scored higher. Second, the change in the ratio had to be uniformly distributed over the energy range. To score this aspect each of three independent response ratios was divided into 6 graphical regions over the energy range from 20 keV to 1.25 MeV. Each region was scored based on having an optimal change in the response ratio per change in photon energy. Too steep a change in the response ratio, with respect to energy results in large errors in energy discrimination from normal TLD measurement fluctuations, and too slight a change results in no ability to energy discriminate. Higher scores were assigned when a change in photon energy produced a proportional change in the response ratio. The optimization function calculated a single figure of merit for each holder design modeled by combining the results for each energy bin and response ratio in the design.

Based on the MCNP results, three prototypes were built and tested at the Air Force Dosimetry Center, San Antonio, Texas. MCNP response ratios agreed to within 10% of the experimentally measured ratios giving validity to the computer models used. Figure 5 shows the experimental results for the various element response ratios with the best results from the thick plastic (1006 mg/cm2) over thick tin (1113 mg/ cm2) ratio because this ratio has the greatest and most uniform change in value over the energy range so that better energy discrimination is possible. Using an equivalent mass thickness of copper in place of the tin filter yielded about the same results (not shown in Figure 5).

In the final design, additional plastic (acrylic) was put on the front of the metal filters based on a study from Ontario Hydro and Electric Corporation, Canada, that showed the additional plastic prevented double valued functions from occurring at energies between 120 keV and 1.25 MeV[13].

The new set of filters offers two advantages and one disadvantage over the existing MT set of filters. First, three independent ratios exist vice two. This allows for better energy discrimination and for neural networks to be used for photon dose calculation. Good neural network results could not be obtained with only two independent ratios, and thus neural networks could not be used in the MT system where only two independent ratios exist. Second, the mass thickness of the deep dose filter was only 600 mg/ cm^2 in the MT holder. This was too thin and allowed some of the high-energy beta particles to induce a signal on the deep dose element when theoretically they shouldn't contribute to the deep dose. The disadvantage of the new set of filters is the loss of symmetry between ^{7}Li and ^{6}Li elements. This complicates the albedo neutron measurement for the MCP system. In the MT system the ^{6}Li and ^{7}Li elements could be subtracted to yield the neutron dose. In the MCP system a more complicated calculation is necessary for exposures with mixed fields of neutrons and x-rays. This will be discussed in a later section of the paper.

DOSIMETRY ALGORITHM DESIGN

The functions of the USNDC dosimetry algorithm are common to most large scale dosimetry processors and include: (1) the calculation of occupational dose equivalents from TLD measurements, (2) the merging of the dose data with personnel information, and (3) the generation of electronic and paper reports for review, approval, dissemination, and archiving. The MCP algorithm is a radical departure from the MT algorithm in the way correction factors are determined, control values are calculated and subtracted, and energy discrimination occurs.

The USNDC approach is somewhat unique and there are many important features to point out. First, each reader is calibrated to ^{137}Cs with a NIST traceable local transfer source with TLDs in holders on phantom in accordance with ANSI N13:11 (see appendix of Cassata et al. [14]). This results in a point calibrated system with a unique reader calibration factor for each element position for each reader. At the time of reading, the reader also applies unique element correction factors for each TL element to provide a system with uniform sensitivity. This process has significant advantages over more traditional methods of reading a relative or "mr*" value and later applying a traceability factor in the algorithm. By point calibrating each measurement to a national radiation standard at the reader level, readers do not need to be matched to each other. When this system is used, TLDs could be taken to any NIST traceable reader regardless of the location and read out with the same result. Additionally, quality assurance is better served since technicians can observe measurements and set quality assurance alarms in the readers to absolute quantities rather than arbitrary baseline measurements. With this system, the quantity that results from the read process is a Cesium Equivalent Dose Equivalent (CsEDE) in Sv. If the exposure on the TLD was from ^{137}Cs, then the energy correction to obtain the absolute or true dose equivalent in Sv would be unity.

In the USNDC MCP system all TLDs are read out, data secured, and then processed in the dose algorithm. This separation of processes provides for the maximum throughput, reliability, and versatility. Once processing technicians calibrate and load readers with up to 1400 TLDs, they can review final reports from the previous day, while still monitoring the current reading of TLDs. The initial generation of reports is done by a separate group of transcription technicians who run the dosimetry algorithm. They provide an independent review of the data prior to sending the reports to the processing technicians for final review. These processes are monitored and reviewed by the quality manager so that three independent quality assurance checks occur in the process of the dose calculation.

Dosemeters can only measure the total dose received. Yet, the quantity of interest is the occupational dose. The difference is the dose the dosemeter receives while not being worn for occupational exposure such as during transit times or during non-working hours. To account for the non-occupational exposure, control dosemeters are used. Control dosemeters are sent with each batch of dosemeters issued and are treated identically to the dosemeters issued during non-use times. For example, when the worker goes home, ideally the issued dosemeter is placed on a rack with control dosemeters in a space where no occupational exposure exists.

While the use of control dosemeters is not unique to the USNDC, the MCP system has some unique features. First, a four-tier rate based control calculation is used as discussed in the following paragraphs. Second, daily rates are always used in any of the tiers to be discussed in order to make extrinsic quantities intrinsic (independent of the length of use). Rate based calculations for controls are important because dosemeters sometimes get separated from their original batches and may be sent back for processing with batches having different intervals of issue periods. Rate based calculations are also important in the MCP quality assurance scheme because daily rates from any tier are always checked with historical values from each location and may be flagged for investigation when they differ from historical averages by more than three standard deviations, or when absolute quality assurance limits are exceeded. Third, control dose equivalents are subtracted after the total dose on the TLD has been calculated to avoid the "error in the ratio" problem. The error in the ratio problem occurs when control values are subtracted prior to taking response ratios if the dose on the personnel dosemeter is approximately the same magnitude as the dose on the control dosemeter. In this case the net result can be a small positive number, zero, or even be a negative value. Ratios of these measurements are meaningless and can't be used for energy discrimination. Fourth, control dosemeters are treated as any other dosemeter in the algorithm. A shallow, deep, and neutron dose equivalent daily rate is calculated for each control card based on the responses and response ratios on the control TLD. In the authors' opinions, this is the more correct way to handle control calculations since a properly energy characterized dosemeter will yield the correct response regardless of the energies of the fields exposing the TLD, whether it be from background radiation, occupational fields, or combinations of each.

Tier-one of the control scheme uses the control dosemeters assigned by the customer for that batch of TLDs. This is the most ideal case. A minimum of two valid control dosemeters is necessary to proceed with tier-one. A statistical test is done between control dosemeters to assure a consistent set of measurements. The controls are considered valid when the lowest daily rate plus three standards deviations result in a daily rate greater than the highest daily rate minus three standard deviations. If these values do not overlap, then the highest daily rate is conservatively thrown out and the next highest daily rate is checked. This process is repeated until there are less than two controls to proceed. At which point, tier-two of the control scheme is employed.

Tier-two of the control scheme automatically looks for unused dosemeters in the batch when tier-one fails. Tier-two is the next best case. Customers are given 10% more dosemeters than assigned personnel to handle unexpected needs and visitor monitoring. Customers are asked to treat unused dosemeters identically to control dosemeters in the event that some of the unused need to be used as controls. Tier-two controls are quality tested for internal statistical consistency as described in tier-one. When less than two valid shallow, deep, or neutron measurements exist, tier-three of the control scheme is used.

Tier-three of the control scheme is automatically invoked and calculates an average shallow, deep, and neutron control daily rate from the valid control daily rates for one year prior to the current date. The average daily control rate is listed as well as the individual historical values so that the transcription technician can accept the average value, choose another value, or enter one of his own, including zero. When no valid historical controls exist for that customer tier-four is automatically invoked.

Tier-four uses a historical value from a similar customer. First, historical values are chosen from customers with similar functions, and second, from customers with similar geographic locations. The transcription technician is given the option to accept the average daily rate, choose another value, or enter one of his own as discussed in tier-three.

The MCP dosimetry algorithm processes the information from each dosemeter one at a time until the entire batch is done. Each dosemeter dose calculation is performed independently of the others in the group prior to calculating and subtracting control values. At this point, each dose calculation goes down one of three branches to calculate a total (occupational plus background) dose equivalent in Sv. The criteria to determine the branch used have been empirically determined through a comprehensive characterization of the response of the TLD to numerous beta, photon, and neutron fields. The measurements on the dosemeter provide all the information necessary to invoke one of the branches so that no operator intervention is required. However, operator information can be entered to refine the calculation and neutron spectral information must be known or assumed since the MCP dosemeter is an albedo device.

Branch one is for calculating a shallow dose correction factor to apply to the element behind the open window when greater than 80% of the total dose on the dosemeter is due to a pure beta exposure with beta energies greater than 0.25 MeV. Branch one is invoked automatically when the ratio of the window/plastic measurement is greater than 5 and the ratio of the plastic/ thin copper measurement is less than 0.7. Once invoked, if the ratio of the window/plastic measurement is greater than 70 and the ratio of the plastic/ thin copper measurement is less than 0.1 a shallow dose correction factor of 1.81 is used, otherwise a value of 0.787 is used. These ratios and correction coefficients were determined empirically and based on the fact that a 2 MeV beta can only penetrate about 1000 mg/cm^2 of plastic.

Branch two is for calculating the deep photon and albedo neutron doses. The ability to measure the neutron dose is a complex function dependent on: (1) the energy of the neutrons, (2) the energy of the photons if they are also present, and (3) the ratio of the neutron dose to the total dose. This branch will be invoked when the ratio of the TLD-600 response (in CsEDE Sv units) to the sum of all four responses (in the same units) is greater than 0.32. This correlates to the condition when greater than 10% of the total dose on the dosemeter is due to neutron exposure with energies less than 1 MeV and photon energies greater than 200 keV. (For photon energies less than 200 keV as much as 30% of the total dose on the dosemeter may need to be from neutrons in order to invoke this branch.) When greater than 1 MeV neutrons are measured, the approximate average energy of the neutrons being measured must be entered into the algorithm to invoke this branch reliably. Measurements of mixed fields of betas and neutrons have not been considered in the design of the MCP algorithm to date.

Branch three is invoked when one and two are not. It is for calculating the shallow and deep dose equivalent due to single photon fields, mixed fields of betas and photons, and mixed fields of photons with photons. The energy ranges for the photon fields from 20 keV to 1.25 MeV, and from 0.25 MeV to 2.3 MeV for the beta fields. This branch uses functional expansion neural networks (FENN) to calculate shallow and deep dose correction factors ($C(H)_s$, $C(H)_d$). [4,5] The element response behind the 1000 mg/cm^2 plastic filter is multiplied by $C(H)_d$ to calculate the deep dose and the element behind the Mylar window is multiplied by $C(H)_s$ to calculate the shallow dose.

The design of the FENN is shown in Figure 6. Three independent ratios are input into the network. These input ratios are functionally expanded with log functions raised to powers of one through four. The choice of using log functions was the result of an empirical study where several different functions were tried. Log functions resulted in the best convergence and lowest global error in the test examples used. The output of this neural network can be written as the following equation where Z1, Z2, and Z3 are the response ratios defined in Figure 6.

$$\begin{aligned} C(H)_d = {} & W1*[\mathrm{Log}_{10}(Z1)]^1 + W2*[\mathrm{Log}_{10}(Z1)]^2 + W3*[\mathrm{Log}_{10}(Z1)]^3 + W4*[\mathrm{Log}_{10}(Z1)]^4 \\ & + W5*[\mathrm{Log}_{10}(Z2)]^1 + W6*[\mathrm{Log}_{10}(Z2)]^2 + W7*[\mathrm{Log}_{10}(Z2)]^3 + W8*[\mathrm{Log}_{10}(Z2)]^4 \\ & + W9*[\mathrm{Log}_{10}(Z3)]^1 + W10*[\mathrm{Log}_{10}(Z3)]^2 + W11*[\mathrm{Log}_{10}(Z3)]^3 + W12*[\mathrm{Log}_{10}(Z3)]^4 \\ & + W13 \end{aligned} \qquad \text{Eqn 1.}$$

Prior to training the weights (Wi's) represent unknowns. Training results in determining these weights. For the FENN, training is accomplished by linear regression on a set of training examples. Each training example consists of thirteen numbers, the twelve log power terms shown in Equation 1 and the deep or shallow correction factor. After training the neural network becomes a static non-linear algebraic equation where the inputs are the independent variables and the outputs are the dependent variables. No further learning occurs while using the network to solve problems. Retraining the network is analogous to creating a new version of the algorithm.

For the MCP FENN used at the USNDC, 1000 examples were used for training of the shallow and deep neural networks. The 1000 training examples were comprised of the 25 fields listed in Table 1. in ratios of 1:0, 1:3, 1:1, 3:1 with ^{137}Cs and 10 repeat measurements were done for each case (25*4*10=1000). The linear regression was done with Microsoft EXCEL.

To reduce costs, and to provide a richer set of training data, the mixed field responses were mathematically constructed by using superpositions of single field response functions as follows. For each element position on the dosemeter, a single field linear response function was written in the form of Y=M*X, where Y is the light output of the element in CsEDE Sv, X is the delivered dose equivalent in Sv, and M is an proportionality constant empirically determined from irradiation data. To produce statistically valid repeat measurements, a term to account for dosemeter variability was added to each linear expression of the form 1.5*(COV)*(RANDOM)*MX, where COV is the measured coefficient of variation for the field being modeled and RANDOM is a random number generator for a uniform distribution from -1 to +1. A Mann-Whitney rank sum test was used to compare experimental mixed field response data with modeled data(15). Also for each group of repeat measurements, a comparison of the average value, average deviation, and sample standard deviation, was done against a group of experimental measurements. These tests showed that the modeled data produced by this method were statistically indistinguishable from real data taken at NIST, showing that it is not necessary to perform mixed field exposures for dosimetry devices that are based on the principle of superposition.

A second neural network calculation was performed using the same input ratios discussed in the FENN. This approach took advantage of a software program called "PREDICT", by NeuralWare, to build, train, and test the optimal network design from within Microsoft EXCEL. (16) PREDICT uses a multi-layer perceptron (MLP) with gradient back propagation (GBP) training. The MLP consists of an input layer (element response ratios), multiple hidden layers with applied transfer functions at each node, and an output layer (shallow or deep correction factor). GBP is a method for assigning responsibility for the error in the model to each of the processing elements in the network by propagating the gradient of the objective function back through the network to the hidden nodes. Based on the degree of responsibility, the weights of each individual processing element are modified iteratively to improve the objective function. The objective function used for GBP was the root mean square error (RMS) shown in Equation 2.

$$RMS = \sqrt{\frac{\sum_{i=1}^{N} \sum_{j=1}^{K} \left(V_{ij} - O_{ij}\right)^2}{(N)(K)}} \qquad \text{Eqn. 2}$$

Where: V is the known training value.
O is the network output.
N are the number of training examples.
K are the number of ouputs.

GBP of a MLP results in a non-linear regression of the data in function space or hyperspace. Hyperspace is an abstract concept that is not unique to neural networks. MLP function space is N-dimensional, where the number of dimensions is equal to the number of inputs. For the MCP dosimetry model of three inputs, the solution space can be conceptualized as a four parameter equation of state with Z1, Z2, Z3, $C(H)_d$ as the state variables (the ideal gas law is an example of an equation of state that most people are familiar with). The output from an ideal dosemeter would produce an equation of state where any three of the values would uniquely define the fourth. Because a real dosemeter typically only has a maximum of three independent ratios, it behaves as a crude spectrometer with many places in the solution space that have multi-valued points, i.e., two or more values for the correction factor for a single set of response ratios. This is a mathematically irresolvable condition for the network and the network will attempt to regress a solution between multi-valued places in the solution space.

The FENN and MLP/ GBP methods were compared by applying both methods to several sets of test data. First, using the USNDC NVLAP 2000 proficiency data resulted in no single measurement greater than 10% different and an average |B|+S over all categories less than 1% different between the two methods. Producing the same result through two different neural networks provided a degree of confidence in the methodologies used. Further comparison of these two methods on a more comprehensive set of data showed closely correlated bias results over the mixed photon exposures tested. This implied that both neural networks effectively minimized the global error and had properly characterized the solution space. The FENN was chosen over the MLP with GBP training because of its simplicity and ease of implementation.

Neural networks are a rich set of mathematical tools that can be used to develop complex relationships between inputs and outputs. In addition to using neural networks to calculate correction coefficients, they have also been used at the USNDC as: (1) classifiers to determine if a low energy photon or beta component is present in a high energy photon field, and (2) noise reducers to lower the coefficient of variation of an input variable that has a greater noise level than other input variables, such as for the thin element in the MT system. Extensive neural network research at the USNDC has resulted in the following observations.(17)

- While there are no theoretical limits to network size, practical limits exist. In general, input nodes should be kept from 3 to 10 and absolutely no more than 20, hidden layers from 0 to 2, and hidden nodes from 5 to 15.
- Neural networks are especially prone to solutions that are over fit, i.e., not general enough. Figure 7 shows an example of two curves that fit the data, with one that is over fit. The tendency to over fit increases with the complexity of the network. Adding layers and or nodes increases the complexity and the tendency to over fit.
- Neural networks are only capable of interpolation. They are unable to extrapolate beyond where they have been trained. Neural networks may even have difficulty near the edge of a training boundary where curvatures rapidly change.
- Neural networks are especially suited to dosimetry problems because they are able to handle noisy inputs due to the dense connectivity between nodes. The nemesis of any dosimetry algorithm is the lack of precise repeatability in the measurement of redundant exposures. The separation in responses between elements is small, so that even a small departure from the ideal response results in large errors in energy discrimination. With neural networks any one input has less of an effect on the outcome and responsibility is shared among all connections.

- The quality of solution depends on the quantity and distribution of training data. If only four pairs of training data are used it is likely that a new set of inputs would be incorrectly categorized. Establishing the real solution boundary requires training over the entire solution space in a uniform matter. If training occurs non-uniformly, then certain parts of the data may be treated as outliers and the solution may be shifted. The highly concentrated solution space causes the solution to be weighted too heavily in that direction. The falsely identified outliers could have been valid data but fewer examples existed because the data in those places were harder to obtain. Figure 8 illustrates this concept.
- Modeling the response of a dosemeter to all radiation fields is especially useful in developing, training, and testing neural networks. However, the noise of the device should also be modeled and training should be done with replicates of each condition to keep the solution general and avoid over fit solutions.
- A preliminary study showed a 3% reduction in |B|+S for deep dose measurements by calculating the deep dose equivalent from each element and averaging the result. This would require a separate FENN for each element position. This suggests that using the average response from two identical badges may be as good an improvement as using additional filters on a single badge.
- With personnel dosimetry measurements it is better to optimize an algorithm with an objective function that minimizes the maximum error rather than the average error. In personnel dosimetry, any one individual measurement is as important as the average of all the measurements since each person must be equally protected.

ALBEDO NEUTRON RESPONSE

Both the MT and MCP dosemeters are albedo devices, meaning they measure scattered thermal neutrons emitted from the body. These dosemeters also measure incident thermal neutrons since no cadmium was used in the filtration of the holder to absorb thermal neutrons. The decision not to use cadmium was based on maximizing sensitivity. The ^{252}Cf equivalent dose equivalent neutron response (CfEDE) for both materials is obtained by subtraction of the ^{7}Li response from the ^{6}Li response and multiplying the result by a correction factor (CsModCf) to convert to a moderated ^{252}Cf calibrated system. The deep dose equivalent (DDE) is then calculated by multiplying the result by a source and site-specific neutron energy correction factor (NECF) that is a function of neutron energy, distance between the source and person, geometry of the surroundings, and the material properties of the surroundings. Equation 3 shows this calculation.

$$(\mathrm{CsEDE}_{\mathrm{Li\text{-}6}} - \mathrm{CsEDE}_{\mathrm{Li\text{-}7}}) * \mathrm{CsModCf} * \mathrm{NECF} = \mathrm{DDE}_{n} \qquad \text{Eqn. 3}$$

The NECF for neutron sources from occupational environments is determined using a unfolding algorithm that uses ratios of measurements from a cylindrical BF_3 gas filled proportional counter, model Army Navy Portable Device RADIAC 70 (ANPDR-70). Ratios are calculated from measurements taken with varying amounts of polyethylene around the BF_3 tube. The technique is similar to using an unfolding algorithm with bonner spheres.

Table 2 lists the results of a USNDC study of neutron response characteristics for the MT and MCP material for neutron energies from thermal to 14.2 MeV. The data in the first two columns of this figure shows that the MCP material produces on average about 3.9 times less light per Sv delivered by neutrons than does the MT material. This behavior may be explained as a micro-dosimetry effect of the MCP material. Neutron capture with ^{6}Li results in the high linear energy transfer (LET) particles shown in Equation 4. The MCP material saturates along the dose tracks of these particles more quickly than does the MT material causing a decrease in efficiency to produce light per absorbed energy unit. This same effect is responsible for the non-supralinear properties at high dose levels and for the increased tissue equivalence for low energy photons.

$$ {}^{1}_{0}\mathrm{n} + {}^{6}_{3}\mathrm{Li} \rightarrow {}^{3}_{1}\mathrm{H} + {}^{4}_{2}\mathrm{He} \qquad \text{Eqn. 4} $$

Even with this effect the lower level of detection for pure exposures with moderated ^{252}Cf was calculated to be 50 μSv for the MCP material because with this spectra (with average neutron energies of 0.5 MeV) there still exists a light advantage from neutron exposures as compared with high energy photon exposures. Moderated ^{252}Cf exposures result in 3.33 times more light than ^{137}Cs photons on a per Sv delivered basis for the MCP material.

Both materials were calibrated to moderated ^{252}Cf neutrons by application of the CsModCf term shown in Equation 3. The different values for the MT material (0.08) and for MCP material (0.30) reflect the reduced light output the MCP material experiences. The NECF values for both the MT and MCP materials show that the neutron response is approximately the same for these materials over the energy range indicated. This is expected for two reasons. First, the material composition of TLD-600 and TLD-600H are nearly identical in the proportions of ^{6}Li and ^{7}Li atoms. Second, the neutron capture reaction is dominated by the thermal neutron cross-section, which is about 10,000 times larger than the fast cross-section. Further, the ^{6}Li cross-section has about the same magnitude as the ^{7}Li cross-section at the fast energies so that fast neutron reactions that do occur are subtracted out. Under these conditions the amount of local saturation doesn't change with incident neutron energy since the dosemeter is predominately measuring thermal neutrons. Therefore, the MT material stays approximately 3.9 times more sensitive over the MCP over the entire energy range from thermal to 14.2 MeV neutrons. This is an extremely fortunate result for the processor converting from the MT material to MCP material because a neutron re-characterization over neutron energy is unnecessary. For the US Navy this means that current NECFs are still valid and unfolding algorithms do not need to be redone. Neutron exposures are expensive, time consuming, and difficult to do properly.

The MT dosemeter is symmetric with the same filtration over both the ^{6}Li and ^{7}Li positions so that the measured neutron dose is unaffected by mixed exposures of photons and neutrons. The MCP dosemeter has different amounts of filtration over these positions resulting in the photon response ratios shown in Figure 9. The albedo response was modeled with Equation 5 to understand the effects of the using the MCP material and non-symmetry holder.

$$ DE_{n} = \left(\left[(DDE_{n})(OR_{n/\gamma})_{i} + DDE_{\gamma} \right] - \left[(DDE_{\gamma})(OR_{\gamma 1/\gamma 4})_{j} \right] \right) * CsModCf * NECF \qquad \text{Eqn. 5} $$

Where:
DE_n is the calculated deep dose equivalent from neutrons in Sv.
DDE_n is the delivered deep dose equivalent from neutrons in Sv.
$OR_{n/\gamma}$ is the over response in light that the material exhibits due to neutron exposures as compared with a ^{137}Cs exposure on a per Sv basis.
DDE_γ is the delivered deep dose equivalent from photons in Sv.
$OR_{\gamma 1/\gamma 4}$ is the photon over response of the less filtered element with respect to the more heavily filtered element.

Equation 5 illustrates two shortcomings of the MCP system regarding neutron measurement. First, the light advantage for neutron exposures for the MCP material is lost at neutron energies above 1 MeV as compared to energies above 4 MeV for the MT material. At these energies the light output from both neutrons and high-energy photons are about the same on a per Sv basis. This shows up as reduction in the $OR_{n/\gamma}$ value in Equation 5, which results in a smaller difference between responses between the neutron sensitive and neutron insensitive elements on the TLD making it more difficult to measure neutron exposures. Second, the MCP holder is not symmetric so that photon energies below 300 keV cause a 10 to 235 percent over response on the non-neutron sensitive element in the albedo calculation, which results in masking the neutron exposure. This shows up as an increase in the $OR_{\gamma 1/\gamma 4}$ term in Equation 5, which results in a smaller difference between responses between the neutron sensitive and neutron insensitive elements on the TLD making it more difficult to measure neutron exposures.

The effects of not correcting for the photon over response on the less filtered element are shown in Figures 10 and 11. These graphs demonstrate that measuring exposures from mixed fields of photons and neutrons require no special photon correction prior to subtraction when photon energies are above about 200 keV and neutron energies are below about 1.0 MeV. For these conditions a simple subtraction of the ^6Li and ^7Li responses will result in errors that are less than about 10% in measuring the deep dose equivalent. However, measuring mixed fields of photons and neutrons at other energies could result in a significant under estimation of the deep dose equivalent. This problem is currently being addressed by the development of a correction function to apply to the less filtered element.

OPTIMIZATION OF MECHANICAL DESIGN OF TLD CARD AND HOLDER.

Mechanical considerations in design can be as important as dosimetric properties. Adoption of a new paradigm required a critical review of these aspects as well. The MCP system has the following design improvements over the MT system.

The thinnest chip of the MT system was increased in thickness from 0.0914 mm to 0.254 mm to provide more reliable glow curves, reduced variability, a greater signal to noise ratio, and improved life span. Figure 12 shows that this only increases the low energy beta correction factor by about 10% so that no significant scaling errors occur.[18] This design change was critical to the use of neural networks since all measurements are used equally in neural network dose calculations.

The TL element shape was changed from a square to a round cross-section to reduce stress concentrations in the manufacture of the element and Teflon encapsulation. This results in an element with greater physical integrity and a better encapsulation. Both improve the life span of the card. Cracking elements and square corners both contribute to Teflon separation around the TL element, which is the primary cause of MT card failure of the thin element. When the Teflon sheets do separate, air gaps are formed, which cause a thermal barrier to be formed during heating. This results in lower peak centerline temperatures and a subsequent 15-25 percent decrease in light output.

An analysis was conducted on the MT holder to identify areas for improvement with the following results.

- The holder should be hinged so that the front and back don't get separated.
- A window should be included to view the TLD number without opening the holder.
- The Mylar window should be installed with a sonically welded inset ring to provide a better seal.
- Stiffening rails should be added to each side to reduce flexibility and bowing.
- An orientation hole should be added to prevent misuse of the opener and enhance the operability of the automatic opening machine.
- The belt loops should be further separated to increase the leverage on the sailor's belt and decrease the fulcrum action.
- The neoprene gasket should be replaced with more durable silicone.

The MCP holder was successfully tested to be water tight to 20 meters and air tight to an equivalent reduced pressure of 12,000 meters.

ENGINEERED QUALITY ASSURANCE

Belonging to the NVLAP compels the processor to adopt engineering controls over administrative ones, automated processes over manual ones, and quality control procedures (QC) wherever possible. In keeping with this philosophy, the MCP system has been designed with a higher degree of automation and more engineering controls as outlined below.

TLD readers are engineered to recognize card types so they can't be used for the wrong function. Additionally, TLD cards have been color coded with respect to function to help USNDC technicians avoid making mistakes during processing. Gold are master standard cards that only get read once per year to check sensitivity of the calibration population, which are blue. A minimum of three QC cards irradiated to a known value are required to be read along with each group of TLDs processed.[19] QC cards are green so that the processing technician can visually ensure QC cards have been placed in the first, last, and every 50th position within each group of customer TLDs processed. Black cards are special QC cards used in the automated card calibration process to ensure that the behavior of the reader and irradiator don't change over long 20 hour runs. The same set of three black cards is calibrated at the beginning and at the end of the process ensuring that element correction factors on these cards have not changed by more than 3% from the beginning to the end of the batch calibrated. Cards shipped to customers are red and go through a separate machine (Bicron model 8800I ID Machine) which automates a final quality assurance check to make sure they have been properly annealed, calibrated, and inventoried.

Every new TLD card is calibrated three times in an automated card calibration machine (Harshaw Model 8800PC reader with internal ^{90}Sr source) that anneals, irradiates, and reads each TLD successively thereby eliminating variations in irradiation geometry, fade, or human error. A TLD is automatically rejected when (1) the calibration results in a coefficient of variation of more than five percent for the three runs, (2) when it has a sensitivity more than 15% different from the mean sensitivity of the calibration population, and (3) when TLDs are recalibrated and have more than 15% difference from the previous calibration value. New TLDs are also irradiated with a neutron source to check for proper placement of the ^{6}Li and ^{7}Li elements.

In the MT system, holder acceptance testing was done by visual inspection of all holders and selecting 10% for radiation testing with a low energy photon beam. Response ratios had to be calculated to determine if the right filters were in the right positions with correct thickness. In the MCP system an improvement was made through eddy current testing of 100% of the holders. A collaborative effort with Battelle Pacific Northwest National Laboratories (PNNL) resulted in the design and construction of two eddy current testing devices to ensure the correct filters were placed in the holder. Eddy current testing is less expensive, doesn't involve radiation, and is more reliable than traditional methods. Eddy current testing is a non-destructive test that uses a coil of wire to induce a current in the surrounding metal and a secondary coil of wire to measure the induced current. Changes in material type, consistency, or thickness will result in a change in the expected induced current indicating a materials problem. MCP holders are also serialized on the half of the holder with the filters so these quality assurance tests can be tracked and documented.

Transitioning from the MT system to the MCP system needed to be as safe and effortless as possible. One concern was the possibility of using an MT TLD card in an MCP holder or vice versa. To prevent an MT TLD card from fitting into an MCP holder a key and notch system was employed. The new MCP card has two curved notches in the upper half of the TLD card and the MCP holder has two extra extents that match the TLD card. Unfortunately, there was no way to prevent an MCP TLD card from being used in an MT holder without modifying the existing MT cards and holders. A study is underway to determine the maximum error that can occur if this happens.

The key and notch system will be useful in the future plans of the USNDC. Limited quantities of specialized cards and holders will be offered and used simultaneously with the existing MCP system. The key and notch system will provide an engineering control to prevent mistakes from being made.

Another concern in transitioning from the MT system to the MCP system was the possibility of using the wrong time temperature profile. Heating MT cards to the MCP profile under estimates the dose and heating MCP to the MT profile destroys the card. To prevent this, the reader has been engineered to recognize which card is being read and automatically applies the correct heating profile.

To make the transition from the MT system to the MCP easier, cost effective, and more versatile, it was decided that the MCP system would be calibrated using the MT material. Both element and reader calibration for the MCP system was accomplished with the MT material. Due to the linearity of both materials, the NIST traceable point calibration of the MT material could be transferred to the MCP material by the use of experimentally determined proportionality constants. Once these constants were entered into the reader software they are automatically applied during the reading of an MCP card to maintain the point calibrated cesium equivalent dose equivalent values discussed earlier. The advantages of this methodology are (1) the reader only has to be calibrated once but can read both materials, (2) separate sets of calibration cards for each system are unnecessary, and (3) all dosimetry materials are tied to a single reference. This methodology provides versatility because it allows any dosemeter material to be read under a single calibration, including extremity chipstrates and ringlets. Ultimately, this saves money, time, and labor. Normally, at least one percent of the population is set-aside as calibration dosemeters. The calibration population has to be periodically checked for sensitivity changes and maintained over time. Readers need to be calibrated for each material. These things can be avoided with this system.

One consequence of using the MT material to calibrate the MCP is that the element correction factors are about a factor of 10 times smaller since the MT material is about 10 times less sensitive. However, this difference cancels out when the reader calibration factor is applied because it is a divisor while the element correction factor is a multiplier. Typical element correction factors range from 0.077 to 0.143 under this system.

OPTIMIZED READER

The Harshaw TLD Model 8800PC Reader electronics has a linear dynamic range of 7 decades. The limiting factor is the photomultiplier tube (PMT) which goes supralinear as the upper limit of the tube is approached. Two design objectives were used in optimizing the PMT tube voltage. First, to keep the PMT voltage high enough to maintain the existing lower limit of detector of 30 μSv and resolution of +/- 10 μSv at 300 μSv at the 90% confidence level for the less sensitive MT material. And second, to keep the PMT voltage low enough to be able to read the accident doses with the high sensitivity material without causing the PMT to go supralinear. The desired operating range for the MCP system was 10 μSv to 10 Sv. These design objectives were met by setting the PMT voltages in the range of 650 to 700 volts and the addition of a blue glass filter. The blue glass filter served another purpose described in the next paragraph.

One of the objectives of the MCP system was to be able to read it on land or at sea with only external power supplied. The current standard is to use liquid nitrogen tanks to provide nitrogen gas to the reader, which is then heated by the reader in order to read out the TLD. To eliminate the need for liquid nitrogen tanks, an internal air generator was used to supply pressurized dry filtered air to the reader. The use of hot air to heat the dosimetry elements resulted in an additional background signal of approximate 30-40 μSv due to the oxygen content in the air. Although the additional background signal is removed by subtraction of the control dosemeters, a reduction of this inherent additional signal was sought. Several band pass optical filters were investigated to eliminate this unwanted signal. A reduction of approximately 10-20 μSv in this signal was obtained through the use of a red absorbing blue-violet glass filter that only allowed light between 300 to 520 nm to pass through the lens to the PMTs. Hot air heating raised the demonstrated lower limit of detection of the MCP system from 10 μSv to 30 μSv, which is on the order of the MT system.

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CAPTIONS FOR FIGURES AND TABLES:

Figure 1. Photon Energy Response of MT and MCP Materials

Figure 2. Representative Output from Usage Test August 1997.

Figure 3. 120-Day Fade Study Results.

Figure 4. Optimized Holder Design for LiF:Mg,Cu,P TLD. Note: ABS is a type of plastic and PTFE is a type of Teflon.

Figure 5. Experimental Response Ratios from MCNP Optimized Prototype Holder

Figure 6. Expansion Neural Network for Calculation of Deep Dose Correction Factor to Apply to the Element behind the 1000 mg/cm^2 Plastic

Figure 7. Over fitting experimental data. A neural network can always be constructed and trained so that the training data has zero error. However, the network may have no ability to predict the solution on other, non training, data inputs. This is over fitting or the lack of generality. The more complex the network the more likely this will occur.

Figure 8. Illustration of the adverse effects of using an uneven data distribution for training. The solution is skewed toward the more densely distributed data when the real solution might be considerably different

Figure 9. Illustration of the variation of the ^{7}Li/ 6Li response ratio as a function of photon energy due to the non-symmetric filtration in the MCP dosemeter.

Figure 10. Illustrates the effect on not correcting for the over response of the less filtered element for various mixed photon neutron exposures for neutrons of the same energy as the neutron calibration energy. All photon/ neutron ratios are dose equivalent ratios.

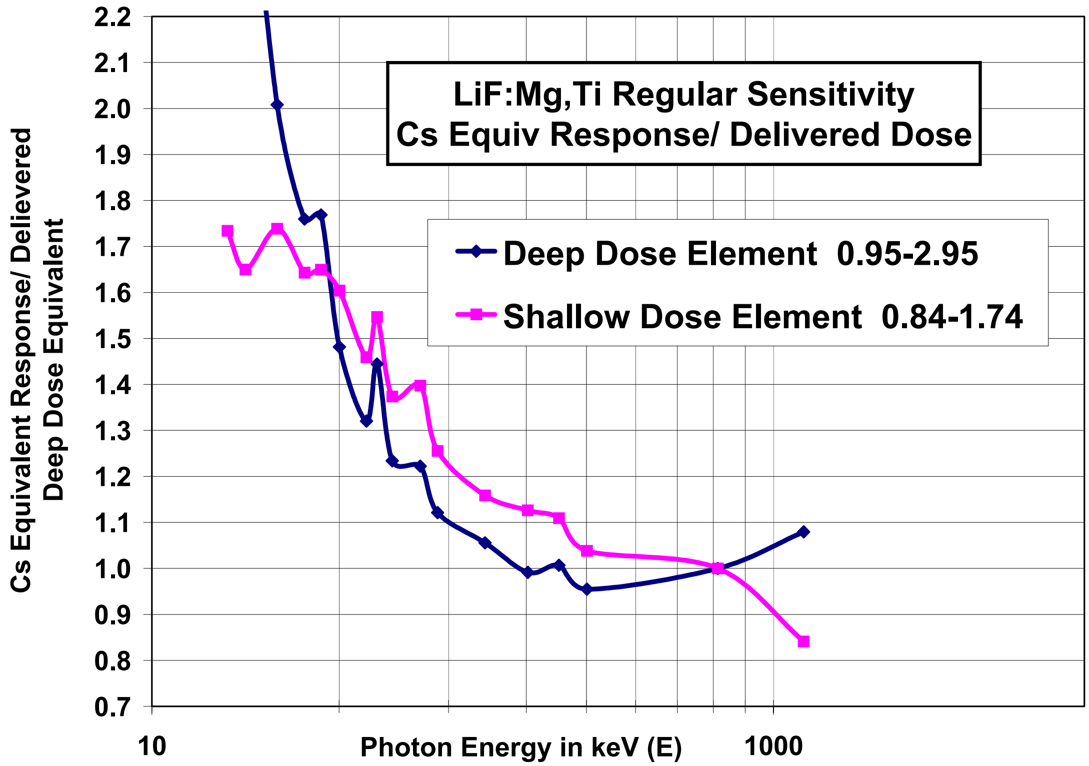
Figure 11. Illustrates the effect on not correcting for the over response of the less filtered element for various energy neutrons for 50/ 50 mixed photon neutron exposures. All photon/ neutron ratios are dose equivalent ratios.

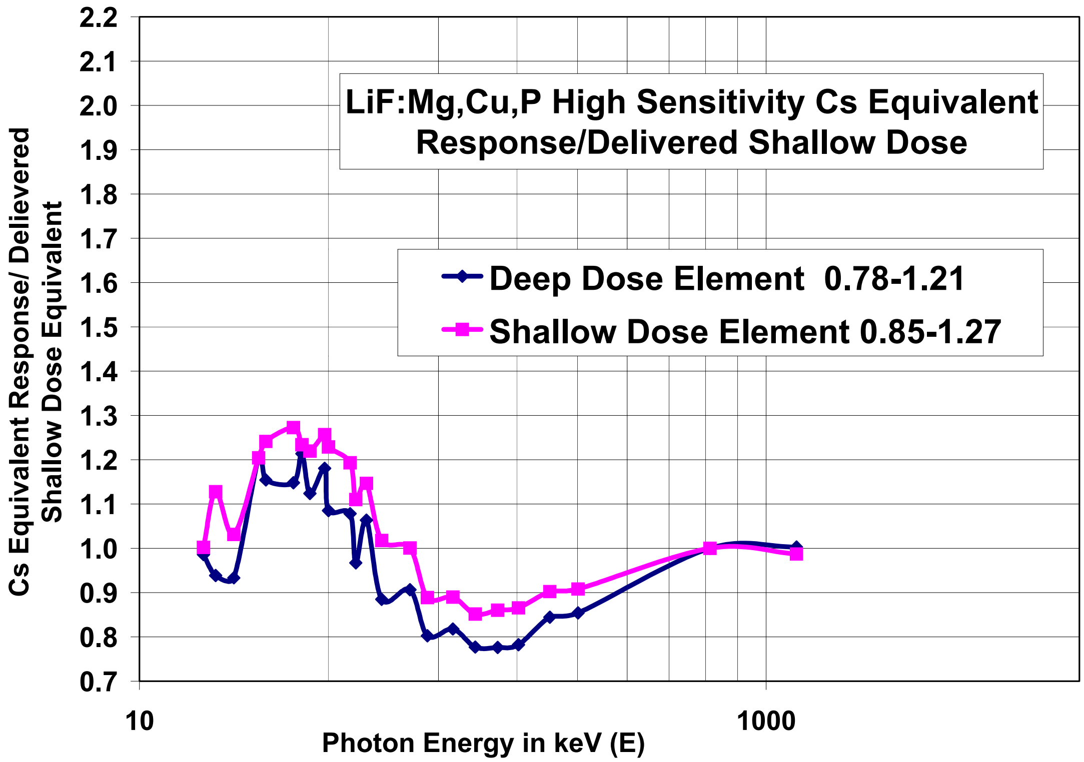
Figure 12. Relationship between the magnitude of the chip correction factor and the chip thickness for various beta irradiations. The energies in MeV are the $T_{\beta\text{-max}}$ values from the chart of nuclides.

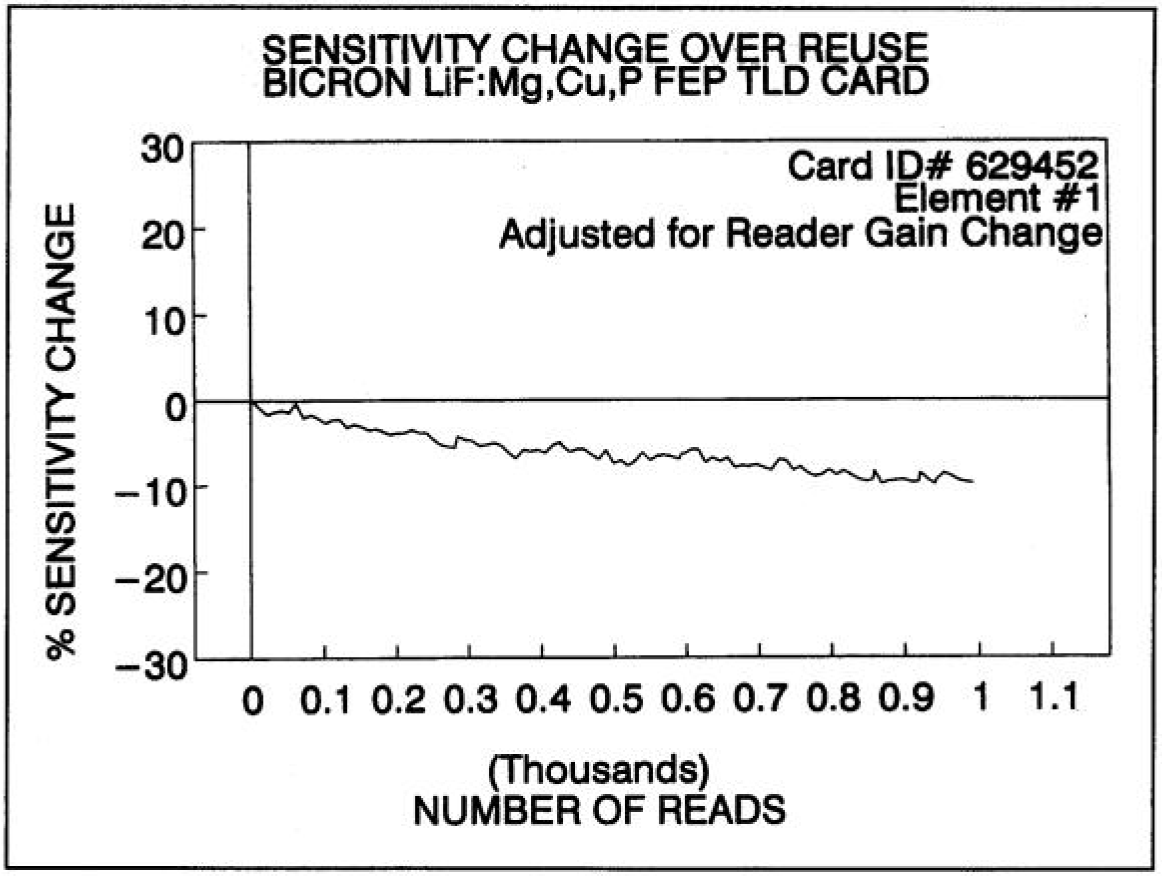
Table 1. Fields Used to the Train the MCP Neural Network. The beam code nomenclature is the standard used by NIST and ANSI N13:11. The first letter is used to designate low (L), medium (M), high (H) filtration, or fluorescence (K) and the number is the kVp on the x-ray tube.

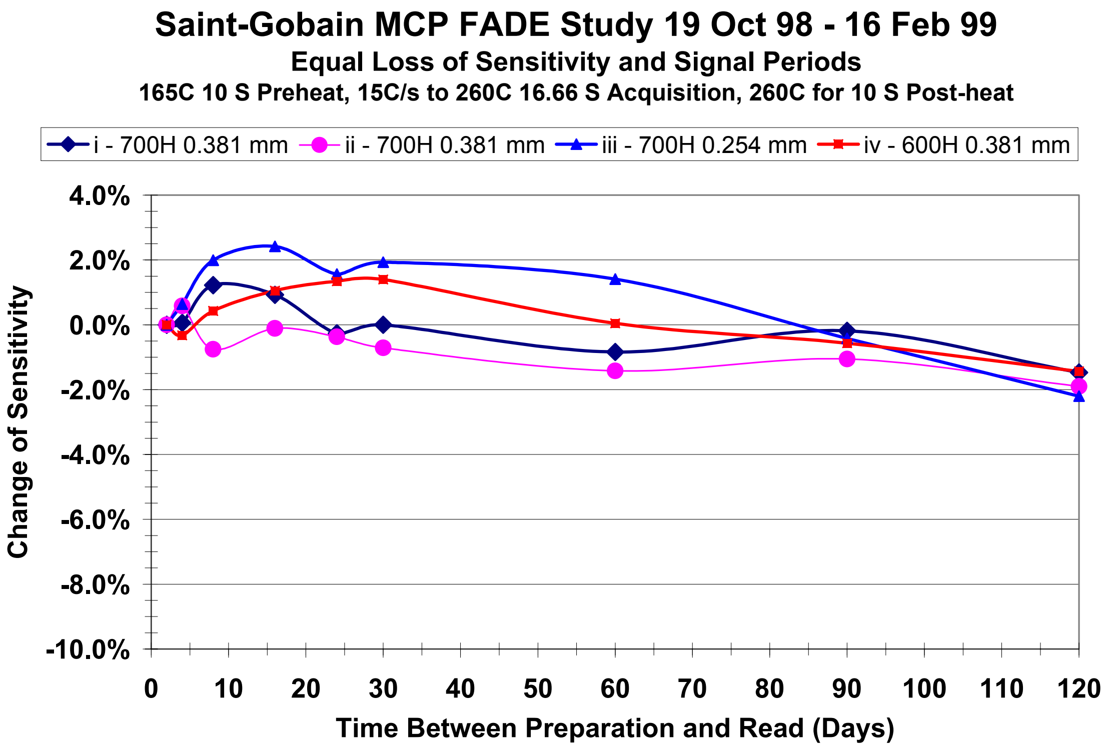
Table 2. Comparison of MT and MCP neutron properties.

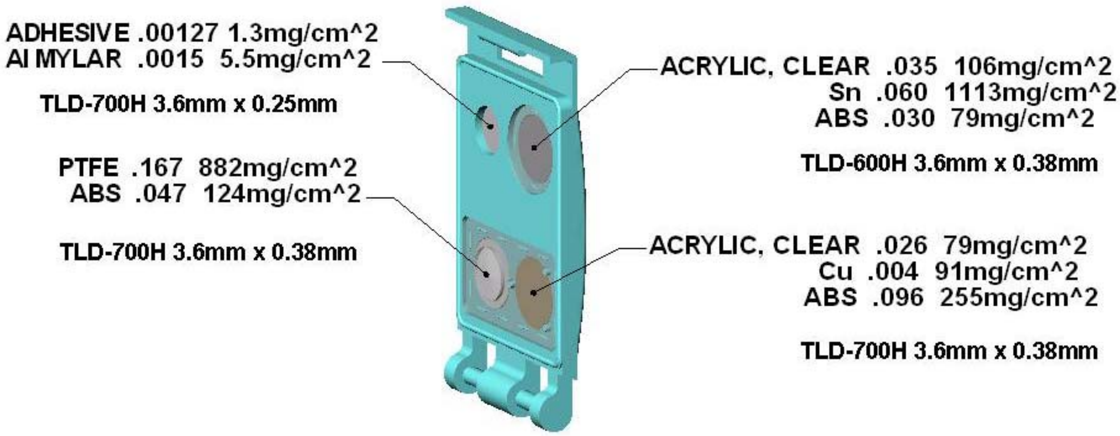
FIGURES (ONE PER PAGE)






SENSITIVITY CHANGE OVER REUSE
BICRON LiF:Mg,Cu,P FEP TLD CARD
Card ID# 629452
Element #1
Adjusted for Reader Gain Change
% SENSITIVITY CHANGE
30
20
10
0
−10
−20
−30
0 0.1 0.2 0.3 0.4 0.5 0.6 0.7 0.8 0.9 1 1.1
(Thousands)
NUMBER OF READS


Saint-Gobain MCP FADE Study 19 Oct 98 - 16 Feb 99
Equal Loss of Sensitivity and Signal Periods
165C 10 S Preheat, 15C/s to 260C 16.66 S Acquisition, 260C for 10 S Post-heat
i - 700H 0.381 mm
ii - 700H 0.381 mm
iii - 700H 0.254 mm
iv - 600H 0.381 mm
Change of Sensitivity
4.0%
2.0%
0.0%
-2.0%
-4.0%
-6.0%
-8.0%
-10.0%
0
10
20
30
40
50
60
70
80
90
100
110
120
Time Between Preparation and Read (Days)


ADHESIVE .00127 1.3mg/cm^2
Al MYLAR .0015 5.5mg/cm^2
TLD-700H 3.6mm x 0.25mm
PTFE .167 882mg/cm^2
ABS .047 124mg/cm^2
TLD-700H 3.6mm x 0.38mm
ACRYLIC, CLEAR .035 106mg/cm^2
Sn .060 1113mg/cm^2
ABS .030 79mg/cm^2
TLD-600H 3.6mm x 0.38mm
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ABS .096 255mg/cm^2
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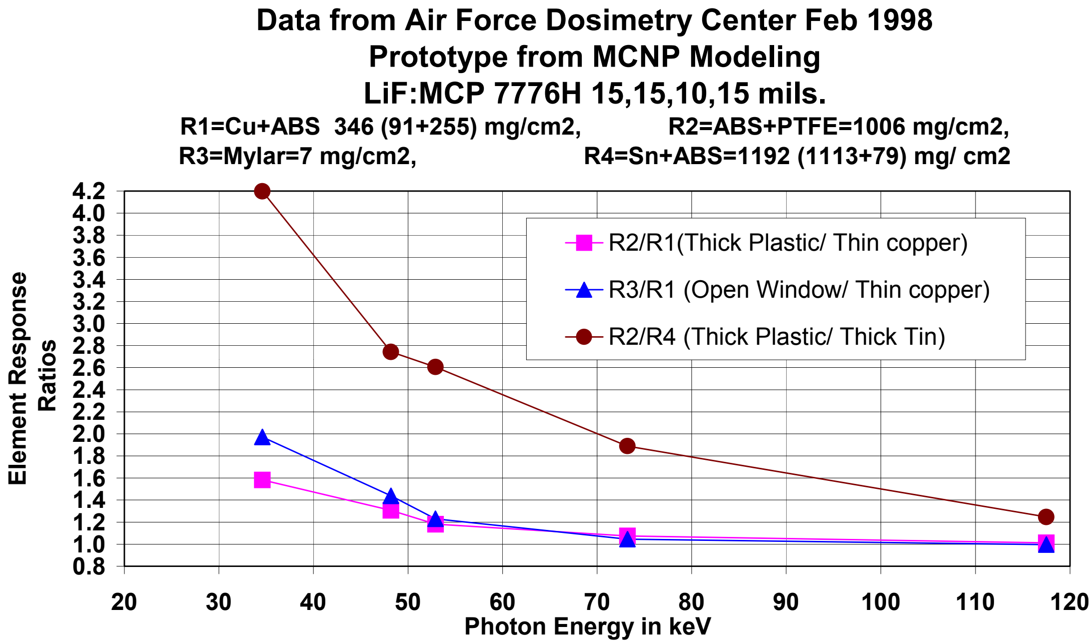
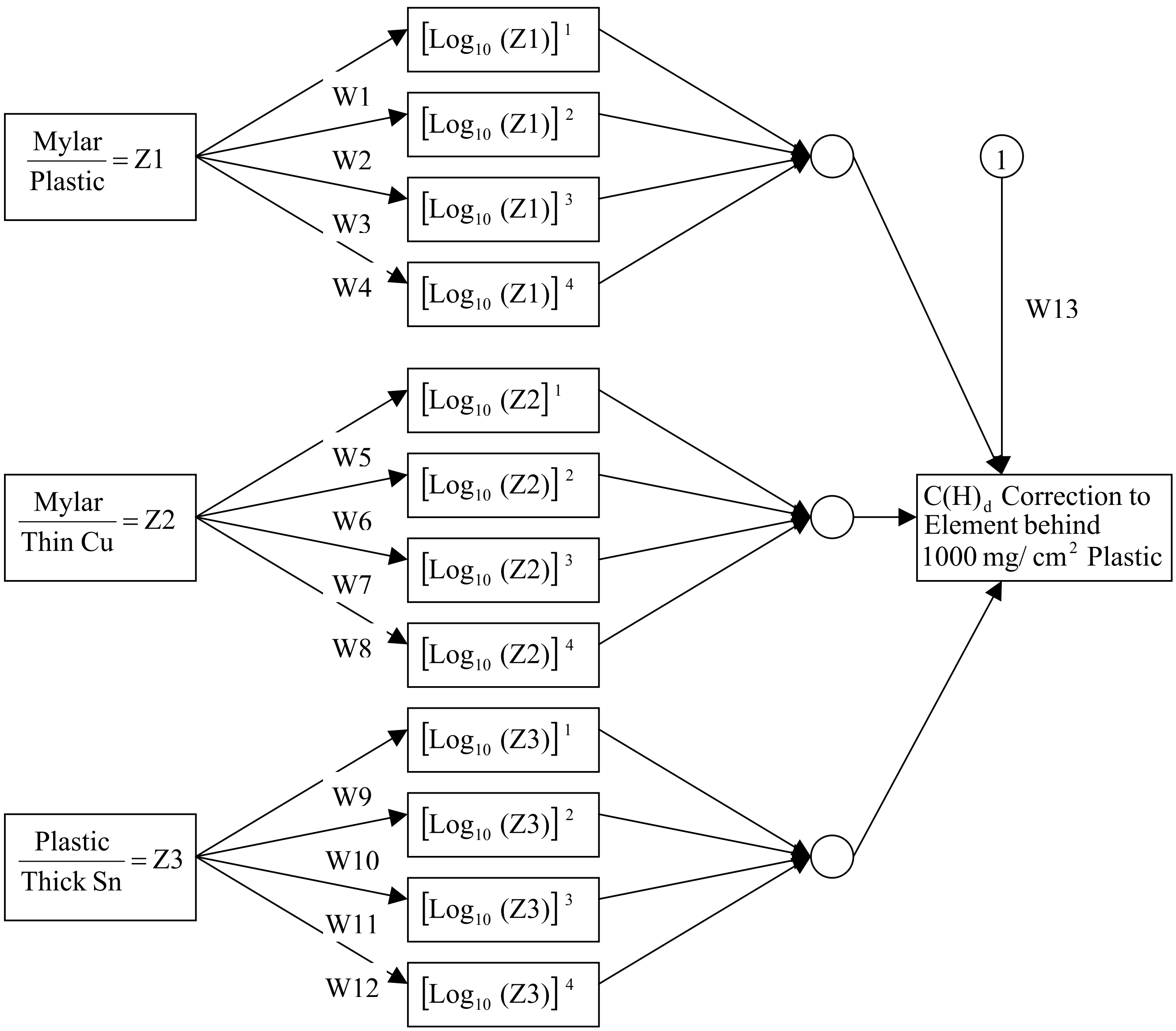

Data from Air Force Dosimetry Center Feb 1998
Prototype from MCNP Modeling
LiF:MCP 7776H 15,15,10,15 mils.
R1=Cu+ABS 346 (91+255) mg/cm2,
R2=ABS+PTFE=1006 mg/cm2,
R3=Mylar=7 mg/cm2,
R4=Sn+ABS=1192 (1113+79) mg/ cm2
Element Response Ratios
Photon Energy in keV
R2/R1(Thick Plastic/ Thin copper)
R3/R1 (Open Window/ Thin copper)
R2/R4 (Thick Plastic/ Thick Tin)
4.2
4.0
3.8
3.6
3.4
3.2
3.0
2.8
2.6
2.4
2.2
2.0
1.8
1.6
1.4
1.2
1.0
0.8
20
30
40
50
60
70
80
90
100
110
120



Mylar / Plastic = Z1
Mylar / Thin Cu = Z2
Plastic / Thick Sn = Z3
W1
W2
W3
W4
W5
W6
W7
W8
W9
W10
W11
W12
W13
[Log10 (Z1)] 1
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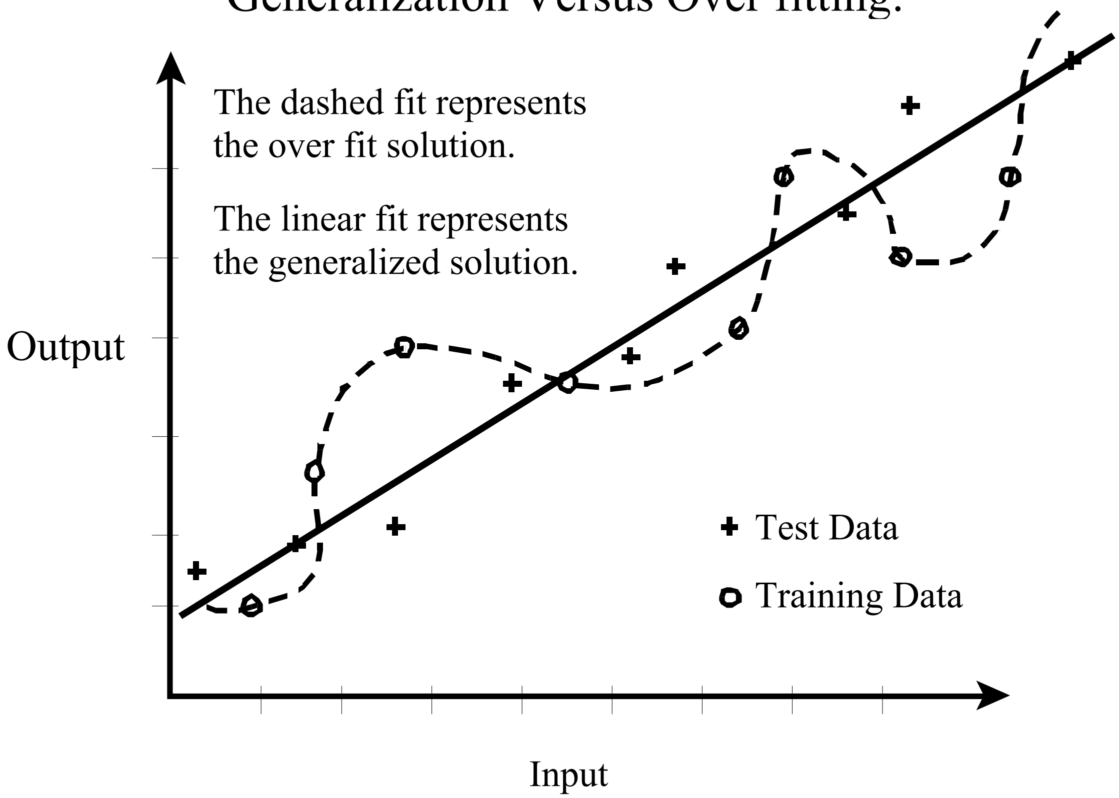
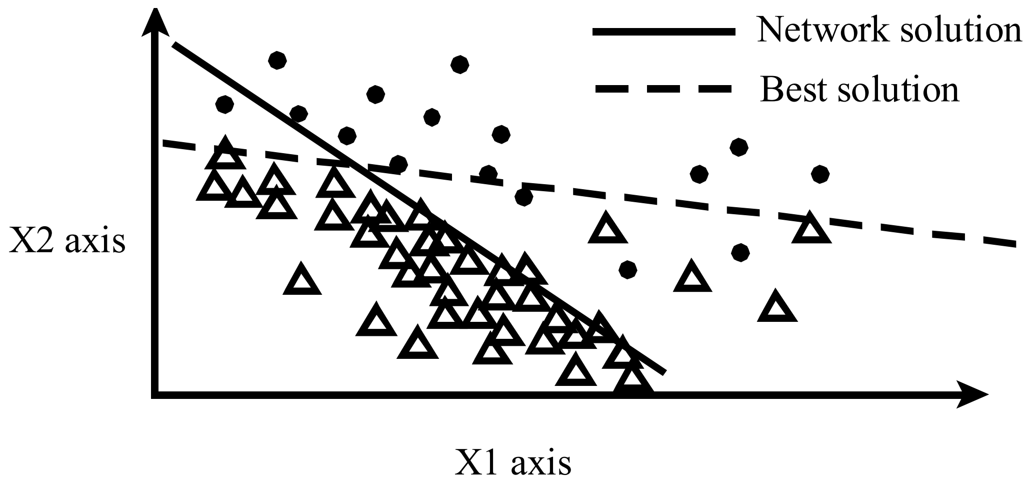
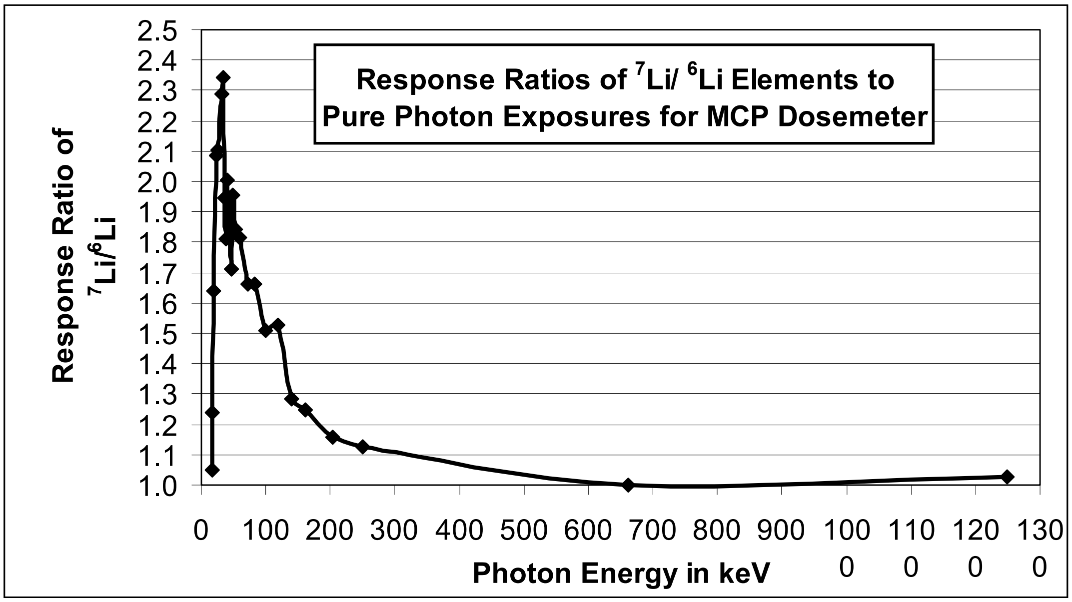
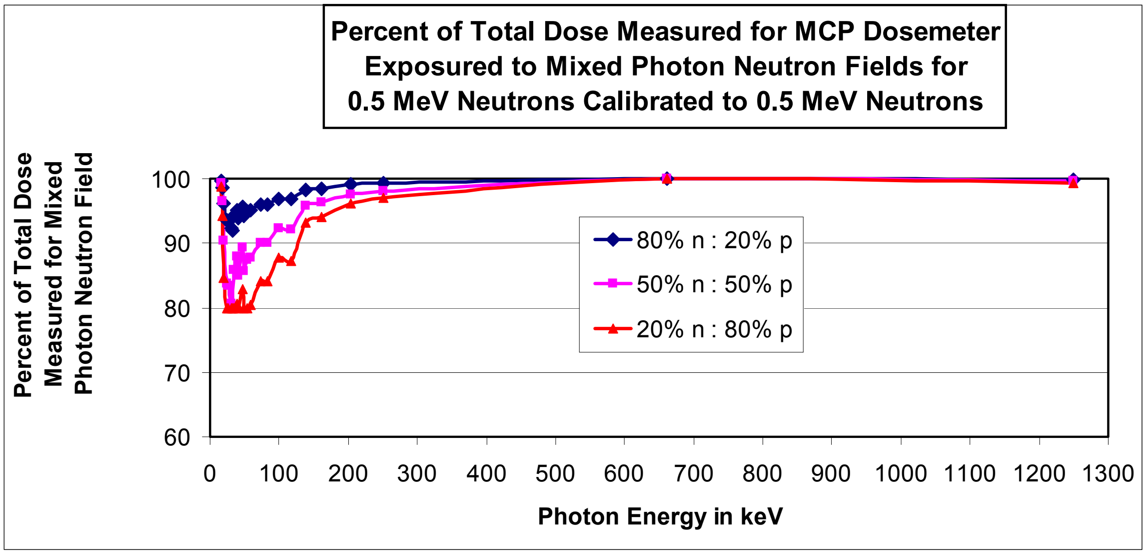
1
C(H)d Correction to Element behind 1000 mg/ cm2 Plastic

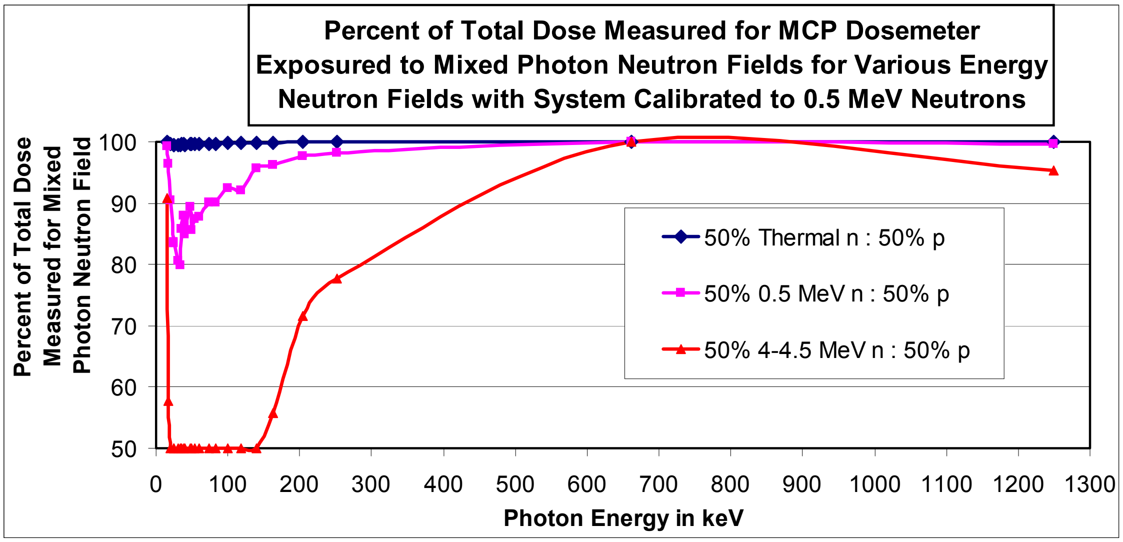
Generalization Versus Over fitting:

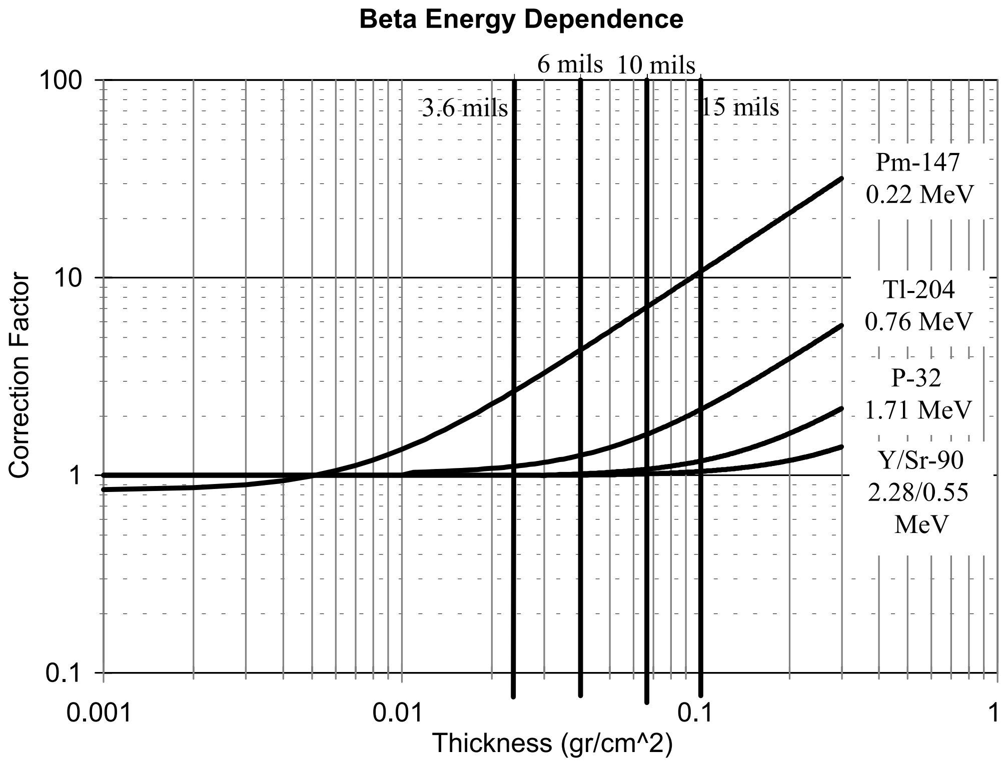



Network solution
Best solution
X2 axis
X1 axis


Response Ratios of 7Li/ 6Li Elements to Pure Photon Exposures for MCP Dosemeter
Response Ratio of 7Li/6Li
2.5
2.4
2.3
2.2
2.1
2.0
1.9
1.8
1.7
1.6
1.5
1.4
1.3
1.2
1.1
1.0
0 100 200 300 400 500 600 700 800 900 1000 1100 1200 1300
Photon Energy in keV


Percent of Total Dose Measured for MCP Dosemeter
Exposured to Mixed Photon Neutron Fields for
0.5 MeV Neutrons Calibrated to 0.5 MeV Neutrons
Percent of Total Dose
Measured for Mixed
Photon Neutron Field
100
90
80
70
60
0
100
200
300
400
500
600
700
800
900
1000
1100
1200
1300
Photon Energy in keV
80% n : 20% p
50% n : 50% p
20% n : 80% p


Percent of Total Dose Measured for MCP Dosemeter Exposured to Mixed Photon Neutron Fields for Various Energy Neutron Fields with System Calibrated to 0.5 MeV Neutrons
Percent of Total Dose Measured for Mixed Photon Neutron Field
Photon Energy in keV
50% Thermal n : 50% p
50% 0.5 MeV n : 50% p
50% 4-4.5 MeV n : 50% p
100
90
80
70
60
50
0
100
200
300
400
500
600
700
800
900
1000
1100
1200
1300


Beta Energy Dependence
6 mils
10 mils
3.6 mils
15 mils
100
10
1
0.1
Correction Factor
Pm-147
0.22 MeV
Tl-204
0.76 MeV
P-32
1.71 MeV
Y/Sr-90
2.28/0.55
MeV
0.001
0.01
0.1
1
Thickness (gr/cm^2)

TABLES (ONE PER PAGE):

Field #	Beam Code	Average Energy	Field #	Beam Code	Average Energy
1	H20	16 keV	13	M100	53 keV
2	K17	17 keV	14	K59	59 keV
3	M30	20 keV	15	M150	73 keV
4	H30	24 kev	16	H100	83 keV
5	K25	25 keV	17	M200	100 keV
6	K31	31 keV	18	H150	118 keV
7	H40	33 keV	19	M250	139 keV
8	M60	35 keV	20	H200	162 keV
9	H50	39 keV	21	H250	204 keV
10	K40	40 keV	22	H300	251 keV
11	H60	47 keV	23	Cs	662 keV
12	K49	49 keV	24	Co	1250 keV
			25	Sr	2.28 MeV

	Light Advantage (response ratio of neutron/gamma per Sv delivered)		CsModCf Conversion Factor		NECF		% Diff
	MT (+/- 7.1%)	MCP (+/- 4.2%)	MT	MCP	MT	MCP	
NIST Thermal (0.0375 eV)	363	109			0.034	0.030	-11.6
NIST Moderated Cf (0.5 MeV)	12.5	3.33	0.08	0.30	1.0	1.0	0.0
NIST Bare Cf (2.0-2.3 MeV)	1.30	0.33			9.6	10.1	5.4
USNA PuBe (4.0-4.5 MeV)	0.99	0.23			12.6	14.4	14.3
USNA Fast 14.2 MeV	0.32	0.08			38.7	43.4	12.2

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