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Review of the State of the Art in
Personnel Neutron Monitoring with Solid
State Detectors

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Review of the State of the Art in Personnel Neutron Monitoring with Solid State Detectors*

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Abstract

Thirty years of development in personnel neutron dosimetry are bearing fruit. Albedo systems are the mainstay at many facilities and continue to be refined. Advanced electrochemical etching techniques for CR-39 now yield a dose equivalent response that is nearly constant from 0.1 to 4.0 MeV. Recent studies include use of converters to enhance CR-39 response at both low and high energies. Moreover, methods have been suggested for use of CR-39, either alone or in conjunction with albedo and other detectors to provide spectral information as a step to more accurate dosimetry. Limitations in the use of CR-39 primarily center on the lack of consistent, high-quality, dosimetry-grade material, significant angular dependence, and poor dose equivalent response at both low (thermal and intermediate) and high energies. Work continues on silicon diodes, with some new designs. TSEE has been studied, but without much advance. The most attractive new dosimetry technique is the bubble-damage or superheated drop detector. Metal-on-silicon (MOS) microelectronics present exciting possibilities for the future.

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Introduction

There are a number of unsolved problems in personnel dosimetry that continue to provide an impetus for solid state detector development and refinement. No single detector or detection mechanism has or is likely in the near future to have the combination of energy response, sensitivity, orientation dependence characteristics, and dynamic range necessary to fully meet the needs of a complete personnel dosimeter. Although cost is a concern, at this point it is not a major obstacle to implementation of a dosimetry system for small numbers of workers.

Three levels of activity are currently underway in solid state detector development. The first is refinement of systems that represent significant improvements in dosimetry capabilities. Although evolving CR-39 track detection systems primarily fall in this category, work is also continuing on improvement in use and understanding of albedo detectors and dosimetry systems based on other track etch detectors for applications where the deployment of such systems make sense. Discussion of a national initiative to standardize an albedo system is presented in these proceedings.(1) The second level of activity focuses on pursuit of newer detection mechanisms with characteristics that may represent significant advancement over CR-39, albedo detectors, or even the limited number of NTA dosimeters still in use. Superheated drop or bubble detectors are drawing the major fraction of attention in this research class. Finally, there is research on even newer detection techniques that could provide long-term solutions for the dosimetry problem. My personal favorite in this class is the detection of soft errors in MOS or RAMs.

Figure 1 can be used to illustrate relationships in the solid state detector family. The history of research in solid state has featured a continuing climb up the tree in a search for the branch or branches that might hold the fruit of a universal neutron dosimeter. Like a real tree, growth through developing technology has created and will continue to create new branches that might bear the illusive fruit.

CR-39

Serious CR-39 development is being conducted at a number of laboratories throughout the world. It has a demonstrated sensitivity to neutrons with energies below 100 keV. It also has a limit of detection, when processed properly, as low as 0.08 to 0.1 mSv. Recent work by Hankins, et al.[2,3] has identified a processing method that lends itself to automation, at least on a moderate scale. Unfortunately, use of poor quality material, bad experiences with commercial dosimetry services, and other problems have caused a number of researchers and dosimetrists who had initially been attracted to CR-39 to become disenchanted with the results. It will take a long, consistent experience by those who have chosen to continue the research to demonstrate the dependability and quality of performance necessary for routine dosimetry applications.

The major unaddressed CR-39 issues are lack of a truly dosimetry-grade material, significant angular dependence, and a sensitivity that may be marginal if a change in quality factor is adopted.

Developments by Tommasino, et al.[4] and Hankins, et al.[3] have significantly improved CR-39 energy response (Fig. 2). Hankins and Homann[5] have developed an electrochemical etching process that is controlled by a programmable hand-held calculator. However, CR-39 underresponds for certain classes of neutron spectra (i.e., lower energy neutrons from power reactors, or high-energy accelerator-produced neutrons).

Efforts to improve the response in these energy ranges using radiators or convertors have been presented at this symposium.[6,7] In comparison, albedo detectors and NTA have response functions that may cause even greater errors for many operational situations. Energy response deficiencies, together with a need for improved accuracy with implementation of an increase in Q is prompting an increased interest in the ability of a dosimeter to characterize the exposure spectrum, even if very crudely. Two techniques can be used that take advantage of differential detector responses and suggest the value of having multiple detector elements in a neutron dosimeter.

The albedo and CR-39 responses are significantly different. The responses from these detectors could be used to identify the neutron contributions below and above 0.1 MeV separately, as a crude spectrometer for more accurate dosimetry. Addition of a second track detector--polycarbonate--would provide additional information on the neutron contribution above 1.5 MeV (Fig. 3). Figure 4 illustrates the spectral estimates that could be determined from responses of these three detectors exposed to three significantly different spectra.

A second "spectrometry" option would involve use of the responses of two CR-39 samples etched under different conditions. Figure 5 presents the energy response of CR-39 etched at 0 kV/cm and 47 V/cm. There is a significant relative suppression of response between 0.1 and 1.0 MeV using 0 kV. This is an energy range of particular interest for power reactor work. Three spectra unfolded from these two responses (together with an albedo component) are presented in Fig. 6.

A different technique currently under study by Hankins and Westermark focuses on the relationship between neutron spectrum and track or pit size distribution.[8] Use of this relationship would have the distinct advantage that the information necessary to apply accurate calibration factors could be derived from a single CR-39 sample.

Bubble or Superheated Drop Detectors

The most widely heralded development in the last three years has been the bubble or superheated drop detector (SDD).* [9,10] Based on a principle that was identified in the 1950s, superheated liquid drops are incorporated in a fluid or semisolid gel. A charged particle resulting from a neutron interaction in the medium interacts with the drop, causing it to expand. In the gel, it expands to a readily visible dimension so that the number of bubbles can be counted and related to the incident neutron fluence. In a liquid medium, the bubbles simply expand and dissipate.

Two laboratories have taken the lead in drop detector development, but they have pursued the development along somewhat different lines. Robert Apfel at Yale first identified the possibility of neutron detection using this mechanism.[11] His group has chosen to focus on detection of events in a liquid using acoustic techniques because of the problem of stabilizing bubble formation in solids.[12,13] Dr. Ing at the Chalk River Nuclear Laboratories was attracted to the potential simplicity of optical counting methods analogous to those used for conventional track detectors.[14] The attraction of bubble detectors comes from a lack of angular dependence, very high sensitivity, self-developing response in real time, and the possibility for selectable energy response. The latter characteristic lends itself to development of a spectrometer using an array of detectors.

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* SDD is a trademark of Apfel Enterprises, Inc., New Haven, CT, USA.

One of the significant aspects of the last two years is that a number of laboratories are now having the opportunity to evaluate detectors produced by the Chalk River Group. Much of the claim for these detectors has been supported. However, two reports in this symposium[15,16] also point up significant limitations that prevent operational deployment of the current versions.

The detectors are very sensitive--at this point, too sensitive. One report places an upper limit of about 100 bubbles in a single detector (0.05 to 0.1 mSv) on the dose that can be measured visually.[15] Use of photographs could extend that limit by a factor of 5. The same study found a decrease in sensitivity of stored detectors of more than 50% over a three-month period. Both groups found a nonuniformity in bubble formation throughout the detector volume. Variation in sensitivity with temperature is a distinct problem, as is shock sensitivity. In one case, a detector left in the glove compartment of a car (a practice not unusual among radiation workers) was found to have innumerable small bubbles.[16] Finally, both groups found a similar reduction of equivalent response. In one study, this reduction was a factor of 4 from 0.144 MeV to 5.0 MeV, although the detectors did exhibit a significant and useful response at intermediate energies (2 keV and 24-27 keV).

The radiation protection community has not had an opportunity to evaluate the SDD. Because of the difference in operating principle, there are likely to be differences in some of the factors discussed (limit of detection, upper dose limit, etc). Although initial experience with the bubble-damage detectors has identified problem areas and the need for developmental work, both the bubble-damage detectors and SDDs have the potential to become valuable components of the neutron dosimetry inventory. Their development should be encouraged and followed.

Other Detection Mechanisms

Although a large fraction of the work and attention in neutron dosimetry has been focused on the areas just discussed, research is being carried out in other solid state areas that may well offer exciting options for the future. Perhaps the most intriguing of these areas is that of the detection of upsets or "soft errors" in dynamic random access memories (dRAM's). The dRAMs are arrays of large numbers (typically 64k or 256k) of metal-on-silicon (MOS) elements. Binary information is stored in these arrays. After irradiation with charged particles, the information stored in these arrays is inventoried to determine how many changes in the binary levels (soft errors) have occurred. The fraction of changes can then be related to the charged particle fluence.

This technique is attractive because of the analogy that is easily drawn between an array of microelectronic elements and a volume of human cells.(17) Moreover, a tiny dosimeter based on such "high-tech" principles is aesthetically appealing, leading to visions of a variety microelectronic dosimeters, perhaps even worn as jewelry. Studies have been made with alpha particles(18-20) and recoil protons,(18) although in the latter case the results were not conclusive. The limit of sensitivity of these arrays decreases as the dimensions of the individual elements are reduced, so that as microelectronics technology advances the potential for application of this technique to neutron dosimetry should improve significantly. Some of the most recent research in this area is presented in this symposium.(21)

Other solid state neutron dosimetry research areas are also active. Silicon diodes have been of interest for some years. A recent report summarizes development of a small dosimeter for neutron and gamma measurement.[22] However, directional dependence and cost remain limiting factors. TSEE has also not been forgotten.[23] Again, however, old problems (gamma sensitivity and low energy neutron insensitivity) are serious obstacles.

Summary

Solid state personnel neutron dosimetry is an art that has and is evolving slowly, a process that could cause a certain degree of emotion and impatience.[24] However, it should be recognized that dosimetry research is driven by economics. If the lack of adequate dosimetry were seen as a sufficiently serious problem by the cognizant funding sources, the solutions would come much more rapidly. However, that has not been the case. Fortunately, the picture seems to be getting brighter, as many of the papers in this proceedings should suggest.

Some laboratories have refined TLD albedo systems and developed enough confidence in their performance that they feel comfortable in developing them as national standards. For others, the limitations of albedos have caused them to search elsewhere. Many of these have been concentrating on electrochemically etched CR-39, attracted by its fast neutron response, low neutron energy threshold, and photon insensitivity. Recent work has improved the performance of CR-39 to the point that it is ready to use in large scale operational programs,[3,25] if processed and evaluated properly. This is particularly true if it is used in combination with an albedo detector and, perhaps, additional fast neutron sensitive detectors. Current work indicates that it can certainly be used to provide spectrometric information. However, the work is not complete, and sources of a truly dosimetry grade material are still required.

There is life after CR-39. Work in new areas is going on and should be encouraged. In the forefront is the development of bubble-damage or superheated drop detectors. These will offer advantages in sensitivity, angular independence and energy response that may not be shared by CR-39 or albedo detectors. However, dosimeter cost will be a limitation. Beyond these, we can look forward to the evolution of microelectronic detection elements in personnel dosimeters. These could add yet another dimension to long term solution of the neutron dosimetry problem.

At this point, there is no one detector or detection mechanism that meets personnel dosimetry requirements for energy response, sensitivity, angular response, low cost, photon insensitivity, etc. for all operating situations or facilities. However, there are dosimeters that will meet one or more of these needs. An effective dosimetry system, therefore, will call for a carefully integrated combination of techniques that, as an ensemble, will provide the necessary solutions for particular applications. For example, a well integrated dosimetry system may include (1) a large number of "inexpensive" dosimeters (albedo, CR-39 and, the like), (2) a smaller number of more expensive detectors having characteristics that compliment the basic system (i.e., bubble-damage detectors, SDDs, etc.), and (3) a few highly sophisticated instruments that are capable of providing detailed information on neutron spectra and/or L.E.T. It is encouraging that the research needed to yield a wider range of options for the dosimetrist is bearing fruit.

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FIGURE CAPTIONS

1. The family tree of personnel neutron dosimetry.

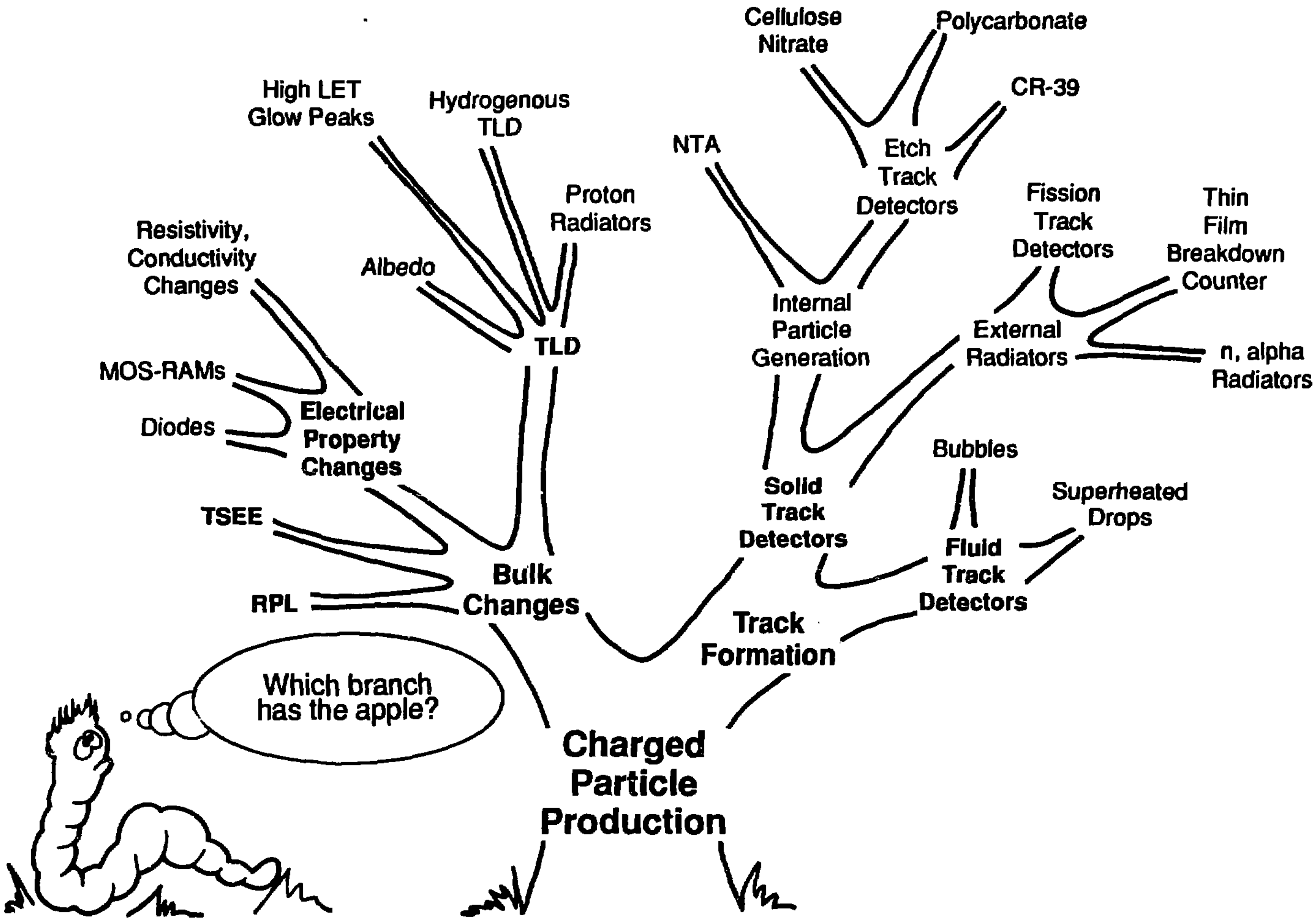
2. CR-39 neutron energy response function.

3. Neutron energy responses for albedo, electrochemically etched CR-39 and electrochemically etched polycarbonate.

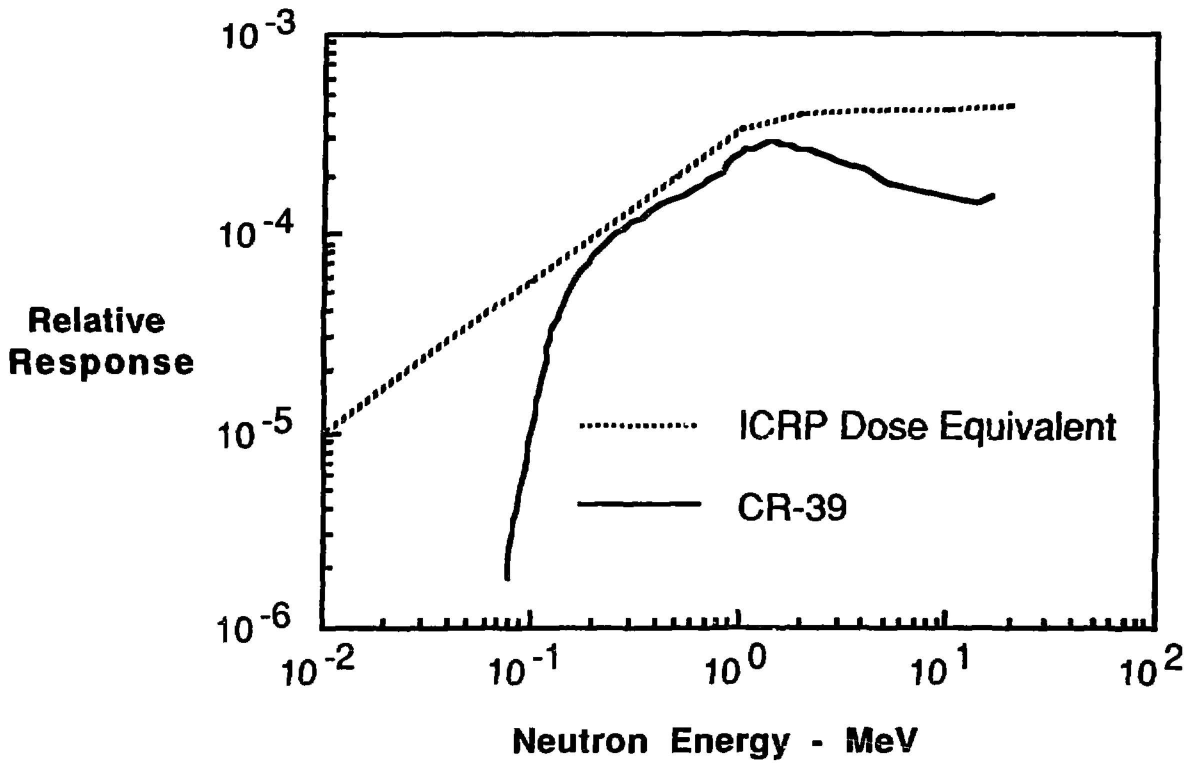
4. Comparison of reference, operational neutron spectra with those calculated using albedo, CR-39 and polycarbonate responses (Figure 3), for (a) containment of a PWR, (b) a glove box used for handling transuranic nuclide and, (c) an unmoderated ^{252}Cf calibration source.

5. Comparison of neutron response functions for albedo and CR-39 using two different electrochemical etching conditions (0 kV/cm and 47 kV/cm).

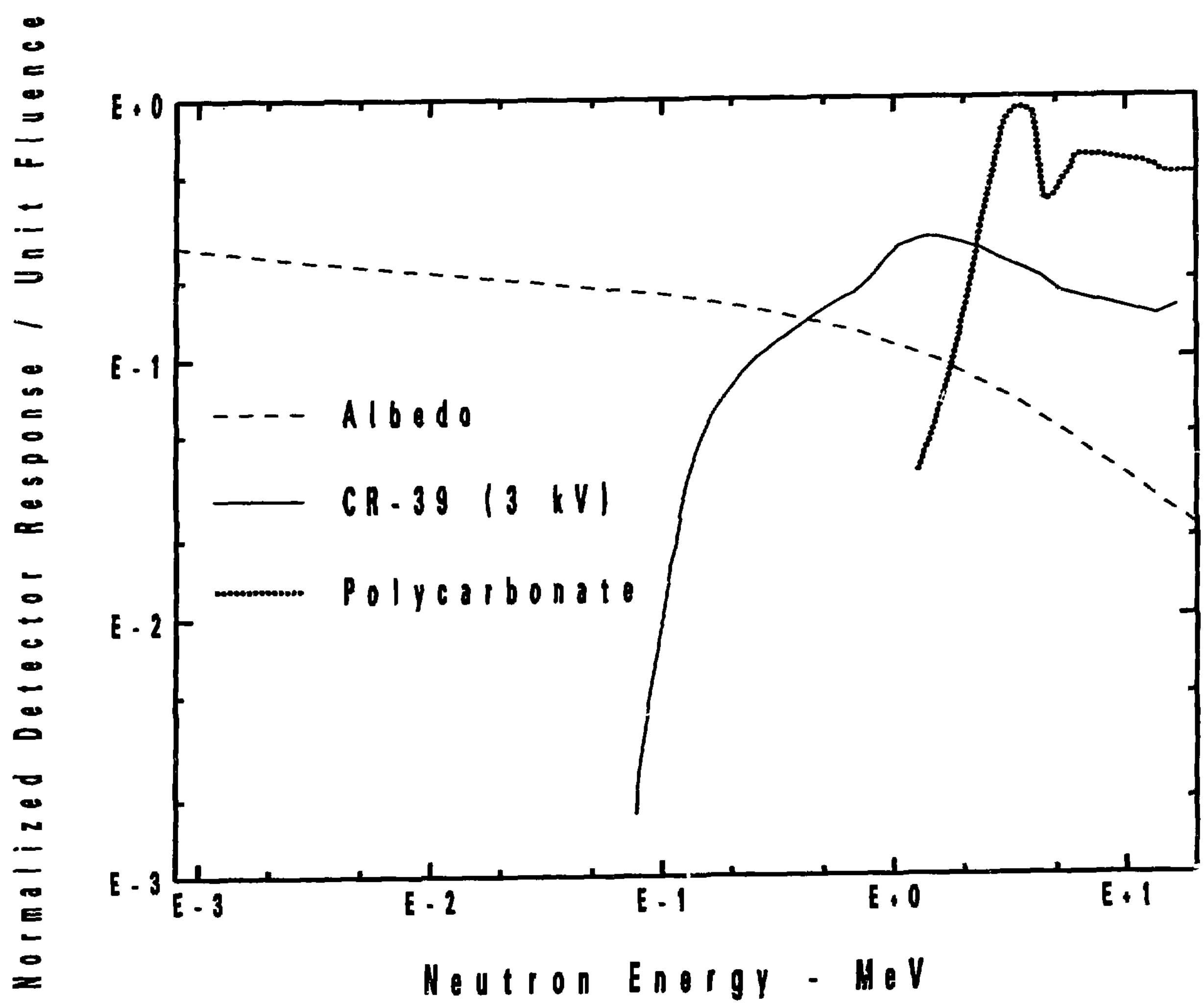
6. Comparison of reference, operational neutron spectra with those calculated from the responses of an albedo detector and CR-39 etched under two different conditions (Figure 5), for (a) containment of a PWR, (b) a ^{252}Cf source moderated by 20 cm of aluminum and, (c) an unmoderated ^{252}Cf calibration source.

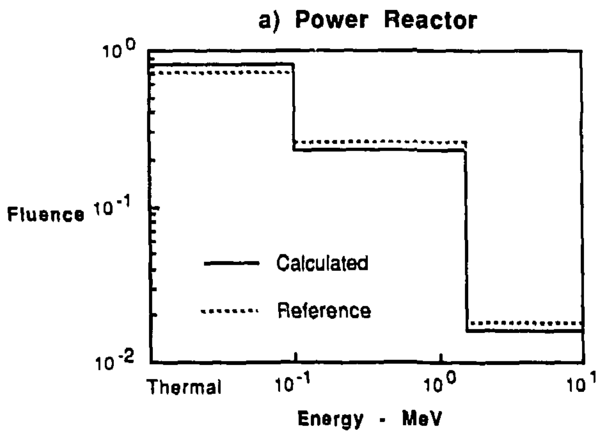


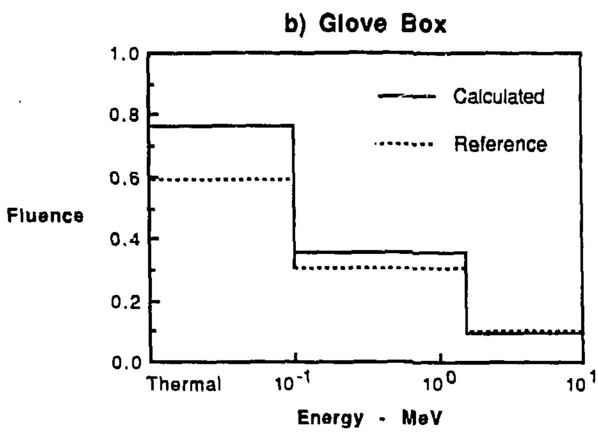
Cellulose Nitrate
Polycarbonate
CR-39
High LET Glow Peaks
Hydrogenous TLD
NTA
Etch Track Detectors
Proton Radiators
Fission Track Detectors
Thin Film Breakdown Counter
Resistivity, Conductivity Changes
Albedo
Internal Particle Generation
External Radiators
n, alpha Radiators
TLD
MOS-RAMs
Diodes
Electrical Property Changes
Bubbles
Solid Track Detectors
Superheated Drops
TSEE
Fluid Track Detectors
Bulk Changes
RPL
Track Formation
Which branch has the apple?
Charged Particle Production

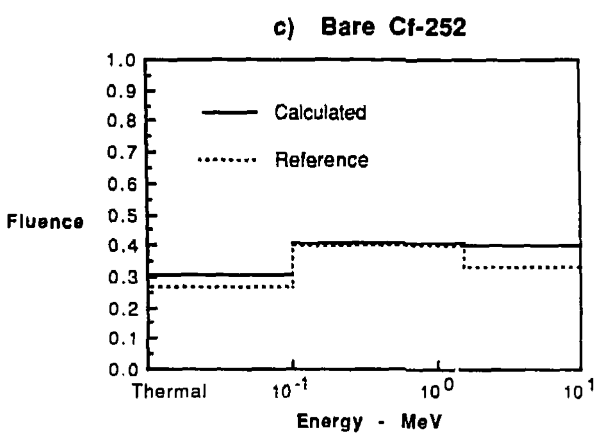


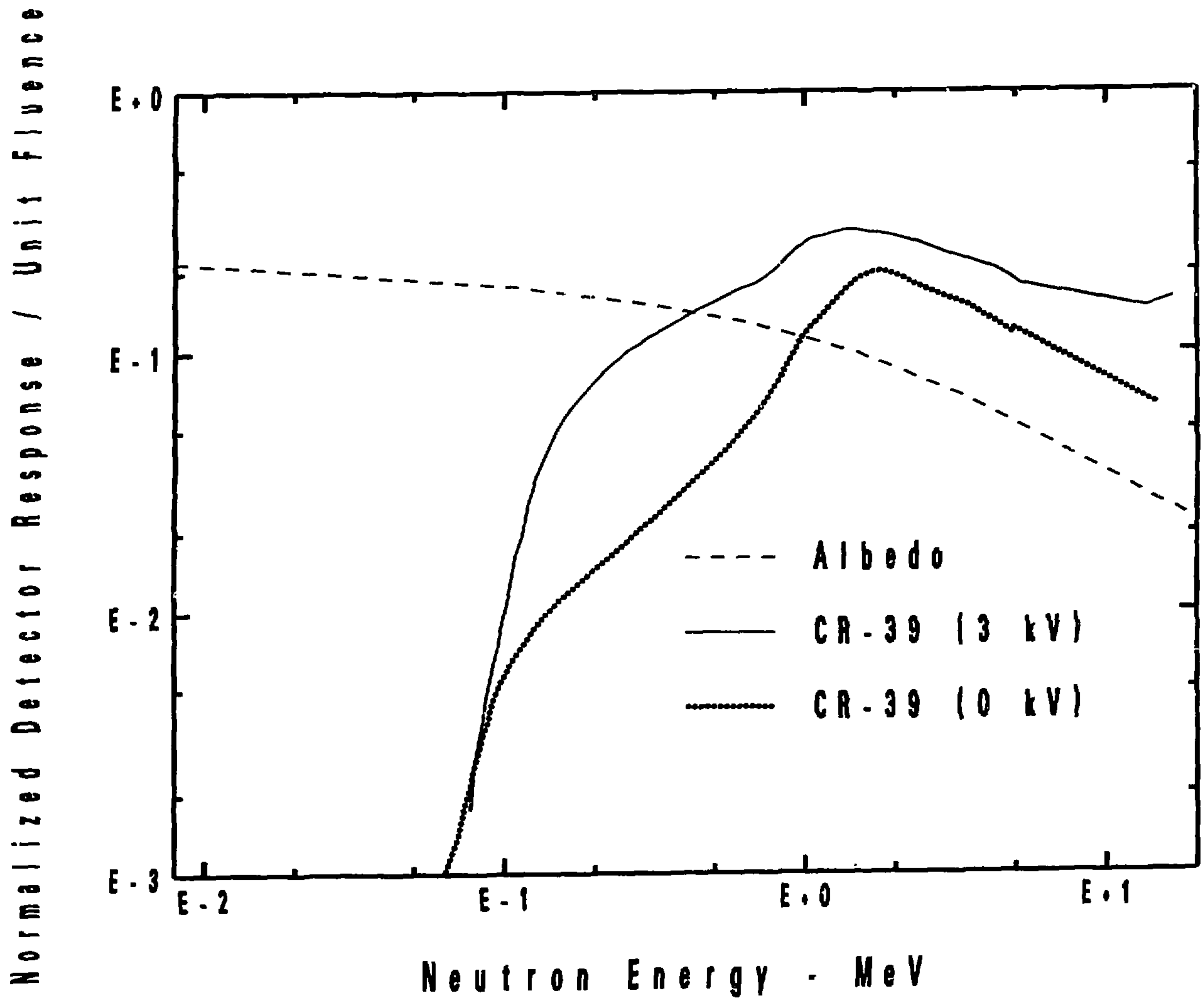
Relative Response
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-2}
10^{-1}
10^{0}
10^{1}
10^{2}
Neutron Energy - MeV
ICRP Dose Equivalent
CR-39


Normalized Detector Response / Unit Fluence
E+0
E-1
E-2
E-3
Albedo
CR-39 (3 kV)
Polycarbonate
E-3
E-2
E-1
E+0
E+1
Neutron Energy - MeV

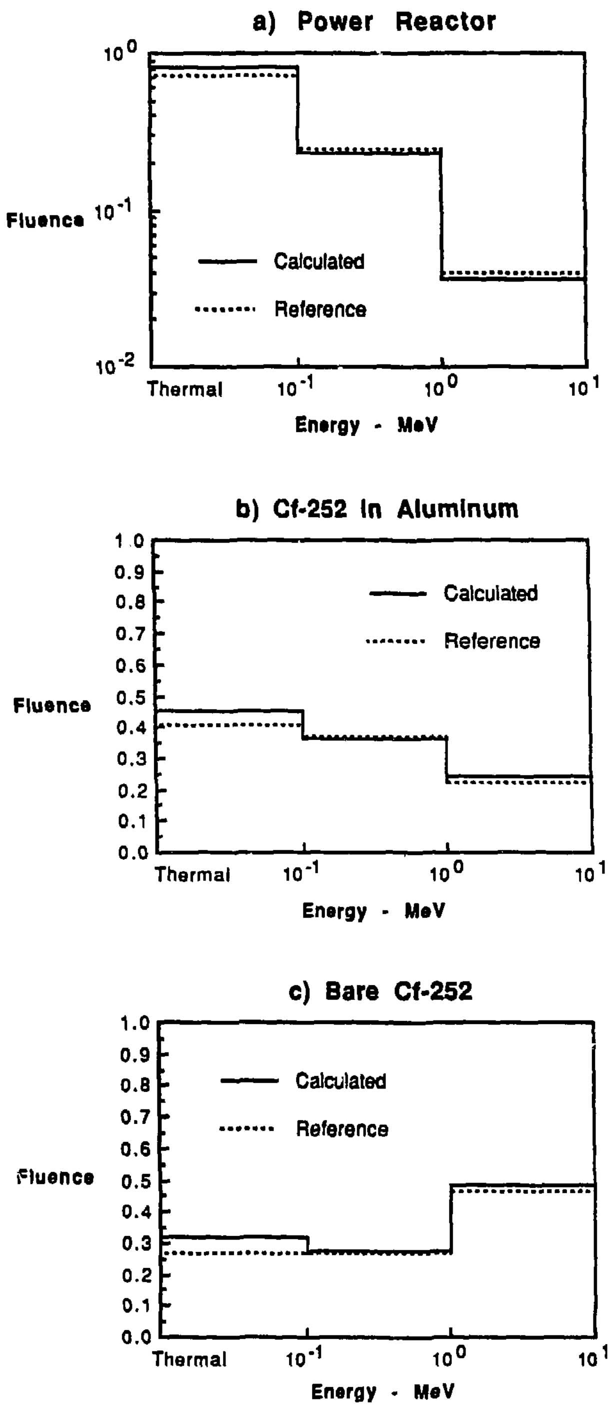

a) Power Reactor
Fluence
10^0
10^{-1}
10^{-2}
Calculated
Reference
Thermal
10^{-1}
10^0
10^1
Energy - MeV


b) Glove Box
Fluence
1.0
0.8
0.6
0.4
0.2
0.0
Calculated
Reference
Thermal
10^{-1}
10^0
10^1
Energy - MeV


c) Bare Cf-252
Fluence
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.0
Calculated
Reference
Thermal
10^{-1}
10^0
10^1
Energy - MeV



Normalized Detector Response / Unit Fluence
E+0
E-1
E-2
E-3
E-2
E-1
E+0
E+1
Neutron Energy - MeV
Albedo
CR-39 (3 kV)
CR-39 (0 kV)



a) Power Reactor
Fluence
Calculated
Reference
Thermal
Energy - MeV
b) Cf-252 in Aluminum
Fluence
Calculated
Reference
Thermal
Energy - MeV
c) Bare Cf-252
Fluence
Calculated
Reference
Thermal
Energy - MeV