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ARAB REPUBLIC OF EGYPT
ATOMIC ENERGY ESTABLISHMENT
RADIATION PROTECTION DEPARTMENT

SOME ASPECTS ON NEUTRON DOSIMETRY

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B. A. HENAISH AND S.K. YOUSSEF

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NUCLEAR INFORMATION DEPARTMENT
ATOMIC ENERGY POST OFFICE
CAIRO, A.R.E.

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CONTENT

ABSTRACT

The American National Council on Radiation Protection and measurements[1] has recently issued a statement regarding dose limitation system for neutrons. The changes proposed in that statement presented substanial problems regarding the personnel exposure to neutrons and had pointed out the need to reassess an adequate current neutron dosimetry practice. Generally, the same types of dosimeters i.e. Nuclear Track (NTA films) and TLD-Albedo, have been used at major nuclear facilities over the past 15 years. More recently, other dosimetry methods such as track etch with polycarbonates such as CR-39 have been developed. However these should be recognized as local systems aiming to the development of better and more applicable dosimeters.

In addition to advances in personnel neutron dosimeters, improvement in the characterization of neutron fields specially their energy spectra at work locations is needed to be defined. In most cases, major fractions of the neutron dose may be delivered by neutrons of energies less than 100 keV. While some of the recent developments in track etch techniques show promising results for accurate detection of energies above 200 keV, while the improvement in detector accuracies and sensitivities to energies below 200 keV are still also needed.

In the context of these problems and their possible solutions, investigators all over the world are encouraged to increase their collaboration with international authorities[1,16]. We are here believing that there should be an urgent need to initiate new programs oriented to the resolution of neutron dosimetry problems, and efforts are mainly intended to the development of new ideas.

The purpose of this study is to survey out the personnel dosimetric systems currently in use at major nuclear facilities and to review recent advances in neutron dosimetry in order to offer improvement. Unfortunately, personnel neutron dosimetry do not meet current needs in Egypt and serious problems exist now and will increase in the near future when our country will achieve its ambitious nuclear plan. In addition, a significant number of workers is expected to be exposed to neutrons from accelerators that will be soon utilized by the medical community.

I- INTRODUCTION

The problems encounting the dosimetry of neutrons are of various nature than that in case of gamma radiation. However the fluence of neutron crossing any tissue materials is having significant change and variation in the energy spectrum;

(a) at the point of interest or

(b) as the fluence goes deep in the crossed material (induced secondary neutrons).

Furthermore accurate neutron dose evaluations are too difficult to acheive;; that is due to the wide variation in the linear energy transefered (LET) to the tissues material as absorbed dose. Since under the calibration laboratory controlled conditions, it is possible to perform the calibration of the neutron dosimeters with certain limitations of accuracy. However the performance of such calibrations could be done under known;; (a) degradations of neutrons energy spectrum, and (b) beside careful evaluations of induced energy spectrum contaminations due to secondaries. The deduce calibration factor of the dosimeter is also a parameter of many functions, among them the dosimeter energy response. Furthermore the accuracy of the neutron dosimeters in the field of use as personnel evaluation system still a problem of postelations, urgemets and concerns by the various international organizations(1-16). However in the field of use the neutron energy spectrum is not known i.e. The dose equivalent delivered by single neutrons may vary by a factor of 70 in the useful range of neutron energies.. However the detection systems currently used for personnel neutron dosimetry at most nuclear facilities (NTA film and TLD-albedo dosimeters) although are still being improved, but still they are having energy response problems that make them inadequate for general wide spread use. Concerns about the effect of low level radiation may lead to a lowering of the maximum permissible dose for neutrons[1]. The degree of hazards involved from the high LET neutron radiations are still under question and may be greater than that has been assumed in the past[2]. If the neutron dose limits are decreased or the neutron quality factors are changed or redefined, the personnel neutron dosimeters that routinely used today will be inadequate.

The US-NRC has developed basic standards performance specified the personnel neutron dosimeters[3,4]. The silant features fulfill those standards could be summarized as following;

1- Personnel neutron dosimeters should be capable of measuring neutrons dose equivalents in the range of 300 mrem to 10 rem per quarter of a year. It should be having stable memory for keeping the stored information under various ambient environmental without any sorting of fadings.

2- The accuracy of 10 dosimeters exposed to an unmoderated ^{252}Cf source in the range of 100 mrem to 3 rem should be within ± 50% of the true dose equivalent.

3- The neutron dosimeter should be able to measure I rem of neutrons in the presence of 3 rem of gamma rays with an energy of 600 keV in mixed radiation fields.

4- The neutron dosimeter should meet the above requirements when subjected to the following environmental conditions:

(a) temperature extremes of $0^{o}C$ and $45^{o}C$ for 1 week.
(b) relative humidity of 90% for 1 week.
(c) mechanical shock due to a drop from a height of 1.5m
(d) exposure to light (sunlight, or normal room light).

Furthermore, the performance of that standards by NRC does not postulate any detailled informations fulfill the conditions related to the energy response of the dosimeter. However the direct effect of neutron radiation on the tissues is of changeable orders in a parameter with its quality factor and its relations to LET. This quality factor[2,7,8,16,17,18,19] was found of;; (Q)$\simeq$ 3 for thermal neutron, (Q)$\simeq$2 to 0.1 KeV, (Q)$\simeq$2.5 for 5 (KeV), (Q)$\simeq$5 for 20 KeV, (Q)$\simeq$11 for 10 MeV and then (Q) goes down gradually as neutron energy further increase up gradually.

However the authers are pointed out their too long gained experiences in that field where,

(1) In the practical field of use the radiation users are irradiated to unhomogenious neutron fluences (various LET) and levels.

(2) The rigional continuous changes in ambeint environmental conditions, since the problems encounted the dosimetry of neutron is not easy tasks. It needs more efforts. Meanwhile a certain limitations of accuracy and precision in the neutron dose evaluations and beside energy spectrum definitions in correspondance to that postulated by the international side seems to be absolutely needed. In addition, ANSI has published a draft of a proposed standard[5] which lists criteria to be used for testing personnel dosimeters.

The concept of quality factor was introduced in health physics to account for the degree of hazard from equal doses of different types of radiation. For a given dose (in rads or greys), for example, neutrons produce more biological damage than gamma rays. Quality factor is a function of the LET produced by each type of radiation. Radiation dose limits are based on a limited knowledge of a number of effects that occur at a fairly high dose. It has been assumed (the so-called "linear hypothesis") that, for any one type of radiation, the radiation risk is directly proportional to the radiation dose. Rossi[6] points out that the linear hypothesis has been applied to both high LET radiation (neutrons) and low LET radiation (X and γ rays). This implies that quality factors and relative biological effectiveness (RBE) have a fixed value regardless of dose level involved in a neutron or γ ray exposure. However, Rossi states, theoretical and experimental evidence indicate that the RBE increase with decreasing dose or decreasing level of effect, reaching values that can be 100 or more for the doses of interest in radiation protection, and therefore, current estimates of cancer risk are too high for low LET radiation, but too low for high LET radiations[6]. Rossi has also proposed that the entire basis for the definition of quality factor be changed[2,7,8,] . The effect of these proposals may well be a significant increase in the quality factors for fast neutrons.

The NCRP is currently considering changing the neutron dose limits. Their recently issued "NCRP Statement on Dose Limit for Neutrons"[1] indicates that they may recommend lowering neutron dose limits by anywhere from a factor of 3 to a factor of 10 below the current limits*. One method of effecting these reduced dose limits would be to increase neutron quality factors by factors of 3 to 10. However, NCRP noted in the statement that the basis for defining quality factors may change substantially, and its future recommendations may be more than an updating of previous NCRP recommendations or a simple increase of the neutron

* The current annual dose equivalent limit is 5 rem. This corresponds to 2.5 rad/yr for a quality factor of 2 for thermal neutrons, or 0.45 rad/yr for a quality factorof 11 for 0.5 MeV neutrons.

quality factors. No formal action has been taken up to date, and the decision may be contingent upon the recommendations of a future report by the committee on the Biological Effects of Ionizing Radiation of the National Research Council. Adopting the proposed changes, either a significant increase in the quality factors for neutrons or a reduction in the limit for exposure to neutron radiation, would cause serious problems for neutron dosimetry.

II- ACCURACY OF NEUTRON DOSIMETERS

It is difficult to assess the accuracy of neutron dosimeters because of the diversity of dosimeter designs in use. Each nuclear facility has to develope its own neutron dosimeter to meet problems specific to the site. Even tests comparing dosimeters may not be indicative of dosimeter accuracy because of differences between the neutron spectra in the test situation and those in the field exposure. Some general conclusions can be drawn, however. The accuracy of n neutron dosimeters is generally poorer than that of gamma dosimeters, as evidenced by various intercomparisons[9-14]. A dosimeter survey indicates that, under well defined irradiation conditions, the difference between the actual and indicated dose equivalent exceeds 60% in about 45% of the neutron dosimeters surveyed[15].

There are several reasons for the relatively poor accuracy of neutron dosimeters::

1. All neutron dosimeters in use today are energy sensitive, and the neutron energies encountered in various facilities vary from 0.025 eV (thermal) to 300 GeV.

2- Neutron quality factors vary between 2 and 11, whereas gamma rays have only a single quality factor of 1.

3- Many neutron dosimeters are sensitive to gamma rays, and because the two types of radiation usually occur together, the interpretation of neutron dosimeter readings is complicated.

In many instances, it is difficult for personnel neutron dosimeters to meet the recommendations of NCRP Report[16] concerning the accuracy of personnel dosimeters. The report stated that the precision of a dosimeter measurement should be ± 10% and that the accuracy of the measurement will depend on the level of exposure:

a) at levels less than of the maximum permissible dose (MPD) a factor of 2 is acceptable.

b) at the level of maximum permissible dose, ± 30% accuracy should be achieved.

c) at levels higher than the MPD, such as those that might, occur during emergencis, an accuracy of better than ± 20% is desirable.

III- TYPES OF NEUTRON DOSIMETERS

Many types of neutron detectors may be of useful use as personnel neutron dosimeters. Because of diversity of data on these detectors, the details of how they function will be given later by the same authers in a separate report. Some of the more pertinent information is summarized here in brief descriptions and tables.

3.1. Dosimeters Currently in Use:

Two types of personnel neutron dosimeters are widely used at major facilities:

1. nuclear track emulsion (NTA film) dosimeters

2. thermoluminescence (TLD albedo) dosimeters,Fig(1)
A comparison between the hypothetical ideal dosimeter and the NTA film as well as TLD albedo dosimeters is given in Table (1).

3. Track etch devices have been under investigation for more than 15 years and are being used for routine neutron dosimetry in Europe. The two basic types of track etch dosimeters are:

   i) fission track etch dosimeters, in which the neutrons interact with fissionable foils to produce fission fragments that damage the plastic or mica film and tracks that are visible when the film is etched,

   ii) recoil track etch dosimeters, in which neutrons interact with carbon or hydrogen in plastics to produce tracks.

A comparison between the ideal dosimeter and the track etch dosimeters is given in Table (2).

3.2. Possible Future Neutron Dosimeters::

Several other types of neutron detectors have been studied and might, with additional research, be usable as personnel neutron dosimeters. Combination dosimeters combine TLD-ablbedo dosimeters with track etch or deep-trap TLDs to compensate for the energy dependence of the TLD-albedo dosimeters. Silicon diods have been shown through preliminary research to have a flat energy response and could be used as an integrating dosimeter if the lower detection limit can be improved. These two detectors are compaired with the ideal dosimeter in Table (3).

Finally, many different types of neutron detectors may be used as neutron dosimeters in the futrue, but considerable research on the lower detection limit, energy respone, etc. will be required before these neutron detectors can become useful personnel dosimeters.

These devices include the following:

1. plastics-Certain plastics exhibit changes in electrical conductivity when irradiated.

2. electrets these electric analogs of permanent magnets undergo changes in electric field strength when exposed to radiation.

3. The superheated drop detector-Small drops of superheated liquid in a viscous gel vaporize when struck by neutrons.

4. electronic devices-With the introduction of inexpensive microelectronics, different types of neutron detectors, such as recoil chambers, ^{3}He counters, and low voltage capacitors with fissionable foils, can be made into neutron-sensitive alarming dosimeters.

5. thermally stimulated exoelectron emission (TSEE) devices-When certain materials are heated, they emit electrons in proportion to the absorbed radiation dose.

6. lyoluminescent chemicals-Some orgenic compounds emit light when they are dissolved and the amount of light is proportional to the radiation dose received by the compound.

The characteristics of these neutron detectors are listed in Table (4).

IV- DISCUSSION

The effects of environmental factors on dosimeter response are reasonably well known. Nuclear track emulsion film suffers from track fading and is sensitive to temperature and humidity; it also fogs from low energy gamma interference. At high energy accelerator facilities, mouns are interpreted as gamma exposure on the NTA film.

Thermoluminescence dosimeters also suffer from environmental effects. Chalk dust, dirt, and oil from finger print have been found to cause false readings unless the TLDs are thoroughly cleaned. Perfumes and some cosmetics spilled on the TLDs can cause high readings even after the TLDs have been thoroughly cleaned in alcohol. Some solvents used to clean dosimeters may fluoresce. Another problem encountered here for TLDs is the radioactive contamination on dosimeters. However this effect can be estimated by placing new chips in the badge.

Mixed radiation fields influence the accuracy of neutron dosimeters. NTA films fog badly when exposed to 1000 mrem of photon radiation. This effect is especiall had for low energy photon fields such as those from ^{241}Am and plutonium. Mixed fields affected TLDs also, because the ^{6}LiF chips are gamma sensitive, and the cadmium filters used to shield the chips emit gamma rays from absorbing neutrons. Low energy X rays tend to mask neutron exposures becaues of the methods used to correct for the photon exposure registered by the ^{6}LiF chips.

The lower limit of detection reported varies quite a bit depending upon the dosimeter used. TLDs are very sensitive to low energy neutrons. NTA film dosimeters also respond to thermal neutrons via N (n,p) reactions in the emulsion. For thermal neutrons, the lower limit of detection reported varies from 0.01 mrem ± 50% to 50 mrem ± 50%, with an average of 10 mrem.

V- RECOMMENDATIONS

The future of personnel neutron dosimetry is uncertain at present in Egypt. Exiting personnel neutron dosimeters are not fully adequate to meet the current needs of workers and the recommendations of regulatory agenices. The NCRP is now examining the risks associated with both high and low LET radiations, and may in near future lower neutron dose limits or redefine or increase the quality factors for fast neutrons(1). Either change could have two effects :
a) it might increase the number of persons to whom neutron dosimeters would be issued, b) it would increase the need for greater accuracy in personnel neutron dosimetry. In the interim, NCRP has recommended that "steps be taken to reduce the potential exposure of individuals who may receive neutron doses that are a substantial fraction of the current maximum permissible dose"(1).

Unfortunately, no truly adequate neutron dosimeter is available for use in Egypt today. The accuracy of personnel neutron dosimetry is poor, as evidence by dosimeter surveys and by dosimeter comparison studies such as that of Plato and Hudson(9). Many neutron dosimeters do not meet the NCRP's recommendations on dosimeter accuracy[15]. Significant improvements must be made in personnel neutron dosimetry if an accuracy comparable to that of gamma dosimetry is to be achieved.

Concern about the effect of low level radiation is increasing, and more accurate dosimeters may be needed to measure these low levels. At present neutron dosimeters have a lower detection limit of to 50 mrem under ideal conditions. There is also some evidence that neutrons and other high LET radiations poses a higher degree of hazard than has been assumed in the past [2,7,8]. If the neutron quality facotre currently under study be NCRP are revised, NTA dosimeters will have neither sufficient accuracy nor a low enough detection limit to meet the requirements of NCRP[15]. TLD albedo dosimeters may have an adequate lower detection limit, but their severe energy dependence problem must still be resolved.

One solution to the energy sensitivity problem of the TLD-albedo dosimeter may be to use it in conjunction with another dosimeter that is more sensitive to higher energy neutrons (above 100 keV); such as:

a. Combination TLD-Albedo, and Track Etch

b. Combination TLD-Albedo, and NTA Film

c. Combination TLD-Albedo, and Deep-Trap TLD

Alternatively, additional research needs to be done on other neutron detectors, such as silicon diods, plastics that exhibit changes, in electrical conductivity when exposed to neutrons, plastics that act as semiconductors, electronic devices, electrets, and the superheated drop detector. It would be possible to determine the suitability of some of these devices by exposing them to monoenergetic neutrons to determine their energy response and lower limit of detection. Thos with desirable characteristics could then be developed further. This research might reveal a new and more accurate personnel neutron dosimeter that would be suitable for future dosimetry needs.

In few words, we believe there is an urgent need for our country to initiate new programs oriented to the resolution of neutron dosimetry problems. Our present sincere effort is intended to provide a basic reference point for the development of new ideas and we have the honour to collaborate with any investigator who will find himself interested in exploring a new reasonable solution for this serious problem.

REFERENCES

1. National Council on Radiation Protection and Measurements, "NCRP Statement on Dose Limits for Neutrons" Washington, D.C. (1980).

2. Rossi, H.H., "The Effects of small doses of Ionizing Radiation; Fundamental Biophysical Characteristics" Radiat. Res. 71, 1-8, (1977a).

3. U.S. Nuclear Regulatory Commission, "Personnel Neutron Dosimeters", Regulatory Guide 8.14, Washington, D.C. (1980).

4. American National Standards Institute, "Personnel Neutron Dosimeters (Neutron Energies less then 20 MeV), ANSI N319-1976, New York, (1976).

5. American National Standard Institute,"Draft American National Standard Criteria for Testing Personnel Dosimetry Performance, ANSI N13.11, New York, (1978).

6. Rossi, H.H., "Lower Exposure Limits", Nuclear News 23 (1), 36(80).

7. Rossi, H.H., "A Proposal for Revision of the Quality Factor", Radia. Environ. Biophys. 14(4),275(1977b).

8. Rossi, H.H., and C.W. Mays, "Leukemia Risk from Neutrons", Health Phys. 34,353-360, (1978).

9. Plato, P., and G. Hudson, "Performance Testing of Personnel Dosimetry Services, NUREG/CR-1064, U.S. NRC, Washington, D.C., (1979).

10. Gilly, L.W., H.W. Dickson and D.J. Christian, "1976 Intercomparison of Personnel Dosimeters, ORNL/TM-5672, Oak Ridge National Laboratory, Oak Ridge, Tennessee, (1976).

11. Gilly,L.W., and H.W. Dickson,"Third Personnel Dosimetry Intercomparison Study, ORNL/TM-6114, Oak Ridge National Laboratory, Oak Ridge. Tennessee, (1979).

12. Schraube, H., and H.G. Paretzke, "Neutron Fluence Measurements with Track Detectors;;;Preliminary Results of INFIT." In Internation. Conference on Solid State Nuclear Track Detectors, Neuherberg/Munchen, CONF-76094-18, National Technical Information Service, Springfield, Virginia (1976).

13. Caswell, R.S., L.J. Goodman and R.D. Colvett, "Intern. Intercomparison of Neutron Dosimetry", In Radiation Res., Biomedical, Chemical and Physical Perspectives, ed. D.F. Nygaard, Academic Press, New York, (1975).

14. Goodman, L.J., "Nonparametric Analysis of International Neutron Dosimetry Intercomparison", In Neutron Dosimetry Workshop, Rijswijk, Netherlands. CONF-760533-2, National Technical Information Service, Springfield, Virginia, (1976).

15. Chabot, G.E., M.A. Jimenez and K.W. Skrable, "Personnel Dosimetry in USA", Health Phys. 34,311, (1978).

16. National Council on Radiation Protection and Measurements "Instrumentation and Monitoring Methods for Radiation Protection" NCRP Report No. 57, Washington, D.C. (1978).

17. W.S.Snyder and C.Neufeld "on the passage of Heavy Particle through tissue" Rad.Res. 6(67((1967). Reprinted in NBS Hand book 63,

18. Auxier G.A., snyder W.S. and Jones T.D., "Neutron interactions and penetrations in Tissue" Attix Rad. dosimetry Vol.I chapt.(6)

19. Protection Against Neutron Radiation "NCRP Rept. No.38 1971..

Table (1)

Comparison of NTA-Film and TLD-Al be do with Ideal Dosimeter (10,13,14)

Factor	NTA-Film	TLD-Albedo	Ideal Dosimeter
Sensitivity	poor sensitivity except for for high E(50mrem)	lower detection limit of 1-50 mrem for fast neutron	down to 10 mrem
Interferenc from Gamma	serious interference photon darken film	photon response must be subtracted out	no interference from ph-otons or particles
Stability	serious fading requires careful handling	can be stabilized with proper annealing	no fading problem with time
Environmen-tal Factors	track fading at high hum-idity and temperature needs special packaging	unaffected by temperature humidity,shock and affec-ted by dirt,oil contamin-ants	unaffected by temperature humidity, mechanical shock
Energy Response	respons to neutrons of E 0.7 MeV with a factor of 3 from 0.7 to 14 MeV	varies by a factor of 600 from 1 ev to 10 MeV	similar to that of soft tissue or must indicate E for proper interpretation
Angular Response	some angular dependence	some angular dependence	no angular dependence
Cost	film not expensive, but optical readout tedious	moderate initial expense	moderate cost
Application	high E neutrons	any location where calib-ration factor has been established except for high energy fields	all neutron energies

Table (2)

Characteristics of Track Ech Dosimeters[12]

Factor	Np-237	Th-235	Recoil Track Ech Dosim.
Sensitivity	10-100 mrem depending on E and foil size	100 mrem depending on foil size	20-60 mrem depending on plastic type and neutron energy
Interference from Gamma	free of γ-interf. below photo-fission threshold	free of γ-interf.blow photo-fission threshold	free of γ-interference
Stability	good track stability	good track stability	good track stability
Environ-mental Factors	unaffected by moderate T ($<100^{\circ}$C)or mechanical shock	unaffected by T,humidity and mechanical shock	unaffected by normal ambient T,humidity and mechanical shock
Energy Response	matches dose-equivalent curve within factor of 2 for most energies	responds to neutrons with energies above 1 MeV	polycarbonate-threshold of 1.5 MeV and CR-39-threshold of 200 keV
Angular Response	serious angular response	some angular response	some angular response
Cost	high initial cost of Np-foils	moderate expense	inexpensive
Applica-tion	most neutron energies except thermal	high-energy neutrons	fast neutrons

Table (3)

Characteritics of Combination Dosimeters and Silicon Diods (5,13)

Factor	TLD-Albedo & Track Etch	TLD-Albedo & Deep-Trap TLD	Silicon Diods
Sensitivity	1 to 20 mrem depending on E	1 mrem depending of E	500 mrem for fast neutrons
Interference From Gamma	γ-response must be subtracted out for TLDs	γ-response must be subtracted out for TLDs	insensitive to Gamma
Stability	good stability; little fading	stability of deep-trap TLD not known	can apparently be used as integrating desimeter
Environmental Factors	unaffected by ambient T, humidity & mechan.shock	probably not affected by T, humidity and mechanical shock	unaffected by environmental factors
Energy Response	wide E-range; TLDs: slow & intermed. Track etch: high energies	E-response of deep-trap TLD not known	relatively flat E-response from 200 keV to 16 MeV
Cost	moderate;including costs for two systems TLD & TE	inexpensive;to low-cost addition of deep trap TLD	moderate to high
Application	widespread use	widespread use possible	fast neutrons

Table (4)

Neutron Dosimeters that may be used in the Future[11]

Factor	Plastics	Electrets	Superheated Drop Detectors	Electronic Devices	TSEE Devices	Lyoluminescent Chemicals
Sensitivity	10 mrem for fast neutr.	unknown	can be made to any sensitivity	depends upon devic	high sensitiv	400 mrem
Interference to γ & β	unaffected by γ & β	sensitive to gamma	not sensitive to Gamma	can separate γ & n events	highly sensitive to Gamma	sensitive to Gamma
Stability	unknown	unknown	unknown	unknown	unknown	unknown over long time
Environmental Factors	unknown	unknown	sensitive to T & pressure changes	should have littl effect	should have little effect	little effect
Energy	unknown	unknown	unknown	matches that of tissue with F-2. for 0.5 eV to 14 MeV	unknown	unknown, but should match that of tissue
Cost	inexpensive	moderate	inexpensive	very expens.	inexpens. to moderate	expensive because ultra-pure chemicals required
Application	fast neutrons	fast neutron	fast neutrons	alarming dosimeters	fast neutrons	[illegible] neutrons