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PERSONNEL NEUTRON DOSIMETRY

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by Dale Hankins

The following is an edited transcript of the presentation delivered by Mr. Hankins

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By Dale Hankins

1. INTRODUCTION

I appreciate the opportunity to be here and speak to you this morning. I am going to talk about personnel neutron dosimetry. I believe I talked to this group, or an equivalent group, on neutron dosimetry several years ago. Today we will zero in on just personnel neutron dosimetry.

I practiced this talk at Livermore before a group of people, and they (those who were honest enough to give me an appraisal of the talk) told me that it was too technical. So what I have done is to retain the technical material but supplement it with some of the basic principles of personnel neutron dosimetry. I think you will understand it; there is something in it for everybody. If you don't already understand albedo neutron dosimetry, I hope that you will by the time we are finished.

2. ACCURACY OF PRESENT PERSONNEL NEUTRON DOSIMETRY

What is "state-of-the-art" at the present time for personnel neutron dosimetry? I am using the results from the Seventh Personnel Dosimetry Inter-Comparison Study at Oak Ridge. Each year at Oak Ridge they perform a study in which they have organizations mail in their personnel neutron dosimeters. Oak Ridge exposes the dosimeters to the health physics research reactor and then returns them to the participants for evaluation. Each participant reads his dosimeters and sends the results to Oak Ridge. The results may or may not be an accurate indication of the state-of-the-art. We and other participants knew these dosimeters were being used in a test, and we gave them a little extra care. On the other hand, there are some people in this study who are doing experimental dosimetry, and their results are way out in left field. Finally, some of the participants just mailed in a commercial system, had it irradiated at Oak Ridge, and then sent it to the commercial processor for evaluation. Figure 1 summarizes the results of these tests. Each circled item means that the participant did not manage to meet the passing criteria for that exposure category. The lines indicate categories in which they did not participate.

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Table 18. Neutron dosimetry performance of Seventh PDIS participants relative to NRC criteria[a]

	Organization	Neutron dosimeter type	1-None[c]	2-None	3-Lucite	4-Lucite	5-Lucite/Concrete	6-Concrete
			Performance of dosimeter relative to accuracy criteria[b]					
TLD	AIRP	TLD	Y	—	N	—	N	N
	IFEN	TLD	Y	Y	N	N	N	N
	KK	TLD, sphere	Y	Y	Y	Y	N	Y
	CrPD	TLD	N	Y	Y	Y[e]	Y	N
	TAFC	TLD	N	N	N	N	N	N
	TVA	TLD	Y	Y	Y	Y	Y	Y
ALBEDO	APS	TLD-albedo	Y	Y	N	N	N	Y
	BNL	TLD-albedo	Y	Y	Y	N	N	Y[e]
	EML	TLD-albedo	Y	—	Y	Y	N	Y
	KK	TLD-albedo	Y	Y	Y	Y	N	Y
	NNMC	TLD-albedo	Y	Y	N	N	N	Y
	RFP	TLD-albedo	Y	Y	Y	Y	Y	Y
	RPB	TLD-albedo	Y	Y	Y	Y	Y	Y
	SRL	TLD-albedo	Y	d	Y	—	—	—
	TPC	TLD-albedo	Y	Y	N	N	N	Y
	WPPS	TLD-albedo	N	N	Y	Y	Y	N
FILM	CEER	Film	N	N	N	—	—	N
	OSU	Film	N	N	Y	N	N	N
	PPPL	Film	N	N	N	N	N	N
TRACK	EIR	Track	Y	Y	Y	Y	Y	Y
	LLNL	Track	Y[e]	Y	N	Y[e]	Y	Y
	NRC	Track	Y[e]	N	Y	Y	Y	N
	PPPL	Track	Y	Y	Y	Y	Y	Y
	UW	Track	N	N	N	N	N	N
	YALE	Track	N	d	Y	d	N	Y
COMBINATION	EGG	Activation	Y	—	—	—	—	—
	EML	Combination	Y	Y	Y	Y	Y	Y
	LAND	TLD, track	Y	N	Y	Y	Y	N
	ORNL	Albedo, film	N	N	Y	Y	Y	Y
ACCURACY	Percent meeting accuracy criteria[f]	±50%	69	63	64	63	46	58
PRECISION	Percent meeting precision criteria[g]	±30%	90	92	89	88	100	92

±50% ~65% 46 58

±30% ~90%

[a] Personnel neutron dosimetry criteria specified in NUREG 8.14, Rev. 1 (1977): Accuracy = ±50%, Precision = ±30%.

[b] Y indicates the average of measurements was within ±50% of the reference dose equivalent for the run.
N indicates the average of measurements was outside ±50% of the reference dose equivalent.

[c] Run number - shield.

[d] Did not report any measurements for this run.

[e] Standard deviation of the individual measurements about the mean was not within ±30% for this run.

[f] Based on an average of neutron dose equivalent results reported by each agency.

[g] Based on the distribution of individual measurements about the average reported by each agency.

Figure 1

Results from ORNL Seventh Personnel Dosimetry Intercomparison

What type of criteria was used for "passing"? They were shooting for plus or minus 50 percent. That means that if the dosimeter were given 500 millirem (which is typical for this particular type of intercomparison), the dosimetry reading should be somewhere beteen 250 and 750 (mrem). This is not a very tight criterion.

Oak Ridge broke the results down into several categories, one of which is TLD. When you look at the writeup, it is not entirely clear what they meant by TLD. In some cases there may have been a bare TLD and in other cases there may have been albedo dosimeters. In this study, the albedo, film, track etch and combination categories were not clearly defined.

The interesting thing about the data is that some people passed in almost every category. There was one group using TLDs who managed to pass every one of the tests. In the albedo category, there were two groups who managed to pass all the criteria. Nobody in the film category passed any test except for one, and I think that was due to luck. There were two groups who passed using the track-etch system. One of the interesting points is that one participant who passed used a commercial supplier. The next participant in line, who failed every test, had the same commercial supplier. It is not clear what happened. In track-etch there were also quite a few failures. The failures are caused by the material. The material we are presently using for track etch is not very good, and studies are under way now to improve it. In the combination type, one of the groups was able to pass in all categories.

What about the precision of these measurements? Three dosimeters from each participant were exposed to the bare assembly, to the assembly when shielded with lucite, and lucite plus concrete. The participants were not told about the exposure conditions. The Figure 1 data shows that about 90 percent of the participants passed the precision test, but only about one-half to two-thirds of the participants were able to convert their dosimeters response to exposure. You will notice quite a few failures for the TLD-albedo and TLDs. You would expect this if you did not know the exposure conditions.

Where did the participants fail and why? Figure 2 shows a plot of the response as a function of the different shields. Each shield type has a different neutron energy (see Figure 2). The lower the median energy, the greater the proportion of thermal neutrons present. You will hear me talk a lot about thermal neutrons today. Even though they normally contribute very little to the dose, they present a considerable problem when using an albedo or bare TLD as a neutron dosimeter.

The data in Figure 2 shows a problem with the response of bare TLDs. I suspect the reason is that the processors probably did not apply an energy correction factor. They probably used a single factor and applied it for all of the exposures. You just can not do that; you have to make a proper correction for each energy. Since one individual did pass this category, the curve shown should probably have a greater slope since this is an average of all the dosimeters. The same problem, energy correction, also exists for albedo dosimeters. Some people using albedo dosimeters apparently did not apply an energy correction factor, and this shows up in the results.

3. <u>NEUTRON DOSIMETRY REQUIREMENTS</u>

What criteria are you required to meet? Neutron dosimeters are not required if the neutron dose is not going to be greater than about 300 millirems per quarter. I think you will be in trouble, however, if you try to abide by that. If you are going to give someone close to 200 millirems of neutrons, I think that you had better put a neutron dosimeter on that person. You aren't required to have a neutron dosimeter if the neutron dose is not going to be more than 10 percent of the total dose; that is, if it is mostly beta or gamma with just a little bit of neutrons. If you don't use neutron dosimeters, you need to have this condition well documented. You may want to play this by ear; a union may not like the idea of having members exposed to neutrons without being monitored. If you have a neutron dosimeter that lacks sensitivity, and many of them do, then in place of a measurement you may substitute calculations. These calculations can use either neutron to gamma ratios or the neutron dose rate and the occupancy time.

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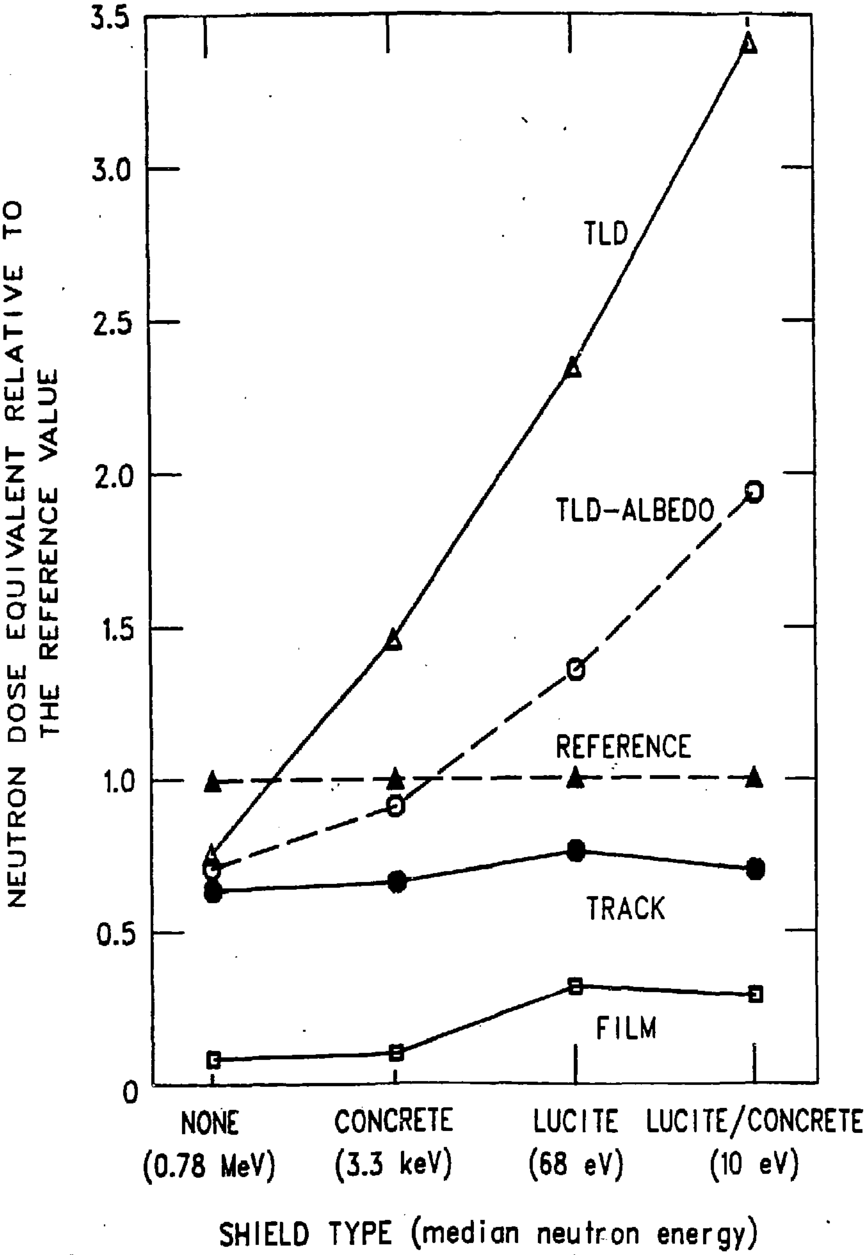

Neutron dose equivalents for various HPRR spectra by dosimeter type normalized to reference values for the Seventh PDIS.

Figure 2

Results from the ORNL Seventh Personnel Dosimetry Intercomparison

4. REM METERS AND FIELD CALIBRATIONS

You have to perform a field calibration if you are using either albedo neutron dosimeters or the bare TLDs. There are two methods for doing this; in one you use a ratio of readings from 9-inch and 3-inch detectors and in the other you expose the dosimeters on a phantom. It is not sacred that you have to have 9- and 3-inch detectors; the English, for example, use two different types of neutron instruments and do the same type of thing. Exposing dosimeters on phantoms is probably the best technique, but I am not going to dwell on that today because it is not a very practical technique except for experimental work.

You are allowed to use a rem meter as the basis for your dosimeter calibration. Either the 9-inch sphere or the Anderson-Braun type rem meter can be used as a reference instrument. Remember that one of the problems with rem meters is that they tend to over respond. I am going to spend some time in this talk concerning the problems with these meters. I am doing this because you are requiring the albedo neutron dosimeter or the bare TLD to have the same response as a rem meter. So what happens if your rem meter isn't right? Your personnel neutron dosimetry won't be right. You may or you may not want to correct for the over response. I will address that later.

About four commercial neutron instruments are available in the United States. These are shown in Figure 3. One is a 10-inch sphere, which is a Los Alamos design and is sold (I believe) by Texas Nuclear. The 9-inch sphere is sold by Eberline as the PNR4. The Studsvik instrument is made in Sweden and is now distributed in the United States by Combustion Engineering. There is one version of the Anderson-Braun instrument commercially available, but I don't know which company makes it.

These instruments are all basically the same. The 10-inch sphere is just a solid hunk of polyethylene. The Anderson-Braun instrument has a boron-loaded polyethylene sleeve inside the polyethylene surrounding a BF_3 tube. Figure 4 shows an Anderson-Braun meter before and after some modifying work we did at Livermore. The original design had a very poor

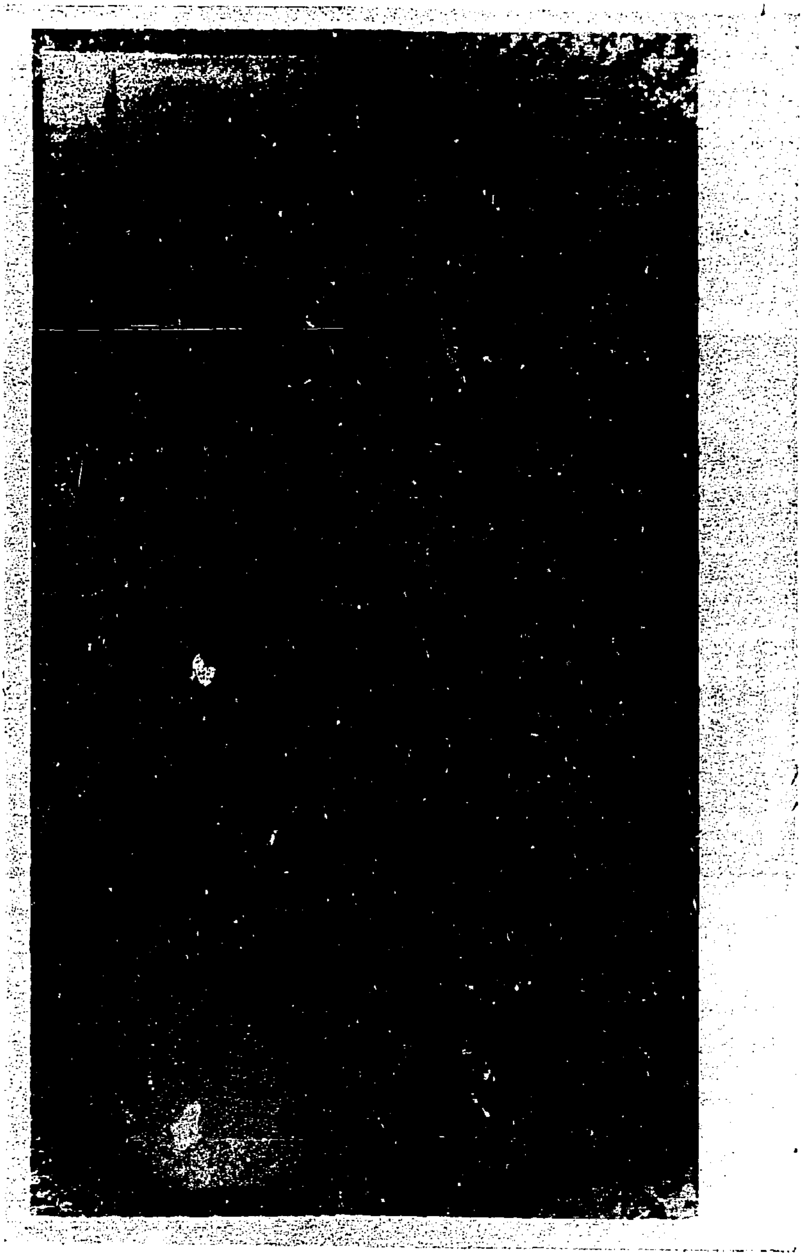

Figure 3

Four Neutron Rem Meter Instruments Used in Every Dependence Study

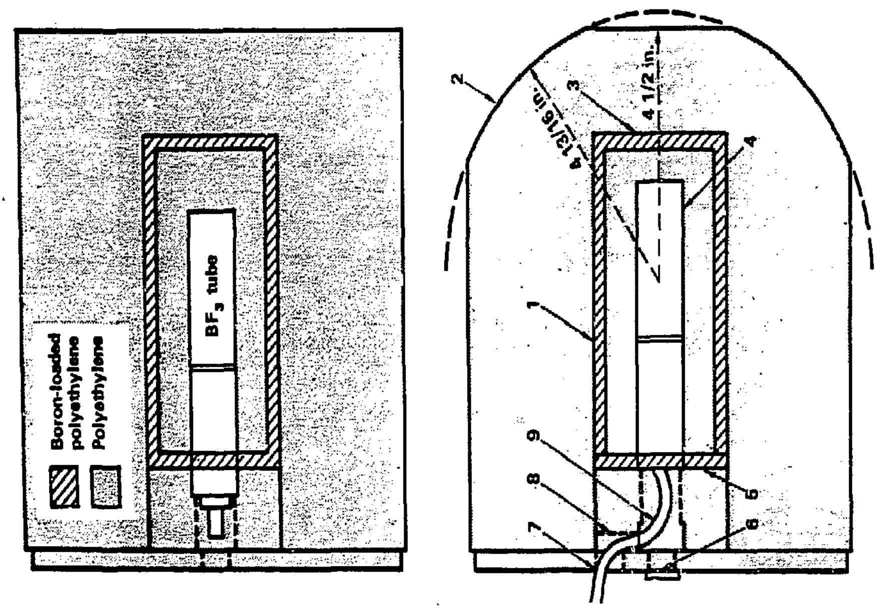

Figure 4

Anderson-Braun Rem Meter Instrument Before and After Modification energy dependence and directional response. To improve it, we rounded the corners to make it look like the Studsvik. The 9-inch sphere is really a sphere within a sphere (Figure 5). If you take one of them apart, you will find a small sphere about 2-1/2 inches in diameter, which is covered by 1.1 mil cadmium foil. The PNR4 instrument, which is the one we use at Livermore, is usually used with a scaler when determining the 9- and 3-inch ratio.

What is the 3-inch sphere? (See Figure 6.) It is simply a 3-inch diameter polyethylene sphere covered with ten mils of cadmium. It also has a 10-mil cadmium sleeve over the exposed end of the BF_3 tube. When shipped from Eberline it is in a styrofoam block, which is an integral part of the 3-inch sphere. Many people have thrown it away thinking it was just packing equipment. It is not! During use, you put the 3-inch sphere in the styrofoam holder so the 3-inch sphere and the 9-inch sphere will be the same distance above the floor. If you buy a 3-inch sphere, don't throw the holder away. Keep it!

You can use the PNR-4 instrument with the bare probe. This is how you get your incident thermal neutron measurements. When the probe is removed from the 9-inch sphere, it responds almost exclusively to thermal neutrons and has a sensitivity of 80 times the sensitivity of the instrument with the probe in the sphere. Consequently, when you make measurements with the bare probe, divide the response by 80 to obtain the thermal neutron dose rate. The "percent-thermal-neutrons" is useful for personnel dosimetry. To determine the percent-thermal-neutrons calculate the thermal dose rate with the bare detector and divide it by the dose rate that you get when the probe is in the 9-inch sphere. Convert this fraction to percent. Also shown in figure 6 is a cadmium sleeve that you can use on these probes. We found that for practical purposes the additional piece of information obtained with the cadmium sleeve was not worth the effort. Any measurements we refer to as "percent-thermal" are taken without a cadmium sleeve. Putting a cadmium sleeve on the probe helps only when you are exposed close to a source and then the probe responds primarily to fast neutrons.

Figure 5

Details of the 9"-Sphere Rem Meter

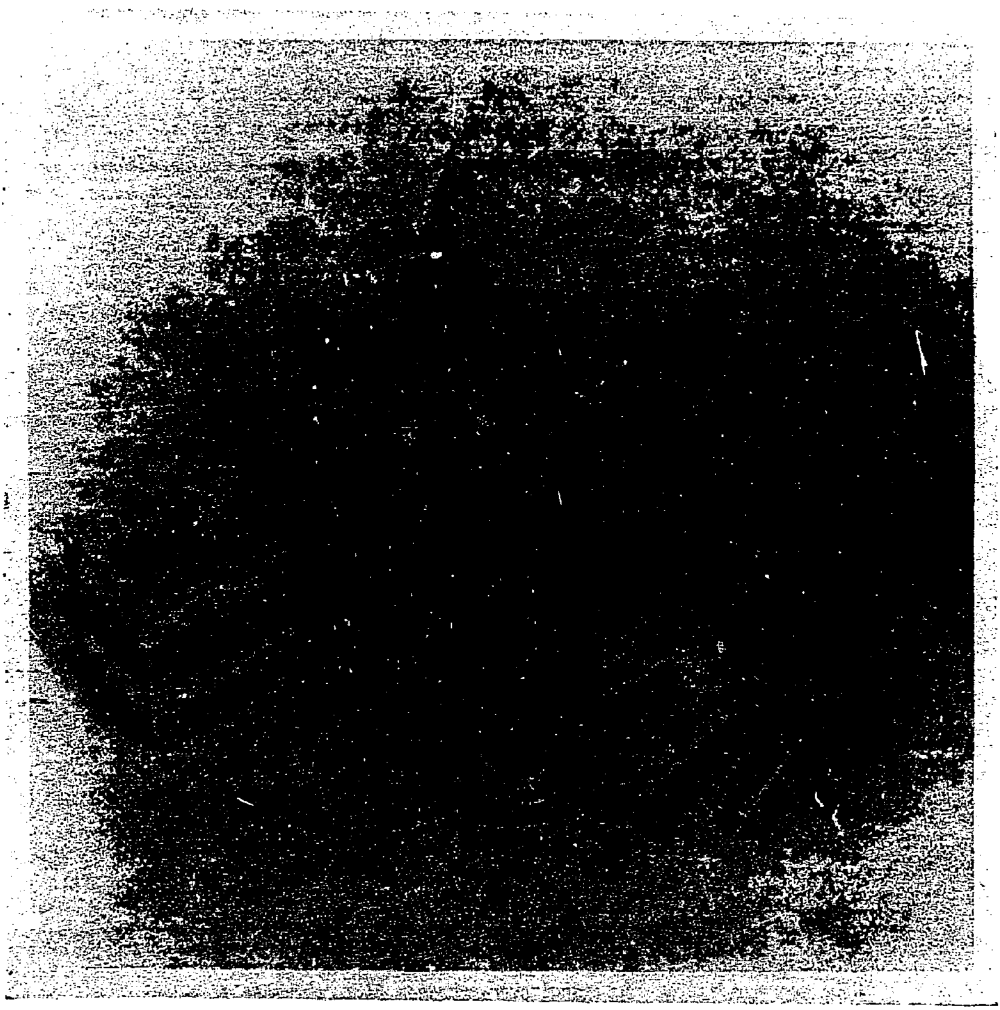

Figure 6

PNR-4 Rem Meter with 3-inch and 9-inch Detectors

What is the energy dependence of rem meters? In Figure 7 you can see four sets of data generated for the four survey meters shown in Figure 3. Figure 8 shows the dose curve (inverse of RPG curve) you are trying to follow. The instruments are designed to have a response that approximates the dose or rem curve and, consequently, you have a rem meter."

The latest data available on the response of rem meters is shown in Figure 9. These data were recently published and show that the energy dependence is basically the same for all rem meters. As Figure 9 snows, all rem meters overrespond in the low energy region and underrespond in the fast region.

TABLE 1

Multisphere and Rem Data from Farley Nuclear Station

Location	Dose rate (mrem/hr)		Radio of 9-in. to Multisphere
	9-in. spehere	Multisphere	
1	0.34	0.185	1.8
6	170	107	1.6
9	37	18.5	2.0
16	420	229	1.8
			Average 1.82

How important is the low energy over-response of a rem meter at a reactor? Table 1 shows the results we obtained at the Farley Nuclear Plant. We found that the 9-inch sphere over-responded when compared with multi-sphere by 1.6 to 2 with an average of 1.8. The multi-sphere technique probably provides the most accurate neutron dose rates of any presently available method. There is another report out from Battelle

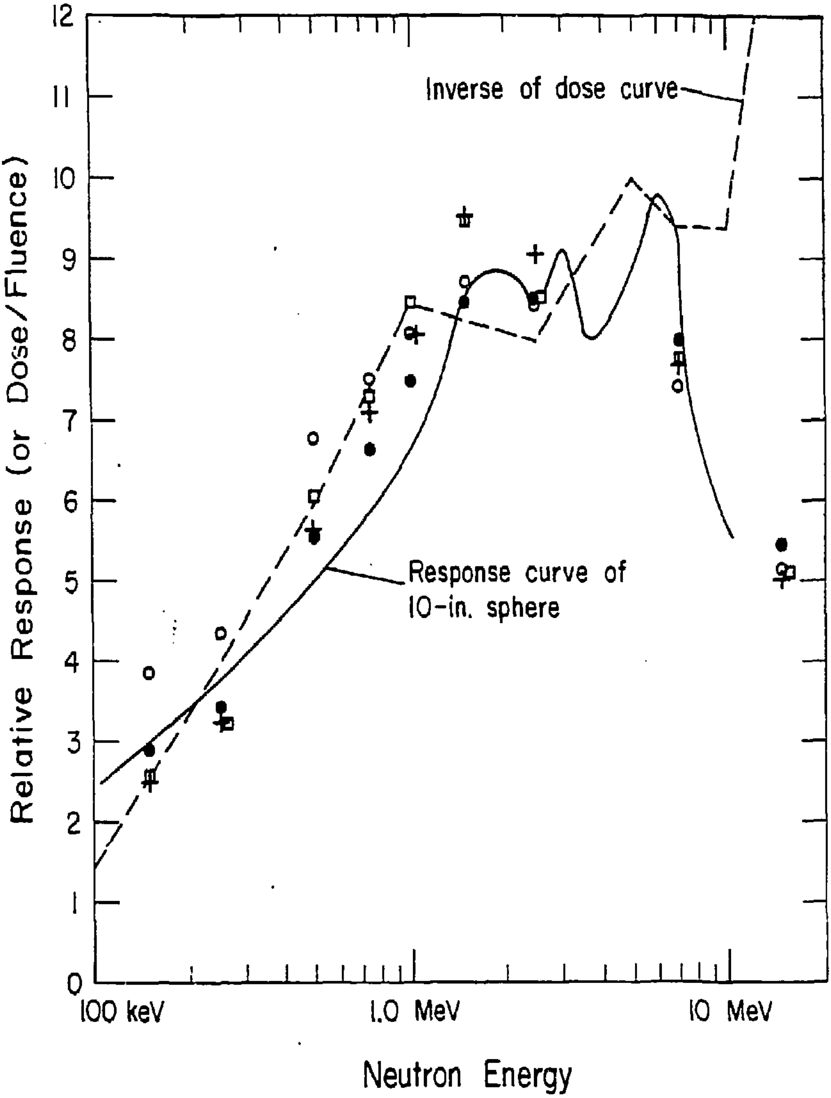

Figure 7

Energy Dependence of Four Rem Meters Between 100 keV and 20 MeV

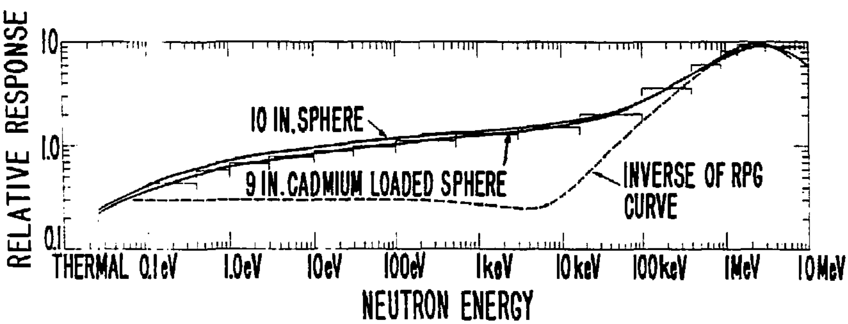

Figure 8

Energy Dependence of 9- and 10-inch Spheres from Thermal to 10 MeV

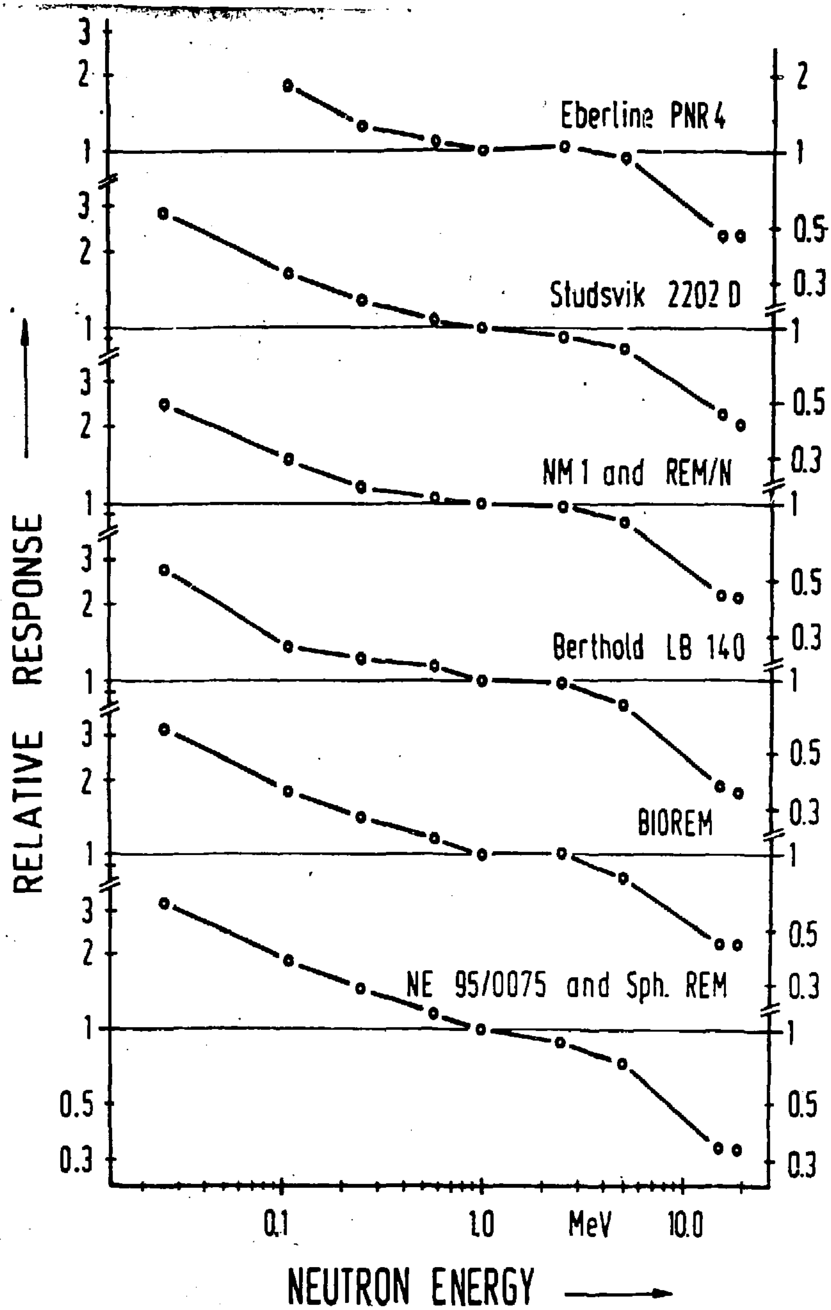

Figure 9
Energy Dependence of Rem Meters from Recent Work in Germany
The Valves are Normalized to 1 and 1 MeV. The responses of the instruments are shown relative to the valves they are supposed to read according to ICRP 21.

called "Neutron Dosimeter at Commercial Power Reactors." It shows rem meter overresponses varying from 1.5 to 2. Consequently, you can generally estimate that your rem meter is going to overrespond by about 80 percent. This also means that your albedo neutron dosimeter is going to overrespond by about 80 percent. I recommend that you correct for that error, but to do that you have to justify the correction. That means someone is going to have to do some multi-sphere measurements in your plant at the same location where you use your survey instruments. It doesn't seem logical to me to report doses that are too high when you know they are wrong.

5. PERSONNEL NEUTRON DOSIMETER TYPES

The five basic types of personnel neutron dosimeters are Albedo-TLD, NTA films, track etch of polycarbonate or CR-39, TLD 100 or 600, and fission fragment track etch. I am going to spend most of my time today talking about albedo neutron dosimeters because I believe they are the type of dosimeter that you at power reactors are going to be using for the foreseeable future. They have high sensitivity and some other good features which I will discuss. I am going to talk very little about NTA film because it just does not work at reactors. I am going to discuss electrochemically etched polycarbonate plastic film including CR39, which is the newest development. I will discuss the thermal neutron response of TLD 100 and 600 and then spend a little time on fission fragment track etch.

NTA film problems include an energy threshold of somewhere between 0.7 and 1 MeV. If you're honest, you'll say the minimum energy is around 1 MeV because most film readers, after looking at these films for a while, just do not see the small tracks. Later I will show you a neutron spectrum taken at a reactor and explain why NTA film is particularly poor at a power reactor. Fading is a severe problem and is accentuated by high humidity. Film must be read with a microscope, which is time consuming and not very accurate.

There can be a masking problem if the gamma background is high. So, what I am saying is, don't consider NTA film at a power reactor. Also, the NRC no longer accepts NTA film.

Our badge at Livermore is shown in Figure 10. Everybody is issued the disc that contains three TLDs. One is a TLD-700, which is used for beta; another, TLD-700 for gamma; and then we have either a TLD-100 or 600. We are in the process of changing from TLD-100, which is natural lithium, to the TLD-600 which is more sensitive to neutrons. If an individual is going to be working in an area where there could be a criticality accident, we issue a nuclear accident dosimeter (NAD) that contains the usual things like gold and sulphur. If a person is going to be exposed to neutrons, we give him an albedo neutron dosimeter. We are using the Hankins-type albedo neutron dosimeter. I originally designed that albedo as an interim dosimeter, but nothing better has come along, in my opinion.

We put the albedo neutron dosimeter in a little attachment that hooked onto the NAD badge. Recently we have added in the albedo three pieces of polycarbonate and two pieces of CR39, so we now have three types o neutron dosimetry in one package.

You can use a bare TLD to determine neutron exposure if you know the percentage of the neutron dose delivered by thermal neutrons. You then find your calibration factor from a curve such as Figure 11, which is for TLD-100 material. For example, if the percentage happens to be 3 percent thermals, you then come across on the curve and the calibration factor is roughly one. So in this case you have approximately a one-to-one relationship. If the TLD reading is 1mR, then the individual was exposed to 1 millirem. As you can see from the scatter in data, this is not a very accurate technique, but it is one that can be used. One of the nice features is that for many jobs this percent thermal doesn't change very much. You will find that it is similar in many areas, and consequently you can do a reasonably good job determining the man's neutron exposure from just a bare TLD.

When would you want to use a bare TLD? Eberline provides a commercial service where they take a single lithium flouride TLD and they use a two-stage readout. If you happen to have the Eberline service, what you need to do is take the neutron reading they give you, go to Figure 11 and correct the Eberline dosimeter reading to dose. Alternatively, you can

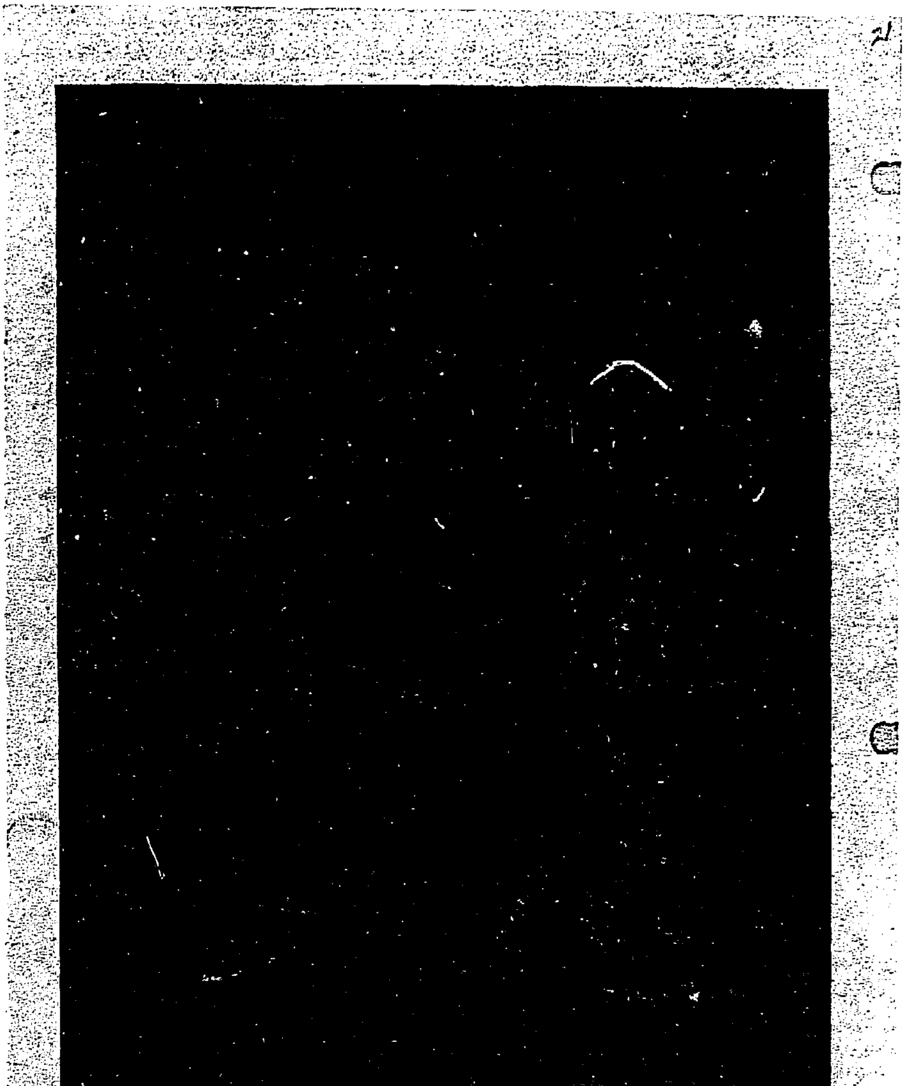

Figure 10

Photo of the LLN Dosimeter Badge Including NAD and Albedo Dosimeter

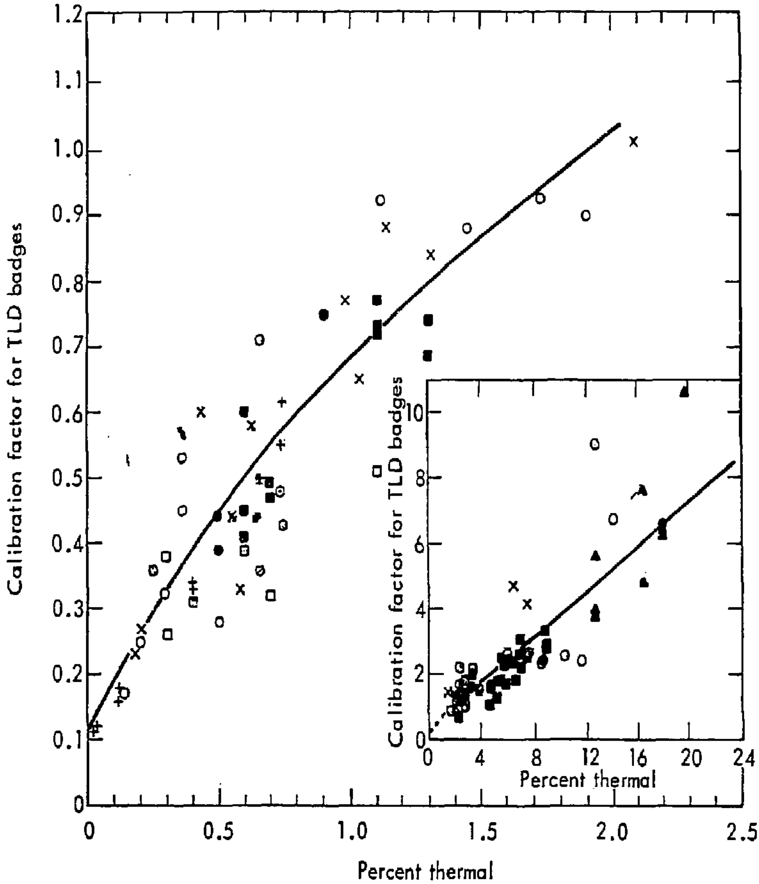

Figure 11

Curves Used to Evaluate the Neutron Response of a Bare Li-100 TLD Dosimeter place dosimeters in your plant on a gallon jug of water or something of that nature. Table 2 shows data from the reactor at the Farley plant. The reason I have it here is to show that the thermal neutron component remains fairly constant. At that reactor we found a range of 2.4 to 5.2 percent thermal neutrons. Most of these numbers are in the 3-4 percent range. So what we are saying is that inside that reactor the percent thermal doesn't change very much. Consequently, at that particular reactor, they could use a bare TLD for their neutron dosimetry and do a good job. However, they could do a better job with the 9-3 ratio and the albedo neutron dosimeter. We recommended that they use the albedo dosimeters rather than the bare TLD. We found that the gamma-to-neutron ratio was not a very good technique to use at Farley (see Table 2).

5.1 Albedo and Bare TLD Neutron Dosimeters

What is an albedo neutron dosimeter and how does it work? Figure 12 shows what I refer to as the basic albedo neutron dosimeter. Nothing is sacred about the 15 mils of cadmium--it can be 30, 40, any thickness you want--the point is that you use a piece of material to absorb thermal neutrons. It does not have to be cadmium; it can be boron. The dosimeter is worn against the body. When fast neutrons enter the body, they are thermalized, and part of them come back out of the body. Those neutrons that come back from the body are called albedo neutrons, and the dosimeter is designed to detect these albedo neutrons. The dosimeter in Figure 12 has two pairs of TLDs--one Lithium-6 TLD and one Lithium-7 TLD--on each side of the cadmium sheet. Lithium-6 TLD contains the isotope Lithium-6, which is sensitive to neutrons. The Lithium-7 TLD has the Lithium-6 isotope removed and, consequently, it is not sensitive to neutrons. What you have is one TLD that is neutron and gamma sensitive and one that is sensitive only to gamma. You simply subtract the gamma response from the gamma plus neutron response to find the neutron component.

Now why do you need the cadmium? Well, thermal neutrons are a problem with albedo neutron dosimeters because they will leak behind (or penetrate through) the cadmium and are detected. The Lithium-6 TLD on the top of the dosimeter (away from the body) is roughly 100 times

Location	Other dosimetry	Ratio 9/3-in. spheres	Neutron dose rate, 9-in. sphere (mrem/hr)	% thermal neutrons in dose	Gamma dose rate (mR/hr)	Ratio n/γ
1	Multisphere	0.13	0.34	5.2		
2		0.12	0.92	4.0		
3		0.14	21	2.4		
4		0.14	110	2.5	15	7.3
5		0.13	310	2.9	17	18.2
6	Multisphere	0.12	170	3.6	25	6.8
7	ORNL[a]	0.14	1160	3.3	180	6.5
8		0.12	190	3.7	20	9.5
9	Multisphere	0.13	37	4.6	10	3.7
10		0.13	48	4.2	9	5.3
11		0.13	40	4.1	40	1.0
12	ORNL[a]	0.13	580	3.4	80	7.3
13		0.13	140	4.4	23	6.1
14		0.13	87	3.6	15	5.8
15	ORNL[a]	0.14	960	3.2	140	6.9
16	Multisphere	0.14	420	3.2	60	7.0
17		0.14	350	3.3	50	7.0
18		0.15	520	2.8	70	7.4
19		0.17	910	2.5	100	9.1
20		0.14	620	3.4	90	6.9
21	ORNL[a]	0.15	630	3.7	80	7.9
22		0.14	250	3.8	46	5.4
23		0.15	170	3.1	28	6.1
24		0.14	1020	3.3	150	6.8
25			260	3.4	32	8.1
26		0.15	180	3.1	26	6.9
27		0.14	190	3.2	29	6.9

[a]ORNL made measurements at these locations using fission foils and activations of gold and sulfur.

Table 2. Survey Results Obtained with PNR-4 Neutron Instrument and the Plant Gamma Instrument

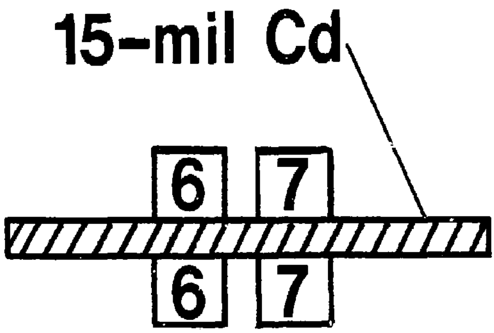

Figure 12

Basic Albedo Neutron Dosimeter

more sensitive to thermal neutrons than it is to fast neutrons. You have to prevent thermal neutrons from getting to the TLDs located below the cadmium against the body. You can do it by using a great big piece of cadmium as an absorber. One of the earlier English dosimeters had a cadmium absorber about 3" x 4". Unfortunately for smaller dosimeters, some of these thermal neutrons miss the cadmium, are reflected in the body, and come back out where they are detected by the Lithium-6 TLD next to the body. Consequently, the reading of that TLD is going to be high. You must make a correction for the thermal neutrons leaking behind the cadmium (or through it) if you are going to use albedo neutron dosimeters accurately.

What do albedo neutron dosimeters look like? Figure 13 shows a number of designs. Part B of Figure 13 shows one that they are using at Hanford. You don't have to have the TLDs on top of the cadmium. However, you really should have a Lithium-7 TLD under the cadmium. The Hanford dosimeter suffers from that problem. The Hankins-type albedo has cadmium all the way around it; consequently you don't have the thermal neutron problem. There is some thermal neutron leakage through that 30 mil cadmium, but it is balanced and it is the reason we have 30 mil thick cadmium. It was very carefully designed. The thermal neutron response is equivalent to the albedo response at about 1 MeV, so consequently you only need two TLDs. It does not have as much sensitivity as some of the other dosimeters because it has the cadmium all the way around it. Part D of Figure 13 is an English dosimeter. You will see a lot of these things in England or Europe. In order to solve the thermal neutron problem, they hide the TLDs by putting them in a thing that looks like a top hat. Part E shows a type of dosimeter we studied at Livermore. The cross section of these two materials, boron and cadmium, indicate that you should be able to do some interesting things with the albedo spectrum. It works well if you don't go out in the field. We did not use this dosimeter because it didn't work in the field.

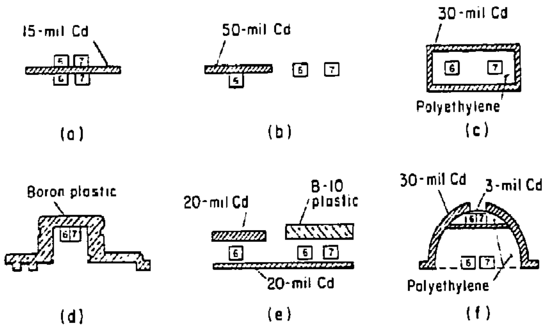

Figure 13

Several Albedo Neutron Dosimeter Designs

Part F of Figure 13 shows the Hoy dosimeter. Some of your people may be wearing this belt-mounted dosimeter; two inches in diameter, very heavy, and very high sensitivity.

The biggest problem with albedo neutron dosimeters, of course, is the energy dependence. Figure 14 shows a curve for the energy dependence of a Hankins-type albedo dosimeter. This curve also applies to all albedo neutron dosimeters. What you want is a flat curve and you don't have it. If you calibrated in the high energy region and then you used it in a reactor region where we have a lot of low energy neutrons, the dosimeter will overrespond. According to this curve (Figure 14), if you expose the dosimeter to 1 MeV neutrons and use it in a reactor, you would be overresponding almost two orders of magnitude. In fact, you never calibrate at 1 MeV. You should calibrate with a D_2O moderated Californium-252 source which has an energy spectrum closer to that of a reactor. Using this source for calibration you will get a 10-20 percent overresponse at a reactor.

If you are going to use a dosimeter with this poor energy dependence, you must have a calibration factor. How do you get that calibration factor? The technique that I recommend is one using the ratio of dose rates for the 9- and 3-inch spheres. How does that work? Figure 15 shows the ratio of 9- to 3-inch sphere as a function of calibration factor. Let's assume that the 3-inch sphere and the 9-inch sphere gave you the same count rate, so the ratio is 1. From Figure 15 you can see that the calibration factor is about 0.25. You divide the TLD reading by the calibration factor to get the dose that the individual received. The little box on Figure 15 contains some information that was obtained at the Farley plant; it looks basically the same at all power reactors.

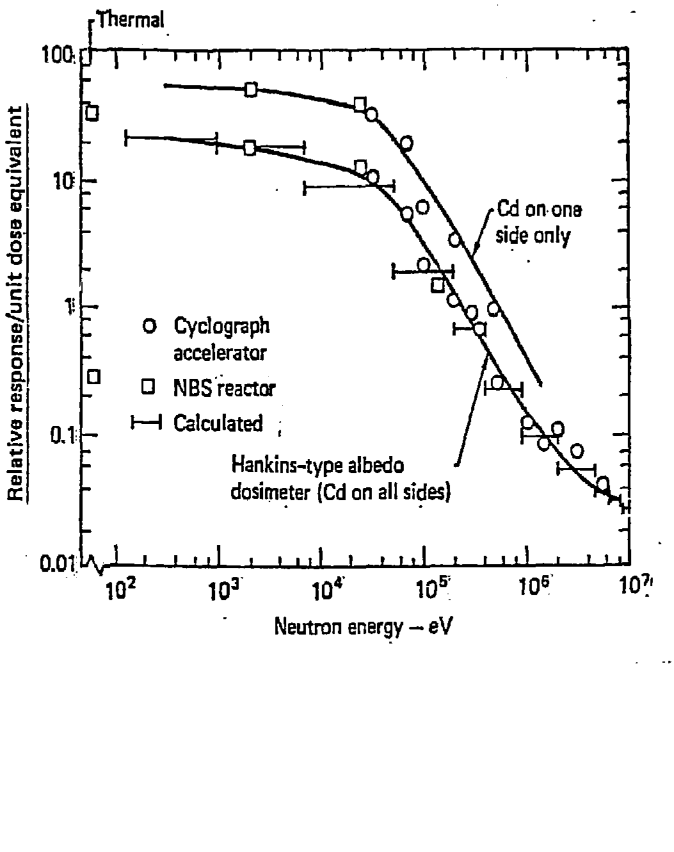

Figure 14

Energy Dependence Curve for the Hankins-type Albedo Neutron Dosimeter

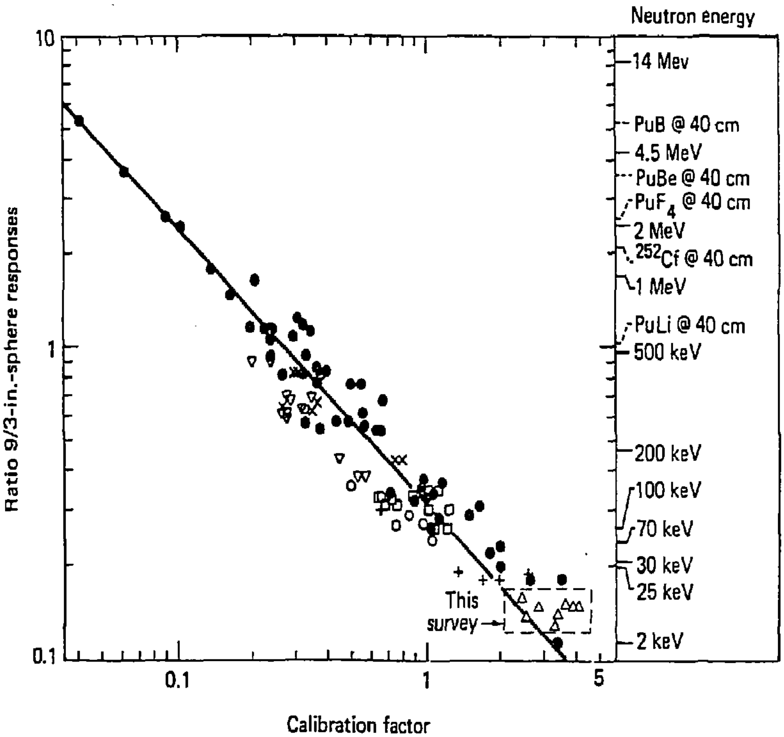

Figure 15

Curve Used to Obtain the Calibration Factor for Albedo Neutron Dosimeters

Albedo neutron dosimeters are very sensitive. For instance, the 9 to 3 ratio is about 0.1 at a reactor, and the correction factor is about 3.5. Therefore, one millirem of neutron exposure will show up as about 3.5 mR on the TLD reading. If your TLD reader has a sensitivity limit of about 10 mR, which is typical for TLD readers, then one can easily see three millirems of neutron exposure inside a reactor. This example is for a Hankins-type albedo dosimeter, which is a low sensitivity dosimeter. The sensitivity can be made even higher if you use one of the other types of albedos. Because of this, albedo neutron dosimeters will continue to be used even if better "dosimetry" does come along.

How do you use albedo dosimeters in the field? What you do is make a series of measurements with the 9- and 3-inch spheres, and determine the calibration factor. Figure 16 shows some data that we obtained at the Los Alamos Plutonium-238 facility. I have plotted the correction factor as a function of dose rate. That is not to imply that the 9 to 3 ratio has anything to do with dose rate; it does not. The reason we plot it this way is so you can weight the data according to where people are working. You notice in Figure 16 that I did not give very much credit to the points with higher calibration factors. The locations with lower calibration factors are where the people are going to get high neutron exposures. We came up with a calibration factor of 0.34, which let us detect neutron doses within plus or minus 30 percent. That's pretty good. Figure 17 shows some data that we took at the Livermore Plutonium Building. It shows data for the offices, hall, and rest of the building. You can pick up both of the latter within about 20 percent at a calibration factor of 0.58. The data at the top of Figure 17 illustrate one of the problems of albedo neutron dosimeters. Outside the vault and across the hall were offices for the administrators. They were exposed to these low energy neutrons, and the calibration factor for them was considerably different. Fortunately, these people did not frequently get back

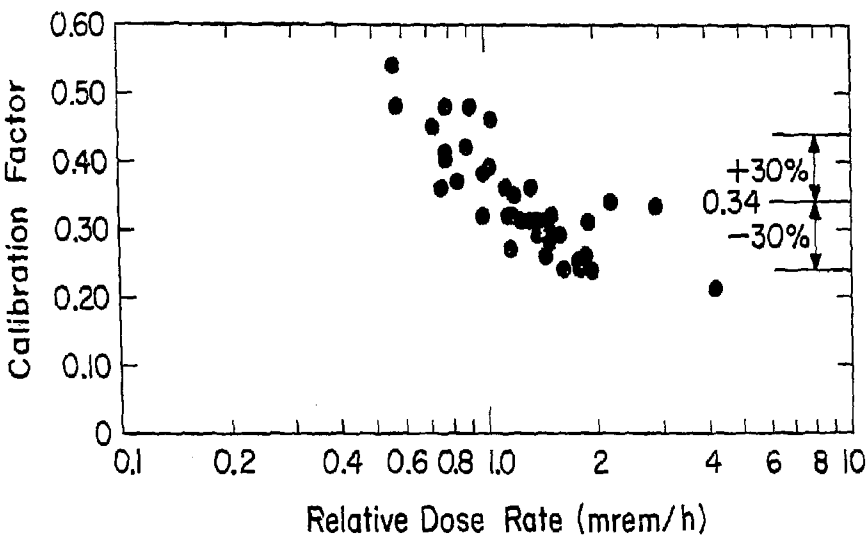

Figure 16
Plot Used to Determine the Albedo Neutron Dosimeter Calibration Factor Applicable at the Los Alamos Plutonium 238 Facility

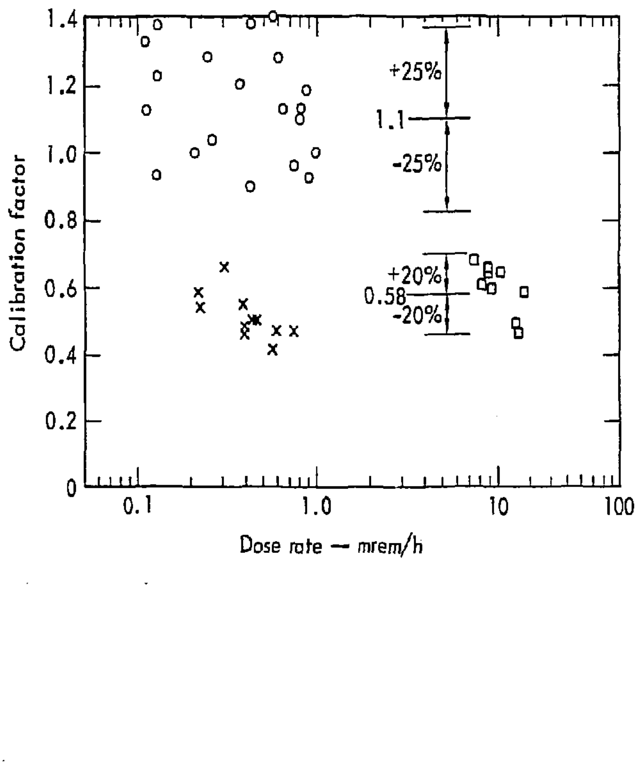

Figure 17
Plot Used to Determine the Albedo Neutron Dosimeter Calibration Factor at the Livermore Plutonium Building

into the facility. If they did, we really wouldn't know which calibration factor to apply. You wouldn't know whether the exposure occurred in the office area or within the facility. You have to know where the individual was exposed or you can make a fairly large error in his exposure.

Figure 18 was compiled from data obtained in the LLNL Plutonium Storage Vault. The calibration factor appears to be a function of dose rate; however, these data were obtained at different distances from kilogram quantities of plutonium. If you put a neutron source in a room, the dose delivered by scattered neutrons is fairly constant throughout that room, but when you move in close to the source, then you are seeing mostly fast neutrons coming directly from the source. The calibration factor for the albedo neutron dosimeter decreases as you move from an area of scattered (lower average energy neutrons) to an area of higher energy neutrons. We selected a calibration factor of 0.7 for this room.

What about a reactor? Figure 19 shows the neutron spectrum inside the containment at Farley. The important feature is that there are no fast neutrons. Previously we talked about NTA film. It has a threshold near 1 MeV. This only permits you to see the part of the neutron spectrum above 1 MeV, which is only a small part of the neutrons to which you are being exposed. The same thing is true for polycarbonate dosimeters. Albedo dosimeters are sensitive to the entire neutron energy range. A new material, CR39, is sensitive to neutrons with energies down to about 150 KeV.

At Farley we measured the 9 to 3 ratio from low dose rates (outside the containment) to dose rates of about a rem per hour. The 9 to 3 ratio remained very constant, as Figure 20 shows. By using a calibration factor of 2.65 you could get within about 13 percent. Can you actually do that well in the field? You cannot. We placed some dosimeters in the containment at different dose rates and at different locations and we came up with a calibration factor of about 3.5

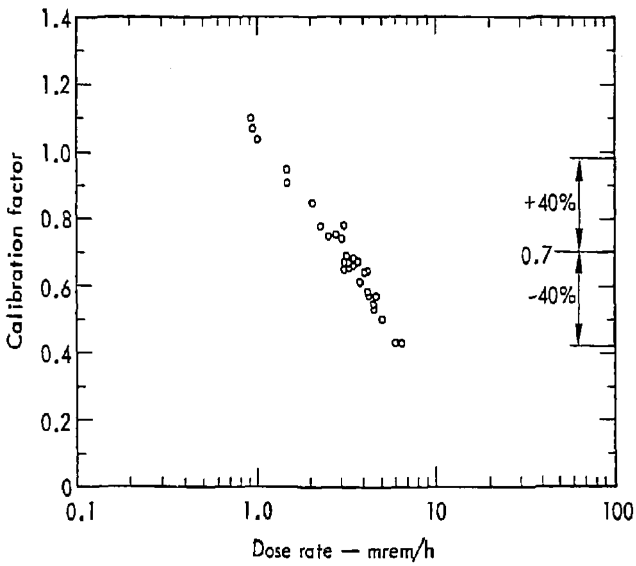

Figure 18
Plot Used to Determine the Albedo Neutron Dosimeter Calibration Factor at the Livermore Plutonium Storage Vault Neutron Calibration Factors

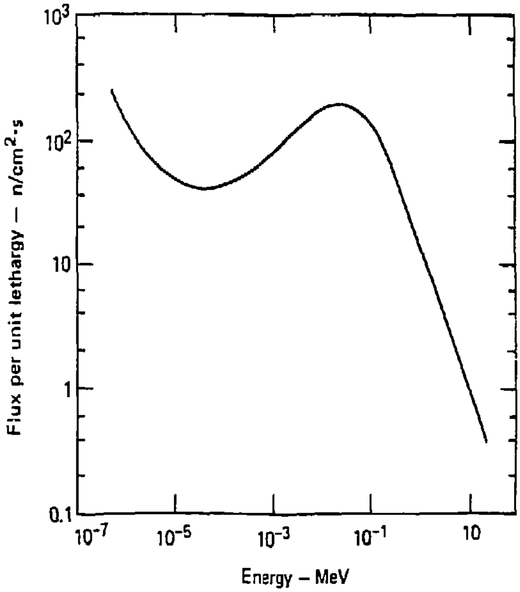

Figure 19
Neutron Spectrum Inside of the Farley Containment Building

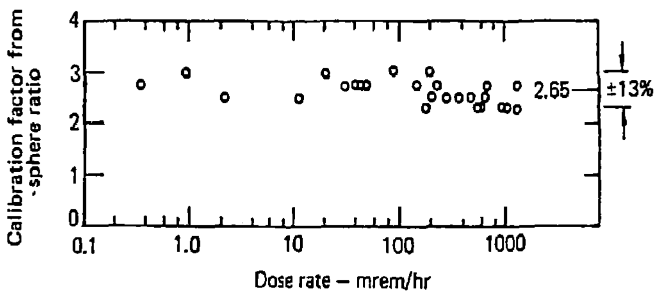

Figure 20
Calibration Factors Determined Using the 9/3-inch
Sphere Technique as a Function of Dose Rate;
Results Obtained at the Farley Nuclear Reactor

plus or minus 25 percent. Part of this spread is because of the way we had to make the measurements when we took the dosimeters inside the containment where they were being exposed before we got them in place. Time restrictions and consequently low total exposures also contributed to the scatter in the data. In spite of these problems, I feel we can measure neutron exposure inside the Farley plant within plus or minus 25 percent with an albedo neutron dosimeter.

There are some other problems with albedo neutron dosimeters which I want to discuss. One is that the cadmium around the TLD chips shields the chips from some of the gamma exposure. The gamma response shown in Figure 21 shows the response of the TLDs inside the neutron dosimeter is nearly zero below about 100 KeV. What that means is that if your people are being exposed to gamma with energies below 100 KeV, those gammas are not going to be detected by the TLD that is under the cadmium. Consequently, you have to have another TLD outside the cadmium to determine the gamma dose. That is particularly important for us in the plutonium business because we have Americium-241 with a 60 KeV gamma. You may have this problem at a reactor if significant exposure results from Xenon-133.

Another TLD problem occurs when you put the dosimeter on a person. You get back scatter from the body, or albedo if you prefer, of the gammas coming back from the body. The dosimeter can overrespond by about 80 percent, as is shown in Figure 22. That is important to us in the plutonium business because the overresponse is greatest at about 60 KeV. If an individual is exposed in our plutonium facility, the TLD reading that you get from the gamma is going to be high by about 80 percent. When exposed to Americium-241 we have observed values as large as a factor of 10 different between the reading of the bare TLD and the reading inside the albedo neutron dosimeter.

What is the effect of distance from the body on the albedo neutron dosimeter? You may have heard that albedo neutron dosimeters have to be worn tightly against the body and that they cannot be allowed to

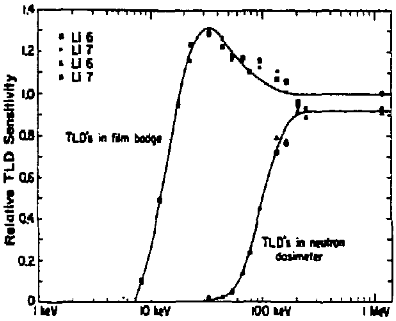

Figure 21
Response of TLDs to X and Gamma Rays in Air and Located
Inside the Hankins-type Albedo Neutron Dosimeter

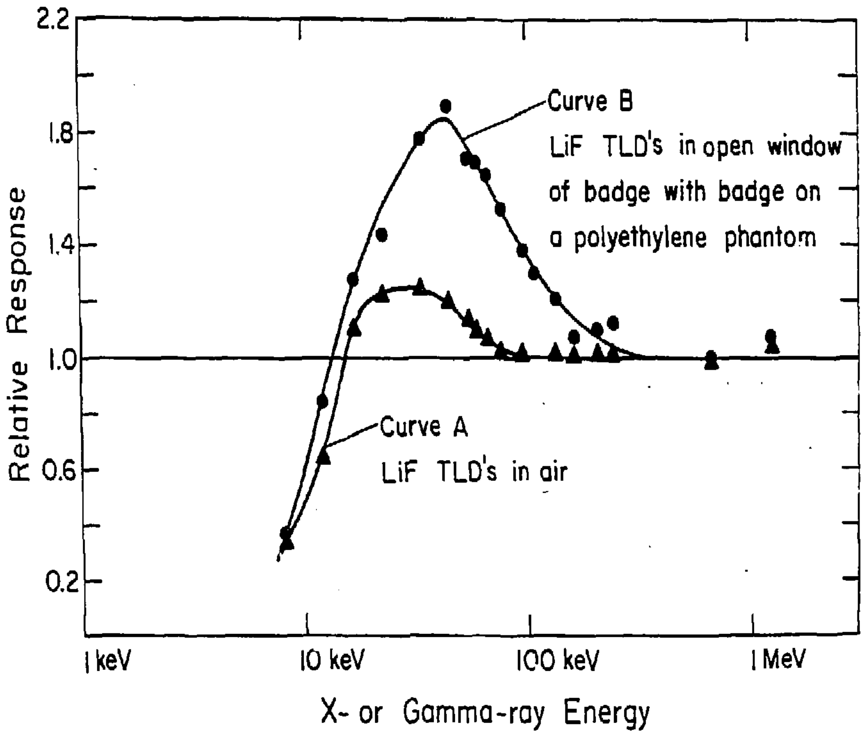

Figure 22
Response of TLDs to X and Gamma Rays When in Air or on a Phantom

swing away from the body. Why is that so? Figure 23 shows the effects of moving various albedo dosimeters 1, 2, 3, or 4 centimeters away from the body at various distances from the source. These data were obtained using a Californium-252 neutron source. If you let the dosimeter swing away from the body, the response drops. For the accuracy we are talking about in albedo neutron dosimeters, the drop is insignificant for a CF-252 neutron spectrum. But consider the thermal neutron response shown in Figure 24. If you let the dosimeter swing away from the body by as little as one centimeter, the response will jump a factor of 2. However, you have to weigh that against the percentage of thermal that is present. If there are very few thermal neutrons, then it doesn't make too much difference if the badge pulls away from the body. But at a reactor there are about 3 to 6 percent thermal neutrons. Consequently, the thermal neutrons require that you hold that albedo dosimeter next to the body. That doesn't apply for the Hankins-type dosimeter because the cadmium enclosure eliminates most thermal neutrons. The Hankins albedo dosimeter can be worn up to about 3 centimeters from the body and its response doesn't change. It can also be worn backwards and it doesn't affect its response.

What is the directional response of neutron dosimeters? It varies depending on neutron energies. Since you are reactor people, let's go back again to the Farley plant. Table 3 shows the ratio of the neutron response on the front of a phantom compared to the back of the phantom. On the back the dosimeter readings are as low as about 0.22 to 0.26 and as high as 0.63. These vary quite a bit, but the average is roughly about 0.40. Therefore, if you have your dosimeters on the front of an individual who is exposed from the back, you are going to be low on the neutron reading by about 60 percent. Now what happens to the gamma exposure? Fortunately it is reduced by about the same factor (see Table 3), about 50 percent. Generally your dosimeter results are going to be low by the same amount on the back with either neutrons or gammas. This applies only for albedo

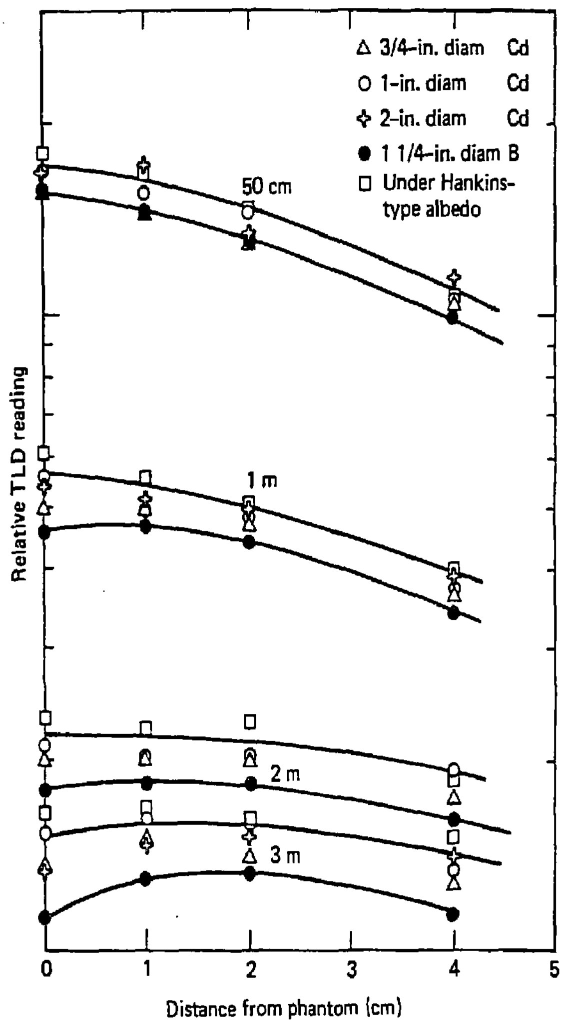

Figure 23
Response of an Albedo Neutron Dosimeter to U-252 at Various Distances from a Phantom and at Several Source-to-Phantom Distances

Location	Calibration factor[a]		Back: front[b] calib. factor ratio	
	Dosimeter on phantom front	Dosimeter on phantom back	Neutron	Gamma
7	3.92			
12	3.67			
9	2.71	1.71	0.63	0.96
6	3.54	1.73	0.49	0.49
19	2.57	1.08	0.42	0.55
15	4.33	0.94	0.22	0.37
16	3.03	1.61	0.53	0.61
24	4.26	1.10	0.26	0.40
Average	3.50	1.36	0.43	0.56
Deviation	+22%, -27%	+27%, -31%		

[a]TLD reading divided by neutron dose from 9-inch sphere rem meter.

[b]Of phantom.

Table 3: Calibration Factors and Ratio of Albedo Neutron Dosimeter Readings for Frontal and Back Exposures

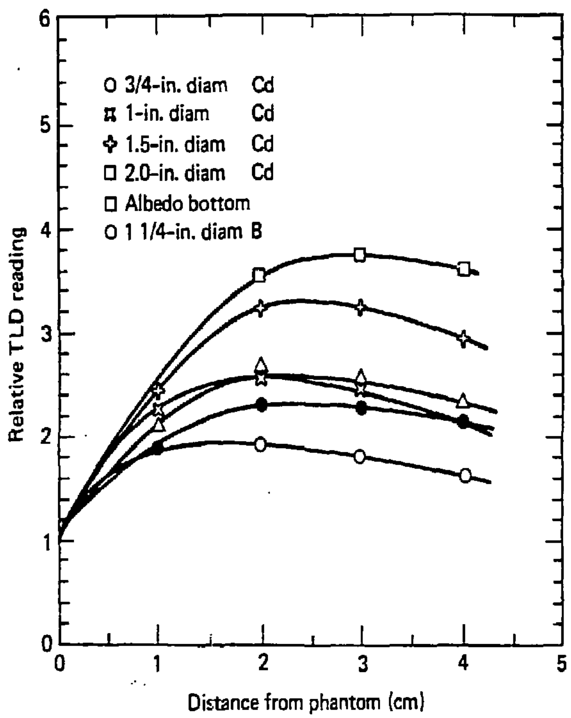

Figure 24
Response of Albedo Neutron Dosimeters to Thermal Neutrons at Various Distances from a Phantom

neutron dosimeters. If you have a neutron dosimeter that is only sensitive to fast neutrons, the neutron response essentially goes to zero because the body is a very good absorber of neutrons.

Figure 25 is a curve that I published previously. People are misusing this curve, and I use it here to illustrate a point. We were using an accelerator, and the operator told us that he was giving us a particular neutron energy. When I checked the 9 to 3 ratio, I found that he was not giving us the desired energy. After checking, it was found that they were providing the neutron energy we asked for but that the beam was contaminated with some other energy neutrons. What this illustrates is that you can use the 9 to 3 ratio to determine neutron energy for a mono energetic source, but not for a mixed energy source. The 9 to 3 reading only tells you an average neutron energy, so you can't be sure what the neutron dose is.

Piesch, in his studies in Germany, found that if you use the thermal neutron reading on top of an albedo dosimeter, you can obtain some information about the calibration factor. This works well in the calibration labs, but not in the field. Figure 26 shows data that we took while trying to find a relationship between the thermal reading on top of the albedo badge and the calibration factor. Such a relationship does not exist. There are large variations in the thermal neutron component of the dose that are caused by things as mundane as a table top or some small scattering material in the area. You will see articles in the literature by people who are making similar studies. It does work well in the calibration facility with a particular source, but it does not work in a reactor or plutonium plant.

At the present time we are looking at how the albedo neutron dosimeter readings agree with the bare TLD readings. Figures 27 and 28 show the TLD readings of bare TLD versus the TLD readings of the albedo neutron dosimeter. As you can see, the agreement is poor. These data are from two individuals doing the same type of job over the last 4-5 years. Even for a single individual doing the same job all the time, we do not get good agreement between the albedo neutron dosimeter and the bare TLD.

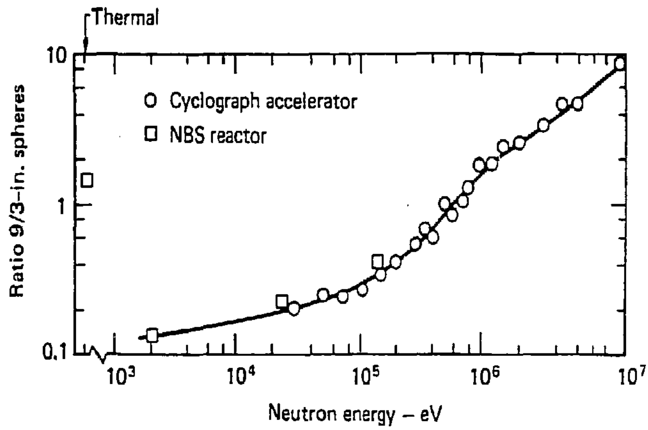

Figure 25
Neutron Energy Versus 9 to 3 Ratio
for the 9-inch Sphere Rem Meter

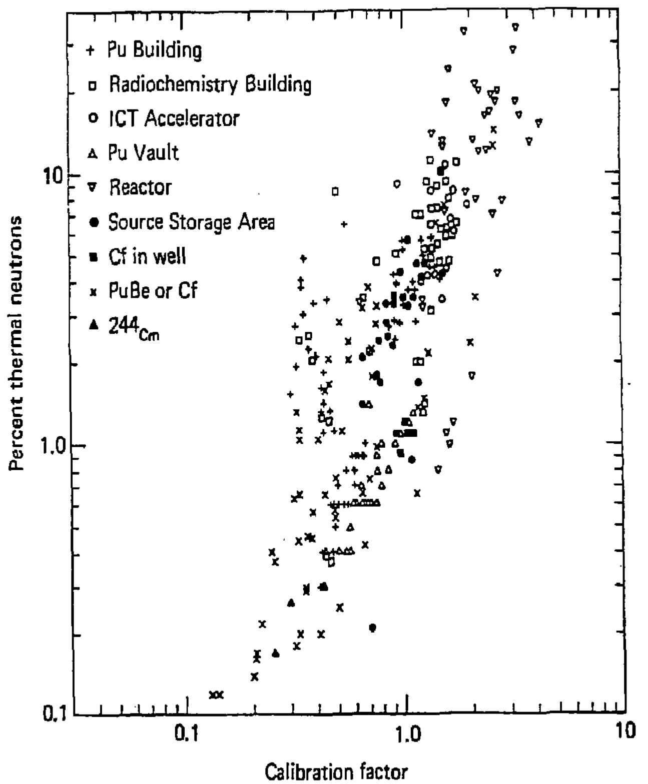

Figure 26
Percent of Thermal Neutrons as a Function of the Calibration Factor for Albedo Neutron Dosimeters

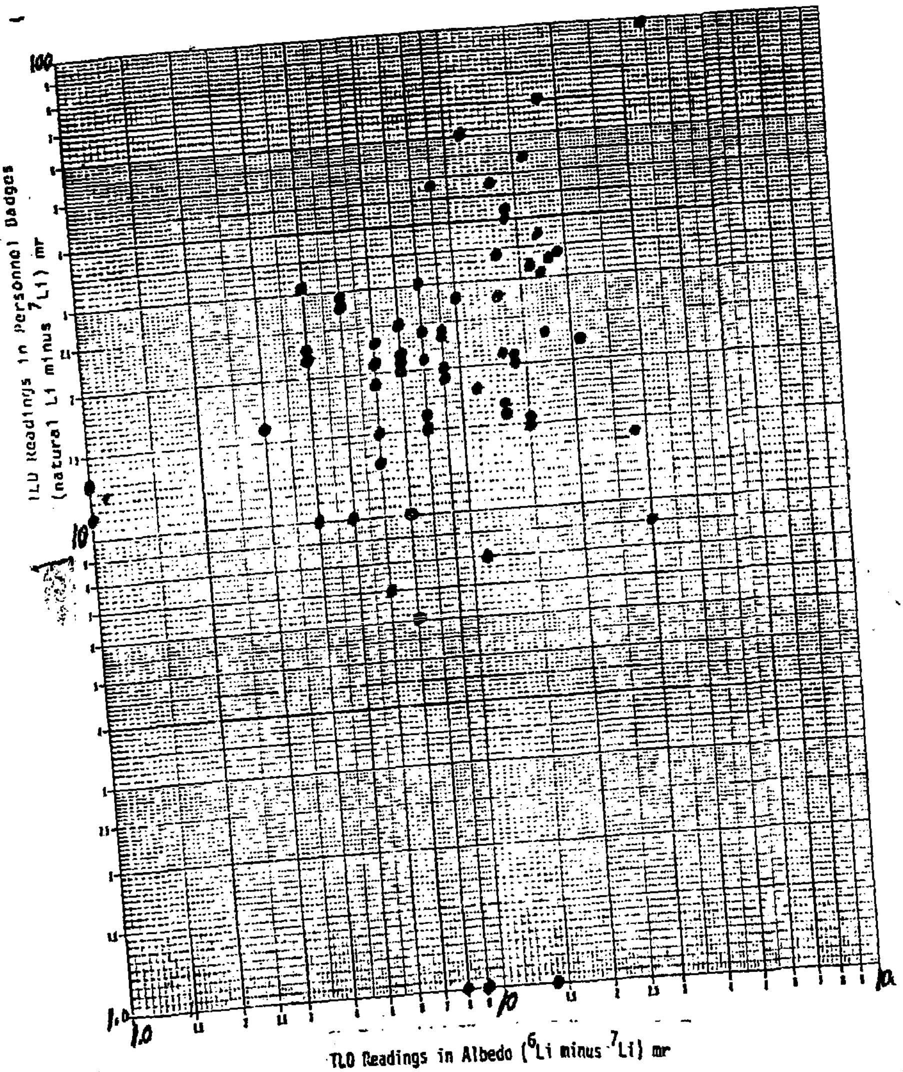

Figure 27
TLD Readings from a Bare TLD-100 Versus TLD Readings of an Albedo Dosimeter (for an individual)

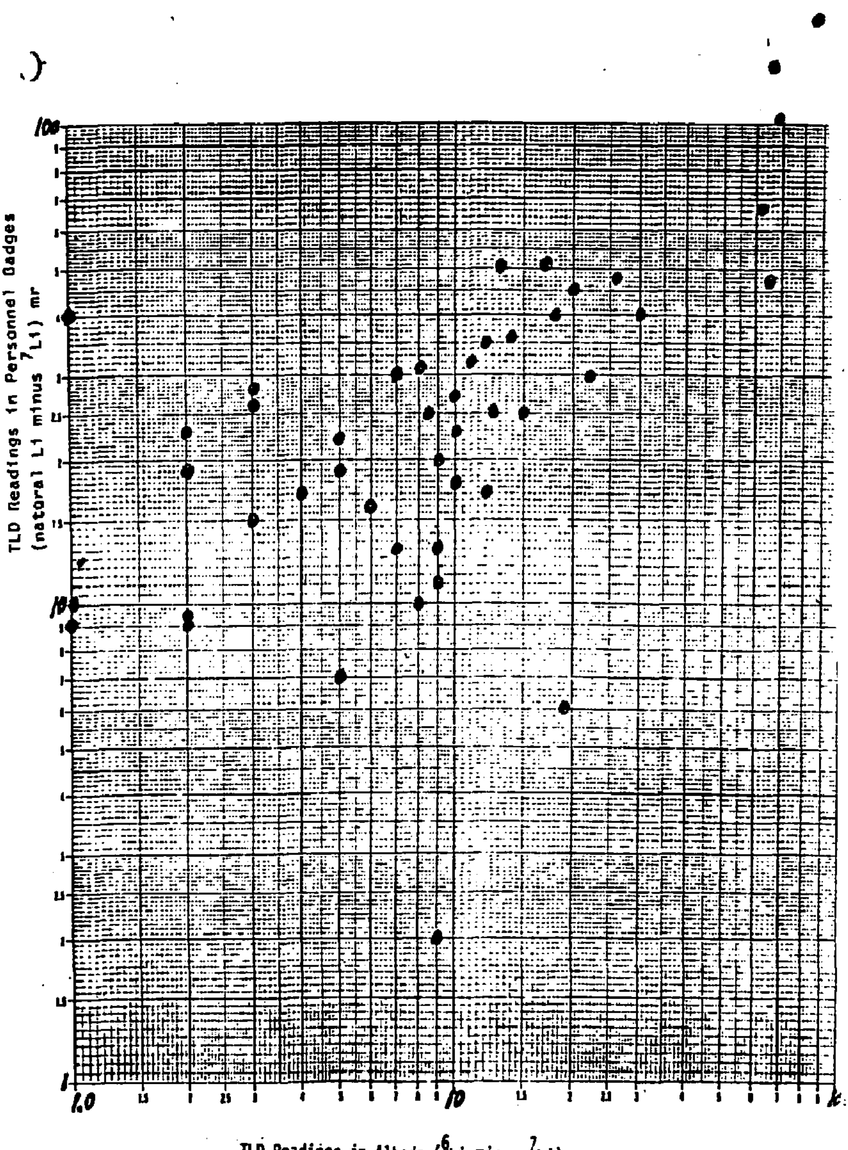

Figure 28
TLD Readings From a Bare TLD-100 Versus TLD Readings
From an Albedo Neutron Dosimeter (for an indivudal)

How do the different dosimeters compare when used at power reactors? Table 4 shows the exposure that I received during the work I did at the Farley plant. NTA film indicated zero dose, but does not include the gamma exposure. The rest of the dosimeters include gammas. As you can see, the exposure ranged from zero to 1700 mrems. The people at the reactor assigned me 1701 mrem based on stay time and the pocket dosimeter readings. I have a little problem with this range of possible exposures. What I assigned myself when I returned to the lab was 450 mrem because I felt the albedo neutron dosimeter was the most accurate. What the plant people didn't know is that I stayed out of the hot spots. I set up my dosimetry experiments, started the timer and retreated to an area where the neutron dose rate was low. Consequently, I was able to minimize my dose. The plant could not correct for this because they were using stay time and dose rates to calculate my exposure.

The Navy uses an interesting albedo dosimeter for the people who work with nuclear weapons on submarines, aircraft carriers, and in shipyards. Figure 29 shows this very simple dosimeter which contains only 2 TLDs. From this dosimeter they obtain the gamma and the neutron exposure. I was asked to audit their dosimetry program and when I saw the dosimeter, I was sure it wasn't going to work. The reason I was sure it wasn't going to work was because they are trying to use only two TLDs to determine the gamma dose and the neutron dose. There are two problems; one is the gammas produced by thermal neutron capture in the cadmium, and the other is the absorption by the cadmium of X-rays and gammas with energies less than 80 KeV. In looking at the data they had, we found there were very few thermal neutrons aboard ships, and the thermal neutron component and 9 to 3 ratio was constant. Consequently, thermal neutrons are not a serious exposure or dosimetry problem for the Navy. We also found that the Navy uses weapons which are shielded so that there are no gamma energies less than 80 KeV. These dosimeters have absolutely no beta response, but for this application none is needed. The Army couldn't use this dosimeter because they have weapons which have beta exposures and are

	MREM
NTA FILM	0
PERSONNEL TLD X γ/N RATIO	136
ALBEDO NEUTRON DOSIMETER (γ + N)	450
POCKET DOSIMETER X γ/N RATIO	474
TLD 100 (THERMAL)+PERSONNEL TLD (γ)	317
CALCULATED (STAY TIME + POCKET DOSIMETER)	1701

Table 4: Dose Evaluated Using Several Dosimeters or Methods for Work Done in the Farley Containment

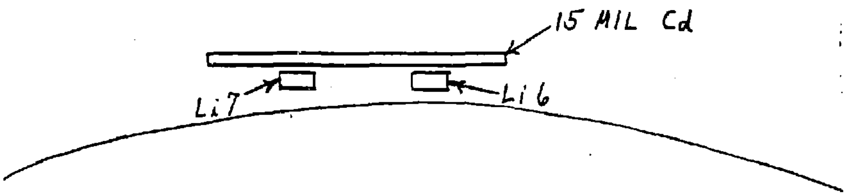

Figure 29
U.S. Navy Neutron and Gamma Dosimeter

shielded differently. The Navy's neutron dosimeter is applicable to a very special case. You cannot use this type of dosimeter at a reactor.

5.2 Other Dosimeter Types

I am going to leave albedo neutron dosimeters and discuss some other dosimeter types. What about the Neptunium fission fragment dosimeter? It is actually quite a good dosimeter, but is also radioactive. Even if you put a reasonable amount of lead shielding around the dosimeter, you are going to expose the wearer. About 20 years ago the AEC told us that they would not accept a neptunium neutron dosimeter. Some people apparently didn't believe them and went ahead and developed the dosimeters. As far as I know England is the only place where these dosimeters are used today. Thorium can also be used to make a fission fragment dosimeter, but the reaction cross section is too small to give the needed sensitivity, and the dosimeter is also radioactive.

Now let's discuss track etch dosimeters. What is track etching and how does it work? When you expose a piece of polycarbonate film or CR39 plastic to neutrons you cause small damage sites in the plastic. When you etch the plastic, the damaged areas are preferentially etched and you end up with a little hole or track. Originally when we were using these materials we used a microscope to count tracks just like you do with NTA film. After electrochemical etching, a little tiny track, which you normally wouldn't be able to see, becomes visible. These holes are fairly large. You can take this polycarbonate or CR39 film and hold it up to the light and see little specs all over the film. These tracks are counted on a microfiche reader rather than with a microscope. If you look at one of these tracks from the side you see a little entrance hole and little tree-like structures as shown in Figure 30.

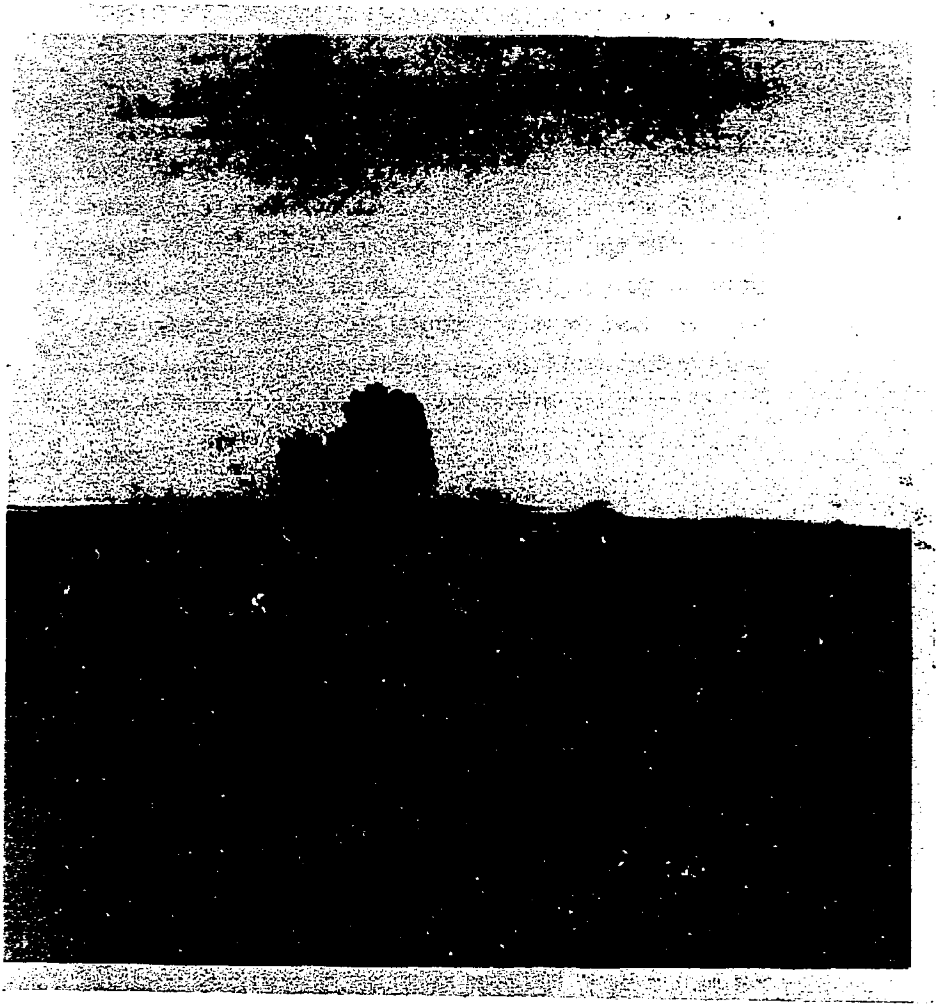

Figure 30
Tree Formation in Polycarbonate Following Electrochemical Etching

Polycarbonate unfortunately has a threshold of about 1 to 2 2 MeV (Figure 31). It is commercially available, and you can buy the dosimeter service from at least one of the commercial dosimetry companies. For reactor purposes, it is of no value. The threshold is too high, and you can detect too small a percentage of the total neutrons. Figure 32 shows the energy response for various etching conditions of material called CR39. The response can be fairly flat and extends down to about 100 KeV with proper electrochemical etching. This material can be used at a reactor. There is one commercial supplier that has CR39 in their dosimeter. Unfortunately, that commercial supplier (Landauer) does not use electrochemical etch at this time; they are using a chemical etch and the response looks more like curve 5 on Figure 32. The response has a hump at about 2 or 3 MeV and is not quite as good as what you can get with an electrochemical etch.

Unfortunately the quality of the CR39 material that we presently have is very poor. CR39 is made for mirrors and things of that type and consequently the procedures used to make the material is not adequately controlled for dosimetry purposes. It requires cooling over an 8-12 hour period, and they don't always cool it at the same rate. There is a study at the Berkeley Laboratory that is being funded through the neutron dosimetry program at Hanford, and they are trying to find a better or more consistent material. Hopefully, within a couple of years they will have good, commercially available CR39 or equivalent type material. When that occurs this is a dosimetry that you may want to consider. The advantages are obvious; there is little energy dependence, and the threshold is low enough that you can use it in a power reactor. The sensitivity is roughly 1 track per millirem, which is not too bad, but you must have at least 10 tracks to get acceptable statistics. You are still able to detect about 10 millirem with this dosimeter.

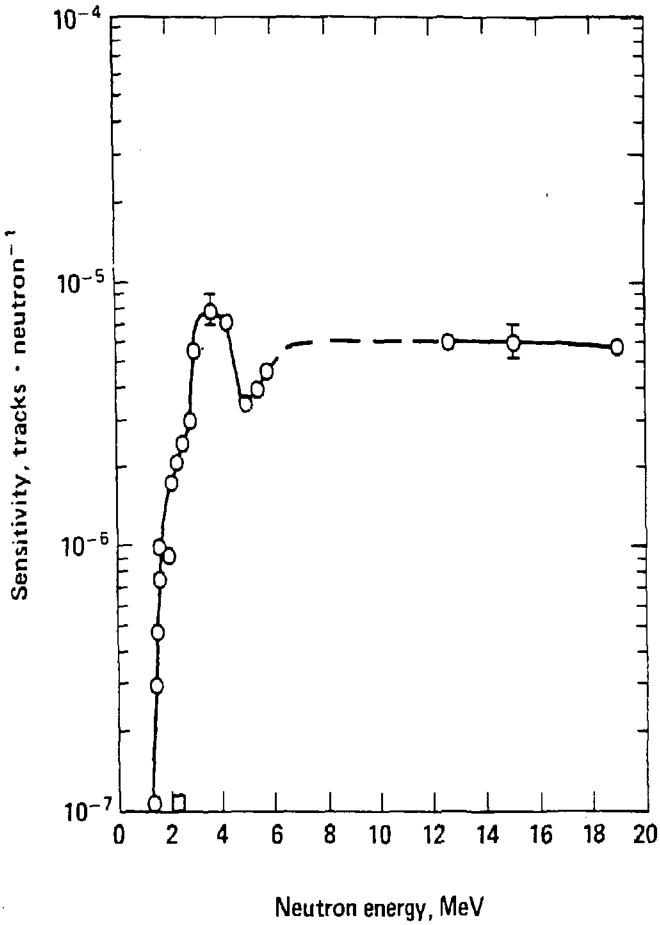

Figure 31
Energy Response of Chemically Etched Polycarbonate

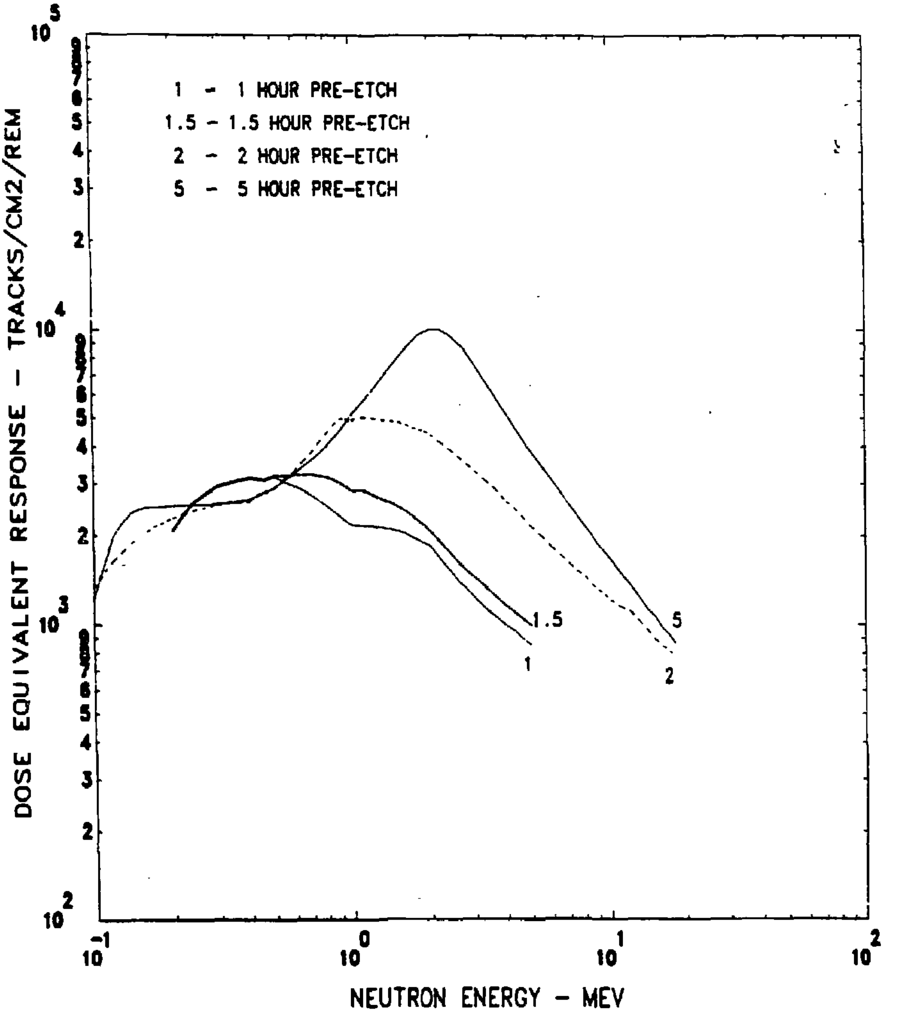

Figure 32
Energy Response of Electrochemically Etched CR-39
Showing Effect of Various Pre-etch Times

6. QUALITY FACTOR CHANGES

You have heard discussions about possible changes in the quality factor for neutrons. Rossi, for example, suggested that the quality factor should be increased by a factor of 10, 70, or possibly as high as 100. What is going to happen? The answer at this time is that nothing is going to happen right now. One of the things that is confusing the issue is some work that was done at the Lawrence Livermore Laboratory on recalculating the neutron dose from Hiroshima. The recommendations of Rossi were based primarily on the fact that the people at Hiroshima had more cancers than the people at Nagasaki. The new calculations by Livermore and Oak Ridge show that the neutron dose has dropped significantly. In the early studies they did not consider the amount of moisture in the air at Hiroshima. It was a very humid day and the neutrons did not go as far in the air as originally thought. As a result, the neutron dose was less than originally believed and the gamma dose was greater. The increased gamma dose could account for the excess cancers in the Hiroshima survivors. The Nagasaki doses never included much neutron dose and the new calculations show an even smaller neutron contribution. With that kind of confusion thrown into the situation, I don't think that the quality factor changes are going to occur in the near future.

7. DOSIMETRY SYSTEM OPERATIONAL PROBLEMS

Let's consider what can happen to a dosimetry system that is working well? I recently changed jobs at Livermore Laboratory and am no longer responsible for reviewing our neutron dosimetry program. Recently they required me to document what I had been doing all these years. In doing so, I found some interesting things that have happened since I gave up the dosimetry program. One was the value of the calibration source. They suddenly decided the value I had been using for the last six or seven years wasn't right and so they changed it by 14.5 percent. Then they put new Lithium-6 TLDs into the dosimeters. This caused a decrease in sensitivity by 20 percent because the new TLDs were less sensitive to neutrons by 20 percent than the old TLDs. We observed an 18 percent difference, but when you add 14.5 and 20 you don't get 18 percent. Where was the other problem? That was very difficult to find. Finally, I found that they had changed the phototube and the reading parameters which increased the neutron sensitivity by 24 percent. Well, as you can see, even a pretty good dosimetry program requires careful attention to keep it working well.

8. NEUTRON DOSIMETRY FOR A CRITICALITY ACCIDENT

I want to quickly discuss neutron dosimetry for a criticality accident. If you have a criticality accident or are called in to assist after one has occurred, the first information that you need to get from the exposed individual is the blood sodium activation. Take a blood sample, count it and just keep the information. There will be lots of people around to help you evaluate the data; take my word for it. Also, you will need a sulphur fluence, which you get from a sample of the hair. You don't have to scalp the guy, but give him a good hair cut and count that hair. If you are the first person at a criticality accident or if it happens to be at your plant, count the blood, count the hair, and save the data. From this information someone can come up then with the neutron dose.

9. SUMMARY

To summarize this entire talk, albedo neutron dosimeters are the best dosimeter to use at a power-reactor and will be with us for a long time. The calibration factor does not change very much from reactor to reactor. They have high sensitivity and can be used to accurately determine neutron exposure. I recommend the use of the Hankins-type albedo neutron dosimeter because I think it is still the best one on the market. It doesn't have to be held tightly against the body. You can wear it wherever you want to, and it doesn't have to be right side up. It does have relatively low sensitivity, but for your purposes it has quite adequate sensitivity. I think in the near future (2-3 years) you will see good track etch dosimeters. You will need to evaluate whether you want to change from albedo neutron dosimeter to track etch at that time. You may be forced by the NRC into using track etch dosimeters even though you may not want to.

By virtue of what I have not said, there are no other dosimeter systems that are worth talking about at this time. A workshop on personnel dosimeters was held last year, and there is nothing new coming along. You are not going to see, at least within the next five years, a new neutron dosimetry technique.