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SSTR AND EMULSION TECHNIQUES AND THEIR APPLICATIONS FOR FBR, LWR, AND MFER PROGRAMS

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ABSTRACT

Current and projected techniques for using Solid State Track Recorders (SSTR) and Nuclear Research Emulsions (NRE) for the measurement of various nuclear parameters in Fast Breeder Reactor (FBR), Light Water Reactor (LWR), and Magnetic Fusion Energy Reactor (MFER) programs will be presented. Two categories of SSTR, one for fission fragment detection and the other for alpha particle detection are of importance in reactor applications. Etching, annealing, and track read out techniques will be discussed.

For FBR programs, SSTR for fission fragments are used together with various fissionable isotopes to provide information on neutron fluence and fission rates at in-core and out-of-core locations. Fission rates coupled with radiochemical, gamma spectrometry, and mass spectrometry techniques provide measurements of absolute fission yields and capture to fission ratios. SSTR for alpha particles also offer promise for the measurement of alpha particle production from ^{10}B, ^{6}Li, and other nuclides. SSTR for fission fragments and alpha particles will be used for Pressure Vessel Surveillance (PVS) in the LWR program to give information on neutron fluence-spectra. The use of SSTR for neutron fluence, helium production, Primary Knock-on Atom (PKA) observations, and tritium breeding measurements are also projected for the MFER program.

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NRE provide information on neutron spectra, including angular anisotropies. Three specific interactions, n-p scattering, $^{6}Li(n,t)^{4}He$, and $^{10}B(n,t2\alpha)$ will be discussed in terms of the specific kinds of information each can provide for the FBR, LWR, and MFER programs.

1. INTRODUCTION

Having set a goal of high accuracy in the measurement of neutron fluence as a function of neutron energy in various reactive assemblies, the involved scientific and engineering community is finding it necessary to use a variety of experimental techniques and calculational procedures to reach these goals. No single experimental technique has proved adequate to cover the entire energy range of interest, and so much information, such as cross section data, is needed to obtain high accuracy, that a multi-method approach has proved to be mandatory. Other goals, such as high accuracy in the measurement of fission rates, fission yields, and helium production rates also make it necessary to use a multi-method approach.

It is not for purely academic reasons that high accuracy goals have been established. The economics of nuclear power requires optimized reactor designs. Safety considerations require that highly reliable knowledge of the neutron flux as a function of position be known, and that the various nuclear reaction rates be accurately measured.

Techniques for the measurement of neutron spectra and of various nuclear reaction rates in material media fall into two general categories: (a) active, and (b) passive. Active techniques involve the use of proton recoil counters, ^{6}Li spectrometers, fission counters, etc, that give information in the form of electronic signals. Passive techniques involve the use of multiple foils, Solid State Track Recorders (SSTR), Nuclear Research Emulsions (NRE), etc, in which the information is stored and processed after the irradiation is complete.

An important advantage of passive techniques is that they are generally much less expensive than active ones. Passive detectors can often be irradiated simultaneously at various locations in the reactive assembly, maximizing the knowledge gained without renormalization, and minimizing the operating time of the reactor devoted to such measurements.

The purpose of this paper is to focus on the type of information that can be obtained through the use of SSTR and of NRE, and specifically to comment on the state of the art and plans for improvement in the application of these techniques for measurements in US FBR, LWR, and MFER programs.

A good summary of the range of applications of SSTR can be found in the text by Fleischer, Price and Walker.[3] SSTR have a number of characteristics that make them especially useful in reactor applications. Among these are the following:

(1) SSTR are small in size, offering the capability of high space resolution in the measurement of heavy charged particle emission, and produce small perturbations when inserted into the medium of interest.

(2) SSTR provide time-integrated observations and give a permanent record that can be evaluated off-line by different read-out techniques.

(3) SSTR have an enormous range of sensitivity, which can be adjusted by the strength or geometry of the source of fission fragments or of alpha particles. The dynamic range of observable track density varies at least from one $\sim$ one event/cm^2 to $\sim 10^8$/cm^2.[3] A comparable dynamic range is also afforded by variation of source strength. These two factors can be applied in consort to provide SSTR techniques with a range of sensitivity that is virtually unmatched.

(4) SSTR record events with high efficiency (if desired), and afford absolute measurements, after suitable calibration.[4]

(5) SSTR, even in the present state of the art for recording fission fragments, yield high accuracy[4] $\sim$ 1 to 2% (1σ). Although differences in the measurement of absolute fission rates as compared with the NBS fission chamber have been detected,[5] these differences are small ($\sim$ 2-3%) and systematic and thus subject to correction. Further studies are expected to eliminate or reduce these differences.

(6) SSTR yield absolute fission rates independent of the knowledge of any nuclear cross section and of any other neutron standards.

(7) SSTR are highly selective in recording the events of interest in a mixed radiation field. Although the influence of high gamma radiation on the track recording characteristics of various SSTR requires further study,[6,7,8] these are not likely to be sources of concern, except for measurements at high power. Muscovite mica, for example, is so selective in recording fission fragments as against alpha particles, that distinct fission fragment tracks have been observed[9] in a background of 4×10^{13} alpha particles/cm^2, and this limit may be somewhat higher.

(8) Some SSTR, such as natural quartz crystals, can be used to record and retain fission fragment tracks at elevated temperatures,[10,11] thus introducing the possibility of making absolute fission rate measurements in the core of a reactor operating at power.

(9) In many applications the source thickness used with SSTR is so small that flux depression and self-shielding problems are essentially non-existent.

A principal objection to SSTR techniques is the difficulty of data read-out, and this difficulty should not be underestimated. Manual scanning is slow and must be done with great care to keep errors small. Although Poisson statistics apply to track counting,[4] sources of systematic errors in track counting techniques must be carefully evaluated. High accuracy in manual track counting has been demonstrated.[4] In some

cases, automatic track counting procedures approach the accuracy possible by manual counting,[12],[13],[14] and the automatic techniques will certianly improve, offering an even brighter future for the application of SSTR techniques in reactors.

Nuclear Research Emulsions (NRE) have a limited but important application for neutron spectroscopy in reactive assemblies. Like SSTR, they are also compact in size, offering high space resolution and small perturbations. In NRE used to record recoil proton tracks resulting from (n,p) scattering, edge effect corrections can be reduced to zero up to at least 3 MeV by accepting tracks sufficiently far from the emulsion surfaces.[15],[16] This is an advantage compared with proton recoil proportional counters.[17] Another important advantage, as compared with other techniques, is that neutron spectra determined from proton recoil tracks in NRE are based upon the classical cross section for (n,p) scattering. This cross section is known to the highest accuracy over the entire neutron energy range of interest in reactor applications. NRE also offer the promise of measurements of the neutron angular flux.[18],[19]

NRE require small fluences ($\leq 3 \times 10^9$ neutrons/cm^2) and are highly sensitive to gamma radiation. They are thus limited to measurements at very low power. Range straggling also seriously limits the energy resolution ($\sim$ 50 kev) at low energies.

Track readout techniques for NRE are slow and difficult, but semi-automatic techniques have been used and are being improved (see Section 4 below).

2. Fission Fragment SSTR

Certain SSTR, such as Muscovite mica, quartz glass, and quartz crystals require a high density of ionization along the path of a charged particle in order to produce an etchable track.[2] All fission fragments produce a sufficiently high ionization density to produce tracks, but

alpha particles, even at low energy, do not. This makes such SSTR ideal for the recording of fission events in a high background of alpha, beta, and gamma rays.

For a given etching solution and temperature, each SSTR is characterized by V_T, the track etch velocity, and V_G, the bulk etch velocity. V_T depends mainly upon the primary ionization rate along the track,[2] and for isotropic media V_G is usually the same in all directions. V_G may have different values along different crystallographic axes in crystalline substances, such as mica and quartz crystals. For a track to be revealed, $V_G < V_T \sin \theta$, where θ is the angle between the track and the SSTR surface. As can be seen from Figure 1, the efficiency for recording a track is expected to be $\eta = 1 - \sin \theta_c$ where $\sin \theta_c = V_G/V_T$. For Muscovite mica, $V_G = 0$ in a direction perpendicular to the cleavage planes. Thus, it is expected that the efficiency for recording tracks of fission fragments should be 100%. Scattering from the fission source backing material could give an efficiency > 100%. However, tracks nearly parallel to the mica surface under given etching conditions may not produce sufficient optical contrast to be observed using ordinary optical microscopy techniques.

Rather than assume 100% efficiency for mica, an empirical calibration of the "optical" efficiency has been made for etching 90 minutes in 49% HF at room temperature.[4] In order to measure the optical efficiency, i.e., the ratio of tracks counted/cm^2 to fissions occuring/cm^2, mica SSTR were exposed to fission fragments produced by a very thin spontaneous fission source of ^{244}Cm in direct contact with the mica. The optical efficiency was found to be (94.8 $\pm$ 0.53)%. A similar measurement was carried out for Makrofol N, a polycarbonate plastic. The efficiency obtained was (95.2 $\pm$ 0.53)%. For both the mica and Makrofol N measurements, the ^{244}Cm source had been calibrated with a low geometry counter. Both alpha particles and fission fragments of the ^{244}Cm source were counted with solid state surface barrier detectors.[4]

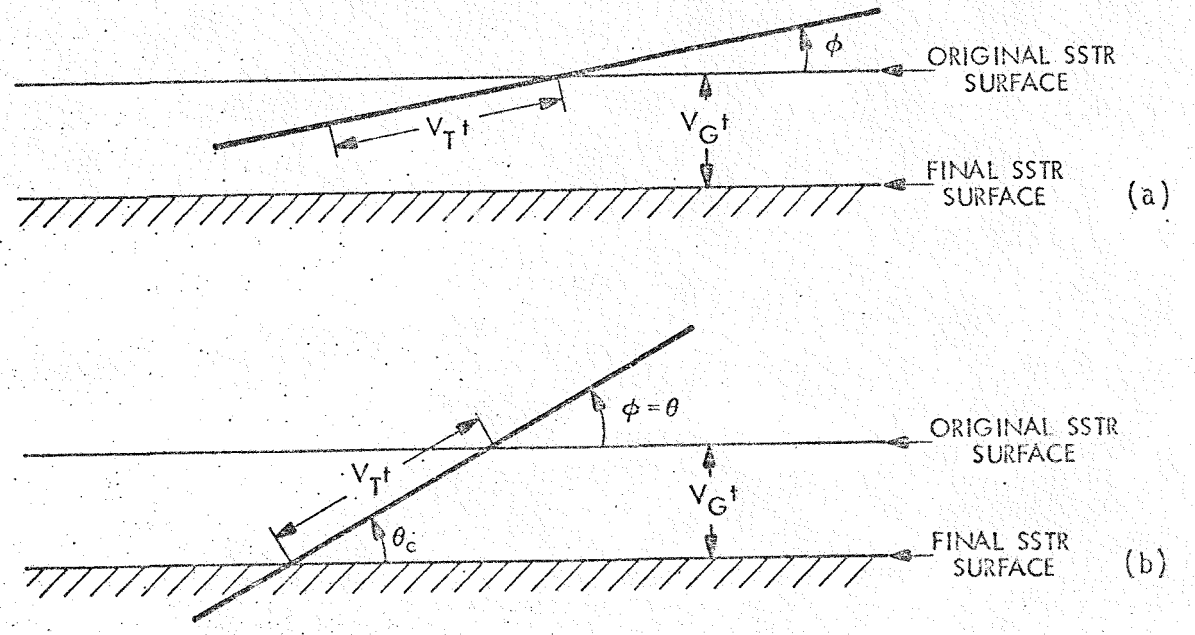

FIGURE 1. The Geometry of Track Registration:

(a) For an angle of incidence less than $\sin^{-1}(V_G/V_T)$, SSTR surface is removed at a greater rate than the component of V_T normal to the SSTR surface and hence no track is observed;

(b) At and above the critical angle, $\theta_c = \sin^{-1}(V_G/V_T)$, tracks will be observed.

The optical efficiency for mica has been used, in turn, to determine the effective number of uranium atoms/cm^2 on the surface of uranium metal from which all fissions will be observed in mica SSTR placed in contact with this surface.[4] This result is (1.0981 $\pm$ 0.015) x 10^{19} ^{238}U atoms/cm^2 and is called the asymptotic sensitivity.

The above optical efficiency and asymptotic sensitivity for mica have been used in the measurement of a number of absolute fission rates. Among these are the spontaneous fission decay constants of ^{238}U and ^{241}Am,[9,20] of various absolute fission yields,[21] and of absolute slow neutron flux.[22] Thus far, these results have stood the test of time and appear to be accurate. It needs to be emphasized that these results are independent of the measurement of any nuclear cross sections and of any other neutron standards. The dependence of the asymptotic sensitivity on the charge and mass of the source medium has been investigated by R. Gold.[23]

Table I lists the important characteristics that are known or need to be known for precision measurements of absolute fission rates with those SSTR most likely to prove useful for reactor applications. In order to use fission SSTR in reactive assemblies operating above room temperature, it is apparent that better knowledge is needed of the annealing characteristics of selected SSTR.

Regarding annealing effects, it is known that the radiation damage produced by a heavy charged particle in a given SSTR can be effected at elevated temperatures so that the etching characteristics for track revelation are radically changed; in some cases to the extent that no tracks are revealed at all. The best summary of SSTR annealing characteristics available at this time appears in the text[2] by Fleischer, Price, and Walker. An examination of the work on which this summary is based reveals that more complete and more accurate information is needed. For this reason, a program has been launched at the Hanford Engineering Development Laboratory (HEDL) to improve this knowledge so that accurate

TABLE I

CHARACTERISTICS OF SSTR CANDIDATES FOR REACTOR APPLICATIONS

SSTR	Optical Efficiency (%)	Asymptotic Sensitivity[d]	Temperature at[e] Which Track Fading Begins	Temperature for Total[e] Fading for One Hour Annealing
Muscovite Mica	94.8 ± 0.53[a]	(1.098 ± 0.015) x 10^{19} ^{238}U atoms/cm^2 (a)	275-450°C	540-700°C
Makrofol N	95.2 ± 0.53[b]	---	100°C	200°C
Lexan	---	---	---	> 185°C
Quartz Glass	∿ 70[c]	---	---f	---f
Natural Quartz Crystal	∿ 80[c]	---	1000°C	1050°C

(a) Etched 90 min in 49% HF (Reference 4).

(b) Etched ∿ 20h in 6.2 N KOH at room temperature (Reference 4).

(c) Better results awaiting ^{244}Cm source calibration at HEDL.
Quartz glass etched 5 minutes in 48% HF at room temperature.
Quartz crystal etched in boiling 65% NaOH for 25 minutes.

(d) Needs to be known only if used with asymptotically thick sources.

(e) From tabulation on pp. 80-83 of Reference 2.

(f) Depends on how glass was manufactured: each batch must be tested separately.

corrections for track losses in SSTR due to annealing can be made. It is even better to define a maximum temperature and associated maximum exposure time for a given SSTR, that will make such corrections unnecessary.

3. Alpha Particle SSTR

A number of plastics record etch pits or tracks produced by alpha particles. Among these are cellulose nitrate (CN), polycarbonate (PC), cellulose acetate (CA), and cellulose acetate butyrate (CAB). In this paper, two of these--CN and PC are singled out as offering the best promise to date for precision alpha particle measurements in reactive assemblies.

Much of the pioneering work on CN was done by E. V. Benton.[24] Because the track recording characteristics of CN were found to be sensitive to the manufacturing process, aging, ultraviolet exposure, storage temperature, etc. Benton[24] and others[25,26] made their own CN, at least until a commercial source produced specifically as a SSTR material became available. Various types of CN are now manufactured by Kodak Pathe in France. The principal types are: (a) LR 115, which consists of a thin layer of CN (6 - 12 μm) dyed a deep red and on polyester backing. (In one form it can be stripped from the backing material.) (b) CA 80-15, dyed pink and 100 μm in thickness. It can be obtained coated with lithium borate so that it can record tracks of ^{4}He and ^{7}Li, etc, without the use of an auxiliary source. These materials should be refrigerated and exposed to as little light as possible before use, and each batch should be calibrated just before use.

G. Somogyi and coworkers[27,28] have made extensive studies of alpha-sensitive plastics. They have found that the track diameter depends upon the alpha particle energy, and for alpha particles incident perpendicularly on Makrofol E polycarbonate, an energy resolution of 50 kev can be obtained from track diameter measurements; the resolution is not very

energy sensitive, at least up to 6 MeV. They use an etching bath composed of KOH, ethyl alcohol, and H_2O. Qaqish and Besant[29] have demonstrated that comparable resolution can be obtained in CA 80-15 CN, and Lück has obtained similar results with his CN.[30]

C. Besant and coworkers[31] have been investigating the applicability of CN plastics for the measurement of boron reaction rates in low power critical assemblies. These results look promising, but further work is needed.

The use of multiple foil (n,α) reactions has been proposed for application in fast neutron spectrometry.[32] Some potentially useful reactions are listed in Table II. The use of Makrofol E and of the various kinds of CN produced by Kodak Pathe are being investigated at HEDL and at Macalester College for applications relating to helium production, etc. Resolution comparable to that reported by Somogyi et al, by Besant et al, and by Lück has been confirmed.

Instead of using an alcoholic etch bath, Lexan PC, similar to Makrofol E, can be sensitized for alpha particle registration by exposing it to intense ultraviolet radiation.[33],[34] Lexan with windows in the ultraviolet region must be selected.

4. Nuclear Research Emulsions

Extensive applications of nuclear research emulsions (NRE) have been made in nuclear, high energy, and cosmic ray physics.[35] In this paper, the current status in the application of NRE to neutron spectroscopy is reviewed.

A comprehensive review of the early work on NRE as applied to neutron spectroscopy has been given by L. Rosen.[36] A forecast of its continuing usefulness in reactive assemblies has been made by R. Gold.[37]

TABLE II

SOME (n,α) REACTION CANDIDATES FOR SSTR DOSIMETRY

Reaction	Q Value (MeV)[a]
$^{6}Li(n,\alpha)^{3}H$	4.7846
$^{10}B(n,\alpha)^{7}Li$	2.7916
$^{12}C(n,\alpha)^{9}Be$	-5.7044
$^{12}C(n,3\alpha)n$	-7.2700
$^{19}F(n,\alpha)^{16}N$	-1.5244
$^{27}Al(n,\alpha)^{24}Na$	-3.1314
$^{63}Cu(n,\alpha)^{60}Co$	1.7146
$^{197}Au(n,\alpha)^{194}Ir$	6.9666

(a) For reactions in which the residual nucleus is left in the ground state.

The most useful work on neutron spectroscopy with NRE has made use of n-p scattering. Fortunately, the n-p scattering cross section is very well known over the entire neutron energy range of application in FBR, LWR, and MFER programs. Three basic techniques are available:[36]

(1) The NRE is placed edge-on in a neutron beam (emulsion plane parallel or nearly so to the neutron direction), and proton tracks produced near the leading edge are measured. If the angle between the neutron beam and proton track is denoted by θ, then $E_p = E_n \cos^2 \theta$, where E_p is the proton energy (deduced from the proton range R_p) and E_n is the neutron energy. A good example of this method, which has proved very useful when the neutron direction is known, is the precision measurement[38] of the neutron spectrum produced in the fission of ^{235}U by thermal neutrons. Here the resolution depends primarily upon the degree of collimation, range straggling, and the choice of θ_{max}, usually $\leq 20°$.

(2) The NRE is placed in an evacuated chamber and a thin hydrogenous radiator is placed in a neutron beam. The range, R_p, and angle θ with respect to the neutron direction, of the proton recoils coming from the radiator are measured. The neutron energy E_n is then deduced as in (1). The resolution depends primarily upon the radiator thickness, range straggling, the degree of collimation, and θ_{max} selected for the measurement.

(3) The NRE is placed in a fast neutron environment such as in a reactor assembly where the direction between the neutron and recoil proton is unknown. In this case, all proton tracks meeting certain criteria regarding the distance of their beginning and end from either emulsion surface are measured. This technique has been investigated and used by J. Roberts, et al,[15,16] by C. Beets et al,[39] and by R. Lehman et al.[40] The first two groups have measured neutron spectra in fast critical assemblies, and the last (R. Lehman et al) has been primarily concerned with neutrons in accelerator shielding. The neutron fluence $\phi(E)$ is determined from the relation:

$$\phi(E) = \frac{E}{\sigma(E)\, n_p} \quad \frac{dM(E)}{dE} \quad , \qquad (1)$$

where E is the neutron or proton energy, $\sigma(E)$ is the n-p scattering cross section at energy E, n_p is the number of hydrogen atoms per unit volume of the emulsion, and M(E) is the number of proton tracks per unit volume at energy E.

The neutron spectra from $0.3 < E_n < 1.0$ MeV obtained by this method in NRE have compared well with the spectrum measured by time-of-flight.[16] It should also be emphasized that the absolute integral reaction rate for n-p scattering over a given energy range can be approximated from Equation 1, provided the number of neutrons above $(E_n)_{max}$ is small or reasonably well known. If the angular distribution of the incident neutrons is isotopic, Deckers[41] has shown that only R_p projected in the emulsion plane need be measured. Since the neutron spectrum is deduced from the slope of the proton spectrum, many more tracks have to be measured to obtain good statistical accuracy as compared with methods (1) or (2).

The use of NRE loaded with ^{6}Li has been investigated by J. Roberts and F. Kinney[42], and by C. Beets et al,[39] in the energy range below 1 MeV. Whereas some information down to $E_n \sim 100$ kev can be obtained, the energy resolution is poor, and the broad resonance at 240 kev introduces serious problems. The use of $^{10}B(n,2\alpha t)$ for E_n from 4 to 10 MeV has also been proposed.[43]

As mentioned above, it is proposed[18] that NRE techniques involving n-p scattering, the disintegration products of $^6Li(n,t)^4He$ and of $^{10}B(n,2\alpha t)$ be used to give information on the angular flux of neutrons in MFER environments. Under special conditions, n-p scattering has been used by Iijima and Nomoto[19] to measure the angular flux. Further study is needed to obtain good estimates of the degree of anisotropy that can be detected by each of these techniques.

5. Track Readout Techniques

As pointed out in Section 1, one of the chief drawbacks in applying SSTR and NRE is the difficulty of obtaining accurate and rapid readout of track data. Reliable and accurate results can be obtained by manual scanning with optical microscopy,[4] but if many results are needed, considerable scanning time is required. The great care that must be exercised in order to achieve the objectivity required of high accuracy SSTR measurements has already been emphasized at the first of these symposia in Petten.[44] For these reasons, various methods of automatic or semiautomatic scanning have been tried or are being developed.

For track counting in SSTR, an optical microscope equipped with stepping motors on both the stage and the fine focus control was developed by Cohn and Gold.[13],[14] The instrument, interfaced with a computer, was quite successful for counting fission tracks in Makrofol N SSTR, but the counting rate was quite slow. Problems were encountered in automatic focusing when mica SSTR were used, as it was difficult to keep the surface of the mica in focus even with automatic control of the fine focus.[13]

Various investigators, such as C. B. Besant[12] et al, have had reasonably good success by coupling a Quantimet system to an optical microscope. Measurements of fission track densities have been reported in which accuracies of about 3% are claimed. As these techniques with the Quantimet (or similar systems) are refined, it is expected that they can yield accuracies of $\sim$ 1 or 2% for many applications, such as fission rate measurements. Automatic systems will need considerable cross-checking against measurements carried out with manual techniques, for which high accuracy has already been established.[4]

A word should be said about the ingenious system developed by Cross and Tommasino[45] and investigated by many others for a rapid electrical method of track counting. Holes produced in a thin dielectric material,

such as Makrofol PC, by etched damage trails of heavily ionizing particles, are counted electrically--the so-called "spark" method of counting. Whereas this spark method has been improved[46] to the extent that holes can be counted repeatedly in a given foil to an accuracy of 1 to 2%, variations in foil thickness and etching characteristics have thus far limited the reliability of the technique to accuracies in the 5-10% range. If precautions are taken to use the method carefully, it is a recommended technique for applications in which this kind of accuracy is adequate. The reader may also wish to investigate "break-down" counter techniques,[47],[48],[49] which are a more recent outgrowth of the spark method.

For NRE, manual scanning techniques with an optical microscope have usually been used and are described by L. Rosen.[36] R. Lehman et al,[40] have used optical microscopes equipped with encoders in the x,y, and z coordinates to give digitized output that was punched on IBM cards.

As a result of the rapid advancement in computers in recent years, vast improvements are possible. Although complete automation of track read-out from NRE would be very difficult, an interactive system can be used. At HEDL, a Zeiss Universal Microscope equipped with a motorized stage is being interfaced to a special minicomputer. The fine focus control is also being motorized, and a digitized filar micrometer eye-piece will be available to measure the projected length of very short tracks. This interactive system is expected to increase the speed of NRE track measurements considerably and to reduce measurement errors. This system should also prove useful for certain SSTR applications, such as in the range measurements of alpha particles. Additional work on automatic SSTR readout techniques is on-going at HEDL. While proprietary requirements preclude the discussion of details, it appears that significant advancements will be made.

6. Specific Reactor Applications

This section gives examples of the specific plans that have been developed for the application of SSTR and the NRE in the LMFBR, LWR, and MFER programs. It should be emphasized that SSTR will play a particularly important role in the Fast Test Reactor - Reactor Characterization Program (FTR-RCP), and NRE will also contribute significantly to characterizing neutron spectra in the same program. Applications of SSTR and NRE in the LWR program, especially for Pressure Vessel Surveillence (PVS) studies, are also expected as plans unfold. A similar statement can be made for the characterization of the D-Li neutrons for damage studies of materials in simulated fusion reactor environments.

a. Applications of SSTR and NRE in the FTR-RCP

Plans have been formulated to conduct experiments in the FTR-RCP at three different power levels: (1) Very Low Power (VLP), (2) Low Power (LP), with the FTR operating at about 4 MW, and (3) High Power (HP), at about 400 MW. Since track densities and gamma ray background must be kept low ($\sim$ 1R), NRE can only be used at VLP. To keep proton track densities low, the neutron fluence must not exceed $\sim 3 \times 10^9$ neutrons/cm^2. Since the neutron intensity decreases rapidly with increasing distance from mid-plane, three emulsion irradiations have been recommended, including a background irradiation. The background irradiation would be performed with all rods in, $k_{eff} \cong 0.9$ for about eight hours. The second irradiation will require $k_{eff} \cong 0.98$ for a 1.5 hour duration, and for the exposure of NRE beyond the core region in the third irradiation, a one watt power level will be required for about eight hours. It is planned to use Ilford L4 type emulsions, since these are fine grain emulsions and should give data down to $\sim$ 0.3 MeV and up to at least 3 MeV. Data at higher energies will be available in these emulsions, but would require much more extensive scanning to obtain meaningful statistics, and care must be taken to evaluate the probability that long proton tracks will escape through the emulsion surface.

SSTR fission rate measurements at VLP are also planned. Absolute fission rates as a function of isotope and position will be made with SSTR and radiometric dosimeters, which can be compared with NBS absolute fission chamber results. These measurements will provide absolute fission rate measurements for power normalization with subsequent LP and HP irradiations.

In Table III, axial locations recommended for those VLP experiments most directly related to measurements with SSTR are compared with recommended locations for VLP-SSTR measurements. Table IV gives SSTR fission deposit requirements for the high priority isotopes at these various locations. These requirements are designed to give statistical precision at least as good as 1% (1σ).

In the measurements at LP, SSTR will be used primarily to determine the absolute number of fissions/gm of various isotopes so that absolute fission yields can be measured. In the LP fission yield experiments, irradiation capsules containing radiometric dosimeters in close proximity to SSTR will be exposed in specially designed FTR fuel pins called characterizer pins. Exposures of SSTR and radiometric dosimeters in close proximity provides not only fission product yields but conversion factors for the direct use of radiometric dosimeters, i.e., the so called k-factors, which give absolute fission rate calibration factors for the given radiometric counting system. The radiometric dosimeters are analyzed off-line by appropriate gamma-ray spectroscopy counting systems for specific fission products.

Since both fission product yields and k-factors can exhibit neutron energy dependence, in-fuel measurements over a wide range of in-core locations will be mandatory to meet FTR-RCP accuracy goals. The LP irradiation will provide a unique opportunity for direct in-fuel observations. Tables V and VI give recommended LP fission rate locations and the SSTR fission deposit requirements, respectively. The recommended locations for these SSTR-LP measurements are also shown in Figure 2. Of

TABLE III

AXIAL DOSIMETRY LOCATIONS RECOMMENDED FOR VLP IRRADIATIONS*

γ-Spectrometry (IRT Expt. 1)	n-Spectrometry (IRT Expts. 3-4)	γ-Calorimetry (IRT Expt. 6)	NBS Fission Chamber (IRT Expt. 7)	SSTR Fission Rates (IRT Expt. 8)	(IRT Expt. 11)
0	0	0	0	0	0
53	53	53	38	38	38
122	122	122	53	53	53
				122	122

*Distance above mid-plane in centimeters.

TABLE IV

VLP-SSTR FISSION DEPOSIT REQUIREMENTS

Isotope	Expt. 8		Expt. 11	
	Thickness[a]	No. of Deposits	Thickness[b]	No. of Deposits
^{239}Pu	0.5	3	0.1	3
	9.0	1	1.8	1
^{240}Pu	2.5	2	0.5	2
	20.0	1	4.0	1
	125.0	1	$7.5 \cdot 10^{2}$	1
^{241}Pu	0.5	3	0.1	3
	9.0	1	1.8	1
^{235}U	0.5	3	0.1	3
	9.0	1	1.8	1
^{238}U	20	2	4.0	2
	120.0	1	32.5	1
	a_∞[c]	1	$1.5 \cdot 10^{4}$	1
Inner Driver	2.5	3	0.5	3
	35.0	1	7.0	1
Outer Driver	2.5	3	0.5	3
	35.0	1	7.0	1

a) Deposit thickness in ug/cm^2; $1.27 \cdot 10^{-2}$cm SS source backing - 1.905 cm diam.; active deposit diameter 1.27 cm.

b) Deposit thickness in $nanograms/cm^2$; $1.27 \cdot 10^{-2}$cm SS source backing - 1.905 cm. diam.; active deposit diameter 0.35 cm.

c) Asymptotically thick source, $a_\infty = 1.098 \cdot 10^{19}$ atoms/cm^2 for ^{238}U.

TABLE V.

AXIAL LOCATIONS FOR LP FISSION PRODUCT YIELD MEASUREMENTS

Characterizer Assembly (CA)	Axial SSTR Location[†]
2101*	0, ±38, ±53, + 122
2304	mid-plane only
2405*	0, ±38, ±53, + 122
2507	mid-plane only
2608*	0, ±38, ±53, + 122
2711	mid-plane only
2811	0, ±38, ±53
2404	mid-plane only
2606	mid-plane only
2707	mid-plane only
2909	mid-plane only

[†]Distance in centimeters, above and below mid-plane (z = 0).

*An additional central pin location, Z = -122 cm, is used for ^{239}Pu only.

TABLE VI

PRIORITY NO. 1 LP-SSTR FISSION DEPOSIT REQUIREMENTS*

Isotope	Thickness	No.	Thickness	No.	Thickness	No.	Thickness	No.	Thickness	No.
^{239}Pu	8×10^{-3}	15	1×10^{-2}	6	3×10^{-2}	6	9×10^{-2}	5	3×10^{-1}	2
^{240}Pu	4×10^{-2}	10	6×10^{-2}	4	3×10^{-1}	4	2.0	5	5.0	3
					8.0	1	120	3	800	1
^{241}Pu	5×10^{-3}	15	1×10^{-2}	7	3×10^{-2}	5	1×10^{-1}	3	3×10^{-1}	1
^{235}U	8×10^{-3}	15	1×10^{-2}	7	4×10^{-2}	5	8×10^{-2}	2	3×10^{-1}	2
^{238}U	3×10^{-1}	10	5×10^{-1}	3	1.6	5	5.0	3	27	2
					70	4	110	3	16,000	1

*Deposit thickness in nanograms/cm^2, 0.44 cm diameter SS 316 backing, 0.0127 cm thick, with an active deposit diameter of 0.35 cm centered on the SS backing.

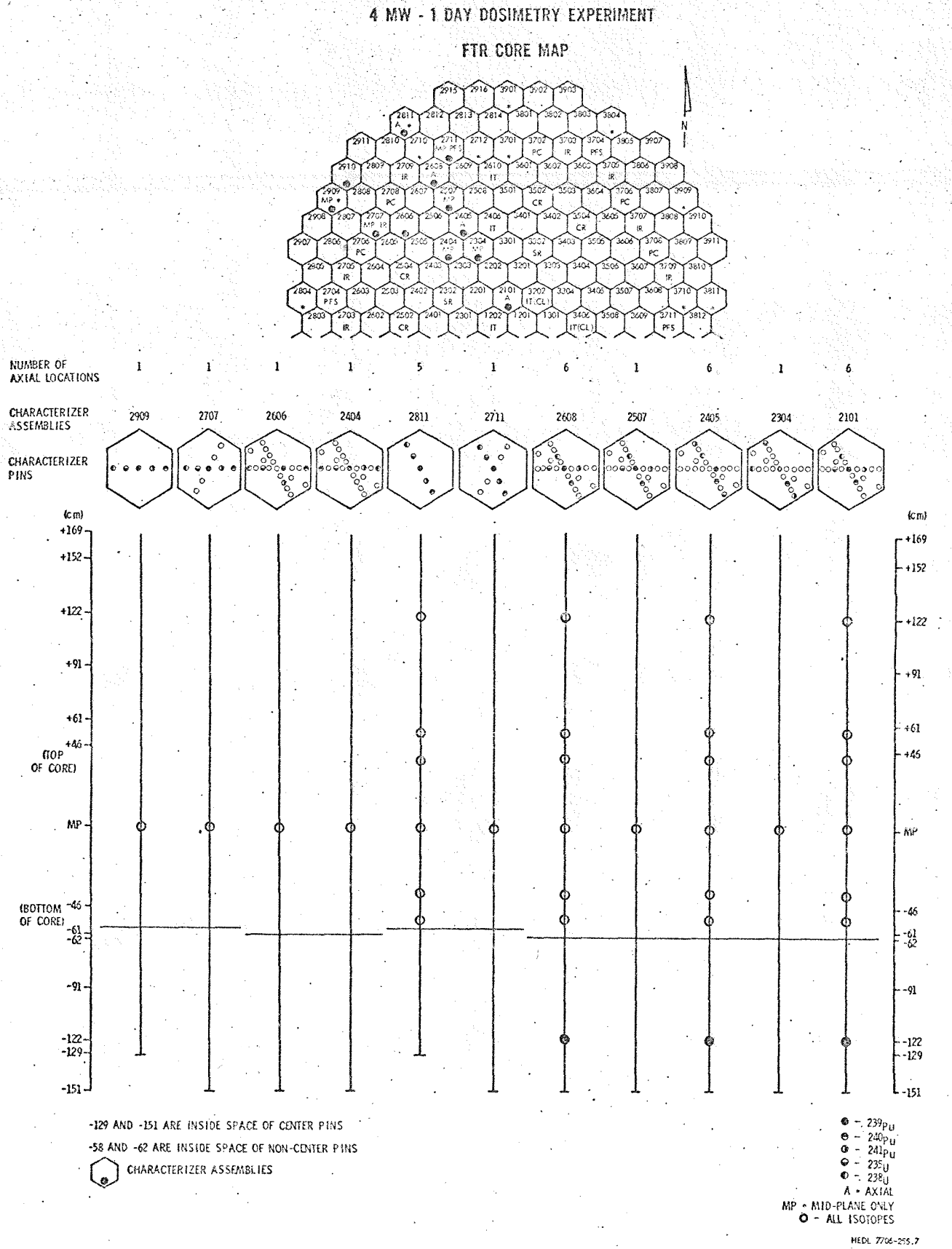

FIGURE 2. Priority No. 1 Dosimetry Locations for the LP Fission Product Yield Irradiation.

lower priority are measurements with ^{232}Th, ^{233}U, ^{237}Np, and ^{242}Pu. In addition, (n,α) reactions with ^{6}Li and ^{10}B can only be made at VLP, since plastic SSTR can not be used at the high temperature ($\sim$ 400°F) environment of the LP irradiation.

SSTR fission rate measurements will also be conducted at HP. Here, fission source deposit requirements are in the sub-nanogram range, and only natural quartz crystals appear to be suitable SSTR candidates.[2] In any other SSTR material known, the radiation damage along the path of a fission fragment will anneal at HP in-core temperatures, so that etching will not reveal tracks. As mentioned above (Section 3), further experiments to evaluate the annealing characteristics of quartz crystals and of other SSTR are in progress at HEDL.

Natural quartz crystals contain, perhaps, the lowest levels of trace heavy element impurity of all possible SSTR candidates for HP applications. Since HP source deposit requirements lie in the sub-nanogram range, trace heavy element impurities could produce high enough background track densities to compromise accuracy goals. Of all SSTR, these two remarkable attributes make natural quartz crystals a truly beautiful gift of nature, in that they are uniquely suited for HP applications.

(b) Applications of SSTR and of NRE in the Light Water Reactor - Pressure Vessel Surveillance (LWR-PVS) Program

As in the case of the FTR-RCP, a variety of techniques to measure the neutron fluence as a function of energy and position are needed for the LWR-PVS program. The techniques developed for the standard and reference fields need to be applied to various controlled fields such as PV-mockups, the Oak Ridge Reactor Pool Critical Assembly (PCA) and Pool Side Facility (PSF), as well as actual operating light water reactors. The use of SSTR and of NRE is being planned to contribute to our knowledge of the neutron fluence to be correlated with radiation damage in LWR pressure vessels.

Selected

Again, the use of NRE will be limited to environments in which the neutron and gamma fields are low in intensity; preliminary tests are in progress to determine which environments are suitable. As in the case of the FTR-RCP, NRE will give data on neutron spectra, primarily from 0.3 to 3 MeV, including information on the angular flux.[18] As before, the absolute recoil proton track distribution also gives knowledge of the intergral n-p scattering over selected energy intervals. Since the n-p scattering cross section is so well known, this information should provide a good check on normalization for data from other sensors as well as for incorporation in multiple foil unfolding codes such as SAND-II.[1]

Selected SSTR, along with multiple foil techniques, will again play a major role in the LWR-PVS program. In tests associated with an actual operating reactor, where the flux level is not likely to be constant with time, the ~~time-in~~ integrating nature of SSTR is an important characteristic for total fluence measurements. The wide range of sensitivity of SSTR to neutrons and insensitivity to other nuclear radiation, along with other advantages (see Section 1), combine to make the role of SSTR a valuable one in the LWR-PVS program. Again, for environments in which the temperature is high, the annealing characteristics of selected SSTR need to be well understood, and care needs to be exercised in the preparation, calibration, and selection of sources of fission fragments and of alpha particles.

Speculations on possible contributions of photo-fission to observed nuclear reactor phenonomena, especially in reactor dosimetry, have been contemplated for many years. Since high energy gamma-rays are not attenuated nearly as well as neutrons by the water moderator of LWR, a significant background due to photo-fission could be present in data obtained from some of the fissionable isotopes selected for LWR-PVS neutron dosimetry. However, the relative contribution of photo-fission to the total fission rate changes rather sensitively from one fissionable isotope to the next. In view of the many fissionable candidates available

for neutron dosimetry, e.g., ^{232}Th, ^{235}U, ^{237}Np, ^{239}Pu etc., SSTR measurements with appropriate combinations of these fissionable isotopes should provide estimates for the contribution of photo-fission, if it exceeds a few percent. Since many SSTR dosimeters can be simultaneously used at one location, this approach of investigating photo-fission contributions has a number of distinct advantages. Perhaps the most notable of these advantages is the ability to provide in-situ observations at critical locations in actual LWR-PVS environments.

(c) Application of SSTR and NRE in the Magnetic Fusion Energy Reactor (MFER) Program

The $^{6}Li(n,\alpha)$ reaction plays a fundamental role in MFER, since it will be used for tritium breeding. Since this reaction is such an important part of the fusion cycle, it plays a basic role in the design and optimization of MFER. To forecast the amount of tritium produced, accurate knowledge of this cross section is needed up to 14 MeV. The latest developments in alpha particle SSTR, as described in Section 3, make these detectors ideally suited for such cross section measurements. Beyond the general benefits of SSTR already cited, a fuller account of the specific advantages of SSTR for such crucial cross section measurements can be found in very recent reports.[50,51]

Fast neutron spectra will be much harder in controlled fusion reactors and in accelerator based D-T and D-Li sources than in LWR and FBR environments. Techniques developed for fission reactor applications may not be readily applied to spectra arising in MFER environments. Multiple foil activation, as well as unfolding techniques developed for their interpretation, will undoubtedly continue to be of major importance, but much improved neutron activation cross section data for the region from 15-30 MeV will be needed.

It appears that the use of both fission fragment and alpha particle SSTR will make important contributions to our knowledge of MFER neutron

spectra. All of the advantages of SSTR will be important here. But, as is true for multiple foil activation, additional data on neutron induced fission cross sections and on (n,α) reactions are needed for the proper interpretation of the results. Also, additional work will be required to measure alpha particle spectra with SSTR; due to a high background of C, N, O recoils in the plastic SSTR, not only will it be necessary to measure track diameters but also track lengths in order to do reliable alpha particle spectroscopy.[29] The C, N, O recoils, however, are themselves a potential source of neutron fluence information, as is already being exploited in neutron personnel dosimetry, especially through the use of electrochemical etching.[52] As better track recorder materials are found and developed, it is reasonably safe to forecast that the attractiveness of these techniques is likely to improve with time. It may even be possible to do neutron spectroscopy with proton recoil tracks in SSTR, if improvements in sensitivity continue.[53]

Some (n,α) reactions that are likely to be useful for neutron fluence measurements which have already been given in Table II. Other possibilities for the high energy end of MFER neutron spectra not listed include neutron induced fission or other reactions in nuclides with atomic number $Z < 90$. Here again, cross section data is needed and a consideration of these possibilities merits serious attention.

It has been proposed by R. Gold[54] to use SSTR to obtain data on Primary Knock-on Atoms (PKA) resulting from neutron interactions in stainless steel and in other materials that may be used in CTR. Information on PKA spectra can only strengthen our knowledge of damage cross sections and damage functions. To investigate the feasibility of obtaining information on PKA spectra, it is proposed to study the possibility of using such SSTR as phosphate glass and Lexan to measure leakage spectra from the surface of the material being irradiated.

In addition to passive PKA measurements with SSTR, active PKA measurements may be feasible, for example, with proportional counters.

It is well known that finite-size effects hamper the high energy applicability of 4π-recoil proportional counter neutron spectrometry.[17,37] Rather than considering such wall events as a nuisance, PKA observations in proportional counters may amusingly enough be possible by focusing on such wall events. The isotope or material of interst can either form the counter wall, or an appropriate liner of this material can be inserted into the proportional counter to form the cathode. Highly specialized proportional counters will, no doubt, be required. Such counters will have to be specifically designed, constructed and appropriately filled in order to carry out such investigations. Pulse-shape (rise-time) discrimination will undoubtedly be useful to resolve PKA events from background.

Unfortunately, active ionization-type observation of such low-energy heavy ion PKA spectra does possess an important fundamental limitation. The electronic stopping power of these low energy heavy ions decreases drastically relative to the nuclear stopping power for decreasing heavy ion energy. Indeed, this very behavior has already been advanced as the basis for the remarkable ability of Si(Li) detectors to discriminate against fast neutrons in Compton-Recoil Gamma-Ray Spectroscopy. A fuller discussion of this phenomenon can be found in a companion paper presented at this symposium.[55]

In constrast, SSTR observations do not suffer from this basic limitation of active ionization-type measurements. It has been shown[56] that the energy loss of slow heavy ions in dense SSTR media is due primarily to nuclear scattering rather than to ionization. Thus, SSTR can be used to measure lower particle energies than ionization detectors such as proportional counters. Tracks in SSTR, resulting from the slowing down of heavy ions through nuclear collisions, have been observed through etching such materials as mica, phosphate glass, and

Lexan PC.* One should be able to take advantage of this property by using track replication techniques[57] and scanning electron microscopy to measure PKA spectra, which will be harder (more energetic) and more copious in MFER than FBR or LWR environments. Clearly, much work has to be done to develop suitable techniques for such measurements and to establish limits of accuracy. One serious limit on accuracy of energy measurements is the large range straggling for such slow particles. Nevertheless, the use of SSTR for measurement of PKA spectra looks promising and a careful investigation is clearly warranted.

Another phenomenon that may prove useful for information on PKA spectra is "etch induction time", as recently studied by Ruddy et al.[58] The time of the observed initiation of the etching process at the surface of CN, after irradiation with ions of different charge and energy, is a function of charge (or mass) and energy. This phenomenon needs further study, especially for its utility in the measurement of PKA spectra.

Due to the accurate knowledge of the n-p scattering cross section up to 30 MeV and beyond, NRE offer great promise for neutron spectra and fluence measurements in the MFER program. However, owing to high gamma-ray sensitivity, NRE must be used at "reactor" startup, before large quantities of gamma emitting nuclides have been produced from neutron capture at high power operations. Proton escape probabilities from emulsion surfaces must be carefully evaluated for these higher energy spectra and competing reactions in the emulsion need to be studied. The use of other charge particle reactions, and the fact that angular flux information can be obtained, have already been mentioned. All of these factors are considered in greater detail in a companion paper presented at this symposium.[59]

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*Woods, Hart, and Fleischer (1973, unpublished but referred to on p. 142 of Ref. 2) found that tracks can be etched of Fe ions with energies only above $\sim$ 50 kev/nucleon in phosphate glass. J. H. Chan, using a Scanning Electron Microscope (SEM) to study formvar replicas of etch pits in Lexan detected Fe ions down to $\sim$ 3 kev/nucleon (unpublished, but referred to on pp. 142-43 in Ref. 2).

NRE should be used for the characterization of accelerator based intense neutron sources, which are used to provide simulated MFER environments for radiation damage studies. The neutron flux generated by these accelerator sources such as the D-Li reaction, is a very rapidly varying function of energy and angle. In such environments, NRE afford the following unique advantages:

(1) Absolute measurements are possible; reliance on the well known (n,p) scattering cross section has already been stressed.

(2) Low cost relative to alternative methods; low intensity exposures can be simultaneously conducted at many different angles.

(3) In-situ observations with virtually no perturbation of the environment.

(4) Spectral measurements can be extended down to about 0.3 MeV, which is lower than alternative methods.

In view of these extensive advantages, NRE provide an excellent complement to active spectrometry methods, such as time-of-flight or telescope counters, for the study of these simulated MFER environments.

7. Conclusions

As has already been emphasized, accurate knowledge of neutron fluence and of various reaction rates in neutron fields associated with the FBR, LWR, and MFER programs can only be obtained by employing a variety of techniques, both active and passive. It has been the purpose of this paper to discuss the kinds of information that are expected to come from the use of SSTR and of NRE in these programs. Some of these forecasts, such as the use of SSTR to measure PKA spectra and the feasibility of using plastic SSTR for accurate (n,α) measurements in reactive assemblies are somewhat speculative, since neither are accomplished facts. Nevertheless, the continuing progress and widening applicability

of SSTR techniques warrants considerable optimism, even in these areas. Techniques have already advanced to the point that most of the proposed applications are feasible and, if carefully executed, should give the desired accuracy.

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