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DOSIMETRY PROGRAM
FOR
CHARACTERIZATION OF THE FMIT FACILITY

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ABSTRACT

The environmental characterization program for the Fusion Materials Irradiation Test (FMIT) facility is presented. Requirements for the development and testing of Magnetic Fusion Energy (MFE) materials together with the complexity of the FMIT (d,Li) generated radiation field warrant a multifaceted dosimetric approach. Specific passive, active and calculational dosimetry efforts comprising this multifaceted approach are described. Special emphasis is given to those dosimetry capabilities uniquely required to characterize FMIT.

I. INTRODUCTION

In support of materials development for the Magnetic Fusion Energy (MFE) program, the United States Department of Energy is constructing an intense neutron source known as the Fusion Materials Irradiation Test (FMIT) facility.(1,2) The FMIT facility will generate an intense source of high energy neutrons for the systematic study, evaluation and development of fusion reactor materials. The Li(d,n) reaction will be used to produce this intense neutron source. A prototype linear accelerator will provide a high current deuteron beam (~100 mA, 15-35 MeV) that will impinge on a target of flowing liquid lithium. The objective for FMIT is a maximum flux intensity of 10^{15} neutrons/($\mathrm{cm}^2\cdot$sec) with a mean energy of 14 MeV.

The unperturbed steady state neutron volume/flux goals are approximately 10 cm^3 at 10^{15} n/(cm^2·sec) and 500 cm^3 at 10^{14} n/(cm^2·sec).

With these capabilities, FMIT will provide entry into a new realm of fusion reactor material testing. No irradiation facility yet built approximates the irradiation environment planned in FMIT, and full exploitation of this unique facility demands characterization of the irradiation environment to a degree consistent with MFE program accuracy requirements. For proper characterization in the 10 to 30% uncertainty range (1σ), FMIT facility design must be flexible enough to include both present and future dosimetry needs. These neutron and gamma-ray dosimetry needs, in turn, strongly impact the design of the FMIT test cell and its physical environment.

The evolution and general philosophy underlying the FMIT dosimetry program are described. To be sure, methods used for characterization of fission reactor environments all apply and are necessary, but the dosimetry task for FMIT is considerably more complex. Characterization of the FMIT test volume is complicated by several factors: 1) large flux component of very high energy neutrons; 2) steep flux and energy spectrum gradients within the test volume; 3) highly directional neutron flux, as opposed to the essentially isotropic flux in a fission reactor; 4) irregular production of secondary neutrons within the test assembly; and 5) great sensitivity of the preceding factors to source instabilities.

As a result of extensive planning and peer committee reviews, it was concluded that present state-of-the-art active, passive and calculational neutron dosimetry methods have significant shortcomings when individually applied to the characterization of the FMIT test volume environment. For example, except for the hydrogen (n,p) reaction, cross sections are not well known at high neutron energies, and conventional active detectors may not be reliable, considering high flux levels and large angular, spatial, and local temporal variations of the neutron energy spectrum. Passive detectors, while more suitable for high flux environments, do not provide the necessary real time information such as temporal variations of the (d,Li) neutron source. Flux gradients, directionality and source instability militate against a characterization based largely on a calculational approach. While it is reasonable to expect technical advances tending to improve this situation over the long term, it is not reasonable to assume that these advances will eliminate the need for a multifaceted approach for FMIT dosimetry. It has, therefore, been concluded that characterization of the FMIT radiation environment will be accomplished by a prudent combination of three general approaches, namely: 1) passive dosimetry, 2) active dosimetry and 3) calculational dosimetry. These three general approaches must be supported by evaluation and testing in low intensity benchmark field mockups as well as by longer range efforts to improve the accuracy of general nuclear data, such as cross sections that have a vital impact upon dosimetry accuracy.

In the next section the basic elements of these three general approaches are reviewed. Unique dosimetry capabilities that will exist in the FMIT facility are emphasized. The current status of these basic elements is discussed, including the most recent tests and evaluations. Time and space constraints unfortunately permit only brief consideration of benchmark fields for low intensity testing of FMIT dosimetry concepts as well as the need for gamma-ray characterization. These two topics are touched upon in the last two sections, respectively.

II. FMIT DOSIMETRY ELEMENTS

Each general approach, namely Passive Dosimetry (PD), Active Dosimetry (AD), and Calculational Dosimetry (CD), calls for special program elements. The general relationship among PD, AD, and CD elements is shown by block diagram in Figure 1. To implement these program elements, a number of dosimetry stations have been identified for specific dosimetry purposes at FMIT. These dosimetry stations are summarized in Table 1 and are discussed in sequel. PD, AD, and CD approaches are next described separately.

Passive Dosimetry

Passive dosimetry will be applied in-situ (i.e. within material test assemblies) at various locations throughout the test cell and in beam geometry for passive pinhole radiography at the 0° and 180° dosimetry stations. These PD elements will provide information to the Dosimetry Data Acquisition System (DDAS) for combination with AD and CD data, as depicted in Figure 1.

A general review of passive techniques for MFE environment was presented at the second in this series of ASTM-EURATOM symposia.(3) In-situ passive dosimetry will be most important for determining neutron spectrum and absolute fluence received by irradiated test specimens.(4) The strong dependence of neutron intensity as a function of distance from the source volume as well as the spatial dependence of the neutron spectrum makes in-situ passive dosimetry obligatory. Further, in a fully packed irradiation test volume, interaction of neutrons with materials in the test-zone will produce non-negligible spectral and flux intensity perturbations.

In order to correctly correlate radiation damage experiments, the necessary spatial spectrum-fluence information can only be delivered by in-situ passive dosimetry. Candidates for passive monitoring are: radiometric (RM) sensors,(5) solid state track recorders (SSTR),(6) helium accumulation fluence monitors (HAFM),(7) and nuclear research emulsions (NRE), which are applicable only for low fluence exposures.(8) A special grid of wire or foil RM sensors is foreseen at key locations in the test cell and can be replaced during or after each cycle. At these key sensor locations,

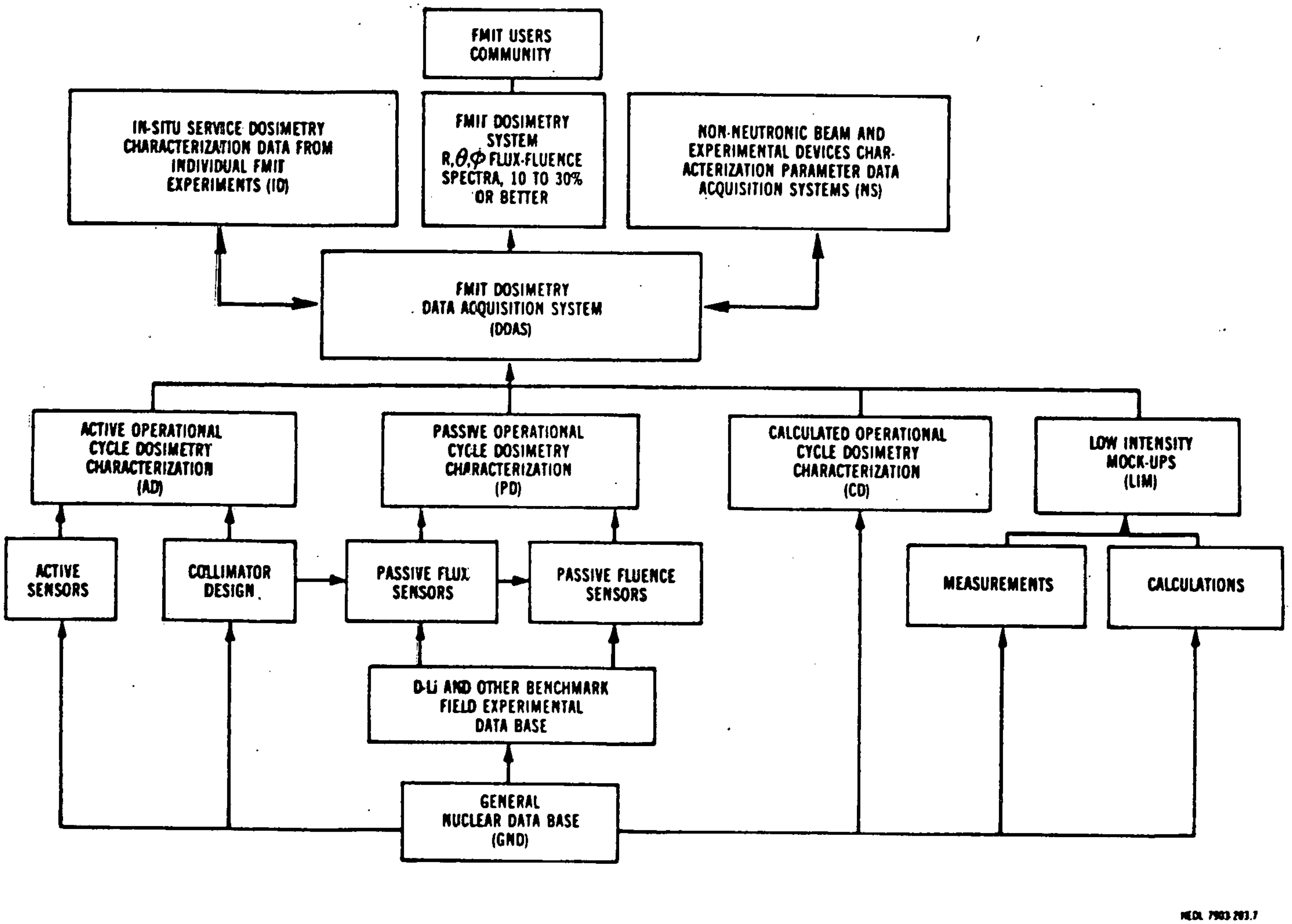

FIGURE 1. FMIT Dosimetry System Program Elements.

TABLE 1

ACTIVE AND PASSIVE FMIT DOSIMETRY SYSTEM STATIONS

Dosimetry Station	Categroy	CANDIDATE DETECTORS	
		Active	Passive
Ex-Test Cell Neutron Radiography Station - 180°	AD, PD	Position Sensitive Proportional Counter or Spark Counter	SSTR
Ex-Test Cell Neutron Radiography Station - 0°	AD, PD	(a) Charged Particle Telescope (b) Associated-Particle TOF System (c) Position Sensitive Proportional Counter or Spark Counter	SSTR
In-Test Cell Active Monitor Stations (Fission and/or Ionization Chamber Sensors)	AD	(a) Long Counters (b) Fission Chambers - Current Mode (c) Fission Chambers - Pulse Mode (d) Gamma Ionization Chambers	N/A
In-Test Cell Passive Monitor Stations (Fission and Non-Fision Reactor Sensors: Radiometric Monitors (RM), Solid State Track Recorders (SSTR), and Helium Accumulation Fluence Monitors (HAFM)	PD	N/A	RM, SSTR, HAFM
Lithium Flow Dosimetry Station	AD	Ge-Intrinsic	N/A
Service Cell Counting Stations (Primarily for Passive Sensors)	PD	Ge-Intrinsic	RM

cycle-to-cycle monitoring can be performed and limited data on the progress of experiments can be obtained.

Radiography stations at 0° and 180° will characterize the spatial and spectral distribution of the (d,Li) source using both passive and active techniques in beam geometry behind a collimator. However, the applicability of active systems at the 180° radiography is expected to be marginal because of the low beam intensity at this station. The present configuration for the 180° pinhole radiography station is depicted in Figure 2. For such a configuration, passive radiography with SSTR will be feasible. Among numerous attributes of the SSTR technique, discrimination against background and the availability of microscopic detail make it particularly appealing for this application.(9) However, due to reduced intensities, source radiography at this position will require an exposure of roughly a month or more at full beam current. Hence, only irradiation test assembly cycle-to-cycle data are anticipated from the 180° station.

Passive neutron spectrometry will also be implemented at the 0° radiography station using a scattering chamber beyond the forward pinhole neutron collimator. The extraordinary energy-dependent proton sensitivity of a new SSTR material, CR-39,(10) will be employed for passive neutron spectrometry applications at FMIT. Throughout the neutron energy range that will exist at FMIT, i.e., up to 50 MeV, only the hydrogen (n,p) scattering cross section is accurately known. Using appropriate hydrogenous radiators in the 0° scattering chamber, the entire FMIT neutron spectrum can be observed with CR-39 placed at suitable (n,p) scattering angles. Hence the proton energy sensitivity of CR-39, which extends up to at least 20 MeV, will furnish unique passive neutron spectrometry at FMIT on both an absolute and time-integrated basis.

The relevance of this remarkable new SSTR for FMIT dosimetry can not be over-emphasized, since it is considered mandatory that the FMIT facility have on-line active and passive neutron detection systems based on reliable and well-established standard reference cross sections. As previously stated, only one cross section can at present adequately satisfy this requirement for the 10 to 50 MeV region, namely the hydrogen (n,p) scattering cross section. It will be essential, therefore, to use this cross section as the standard reference cross section to validate and calibrate all other cross sections needed for active, passive, and calculational FMIT neutron dosimetry.

A brief discussion of the PD counting stations in the FMIT service cell is warranted (see Table 1). These stations will facilitate the use of short half-life RM sensors at FMIT. Rabbit tubes will be used for immediate transfer of such monitors between the FMIT test and service cells. In contrast with reactor materials test environments where work with short half-life monitors is invariably curtailed, many more short half-life RM candidates

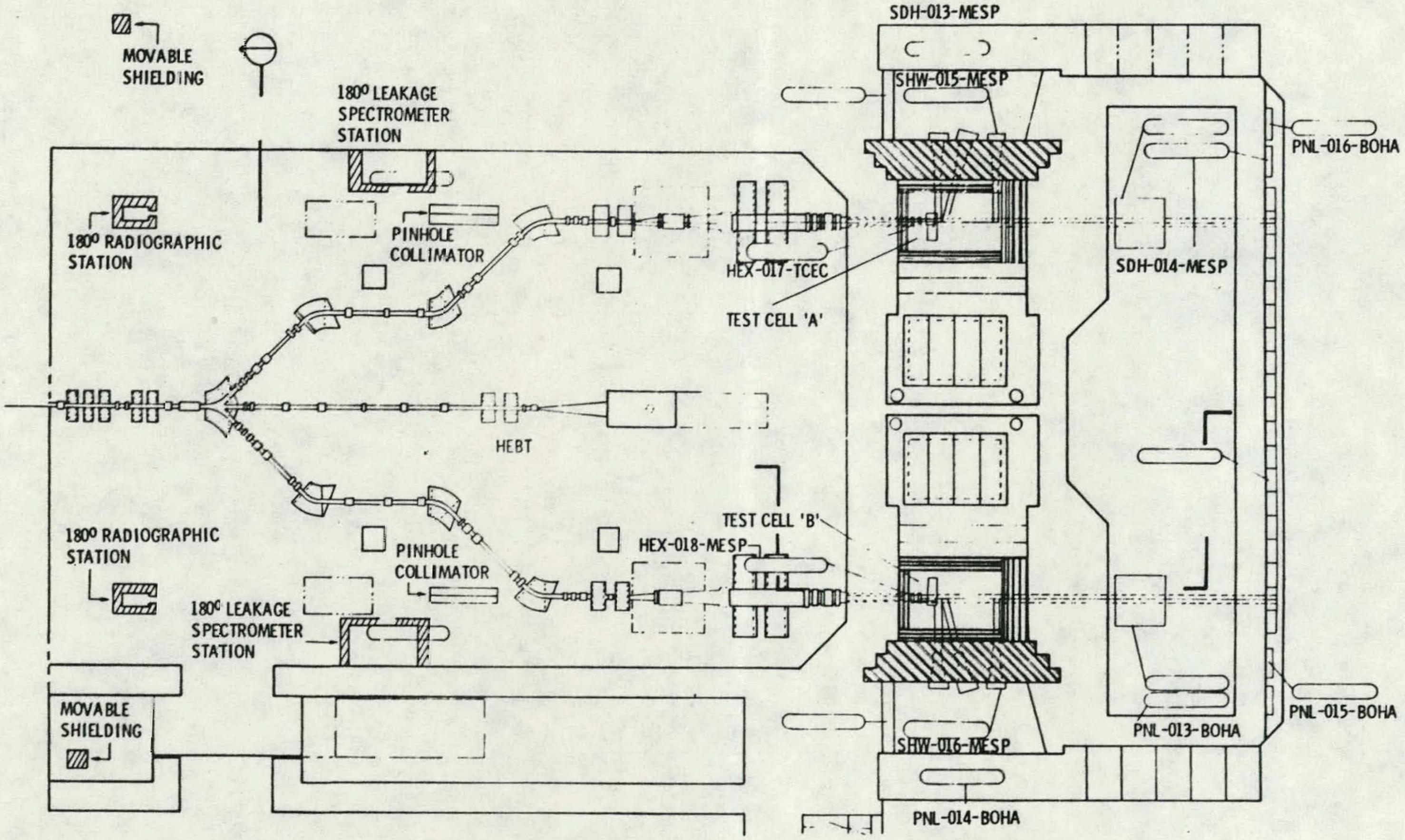

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FIGURE 2. Configuration of the 180° Passive Radiography Station, Viewed from Above.

arise through high energy induced reactions in the FMIT environment. Hence, there is significantly increased applicability and motivation for such monitors in PD work at FMIT.

Active Dosimetry

Active Dosimetry (AD) elements provide information to the Dosimetry Data Aquisition System (DDAS) for use with Passive Dosimetry (PD) and Calculational Dosimetry (CD) information, as depicted in Figure 1. The synthesis of AD, PD, and CD information, together with in-situ dosimetry, will provide the necessary flux-fluence spectral accuracy for FMIT test assembly environmental characterization, with uncertainties in the 10 to 30% range (1σ). As summarized in Table 1, integral and differential AD techniques will be used at specific dosimetry stations both within and outside the test cell.

Three AD assemblies will be used at strategic locations within the test cell. These in-cell assemblies will contain integral detectors, such as long counters, fission chambers and ionization monitors. Neutron time-history data from these AD in-cell assemblies will be monitored on-line by the DDAS as well as by FMIT plant operations.

Beyond the forward collimator of the 0^{o} radiography station, active techniques will be used for neutron spectrometry and spatial intensity measurements of the (d,Li) source. Components of the 0^{o} radiography station are outlined conceptually in Figure 3. Access is limited due to shielding requirements entailed by the intense flux of high energy neutrons. Among the more promising leakage neutron spectrometry concepts are:

1) Charged Particle Telescope
2) Associated-Particle Time-of-Flight (TOF)
3) Coincidence Analysis of the $^{6}Li(n,\alpha)$ Reaction
4) Magnetic Analysis of (n,p) Scattering

Radiography and spectrometry at the 0^{o} and 180^{o} dosimetry stations require a special collimator design. Candidate materials for the collimator are tungsten, copper and iron.(11) Due to its large size, the FMIT source (3 cm x 1 cm) cannot be seen through a classical collimator. Two collimator concepts can be considered, either a pinhole camera(12) or a hodoscope camera.(13) For example, Figure 4 shows a conceptual design of a pinhole camera at the 0^{o} radiography station (for a source of 10 cm x 1 cm). Just behind the collimator, the radiator foil of an active spectrometer permits on-line measurement of the total neutron source output and the spectrum (at a given angle). Although not shown in Figure 4, the scattering chamber employing CR-39 for passive neutron spectrometry can be used simultaneously. Far behind, just before the beam stop is either a position sensitive counter or a large area SSTR which

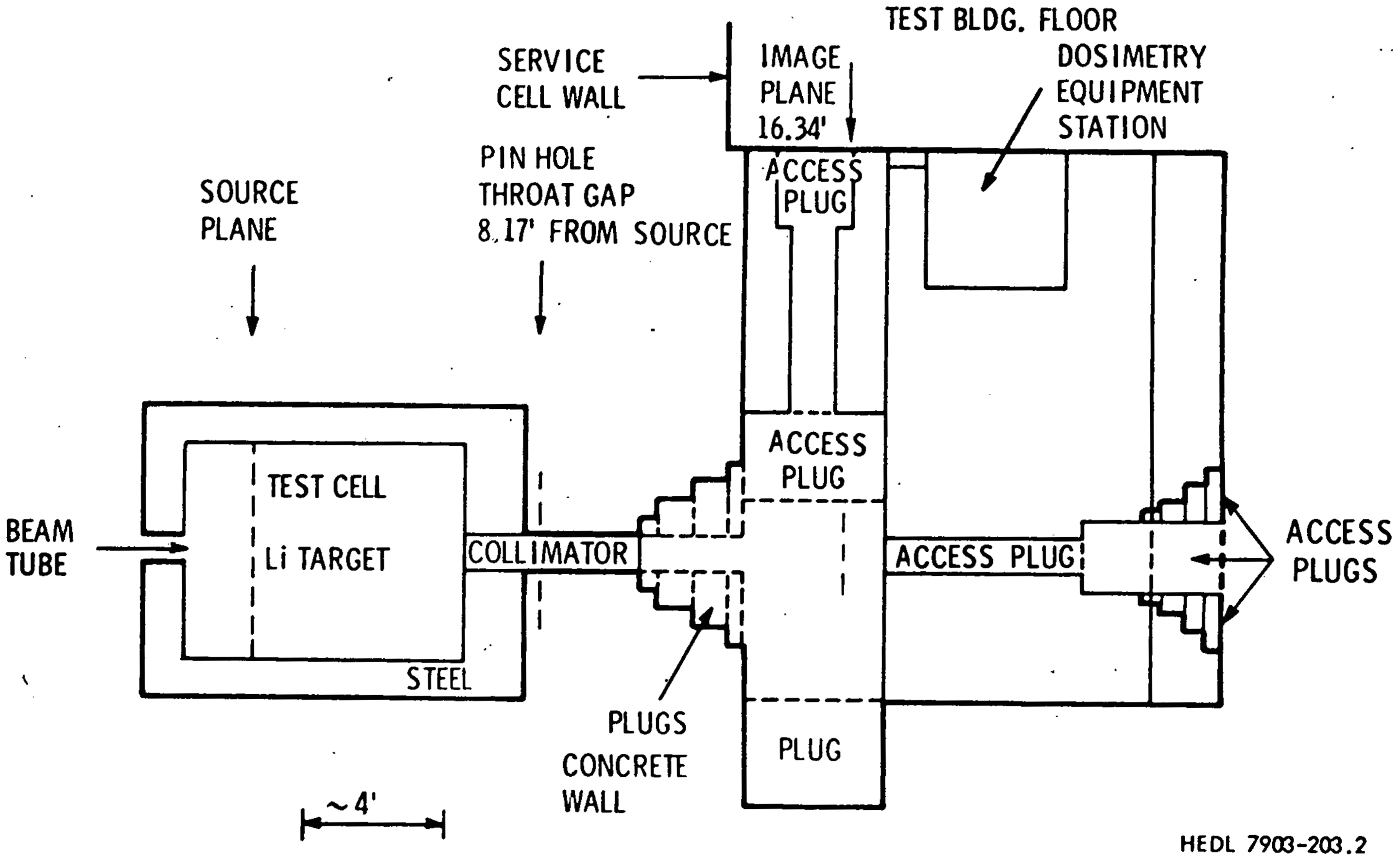

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FIGURE 3. Side View of the 0° Radiography Station.

measures the (d,Li) source intensity distribution. Both the spectrum and the source intensity distribution must be measured because the detector efficiency depends on the energy of the neutrons (through the cross section) and on the location inside the source volume where the neutrons are generated (through the angular dependence of the collimator transmission). Knowledge of source intensity distribution permits calculation of a mean geometrical efficiency for the active spectrometer.

Use of SSTR techniques for observation of neutron source spatial intensity distribution permits measurements within relatively short distances from the collimator throat gap. Other detection systems, such as an array of fission chambers or scintillators would require a location at much greater distances from the collimator and could be prohibitively expensive. In the example shown in Figure 4, 50 feet or more would be required instead of the 12 feet indicated. Solid state surface barrier detectors could also be used, but they suffer from radiation damage, which reduces their useful life and hence increases costs. However, active systems would permit the distinct advantage of on-line measurement of the (d,Li) source spatial distribution. A recently developed position-sensitive proportional counter(14) possesses spatial resolution on the order of millimeters and consequently is an excellent candidate for this application.

Preliminary calculations show that a collimator resolution of about 1 mm can be obtained for the FMIT neutron spectrum.(15) This collimator resolution will provide adequate definition of the neutron source for the most recent FMIT target design, which is 1 cm x 3 cm. Depending on available space, collimator resolution can further be improved, if necessary. In the hodoscope concept, the collimator consists of an array of very small slits. Each slit views only a small part of the source. An array of detectors is placed behind the collimator, so that each detector counts only the neutrons which leak through a single slit. While the spatial source distribution is observed, measurement of the total neutron output and spectrum is more difficult. For on-line measurements, a complete array of detectors is required, so that a hodoscope collimator system would be obviously more expensive than a pinhole camera collimator system.

Although more expensive, an advanced hodoscope collimator system provides the possibility of Fresnel imaging. The actual image must be transformed by suitable mathematical methods.(16) Such a Fresnel imaging system has advantages over a single pinhole collimator, since the signal rate is greater and the signal-to-background ratio is improved proportionately by up to a factor of 100. However, equipment and software required for mathematical transformation of the image would even further increase the cost of such an advanced hodoscope system.

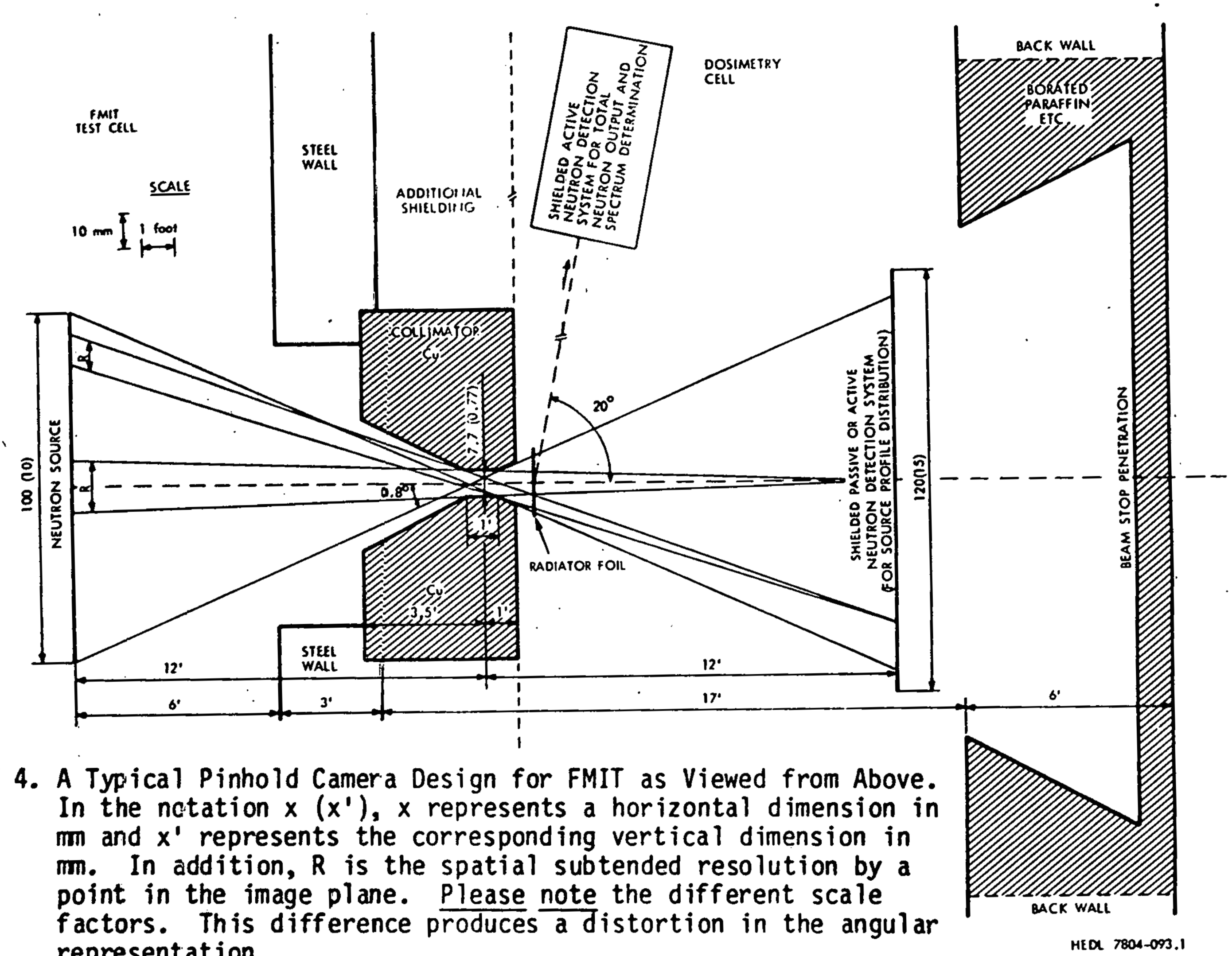

FIGURE 4. A Typical Pinhold Camera Design for FMIT as Viewed from Above. In the notation x (x'), x represents a horizontal dimension in mm and x' represents the corresponding vertical dimension in mm. In addition, R is the spatial subtended resolution by a point in the image plane. Please note the different scale factors. This difference produces a distortion in the angular representation.

Pinhole or hodoscope collimators can also be considered for the 180° radiography station for source spatial distribution, absolute source strength measurements and neutron spectrometry. In this direction, one observes source neutrons together with albedo neutrons arising from general interactions in the test cell. Consequently neutrons perturbations are minimum or even negligible for the 180° radiography station, so that observations are more independent of the test cell loading and configuration.

The Li-flow dosimetry station (see Table 1) is another AD element worthy of note. This station utilizes high resolution Ge detectors to measure radioactivants in the flowing Li. Ge detectors view the lithium transport pipe through appropriate gamma-ray collimators at selected distances downstream of the target. The role of the Li-flow dosimetry station in AD at FMIT is significant in that it provides:

1) Time history information on total neutron yield to DDAS and FMIT plant operations
2) Li target impurity information to DDAS and FMIT plant operations
3) Li flow stabiliy information to DDAS and FMIT plant operations
4) Source neutron spectrum stability information to DDAS and FMIT plant operations

Calculational Dosimetry

Since in-situ test assembly fluence-spectra are of primary importance, CD techniques will be used mainly in support of in-situ dosimetry. As illustrated in Figure 1, CD will furnish starting or initial spectral for unfolding codes utilizing in-situ dosimetry data. However, CD estimates of initial (r,Θ,ϕ) test cell spectra depend crucially upon the FMIT neutron source spatial and spectral distributions. Therefore, it is considered essential that the FMIT neutron source intensity profile be monitored by both AD and PD systems. These systems will provide necessary calibration and normalization points for the adjustment of CD methods. The status of (d,Li) neutron source measurements will be considered in a separate presentation in this symposium session.(17)

Data analysis unfolding methods for evaluating FMIT dosimetry measurements and calculated flux-spectra will be based on efficient algorithms combining features from generalized least-squares and maximum likelihood techniques.(18) Proximity of FMIT test specimens to the neutron source and characteristics of the source and test cell lead to rapid variations in both the spectral shape and magnitude of the neutron flux as a function of position in the test cell. These variations are strongly correlated with one another and can in part be calculated a priori from transport theory or Monte Carlo methods. Hence, an optimum evaluation of PD results should simultaneously consider measurements of different types and spatial locations along with calculational estimates of the neutron flux-spectra. A simple example emphasizes this point.

Assume that two identical sets of passive monitors are exposed at two separate locations, where calculations show a large difference in spectral shape. The problem is to combine this information with CD to determine the actual spectral shape and flux normalizations at both locations.

Proposed methods allow the simultaneous inclusion of multiple flux-spectra as well as multiple and diverse spatial and spectral data, including both PD and AD measurements. A priori information is to be assigned to all aspects of the evaluation process to ensure objective weighting of input sources, including all dosimetry measurements, cross-section evaluations and flux-spectra calculations. Results from the unfolding process will include appropriate adjusted spectra and cross sections along with complete uncertainty and correlation information. Statistical tests will be used to check for any inconsistencies in measured data, cross-section evaluations or calculated flux-spectra. This type of comprehensive treatment is particularly important for FMIT because of relative lack of cross section data and dosimetry experience in diverse high energy neutron environments.

As for calculational methods themselves, neutron transport techniques used in CD work for FMIT can not be viewed as a mere extension of reactor analyses. One does not have an extended neutron source with a well known primary spectrum, namely the prompt fission spectrum such as arises in reactors. Rather one has a highly localized source with spatial and spectral characteristics not nearly as well known. In contrast with the near homogeneity found in most reactor environments, the FMIT test cell is highly heterogenous. Finally the steep angular and spatial gradients of both intensity and spectrum are atypical of reactor environments.

These factors militate against adapting the more conventional neutron transport analysis for CD work at FMIT. It is not surprising, therefore, that in initial efforts reliance was placed mainly upon Monte Carlo methods.(19,20) It is well known, however, that Monte Carlo techniques are quite sensitive to cross-section uncertainties. This problem is unfortunately aggravated by the current status of neutron cross sections in the high energy region germane to FMIT. In fact, the present world-wide consensus is that cross sections are generally not well known at high neutron energy and may not be known any better for years to come.(21,22)

Some less apparent CD tasks essential to the FMIT dosimetry program must be mentioned. Two- and three-dimensional transport and Monte Carlo calculations will be required to support the evaluation and development of AD and PD techniques. Analyses will be required to design collimators, to predict sensor response as a function of position within the test cell, and to study relative benefits of candidate PD and AD techniques. It is also necessary for CD to treat perturbations introduced by test specimens and sensors, as well as to consider the effect of wall return. A constant upgrading of the cross-section data base will be necessary, particularly as evaluated cross-section sets are extended into the energy regime above 20 MeV. Finally, an important CD function is furnishing (r,θ,ϕ) cycle-to-cycle neutron exposure maps to prospective FMIT users for design and analyses of radiation damage experiments.

III. BENCHMARK FIELDS

The utility of benchmark fields for characterization of reactor radiation environments is firmly established.(23,24) Benchmark field experiments will provide significant benefits to the FMIT dosimetry program, particularly in view of the status of dosimetry techniques and nuclear data at high energy. In fact dosimetry at FMIT, or more generally fusion dosimetry, must be quantitatively tied to fission reactor dosimetry as well as D-T neutron source dosimetry. Irradiations in all three of these neutron environments must be placed on a common basis. This basis is best provided by a D-Li (or D-Be) Standard Benchmark(3) incorporated into a set of other standard benchmarks. Other benchmarks fields, which are expected to be available and used for nuclear data development and testing, are discussed and identified elsewhere.(23-26) Particularly important fields which will be used to test some FMIT dosimetry systems concepts as well as to develop nuclear data will be the Rotating Target Neutron Source RTNS-II at Lawrence Livermore Laboratory (LLL) and the low-intensity 14 MeV field at the National Bureau of Standards (NBS).

Low current operation of FMIT will serve as a Controlled Environment Benchmark which permits execution of the first phase of the environmental characterization program for the FMIT facility. Prior to the availability of FMIT, other suitable Controlled Environment Benchmark fields will be considered. Many of the first phase characterization measurements can be made using low current startup conditions at FMIT. Only checkpoint measurements at full power with active and passive systems are then required, together with those measurements possible only at full power FMIT operation.

IV. GAMMA-RAY CHARACTERIZATION

As we have learned painfully from efforts in fission reactors, the effects of gamma-rays must not be overlooked. The gamma-ray component of the test cell radiation field significantly impacts upon both radiation dosimetry and damage experiments performed at FMIT. The general importance of the gamma-ray field in radiation damage experiments was reviewed for FBR environments,(27) and the need for gamma-dosimetry efforts at FMIT can be easily surmised from this review. The gamma-ray component directly affects neutron dosimetry by establishing applicability limits for neutron dosimetry techniques as well as intrinsic experimental errors which arise through sensitivity to the gamma-ray component. On the other hand, knowledge of gamma-heating in test specimens and assemblies is extremely important to the materials experimenter for design and analysis of FMIT irradiation tests.

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