



A TECHNICAL REPORT PUBLISHED BY THE INTERNATIONAL ATOMIC ENERGY AGENCY, VIENNA, 1971 The IAEA does not maintain stocks of reports in this series. However, microfiche copies of these reports can be obtained from INIS Microfiche Clearinghouse International Atomic Energy Agency Kärntner Ring 11 P.O. Box 590 A - 1011 Vienna, Austria on prepayment of US \$0.65 or against one IAEA microfiche service coupon. PLEASE BE AWARE THAT ALL OF THE MISSING PAGES IN THIS DOCUMENT WERE ORIGINALLY BLANK

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L Introduction

The meeting of specialists on fast reactor spectrum measurements and their interpretation was held at the Argonne National Laboratory in accordance with the recommendation of the International Working Group on Fast Reactors, and in agreement with the U. S. Atomic Energy Commission. Representatives from nine countries and two international organizations took part in the meeting chaired by Martin Wiener of the United States Atomic Energy Commission. The list of attendees and their affiliation is given in Appendix A.

R. B. Duffield, Director of the Argonne National Laboratory, welcomed the attendees and wished them success with the meeting.

The final agenda, Appendix B, was adopted.

TUESDAY MORNING

II. Opening Remarks and Fast Neutron Spectrum Measurements in the U.S.

<u>M. Wiener</u> of USAEC opened the meeting by outlining the U. S. efforts in the area of neutron spectrometry for fast reactors, presenting a sketch of the accuracy requirements for the spectrometers as related to their application to core design, and finally by suggesting some questions that the papers and discussions should answer.

The goals or questions were as follows. What are the useful energy ranges for each technique? What is involved in extending these ranges? Do they overlap adequately for normalization purposes? What are the limitations and dangers in normalizing spectra from various techniques? What are the limits of resolution of each technique? What is the current accuracy? What are the limits of improved accuracy? What is the need for accuracy? And what are we going to do about all this?

He presented a simplified sensitivity analysis performed on the effect of the spectral shape on fuel inventory (enrichment) and breeding ratio. Calculation of these parameters were made for the ZPR-3/48 spectrum while varying the proportion of flux in the broad energy bands of 1 - 6, 6 - 185, and 185 - 1000 keV. The results (Figure 1) show that if one wishes to know these parameters to $\pm 3\%$, the gross spectral shape should be known to roughly $\pm 3\%$. Core designers would like $\pm 3\%$ spectral accuracy within each lethargy group, and within finer energy subdivisions near major resonances. Broad features of the spectrum are sufficient for the general random resonance fine structure.

He outlined the U. S. efforts in time-of-flight spectrometry, proton recoil proportional counters, and various other spectrometers. The two major goals of the program are testing cross section compilations (RPI and ORNL) and providing critical assembly spectra to check out calculational design methods and ensure accurate calculational techniques for important design parameters such as fuel inventory, breeding ratios, and reactivity coefficients (ANL and GRT).

At RPI, time-of-flight spectrometry is carried out from 0.01 to 10 MeV to make integral checks of differential nuclear data for the LMFBR program by comparing position-dependent angular flux spectra with calculations that utilize the same well-known driving source. They have



Figure 1. Effect of Spectral Shape on Fuel Inventory (enrichment) and Breeding Ratio

codes for generating group constants from standard files such as ENDF/B to perform one and two dimensional transport calculations. Simple age theory calculations are also used. For iron, they find that ENDF data leads to better agreement than Karlsruhe data because of better cross sections at 30 to 300 keV, but that more measurements are needed here, and that the 27 keV resonance minimum in ENDF/B data is too low and needs revision. Measurements on depleted uranium assemblies lead to some of the same conclusions. The resolution of the ENBF/B data is inadequate, but this doesn't significantly affect basic reactor design parameters. Defects in some standard computer codes have been revealed. New cross section libraries are being investigated. Fast spectra from aluminum and metallic sodium, and from the interface of dissimilar materials will be utilized.

In the ORNL efforts, neutron spectrometry is applied to shielding problems using the tower shielding facility. Spectra have been measured with the linac ORELA, both by time of flight and by unfolding with the same NE-213 spectrometer. They have developed unfolding techniques, such as FERDOR. They have also used proton recoil proportional counters, 10 Bfilter spectrometers, 3 He and 6 Li diode spectrometers, foil measurements, and "Bonner spheres". NE-213 is used for spectra above 0.8 MeV, proton-recoil proportional counters from 50 keV to 0.8 MeV, and the 10 B-filter below 1 keV.

At ANL, some work was done with cloud chambers and proton-recoil telescopes exposed to leakage neutrons, internal irradiations of protonloaded emulsions, and the ⁶Li coincidence-summing sandwich spectrometer. A time of flight capability is being developed for ZPR-6 which will be pulsed with a tandem dynamitron. Measurements will be made with good energy resolution down to 200 eV and will provide an interesting comparison at higher energy with the proton recoil proportional counter. This will be the first attempt in the U.S. for time-of-flight measurements on full scale Pu cores. The main effort at ANL has been with proton recoil proportional counters placed in critical assemblies. Pulse shape discrimination (PSD) allowed spectrometric measurements down to ~ 1 keV. These counters are highly efficient and cause no radiation buildup in the core material. In fact, their high efficiency requires a low radiation background to avoid swamping the counting electronics. About 10% energy resolution is achieved except at low energy. Statistics are a few percent and the high energy limit is 2 to 3 MeV.

The Gulf Radiation Technology program was initiated about three years ago to develop time-of-flight spectrometry and data-interpretation techniques, and to apply theoretical analyses as integral checks on fast reactor physics techniques and data. The subcritical time-of-flight spectral facility was constructed for use with a 20m, 50m, 100m, and 220m flight path. This is a split bed machine with a matrix configuration identical to the ZPR critical assemblies. A large volume of the core can be viewed by the flight path for position dependent spectral measurements. Ten assemblies of various sizes and compositions have been measured, for 100 eV to 8 MeV neutron energies in most cases, with ²³⁵U core loadings of 70 to 450 kg. Experiments have ranged from hard spectrum $^{235}U/^{238}U$ metal assemblies to soft spectrum oxide fueled LMFBR reactors. Fast reactor kinetics data have been obtained, primarily for making emission-time corrections. Important measurements are now underway on proton-recoil and time-of-flight comparisons to better understand the limitations of each method. Response functions of proton-recoil detectors are being measured to accurately determine the corrections necessary to unfold the spectra with differentiation techniques. The response matrix unfolding method may also be applied to obtain more meaningful comparisons.

III. Proton Recoil Spectrometry with Proportional Counters

Paper 1

E. F. Bennett of ANL discussed measurements with a 9.5 mm diam hydrogen-filled counter (8 atm H₂, 1/30 atm CH₄ for gas-gain stability and 1/30 atm N₂ for energy calibration with thermal neutrons initiating the $14N(n, p)^{14}C$ reaction) for 1 keV to 100 keV and a 16mm diam methane filled counter (8 atm of CH₄) for 100 keV to 2 MeV. The upper energy limit is set by problems with excessive end effect and down scattering corrections there. The high sensitivity of these proportional counters requires that they be small for Pu fast assemblies because of spontaneous fission from ²⁴⁰Pu in the core and because the spectrum is needed for an assembly with k_∞ near unity. Also, the small counters have additional advantages in that they cause smaller flux perturbations in the core and can follow the effects of heterogeneities to some extent.

The H_2 counter is used at low energies because the gas ionization constand W is very nearly constant above 10 keV and carbon-recoils are eliminated. Carbon recoils cannot be eliminated by pulse risetime discrimination in contrast to the gamma-ray events. The gamma-discrimination is used with both the CH_4 and the H_2 counters, but not at the highest energy end where no gamma-ray pulses are possible. Figure 2 shows a rate-of-rise spectrum for a mixed neutron-gamma source and one for a pure gamma-ray source, each for a narrow range of total ionization. A fit to the latter spectrum facilitates subtracting out the gamma-ray background under the proton-recoil peak.



Figure 2. Specific Ionization Spectrum Illustrating Gamma-Neutron Shape Discrimination in Proportional Counter

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W was deduced for H_2 below 10 keV (see Figure 3) by a measurement of the neutron spectrum (Figure 4) from a depleted uranium block. This spectrum is known to drop to zero below 5 keV. It is important (but perhaps not yet practical with proton-recoil spectrometers) to measure below 1 keV because about half the doppler effect is due to neutrons of those energies. The low energy limit on the CH_4 counter is set by interfering carbon-recoils. The correction for these is not accurate. For one thing, neutron elastic scattering off carbon is assumed to be isotropic in the correction.

The H_2 and CH_4 filling is done from bulk supply without purifications, leading to a degradation in resolution and a lower maximum gas pressure $(\sim 8 \text{ atm})$ attainable before the resolution begins to deteriorate rapidly. In obtaining a spectrum, the gas gain is changed several times for each counter so that each gas gain value gives a spectral segment corresponding to a given voltage. The segments are normalized to the fluence upon the detector for each run and taken together to obtain the entire spectrum. There is 1 - 2% agreement in the overlap region for successive voltages and poorer agreement near 100 keV where the H_2 and CH_4 counters overlap. Figure 5 shows a neutron spectrum measured in the FTR-3 core of ZPR-9, and compared to a MC^2 calculation (solid line). Note the error above 1 MeV, the inability to fit the 0.6 MeV hole in oxygen (due to dirty methane filling?), the 29 keV Fe resonance showing the need to raise the cross section in the compilation at 27 keV, and difficulty near the sodium resonance at 3 keV. The fine-group MC^2 calculation was smeared by the counter resolution to facilitate comparison.

In the discussion of E. F. Bennett's paper, he was asked by Wiener why the field corrections were large in the 100 - 400 keV region. Bennett pointed out that although the field corrections were large at 100 - 350 keV, percentage-wise they're only 4 - 5%. The sign of the field corrections changes at lower energies, and the magnitude increases to $\sim 50\%$ or more near the sodium resonance where the flux is badly depleted. In general, the sign and magnitude everywhere largely depend on the shape of the spectrum.

Bennett pointed out that they unfold by working always from high energy to low, and use calculated response functions rather than measured in order to correct the data to what would be obtained from an ideal counter that had flat responses. The approximations required in this approach introduce systematic errors that are by no means trivial. This idealized pulse height spectrum is differentiated to obtain the energy spectrum. No matrix methods of unfolding are used. He stated that the measured spectra were area-normalized to the MC² calculations, but they can provide any theoretician with the exact reactor configuration and the absolute fluxes.



Figure 3. Dependence of W Upon Ionization. Energy and Ionization are Assumed to Approach the Same Value as Both Increase.



Figure 4. Neutron Spectrum in a Depleted Uranium Slab Showing the Effect of Response Corrections



Figure 5. Central Neutron Spectrum in FTR-3, A Plutonium Fueled Fast Critical Assembly

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The critical assembly had to be run 1.5 - 2% subcritical to keep down the count rate which tends to be high due to 240 Pu spontaneous fissions in the core. A 0.051-cm thick layer of lead is placed around the counter to desensitize it from beta and gamma surface emissions from uranium. No spectrum corrections are needed for this thickness.

The sensitivity of the cylindrical counters to neutron flux spectrum anisotropies was discussed in view of the fact that Bennett recently applied response corrections to Snell block measurements, where anisotropies are serious. Bennett indicated that all response calculations, mainly wall and end-effect types, have been done for isotropic flux. In the center of large fast-reactor cores, isotropy is not a problem. They tried to limit their flux pattern to a so-called cylindrical symmetry in which the pattern does not change much axially. Some possible radial falloff may be present, but he feels this would still make the isotropic calculations valid.

Paper 2

<u>A. M. Broomfield</u> of Winfrith first presented the results of a study of the sensitivity of the reactor parameters to spectral shape. Starting with target accuracies (1 standard deviation) of ± 0.005 in k, ± 0.03 in breeding gain, and $\pm 10\%$ in doppler coefficient, they estimated a required accuracy in spectral shape of $\pm 10\%$ from 0.5 to 10 keV and about $\pm 4\%$ from 10 to 4000 keV with poorer accuracy outside these limits (more about these sensitivity studies in the Thursday afternoon informal session).

Calculations of the spectra were made with the MURAL code, which utilizes about 2000 groups for a multi-region cell, in conjunction with a spectrum editing code TOFFEE. From the same MURAL calculation, TOFFEE produced scalar flux spectra for comparison with incore spectrometers and directional spectra such as are observed by time-of-flight measurements. TOFFEE was also used for smearing the spectra to match the experimental resolution. The FGL4 library fine-group set was used, having 2176 groups of 1/128 lethargy width from 10 MeV to 0.414 eV. MURAL treats inelastic scattering in fine group form.

Spectral measurements were made on two zero-power fast assemblies; Vera at AWRE Aldermaston, used for basic neutronics studies of small multiplying systems, and Zebra at A. E. E. Winfrith, a large system for physics studies of plutonium-fueled fast power reactors which can accommodate cores of over 1000 kg of fissile material.

In-core spectral measurements were made with the 39mm diam spherical hydrogen-filled counter design developed by Benjamin , et al, (1) and spectra of an extracted beam were recently measured up to 2.5 MeV by

using a 152mm counter filled with 2 atm methane. Good counter resolution was achieved by degassing at 200°C, heating the collecting wire to 1200°C, and purifying the hydrogen filling gas through an Ag-Pd diffusion tube. Resolutions range from 3.5 to 10%, with the best 10 atm filling giving 6%. Hydrogen fillings of 1, 3 and 10 atm are used for overlapping ranges of 50 - 300 keV, 100 - 600 keV and 200 - 1200 keV respectively with the 39-mm counter. Typical gas-gain settings for the 3 atmosphere hydrogen filling correspond to energy ranges of 2 - 5, 4 - 15, 10 - 40 and 25 - 100 keV. Changes in gas gain between the voltage settings used for calibration and measurement are determined by using the relationship of Diethorn⁽²⁾. Below 50 keV, pulse-risetime gamma discrimination is utilized, with the aid of two parameter data storage. For gamma-discriminator calibration, a ⁶⁰Co source is used at Winfrith and the shutdownreactor radioactivity at Aldermaston. Neither accurately represents the gamma-ray spectrum that is effective during neutron counting, but the latter does represent the directional distribution. The distribution of gamma-ray risctimes (for a fixed total pulse height) displays a peak with a tail that extends out to the narrow proton-recoil peak. The downside slope of this tail is the region fitted against a gamma-only measurement (and not the entire gamma-ray distribution of risetimes) to improve the precision of background subtraction.

Argus 500 on-line computers are used at both laboratories for data taking and for some processing of the recoil-proton spectra. Preamplifiers with a noise level equivalent to 400 ion pairs and 10 pF input capacitance are used. Improvements of the electronics will include leading-edge pileup rejection and base-line restorers.

The SPEC 4 program⁽³⁾ used for obtaining neutron spectra from protonrecoil spectra was significantly extended in accuracy by utilizing response functions measured from 70 to 2500 keV with monoenergetic neutrons from a Van de Graaff generator for hydrogen fillings of 1, 3 and 10 atm. Observed distortions are worse than the analytical expression of Snidow and Warren⁽⁴⁾ which allows for wall effect distortion alone. A Monte Carlo calculation that included effects of reduced gas gain near the ends of the counter wire came very near the observed responses, but only when the proton tracks were short. A satisfactorily close simulation of the responses was finally achieved by increasing the proton range by 5 -10%, although the reasons for the failure of the wall-effect calculation to correct for the responses is not known.

An attempt to increase the high-energy limit of the 39mm diam counter was made by increasing the (purified) methane pressure to 10 atm, but the ³He peak (from the ³He(n, p)³H reaction) broadened rapidly with increasing pressure and was 20 - 25% low on the energy scale at 8 - 9 atmospheres of CH_4 due to recombination effects in the densely ionizing recoiling triton tracks. The pulse-height versus energy plot at 8 atm CH_4 was linear but the zero intercept was at 0.1 MeV (the lowest-energy point on the plot being at 0.2 MeV). A 2 atm CH_4 spherical counter of 152mm diam was used instead, because the zero intercept was not off put passed through zero on the energy scale. Energy scale determinations of 2 - 3% accuracy are achieved with 3 He(n, p) 3 H reactions in the gas, with a small Pu alpha source on the wire, with observed peaks and troughs from resonance blocks, and by experimental verification of the Diethorn relationship between gas gain and anode voltage.

The development of two independent techniques for spectral measurements is essential because systematic errors in a given technique are otherwise too difficult to ascertain. In the Winfrith and Aldermaston approach, the measurements with the proton-recoil proportional counter and the time-of-flight technique were compared with each other as well as with the MURAL/TOFFEE spectral calculations. Measurements for the VERA 7A assembly were compared with results obtained by Karlsruhe as well, where cylindrical proton-recoil proportional counters were used. Agreement was achieved between the three measurements to within 10% from 1 to 600 keV. The results of the proton-recoil and time-of-flight techniques are shown in Figure 6, along with nuclear-emulsion data above 1 MeV. In Figure 7, the proton-recoil counter results of a measurement on the ZEBRA 8D assembly are shown, compared to a MURAL code calculation (upper). (The time-of-flight spectrum, lower, is discussed later.) Estimated errors in several of the recently performed proton recoil measurements on ZEBRA 8A, 8B, 8C, 8D and 8G cores at Winfrith are 5% at 30 - 1000 keV, 8 - 15% at 10 - 30 keV and 11 - 20% at 5 - 10 keV. Some of the overall accuracy is limited by normalization in that 2 - 3% adjustments need to be made to get good fits in the overlap region. Between 50 keV and 1 MeV they can define the ratio of flux amplitudes to 7%. Normalizations are made to the same fission rate per gram of 235 U.

Some tests of proper sampling over the heterogeneous core were carried out, showing no differences in the uranium or plutonium regions within the 3% statistical accuracy. Perturbation of the spectral shape by the 1 - 12 mm thick lead shields required for measurements below 50 keV was also checked in the 200 - 1000 keV range (where the inelastic cross sections of lead become significant) with and without the lead shields, and no differences were observed within the 2% statistical accuracy of the measurement.

In the discussion of A. M. Broomfield's paper, he pointed out that at Winfrith he and M. D. Carter worked with proportional counters, I. C. Rickard with the ⁶Li spectrometer, and I. H. Gibson, J. P. Hardiman, D. Jakeman and J. Marshall with time-of-flight work. At Aldermaston,



Figure 6. VERA 7A, Neutron Spectrum Measurements

1 ☆



Figure 7. ZEBRA 8D. Upper:- Proportional Counter Spectrum compared with MURAL (full curve) Lower:- Time-of-Flight Spectrum compared with MURAL (full curve)

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C. D. Kemshall and W. J. Paterson work with proportional counters, W. J. Paterson and J. Redfearn with time-of-flight, and J. Redfearn, W. J. Paterson and M. Mackenzie with the double scintillator.

The investigation of heterogeneity effects was not carried out by changing the unit cell while maintaining the same mean composition, he pointed out, but the counter was moved about within the cell. For the rather large counters used, which integrate over the cell rather well, no effects were found within a 2 - 3% statistical uncertainty between 200 and 1000 keV in the most extreme case, that in ZEBRA 8A, where the fissile plates are separated by a lot of graphite. The largest tilt in the calculated spectra was seen between 200 and 1000 keV in the two extreme uranium and plutonium regions where the measurements were made. However, if the fuel regions are very well separated compared to the dimensions of the counter, proper integration over the cell may not be achieved. Estimates of the effects of the steel walls and the lead shield of the counter indicate that these would introduce no more than 1 - 2% tilt.

The one and ten atmosphere hydrogen fillings were pure H_2 , but 5% CH₄ was added to the 3 atm H_2 filling for quenching and improving the stability at high gas gain. They made comparisons with a counter with less than 5% CH₄, and from these comparisons they estimate that as little as 0.5% CH₄ would suffice for quenching and gas gain stability. Measurements in which the CH₄ content was altered were also carried out with a 1 atm filling and the range of useable gas gain was definitely increased by adding 5% CH₄ in this case. The choice of a 5% CH₄ addition followed the work of Bennett, since the U. K. groups haven't as yet carried out the experiments necessary to better define the optimum mixture of CH₄ in H₂.

The change in response functions due to the addition of CH_4 is taken into account, in the calculation of the responses, by including its effect upon the range. The effects on W for CH_4 at lower pressures may not be serious judging from the fact that the extrapolation of the pulse height versus energy plot goes to zero, very nearly.

The Monte Carlo calculations agree well with the measured response functions for track lengths up to one counter radius, but when longer, there is a residual discrepancy which they cannot at present explain. They have adjusted the SPEC 4 code to simulate the observation without knowing what is causing it. They feel, from the Monte Carlo calculations, that this remaining discrepancy can be attributed to the variations in gas gain near the end of the wire. The variation of gas gain along the counter wire was measured by the Aldermaston group by injecting alpha particles at different points along the wire. This variation has been simulated in recent Monte Carlo calculations, and in calculating responses for this simulation they found close agreement with the observation for track lengths equal to the counter radius. Corrections are applied for the difference between the fundamental mode and the subcritical assembly. In the case of a driven assembly, the surrounding driver can perturb the spectrum. In their test zone assemblies, there was a smaller perturbation in the central spectrum with the driver zone removed than in the critical assembly, but these differences are taken into account by running a coarses group multigroup calculation using the order of 6 groups. They calculate correction factors which may be 2 or 3 percent.

Paper 3

<u>M. Marseguerra</u> of CNEN, Italy, stated that at present, CNEN has no fast-reactor facilities. The fast neutron spectrometry studies take place at the Centro di Calcolo (Computation Center) of Bologna where they investigate different methods of data analysis by analytical and stochastic simulation. They began with studies of threshold detectors because of their ease of use and insensitivity to high temperature and gamma background, but soon learned that the analysis can give poor results due to experimental errors and to the large uncertainties and poor correlations of the cross sections. The limited number of threshold detectors normally available also severely limits the attainable resolution.

Two methods of data analysis were studied, one based on utilizing linear programming⁽⁵⁾ and the other one the use of approximate quadrature formulae⁽⁶⁾.

Some experimental work has been done on the calibration of protonrecoil spectrometers with alpha sources. These are the single chamber proportional counters, and the Perlow type in which two proportionalcounter chambers, operated in coincidence, are separated by a proton The pulse-height distribution of the Perlow-type telescope collimator. spectrometer, as measured with monoenergetic neutrons, was accurately calculated by taking into account energy losses in the collimator and statistical fluctuations due to the ionization and multiplication processes and mechanical imperfections. The very objectionable high energy tails reported elsewhere were found to be due to accidental coincidences between the two chambers and therefore easily removed experimentally. With a simulated measurement of the Po-Li neutron-source spectrum, using a single chamber of the Perlow spectrometer, unfolding was carried out with the approach of Burrus. (7, 8) The results agreed well with the input spectrum⁽⁹⁾, and this lead to scheduling a measurement of the spectrum of neutrons emerging from a small fission plate exposed to thermal neutrons.

Assuming the validity of the Diethorn expression, ⁽²⁾ a method was developed for the energy calibration of the spectrometer filled with mixtures of gases. Measurements with alpha particles were made at several filling pressures of methane. The results were only in fair agreement with the Diethorn expression, probably because of the rough value assumed for the attenuation factor (see below). A more precise analysis is now being carried out. They find that for some pure gases, including methane, the multiplication can be more accurately determined by making use of the experimental values of the Townsend first coefficient a (defined as the mean number of secondary electrons produced by an electron per centimeter of path along field lines). The results of experiments comparing the gas multiplications obtained by these two different methods are being analyzed. Attempts were made to correlate the height of the shaped output pulse from an RC coupled amplifier with the width of the pulse, in an effort directed at inferring the attenuation factor from a measurement of the pulse width. This was done in an effort to correct for the resolution smearing effects of varying rise times of the pulses. In practice, this did not work because the height varied too rapidly with the pulse width for the RC time constants used.

Their future work will probably involve the development of single-chamber proton-recoil spectrometry techniques and the comparison of the results with the Perlow-spectrometer data.

In discussion M. Marseguerra's paper, the importance of random coincidences was dealt with. The Perlow counter operated in a flux of 10^5 fast neutrons/cm²-sec, with an efficiency of about 10^{-6} for the 1/3 atm CH₄ filling. It is accidental coincidence-limited at low energies. For a fission-like spectrum (from a fission plate irradiated with thermal neutrons), they expect a lower energy limit of 500 keV. The upper limit should be about 2 MeV.

Paper 4

<u>A. Leridon of Cadarache said that the development of the proton-recoil</u> neutron spectrometer at his laboratory since 1966 has been aimed at obtaining and calibrating a good set of standard counters and associated electronic circuitry, and developing an all-analytical data handling system capable of handling any counter geometry.

Initially, they studied spherical counters (Benjamin type) manufactured by 20th Century Ltd., but had difficulties with resolution and calibration problems. They shifted to cylindrical counters manufactured by "La Radiotechnique" when they learned that wall and end corrections were possible with a cylindrical counter placed in a nearly isotropic

neutron flux. The counters which have been used for the past two years are of 25mm O.D. and 75mm active length, one filled with 1 atm of 76% $H_2 + 1\%$ $CH_4 + 5\%$ N_2 and one with 4 atm of 95% $CH_4 + 5\%$ N_2 . The hydrogen mixture gave a 3 to 4% resolution for the $^{14}N(n, p)^{14}C$ reaction at 620 keV (thermal neutrons incident). A new set of smaller volume counters, 12mm diam by 60mm active length, has been developed for use in higher neutron fluxes. They have twice the above pressures with a 6% resolution for the 2 atm H_2 + CH_4 + N_2 mixture and 15% for the 8 atm CH_4 + N_2 mixture. The (n, γ) discrimination is almost as good as with the larger counters. They will attempt to reproduce the earlier measurements with these new counters before putting them to routine use. The earlier counters were tested for resolution, linearity, and also lowenergy (n, γ) discrimination, with the 620 keV line of the ¹⁴N(n, p)¹⁴C thermal neutron reaction and with neutrons at 5 energies between 5.1 and 22.5 keV produced by the Cadarache Van de Graaff accelerator. The 5 keV point is off for the H_2 + CH_4 + N_2 counter, indicating that the nonlinearity extends upward to a higher energy than that for a pure-H2-filled counter.

The counter electronics feature a high-count-rate system and a novel risetimemeter. The preamplifier output is proportional to the ionization current. The resulting short pulses are amplified and a gating and pulse integrating circuit (working in a large-pulse-height range) effect an integration over the short current pulses for a maximum ion collection time of about 4μ sec.

A novel risetime measuring arrangement is used that provides timing signals at 20% and 70% of maximum pulse height. These actuate a timeto-pulse-height converter whose output gives the second parameter for the biparametric analysis needed for the n, γ discrimination. The maximum possible count rate has been raised from 2000 cps to 15000 with this circuitry, excluding most of the gamma-ray pulses, but at a cost of a factor-of-four increase in the electronic noise. The problem of perturbation of the neutron flux by the thick lead shielding that is usually required for counters with more conventional electronics is circumvented.

The data processing makes use of the approximate differential relationship between the neutron spectrum $\varphi(E)$ and the proton pulse-height distribution P(E),

$$\varphi(E) = -(E/\sigma) dP(E)/dE$$
(1)

and relationship via the response matrix A

$$\mathbf{P} = \mathbf{A}\boldsymbol{\varphi} \quad (2)$$

The neutron spectrum obtained with equation (2) does not give much larger errors or local variations than with equation (1), and it properly takes into account any arbitrary set of responses without the requirement of obtaining an idealized and properly corrected P(E) that can then be differentiated as in equation (1). It does, however, require accurate calculations of responses, unless, of course, they can be measured.

The integral spectrum, in an energy interval $E_2 - E_1$, can be obtained from (1) by integration by parts, obtaining

$$\int_{E_{1}}^{E_{2}} \varphi(E) dE = \left| \frac{E}{\sigma(E)} P(E) \right|_{E_{2}}^{E_{1}} + \int_{E_{1}}^{E_{2}} P(E) d\left(\frac{E}{\sigma(E)} \right), \quad E_{1} < E_{2} \quad (3)$$

Since $\sigma(E)$ varies monotonically with E for hydrogen and can be put in analytical form, $d(E/\sigma(E))$ is well defined. This approach gives a much more accurately determined quantity over the group E_1 to E_2 than does the detailed neutron spectrum. The accuracy of Eq. (3), like Eq. (1) from which it is derived, is clearly limited by the assumption that proper corrections can be made to P(E), such as end and wall effects, before Eq. (1) or (3) is applied.

The spectrometer was compared with the Karlsruhe spherical spectrometer in 1967 and the 8-group results from 4.6 to 1400 keV shown in Figure 8 were within 6% agreement except above 1 MeV ($\simeq 10\%$). Spectral measurements were later made in graphite-uranium subcritical assemblies in which 30% enriched uranium rods, 1.27 cm diam, in stainless cylinders, were vertically loaded in graphite matrices (square array) of 2.63-cm (HUG2), 3.0-cm (HUG3) and 4.5-cm pitch (HUG4). Only C/U was changed, but not U5/U8. The experiment was regrouped to agree with the 25 group calculation and the result for HUG2, 3, 4 are compared in Figure 9. The comparisons are all close to one another so that the differences are well outside of the experimental errors. An integral method of comparison was also applied between 9 and 1350 keV, and also between 9 and 183 keV. The function

$$\Delta R (u) = \int_{u_0}^{u} \psi_{HUG2} (u) du - \int_{u_0}^{u} \psi_{HUG4} (u) du \qquad (4)$$

is shown for three different calculations and for the experiment in Figure 10 with u_0 here being the lethargy corresponding to E = 183 keV. The comparison indicates a systematic error in $(\Sigma_c + \Sigma_f) / \Sigma_s$. They have shown that the maximum of ΔR represents $((\overline{\Sigma}_c + \overline{\Sigma}_f) / \overline{\Sigma}_s) \ge \eta$ where η is



Figure 8. Comparison of Spectral Measurements with Cadarache Cylindrical Counter and Karlsruhe Spherical Proton-Recoil Proportional Counters

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		$\frac{1}{\sqrt{G}} = \frac{1}{\sqrt{G}} = 1$	mparison of Measured I Calculated (25 G. oup) octra for Graphite- axium Subcritical semblies with Pitch of 53 cm (HUG2), 3.0 cm UG3) and 4.5 cm (HUG4)	
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a function of only the dilution if the variation of these cross sections can be assumed to be linear in the considered lethargy range and where the $\overline{\Sigma}$ are average values. Note that by carrying out the calculation in Eq. (4) for differences between HUG2 - HUG3, HUG2 - HUG4, and HUG3 - HUG4, they could tell if the experiments were consistent with one another.

Spectral measurements were made in assemblies loaded with uranium and plutonium fuel in Masurca. These were oxide type reactors with the oxygen simulated by iron oxide (Fe_2O_3) and with sodium diluent. The integral method of checking the spectrum variation was applied to check the variation for the case of uranium plutonium substitution or in the case of different dilution (U5/U8 or Pu9/U8). The agreement was fairly good.

In direct comparisons with the 25 group calculations (Figures 11 - 14), the shape of the difference between the experimental and calculated spectra is similar in many assemblies either with U or Pu. Attempts made to see which cross section affected the spectrum, particularly in groups 8 to 12, showed that Σ_c and Σ_f had a strong effect on the reactivity but a small effect on the spectrum, and the Σ removal (particularly elastic removal) had a strong effect on the spectrum and a rather small effect on the reactivity. In Figures 12 - 14 are shown some examples of the effects of Σ (elastic removal) adjustments on the spectrum.

In the discussion of A. Leridon's paper, he made the clarification that Σ_c was that from ^{235}U and ^{238}U , Σ_f from ^{235}U , and Σ_s due to carbon. He pointed out that the Karlsruhe and Cadarache spherical counters were not the same. Some discussions were started on detector resolution, as related to the unfolding problem, and also concerning smoothing of the data before unfolding or differentiating, but these were put off for the afternoon informal discussion.



Figure 11. Comparison of Measurement and Calculation, R2 - Z2 Assembly



Figure 12. Influence of Cross Section Correction for ZPR III-48 Assembly



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Figure 14. Influence of Correc-									
tions to $\Sigma_{e, r}$ on Spectrum for ZPR						· · · · · · · · · · · · · · · · · · ·			
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TUESDAY AFTERNOON

IV. Informal Session - Proton Recoil Spectrometers

A. M. Broomfield, Chairman. As to the gas purities desired, it was generally agreed that most of the present methods of hydrogen filling give difficulties below 5 keV. Broomfield pointed out that they use a silver-palladium leak for hydrogen purification and suggested that Bennett's Na-resonance (3 keV) displacement failing to agree with calculation may be impurity related. Bennett stated that substantial effects were found in using the 14N(n, p) reaction for calibration, due to the presence of impurities and other effects. He estimated a 4 - 10% resolution degradation due to impurities, but too short of an amplifier time constant can also contribute in underestimating the long tracks whose total charge-collection time may be several microseconds. There are other calibration problems, too. The more densely ionizing track of the tritium recoil in the ³He(n, p)T reaction leads to recombination effects that underestimate the pulse height. A ³He partial filling for calibration may for this reason be worse even though the neutron capture cross section is much higher than for the $14N(n, p)^{14}C$ reaction (the T-recoil takes on a larger fraction of the kinetic energy than does the ¹⁴C-recoil). Bennett also feels that the small nitrogen gas impurity is not important for his mixture of $1/30 \text{ atm N}_2$ per 8 atm H₂.

Effects of impurities in CH_4 and problems at high pressures (> 3 atm) were discussed. Bennett would like to get rid of CH_4 because of effects other than the impurity of the gas, like carbon recoils, and would propose to reduce the proton-recoil track length by using a Kr-H₂ mixture. He cited H. Werle's thesis at Karlsruhe where, Wattecamps pointed out, an 89mm diam x 835mm long counter with two fillings (3 atm CH_4 and 2 atm $CH_4 + 2$ atm Kr) was used in a collimated beam. They went up to 9 MeV. The resolution, he believed, was 10 and 14% for the fillings mentioned above. Winfrith is trying a mixture of A and H₂ to get up to higher energies.

The product of diameter and pressure was considered to be a useful criterion for the upper limit of pressure in counters. Bennett quoted 13 atm-cm, Broomfield 15 atm-cm (30 atm-cm for a 152mm diam counter) and Leridon 10 atm-cm for typical in-core proportional counters. However, absolute pressure itself appears to be a limiting factor. Paterson presented data showing that the zero pulse-height intercept, δ ,

was 100 keV (the lowest energy point for the measurement being at 200 keV) for a 38 mm diam counter with an 8 atm CH₄ filling, and $\delta = 0$ for the same counter but with a 2 atm filling. However, for a 152mm diam counter filled to 2 atm of CH₄, again $\delta = 0$. But then one can never be sure that the same degree of purity has been achieved in such comparisons (Paterson).

The results from more than one counter can usually be normalized very well to reactor power level expressed in neutrons/(fission/gm) of ^{235}U . The Aldermaston group has achieved good accuracy in normalizing different runs to the same flux scale both in-core and in extracted beams. Overlapping results can usually be completely enclosed in a band 10% wide in flux. In intercomparing counters used in the same location, the pressures are measured to about 2% accuracy and the volume to ~ 4 - 5% for their spherical counters, resulting in an overall normalization error of 4 - 5%. The errors in active volume are larger for cylindrical counters, but can be reduced by proper design. A novel method of determining the volume accurately has been employed at Gulf Radiation Technology in which a BF3 filling was used in the same counter and the count rate obtained in a region of known neutron flux. This method is especially useful for cylindrical counters with large inactive regions. Water fillings have been used at other laboratories to get a measure of volume in spherical counters, Sanders pointed out.

In intercomparing H_2 and CH_4 fillings in the overlap region of 100 keV, Bennett quoted an accuracy of about 5% after correcting for C-recoil counts from the CH_4 .

In Cadarache, the same three counters are always used. The agreement between the three is $\sim 3 - 7\%$ and always in the same direction. If the systematic corrections were estimated and applied, this would be reduced to 2 - 4%. In the same assembly, the normalization of the Bennett type cylindrical counters and the Benjamin type spherical counters was seen to be good to 5 - 6%, as quoted by Broomfield.

Energy calibrations are usually carried out with high energy particles such as protons plus tritons in the ³He(n, p)T reaction and with protons plus C-recoil atoms in the ¹⁴N(n, p)¹⁴C reactions. Extrapolations to the low energy, high gas gain region are made using the Diethorn relationship⁽²⁾ between voltage and gas gain. Space charge effects impair the calibration accuracy if the gas gain is too high. Bennett stays below 3×10^5 electrons collected to avoid nonlinearities at the highest gas gain, where large space charge effects are associated with short proton recoil tracks. At the highest energy or lowest gain, he runs into difficulties at ~ 5 x 10⁶ electrons collected per pulse. Bennett indicated that for a calibration that terminates at 15 keV, one may be biased 5% at 1 keV, and to overcome this, a series of calibration sources is needed. The PTFE block with fluorine resonances at 27, 50 and 100 keV has been found useful at higher energies at Winfrith and Aldermaston. Energy calibrations are generally $\pm 2 - 3\%$ accurate above 50 keV and may go up to 5% as seen in observing resonances in the spectra. The errors are mostly due to gas gain and W uncertainties.

Preskitt presented some preliminary data on calibrating proportional counters by time of flight, in which case response functions were obtained for almost monoenergetic neutrons down to a few hundred eV. Data of this type can be used to provide a check on the Diethorn relationship up to very high gas gains and to deduce the variation of W with energy. These early results suggest that W is constant within about 3% above 10 keV, and nearly constant from 1 to 10 keV.

The in-beam calibrations of Bennett type counters showed very little change of spectral shape with change of angle of the detector axis with respect to the beam.

The time-of-rise distribution for pulses of a given size is characterized by a relatively narrow proton-recoil peak and a broader gamma-ray peak whose tail extends out to and including the proton peak. In subtracting the gamma-ray background that falls under the recoil proton peak, the shape of gamma-ray tail is extrapolated out to, and under, the proton peak. Difficulties are encountered in calibrating with gamma rays having a different energy spectrum and angle of incidence than in the experiment in that the shape of the time-of-rise spectrum may not be the same for the two cases. To keep the shape constant, the count rates may also have to be matched in the gamma-ray background measurement and the spectrometry run, because pileup effects and baseline distortion may produce further mismatch. The method of fitting to the downward slope rather than to the entire shape of the gamma-ray time-of-rise peak is the favored way of gamma-ray background subtraction, where the two peaks are well separated and a tail well defined.

In discussing counter end effects, Bennett presented a cylindrical counter whose outer wall was stepped down to a smaller diameter at the ends, where the field definition tubes exist. This eliminated the tail at the low energy end of the monoenergetic neutron peak that is obtained after unfolding (differentiating), but the correction was overdone and he obtained a tail at the high energy end instead. Apparently, an optimum sized change in the counter diameter at the ends can be made to achieve a substantial reduction in field effects for this counter geometry.
An example of improving the resolution of the measured spectra by unfolding was presented by Preskitt. A poor resolution gamma-ray pulse height distribution taken with a Ge(Li) detector is shown in Figure 15, and this spectrum unfolded with the MAZE code developed at Rad Tech is shown in Figure 16. This should be compared to Figure 17, the same spectrum taken with a high-resolution Ge(Li) detector, where it can be seen that most of the washed-out peaks are restored. The ability to pull out these smeared peaks is a strong function of statistics, as well as the amount of added smearing introduced by the detector.

On the subject of errors, Leridon indicated that discussing errors only in broad group structure is meaningful, because of resolution effects and systematic errors such as energy shifts. In detormining errors from 9 to 1300 keV, he quotes a 3 - 4% error has been achieved between any two broad groups after correcting for response function errors. Bennett indicated that the errors in the valleys produced by a resonance are usually very large, say 20%, but if the flux there is say 5% of the flux at the peak, then the error is only 1% of the peak value. Comparison with the flux in the peak of the spectrum is the better way of specifying error, he feels. By getting rid of end effects, the "fine structure" error can be reduced considerably. Some local error reduction schemes have included smoothing the spectra before unfolding. Fabry pointed out, however, that this got rid of real peaks as well, as observed in a proton-recoil spectrum that was also measured with a ⁶Li spectrometer. Leridon reported large errors in gamma-ray subtraction near 10 keV. These determine the lower energy limit for their spectrometry. The error introduced by a spect rometer cutoff of 1.5 to 2 MeV for a reactor spectrum can be reduced considerably if the spectrum above the cutoff point is either calculated or obtained from other measurements. Bennett feels they are now doing this well and if they had difficulties, they would have shown up in looking at many different spectral shapes. The protonrecoil spectrometer error on a percentage basis will be very large at low energies if the spectrum is wory hard. Specification of accuracies attainable with these detectors at the low energy end must therefore be made in terms of a typical spectral shape, and these errors have been mostly quoted for the typical fast breeder reactor spectrum in this meeting.



Figure 15. Poor Resolution Gamma-Ray Pulse Height Distribution, Ge(Li) Detector



Figure 16. Pulse Height Spectrum of Figure 15 Unfolded with MAZE Code. Note that most of the peaks of Figure 17 (High Resolution Data) Appear.



Figure 17. Good Resolution Gamma Ray Pulse Height Distribution, Ge(Li) Detector. Same Gamma-Ray Spectrum as in Figure 15.

WEDNESDAY MORNING

V. Time-of-Flight Spectrometers

Paper 1

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Sanders of Winfrith discussed the fast reactor time-of-flight spectrometry work in the U. K. A broad program of zero-power fast assembly studies has been under way for the past several years with the objective of improving the accuracy of fast reactor core performance predictions via the application of data adjustment schemes. Spectrum measurements form an important part of this effort. The flux spectrum of interest in fast reactor physics extends over a wide energy range from a two hundred eV to several MeV. Current targets (1 std. dev.) for prediction of fast reactor parameters are \pm 0.005 in k, \pm 0.03 in breeding gain, \pm 10% in Doppler coefficient. By studying the sensitivities of these parameters to spectrum shape, it is inferred that the spectra should be known to about \pm 4% over the range 10 keV - 4 MeV, and \pm 10% from 500 eV to 10 keV, with relaxed requirements below and above these limits. Resolution as well as amplitude accuracy is a relevant criterion in evaluating a particular technique.

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In order to meet these requirements, several types of spectrometers incorporating a multiplicity of techniques are needed. The time-offlight technique is particularly useful at low energies (below 1 keV) but it is desirable to stretch it to at least 100 keV so as to get an overlap region for normalization and comparison with other techniques.

Detailed time-of-flight measurements have been made on several VERA and ZEBRA assemblies. The details of the experimental programs on these respective assemblies (9.1, 10) and of the time-of-flight experiments (11, 12) exist in the literature. Five main features of the time-offlight set-up are as follows:

VERA	600 keV deutron accelerator, tritium target Neutron output in pulse $\sim 10^{12} \text{ sec}^{-1}$
	Pulse length up to 4 μ sec, PRF up to 5000
	Flight path length 70 m
·	Lithium - 6 glass scintillation detector mounted
	inside flight tube

 ZEBRA 14 MeV electron LINAC, nat. uranium target Neutron output in pulse ~ 10¹⁵ sec⁻¹
Pulse length up to 3 µsec, PRF up to 200
Flight path 200 m
Lithium - 6 glass scintillation detector mounted inside flight tube

The more recent time-of-flight measurements have been done on four ZEBRA assemblies consisting of plutonium-fuelled test zones with unit k_{∞} , no ²³⁵U driver, and a ²³⁸U blanket ($k_{eff} = 0.85$). The water-cooled natural-uranium target is placed inside the reactor structure, far away from the point of spectral observation—the core center; the extraction channel is parallel to the plane of the fuel plates.

The Zebra time-of-flight detector consists of an array of 14 lithium glass scintillators (12 each of ⁶Li, 2 each of ⁷Li to get y-ray background) 63 mm diameter, 51 mm thick each viewed by a VMP 11/64 photomultiplier. It has been calibrated over the range 100 eV-1 MeV, using two procedures (13). In the first, the efficiency was measured from 100 ey to 1 MeV relative to that of the Harwell boron-vaseline plug (BVP) on the Zebra flight path; in the second, a calibration was made against a standard long counter on the Harwell pulsed Van de Graaff, using the 'Li (p, n) reaction as a source and time-of-flight to separate neutron- and gamma-events in the scintillator. The useful range of these measurements is limited to 60 keV to 1 MeV. Calculations of this glass scintillator efficiency have been made using both transport (TURTLE) and Monte Carlo (GEM) codes. While results from the latter are reasonably consistent, there are considerable discrepancies (Figure 18) between calculation and measurement, rising to 20% in the region 70-130 keV. It is believed that these discrepancies arise from inadequate nuclear data (due to the large amount of multiple scattering; data on all glass constituents-Si, O, etc --- is relevant), and the currently recommended efficiency is taken from the experimental curves, using the calculated shape only below 1 keV. The accuracy of the efficiency varies between $\pm 5\%$ and $\pm 10\%$ (1 std. dev.) in the range 100 eV - 1 MeV. The uncertainty in the efficiency curve constitutes the dominant source of error in the final time-of-flight spectra.

For resolution corrections, the profile of the reactor pulse is obtained using 238 U and 235 U fission chambers. The dieaway time $(1/\alpha)$ in a typical assembly is about 5 usec. The unfolding of the measured spectra to get the actual time-of-flight spectrum (corresponding to an instantaneous reactor pulse) is done using a processing program WINTOF⁽¹⁴⁾ which assumes an energy-independent reactor pulse.



Figure 18. Lithium Glass Detector Efficiency

The relation between the directed spectrum and the cell-average scalar spectrum is determined using a program TOFFEE⁽¹⁵⁾. For an extreme heterogeneous lattice (ZEBRA 8A) the differences between scalar and directed fluxes are only a few percent below 1 MeV, becoming considerably larger above I MeV. (However, I MeV is above the useful upper limit of present Zebra experiments). This spectrum perturbation arising from the insertion of a 90-mm diameter probe to the center of a Zebra test region (H = D = 600 mm) has been calculated for a homogenized cylindrical model in six broad groups covering the range 0-15 MeV; the ratio of perturbed to unperturbed flux does not vary by more than 3% over this energy range. A further perturbation arises from the heterogeneity of the lattice and the necessity of materialremoval to accommodate the probe tube. When plutonium plates were loaded directly above the probe tube, an enhancement of the spectrum above 200 keV was observed, the effect reaching 10% at 1 MeV; otherwise, changing the local geometry of the cell in the vicinity of the probe had no noticeable effect.

The measured spectra are finally compared with calculations based on the code $MURAL^{(16)}$ which calculates spectra in about 2000 groups for a multiregion cell. Figure 7 shows a typical result of the comparison of time-of-flight spectrum with MURAL calculations (proton-recoil counter results are also shown). These results are used in data adjustment procedures.

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As a step toward the intercomparison of results from two (or more) independent experimental techniques, time-of-flight (TOF) and protonrecoil counter (PRC) measurements provide essentially independent techniques (they have no common sources of systematic error) with overlap region extending from 5 keV to 1 MeV, for checking the presence of unsuspected errors in spectrum measurements. The ratios of PRC to TOF quarter-lethargy group spectra for three Zebra assemblies (8A, B, D) are shown in Figure 19. A general trend is observed in the ratios which increase by 10% betw en 600 keV and 20 keV, the PRC giving a slightly softer spectrum than TOF. This trend is consistent with the systematic errors assigned to the two techniques. The most noticeable departure from the general trend is shown by the 8A ratios from 100-300 keV; this is due to uncertainties introduced by the rather large TOF correction factors required in this region as a result of the long reactor pulse for this soft-spectrum assembly, coupled with the peaking of the response of Li-glass detector near 260 keV. Larger differences between PRC and TOF appear below 20 keV and above 600 keV, as is to be expected from the increased uncertainties in the two-parameter PRC technique at low energies and in the TOF technique at high energies. More results on such intercomparisons between techniques are needed and are being pursued.



Figure 19. Comparison of Time-of-Flight and Proton Recoil Counter Spectra for ZEBRA 8A, 8B, 8D

Discussion of Sanders' Paper

In comparing measured spectra with calculations, was proper attention given to the difference between directed angular flux and the scalar flux? The relationship between the emergent flux and the scalar flux was studied theoretically, using the code TOFFEE, for every core considered, so that all measured spectra (both TOF and PRC) are corrected back to the fundamental mode average scalar flux. Below about 1 MeV the corrections are fairly small, but as we come into the MeV region, the corrections become large.

What is the significance of unit k_{∞} for the central zone for TOF experiments? This has no relevance to spectrum measurements; it has to do with early designs for the application of null reactivity method and for certain activation experiments.

How much reactor time is typically needed to perform spectrum measurements? If the accelerator is running reliably, one can do a standard set of experiments including two different detector stations (50 and 200 m) in a week, which is a reasonable time. Auxiliary measurements may require additional time. A great deal of time is also spent in getting the reactor subcritical, installing the target, commissioning the machine, lining up the detectors, etc. Therefore, once the measurements are started, it pays to do a series of systems. After getting set up, to get decent statistics, a typical run with the 200-m flight path takes about eight hours, including the background runs and so forth.

In the results showing the comparison between measured and calculated spectra, to what are the discrepancies at high- and low-energies attributed? We think these have to do with nuclear data errors. The spectra are put into the data adjustment scheme. The high-energy discrepancy seems to point to the adjustment of 238 U inelastic cross section. The low-energy disagreements require adjusting fission and absorption cross sections. Preliminary conclusion seems to be that the 238 U inelastic data which most of us are using are too large and need reducing. The discrepancies in 238 U and 235 U fission ratios have been observed by other people too. Our calculations use the Ravier-evaluated 238 U data.

Is the relatively long LINAC pulse used still small compared to the dieaway time of assemblies? Where does the resolution correction largely come from? Things are adjusted so that both these are nearly equal. Shorter pulses have also been used on some systems. Generally, the two component parts of the correction are comparable.

Paper 2

Wattecamps of Karlsruhe discussed some of the studies of the reliability of fast neutron spectrum measurements carried on there. Spectrum measurements have been under way at Karlsruhe in three fast assemblies: SNEAK, SUAK and STARK. Four different spectroscopic techniques have been available: ³He Spectrometer, Proton-Recoil Proportional Counter, Tin 9-of-Flight and Sandwich Foil Activation Technique. To intercompare these techniques and assess the confidence level of fast reactor spectrum measurements, all four techniques (17) were used on the SUAK facility⁽¹⁸⁾; this is the only one with an associated time-of-flight spectrometry system. The particular SUAK core investigated is called UHC (H:C:²³⁵U = 1.05:6.21:1.0; mean enrichment 27.7%) and very closely resembles the British core VERA (7A) which has been extensively investigated at Aldermaston and Harwell. Results of the intercomparison between the four techniques and comparison with the British measurements are discussed here.

The first major technique, the ³He spectrometer⁽¹⁹⁾ (an outgrowth of the earlier ⁶Li semiconductor sandwich spectrometer) has several advantages: good energy resolution (60 keV), large efficiency, well-known cross section of the basic reaction; it can be run for a long time without radiation damage effects and is not very sensitive to competing reactions in the semiconductor. In a typical SNEAK experiment, involving a 4-hour run at 100 mW, a statistical accuracy of 2% could be obtained in the energy range 100 keV - 5 MeV.

The proton recoil counter has been used for both in-core and out-of-core (beam) measurements. For in-core measurement, a cylindrical counter (94 mm cm active length, 35 mm diam; 3 atm methane) were used. For out-of-core use, to measure the spectrum above 1 MeV, two large cylindrical counters (active length 835 mm, 89 mm diam; 3 atm. methane and 2 atm $CH_4 + 2$ atm Kr) were located in the time-of-flight channel about 3 m away from the core and shielded so that the detector saw the same core area as the time-of-flight detector.

Figure 20 shows the comparison of results from ³He spectrometer with proton recoil measurements and also incore versus out-of-core measurements. The out-of-core is a relative result and is fitted to in-core result in the overlap range 400 keV - 1 MeV. S8 calculations of scalar flux vs vector flux at the core-center indicate that no correction is required for anisotropy below 4 MeV. Included in this figure are also results from the British (Aldermaston) measurements.



Figure 20. Measured and Calculated Neutron Spectra from UHC (VERA 7A)

The main features of the time-of-flight set-up $^{(18)}$ at the SUAK facility are as follows:

Neutron Sources:	D(T, n) He Accelerators: (i) 200 keV D^{+} 2 x 10 ¹⁰ n/sec. instan. (ii) Flash-Tube- 1. 10 ¹⁴ n/sec instan.
Flight Path:	100 m maximum.
Detectors:	(i) ⁶ Li Ne-905, 111 mm diam 25.4 mm thick (⁶ Li - Disk) (ii) ⁶ Li KG 2L x 6, 50.8 mm diam 25.4 mm thick (⁶ Li - Rose) (iii) B^{10} powder and vaseline plug (iv) Ne-213 and NE-102

Several approaches are available for making the resolution correction in time-of-flight measurements. For the energy-independent case, three techniques based on the use of mean-emission time, derivation (exponential), and iteration (non-exponential) can be used. The energy-dependent resolution function is handled by an input listing of the time-dependent mean-emission time.

A systematic and detailed investigation has been undertaken of fast neutron detectors for use in time-of-flight measurements and of the calibration of these detectors. A ¹⁰B powder, vaseline mixture detector has several advantages: a smooth and rather flat response over a large energy range, relies on few isotopical types with well-known cross sections; thus the energy dependence of the efficiency (relative) can be reliably calculated. This detector is used as a standard. However, its efficiency is small (which is especially troublesome below 1 keV) and it requires shielding against stray neutrons and more importantly, against gamma rays. For higher efficiency and easier handling, two lithium detectors "⁶Li - Rose" and "⁶Li - Disk" are routinely used. Calculations and measurements have been performed to determine the neutron detection efficiency in the energy range 10 eV to 200 keV, of a 10 B-powder, 6 Li-rose and 6 Lidisk, relative to the first standard. Calculations for various vaseline -¹⁰B powder concentrations show that equal amounts, by weight, give a good compromise between increased efficiency at higher energies without altering too much the flat shape below 10 keV; a Monte Carlo code is also used to calculate the efficiencies of ${}^{10}\text{B}$ -powder and ${}^{10}\text{B}$ -vaseline detectors using latest cross-section data⁽²⁰⁾. A calculation, in this way, of the Harwell ${}^{10}\text{B}$ -plug shows that the largest difference between this calculation and the Harwell calibration is 9.5% at 150 keV.

The results for the efficiency curve of ^bLi glass detector (25.4 mm thick NE905) are summarized in Figure 21, which includes the calculated efficiency by J. Cameron et al⁽²¹⁾. In summary, the efficiency of the ⁶Li-disk deduced from calibration relative to the ¹⁰B-vaseline plug, should be accurate to within 4%. Since we know that spectrum measurements (by different techniques in overlapping energy ranges) do seldom agree to within their claimed error margin, the practical figure for accuracy is deduced from comparison with the calculation of J. Cameron, et al and the Aldermaston results. From this comparison, the efficiency is claimed to be accurate to within \pm 8% in the energy range 10 eV to 200 keV. This figure gives the error margin at 10 eV if the efficiency is normalized to the exact value at 200 keV. In small energy ranges the error is smaller, according to the smooth shape of cross sections involved and as further indicated by the close agreement, to within 4% in the energy range of 20 keV to 200 keV, of the time-of-flight and proportional counter measurements at Karlsruhe (Figure 22).

For completeness only, the fourth spectrometric technique—the sandwich foil activation—is also mentioned.

The achievable accuracy in the measured spectrum by the four techniques is summarized in Figure 23. (Please note that the vertical scales are not the same in all four cases). For the time-of-flight case, the two results refer to measurements with 100- and 10-meter flight paths.

The final results of measurements and analysis of spectrum in the UHC core are given in Figure 22. Measurements by proton recoil, time-offlight, and sandwich activation techniques are included in addition to the British (Aldermaston, VERA 7A) measurements. The time-of-flight results are normalized to proton-recoil results in the region of overlap, 20 keV - 400 keV. Although ³He spectrometer results are not included here, this technique has already been compared with the proton-recoil technique (Figure 20). A number of conclusions are apparent in this comprehensive Figure 22. If the flux is condensed into lethargy groups of $\Delta u \leq 0.77$, the proton-recoil and time-of-flight techniques agree to within $\pm 2\%$ in the energy range 20-400 keV; below 20 keV, there are systematic deviations. The calculations for the UHC core shown are based on S8 with transport approximation and with 14 MeV extraneous neutron source, taking into account small differences such as composition, geometry and heterogeneity. Measurement and calculation are normalized to the same total flux. The correction for the degree of subcriticality in every case has been included before comparison. The spectrum in the UHC core is dominated mainly by carbon and hydrogen and calculations with various cross section sets agree within 10%. The Karlsruhe measurements and calculation agree to within 15%, and differences of up to 30% appear in the comparison with the Aldermaston results.



Figure 21. Neutron Detection Efficiency of 1" Thick ⁶Li-Glass Scintillator. NE-905, φ 4-3/8"



Figure 22. Comparison of Measured and Calculated Spectrum of Core UHC



Figure 22. (Second Half)



Discussion of Wattecamps' Paper

In the calculations, isn't the effect of the source important at high energies? Accurate calculations are not claimed above 6 MeV. The first group in the set is from 6 to 10.5 MeV. The extraneous neutron source is assumed to be in the first group; therefore, the first group calculated flux is not reliable at all. The second group may also be influenced by this approximation. The third (this is below 4 MeV) and lower groups are calculated with confidence.

What was the distance of the source from the measuring point? 20 centimeters.

Do you allow for anisotropic scattering in the calculations? Only through the transport approximation, in the S_N calculations by the DTF-IV code. It is planned to improve this later by taking into account the anisotropy in the full scattering matrix.

How was the relation between the flux in the beam and the scalar flux studied? By two methods: first by S_N calculations of the vector and scalar fluxes; and second by experimentally comparing the in-core ³He measurements with out-of-core proportional counter measurements. Dr. Sanders indicated that in their TOFFEE calculations, these corrections became very large in the region above 2 MeV. Have these corrections been applied in comparing Karlsruhe beam measurements with the Aldermaston in-core results? No corrections were applied for anisotropy since the rough approximation of the spectrum of the external source is already too crude. However, better calculations in 200 groups are expected shortly.

In describing the several different techniques for the resolution correction, one approach involved an iterative technique when the dieaway is nonexponential; is a constant spectrum during dieaway assumed? Yes. In case of an energy dependent dieaway constant we can only take into account by an energy-dependent mean-emission time <t> which is to be obtained from a calculation. It was pointed out, however, that the assumption of a constant spectrum during dieaway may be a bad one, since the spectrum seems to undergo large changes with time during the dieaway of the assembly.

Paper 3

Preskitt reviewed the Gulf Radiation Technology program of time-of-flight fast reactor spectrometry. This program represents part of a continuing effort extending from early thermalization studies, through fast spectrum measurements on simple nonmultiplying bulk assemblies, to the present studies of fast subcritical systems by time-of-flight techniques. Among the later thermal-assembly experiments was the measurement of the spectrum in a $Pu/A l - H_2O$ system using a 4 m flight path. Fast neutron angular flux spectra have been measured by the time-of-flight technique for a sphere of ^{238}U and ^{235}U , the latter a GODIVA-like critical assembly. The spectrum from the center of this ^{235}U sphere is shown in Figure 24 and yields the parameters of the fission spectrum; these data are the same as in the present ENDF/B.

The present set of experiments comprises a series of time-of-flight spectrum measurements^(22, 23, 24) in a simple two-zone subcritical fast system, designated STSF, similar to the Argonne ZPR assemblies. These studies were made principally to investigate two of the main effects responsible for the variation of the spectrum shape along the reactor radius: the structure of the core cell and the presence of a thick iron reflector. Therefore measurements have been made showing the fine spatial structure of the flux in a core cell and the gross differences in the flux one observes between the core and the reflector.

Ten different cores of the Subcritical Time-of-Flight Spectrum Facility (STSF) have so far been studied, using the Rad Tech Linear Accelerator as a pulsed neutron source. The STSF is a split-table assembly machine with an aluminum fuel support matrix previously used on the ZPR-3 reactor at Argonne; various material mixtures and geometrical configurations of fast reactors can be mocked up and their neutron spectra measured by time-of-flight techniques. The assembly machine is positioned at one end of a 220-meter evaculated flight path. The Linac target consisting of air-cooled closed-packed bed of uranium shots, designed for powers of up to 10 KW, is located near the center of the core. A reentrant hole of size 25.4 mm x 50.8 mm can extract the beam from any point in the core or the iron reflector. The exit channel is perpendicular to the fuel plates so that measurements can be made within the cell. The cores are typically \$10. subcritical ($k_{eff} = 0.93$). Two detectors are used for spectrum measurements. A 127-mm diam by 127-mm long NE-213 proton recoil scintillator⁽²⁵⁾, located at 215 meters, is used to cover the range from about 8 MeV down to about 700 keV. A Lithium glass detector⁽²⁶⁾, located at 113 meters, covers the energy range 4 MeV down to 200 eV. The assembly is pulsed by the Linac with 100 and 200 nsec bursts at repetition rates up to 360 per second.

The correction to the time-of-flight spectrum, due to the finite dieaway time of the assembly, is made using a new approach developed by $d'Oultremont^{(27)}$. Measurements of the same spectrum with a 25.4 mm



Figure 24 Comparison of calculated and measured neutron spectra at the center of the U^{235} sphere.

50.8 mm and a 12.7 mm x 50.8 mm beam hole established that there was no spectral distortion due to the reentrant hole.

Figure 25 shows the calculated and measured (TOF) spectra for the core STSF-4 (UO₂/Na Void, similar to ZPR V1-6). The calculations are 29 group, S_{12} (based on the 1DF code) with P_3 scattering. Included in this figure are also the results of Bennett's proton recoil counter (PRC) measurements in ZPR V1-6 core. TOF and PRC compare reasonably well except near 100 keV and over 1-5 keV. (Please see Bennett's comment under Discussion.) Another TOF-PRC comparison is shown in Figure 26 for the STSF-1A core ($^{235}U/^{238}U/BeO$, similar to ZPR III-57). The agreement here also is fairly good except for the discrepancies over 20-100 keV. Interestingly, Pu- α measurements on this assembly gave good agreement with the (revised) data of Weston et al⁽²⁸⁾ if measured spectra are used - better with TOF than PRC. The additional structure in the PRC data may be due to the aluminum surrounding the proton recoil counter.

A detailed set of measurements on the core $STSF-2 (^{235}U/^{238}U/C$, similar to ZPR III-17) have recently been completed. A typical result of the measured and calculated spectrum ratios for this assembly is shown in Figure 27. This figure shows that although there is good agreement between the measurement and calculation of cell heterogeneity, some systematic disagreements exist between calculated and measured core spectra. To pin point the cause of such disagreements, it is necessary to analyze in detail all possible sources of error in the measurement and calculation.

One can summarize the general situation regarding the accuracy that can be associated with time-of-flight spectrum measurements on fast subcritical cores. Among the major possible sources of error are: (1) statistical uncertainty, (2) detector efficiency, (3) neutron meanemission-time correction, (4) background evaluation, and (5) neutron beam alignment and collimation. The typical uncertainty per channel content (after background correction) is approximately 15% below 500 eV and above 3 MeV. Between 500 eV and 3 MeV the statistical uncertainty is negligible. A channel has an energy width ΔE such that $\frac{\Delta E}{E} = 0.05$. The NE-213 liquid scintillator efficiency is known between 6 and 0.8 MeV with a precision equal to or better than $\pm 5\%$.⁽²⁵⁾ The Lithium - glass detector has been calibrated up to 1.3 MeV against a low pressure ³He detector with accuracies better than 7% up to 720 keV and about 10% at 1.3 $MeV^{(26)}$. The fraction of the correction factor relevant to neutron mean-emission time is believed to be known with a precision of $\pm 5\%$ or better below 1 MeV, 10% over 1-3 MeV and 20% at higher energies.



Figure 25 STSF-4 (Drawer M-13). Measured and calculated spectrum at the surface of a ²³⁵U plate.



Fig. 26 Comparison of measured time-of-flight spectrum to measured proton recoil spectrum



Fig. 27 Experimental and calculated ratios of the spectra at the surface of the depleted uranium and carbon plates to the spectrum at the surface of the enriched uranium plate

Combining these funcertainties, we have the following estimate of the overall relative ferror per channel:

oelt -			
-322.7% for 3 MeV $\geq E \geq 1$ MeV,			
15% for 1 MeV \geq E \geq 0.1 MeV,	nu ja v		
8% for 100 keV \geq E \geq 1 keV,			
∋10% for E ≤ 1 keV		` ` ;	

best lagrance as the set of the statistical uncertainty drops to a fraction of one percent excepting above 5 MeV, where it is 5% or more.

Discussion of Preskitt's Paper part of or a context withing borg

Have you compared your ²³⁵U-sphere results with the data from GODIVAd measurements at LASL? Yes, and the agreement was quite good? Also the spectrum in this sphere measured by McElroy of Hanford (by unfolding foil activation results) gave reasonably close agreement with the time-off flight spectrum, thus allowing some check of the accuracy of foil unfolding techniques 19.14

In view of the interest in the fission neutron spectrum) have your data uses been published and/or included in ENDF/B? The data has been published (in ANS Transactions) and we have recommended that it be put into <u>ENDF/B</u> data. It is also included in this Report (Figure 24).

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Have you checked to see if your comments regarding the perturbation due to the probe tube apply algorite measurements in the reflector region where the spectrum is changing rapidly with position? We haven't checked that, but we certainly expect more of an effect in the reflector regions. The synce magnitude of the perturbation effect is coupled to the gradient of the flux along the sube cando in the vicinity of the point of measurement; this gradient gets to be quite large at reflector boundaries and in reflectors. We would be interested in measuring this in the future.

bothson both both both positive and negative gradients hy_0 extracting Have yould ried looking at both positive and negative gradients hy_0 extracting the beam at both lends of the reflector? Yes; there is an enormous difference in the spectrum between 0° and 180° at the (iron) reflector more leinterface to The spectrum coming into the core has large fluctuations due to the dimension resonances; in the spectrum coming out of the core these of resonances are much less pronounced of the core these of the form of the core these of the second core for the spectrum of the spectrum coming out of the core these of the spectrum of the spectrum of the spectrum of the core these of the spectrum of the spectrum

Bennett commented about the PRC/TOF disagreements for the STSF -4... core (Figure 25).) The results of this old PRC measurement have been confirmed in a recent measurement. In these measurements, the core may not have been sufficiently voided with sodium, so that the observed disagreements may arise from the fact that the TOF (STSF-4) and PRC (SPR VI-6) measurements may not have been made on identical cores. Preskitt pointed out that since the core sizes in the two cases also were different, this example (Figure 25) should not be taken as an unambiguous and strictly valid comparison of the two techniques.

In the various comparisons of calculated and measured spectra, are these on an absolute or on a normalized scale? They are on a normalized scale. The experiment is normalized to calculation in terms of the ²³⁵U fission rate. That is, measured and calculated spectra multiplied by the ²³⁵U fission cross section are integrated as a function of energy to give the same fission rate. Foils are also used in each measurement, so that good relative normalization from point to point is also available, if we want to make spatially dependent comparisons also. But so far the interest has mainly been in the spectrum at core center only, since resolution corrections can be made with confidence. However, recently we have developed the capability to make accurate resolution corrections for measurements in the reflector or in other regions.

Concerning (the TOF-PRC) comparison with Powell's data (Figure 26), how was the extracted-beam angular flux changed to scalar flux? This correction has not been incorporated in the comparison.

Paper 4

Kazansky of the Institute of Physics and Power Engineering discussed the incipient neutron spectrometry program at the BFC physical assembly at Obninsk in USSR. The actual investigation of neutron spectra at the BFC facility is expected to start some time in 1971. However, studies of several integral parameters relevant to the development of fast reactors have already been under way, with the general over-all objective of checking calculational methods and multigroup cross section sets. Interest in the neutron spectra specifically derives from several conthe knowledge of neutron spectra permits us to siderations. First, interpret the observed discrepancies between calculated and measured reactor integral characteristics (such as critical mass, fission-density distributions in a core and reflector, average cross-section values of fissionable and structural materials at different points, materialsworths, neutron lifetime, etc.) more simply and clearly. In fact, if the neutron spectrum is known well, the discrepancies between measured and calculated average cross sections can be related to either errors of differential cross sections or errors dealing with cross section averaging. Secondly, a comparison of calculated and measured neutron spectra for physical assemblies of simple composition and configuration allows us not only to specify multigroup cross section sets but also to introduce clarity into calculational methods.

Precision measurements of a number of integral characteristics being carried out at physical assemblies of the BFC facility and their comparison with calculations shows that it is necessary to assume real neutron spectra being softer than predicted in order to achieve satisfactory agreement. This effect (i. e., the necessity of increasing the low-energy neutron fraction in calculations) has been clearly demonstrated in the investigations of specific activations (e. g., 197Au, 181Ta, 63Cu) and material reactivity effects (e. g., 197Au, 239Pu, 235U) for different sample sizes; calculated spectra were changed (sc tened) by introducing hydrogen in the system. For example, softening of calculated neutron spectrum by introducing 5 atom per cent hydrogen relative to the number of 235U nuclei (which increased the relative neutron fraction at about 1 keV by a factor of 1.5) gave a good agreement between measured and calculated functions for all materials. Further, for such softer spectrum, better agreement was obtained between measured and calculated values of average cross section ratios for fissionable and nonfissionable materials.

The actual planned program of the investigation of fast reactor spectra at the BFC facility will involve detailed measurements of interior as well as leakage neutron spectra. For these time-of-flight measurements the electron beam from the pulsed accelerator, microtron (30 MeV, 10 ma, 1-3 msec, 5-500 Hz, 10^{12} n/sec average yield) will be introduced into the core of the assembly under study; the neutron source will be a uranium target. Evacuated flight paths of 43, 215, and 750 meters will be used. Two neutron detection systems consisting of helium proportional counters (d = 18 mm, L = 500 m and He pressure = 10 atm.) are available. The first is a battery of 150 counters, the second comprises helium counters placed in a hydrogeneous moderator, thus increasing the efficiency by a factor of 50 around 1 MeV and about a factor of 2 near 300 eV according to preliminary measurements.

Taking into account the pulse shape in the reactor and time characteristics of the detectors, it is estimated that time-of-flight measurements of neutron leakage spectra can be made in the energy range from about 500 eV to 1 MeV with adequate resolution and acceptable count rates, using the two flight path lengths. The lower limit is determined by the background and the upper one by the energy resolution $\&_{eff}$ and flight path length). It is also proposed to measure the neutron leakage spectrum in the energy range below 1 keV with resonance foils and by the filter method; above 200 keV, an incore stilbene scintillation counter will also be used to measure the spectrum since its resolution is better than the time-of-flight spectrometer above 500 keV.

The time-of-flight measurements will, of necessity, have to be made on the subcritical core. Calculations indicate that differences between the spectra of critical and subcritical reactors (k_{eff} changed from 0.90 to to 1.0), although not appreciable at the core center ($\leq 10\%$), may be quite large (as high as 50% or more) in single neutron groups at positions near zone boundaries. It is therefore planned to measure the spectra inside the critical reactor with the help of resonance foils, the penetration method (below 5-10 keV), and the scintillation counter (above 500 keV).

Possible errors in the measured spectra can arise from the heterogeneous structure of the physical assembly and from perturbation of the exit channel. To eliminate the more important first effect, the core center will be made of a homogeneous region. The correction for the second effect will be estimated by measuring the neutron spectra by a proportional counter, with and without the exit channel.

The measured neutron spectra will be compared with the results of multigroup calculations basel on a code incorporating the Gruding-Foertzel approximation, calculating the neutron spectra in up to 250 energy groups; an auxiliary code generates group cross sections from microscopic data. Preliminary indications are that discrepancies between calculated and measured spectra allow us to evaluate the group cross section sets if such discrepancies are in the range 10-20%.

Discussion of Kazansky's Paper

In the calculation of spectra in the subcritical state, how were the calculations done and how was the reactor made subcritical? The reactor consisted of three 20000 of variable enrichment. The group flux β_{ij} (at position i, group j) in the subcritical reactor was related to the group flux β_{ij} in the critical reactor. The calculations were based on diffusion theory. The reactor was inade subcritical by changing the radius of the inner zone and bringing the second zone and the reflector closer to the center without changing their widths. In a second series of calculations, the width of the second section was changed.

In view of the large possible differences in space-dependent spectra from subcritical to critical configurations, it is important that the details and implications of this be carefully examined. In calculating the subcritical spectra, were these the so-called Q-calculations (subcritical reactor with source included) or K-calculations (an eigenvalue problem in which the fission cross sections are uniformly changed to achieve criticality)? The calculations were made for cores without an external neutron source. Since the neutron flux in the subcritical reactor converges, an artificial method is adopted to keep up the flux in the subcritical reactor without the source. For this, the neutron flux was divided by k_{eff} after each iteration. This process leads to what are called quasistationary spectra. I think it is the same or something analogous to what you referred as being K-calculations. Sanders observed that he had done source type calculations and found that the reactor driven by a source quite often has a spectrum closer to the fundamental mode than the critical system. Preskitt pointed out that the difference in spectra between critical and subcritical cores appears to be associated not with the boundary but with the source. The closer one gets to the source, the larger is the difference in the spectrum, so that on the basis of such a Q-calculation, one can find how far away the source should be located so that the difference is negligible and no correction is necessary. This effect may require measurements to be made about 10 cm from the source; further, to get a reasonably asymptotic spectrum, one should be about 20 cm or so from the boundaries. If a large enough central zone (driven by a highly multiplying outside zone) is used so that equilibrium is achieved, there should not be expected any significant variation in the time-of-flight measured spectrum (at the center) compared to the spectrum in a large reactor.

Schmitt said that in France, spectrum measurements were made in the same assembly in the critical (proton-recoil measurements) and subcritical (time-of-flight, spectral indices measurements) states and no significant difference was found between the critical and subcritical results.

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Paterson observed that on the simple VERA systems with just two zones, the difference between the source-driven subcritical spectra at the core center and the critical spectra are not very great, typically less than 10% overall change between 100 eV and 10 MeV. An interesting feature about these calculated effects is that the ideal position for the source (for the correction to be smallest) is at the core-reflector interface. The difference gets worse (larger) as the source is moved either towards the core center or out into the reflector.

How many energy groups were employed in the calculations? Twentysix groups.

Why isn't the upper energy limit higher than 1 MeV if a 750-m flight path was used? The 750-m flight path is not currently planned to be used for reactor measurements.

In connection with the use of a scintillation counter inside the core for measurements in the energy range above 500 keV, what method is proposed to be used? The scintillation counter will be used with pulse-shape discrimination. A stilbene scintillator has been inserted in the reactor. There are great difficulties with the gamma background, but the problem can be solved. It also depends on how long the reactor has operated; for example for irradiation of foils.

Paper 5

J. W. N. Tuyn described the upcoming time-of-flight experiments with the STEK reactor at Reactor Centrum Nederland in Netherlands. STEK is a zero-energy fast-thermal coupled reactor, built in order to perform integral measurements of fission product cross sections in several different fast reactor spectra. An accurate knowledge of the different neutron spectra is required for the current interpretation of such integral cross section measurements. A significant fraction (up to 90%) of the total reactivity effect of a complete fission product mixture sample is calculated to be caused by neutrons in the energy range below 5 keV. This implies that measurement of the neutron energy spectrum in this range is of particular interest - the more so as spectrum calculations show considerable uncertainties due to heterogeneity effects, etc.

In order to obtain detailed spectrum information in keV range, time-offlight experiments with STEK are planned. Some supplemental measurements using a hydrogen-filled proton-recoil proportional counter are expected to yield neutron spectra from 1 MeV down to a few keV, thus providing a useful overlap between the energy ranges covered by the two techniques. Some preliminary spectrum studies have also been made, using fission ratios, ¹⁰B filter method, resonance detectors (for energies below 10 kev) and ³He- and ⁶Li-spectrometers (for the MeV region).

For time-of-flight experiments the subcritical fast zone of STEK (with the surrounding graphite removed to shorten the reactor pulse for better resolution) is pulsed with 14 MeV neutrons from a SAMES T400 electrostatic neutron generator (rotor type), operating at 400 KV and about 10 mA ion current during the pulse. The pulse length can be varied between 0.2 and 8000 μ s, the pulse repetition frequency between 1 and 10⁴ Hz. The neutron output rate within the pulse is expected to be about 10¹² per sec. This source strength determines the lower limit of the energy range amenable to the measurement. A horizontal section of the arrangement of drift tube and flight tube in the STEK core 4000 is shown in Fig. 28. The extract beam hole will have a cross-section of 25 cm² or 50 cm², which according to previous experiments on VERA reactor⁽²⁹⁾, is expected to cause only a small perturbation. However, this effect will be checked by measuring, e.g., $238 \text{ U/}^{235} \text{ U}$ fission-rate ratios in the core with and without the beam hole.

The evacuated flight tube has an over-all length of 55 meters. A flight path length of 50 m yields a resolution of about 20% near the upper limit of the desired energy range.

As neutron detector, a hexagonal array of seven Lithium-glass scintillators of 8.9 cm diameter and 2.5 cm thickness will be used, each





viewed by an EMI 9531 R photomultipler, six of the glasses contain 7.7 Wt% lithium enriched in ⁶Li to 95% (type NE-912) and one contains 8.3 Wt% lithium depleted in ⁶Li giving 99.99% ⁷Li (type NE-913). The ⁷Li glass detector will be used for the measurement of the time-dependent γ -background, since ⁶Li glass detectors are sensitive to both neutron and gamma events. The ⁶Li-glass detector efficiency will be calculated as a function of energy using a Monte Carlo programme; these calculations will be checked by calibration measurements with monoenergetic neutrons and by comparison with a calibrated detector. The whole well-shielded detector unit is placed inside the flight path and can be moved on a rail so as to vary the flight path length.

Considerations of the decay time and energy resolution indicate that the expected upper limits of the energy range for most of the different fast reactor cores are sufficiently high to give a liberal region of overlap with the energy range to be covered by the proton recoil technique; a region of overlap is always attained when an energy resolution of greater than 20% is accepted.

The measured spectra will also be compared with diffusion calculations using the Russian 26-group ABN cross-section set. As is expected, the spectrum of the fundamental static mode distribution in the modified subcritical fast zones will differ from the critical fast-thermal coupled STEK cores. This is shown typically in Figure 29 for the STEK 1000 spectrum. The lower limit of the energy range to be measured is about 20 eV and the difference in this case is only about 20%. It is expected that the spectra of critical systems can be derived from the measured subcritical spectra after application of computed correction factors.

In the measurement of neutron spectra in the fast zones of STEK by the time-of-flight technique, if one takes into account the correction for the difference in spectrum in the critical versus subcritical core, the experimental errors due to the spectral distortion caused by the beam extraction, the uncertainty in the detector efficiency, the statistical errors, etc, the over-all accuracy of the derived neutron spectrum for the critical reactor is expected to be about 10%.

According to current time-schedule, the first spectrum measurements are expected to start by the end of calendar 1970.

Discussion of Tuyn's Paper

Wiener pointed out that it is also important to consider how the reactor was made subcritical - by moving a control rod, changing the size, introducing poison, etc. - since the spectrum may be significantly different in each case.



Figure 29. Ratio of the Central Neutron Spectrum of the Subcritical Fast Zone SZ-1000 and the Critical Coupled STEK-1000 Core

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Paper 6

A. Schmitt of Cadarache briefly discussed the time-of-flight fast reactor spectrum measurements program at Cadarache. The preliminary interest is in the fundamental mode spectrum which can be explicitly calculated and clearly interpreted. The purpose of time-offlight measurements is two-fold: first, for comparison with protonrecoil-counter measurements to reinforce confidence in this technique and second, to obtain information about the low-energy part of the spectrum.

So far only some preliminary measurements have been initiated, principally to assess the sensitivity of the method to the detailed features of the spectrum. Inasmuch as there is no available time-of-flight spectrometry system at Cadarache to be used in conjunction with the fast critical facility MASURCA, the Geel Euratom facility was rented for one month to perform the initial experiments.

These measurements involved a graphite block (90 cm x 54 cm) in which a square lattice of 3 cm pitch was formed using 30% enriched cylindrical metallic fuel, similar to the MASURCA assembly. Three different media of varying heterogeneity have been studied. The experimental set up comprised the Geel LINAC (64 MeV, 100 nsec pulses, 200 pulses per sec.), a water-cooled uranium target (maximum power ~2 KW), a 200meter flight path and a ¹⁰B plug detector with four NaI crystals. This detector has been calibrated with the Cadarache Van de Graaff using a long counter as reference. An NE-213 scintillator was also available for use. The background determination was made with a ⁷Li scintillator placed in the flight path. The time response of the media to a neutron burst was measured using ²³⁵U and ²³⁸U fission chambers.

In addition to the time-of-flight measurements on the three critical media, some preliminary proton-recoil measurements were also made with the counter placed in the extracted beam. For these latter measurements the accelerator was run at 800 pulses per second, dissipating about 500 watts on the target.

These experiments were completed only in October 1970 and no results or detailed information is as yet available. Such studies are expected to continue. Subsequent to the investigation of central fundamental mode spectra leading to confidence in calculational procedures, spectra in other spatial regions of the core may be studied.

Discussion of Schmitt's Paper

Preskitt expressed interest in the beam measurements using a proton recoil counter in conjunction with the LINAC source. Were there any problems with the gamma flash at such short flight path? Leridon pointed out that the electronics was gated off during the gamma flash (without shutting off the high voltage on the detector) and opened 100 nsec after the gamma flash. However, the detailed information about any problems due to gamma-flash must await the analysis of experimental results.

Bennett raised the question of the modest count rates expected with the counter in the extracted beam and the effect this might have on the level of precision of the measured spectra. Leridon agreed that the count rates were low, typically about 50 CPS in the counter requiring about 40 hours for one spectrum measurement. However, a definitive assessment of this problem will be available only when the results have been completed and evaluated.

In response to Broomfield's question as to whether the response functions were calculated for the beam geometry, Leridon said that so far all calculations had been done with an isotropic flux only but not much difference was expected. (The calculation of the response matrix for directional flux is now available).
WEDNESDAY AFTERNOON

VI. Informal Session - Time-of-Flight Spectrometry

A. Schmitt, Chairman. Kazansky was asked to give details of physical assemblies to be studied in U.S.S.R., and the long-range program of reactor physics at the BFC facility. He indicated that basic interest was in assemblies with neutron spectra similar to that in the BN-350 reactor, although the first assemblies to be studied would be much The entire program of the study of neutron spectra will simpler. consist of two aspects. First, the studies geared to practical applications to meet the immediate needs. These involve investigations to uncover sources of disagreements between measured and calculated spectra so as to be able to calculate reactor spectra more accurately and take into account heterogeneity effects etc. in the calculations. Second, from the long-range point of view, detailed investigation of neutron spectra in sufficiently simple assemblies will be undertaken so as to better understand multigroup cross section sets. This is a difficult problem since even in simple assemblies there are a great many different ways of changing the various cross sections to obtain better agreement between measured and calculated spectra. In addition, the perturbation theory results developed by Usachoff and Zerizky may be used to find the most sensitive functions and parameters, the measurement of which will then be attempted in addition to neutron spectra. Inasmuch as spectrum measurements are expensive, careful sensitivity calculations will be made to define the magnitude of differences between measured and calculated spectra which can aid us in clarifying the problem of multigroup cross section sets. The potential of other integral reactor characteristics in providing useful information will also be explored.

Schmitt invited discussion of targets used in time-of-flight spectrometry. Most of the targets used in conjunction with a LINAC are limited to about 2 or 3 kW power dissipation. Water cooling of targets may involve safety hazards. For use with multiplying reactor assemblies, targets are placed far away from the point of measurements and do not have to be designed for isotropy of the angular distribution of emergent neutrons. The target used with the ZEBRA assembly in U. K. consists of gold and uranium plates separated by water gaps, with a closed-circuit flow of H_2O or D_2O . In the USSR, spherical air-cooled targets of natural uranium will be used, although some preliminary work is being done with lead targets. At Rad Tech, a target consisting of a close-packed bed of spheres of natural uranium (0. 127 cm diam), with air cooling has been designed to withstand a thermal power of up to 10 kW; it is generally run at powers of about 2 to 5 kW. At 5 kW, the neutron output is about 10^{12} neutrons per pulse. There are no special fuel handling problems with operations at these powers, if schedules are planned so as to allow cooling over a weekend before changing of fuel drawers. Schmitt pointed out that the over-all target design involves an optimization with respect to power dissipation, size of the extraction channel and the capacity to handle the fuel.

Most groups agreed that there is no significant problem due to perturbation of the extraction channel for measurement of reactor spectra at core center (fundamental mode). The usual cross-section sizes of the existing channels are 25.4 mm x 50.8 mm or 50.8 mm x 50.8 mm. For measurements in the regions of strong flux or spectral gradients, the possible effect of perturbation by extraction channel may be significant and requires further study.

The reactor assemblies for time-of-flight measurements are, of necessity, subcritical; measurements have been reported for k_{eff} values of 0.85 to 0.95. In using these measured spectra for comparison with calculations or other techniques, it is important that appropriate corrections to account for subcriticality be made carefully. This should include consideration of the manner in which the assembly was made subcritical prior to the time-of-flight measurements.

Schmitt introduced the subject of detectors for time-of-flight fast reactor measurements and the approaches to the calibration of these detectors. The most commonly used detectors are the ¹⁰B plug - NaI system and the ⁶Li glass scintillator. The ¹⁰B plug has a smooth response over the energy range of interest, but the absolute efficiency is only 10 to 20%. The ^bLi glass, on the other hand, has an absolute efficiency of about 80-90% in the low-energy range; at higher energies, (above 100 keV) the efficiency can be increased and the curve made smoother by adding a small thickness (~ 12.7 mm) of polyethylene; this introduces only marginal time smearing (~ 10 nsec.) Tuyn and Sanders mentioned that the liquid scintillator NE-321A, with ¹⁰B loading, can give a nearly flat efficiency up to about 100 keV; above this energy, proton recoils begin to be detected and efficiency begins to rise, increasing by a factor of 2 in the range 200 keV - 1 MeV; pulseshape discrimination is also possible. However, this detector has not yet been actually used. Dr. Preskitt mentioned that one advantage in the use of ⁶Li glass detector appeared to be the possibility of using pulse-shape discrimination to reject y rays, but the Rad Tech experience in this regard has not been satisfactory since this rejection process reduces the efficiency by a factory of 2 to 3; it therefore seems to be better to measure the y rays as a background and subtract out their contribution. Dr. Wattecamp agreed with this.

As regards calibration of detectors, Schmitt observed that a Van de Graaff (pulsed) can be used for energies down to about 70 keV. How about lower energies? Among the possible approaches mentioned were the use of tailored spectra and such standards as ${}^{10}\text{B}$ (n, α), ${}^{3}\text{He}(n, p)$, H-scattering cross sections and a thin ${}^{10}\text{B}$ bank. ${}^{3}\text{He}$ can be used from thermal to about 750 or 800 keV; its cross section has been measured at Rad Tech over this energy range, with over-all accuracy of about 7-8%, relative to ${}^{3}\text{He}$ total cross-section which is known to about 2-3%. At Rad Tech a large methane proportional chamber has been used as a standard for hydrogen cross section over the range 50 keV to 2 MeV and can be adoped as a standard.

By way of summarizing the situation with respect to detector calibration and the associated accuracy, Sanders said that at the ZEBRA facility, the calibration has been done against a long counter or a boron-yaseline detector. Over most of the energy range, the efficiency of the ^oLi glass detector is believed to be known to $\pm 7\%$ (one standard deviation); above 500 keV, the error rises to about 15%. In order to meet the accuracy target requirements of 5% on measured spectra the currently achievable detector calibration accuracy must be improved by a factor of 2. A combination of approaches involving recalibration, cross-check between laboratories, better nuclear data, etc. may be useful. Another avenue may be found in a new flat-response detector consisting of a ¹⁰B vaseline sphere with a reentrant hole, being developed by Coates at Harwell. Preskitt pointed out that the choice of a particular detector is a matter of convenience and custom and any selected detector can be calibrated to similar accuracy. In general agreement with Sander's observation, the Rad Tech experience also indicates that the ^oLi glass efficiency may be taken to be known to about \pm 5% to 7% up to 200 keV, the the accuracy getting worse at higher energies; this detector is used only up to about 1 MeV; for higher energies, the NE-213 scintillator is used and has higher efficiency. Wattecamps at Karlsruhe has principally used tailored spectra to calibrate the ⁶Li glass detector and feels that the efficiency accuracies of better than \pm 8% in the energy range of a few hundred eV to 200 keV would be unrealistic. Paterson noted that the differences between the calculated and measured efficiency curve for the ⁶Li glass detector are large and render claims of 5-7% accuracy open to skepticism. He recalculated the Rad Tech ^OLi detector using a U. K. data set and found reasonable agreement with measurements. However, the same calculation and data failed below 100 keV by up to 30% to predict the measured efficiency of the Winfrith detector; it may be that effects other than just the ⁶Li cross section (such as the contribution of silicon, oxygen, etc.) are also important. Evidently, this problem requires intensive further study.

Bennet described plans for a time-of-flight set-up at Argonne for measurements with the ZPR-VI assembly. This set-up will use, as source, a tandem accelerator (operated in single-ended mode) and a 100-meter flight path. A large, thin-walled proton recoil chamber, along with a large, flat-response manganese bath unit will be examined for use as absolute flux monitors instead of the usual long counter. However, it was felt that his preliminary hopes of achieving a calibration-accuracy of 7-10% over the range 10 keV to several MeV may be unrealistically optimistic. The use of several different detectors will be considered at this ANL time-of-flight set-up.

In winding up the session, Schmitt felt that among the other problems and areas which could not be discussed due to limitations of time but are nonetheless important in the context of time-of-flight fast reactor spectrometry are the heterogeneity problem, considerations involved in the comparison of time-of-flight-measurement spectra with calculations and with the results of other techniques, the need and problems of measuring fluxes in regions of spatial gradients, the question of response function in time-of-flight technique and the resolution problem associated with the finitely long dieaway times, and finally the description of standard spectrum media which could provide measurements or comparison of results between different faboratories. Continuing activity in all these areas is to be encouraged.

THURSDAY MORNING

VII. Other Spectrometers

Paper 1

<u>W. J. Paterson</u> of Aldermaston discussed work in the UK using methods other than proportional counter and time-of-flight. At present three methods are being used, the ⁶Li-film diode spectrometer, nuclear emulsions and a double scintillator method.

During the last five years or so the ⁶Li-foil diode method has been used at the Harwell, Aldermaston and Winfrith establishments. It offers, in principle, a means of measuring fast reactor spectra with a single incore detector from energies of a few keV up to several MeV based on the reaction ⁶Li(n, T)⁴He + 4. 78 MeV. Below about 200 keV the spectrum is obtained from the triton pulse height distribution by an unfolding process, while the upper end of the spectrum is obtained from the distribution of the sum (alpha + triton) pulse heights. Measurements of the spectra in Zebra assemblies 8A, 8B and 8C made with this spectrometer have been reported by Silk and Wright. ⁽³⁰⁾ The main problems encountered with the method are:

- (a) inaccuracies in the available data for the cross section of the reaction and for the angular distribution of the tritons required for the triton unfolding method;
- (b) the diode resolution deteriorates under neutron irradiation with an accompanying increase in back-bias current. Thus a spectrometer may survive only one or two measurements of high statistical accuracy;
- (c) when depletion depths are adequate to stop the fastest tritons the background events become an appreciable fraction of the total at high energies;
- (d) the detector resolution is affected by the gamma-ray intensity in the reactor;
- (c) sensitivity of the unfolding process to errors in the response functions.

Recent work by Rickard at Winfrith has been aimed at overcoming some of these problems. Detectors now used in Zebra have diode areas from 100 to 200 mm², diode separations 1 to 4 mm and a 6 LiF film (deposited on one of the diodes) of 0.8 to 2.5 μ g/mm². The FWHM of the sum peak is 130 keV rising to 250 keV in the 30r/hr reactor environment. The background distribution is measured using a dummy spectrometer of similar diodes without a lithium deposit. The adequacy of this method of background subtraction has been checked using spectrometers with varying thicknesses of lithium deposit (and therefore different background fractions) in the same spectrum. Similarly the adequacy of the depletion depths used has been demonstrated by variation in the same spectrum. Measurements of the detector efficiency have been made up to 4 MeV using a Van de Graaff. These measurements, which are effectively a new measurement of the (n, T) cross-section, are believed to be accurate to about \pm 5%. The most recent measurements have been made on Zebra 8H, a unit k-infinity test region of enriched and natural uranium plates. Results, shown in Figure 30, have been normalized to the MURAL calculation between 10 keV and 180 keV. No separate adjustment of triton and sum peak results has been made. The errors are assessed at $\pm 15\%$ up to 500 keV improving to $\pm 5\%$ at higher energies where the measured efficiencies are used.

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The <u>nuclear-emulsion method</u> is used on all VERA assemblies using the procedure described by Benjamin and Nicholls. ⁽³¹⁾ The main causes of systematic error are:

- (a) uncertainty in the detailed curvature of the range vs. energy curve which introduces errors chiefly below 1 MeV. The magnitude is difficult to assess but is probably about $\pm 5\%$ S. D.
- (b) An energy-independent error in absolute flux level which arises from uncertainty in the hydrogen content of the emulsions. This probably less than $\pm 5\%$ S. D.

The main disadvantage of the method is the long scanning time required which is typically greater than 200 hours per spectrum. However the hydrogen scattering cross-section is accurately known and other sources of systematic error are possibly less than in competing methods in the energy range above 1 MeV. The plates used can fit into very small cavities and having an isotropic response they can be used in anisotropic fluxes.

A <u>double scintillator time-of-flight method</u> has been developed at Aldermaston for use on VERA assemblies for measurements up to 8 MeV in support of the nuclear emulsion measurements. The principle of the method is given by Legge and Van der Merwe⁽³²⁾ who used it to measure



Figure 30. ZEBRA 8H - Li6 Semiconductor Spectrum Compared with MURAL (full curve)

the spectrum of a PuBe source above 3 MeV. With the neutron beam intensities available at a few meters from fast reactor assemblies operated at 10 to 50 watts a much simpler detector than that of Legge and Van der Merwe can be used and the lower energy limit extended down to 400 to 500 keV. The equipment used on VERA consists of a thin disc of plastic scintillator in a continuous beam from the reactor and a second larger scintillator located outside the beam to detect neutrons scattered through 45° from the first. The thin disc is 7.5 cm diam by 3 mm thick NE-102A coupled to a 56DVP05 photomultiplier by a thin, hollow tube. The second detector is 10 cm diam by 5 cm thick NE-102A mounted directly on a 56DVP03 photomultiplier. The flight path between the scintillators is 1.3 m. The resolution of the spectrometer measured at 2.5 MeV is 18% $\triangle E/E$. The main component of this below 5 MeV is energy-independent and is due to geometrical effects, i. e., variations in scatter angle and flight path. An energy-dependent component due to the time spread (\sim 3 ns) in the detectors and electronics is only significant at higher energies. The pulses corresponding to neutron scattering from the carbon at 45° in the first scintillator can be biased out because the neutron gives up only about 5% of its kinetic energy to the carbon nucleus and the carbon recoil light-output per unit energy in the plastic scintillator is much lower than for proton recoils. Because only scatters of about 45° are measured the threshold bias on the thin, first scintillator does not affect the efficiency of detection of neutrons above a certain energy and the energy dependence of the efficiency can be readily calculated. For the large second detector however, the efficiency vs. energy must be measured with threshold levels used in measurements. This has been done between 150 keV and 4 MeV which corresponds to the range 300 keV to 8 MeV for the energy of neutrons incident on the first detector.

In Figure 31, the time distribution obtained from a measurement on VERA 3A is shown. The features in evidence from left to right are the chance coincidence background before time zero, the gamma-ray peak at ~ 4 nanoseconds after time zero, then a short period of more background followed by the broad neutron time-of flight distribution from which the incident neutron energy spectrum is obtained. This distribution was obtained in about 4 hrs with the reactor operating at 8 watts. The first detector was 7 m from the reactor core and the limiting collimator close to the core was 38 mm diam. The fall-off in the neutron time distribution after 160 nanoseconds is caused by the threshold level on the first scattering detector. High threshold measurements have a low random background and are used to measure the high energy part of the neutron spectrum. Lower thresholds are used to obtain results at the low energy end (to the far right) where the background effects are not so important. At lower thresholds there is evidence of additional counts occurring between the gamma peak and the neutron distribution.



Figure 31. Double Scintillator Time Distribution VERA 3A

These are attributed to scatters from carbon nuclei which would first appear at the shortest flight times. The background is measured by inserting a shadow shield absorber between the two scintillators. The almost flat distribution obtained is normalized to the chance coincidence rate to the left of the gamma-ray peak in the spectrum measurement and subtracted.

Figure 32 shows the spectrum deduced from the time distribution of Figure 31, arbitrarily normalized to nuclear emulsion and proportional counter results. Figure 33 shows a calculation, a proportional counter measurement and a double scintillator measurement for VERA core 1B all independently related to the same flux scale.

The advantages of this spectrometer are:

- (a) the equipment is much cheaper than that for pulsed source time-of-flight in the same energy range;
- (b) the detector efficiencies are readily determined;
- (c) no information on the scintillator response functions is needed and none of the uncertainties of unfolding are involved;
- (d) in typical VERA assemblies adequate statistical accuracy is obtained in 20 to 100 watt hours running time.

At the moment, the energy resolution leaves room for improvement. The other disadvantage, common to all beam methods, is that it is usually necessary to convert the measured directed spectrum to the cell-average spectrum. This conversion has been calculated for all the VERA cores using the codes MURAL and TOFFEE⁽³³⁾ and the corrections are typically 10% to 15% differential change between 400 keV and 8 MeV.

In the discussion of Paterson's paper, he said that the nuclear emulsions are placed in a cavity inside the assembly.

Fabry asked if the 6 Li detectors, when calibrated with monoenergetic neutrons, were rotated to different angles with respect to the incident neutrons so as to obtain a calibration applicable to the isotropic flux situation in a reactor. Paterson said that this was planned but had not yet been done. The measured efficiencies indicate there is a large error above 4 - 5 MeV.



Figure 32. Comparison of Double Scintillator and Nuclear Emulsion Results in VERA 3A

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Figure 33. Comparison of Double Scintillator with Proportional Counter and Calculated Spectrum VERA 1B K 0.9

The in-beam normalization of the double crystal spectrometer was carried out by replacing the spectrometer with a large ²³⁵U fission counter (in the beam), making a separate measurement, and relating this to the flux during the spectrum measurement. The spherical proportional counter was also placed in the beam at this 7-meter position. They had two values of core-to-beam ratio, one using the fission counters and the other the proportional counter. In this case, they were in good agreement but low count rates in the beam make this measurement difficult. Present indications are that the proportional counter is the best detector to use.

The double scintillator is easier to calibrate than the single scintillator, since you need to measure only the efficiency of the second detector with neutron energy at the bias level used in the measurements, and do not need to have an accurate description of the complete response functions. The neutron energy in the double scintillator method is determined by time-of-flight, and this is much simpler than unfolding pulse height distributions.

Can one use the 14 MeV neutron calibration source, vary the scattering angle from the first scintillator by moving the second, and thus get neutrons of all energies below 14 MeV for calibrating the efficiency of the second detector? No. Count rates are too low with their equipment for this kind of calibration.

The limit in the data accumulation rate is the tolerable count rate of the first detector. This is 10,000 to 20,000 counts/sec of neutron plus gamma events. The efficiency of the second detector is 50 to 80%, depending on the energy. The true coincidence count rate is a few counts per second.

In future work with the double scintillator spectrometer, a smaller than 45° angle to the second detector will be tried. Higher count rates and therefore a larger scintillator separation may be used, yielding an improvement in energy resolution.

Paper 2

E. A. Straker of ORNL said that the neutron spectrometry efforts at his laboratory are related to the shielding aspects of the fast reactor program. The neutron transport problem is of interest from the point of view of neutron leakage and activation, structural damage, and biological damage. Spectral measurements are used for evaluating cross section compilations for fast neutron transport, where the cross sections at the minima in the total cross section are especially important. Because of the sensitivity of some of the flux measurements to cross sections, a 20% spectral accuracy can correspond to a few percent check of the cross section value. Table I lists a number of spectrometry techniques that were reviewed. Li⁶ diode spectrometers have been utilized, as described in References 34 - 36. By shielding the diodes (See Figure 34) from the direct beam of neutrons and gamma-rays, ${}^{(36)}$ spectra were measured as a function of thickness of water shield for a swimming pool type reactor. ${}^{(37)}$ Films of ⁶Li and ⁷Li were remotely inserted between the diodes for measuring the ⁶Li(n, a)³He reactions and the background, which was reduced to about 10% of the signal.

The ⁶Lil scintillator was utilized in the late 1960's because of the much higher efficiency. The a and T responses differ by too large a degree, resulting in a poor resolution unless cooled to -140° C, where the resolution improved by roughly a factor of 2 (~10%). A ⁷Lil scintillator was used for background subtraction. It was assumed that the ⁷Lil shifts the background spectrum to low energies by 1.1 MeV, because a Q = -1.47 MeV for the ⁶Li(n, dn') a reaction and -2.57 MeV for the ⁷Li(n, Tn') a reaction.

The ³He spectrometers are more useful now that pressures of up to 1000 psi are used. The resolution doesn't degrade rapidly with pressure. At higher energy, the ³He(n, d) reaction complicates the results. At Los Alamos, the ³He counter was used in a beam geometry with the detectors at 90° out of the beam and biased such that the triton, whose energy at 90° is 0. 191 MeV for all neutron energies, is biased out. In another type counter⁽³⁸⁾, the filling gas between the diodes has been used as two proportional counters for dE/dx determinations so that γ events as well as the (n, a) and (n, d) events could be tagged. A fourfold coincidence is demanded to reduce counts due to gamma-rays and charged particles. It was designed to operate in fields of 10⁴ - 10⁵ R/hr, but the efficiency was low, the chance coincidences too high, and there were problems with the anisotropy of the device.

Another use of the ³He(n, p)T reaction has been made in the ³He proportional counter. (39) Pulse-shape-discrimination is used to reject gammarays, ³He recoils, and ³He(n, d)²H reactions, and to reduce wall effects. Because of the pulse shape discriminator, two dimensional data accumulation must be utilized and the energy dependent efficiency determined (for each PSD setting).

The Bonner Ball technique incorporates a set of spherical moderators of varied size and composition, sometimes with 10 B shells added, and generally surrounding either a 6 Li(Eu) scintillator or a spherical BF3 counter. The various spheres produce a set of responses having a progressively higher neutron-energy cutoff with increasing wall thickness. The outputs of all the detector-sphere arrangements of the set are used in conjunction with a folding program (iterative technique) to obtain a poor resolution spectrum.

Method	Detector	Resolution	Efficiency	Energy Range (eV)	Gamma Sensitivity
Time of Flight	Organic Scintillator Proportional Counters	0.1 - 10%	10 ⁻⁸ - 10 ⁻⁶ With Collimation	$10^{-2} - 10^{8}$	Low to High
Nuclear Reaction He ³ (n, p)H ³ Li ⁶ (n, a)H ³	He ³ Proportional Counter He ³ Sandwich	2 - 20%	$10^{-5} - 10^{-3}$	10 ⁵ - 10 ⁷	Low to Medium
	Lithium Sandwich	2 - 20%	$10^{-8} - 10^{-6}$ With Collimation	$10^5 - 10^7$	Low to Medium
	Lithium iodide	10 - 30%	$10^{-4} - 10^{-2}$	$10^5 - 10^7$	Medium to High
Proton Recoil	Proton Telescope	10 - 20%	10 ⁻⁸ - 10 ⁻⁶ With Collimation	$10^6 - 10^7$	Low to Medium
	Proton Recoil (Scintillator)	10 - 30%	0.1 - 0.4 Requires Unfolding	$10^5 - 10^8$	Medium to High
	Proton Recoil (Proportional Counter	5 - 20%	10 ⁻⁴ - 10 ⁻¹ Requires Unfolding	10 ³ - 10 ⁶	Medium to High
	Emulsions	5 - 30%	10 ⁻⁷ - 10 ⁻⁴ Requires Reading	10 ⁶ - 10 ⁷	Medium to High
Filter Trans- mission	¹⁰ B Filter with BF ₃ Detector Bonner Balls	Poor	10 ⁻⁶ - 10 ⁻¹ Requires Unfolding	10 ⁻² - 10 ⁴	Low
Foil Activation	Foils	Poor	10 ⁻⁷ - 10 ⁻³ Requires Unfolding	$10^1 - 10^7$	Low

Table I. Fast and Intermediate Neutron Spectroscopy Methods

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Figure 34. ⁶Li-Diode-Sandwich Spectrometer with Diodes Shielded from Neutrons and Gamma-Radiation Entering Collimator at Left

The ¹⁰B filter technique is similar, except that it utilizes a very thick jacket of ¹⁰B that entirely surrounds a BF₃ detector. A hole in this jacket is used for passage of the neutron beam to the BF₃ detector inside. A set of accurately determined thicknesses of ¹⁰B discs (filters) are placed across this hole, resulting in a family of calculated response curves as shown in Figure 35. The method, as employed at ORNL, utilizes an iterative technique in which the spectrum is initially guessed, folded in, and compared with the experimental output to obtain a better guess of the spectral shape. The rapidity of convergence depends on the complexity of the spectrum, and convergence is most rapid for E⁻ⁿ where n ~ 1.

A neutron spectrum from the Oak Ridge Electron Linear Accelerator (ORELA) was measured by simultaneously recording the pulse height from a NE-213 scintillator, the time-of-flight, and the (γ, n) discriminator output for each event and subsequently unfolding the pulse height distribution for the events identified as neutrons and accepted by the pulse-pileup circuitry. The time-of-flight spectrum determined from these data was compared to the unfolded pulse height spectrum (UPHS) to determine the accuracy of the response matrix utilized with the FERDOR unfolding code. (7, 8) (To illustrate the response functions for a NE-213, a series of responses (40) to monoenergetic neutrons is shown in Figure 36.) A comparison of the two results (time-of-flight and UPHS) is shown in Figure 37, where the solid curve shows the high-energyresolution time-of-flight spectrum, the dashed curve shows this spectrum smeared to match the broader energy resolution of the UPHS spectrum, and the band shows the UPHS spectrum with confidence interval. The agreement between the two types of measurement gives a good indication of the applicability of the response matrix to the particular detector used here, and its accuracy is seen to be reasonably good.

In a discussion of Straker's paper, another application of obtaining pulse height data versus time-of-flight was pointed out by Preskitt. If one obtains a pulse-height distribution for a given time of flight from a fast (delta function) die away assembly, one has the spectrometer response for the energy corresponding to that time-of-flight. If, on the other hand, the pulse height is measured for the same time-of-flight but from a subcritical assembly, the pulse height distribution is that due to a smear of neutron energies because of the long die-away time of the assembly. Unfolding this smear will give the distribution of neutron energies arriving at this time, and from this, the times of emission can be obtained direct-These measurements have been carried out with a 200 meter flight 1y. path and a NE-213 scintillator. The results are soon to be published. Straker and Preskitt agreed that this kind of measurement requires a very long running time. However, it needs to be done only once in order to understand the die away correction. If it can be reproduced by calculation, these calculations can then be subsequently utilized.

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Figure 35. Family of Response Curves Calculated for Various ¹⁰Boron Thicknesses used with ¹⁰B-Filter Spectrometer



Figure 36. Response Functions for 4.60 x 4.65-cm diam NE-213 Scintillator⁽⁴⁰⁾



Figure 37. Time-of-Flight Spectrum (Solid Line) Resolution-Smeared (Dashed Line) to Match Resolution of Unfolded Pulse Height Spectrum (Hatched Band)

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Straker said that some preliminary measurements of pulse height distributions versus time of flight were made at ORNL with a spherical proportional counter, but the combination of a poor time resolution (hydrogen filling with no methane added) and a short flight path introduced too great an energy spread at a given pulse-detection time. This will be looked at further.

Sanders asked if the errors shown by the hatch lines included some systematic component or were purely due to statistics. Straker pointed out that a 2 - 3% uncertainty is included which enters in making fits of combinations of the actual response functions to an idealized gaussian response function. (Editor's note: There are no provisions for indicating misrepresentations of the response functions in the code, and errors of this nature are now shown. Tests such as the time-of-flight and unfolding comparisons presented by Straker are used to evaluate the magnitude of these errors.)

How stable is a measured set of response functions with respect to changes in scintillator, tube and tube base, etc? Using about 5 different scintillators, the reproducibility was good to 5 - 10%. Detector volumes are measured to 2 - 3% with x-rays. Gains are always set with gammaray sources.

Other laboratories have used the same response-function-calculating code to generate responses for both larger and smaller scintillators, but there have been no good tests of the quality of the measurements. A particular Po-Be (30 curie) source, measured at ORNL, is being shipped to various laboratories in the country, along with a stand to enable accurate reproducibility of distance, so that the various spectrometers can be intercompared.

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The two parameter (time-of-flight and pulse height) data have not been used at ORNL to obtain the response functions at the time of the measurement (and then unfold with them) because of the very long time required to obtain good statistics for data in narrow energy intervals. Similar work is being carried out at Gulf Radiation Technology. However, if the very same data are utilized to build up the response matrix for the unfolding and to deduce the time of flight spectrum, the errors go to zero because the data are highly correlated. A separate, shorter, time-offlight run should be made for obtaining more realistic error bars.

Tuyn pointed out that the ¹⁰B filter method, with a ⁶Li glass scintillator as the central detector, was used at his laboratory to measure the central spectrum from the STEK facility. They use the inverse Laplace transform of the transmission function of the device. The results are in good agreement with a calculated spectrum which was an $E^{-1.03}$ spectrum. The measurement went up to 100 keV, and was reliable up to 50 keV. The method is quite poor for spectra with structure, especially narrow resonance type structure.

The use of scintillators for in-core measurements has been tried, Kazansky pointed out. The difficulties include the general one of calibration, (accuracy and stability of the response functions) and of high gamma-ray backgrounds. He feels they can make measurements in a Pu assembly, but will have a high bias, perhaps 0.8 MeV. They work with stilbene which has the additional disadvantage of an anisotropic light yield.

What was the γ/n ratio for Straker's NE-213 measurements at the ORNL linac? For the uranium or lead filter results, it was the order of 0.01, and for the carbon or H_2O filter, it was more like 1.00, without separating the gamma-rays by time-of-flight.

Paper 3

A. Fabry presented fundamental neutronic design data for the $\Sigma\Sigma$ (for SISSIC, Secondary Intermediate Standard Spectrum in Cavity) facility, spectrum calculations for $\Sigma\Sigma$, three types of neutron spectrometers that were used or are being developed at C. E. N/S. C. K., and some neutron cross section deficiencies revealed in the comparison of measurements and calculations.

The $\Sigma\Sigma$ facility described in Table II consists of a 110-mm I. D. aluminum clad B₄C shell just inside a 50-mm thick shell of natural uranium, all centered in a 500-mm diam spherical cavity in the BR1-reactor horizontal graphite thermal column. An in-core spectrometer (time-of-flight techniques cannot be studied) is placed inside the B₄C shell which shapes the low energy neutron spectrum such that the most fundamental reaction rates, like ²³⁹Pu(n, f) and ²³⁸U(n, v), take place within the same energy range for $\Sigma\Sigma$ as for fast breeder reactors. This shell is needed for ⁶Li spectrometry but not for the proton-recoil proportional counter. The total fast flux is 6 x 10⁸/cm²-sec with ~ 300 r/hr of gammas for a 1 MW reactor power level. Most of the gamma flux is due to neutron capture in graphite as both calculations and measurements (with cadmium covering the uranium) show.

The calculations utilized the one dimensional discrete ordinates Sn code $GMS^{(41)}$ with S-4 quadrature for optimizing $\Sigma\Sigma$ design and up to S-8 otherwise. The multigroup cross section set was a 40-group extension of the British FD2 set. ⁽⁴²⁾

Table II. Some Basic Nominal Features of the 22 Facility

- 1. LOCALIZATION: 500 mm diameter spherical cavity in BR1 horizontal graphite thermal column
- 2. SOURCE OF FAST NEUTRONS: 110 kg natural uranium spherical shell (metal
 - outer diameter: 245 ± 0.2 mm
 - thickness: 50 ± 0.1 mm
 - power: ~ 5 watts for a BR1 power of 1 MW
 - Note: A facultative right axial hole 15.5 mm diameter in a special uranium plug allows the introduction of differential neutron spectrometers if required; for activation measurements however, a full plug achieves the continuity of the source.
- 3. BORON CARBIDE SPHERICAL SHELL SCREEN:
 - vibrocompacted natural boron carbide; density: (1.48 \pm 0.005) gr/cm³
 - cladding: 1 mm A1 99.5%
 - thickness 17 mm (including cladding)
 - inner diameter: 110 mm.
 - Note: There are shells both with and without 17 mm diameter right axial holes for introduction of neutron spectrometers or activation foils respectively.
- 4. TOTAL NEUTRON FLUX into inner central void is 6.10⁸ cm⁻² sec⁻¹ at a BR1 power of 1 MW.

This total neutron flux expressed as a ratio to the thermal neutron flux available when the cavity is empty equals 0. 72.

Figure 38 compares the $\Sigma\Sigma$ spectrum with that from a large, dilute fast breeder. Figure 39 shows that the wall return contribution to the neutron flux is less than 30% of the total spectrum above 100 keV, where it is mostly governed by neutron interactions with uranium. This is important for applications of $\Sigma\Sigma$ to nuclear data correlations. Measured fission rates in the uranium show the radial dependence is independent of the angle θ from the axis of the thermal column, so that the spectral shape at the center is the same from all directions. However, the fission rate at the reactor end is twice that at the opposite end.

The Σ source is inexpensive and can allow many laboratories to study fast-reactor spectrometry without the need of a fast assembly. It doesn't exactly match a fast breeder spectrum, and shouldn't, so that a broader range of spectrometry checks is made possible.

The ⁶Li diode spectrometer utilized a collimator between the two diodes to eliminate corrections related to the angle between the alpha and triton The ⁶LiF was deposited on one of the for the energy range chosen. diodes. Both the detector and electronics were somewhat conventional except for the data storage and analysis. With bidimensional data storage of E_T versus $E_a + E_T$, appropriate regions of this display were chosen for obtaining the spectral information while significantly reducing background events. Most of these events fell outside the region of kinematic possibility for the ⁶Li(n, a)T reaction. The accuracy of reproducing the background with a dummy diode could be determined very well. By taking different slices parallel to the E_T or the $E_a + E_T$ axes for obtaining spectral information, a test of the constancy of the spectrum over different slices could be made. The bidimensional analysis can also reject events where the triton penetrates beyond the depletion depth of one of the diodes. The resolution of the spectrometer was 210 keV for a's, 60 keV for tritons and 280 keV for the sum peak. The E_{T} pulse height spectrum is utilized at lower energies and the $E_n + E_T$ spectrum above ~ 600 keV.

Solutions to the two major problems of E_T spectrometry were achieved. These are screening of the response to low neutron energies by the high energy neutron tail, and partial superposition of the E_a distribution on the E_T distribution for neutrons above 360 keV. To achieve this solution, the neutron spectrum was analyzed by decomposing it into partial neutron spectra whose characteristics depend on group width and on the $E_a + E_T$ resolution function. (43)

A Ferguson type proton recoil spectrometer is being developed at C. E. N. that utilizes a thin polyethylene radiator with a surface barrier diode, and a proportional counter region separating the two. ⁽⁴⁴⁾ They feel this should be good down to at least 100 keV. Backgrounds will be measured by removing the polyethylene film.



Figure 38. Comparison of Central Neutron Spectra in Large Dilute Oxide Fueled Fast Breeders and in the $\Sigma\Sigma$ Source Facility





Proton recoil spectrometry is being carried out with I. Girlea of Bucharest who is developing his own counters. The central $\Sigma\Sigma$ spectrum in the meantime has been measured from 0. 16 to 1.5 MeV with a 20th Century Ltd. Benjamin type spherical proportional counter (3.94 cm diam, 3 atm of 97% CH₄ and 3% N₂, having a 1.67 cm proton range at 1.5 MeV). One of five was chosen for its symmetric peaks from ³⁷A conversion electrons and ¹⁴N(n, p)¹⁴C reactions. The SPEC 4 code of Aldermaston, which treats response functions analytically, was used for unfolding the data. To check the reliability of the measurements and the data handling, calibrations were made at 0.6, 1 and 1.5 MeV (\pm 0.022 MeV) neutron energies.

Results obtained with this counter at the center of $\Sigma\Sigma$ are shown in Figure 40, compared with calculations. They agreed well with ⁶Li measurements in the 0.3 - 1.3 MeV overlap range. A deficiency of calculated flux is seen above 0.82 MeV. The S-8 calculation (described above) was based on the FD2 cross section set. ⁽⁴²⁾ The normalization with experiment is between 0.30 to 0.82 MeV. Table III shows a comparison with the same group structure for the measured and calculated

Group Energy	$\varphi(\mathbf{u}) / \varphi_{\mathrm{th}}$			
Limits (MeV)	Theory	Experiment	Percent Difference	
0.183 - 0.302	0, 205	0. 206 ± 4. 5%	+ 0.4%	
0.302 - 0.498	0.270	0.264 ± 5 %	- 2.2%	
0.498 - 0.821	0.267	$0.275 \pm 6 \%$	+ 2.8%	
0. 821 - 1. 35	0.169	$0.213 \pm 9 \%$	+ 25.7%	

Table III

data, with the greatest fine-group experimental error being pessimistically assigned to the broadened experimental group. A preliminary critical appraisal of all $\Sigma\Sigma$ data indicates that the large discrepancy above 0.82 MeV is related to the nuclear data of uranium and is of basic importance to fast reactor physics. Too high a rejection of neutrons from above 1 MeV is predicted by the FD2 set (the ²³⁸U downscattering matrix of this set is based on the evaluation by Parker. ⁽⁴⁵⁾) Similar trends have been recently reported⁽⁴⁶⁾ for the SNELL exponential block, which was computed on the basis of ENDF/B version. It appears that $\sigma(n, n^{i})$ (total) for ²³⁸U above 1 MeV (which mostly relies on BARNARD time-offlight data⁽⁴⁷⁾) is much higher than FD2. Limited integral spherical



shell transmission measurements performed at C. E. N. /S. C. K. ⁽⁴⁸⁾ tend to support the FD2 data for ²³⁸U total inelastic scattering. The thermalfission neutron spectrum of ²³⁵U in FD2 was hardened according to the tentative suggestion of Grundl⁽⁴⁹⁾, and the discrepancy in Table III was decreased from 26% to about 10%. Thus, it is not clear how much of a contribution to the low flux above 0. 82 MeV is due to the uncertainty in the fission spectrum. Transmission measurements, wherein the ⁶Li spectrometer will be used to measure the central spectrum for various additional spherical shells of depleted ²³⁸U inside the B₄C shell, are underway. The transmission of this shell from 100 keV to above the energy where we have no more data for graphite is mainly dominated by ²³⁸U inelastic scattering, so that from such measurements they may be able to distinguish between fission spectrum effects and downscattering effects.

Fabry's question to the conference: in view of the great potential of the 6 Li spectrometer as can now be realized with bidimensional data analysis, shouldn't more be done to request 6 Li(n, a) cross section measurements with greater accuracy? This is now the largest source of uncertainty with 6 Li spectrometry.

Discussion of Fabry's paper. In answer to Fabry's question on ⁶Li cross section requests at the end of his talk, Bennett pointed out that several recent measurements on ⁶Li were reported at the EANDC (European-American Nuclear Data Committee) symposium about one month ago. The discrepancies between the different laboratories measuring these cross sections are less than before. This will appear in the minutes of that symposium. Sowerby of Harwell is now doing a new ⁶Li cross section evaluation and may have it finished in a few months.

Bennett had made measurements in uranium slabs and remembered discrepancies in the same direction in the 1 - 2 MeV region that reflect the same discrepancies in uranium downscattering as reported by Fabry. He didn't remember which σ -set was used as these are constantly changing.

4 Fabry expressed concern over the very large change required in the inelastic scattering cross section of uranium that is implied by his spectral measurements, and the affect it can have on the detailed matrix. Very often, the matrix elements are renormalized to the total inelastic cross section in each group and this is dangerous, he said. This is a question to be resolved by basic nuclear data groups, but it is important to show how spectrometry measurements can really tell us something about this area.

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THURSDAY AFTERNOON

VIII. Informal Session. Other Spectrometers

E. A. Straker, Chairman

Before the session, M. Wiener suggested that applications of the spectrometers be stressed, so that the discussion of techniques would not dominate the session. Also, due consideration should be given to normalization between various spectrometers and intercomparisons between different laboratories.

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The energy range for measurements at the center of the assembly needn't go beyond 4 MeV, it was generally agreed, because there are only slight differences between reactor spectra and fission spectra above 4 MeV and there are few neutrons there. However, a for plutonium becomes very small there, so that there is some concern. Also, the confidence in the accuracy of the spectrum below 4 MeV may be affected if the spectrum above is not known. In time-of-flight measurements on assemblies, where the dieaway time is long, the detector calibration and the unfolding spectra must be well-known up to 8 - 10 MeV to achieve good accuracy in the 1 - 2 MeV range. For shielding, the leakage spectrum is definitely important above 4 MeV.

Bennett asked if any reactor physicist has used the spectra; or have the spectra influenced reactor theorists' evaluation of cross sections or even methods of calculation. Wiener assured him that core designers do worry about spectral agreement, and would like to know if the spectra are known to better than 5 - 10%. The experimentalist must be asked if the experimental accuracies are that good. Preskitt said that better than 10% (but not as good as 5%) accuracy can be achieved from a few keV to 1 - 2 MeV by time-of-flight measurements. Above this, dieaway corrections become large leading to 15 - 20% inaccuracies and below a few keV, back-ground problems become serious. Wiener pointed out the need for a sensitivity analysis to see if we're wasting our time in trying to get better than 10% (say 5%) accuracy. Straker pointed out that it may be more important to know the spectrum at other points (or to know the angular spectrum) to within 10% than to know the one at the center to say 3%.

Sanders said a 5 - 10% accuracy up to ~ 1 MeV should be achievable at UK with the combination of time-of-flight and proton-recoil measurements which should be done together to determine systematic errors accurately. They're improving their techniques above 1 MeV. The errors will be worse near discontinuities in the core, such as at control rods, which are also important regions.

Bennett stated that his accuracies are $\sim 5\%$, larger in some regions and less in others, that they're learning where the inaccuracies are, and by correcting, can go to better than 5% from a few keV to 1 - 2 MeV, and that they may eventually get good accuracies outside this range. He feels the spatial dependence problem (such as near control rods) will come up and will require further reduction in detector size or in the area of beam extraction.

Wattecamps said they will ask their theoreticians if there is need to improve the accuracy from 10 - 15% presently achievable to 5%, a goal that would require a large expenditure of resources.

Kazansky pointed out that the accuracy required depends on the problem before you. They don't need better than 10% accuracy up to 2 - 3 MeV in their 26 group calculational structure. There are few neutrons above that. Above 4 MeV, a 10 - 15% accuracy may be adequate as not many fissions take place there. An accuracy of at least 10% is needed near 5 keV and perhaps 5% up to 500 keV for reactor design. High energy resolution is not required for more accurate cross section estimates over broad energy groups. The high resolution of the time-of-flight method will not be useful until mathematical programs are developed that can utilize it.

Fabry made the point that different spectra should be used to compare errors of various techniques. There may be significant error cancellation in comparing results on the same spectrum. In foil measurements, for example, for more and more similar spectra, experimenters got better and better agreement. If both cancellation of errors and sensitivity to cross sections are great enough, then different spectra need to be used in intercomparisons in order to avoid invalid cross section checks.

Kazansky stated that there exists a sufficient variety of methods for checking both reactor calculations and multigroup cross section sets, such as reactivity coefficients, the ratio of cross sections, and other integral experiments. When stating an accuracy of better than 10%, he had in mind the point that spectral measurements must compete successfully with other experiments. Preskitt pointed out that the measurements of spectra supplement these other methods. Although reactivity measurements, etc can be made very accurately, calculations seldom agree with these quantities. Reactivity effects often cannot be explained in fast reactor physics these days, and for years the reactivity coefficient of boron couldn't be calculated because too hard a spectrum was being calculated. Reactor specifications like multiplication constant or breeding ratio are affected in the first order sense by certain cross sections (i. e., a for Pu). The spectra affect them in the second order sense.

Malaviya said that in their spectrum measurements they don't use multiplying media and only use simple geometries, so that the spectrum is strongly coupled to cross section values. In comparisons with calculations, they can easily pinpoint areas of disagreement and get a direct check on cross sections. From this point of view, there is a serious need of spectrum measurements. In checking certain cross section files (e.g., ENDF/B vs Karlsruhe data), it has been possible to recommend not only preferred data, but also a redirection in emphasis in differential measurements and evaluations.

Leridon discussed <u>sensitivity studies</u> at Cadarache for the effect of cross sections on spectra and other characteristics. The first calculations showed differences between measurements and spectrum calculations that can't be explained by fission or capture cross sections (which effect neutron balance). These are well evaluated by the adjustment method. The inelastic scattering and elastic removal cross sections had a great effect on the spectrum and they are trying to change these to get the correct spectrum and then see what happens to neutron balance. He agreed with Preskitt that it's a second order effect. Straker suggested it may be dangerous to change cross sections to match one result because it usually doesn't match when you go to another assembly. They have done this, Leridon said, because they found systematic tendencies between their calculated and measured spectra, and with Bennett's experiments as well.

Sanders referred the group to a paper (Campbell and Rowland, "The Relationship of Microscopic and Integral Data", under the general topic of "Integral Checks on Fast Reactor Performance", presented at the Helsinki Conference on Nuclear Data last year and published ~ June 1970, IAEA CN 26/116) on a data adjusting scheme. A large number of integral data are simultaneously fed into a least squares minimization program, together with sensitivities and predictions using a given set of differential data, and these integral data are used to adjust the differential data and hence significantly improve the prediction of the properties of their commercial reactor and larger commercial fast reactors. The integral data included 49 values of critical size taken from ZPR3 and ZEBRA experiments

and Los Alamos criticals, 7k, measurements, 19 reaction rate ratios (fission/capture ratios), and 4 spectra from measurements in ZEBRA 8A, B, C and D. A ten-group scheme is used at present, each group of unit lethargy width, and the experimental spectra are expressed as ratios of flux in adjacent groups, $\varphi_{\alpha}/\varphi_{\alpha+1}$. The program allows random and systematic errors to be included, and also correlation between different experiments, such as a constant detector efficiency between four different assemblies. As in all procedures of this type, it is important to assign realistic errors to the integral and additional data. Otherwise, incorrect conclusions will be drawn. As a result of including the ZEBRA measurements in the adjustment scheme, the predicted spectrum in the prototype fast reactor around 1 keV was increased by about 20%. This region is important because of the doppler effect in ²³⁸U. Pendelbury This is doing similar work at Aldermaston. He's using spectral information from the VERA assembly to improve nuclear data, probably in the high energy regicn.

Preskitt said that this optimization approach is sensitive to the reactor calculational techniques used in this data adjustment scheme and it therefore allows only that calculational technique to be done with high precision. It may have less to do with what the actual input data are in some cases.

Sanders stated that they have tested their methods of calculation of the heterogeneous nature of these fast criticals against very complicated and detailed calculations and feel that the nuclear data errors in this case of the fundamental mode are more important than the errors in the calculational model. (This situation could be quite different where there is a strong spatial dependence.)

Absolute intensity. Bennett said it's known to 3 - 4% for the proton-recoil case because the proton cross section is known to $\sim 1/2\%$. It's useful in getting the absolute fission rate, absolute boron rate, and several other integral measurements and these should be measured where possible together with spectral measurements. Paterson pointed out that absolute flux determinations in-core give additional information and can show up faults in techniques not seen in arbitrarily normalizing the spectra. It's easy to determine the absolute flux for in-core spectrometers, but not inbeam measurements where the average flux levels are much lower. But even there, it's still worth trying to do. They monitor the time-of-flight measurements with a fission counter in the in-core position and relate that to the beam fission rate. In this way, they are able to relate a timeof-flight measurement that only goes up to 50 keV to a proton-recoil measurement that only comes down to 50 keV without relying on overlap. Preskitt suggested that to obtain the maximum information from the measurement, one should always measure the absolute flux in the beam

with respect to fission rate at the source end of the probe (with the use of a thin foil-type flux monitor at that position, say). This might well be normalized to the fission rate per gram of 235 U at some standard position in the core, or better yet, if possible, to one fission averaged over the entire reactor. They expect to be doing such normalizations in future measurements, he said.

Problems with in-core use of other detectors were discussed. Fabry indicated that for ⁶Li diodes, the background from (n, p) and (n, c) reactions is ~ 10% at high energies. They can see these in their bidimensional plot because the kinematics are different for Si reactions. (The use of ⁷Li for background subtraction was mentioned. See this morning's sessions for more complete details.) Wattecamps pointed out that background reactions on silicon are relatively lower in ³He counters because of the much higher neutron cross section for ³He. These backgrounds were small below 3 MeV but ~ 10% above this.

Bennett indicated that the proton-recoil spectrometer could possibly be modified to attain these higher energies by using, say, a CO_2 filling for which the shorter ranged carbon and oxygen ions would be used. Measured responses would be required, however, because of the complicated resonance scattering of neutrons on carbon and oxygen (and the incompleteness of the required angular distribution measurements), but this could be done with a lot of work.

The use of scintillators in-core was next discussed. Fabry suggested the use of a light pipe to keep the photomultiplier tube out of the core. Verbinski pointed out that the photoelectron statistics at the photocathode surface (and the related energy resolution and gamma-ray discrimination ability) are poor enough under the best of circumstances and could not stand to be degraded further with long light pipes. Kazansky suggested that the use of a scintillator in-core may be desirable if the large amount of empty space required is made available. Sanders indicated it might be a problem of obtaining pood response functions for small scintillators.

Editors note: A 10 MeV recoil proton has a range that is the order of 1 mm in organic scintillators. Therefore, a scintillator as small as 2.5 - 5 mm on edge could be used. The calibration can be done accurately for NE-213 with calculations such as the 05S Monte Carlo code (R. E. Textor and V. V. Verbinski, ORNL-4160, Feb. 1968) that properly take into account proton-recoil end effects. For reactor spectra, the poorly known (n, p) and (n, c) cross sections on 12 C of NE-213 are small enough up to 8 - 10 MeV to be unimportant. Stilbene has poor energy resolution for isotropic flux and would probably not be useful. Search for a very small photomultiplier tube with small jitter time would be worthwhile since photocathode noise and Čerenkov radiation are both nearly proportional to photocathode area, and excess size is cumbersome in a reactor core. The gamma-ray sensitivity would go down almost as fast as scintillator volume, in addition to which the maximum Compton recoil electron pulse would go down by a factor of 10 to 20 for a 5 or 2.5 mm scintillator vs the 50 mm now in use.

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FRIDAY MORNING

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IX. Summaries by Chairman of Informal Sessions

(A) A. M. Broomfield: Proton Recoil Spectrometry Session

In summarizing the informal session, Mr. Broomfield gave a detailed and comprehensive review of fast neutron spectrometry by the proton recoil counter technique.

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To assess the technique in its proper perspective, it should be recognized that the accuracy requirements on neutron spectra, quoted by most groups are $\pm 5\%$ over the energy range 100 eV to about 4 MeV. The resolution requirements vary somewhat but reactor designers need results to half-lethargy intervals immediately; long range needs of identifying and correctly representing resonance effects may set more stringent requirements on the resolution.

Two types of proton recoil counters have been employed for in-core measurements:

- 1. Cylindrical type developed by Bennett at ANL
- 2. Spherical type developed by Benjamin at Aldermaston

In addition, large counters have been used for measurements in an extracted beam to extend the energy range of this technique to several MeV.

The in-core counters have been used in both plate-type and pin-type core assemblies. These environmental differences are important especially in evaluating heterogeneity effects and to insure the counter is effectively integrating the cell-average flux.

The measurements reported span the energy range of a few hundred eV to about 3 MeV. The lower energy limit varies, but 5 - 10 keV is typical. The upper energy limit is about 1 MeV for in-core measurements; beyond this extracted beam measurements are necessary.

The goal of this technique may be stated as being to achieve the capability to measure spectra over the range of several hundred eV to a few MeV, with a resolution better than 10% and an accuracy of about $\pm 5\%$, (which
refers to the ratio of amplitudes between two points within this energy range). Some of the problems involved in achieving this goal and the identification of areas of future study emerged from the discussions.

The importance of the purity of gas in the counters and the relative merits of different ways of getting the thermal-peak calibration were discussed. Most groups use the nitrogen-line for calibration and no significant distortion of the spectrum due to the presence of this gas is found. Some groups have also use ³He for this purpose and find its high cross section a definite advantage (necessitating a smaller "impurity"). In either case, especially for softer-spectrum assemblies (in the range 500 - 900 keV) one must ensure that the spectral distortion due to traces of N or ³He is negligible. The purity of gases is also related to resolution requirements. There seems to be little difficulty in achieving a resolution of about 10% with an 8-atm hydrogen filling; the British group finds that for small in-core spherical counters, a Ag-Pd leak is useful in getting a resolution of 6 - 10% with hydrogen pressures of up to 10 atm.

There seems to be some question as to the desirability of using methane. A carbon-recoil correction is necessary and if pressure is increased to about 8 - 10 atm in order to obtain high stopping power, the relationship between pulse-height and energy does not pass through the origin, thus introducing an uncertainty at high energies unless this relationship can be accurately determined. There seems to be some difference of opinion as to the methane pressure at which such problems begin to be significant. The relavent criterion seems to be the product of pressure and diameter. The Aldermaston experience points to a limiting value of 30 atm-cm for spherical counters. The Argonne group finds that for cylindrical counters the resolution becomes unsatisfactory for pressure-times diameter values of about 10 - 13 atm-cm. The alternative to the use of high-pressure methane for extending the high-energy limit (with its attendant problems of resolution and energy calibration) may be found in approaches involving either the extracted beam counter measurements (Karlsruhe) or the use of gas mixtures other than methane, such as either argon or krypton with hydrogen (U. K.).

In the determination of the detector response function, end effects are important for both cylindrical and spherical counters. Dr. Bennett at Argonne is developing calculational methods to allow for gas-gain variations due to field effects at the wire; improvements through engineering design are also possible. He feels that significant errors have been present in quoted measurements in the past, especially in the energy range below 10 keV. Efforts directed toward better establishing the response function are also under way at Aldermaston. The effect of these corrections on the measured spectrum depends on the energy range. Over the range 4 keV - 1 MeV changes of about 4% or less may be necessary. However, the size of the correction factor (to be applied to incorporate revision in response function) will be much larger at low energies and may be as high as 20% in the resonance region. Clearly further work needs to be done to ensure that the response functions are correctly represented.

The energy calibration is generally based on the ³He or N line. Attempts must be made to check the gas-gain scales (used for measurements at low energy) directly without relying on the extrapolation of a relationship such as that due to Diethorn. In looking at the results from some cores, it is found that there are significant discrepancies with respect to the positions of resonances, but none of these seem to indicate that the energy scale is established to an accuracy of worse than 5%. Smaller uncertainties (< 3%) are found in the 50 keV - 1 MeV range, whereas at low energies (near about 5 keV) the uncertainty rises to about 5%. In considering these problems with the low-energy scale determination, the variation in the electron-loss-per-ion-pair parameter (W) is also important, especially below 10 keV. The U.S. and Karlsruhe work seems to suggest that there is some variation of W for H₂ between 10 keV and 1 keV. Accurate measurements are needed.

The electronics for proton-recoil measurements were discussed only briefly. Latest developments in electronics now allow higher counting rates to be handled than in earlier work. This is especially important since many environments in which future measurements are to be made have high counting rates due to spontaneous fission in 240 Pu. We can first, use smaller counters with precisely defined geometry and high pressure fillings and secondly, develop electronics which can reliably process pulses from these counters. Thus measurements should be made without reducing multiplication significantly, as close to criticality as possible. The gamma-subtraction technique depends on the 60 Co source correctly representing the electron distribution that is observed in the reactor. Pile-up and base-line distortions in the electronics can cause deviations, especially in the low (below 5 keV) energy range.

The measured spectrum is also affected by the local environment around the counter. The in-core counter is generally placed in a plate-or pintype configuration and may be surrounded by a fuel-element sheath or by lead to reduce the gamma count rate. The effect of these latter coverings on the observed spectrum is less than 1%. Inasmuch as the spacings between the fuel plates are comparable to the sensitive volume of the counter, the counter seems to be effectively measuring the spectrum which is close to the cell-average. However, in any particular case, the effect of heterogeneity must also be considered. When measurements are made in the beam, one must make sure that scatterings in the insulators of the counter which is viewing the beam do not distort the incident spectrum. Also, the response functions should have been correctly determined for the beam geometry.

In comparing spectra measured by different techniques or under different conditions, care must be exercised to make sure that the different spectral data have been corrected to the state where they are directly comparable. For example, in comparing beam measurements and in-core measurements, or proton-recoil versus time-of-flight, correction must be made for possible differences in spectra in critical and subcritical states.

The appropriate corrections for normalization of runs at different pressures are also not to be ignored. There seems to be agreement that normalization of counters with different fillings can be achieved to an accuracy of 5% or better.

Detailed variation of resolution with energy has not been accounted for in a precise way. More work is needed (new codes such as MAZE at Rad Tech may prove useful) to see if more detail can be unfolded than has been possible so far.

Only a few preliminary results on intercomparisons of any kind have been reported. Work at Karlsruhe and Cadarache shows that cylindrical and spherical counter measurements of spectra in a particular assembly are in agreement to within 5 or 6% down to about 2 keV. On the other hand, proton recoil measurements in the VERA assembly at Karlsruhe and Aldermaston show disagreements which have not been resolved. Obviously, there is an urgent need for more intercomparison measurements (under diverse conditions, by different techniques, etc.) so that sources of systematic errors can be isolated.

In conclusion, all groups agree that currently proton recoil counter measurements can be made in the energy range 50 keV - 1 MeV with an over-all accuracy of 5 to 7% (this refers to the ratio of flux amplitudes at two energies within this range and is based on representation in coarse groups; within resonances there could be errors larger than these). Errors depend also on the hardness of the spectrum and on the γ/n ratio at low energies. In spectra typical of LMFBR's at low energies, the cumulative error arising from errors in response-function shape, error in energy calibration and errors in gamma-discrimination can be extremely large — more than 20% below 5 keV. In fact, in hard spectra, amplitudes can be in error by a factor of two. Attainment of an accuracy of 5% below 5 to 10 keV is going to be an extremely difficult task but we already have within our grasp the required accuracy in the 50 keV - 1 MeV range — provided there are no unforeseen sources of systematic error in the measurements. To uncover these, we must make as many comparisons as possible with techniques which are independently based.

(B) A. Schmitt: Time-of-Flight Session

Schmitt summarized the informal session on time-of-flight fast neutron spectrometry. The need for time-of-flight measurements on fast reactor cores arises in two ways: first, for intercomparison with proton-recoil techniques in the region of overlap to uncover sources of systematic error in the proton-recoil measurements and second, to obtain detailed information for the low-energy part of the spectrum in a fast reactor; time-of-flight is the only currently available technique for measurements in this (below 1 keV) range.

In relation to fast reactor systems, the time-of-flight technique can be fruitfully applied to three types of problems:

- 1. the study of spectra in the interior regions of the core.
- 2. the investigation of specific problems relating to shielding or interface regions of fast reactors.
- 3. for several kinds of fundamental studies, such as diffusion problems.

The suitability of the technique and associated problems differ in each case, to some extent. Thus, for in-core (asymptotic region) measurements, at least, there is no major problem due to the re-entrant-hole perturbation, nor to the lining of the beam (if this lining is exactly of the same composition as the core). However, the effects due to the re-entrant hole and the lining could become important if we are in a region of strong spectrum or flux gradients.

The resolution problem in a time-of-flight system begins to be significant as we go to high energy ranges; useful results going up to a few MeV have been reported. The resolution problems arise firstly from the lack of statistics while using a long flight path and secondly from the long finite decay time of the multiplying assembly. More work needs to be done if we are to usefully cover higher energies. The Rad Tech approach (due to d'Oultermont) to relating the time spectrum to the actual neutron spectrum may prove to be useful in this context. Perhaps the most important single outstanding problem in the application of time-of-flight technique to fast reactor systems is that of detectors and their calibration. Most groups are currently using ^oLi and ⁷Li glass scintillators, which are highly efficient, but unresolved discrepancies remain in the calibration of their response as a function of energy. Usually, calibration for the energy range above 70 keV is done using a Van de Graaff system and there seems to be agreement on the calibration curve up to about 200 keV (i. e., to the left of the Li resonance). Below about 100 keV the efficiency is determined with reference to some other time-of-flight system, e.g., using a ¹⁰B plug detector. Disagreement of the experimental efficiency curve with Monte Carlo calculations, especially at high energies, has been noted but not yet explained by both the Rad Tech and U.K. groups. More work on the resolution of these disagreements, (including the examination of Li cross section data) remains one of the urgent tasks. Of interest will also be the results from the use of ³He counters in the time-of-flight spectrometer planned in USSR.

Care needs also to be exercised in the use and interpretation of the 'measured' time-of-flight spectrum, both when we are intercomparing techniques and when we are comparing with calculations. Among such considerations are vector versus scalar flux, and the effect of heterogeneity (i. e., cell-averaging of the flux). Because of the many uncertainties involved, it would be useful to have more direct intercomparisons of time-of-flight results with extracted-beam measurements using protonrecoil spectrometers. Such studies are planned at Cadarache and Aldermaston.

Time-of-flight measurements are always done on subcritical media and appropriate corrections must be made to account for differences between critical and subcritical flux spectra before comparing with calculations or other techniques.

The time-of-flight system for fast neutron spectrometry can be quite expensive, especially if a LINAC is involved in conjunction with a critical facility. (It was pointed out, however, by Dr. Preskitt that this is not necessarily so, if a LINAC is available anyway and time can be rented for spectrum measurements). On the other hand, other kinds of neutron generators may entail problems of poor statistics or poor resolution, depending on the flight path. One approach toward optimizing a time-of-flight system, which is under development at Cadarache, involves an intercorrelation with neutron pulses which are randomly selected. Preliminary calculations show that with a heavy ion accelerator, a 10 microamp ion current can provide the same kind of statistics as a 'classical' time-of-flight experiment with repetitive pulses in a time comparable to a LINAC system. The technique is in its embryonic stage and actual details and evaluation of specific advantages in its use must await further development.

(C) E. A. Straker: Other Fast Neutron Spectrometry Techniques

Straker summarized the informal session devoted to "Other Fast Neutron Spectrometry Techniques" and also commented on the analytical considerations and requirements on fast reactor spectra from the point of view of the core designer.

The four fast neutron spectrometry techniques discussed in this session involving either new ideas or new applications were: (i) Li diode with two-dimensional data analysis to separate out the alpha and triton energies (discussed by Fabry); (ii) the ³He diode with central proportional counter (discussed by Wattecamps); (iii) the double-crystal spectrometer (described by Paterson) and (iv) the use of stilbene for incore measurements (as discussed by Kazansky). All these represent new and improved approaches to the measurement of neutron spectra, especially in the MeV range. All four techniques have been sufficiently developed and, in general, appear to be adequate, except that improved ⁶Li cross sections are needed; these are expected to be available soon, from data already taken. Information on angular distributions of the ⁶Li cross sections is also needed.

Knowledge of the neutron spectra in the energy range above about 5 MeV does not appear to be very important, although the question is still to some extent open, and comprehensive sensitivity calculations are needed — and have been started — to indicate the extent to which detailed knowledge of the spectrum in the high MeV range may affect core calculations. Preliminary indications are that the shape of the spectrum in this energy range is roughly the fission spectrum. The process most important in this range is fast fission in 238 U and this can be measured directly rather than measuring the spectrum.

To meet the short-term needs of the core-designers, there seems to be a consensus that multigroup cross sections can be adjusted so that the core-center flux can be calculated with present core design techniques. Although there is danger in this approach and it says nothing regarding the calculation of spectra in other regions and of other core parameters (for example reactivities and control rod worths), it may be necessary in terms of the time schedule governing many projects so as to develop core design codes for operation on a production basis. One important point to keep in mind is that in the data adjustment procedure, to match the measured and calculated spectra, one must take into account the realistic experimental errors associated with the measured spectra. The long-term procedure must be based on the generation of multigroup constants from pointwise data. The justification for the data adjustment technique to alter the multigroup cross sections is based on the assumption that spectral information in the center of core is more sensitive to cross section data than to calculational technique. However, in general one cannot separate out the sensitivity to cross sections and transport calculational techniques; the situation may be quite the opposite near an interface and in the outer regions of the core. This must be kept in mind while interpreting spectral data in different parts of the core.

The point was raised that in fast critical assemblies quantities and parameters other than spectra in the central regions should be routinely measured — for example, material worths, specific reaction rates, etc may be more sensitive to particular aspects of cross section data. To illuminate this point, core designers and theoreticians should perform more detailed sensitivity calculations to determine which reaction rates or material worths can be usefully measured.

The choice and selection of a particular technique to perform a required set of measurements needs careful planning and consideration inasmuch as a particular experimental group may find one technique easier and more favorable than another, depending on its background, experience, and facilities. The consideration of the use of these four "other" techniques may be prompted either by the desire to get an overlap region with some other technique (e. g., to validate proton-recoil counter measurements over the 500 keV - 1 MeV range) or primarily to obtain spectrum measurements at high (MeV) energies.

A great deal of attention was given to a discussion of the accuracy with which current measurements can be made. Over-all conclusion seems to be that in the energy range 50 - 500 keV an accuracy of 5% can be achieved, without much effort, with the proton recoil technique; outside this range, about 10% accuracy is more typical; whereas in the extreme ranges (e. g., below 3 keV and above 2 MeV) larger uncertainties, of the order of 15%, may exist. There seems to be general agreement that significant improvements in accuracy, by as much as a factor of 2, are possible but expensive in terms of time, money, and effort and before going too much further in improvement of techniques we must await sensitivity calculations to point out more clearly the advantages gained and/or more definitive indications from core designer as to their specific goals and requirements and what additional information they can get if spectra were known to better accuracy (for example, 2 or 3%).

X. Concluding Session

(A) E. I. Inyutin's Remarks

Invutin, in discussing the motivation and the <u>raison d'etre</u> for the meeting, pointed out that the meeting grew out of the recognition, by the International Working Group on Fast Reactors, of the important role of the knowledge of neutron spectrum in interpreting and understanding the many neutronic events in fast reactors. The meeting brought together for presentation and discussion many reports dealing with the several diverse aspects of the measurement and interpretation of neutron spectra in fast reactor systems.

In the direction of giving continuing attention to these problems, Inyutin made three specific recommendations. First, that there be another meeting of the Specialists, some time in 1972, devoted to the problem of the measurement and interpretation of neutron spectra in fast reactors. Second, a status report be prepared summarizing the experience of each participating laboratory and describing in detail the state-of-the-art with respect to methodology, technique, intercomparisons, interpretive approaches, etc. Third, greater attention should be given to optimizing the direction, content, and emphasis of experiments from the point of view of the quality of data, calculational methods, and the requirements of the reactor designer.

Inyutin thanked the U. S. Atomic Energy Commission for organizing this meeting and the Argonne National Laboratory for hosting it and making available its physical facilities.

(B) Plans for Next Meeting

It was agreed that 1972 would be an appropriate time for holding another meeting of this nature, allowing adequate time for new developments, new measurements, analyses, and comparisons to provide material for a meaningful and fruitful review. It was also agreed that the next meeting be somewhat broadened in scope so as to permit representation of core designers and their interests and requirements and some consideration of such additional topics as standard spectrum systems, intercomparisons between methods, evaluation of techniques, etc. Regarding Inyutin's second recommendation, it was felt that the summary Technical Report of this meeting, together with the papers submitted (listed in Appendix C), would constitute a status report of the type envisioned in the recommendation; Inyutin agreed that this would indeed satisfy the spirit of his suggestion.

(C) Standard Spectrum Facility

There was an extended discussion of the need to formulate the detailed composition, geometry, etc of a standard, easily reproducible assembly, amenable to spectrum measurements by a variety of techniques, so that the techniques and equipment used at different laboratories could be meaningfully checked and standardized. It was decided to organize an informal working group for the purpose of considering the question of a standard spectrum facility, as a topic by itself. The membership of this group would include, and be limited to, the following:

- 1. Dr. E. F. Bennett, ANL, U.S.A., chairman
- 2. Dr. A. Fabry, C. E. N., Belgium
- 3. Dr. Yu. A. Kazansky, Inst. Phys. and Power Eng., U.S.S.R.
- 4. Dr. C. Preskitt, Gulf Radiation Technology, U.S.A.
- 5. Dr. J. Sanders, Winfrith, U. K.
- 6. Dr. A. Schmitt, Cadarache, France
- 7. Dr. J. Tuyn, Reactor Centrum Nederland
- 8. Dr. E. Wattecamps, Karlsruhe, Germany
- 9. Dr. J. Grundl, National Bureau of Standards, U.S.A.

This group would be expected to consider the problem of a standard spectrum facility, gather all the available information on the subject, go into the question of the need and requirements for such a facility, and come up with specific ideas and recommendations regarding the details of the facility itself and the kind of studies to be made with it. The group may decide to hold a formal meeting sometime in 1971, under the sponsorship of the IAEA.

(D) Compilation of Integral Data

As a means of facilitating the exchange of information relating to the results of the studies of neutron spectra and other integral quantities in fast systems, and channeling the information to the reactor design and data evaluation groups for their use and comment, it was felt that it would be useful to have a central standard compilation. Malaviya described the efforts at RPI toward evolving a format and a procedure for such a compilation. It was agreed that the different participating laboratories should cooperate in this endeavor toward bringing together their results in an appropriate compilation of this kind.

(E) Chairman's Concluding Remarks

Mr. Wiener, the Chairman of the meeting, expressed his appreciation to the IAEA and to Inyutin for initiating and sponsoring the meeting and giving it continuing encouragement and impetus. He also thanked the various individuals and groups associated with the meeting for their help and cooperation. He made appropriate concluding remarks pointing out the usefulness of the meeting in providing a fruitful exchange of ideas and information, leading, hopefully, to many constructive ways in which the discussions at the meeting might be reflected into and be integrated in the fast reactor programs of the various participating laboratories.

APPENDIX A

Names and Addresses

Attendees of the IAEA Specialist's Meeting Fast Reactor Spectrum Measurements and their Interpretation

- E. F. Bennett, Argonne National Laboratory, Applied Math Division, 9700 South Cass Avenue, Argonne, Illinois 60439, U.S.A.
- A. M. Broomfield, United Kingdom Atomic Energy Authority,
 E. E. Winfrith, Dorchester, Dorset, England
- A. Fabry, Laboratoire du C. E. N., Boeretang 2400, Mol-Donk, Belgium
- E. I. Inyutin, Scientific Secretary, International Working Group on Fast Reactors, IAEA, Karntner Ring 11, P. O. Box 590, A-1011, Vienna, Austria
- Yu. A. Kazansky, The Institute of Physics and Power Engineering, Obninsk, Kalujskaja oblast, USSR
- A. M. Leridon, Ingenieur au Service des Experiences Critiques pour les Neutrons Rapides, DRP/SECNR - Centre de Cadarache, B. P. No. 1, 13 Saint-Paul-Lex-Durance, France
- B. K. Malaviya, Rensselaer Polytechnic Institute, Nuclear Science Dept., NES Building, RPI, Troy, New York 12181, U.S.A.
- M. Marseguerra, c/o CNEN, Via Mazzini 2, 40138 Bologna, Italy
- W. J. Paterson, United Kingdom Atomic Energy Authority, AWRE Aldermaston, Berkshire, England
- C. A. Preskitt. Gulf Radiation Technology, a division of Gulf Energy & Environmental Systems Company, P. O. Box 608, San Diego, California 92112, U.S.A.
- M. Salvatores, Argonne National Laboratory, Applied Math Division. 9700 South Cass Avenue, Argonne, Illinois 60439
- J. E. Sanders, United Kingdom Atomic Energy Authority, A. E. E. Winfrith, Dorchester, Dorset, England
- A. Schmitt, Ingenieur au Service des Experiences Critiques pour les Neutrons Rapides, DRP/SECNR - Centre de Cadarache,
 B. P. No. 1, 13 Saint-Paul-lez-Durance, France

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- E. A. Straker, Oak Ridge National Laboratory, P. O. Box X Oak Ridge, Tennessee 37830, U.S.A.
- A. Tatistcheff, 53 East 96th Street, New York, New York 10028, U.S.A.
- W. N. Tuyn, ReactorCentrum Nederland, Petten, N. H., Netherlands
- V. V. Verbinski, Gulf Radiation Technology, a division of Gulf Energy & Environmental Systems Company, P. O. Box 608, San Diego, California 92112, U.S.A.
- E. Wattecamps, Institut fur Angewandte Reaktorphysik, Kernforschungszentrum Karlsruhe, Karlsruhe, Germany
- M. Wiener,

United States Atomic Energy Commission Washington, D. C. 20545, U. S. A.

APPENDIX B

Agenda

IAEA Specialist's Meeting Fast Reactor Spectrum Measurements and their Interpretation

TUESDAY MORNING, November 10, 1970

- I. Introduction
 - 1. Welcoming Remarks: Dr. R. B. Duffield, Director, Argonne National Laboratory
 - 2. Approval of Agenda

II. Opening Remarks

1. USAEC Spectrometry Program: M. Wiener, USAEC

III. Proton-Recoil Spectrometry

- 1. ANL Spectrometry Program: E. F. Bennett, ANL
- 2. Proton-Recoil Spectrometers: A. M. Broomfield, UKAEA
- 3. Summary of CNEN Activities in Fast Reactor Spectrum: M. Marseguerra, CNEN
- 4. Proton-Recoil Spectrometry: A. J. Leridon
- IV. AFTERNOON Informal Session on Proton-Recoil Spectrometry: Chairman, A. M. Broomfield, Winfrith
- V. WEDNESDAY MORNING, November 11, 1970 Time-of-Flight Spectrometry
 - 1. Time-of-Flight Spectrometers: J. E. Sanders, UKAEA
 - 2. Investigation on the Reliability of Fast Neutron Spectrum Measurements: E. W. Wattecamps, Karlsruhe, Germany
 - 3. Time-of-Flight Spectrometry Program: C. A. Preskitt, Gulf Radiation Technology

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- 4. Program at BFS: Yu. A. Kazansky
- 5. TOF Experiment at STEK: W. N. Tuyn
- 6. TOF Experiment in Cadarache: A. Schmitt
- VI. AFTERNOON Informal Session on Time-of-Flight Spectrometry: Chairman, A. Schmitt, Cadarache
- VII. THURSDAY MORNING, November 12, 1970 Other Fast Neutron Spectrometry Techniques
 - 1. Other Spectrometers: W. J. Paterson, UKAEA
 - 2. NE-213 and Other Spectrometers: E. A. Straker, ORNL
 - 3. Role of Standard Fields: A. Fabry

VIII. AFTERNOON - Informal Discussion, Other Fast Neutron Spectrometry Techniques: Chairman, E. A. Straker

FRIDAY MORNING, November 13, 1970 - Review and Summary

- IX. Summaries by Chairmen of Informal Sessions
 - (A) A. M. Broomfield: Proton Recoil Spectrometry
 - (B) A. Schmitt: Time-of-Flight Spectrometry
 - (C) E. A. Straker: Other Fast Neutron Spectrometry Techniques

X. Concluding Session

- (A) Remarks by Dr. I. Inyutin, Scientific Secretary of IWGFR of IAEA, relating to collection and systemization of the international data on fast reactor spectrum measurements.
- (B) Plans for next meeting
- (C) Selection of working group on fast-reactor standardspectrum sources
- (D) Compilation of Integral Data
- (E) Chairman's Concluding Remarks

AFTERNOON - Tour of ANL Facilities

APPENDIX C

List of Handout Papers at the Meeting

1. M. Wiener: "Fast Neutron Spectrum Measurements in the U.S."

E. F. Bennett, "Neutron Spectroscopy with Proton Recoil Proportional Counters", 3 parts, E. F. Bennett and T. J. Yule
 Part I - Description of Method
 Part II - A Survey of Spectrum Measurements in Several Critical Assemblies on ZPR-6 and ZPR-9
 Part III - Technical Problem Areas

- 3. A. M. Broomfield: "Proton Recoil Counter Techniques in ZEBRA", A. M. Broomfield and M. D. Carter
- 4. UKAEA:
 - (a) "Fast Reactor Spectrum Measurements in VERA and ZEBRA Assemblies. A Progress Report", edited by A. M. Broomfield, J. E. Sanders, and W. J. Paterson
- 5. M. Marseguerra: "Summary of CNEN Activity in Fast Neutron Spectrum Measurements and Data Analysis".
- 6. A. Leridon:
 - (a) "Utilization D'une Chaine a Impulsion de Courant pour la Spectrometrie des Neutrons Rapides in Pile," C. Jeandidier, A. Leridon, M. Moroni and M. Rogerieux.
 - (b) "Linearite et Resolution d'un Spectrometre a Protons de Recul an-dessons de 25 keV", A. Leridon, C. Jeandidier, and D. Calamand, SECNR, Note Technique No. 69-51 - AL/MM, 7 July 1969

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- 7. E. Wattecamps:
 - (a) "Condensed Notes on Fast Neutron Spectrum Measurements of SUAK-core UHC by Four Spectroscopic Methods", Work performed by H. Bluhm, G. Fieg, F. Kappler, M. Muller, E. Wattecamps, and H. Werle.
 - (b) "Neutron Detection Efficiency of Fast Neutron Detectors in Time-of-Flight Measurements", F. Kappler and E. Wattecamps.
 - (c) "Neutronenspektrumsmessungen mit Protonenrückstoffszählern an SUAK-UHC (VERA 7A) und SUAK-UNAT", G. Fieg and H. Werle, Karlsruhe, Arbeitsbericht INR-Nr. 409/70, 14 October 1970
 - (d) "Entwicklung und Erprobung eines ³He-Halbleiter-Sandwich-Spektrometer mit γ-Diskriminierung", H. Bluhm, KFK 1270/2, October 1970
 - (e) "Proposal for a Standard Spectrum to Check Techniques of Fast Neutron Spectrum Measurements", M. Küchle and E. Wattecamps, the paper for the 11th EACRP Meeting, London, Feb. 10-14, 1969.
- 8. C. A. Preskitt: "Measurement and _ nalysis of Neutron Spectra and Kinetic Properties in the Fast Subcritical Assemblies STSF-2 and STSF-2A", P. d'Oultremont, J. C. Young, J. M. Neill, C. A Preskitt, Gulf-RT-10352, October 7, 1970
- 9. Yu. A. Kazansky: "Work Program on Neutron Spectrometry at BFC Physical Assembly", Yu. A. Kazansky.

10. J. W. N. Tuyn:

- (a) "The Time-of-Flight Experiment at STEK".
- (b) "Fast Reactor Spectrum Measurements by means of Boron Filters, " G. H. Hofmeester, Reactor Centrum, Nederland, Petten, the Netherlands.
- (c) "Neutron Spectrometry with Summing Semiconductor Sandwich Detectors inside the Fast Zone of the STEK-4000 Assembly", R. J. S. Harry, Reactor Centrum Nederland
- (d) "A Proton Recoil Counter Set-up for Neutron Spectrum Measurements with a Wide Energy Range", C. F. A. Fruman and C. Lautenbag, Reactor Centrum, Nederland, RCN-Int-68-058, Paper, International Symposium on Nuclear Electronics, Versailles, September 10 13, 1968.

- (e) "keV Neutron Spectrometry by Proton Recoil Technique",
 A. P. J. Mas and J. Montizaan, Reactor Centrum, Nederland,
 RCN-70-024, Paper at tripartite USSR Belgium Dutch
 Symposium on Fast Reactor Physics, Melekess, February 1970.
- 11. E. A. Straker: "Fast and Intermediate Neutron Spectroscopy".
- 12. A. Fabry:
 - (a) "Conceptual Design and Major Items of the CEN/SCK Secondary Standard Neutron Spectrum Facility", A. Fabry, P. Vandeplas.
 - (b) "Survey of the Experiments Performed within the CEN/SCK Secondary Standard Neutron Spectrum Facility", A. Fabry, S. de Leeuw, and M. de Coster.
 - (c) "Improvements in the Use of the ⁶Li(n, a)T Reaction for In-Core Neutron Spectrum Measurements", G. de Leeuw-Gierts and S. de Leeuw, Report 450 (1970)
 - (d) "Application of the Methane Filled Spherical Proton Recoil Proportional Counter in the CEN/SCK Secondary Standard Neutron Spectrum Facility", I. Girlea (I. F. A. Rumania), A. Fabry, and G. and S. de Leeuw (CEN)
- 13. Papers from Japan:
 - (a) "Measurement of Fast Neutron Spectrum with a He-3 Proportional Counter", T. Iijima, T. Mukaiyama, and K. Shirakata, 1970.
 - (b) "Neutron Spectrum in an Anhydrous Sodium Carbonate Pile",
 T. Nanjyo, K. Kanda, Y. Nakagome, and I. Kimura.

APPENDIX D

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