opening a dialogue between people interested in this new venture. As yet uneven in its levels of sophistication, the meeting's tenor was on the applied side since the program was scheduled primarily to provide a basis for an exchange of ideas about needs for further developments in accelerator and beam-handling techniques and for methods of implantation characterization that must be met before doping by energetic ions can become a routine tool in the laboratory. Already, however, intriguing new questions about basic semiconductor physics are being posed. They should move into the center discussion at future meetings.

* * *

The conference was sponsored by the French Atomic Energy Commission, arranged by the CEN-G Electronics Laboratory, and guided by the conference's dynamic secretary, P. Glotin. The conference proceedings are scheduled to appear in a few months.

WERNER BRANDT
Brookhaven National Laboratory and New York University

Theoretical Calculations Gain Importance in Reactor Design

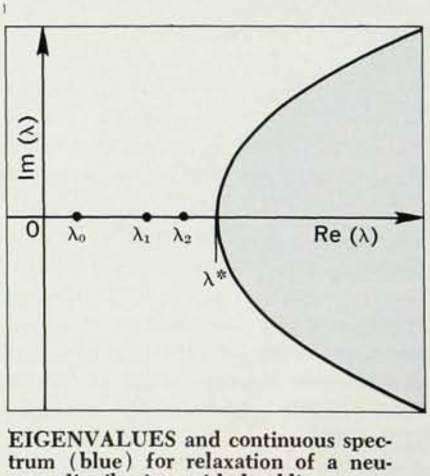
Neutron thermalization and reactor spectra represent two opposite extremes of energy-dependent neutron transport. By now one-speed neutron transport has been thoroughly explored. Even at the Ankara summer school lectures in the summer of 1965 it was clear that many investigators who had been straining to find interesting problems to study with the one-speed equation were turning to an energy-dependent treatment. At the same time, another group that had considerable success in solving infinite-medium problems was adding more dimensions to its calculations. As these two groups have extended their investigations, they have finally begun to attack problems increasingly closer to what a reactor designer considers to be of practical significance.

The International Atomic Energy Agency Symposium on neutron thermalization and reactor spectra held at The University of Michigan in Ann Arbor, July 17 through 24, provided evidence of the needs of reactor designers for much of the esoteric neutron transport theory developed over the past several years. Also it was clear that theorists are recognizing and dealing with finite geometry and energy-dependent problems closely associated with the more sophisticated reactor calculations needed for the present generation of reactor designs.

Ivan Kuščer of Ljubljana University in Yugoslavia, one of the few theorists familiar with both the one-speed and infinite-medium schools, opened the conference by tracing paths followed by theorists as their interests have converged.

The first day of the meeting dealt with (as did the Karlsruhe meeting on pulsed-neutron research in 1965) the eigenvalue spectra of the Boltzmann operator. Although this problem might strike the casual observer as having little practical significance, it was introduced several years ago in an attempt to understand certain pulsed experiments in which the existence of an asymptotic decay mode was not empirically obvious. Thus the problem has immediate practical importance.

Roman Bednarz at the Karlsruhe meeting derived the Boltzmann spectrum for a scattering kernel that is square-integrable, a condition not obeyed by elastic scattering from a solid. M. Borysiewics and J. Mika extended the Bednarz case to isotropic elastic scattering. While the nonisotropic case still remains, it is doubtful that anisotropy qualitatively changes the conclusions.



EIGENVALUES and continuous spectrum (blue) for relaxation of a neutron distribution with buckling.

Although the situation is probably still not completely understood in the finite body, the above papers have clarified the problem. Along the same lines, M. Williams considered the diffusion length in a prism. Time and spatial modes are closely related; indeed the discrete diffusion-length spectrum disappears for sufficiently small bodies. Here the boundary on the discrete spectrum is a function of the transverse buckling of the assembly, which warns the experimenter to exercise care in interpreting such measurements.

As Kuščer mentioned in his review paper, it is important to understand whether the disappearance of the discrete mode is real or whether the discrete eigenvalue becomes imbedded in the continuum. If the latter situation obtains, the "pole" may dominate the neighboring continuum because of its large amplitude, giving a type of pseudoasymptotic behavior. Kuščer suggested further study of this problem.

The related area of neutron waves, after years of experimental effort, is also beginning to find a firm mathematical basis as discussed by Andre Mockel, M. Moore and P. Michael; and Joel H. Ferziger, H. G. Kaper and S. K. Loyalka. The last paper is especially noteworthy because it introduces the two-dimensional singular-integral equation. Although significant progress has been made, further work is certainly required before descriptions of wave phenomena can enjoy the sound theoretical basis occupied by pulsed and steady-state measurements.

Calculation of thermalization phenomena requires a knowledge of the scattering law for thermal neutrons. Presently a combination of measurement and theoretical calculations provide the needed data. Measurements are either differential (direct) or integral (indirect). The former involves measurement of double-differential cross sections using triple-axis crystal spectrometers, pulsed rotor choppers, or rotating crystal spectrometers. Experimental techniques, pioneered by Peter A. Egelstaff, Bertram N. Brockhouse, K. E. Larsen, Robert M. Brug-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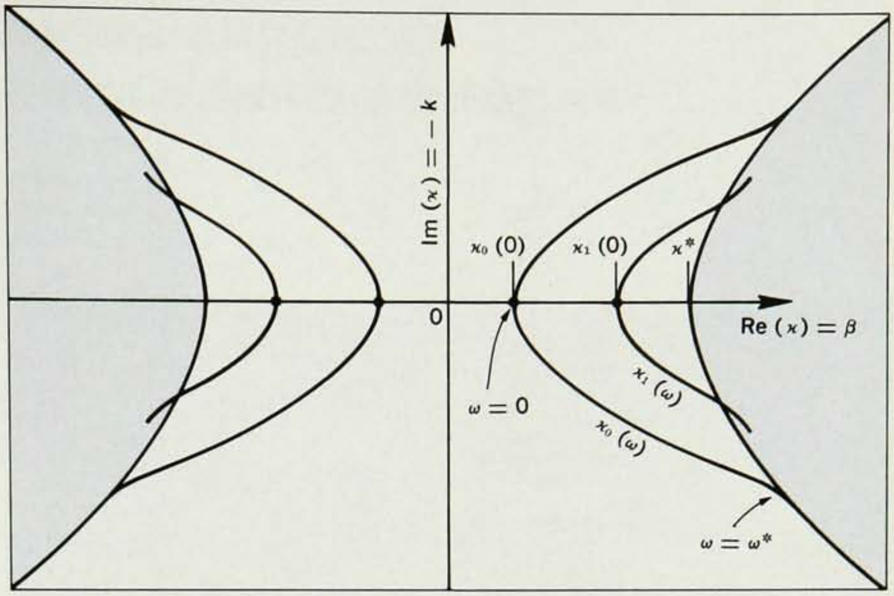
ger and Harry Palevsky, have become highly sophisticated. A necessary concomitant has been the development of high-intensity neutron sources. The role of the Linac as a neutron source is worth noting. Systems that pulse subcritical assemblies with accelerators will improve the situation even more.

The unresolved problem of multiple scattering remains to be solved, a fact emphasized in extensive discussions after E. L. Slaggie's paper. It does not appear possible to cope with this problem by the classical method of extrapolating to zero thickness. Theoretical corrections are quite sensitive to the assumed model and to experimental resolution. Slaggie and others have suggested ways to cope with this problem (which was also discussed extensively at the American Nuclear Society topical meeting in San Diego a year and a half ago), but a final solution is still open. A good computer code, with which the experimentalist could reduce his data, is needed. It should be possible to write a nonlinear equation for the scattering cross section in the presence of multiple scattering that could be solved with a computer. So far, apparently, this brute-force approach has not been tried. I. M. Thorson also discussed this problem and pointed out, as did Surendra N. Purohit, that the problem is particularly severe at low values of α.

A theoretical paper by George C. Summerfield showed that the Krieger-Nelkin method is accurate for large κ^2, and a new, reasonably simple method was presented for low values of κ^2. (Summerfield made a comparison with the "exact" calculations of George W. Griffing or Norman A. Lurie.) The approach is based on the quasi-classical method of Richard Aamodt and coworkers; the cross section for a molecule can be found if the classical equation of motion can be solved. This calculation has been made only of linear or spherical molecules, but, in principle, there is no difficulty when doing the calculation for other types. The major problem of interference effects between nuclei in the same molecule, however, remains unsolved and merits a strong theoretical effort by those concerned.



COMPLEX EIGENVALUES for neutron waves. The blue area represents the continuous spectrum for $\omega = \omega^*$.

John M. Carpenter and Robert A. Schaefer presented a type of inelastic diffraction pattern. In another interesting paper, Juan U. Koppel and J. A. Young attempted to calculate the phonon frequency spectrum (and hence the cross section) of beryllium from first principles.

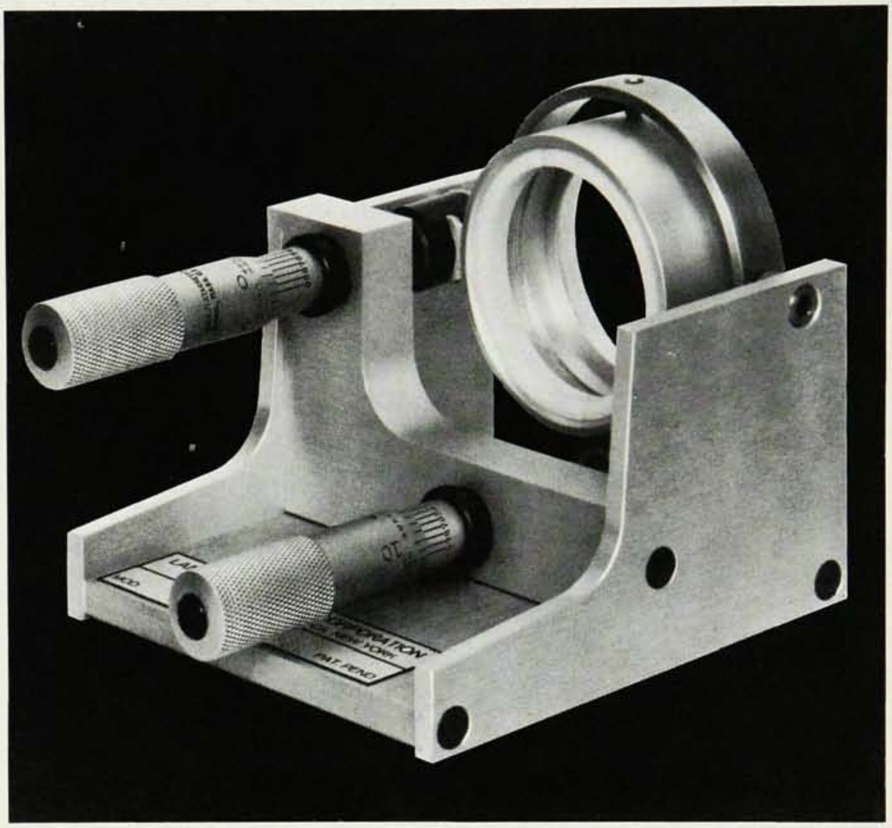
Integral experiments (basically of the type invented by Michael Poole) were reviewed in a paper by J. Robert Beyster. The experimental techniques are now well founded although such problems as reëntrant hole perturbations, which have always been troublesome to experimenters, are still prevalent. Beyster stated that the situation here is similar to the multiple-scattering problem in that extrapolation to zero hole size does not remove the difficulty. L. Caspers and A. Janssen also discussed this problem. It is evident that higher intensity sources, permitting smaller reëntrant holes, will alleviate this problem.

Of particular interest are measurements of spectra as a function of time with a chopper having the pulse from a Linac. In such measurements the quantities calculated by the "thermalization theorist" are measured directly, just as in the original Poole-type steady-state measurements reactor spectra are measured directly. The introduction of higher intensity machines has made such measurements possible: Introduction of even higher intensity devices should improve these measurements.

Beyster remarked that measurement of the spectra as a function of time in some beryllium assemblies has shown an asymptotic decay when theory predicts only a continuum eigenvalue spectrum. A likely explanation is the quasi-discrete eigenvalues discussed at Karlsruhe. These were explored further at this meeting in a paper by M. V. Kazarnovski, L. V. Maiorov and M. C. Yudkevich. They extended the as yet unpublished work of Noel M. Corngold and Kanat Durgun, who consider these quasi-discrete modes as poles in an unphysical sheet of the complex λ-plane. They showed that an earlier explanation of these phenomena by A. Ghatak and Laxman F. Kothari are not in disagreement with the Corngold explanation, thus clarifying a previously puzzling point. This point was also discussed in Kazarnovski's review paper.

Sophisticated reactor design requires an accurate description of the spectrum for calculations of temperature coefficients, plutonium buildup, fuel burnup and other quantities. The steady-state measurement tests the input data for these calculations

Some idea stimulating dialogue about angular orientation devices



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Shake-free sliding magnetic coupling between the adjustment mechanisms and the gimbal rings eliminates the breakaway friction because there is no loading force. The sliding contact is on a cammed surface to reduce interaction between the two rotation axes.

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These devices are sturdy, easy to use, and easy to mount. They are constructed of anodized aluminum and stainless steel to assure long life and trouble-free performance.

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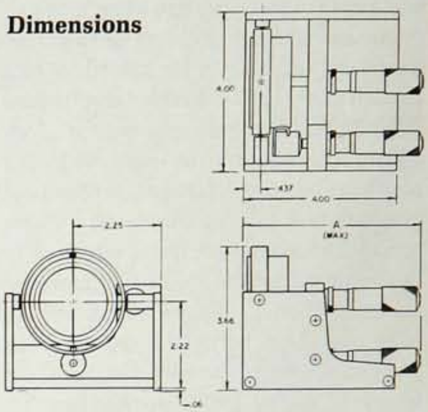
Dimensions



Adjustment mechanism:

	Dim. "A"	Effective Threads Per Inch	Model
Micrometer Head	5.0	40	10.203
Differential Screw	6.2	800	10.253
Differential Screw	6.2	4000	10.263

The precision micrometer head is recommended for most applications. When even higher resolution is required the differential screw models should be used.

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10.203	Angular Orientation Device	$145.00
10.253		295.00
10.263		295.00
10.001	Adaptor Set (specify mirror diameter and thickness)	12.50

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Specifications

	10.203	10.253	10.263
Resolution	1 sec	.1 sec	.02 sec
Resettability	6 sec	.6 sec	.10 sec
Total Angular Motion	12°	2.5°	0.50°
Normal Beam Free Aperture	1.75"	1.75"	1.75"
Maximum OD of Mounted Element	2.00"	2.00"	2.00"

These are some facts and ideas about precision angular orientation devices. If you have some ideas about what they can do for you, we'd welcome your inquiries and orders.

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although the results are less sensitive to the details of the scattering kernel than to the transport and absorption cross sections. The time-dependent measurement, in addition to providing data for basic theory, should be of practical importance in pulsed-reactor design.

Measurements of steady-state position-dependent spectra in paraffin systems carried out at Rensselaer Polytechnic Institute showed better agreement with the Goldman than with the General Atomic kernel. That the details of the kernel are not so important is also suggested by J. J. Volpe's Monte Carlo calculations. However it is important that the effective temperature is given better by the Goldman model. Volpe's results suggest that virtually any kernel other than the simple Wigner-Wilkins will give an adequate spectrum if effective temperature and thermal cutoff are chosen correctly. For long-term reactivity effects, however, this statement is not valid. On the other hand, zero-dimensional depletion codes are in general use. Here is a case in which the reactor designers must improve their techniques.

Several experimental papers described foil-activation techniques. Disagreement exists as to the merit of such measurements. G. S. Stanford indicated that the ultimate accuracy in this technique is yet to be reached. From a practical viewpoint, measurement of spectral indices are important because they are so easily done.

P. Parks' paper was particularly interesting. In a poisoned D_2O assembly he found an exponential decay at a poison value greater than the Corngold limit (analogous to the disappearance of the discrete mode in pulsed experiments). This may be a quasi-discrete mode or else some spatial effects may be coming into play. Theorists should attack this problem vigorously.

Calculations of neutron spectra using the scattering kernels previously discussed were reviewed by Henry C. Honeck. He emphasized providing codes that give sufficient accuracy for the reactor designer to use in, for example, cell calculations. Both integral-type transport codes (such as

CERENKOV RADIATION as seen coming from the U. of Michigan reactor.

THERMOS) and S_N codes were said to provide sufficiently accurate results with the best available scattering kernels. An unresolved question, raised by the Russians, is the discrepancy between S_N and THERMOS. If the discrepancy exists, it is important that the reactor designer be provided with the "correct" code, or at least the region in which each approach is valid. It was stated that THERMOS should be used for tight lattices, but the question appears to be open.

For systems in which epithermal effects play an important role, for example those containing plutonium, the situation is not as rosy as Honeck painted it (by his own admission). D. Bollacasa and D. T. Goldman showed the importance of raising thermal cutoff to several electron volts to obtain an adequate representation of the epithermal spectrum. Unfortunately, scattering kernels are not well known in this region. The new, high-intensity machines, permitting measurements in the epithermal region, will prove valuable.

Throughout the conference much greater emphasis was given to the thermalization region than to the slowing-down region. Presumably, the slowing-down problem, except in the transition region, is very well understood although work continues in special areas. An example is the paper by Pierre Benoist, A. Kavenoky and M. Livolant, who calculate resonance integrals in cells where spatial effects are important. Serious problems still exist, however, in the conversion of slowing-down spectra to group constants and the importance of spatial effects. The calculation of slowing-down spectra in the resonance region is at best a difficult problem because of the large number of energy points needed.

Leakage spectra calculations also need further attention. This was discussed by J. M. Kallfelz and R. Kladnik. Rex G. Fluharty of Idaho Nuclear Corporation presented some new experimental results (which, unfortunately, will not appear in the proceedings) in a special informal session. They calculate solutions of the energy-dependent Milne problem; however, the approximation of plane geometry is open to question.

M. Kazarnovski discussed in a review paper the question of quasi-discrete modes in beryllium. By applying a multigroup formalism, he showed that the results of Ghatak and Kothari can be viewed as an approximation to the more rigorous results of Corngold and Durgun. The lowest energy group is taken below the Bragg cutoff, and the effect of filling this group (the

"Corngold trap") becomes noticeable after about 4 msec. Thus, up to this time, the Kothari approximation is valid and exponential decay is seen.

Kazarnovski's paper also commented on the measurement of decay constants in a medium poisoned with a non-$(1/v)$ absorber (Friedman's method.) Gerald P. Calame's recent calculations cast doubt on the validity of this method, but Kazarnovski states that theoretical explanations of the discrepancy discovered by Calame can be found. He strongly recommends preservation of the method and suggests the use of cadmium absorber distributed in a moderator (samarium was also suggested in the discussion). This method is convenient for the determination of M_2 or, with sufficient source intensity, higher moments of the energy-transfer kernel.

R. B. Perez described measurements of neutron waves in D_2O. He obtained good agreement with the theory of M. J. Ohanian and Paul B. Daitch except at higher frequencies. The high frequency dependence of the dispersion relation is very sensitive to the details of the scattering law, thus providing an excellent test of scattering models. Perez reported the best experimental value for the diffusion coefficient in D_2O to be 1.966 cm^2/sec with the extraordinarily small error of ± 0.001.

The most dramatic aspect of the symposium was the fact that sophisticated theoretical calculations are becoming of practical importance in reactor design. Experimental results are showing the type of agreement with theory that gives the design engineer confidence in using the methods and the data. Further effort toward removing discrepancies will be improved by the use of higher intensity machines. At the same time, computational methods have developed to the point that reactor calculations can be carried out in the detail necessary to improve economics and operating characteristics. Since this is a primary objective of nuclear energy technology, one can conclude that basic research in this area has become of real practical importance.

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