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Reminiscences of the U.S. Program for Applied Nuclear Data

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Abstract. United States industry had developed reliable, sometimes proprietary, systems for thermal reactor design. In 1966, the U.S. Atomic Energy Commission organized a nuclear data effort as part of breeder reactor technology. It was planned that this data technology would be valid in other applications as well. This application independent data library is called Evaluated Nuclear Data File (ENDF/B) and is overseen by the Cross Section Evaluation Working Group (CSEWG). Many iterations of ENDF/B have occurred in the effort to achieve an application independent data library. The latest version, ENDF/B-VI, was issued in 1990. Updates to ENDF/B are issued from time-to-time.

Background

This paper contains reminiscences of the U.S. program for applied nuclear data. No attempt has been made to credit all the laboratories and individuals that made significant contributions to the program since such a list would easily be longer than the paper itself. The major portion of the early nuclear data program in the United States concerned itself with neutrons. The neutron was discovered in 1932 but the need for a nuclear data program did not take place until after the discovery of fission in 1939 and the development of major applications both military and civilian, e.g. atomic bombs, nuclear reactors to create weapon components, nuclear reactors to provide nuclear energy, and nuclear reactors and accelerators for research. Although measured cross sections were collected and compared via compilations such as BNL-325, the applications of nuclear data depended on roughly prototypical experiments that bracketed intended uses, and the collection of rules of thumb, e.g. removal lengths, buildup factors, Fermi ages, etc. Some data were classified but the open international exchange of nuclear data was spurred by the First Geneva Conference on Peaceful Uses of Atomic Energy in 1955.

Design Tools

Besides the heavy dependence on bracketing experiments, calculational systems were developed that consisted of a theory; computer model of the theory, geometry, and materials; and a nuclear data library. The first nuclear data libraries were scant in that not many materials or energy groups were included. At the same time the computer codes were limited in their modeling accuracy and took a long time to complete calculations. With the advent of larger and faster computers, there were fewer compromises in modeling accuracy and there was a demand for nuclear data libraries containing more materials and more cross section detail as a function of energy. To diffusion and transport theory was added Monte Carlo techniques which made uncompromising modeling possible but problematic because large calculation times might be required for convergence.

Thermal Reactors

Thermal reactors became the mainstay of the nuclear energy industry. Prototype experiments were necessary but computer calculations using nuclear data libraries lightened the load. Although the calculations could differ from experiment, consistent bias factors between calculation and experiment could be obtained to render the calculations useful. Commercial successes in the nuclear power industry lessened the need for governmental support and the U.S. government could concern itself with regulating the nuclear industry. Because some of the experiments, codes, and data evaluations used by industrial firms had been generated at their own expense, the information was considered proprietary and not freely exchanged.

Breeder Reactors

With the success of thermal reactors seemingly assured, the U.S. government, namely, the Atomic Energy Commission, turned its attention to breeder reactors which would be needed to provide nuclear fuel for power reactors while not draining fissile and fertile fuel resources. The job of regulating the nuclear power industry was given to a new agency, the Nuclear Regulatory Commission. Governmental resources would be necessary since the development of breeder reactor technology was likely to be beyond the resources of any one company. By starting in the early 1960's it was felt that there was sufficient lead time to develop the necessary technology before thermal reactors would significantly deplete fuel supplies. The technology would of course include the necessary theory, codes and nuclear data bases needed for the design of breeder reactor design.

The government was frustrated by the difficulties in getting U.S. companies to cooperate since they were conditioned to compete rather than to cooperate. By centralizing the funding for breeder reactor technology, the Atomic Energy Commission and its successors, the Energy Research and Development Administration, and the Department of Energy brought the U.S. nuclear power industry into a cooperative mode. Without interfering with private developments the government sponsored the development and maintenance of a limited number of diffusion theory, transport theory, and Monte Carlo codes. There was enough duplication of effort to confirm results but not so much duplication to be wasteful of resources. The Evaluated Nuclear Data File (ENDF) was developed at first to provide a single format for the intercomparison of different nuclear data sets but then used to provide a library of recommended nuclear data for applications (ENDF/B), one data set for each material .

Cross Section Evaluation Working Group

The centralized AEC funding made possible the formation of a working group to generate the ENDF/B and oversee its connections to other components of a reactor design system. Other agencies were invited to join in this effort and the Cross Section Evaluation Working Group (CSEWG) began its activities in 1996. It was a motley crew of workers consisting of government (including some defense units), university, and industrial laboratory personnel; nuclear data measurers and theorists; and reactor engineers and physicists. In other words, the producers and users of nuclear data would work together to generate ENDF/B. In this way, the ENDF/B would have the interdisciplinary expertise needed for the task and would also have a built-in acceptance of the results since the users had a direct hand in its development.

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Seeking perfection at the outset was avoided. The first steps were pragmatic. A version of ENDF/B was to be developed as soon as possible. Each participating organization was asked for a list of materials needed for their applications. Responsibility was assigned for each material in the approved list. While every attempt was made to have the appropriate expert for each task, completing a file for each material on schedule was given priority. Incongruities would be sorted out later in data testing. Data testing techniques were outlined which included few codes and few benchmark experiments. It was realized at the outset that if CSEWG was not careful it would not be able to separate problems in nuclear data from those in codes or benchmark experiments. The first version of ENDF/B was released in 1968 and intensive data testing was begun.

Improvements

Several improvements were made during successive versions of the ENDF/B library.

Nuclear data serving as cross section standards, for measurements, e.g. $^{10}B(n,\alpha)$, $^{235}U(n,f)$, were evaluated with special care by a select committee. Measurements involving these cross sections were renormalized by evaluators to the given standards for a fair intercomparison of different measurements.

The fissile and fertile element isotopic cross sections were evaluated simultaneously. Measurements for these elements consisted of absolute measurements having accuracy of a few percent and ratio measurements, e.g. $^{238}U(n,\gamma)/^{235}U(n,f)$, usually measured to a higher accuracy. The careful combining of absolute and ratio measurements increased the interconsistency of results when calculating benchmark critical experiments where the k_{eff}, the ratio of neutrons produced to the neutrons absorbed and leaked, is known to a high accuracy.

The number of experimental benchmarks were increased to include thermal reactor, fast reactor, shielding, and decay heat examples. The specifications were carefully prepared and reviewed often researching the original laboratory notebooks from the experiments.

Format changes to ENDF/B were approved cautiously and conservatively in the interest of maintaining stability in the use of ENDF/B.

Increased detail and accuracy were provided to the file that included the fission spectrum, delayed neutron data, radioactive decay data, and fission yields.

The energy range of the resolved resonance and unresolved resonance region were extended with succeeding versions of ENDF/B. Finally, the upper energy limit of 10 MeV adopted at the outset, extended later to 20 MeV, was removed altogether in ENDF/B-VI.

Covariance matrices were added to reflect the errors that are present when using ENDF/B data in calculations, e.g. calculations of benchmark experiments.

Charged particle, gamma-ray and electron data were added to ENDF/B. Although not presently as complete as for neutron these added are present to a significant extent and there is no conceptual barrier to their future.

Finally, the increased memory size and speed of computers that became available reduced the need for placing limits on data contained in ENDF/B.

Milestones

In current use is ENDF/B VI, issued circa 1990. Singling out milestones in the development of ENDF/B is difficult because there were many. One problem that had persisted for many years was the seemingly high resonance capture in ^{238}U in integral measurements that could not be explained by the differential data. After much discussion and a special seminar on the subject the difficulty was removed by subsequently improved measurements of the capture widths in low lying ^{238}U resonances and improved numerical handling of the narrow ^{238}U capture resonances in neutronics calculations.

An attractive development was the least squares fitting of differential data, e.g. ENDF/B, to optimize the fit to a large number of critical assembly experiments. The differential data was in the form of multigroup cross sections. Unfortunately, the resulting changes to group cross sections could not be uniquely identified with discrepancies in the data because the changes could also be dependent on other components of the system, e.g. statistical and systematic errors in the integral data and approximations in the computer codes. These concerns were eased by the formulation of fitting procedures that incorporated Bayes theorem and the statistical and systematic uncertainties and cross correlations of both differential and integral data.

Recently, an international team of experts from the U.S. and Europe has removed the long standing discrepancy between differential and integral ^{235}U capture data. The recommended thermal, resolved resonance and unresolved resonance capture data for ^{235}U when used in resonance integral and critical assembly calculations now produce results consistent with experiments.

Today

The U.S. nuclear data efforts are closely linked to international nuclear data efforts that at one time were in a semi-competitive mode with the U.S. in order to preserve their individual capabilities. The shrinking of resources available to nuclear data efforts made cooperation vital to the survival of data evaluation and testing activities. Although different countries may make their own choices for reference data sets, most if not all evaluated nuclear data is in the ENDF/B format which facilitates the exchange of data. Nuclear data files are available today for use in many applications, e.g. reactor design, accelerator-neutron sources, shield design, nuclear medicine diagnosis and therapy, space technology. The development of nuclear data has been relatively rapid and successful despite the fact that the nuclear industry, in general, has not flourished. When the nuclear industry is resuscitated, as expected, it will find that ENDF/B provides a good base for future efforts and hopefully the infrastructure to produce nuclear data libraries, e.g. CSEWG, will still be sufficiently intact to make improvements needed by new nuclear applications.

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