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NEW DEVELOPMENTS IN STANDARDS FOR REACTOR DESIGN

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ABSTRACT

New developments in reactor technology, nuclear data and an ever-expanding infrastructure in data handling, have led to significant improvements in the development and use of reactor physics standards. A wide variety of reactor physics methods and techniques are being used by reactor physicists for the design and analysis of modern reactors. The standards for Reactor Design provide guidance and criteria for performing and validating a wide range of nuclear reactor calculations and measurements. These standards are currently widely used in the nuclear industry. American National Standards Institute reactor physics standards, covering such areas as nuclear data, reactor design, startup testing and decay heat, have been developed and most of them are in widespread use. These standards are regularly undergoing review to respond to an evolving nuclear technology. Most of these standards are now successfully used in the U.S and abroad and are contributing to improvements in reactor design, safe operation and quality assurance. The purpose of this paper is to summarize recent advances in reactor physics standards, to present an overview of the overall program of standards for reactor design and to report on the status of those standards that are currently being developed. New standards currently under development are expected to further enhance these improvements.

1. INTRODUCTION

Recent advances in a maturing reactor technology and improvements in data handling systems have paved the way for significant improvements in reactor design and operation. The need for standards to guide the activities of reactor design and operations became increasingly important as (a) methods for calculating reactors, (b) techniques for monitoring and measuring key reactor operating data and (c) the number of new organizations involved in reactor design, have proliferated. Furthermore, an increased emphasis on safety and quality assurance requirements made standards a most desirable tool to have.

The efforts to develop and use standards in various areas of reactor design and operation, were started in the 1970s by groups of experts, as the nuclear reactor technology was entering an era of technical maturity. These standards intended for specific applications, developed under the auspices of the American Nuclear Society, eventually became American national standards and have been part of the extended group of standards sanctioned by the American National Standards Institute (ANSI). Reactor physics standards, thus created, are designated ANSI/ANS standards. These standards are kept "alive", i.e., they are regularly reviewed and updated to respond to the needs of the analyst/designer as the reactor technology evolves.

The ANSI/ANS reactor physics standards developed to date, their designations and their relations to other reactor physics standards are listed in Table 1.

TABLE 1
ANSI/ANS STANDARDS FOR REACTOR DESIGN

Designation of Standard	**Title of ANSI/ANS Standard**	**Reference**	**Relation to Other Standards**
ANSI/ANS-19.1	Nuclear Data Sets for Reactor Design Calculations	1,2	ANS-19.3, ANS-19.3.4, ANS-19.10
ANSI/ANS-19.3	Determination of Reaction Rate Distribution and Reactivity of Nuclear Power Reactors	3	ANS-19.1
ANSI/ANS-19.3.4	Determination of Thermal Energy Deposition Rates in Nuclear Reactors	4	ANS-19.1, ANS-19.3
ANSI/ANS-19.4	A Guide for Acquisition and Documentation of Reference Power Reactor Physics Measurements for Nuclear Analysis Verification	5	ANS-19.1 ANS-19.3
ANSI/ANS-19.5	Requirements for Reference Reactor Physics Measurements	6	ANS-19.1 ANS-19.3 ANS-19.3.4 ANS-19.4
ANSI/ANS-19.6.1	Reload Startup Physics Tests for Pressurized Water Reactors	7	ANS-19.3 ANS-19.11
ANSI/ANS-19.11	Moderator Temperature Coefficient in Pressurized Water Reactors	8	ANS-19.3 ANS-19.6.1
ANSI/ANS-5.1	Decay Heat Power in Light Water Reactors	9	ANS-19.1 ANS-19.3.4 ANS-19.8

Reactor Physics standards under development, their designations and their relation to other standards are presented in Table 2.

TABLE 2
PROPOSED STANDARDS FOR REACTOR DESIGN

Proposed Standard Designation	**Title of Proposed Standard**	**Reference**	**Relation to Other Standards**
ANS-19.8	Fission Product Chain Yields	10	ANS-5.1
ANS-19.9	Delayed Neutron Parameters	11	ANS-19.1
ANS-19.10	Fast Neutron Fluence in the Pressure Vessel of PWRs	12	ANS-19.1 ANS-19.3

These standards cover a wide range of reactor design calculations as well as measurements. In the following sections, an overview of each of the ANSI/ANS reactor physics standards, currently in use, is given. A brief report on newly proposed standards is also presented.

2. NUCLEAR DATA SETS FOR REACTOR DESIGN CALCULATIONS – ANSI/ANS-19.1

Nuclear data sets consist of basic microscopic nuclear physics data that include, but are not limited to, the important neutron-induced reactions. The data set, in the processed form, is primarily utilized as input to fission reactor core design calculations, but may have applications to other fields, such as shielding, dosimetry, or fusion studies.

Standard ANSI/ANS-19.1 (Ref. 1, 2) identifies and describes the specifications for developing, preparing, and documenting nuclear data sets to be used in reactor design calculations. The specifications include (a) criteria for acceptance of evaluated nuclear data sets, (b) criteria for processing evaluated data and preparation of processed continuous data and averaged data sets, and (c) identification of specific evaluated, processed continuous and averaged data sets that meet these criteria for specific reactor types. The scope of this standard does not pertain to experimental techniques for the measurement of nuclear data or to the development of nuclear model theory. This standard has just been revised and updated to reflect current nuclear data libraries.

There are three major classes of nuclear data used in reactor design calculations: (1) *evaluated nuclear data sets*, derived from basic experimental and theoretical data specified over broad energy ranges; (2) *processed continuous data sets*, derived from evaluated data sets intended for calculations where continuous energy representations are required, such as in Monte Carlo transport codes and (3) *averaged data sets*, also derived from evaluated or processed continuous data sets. These major classes are discussed below.

(1) Evaluated data set. A data set which is completely and uniquely specified over the ranges of energy and angles important to reactor calculations. An evaluated data set is intended to be independent of specific reactor compositions, geometries, energy group structures, or spectra.

(2) Processed continuous data set. A data set prepared by expansion or compaction of an evaluated data set using specified algorithms. Such a data set is intended to be independent of specific reactor compositions, geometries, energy group structures, or spectra.

(3)_Averaged data set. A data set prepared by averaging an evaluated data set or a processed continuous data set with a specified weighting function over a specified detailed energy group structure. The group structure and weighting function are selected so that the averaged data set is applicable to a wide range of reactor analyses, e.g., light water reactors. Application-dependent, collapsed data sets are dealt with in American National Standard for the Determination of Neutron Reaction Rate Distributions and Reactivity of Nuclear Reactors, ANSI/ANS19.3-2002 [2].

This latter class of nuclear data consists of group parameters obtained from the evaluated data sets or from the processed continuous data sets by averaging with appropriate weighting functions over a given group structure. Application of the data to a wide range of benchmark experiments and other reference measurements forms the basis of testing of the nuclear data. In addition to the well-known ENDF/B-VI nuclear data files [3], Chinese, European, Japanese and Russian nuclear data files are cited in the standard.

2. THE DETERMINATION OF NEUTRON REACTION RATE DISTRIBUTIONS AND REACTIVITY OF NUCLEAR REACTORS - ANSI/ANS19.3-2002

The recently revised ANSI/ANS-19.3 standard covers the most fundamental aspects of reactor design. This standard offers guidance for performing and qualifying the complex sequence of steady-state calculations leading to prediction, in all types of commercial nuclear reactors, of: (1) reaction-rate spatial distributions; (2) reactivities, and (3) change of isotopic compositions with burnup in light water, heavy water, high temperature gas cooled and liquid metal reactors. The standard also provides:

(1) Guidance for the selection of computational methods
(2) Criteria for validation of calculational methods used by reactor core analysts
(3) Criteria for evaluation of accuracy and range of applicability of data and methods
(4) Requirements for documentation of the preceding.

This standard thus covers space and energy averaging processes which may be employed to prepare cross sections, consistent with the provisions of standard ANS-19.1, for use in the representation of the core and its environment, and the subsequent calculation of the spatial distribution of neutron reaction rates in the core and calculation of the core reactivity. It must be pointed out that there may be many ways of carrying out the space and energy averaging to obtain few-group cross sections, and no unique path for the preparation or use of cross sections employed in design calculations is defined, required, or recommended by this standard.

For the light water reactors, there are, in general, three distinct steps in performing steady-state reactor physics analyses: library generation, assembly lattice calculations, and reactor core calculations. The purpose of these calculations is to provide the basis for reactor core design, including safety and economic evaluations. The steps for carrying out the reactor physics analysis of an LMR resemble those for light-water reactors. However, greater detail needs to be included in the energy structure used for the reactor calculations, as the essential reactions occur in a wide energy range and as the energy shape changes significantly with design detail and spatial location in the core.

Reactor physics analysis in the heavy water reactor follows a similar path with that of the light water reactors: (a) library generation for the bare lattice containing fuel, coolant and calandria tubes and the surrounding moderator volume but excluding the representation of any interstitial reactivity devices, (b) supercell calculation which accounts for the interstitial reactivity devices and (3) the three-dimensional core calculation which calculates the core reactivity and the global distribution of flux and power.

In principle, the calculational sequence of the high temperature gas cooled reactor (HTGR) is similar to the models used for LWRs. Lattice codes, which read the fine-group libraries, are used to generate few-group (also known as broad group) cross-section data sets. Because the fuel is in the form of coated particles in HTGRs, particle self-shielding can be important and is usually accounted for in the unit cell calculations.

For information purposes only, the standard also includes in its appendix an extensive compilation of state-of-the-art computer codes currently in use by reactor physicists.

3. DETERMINATION OF THERMAL ENERGY DEPOSITION RATES IN NUCLEAR REACTORS - ANSI/ANS-19.3.4-2002

This standard addresses the energy generation and deposition rates for all types of nuclear reactors where the neutron reaction rate distribution and photon and beta emitter distributions are known [4]. Its scope is limited to the reactor core, including blanket zones, control elements and core internals, pressure vessel, and the thermal and biological shielding. Knowledge of the thermal energy source distribution is important for the determination of the temperature field within a nuclear reactor, and thus for the calculation of heat transfer and transport, thermal stress and the many physical and chemical properties of materials which depend upon temperature.

The interaction of neutrons and photons with reactor materials produce charged particles, including fission products, recoil nuclei, alpha and beta particles. As these particles slow down, they lose energy to the surrounding media creating thermal energy. Generally, all of the various phenomena of atomic and low-energy nuclear physics are involved in the conversion of the energy released by fission into the molecular motion known as thermal energy. Table 3, lists the phenomena to be considered in the evaluation of the energy deposition. Of these phenomena, the fission event is the most dominant since it involves the creation of heavy charged-particle fission products that carry about 85% of the total thermal energy generated in the reactor. For many applications, a common approximation is to assume that the kerma, the sum of initial kinetic energies of all charged particles liberated by indirectly ionizing particles, is a measure of the energy deposition. This is a general standard and covers the energy deposition calculations for all classes of reactors from fast to thermal and from research to power reactors.

TABLE 3
PHENOMENA TO BE CONSIDERED IN EVALUATING ENERGY DEPOSITION

(1) Fission
- (a) Fission Products/Kinetic Energy
- (b) Prompt and Decay Beta Particle Energy

(2) Neutron Capture
- (a) Kinetic Energy of Charged Particle Products
- (b) Decay Beta Particle Energy
- (c) Nuclear Recoil

(3) Neutron Scattering
- (a) Nuclear Recoil Following Elastic Scattering Interactions
- (b) Nuclear Recoil Following Inelastic Scattering and Subsequent Nuclear De-excitation

(4) Photon Sources
- (a) Prompt Fission
- (b) Fission Product Decay
- (c) Neutron Capture
- (d) Inelastic Scatter De-excitation
- (e) Transmutation Product Decay

(f) Positron Annihilation
(g) Bremsstrahlung
(h) Atomic De-excitation

(5) Photon Transport

(6) Photon Interactions
(a) Photoelectric Absorption
(b) Compton Scattering
(c) Pair Production
(d) Photonuclear Reactions

This standard provides criteria for: (1) Determination of the energy allocation among the principal particles and photons produced in fission, both prompt and delayed; (2) Adoption of appropriate treatment of heavy charged particle and electron slowing down in matter; (3) Determination of the spatial energy deposition rates resulting from the interactions of neutrons; (4) Calculation of the spatial energy deposition rates resulting from the various interactions of photons with matter, and (5) Presentation of the results of such computations, including verification of accuracy and specification of uncertainty. The standard also provides criteria for verifying the accuracy and specifying uncertainties in the calculation of energy generation and deposition rates. The previously mentioned standard, ANS-19.3, [3]), provides the basis for determining the distributions of neutron reaction rates and photon and beta emitters.

4. REFERENCE POWER REACTOR PHYSICS MEASUREMENTS FOR NUCLEAR ANALYSIS VERIFICATION - ANSI/ANS-19.4

Benchmarking of nuclear methods against reference measurements and data is an important step in the validation and qualification of these methods. Criteria for performing and documenting measurements on light water power reactors, which are to be used as reference in the validation of reactor physics computational methods, are specified in ANSI/ANS-19.4 standard, "American National Standard: A Guide for Acquisition and Documentation of Reference Power Reactor Physics Measurements for Nuclear Analysis Verification" [5]. The standard identifies the types of parameters, test conditions, and experimental data needed for such reference measurements. Considerable confidence is gained in the nuclear analysis methodology when results of calculations of specific reactor parameters compare favorably with corresponding parameters, measured in accordance with the criteria and guidelines of this standard. In most cases, power reactor physics measurements are of an integral nature and as such could be most valuable in testing an overall result. The standard includes: identification of the types of parameters of interest as reference measurements; a brief description of test conditions and experimental data required for such reference measurements; identification of problems and concerns which may affect the accuracy, reliability or interpretation of the data; and criteria to be used in documenting the results of reference measurements.

It must be noted that the reactor used in obtaining experimental results should be described in sufficient detail to allow a meaningful analytical simulation that could be developed for computational purposes. Information about core configuration, reflector composition, fuel description and other reactor components should be provided on an as-built basis. The temperature corresponding to dimensional data should be stated. Design values may be substituted with appropriate design tolerances and known deviations from design specifications, whenever as-built data are not be available. Physical description of the reactor and its components must include: a complete description of the core configuration and composition; fuel assembly and control element description; reactor instrumentation; and reactor operating history.

A distinction must be made between differential measurements and statepoint measurements. In a differential measurement, small changes are made in two operating parameters, whereas in a statepoint measurement, operating conditions are not undergoing significant changes. Table 4 lists typical reference power reactor physics measurements.

TABLE 4
TYPICAL REFERENCE POWER REACTOR PHYSICS MEASUREMENTS

Statepoint Measurements
Zero-Power Critical Configuration
At-Power Critical Configuration
Special Incore Detector Response

Zero Power Differential Measurements
Control Rod Group Worth
Reactor Temperature Coefficient
Soluble Poison Worth

Gamma Ray Spectrometry (“Gamma scanning”)

5. REQUIREMENTS FOR REFERENCE REACTOR PHYSICS MEASUREMENTS - ANSI/ANS-19.5 – 1995

Minimum criteria for the qualification of reference reactor physics measurements obtained from subcritical (including non-multiplying) critical and other relevant experiments for the purpose of verifying nuclear design and analysis methods are specified in standard ANSI/ANS-19.5 [6].

In order to qualify as reference physics data, the measurements must meet the following criteria:

- Documentation Criteria
  - Description of the Experiment
  - Description of Special Instrumentation & Measurement Techniques;Uncertainties
  - Data Evaluation; Error Analysis; Comparison with Independent Measurements

Efforts currently underway, are focused on identifying and documenting high quality measured data obtained from critical and subcritical experiments carried out in the last two decades. The next revision of this standard will include such data as part of an appendix.

6. RELOAD STARTUP PHYSICS TESTS FOR PRESSURIZED WATER REACTORS – ANSI/ANS-19.6.1 - 2002

The purpose of this standard [7] is to confirm that the reload PWR core's neutronic performance characteristics are the same as those predicted during the reload analysis of the new core. This recently revised standard enjoys widespread use both domestically and internationally. The standard provides guidance for the performance of a set of measurements during the startup phase of the new core. These measurements have been selected based on specific criteria. Thus, tests conducted during the startup phase of the reload core are compared with corresponding calculated parameters. Agreement, within established uncertainties, between measured and calculated parameters, provides assurance that the reload core can be safely operated as predicted in the analysis.

7. MODERATOR TEMPERATURE COEFFICIENT – ANSI/ANS-19.11 - 1997

The ANSI/ANS-19.11 Standard, [8], "Moderator Coefficient of Reactivity Reactors", is a relatively new standard initiated in the last few years. It provides guidelines and criteria for the calculation of the moderator temperature coefficient of reactivity in PWRs. This standard is in the process of being reaffirmed.

8. DECAY HEAT POWER IN LIGHT WATER REACTORS – ANSI/ANS-5.1 - 1995

This standard [9] is perhaps the most widely used standard in the nuclear industry. The purpose of this standard is to provide bases for determining the shutdown decay heat power and its uncertainty following shutdown of light water reactors. The contributions from ^{235}U, ^{238}U, ^{239}Pu and ^{241}Pu to the decay heat power is given in both tabular form and analytical form and it can be used to evaluate the safety of LWRs. The contributions from other fissile nuclides can be accounted for by treating them as ^{235}U. Guidance is provided for evaluating the fission product decay heat power using two methods of presentation of the data. In the first method of presentation, data are provided for the decay heat power per fission following an instantaneous pulse of a significant number of fission events. In the second method of presentation, data are provided for the decay heat power from fission products produced at a constant rate over an infinitely long operating period. The standard provides options for obtaining the decay heat power for any arbitrary reactor power history, and includes a correction factor for neutron capture in fission products. For both methods of presentation of the data, guidance is provided for the evaluation of the uncertainty associated with the decay heat power being calculated.

Work is already underway for a revised version of this standard which is expected to be released in the second half of 2002. It will contain improvements in the examples given in the Appendix. This standard, as well as all the above standards, are being constantly reviewed and their use monitored by their respective working groups for possible updates or revisions.

9. PROPOSED STANDARDS

Three proposed reactor physics standards are in various stages of development:

(1) Proposed Standard **ANS-19.8, "Fission Product Chain Yields",** [10], includes an extensive compilation of mass chain yields and uncertainties for U-233, U-235, U-238, Pu 239, Pu-240, Pu-241, Th-232 and Cf-252. A first draft for this standard has already been prepared and is about to be submitted for review by the Reactor Physics Standards Committee.

(2) Preliminary experiments and recent work on the Proposed Standard **ANS-19.9, "Delayed Neutrons Parameters"** [11] tends to reaffirm the validity of Keepin's [12] delayed neutron data. The Working Group responsible for developing this standard is in the process of preparing the first draft.

(3) Proposed Standard ANS-19.10, (Ref. 13), "**Fast Neutron Fluence in the Pressure Vessel of PWRs"** has been completed. An extensive set of criteria and requirements for the determination of fast neutron fluences at the pressure vessel has been prepared.

An up-to-date report on the status of these standards under development is being presented at the Conference.

CONCLUSIONS

An overview of the overall program of standards for reactor design has been presented. New developments in the areas of nuclear data, advances in reactor technology and an ever-expanding infrastructure in data handling have led to significant improvements in the development and use of reactor physics standards. Most of these standards are now successfully used in the U.S and abroad and are contributing to improvements in reactor design, safe operation and quality assurance. New standards currently under development are expected to further enhance these improvements.

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