CURRENT AND NEW REACTOR PHYSICS STANDARDS FOR REACTOR DESIGN, ANALYSIS AND OPERATION

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1.0 INTRODUCTION

Standards for reactor design, analysis and operation were first developed in the mid-1970's to provide basic criteria and guidance to reactor physicists engaged in the analysis, design and operation of nuclear reactors. The first reactor physics standards, created under the aegis of the ANS-19 committee, were for research and power reactors in fundamental areas such as nuclear data, core neutronics, heat generation in the core and decay heat power. Additional standards were developed subsequently in major areas of reactor physics. As the physics of reactor design evolved and matured, the proliferation of reactor physics methods used in core design and analysis on one hand and the technical role assumed by nuclear utilities in the reload licensing field on the other, have enhanced significantly the usefulness of the reactor physics standards and broadened the ranks of their users.

New developments in reactor technology, nuclear data and an ever-expanding infrastructure in data processing and handling, made possible by the rapid expansion of computing power, have led to significant improvements and expansion of the standards. The reactor physics standards presented in this paper are the product of the work of over 200 U.S. and foreign experts and cover a broad range of physics topics from cross sections to power generation. Reactor Physics standards have been adopted by the American National Standards Institute (ANSI) as American national standards and are used in the U.S. and abroad, contributing to sound reactor design, safe operation and quality assurance.

The purpose of this paper is to present the status of reactor physics standards currently in use throughout the industry and of the new standards being developed. The following sections present an overview of the overall reactor physics standards from their inception to the present. A brief history of the standards is presented and is followed by a discussion of the reactor physics standards currently in use and those under development. The role of the U.S. standards in the international domain is briefly discussed.

2.0 A U.S. HISTORICAL PERSPECTIVE

The field of reactor physics began to take shape in the 1940's with the rapidly expanding knowledge of cross sections and of the interactions between neutrons and matter in both the theoretical and experimental domains. However, most of the work, particularly in the area of nuclear fission during that period was classified. As the work was gradually declassified in later years (1950's), it gave rise to the development of improved reactor neutronic methods primarily in the U.S. national laboratories. Several experimental reactor types were introduced. Fast and thermal prototype reactors were built and experimental research provided the mechanism for improving the analytical tools used in the design process. The 1960's saw the emergence of commercial power and neutronics methods mostly developed by vendors. The Light Water Reactors were gaining commercial acceptance. The viability of the LWR, both the boiling water and pressurized water reactors was established worldwide. The nuclear industry and particularly the methodology required to design and predict short- and long-term reactor behavior reached technical maturity. Further advancements in the fields of reactor physics were made possible by the development of large scale multidimensional coupled neutronics/thermal hydraulics computer codes capable of calculating detailed spatial and time effects under a wide variety of operating or accident conditions. A wide diversity of methods became available with players in the field, including universities, national laboratories, vendors and utilities. Major nuclear utilities have now become full participants in the development of sophisticated codes and the computational methods advanced and proliferated. Huge data bases of measured reactor parameters became available to benchmark codes and methods.

It soon became necessary for the reactor physics community to agree on establishing common understanding to the design approach. Thus, ANS-19, the Reactor Physics Standards committee was created under the auspices of the American Nuclear Society with the purpose of unifying all parties and developing commonly accepted standards for reactor design. The contributors to the development of reactor physics standards consisted of technical experts representing a wide range of organizations, domestic and foreign. Initial success in standards development and applications led to expansion into specific topics. The first reactor physics standards were of a fundamental nature such as nuclear data, core neutronics and the acquisition of reference measured data. Additionally, standards were developed on heat generation, startup physics tests for reload cores, decay heat, heat generation in the core and more recently, on moderator temperature coefficients in PWR's. These standards have become national standards

3.0 CURRENT STANDARDS AND STANDARDS UNDER DEVELOPMENT

Table 1 shows the standards currently in use. There are 8 ANSI/ANS established reactor physics standards. These standards provide criteria and guidance for performing and validating a wide range of complex reactor physics calculations and measurements. Most of these standards are interrelated. They establish safe practices by incorporating broad technical expertise and allowing recognized expertise to be applied to specific areas. Existing standards require continuous monitoring and periodic revisions to keep pace with the developing nuclear technology and expanding needs of their users. Most of these standards include useful information in their appendices. It should be pointed out, however, that information contained in the appendices does not constitute part of the standard. Standards listed in Table 1 are discussed in Section 4.0

Table 1
ANSI/ANS REACTOR PHYSICS STANDARDS CURRENTLY IN USE

AMERICAN NATIONAL STANDARD DESIGNATION	SUBJECT OF STANDARD	REFERENCES	RELATION TO OTHER STANDARDS*
ANSI/ANS-19.1	Nuclear Data Sets for Reactor Design Calculations	1	ANS-19.3 ANS-19.3.4 ANS-19.10
ANSI/ANS-19.3	Determination of the Neutron Reaction Rate Distributions and Reactivity of Nuclear Reactors	2	ANS-19.1 ANS-19.4 ANS-19.5 ANS-10.3
ANSI/ANS-19.3.4	Determination of Thermal Energy Deposition Rates in Nuclear Reactors	3	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	4	ANS-19.1 ANS-19.3 ANS-19.5
ANSI/ANS-19.5	Requirements for Reference Reactor Physics Measurements	5	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	6	ANS-19.3 AN S-19.11
ANSI/ANS-19.11	Calculation of Moderator Temperature Coefficient for Pressurized Water Reactors	7	ANS-19.1 ANS-19.3
ANSI/ANS-5.1	Decay Heat Power In Light Water Reactors	8	ANS-19.1 ANS-19.3 ANS-19.8

* All standards listed in this column are American National Standards

Table 2 lists new standards currently being developed. These standards, also referred to as proposed standards, are in various stages of development or completion. ANS-19.10 is in its final stages of internal ANS-19 approval while ANS-19.8 and ANS-19.9 are under development. (in draft form, awaiting review and comments)

TABLE 2
NEW ANS STANDARDS UNDER DEVELOPMENT

STANDARD DESIGNATION	SUBJECT OF STANDARD	REFERENCES	RELATION TO OTHER STANDARDS*
ANS-19.8	Fission Chain Yields	9	ANS-19.3.4 ANS-5.1 ANS-19.9
ANS-19.9	Delayed Neutrons	10	ANS-19.1 ANS-19.3
ANS-19.10	Fast Neutron Fluence at the Pressure Vessel	11	ANS-19.1 ANS-10.3

* Except for ANS-19.9, all standards listed in this column are American National Standards

4.0 Existing Standards

This section presents brief descriptions of the standards currently in use.

4.1 ANSI/ANS-19.1, "Nuclear Data Sets for Reactor Design Calculations"

This standard presents criteria and specifications for the preparation of nuclear data sets for use in reactor physics computer programs employed in the design of nuclear reactors and identifies specific data sets as standards [1]. The data sets discussed in this standard are fundamental physical parameters and, therefore, are sufficiently general to apply to any type of reactor design. While these data sets are intended primarily for use in reactor core analyses, when properly accounting for the group energy structure required for the specific application, they can also be used in, for example, shielding calculations as well as other related problems.

There are three major classes of nuclear data sets: ***(1) Evaluated Data Sets,*** derived from experiments and theory (I.E., ENDF/B-VI and ENDF/B-VII) and specified for incident neutron energy from 0.0001 eV to 20 MeV; ***(2) Processed Continuous Data Sets,*** derived from evaluated data sets for continuous energy applications (such as are used in Monte Carlo transport codes and in multigroup Processing codes) and ***(3) Energy-Averaged Data Sets,*** derived from evaluated or processed continuous data sets by averaging over energy groups (composition-dependent group constants, group collapsing). In addition to the latest version of the ENDF/B cross section library, standard ANSI/ANS-19.1 cites the European, Japanese and Chinese libraries. The National Nuclear Data Center, NNDC, located at Brookhaven National Laboratory, (BNL), has an extensive compilation of nuclear data. This National Center serves the nuclear community in general and the reactor designers and analysts in particular. The Cross Sections Evaluations Working Group, CSEWG, is a BNL-based multi-party cooperative effort to produce the ENDF/B's cross section libraries. Its web site is www.nndc.bnl.gov, where the latest information on cross section development may be found.

To keep up with developing improvements in the nuclear data field, this standard, as are all standards, is constantly reviewed by the ANS-19 Working Group to reflect new advances in nuclear data.

4.2 ANSI/ANS-19.3, "Determination of Reaction Rate Distributions and Reactivity of Nuclear Reactors"

This standard [2] covers the most fundamental aspects of nuclear reactor design. This newly revised standard (2006) provides guidance for performing the complex sequence of steady-state reactor physics predictive calculations in most major types of commercial power reactors (light water reactors, heavy water reactors, high temperature gas cooled reactors, liquid metal reactors as well as research reactors). Thus, it provides criteria for the selection of computational methods of reaction rate spatial distributions, reactivity and isotopics as a function of burnup. It also provides guidance for the validation, verification of calculational methods, evaluation of accuracy and range of applicability of data and methods as well as documentation. The direct relationship between this standard and ANSI/ANS-19.1 (Nuclear Data Sets) is obvious. Furthermore, this standard is closely related to ANSI/ANS-19.4, ("Acquisition and Documentation of Power Reactor Physics Measurements for Nuclear Analysis Verification"), ANSI/ANS-19.5, ("Requirements for Reference Reactor Physics Measurements") and ANSI/ANS-19.3.4, (Thermal Energy Deposition). Finally, because of the required representation of the azimuthal and axial neutron source distribution for use in neutron fluence calculations at the pressure vessel, the standard is also related to ANS-19.10 (Neutron Fluence at the Pressure Vessel Cavity). Because of the use of wide ranging computer codes in the nuclear analyses, ANSI/ANS-10.3, "Guidelines for Documentation of Computer Software") may be cited. The Appendix of the latest edition of this standard covers an extensive listing of commonly used codes spanning the entire sequence of calculations from pin cell calculations to three dimensional burnup simulations. It should be pointed out that appendices in nuclear standards are provided only for general reference and also for the convenience of the user and do not constitute part of the body of the standard.

4.3 ANSI/ANS-19.3.4, "Determination of Thermal Energy Deposition Rates In Nuclear Reactors"

The temperature field inside the reactor core is an important aspect of reactor safety and design. This standard [3] is general and addresses the energy generation and deposition rates for all types of nuclear reactors, from fast to thermal and from research to power reactors for which the neutron reaction rate distribution and photon and beta emitter distributions are known. The production of thermal energy is associated with the interaction of neutrons and photons and photons with matter to produce charged particles, including fission products, recoil nuclei, alphas, betas and electrons. As these particles slow down, they lose energy to the surrounding medium, thus creating thermal energy. Fission is the most important event of these processes because it involves the formation of heavy charged-particle fission products whose kinetic energy amounts to approximately 85% of the total thermal energy generated in the reactor. In some reactor components that are strong neutron absorbers, thermal energy deposition may be dominated by the contribution from n-alpha reactions or photons generated in capture. This information is important for the calculation of heat transfer and transport, thermal stress and material properties which depend upon temperature. Guidance and criteria are provided for performing calculations to evaluate thermal energy deposition rates. Calculation of the energy deposited is based on the neutron reaction rate distribution obtained directly from calculations according to ANSI/ANS-19.3. The use of the ANSI/ANS-19.1 in the ANSI/ANS-19.3 standard also indirectly establishes the energy deposited. Several approximations are often made in the evaluation of the energy deposition rate. These include the assumptions that (a) the charged particle energy is deposited at the point of production and (b) the average energy of the particle is used instead of its spectrum.

4.3 ANSI/ANS-19.4 and ANSI/ANS-19.5, "Benchmarking Standards"

Two reactor physics standards that play an important role in the benchmarking of computer codes are ANSI/ANS-19.4," Acquisition and Documentation of Power Reactor Physics Measurements for Nuclear Analysis Verification" [4], and ANSI/ANS-19.5 "Requirements for Reference Reactor Physics Measurements" [5]. These standards provide the bases for acquiring and documenting reference measurements for nuclear analyses verification and establish requirements for reference physics measurements, respectively. An important addition planned for these standards is the referencing in their respective appendices of valuable measurement data against which methodologies and codes can be benchmarked. A summary of benchmark-related recommendations may also be found in the ANSI/ANS-19.3 standard.

4.4 ANSI/ANS -19.6.1, "Reload Startup Physics Tests for PWR's" and ANSI/ANS -19.11, "Moderator Temperature Coefficient of Reactivity"

Closely related to the benchmarking standards above, the just-published ANSI/ANS-19.6.1 [6], "Reload Startup Physics Tests for Pressurized Water Reactors" (2005), as its title implies, presents criteria and provides guidance for the measurement of key startup physics parameters of reloaded cores for the purpose of verifying the validity of reload predictive analyses. This standard is widely used among nuclear utilities and, as is the case with all standards, it is constantly monitored to ensure applicability to the evolving reactor technology. The ANSI/ANS-19.11 standard, "Moderator Temperature Coefficient for Pressurized Reactors" [8], is a relatively new standard and as the title implies, it provides guidance and criteria for determining the moderator temperature coefficient of reactivity in PWRs.

4.5 ANSI/ANS-5.1, "Decay Heat Power in Light Water Reactors"

The newly revised (2005) Standard, *ANSI/ANS-5.1, "Decay Heat Power in Light Water Reactors" [9],* enjoys widespread use both in the U.S. and abroad. As its title implies, the purpose of this standard is to provide the bases for determining the shutdown decay heat power and its uncertainty following shutdown of light water reactors. The standard provides values for decay heat power from fission products and U-239, Np-239 following shutdown of LWR's containing U-235, U-238 and plutonium. The decay heat power from fission products is presented in tables and analytical representations.

5.0 NEW STANDARDS

Three new standards are in various stages of development:

(1) ***ANS-19.8, "Fission Product Chain Yields"*** [9], includes an extensive compilation of mass chain yields and uncertainties for fast and thermal neutron-induced fission of U-233, U-235, Pu-239, and Pu-241; fast neutron fission for Th-232, U-238 and Pu-240 and spontaneous fission for Cf-252. This new standard is particularly important in the characterization of radioactive wastes, predicting radiation source terms, production of delayed neutrons and various dosimetry applications

(2) ***ANS-19.9, "Delayed Neutron Parameters"*** [10], provides energy-dependent delayed neutron yield and decay data for Light Water Reactor design and control. The standard addresses the identification and characterization of fission products leading to delayed neutron emission; the total delayed neutron yield as a function of energy for U-233, U-235, U-238 and Pu-239; and fractions associated with individual emitters, half-lives and spectra for the classical group representation of delayed neutron data.

(3) ***ANS-19.10, "Fast Neutron Fluence in Pressure Vessels"*** [11], provides the criteria necessary for determining the best-estimate fast neutron fluence in the annular region between the core and the inside surface of the pressure vessel, through the pressure vessel and the reactor cavity over the active fuel of the core, given the neutron source in the core. Both fast neutron flux ($E>1.0$ MeV) computations and measured data from in-vessel and cavity dosimetry are used. The standard applies to both BWR's and PWR's.

6.0 INTERNATIONAL STANDARDS

Over the past few years, the American Nuclear Society has been participating in the development of international standards within the framework of the International Standards Organization (ISO). During an initial meeting in Argentina in 2004, the ANS proposed ANSI/ANS standards for adoption by ISO. One of the standards proposed, the decay heat standard, ANS-5.1, has been submitted and it is now being reviewed by the joint, U.S. and International committee for adoption as an international standard. Three additional reactor physics standards, Nuclear Data Sets, Reaction Rates and Reactivity and Reload Startup Physics Tests are currently being proposed as potential ISO standards. Any modifications to these standards for the purpose of compliance with ISO formatting, will not affect the ANSI/ANS standards. The latter will continue to be used in the U.S. in their current form.

CONCLUSIONS

Standards represent the best knowledge in the nuclear field. The reactor physics standards summarized in this paper provide guidance for verifying and validating nuclear analyses, help meet reactor designers' quality assurance programs and support physicists' efforts to achieve safe and efficient design for a wide range of reactor types.

4.0 REFERENCES

1. *"American National Standard: Nuclear Data Sets for Reactor Design Calculations", ANSI/ANS-19.1,* published by the American Nuclear Society, 2002
2. "*American National Standard for the Determination of Reaction Rate Distributions and Reactivity of Nuclear Reactors", ANSI/ANS-19.3;* Am. Nuc. Soc., 2005
3. *"American National Standard: Determination of Thermal Energy Deposition Rates in Nuclear Reactors", ANSI/ANS-19.3.4*; Am. Nuc. Soc., 2002
4. *"American National Standard: A Guide for Acquisition and Documentation of Reference Power Reactor Physics Measurements for Nuclear Analysis Verification", ANSI/ANS-19.4*, Am. Nuc. Soc., 1994
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7. *"American National Standard: Moderator Temperature Coefficient in Pressurized Thermal Reactors", ANSi/ANS-19.11; Am. Nuc. Soc., 1997*
8. *"American National Standard: Decay Heat Power in Light Water Reactors", ANSI/ANS-5.1; Am. N uc. Soc., 2005*
9. *"Fission Product Chain Yields", ANS-19.8; Standard in preparation*
10. *"Delayed Fission Parameters", ANS-19.9; Standard in preparation*
11. *"Fast Neutron Fluence in Reactor Pressure Vessels"; Standard near completion.*