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Rules Review and Directives Branch,
Div. of Freedom of Information and Publication Services,
Office of Administration,
USNRC,
Washington, DC 20555

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Gentlemen:

My comments address NRC draft regulatory guide EG-1025, "Calculational and Dosimetry Methods for Determining Pressure Vessel Fluence". I believe draft regulatory guide EG-1025 is based on methods and assumptions that are <u>not</u> valid. Consequently, I believe that draft regulatory guide EG-1025 does <u>not</u> serve the public interest.

The enclosed manuscript:

> R. Gold, "Neutron Fluence Determination For Light Water Reactor Pressure Vessels"

summarizes the basis for my conclusion. An oral presentation (B5) based on this manuscript was delivered at the 8th ASTM-EURATOM International Symposium on Reactor Dosimetry, August 29-September 3, 1993 in Vail, CO.

Although I formally requested a copy of EG-1025 some time ago, i.e., on June 22, 1993, I have yet to receive a current draft of EG-1025. Consequently, my assessment of EG-1025 may be outdated, since it is based on a knowledge of this draft regulatory guide that is at least a year old. I would therefore like to again request a current version of EG-1025.

Sincerely yours,

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NEUTRON FLUENCE DETERMINATION FOR LIGHT WATER REACTOR PRESSURE VESSELS

REFERENCE: Gold, R., "**Neutron Fluence Determination For Light Water Reactor Pressure Vessels,**" Reactor Dosimetry, ASTM STP 1228, Harry Farrar IV, E. Parvin Lippincott, and John G. Williams Eds., American Society for Testing and Materials, Philadelphia, 1994.

ABSTRACT: A general description of limitations that exist in pressure vessel neutron fluence determinations for commercial light water reactors is presented. Complexity factors that arise in light water reactor pressure vessel neutron fluence calculations are identified and used to analyze calculational limitations. Two broad categories of calculational limitations are introduced, namely benchmark field limitations and deep penetration limitations. Explicit examples of limitations that can arise in each of these two broad categories are presented. These limitations are used to show that the recent draft regulatory guide for the determination of pressure vessel neutron fluence, developed by the Nuclear Regulatory Commission, is based upon procedures and assumptions that are not valid. To eliminate the complexity and limitations of calculational methods, it is recommended that the determination of light water reactor pressure vessel neutron fluence be based upon experiment. Recommendations for improved methods of pressure vessel surveillance neutron dosimetry are advanced.

KEYWORDS: neutron fluence, light water reactor, pressure vessel, surveillance dosimetry, benchmark field, deep penetration

Over the lifetime of a light water reactor (LWR), radiation will degrade important mechanical and structural properties of the pressure vessel (PV). Neutron-induced embrittlement is among the most serious effects that could compromise PV integrity. This embrittlement process is a complex technological phenomenon that is not completely understood. LWR-PV embrittlement depends on many factors and variables, such as: chemical composition, metallurgical condition, temperature, neutron fluence, neutron energy spectrum and possibly neutron fluence rate.

The Code of Federal Regulations promulgated by the Nuclear Regulatory Commission (NRC) attests to the significance of neutron-induced LWR-PV embrittlement as a major safety issue in the US. Not only must commercial nuclear power plants (NPP) institute surveillance programs, but all operating LWR in the US must meet fracture toughness requirements for both normal operating conditions as well as for emergency conditions, such as accident induced transients that would create pressurized thermal shock (PTS). Because PV embrittlement is evaluated in terms of neutron exposure, NRC has also issued a draft regulatory guide, DG-1025, on PV neutron fluence determination [1].

It must be emphasized that LWR-PV neutron fluence determination has been addressed over the years through voluntary consensus standards that have been developed under NRC and ASTM auspices to treat different

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Each of these CF can possess many sources of uncertainty, which are, in turn, introduced into PV fluence calculations. In many cases these uncertainties are well-defined, but there also exist cases where these uncertainties can be either ill-defined or completely unknown. It must also be emphasized that this particular CF enumeration is non-exhaustive, i.e., additional CF of equal or greater relevance could exist that have not been explicitly identified above.

These CF can act alone or combine in different ways to create limitations in the accuracy and reliability of PV fluence calculations. There exist two broad categories of calculational limitations that must be considered, namely benchmark field limitations and deep penetration limitations. Specific combinations of CF are used to illustrate limitations in each of these broad categories, but only a few such illustrations can be presented here.

Benchmark Field Limitations

The utility of the benchmark field (BF) method for the specific case of PV fluence determinations has been demonstrated by a comprehensive international program called the LWR-PV Surveillance Dosimetry Improvement Program (SDIP) [11]. Under the LWR-PV-SDIP, a calculational methods "Blind Test" was conducted based on experimental results obtained through an extensive international collaboration in specific LWR-PV configurations studied in the Pool Critical Assembly (PCA) low power BF [12]. Results from this international blind test demonstrated that calculations alone can generally be trusted to no better than a factor of two. However when calculations are judiciously combined with BF experimental results, such as through the use of a least squares adjustment code, as described in ASTM standard E944-89, then derived values of neutron group fluxes and neutron exposure parameters are in the range of 5% to 30% (1σ) and 5% to 15% (1σ), respectively, for the PCA BF.

These PCA BF results can not be arbitrarily extended to the LWR-PV environment of a specific NPP without adequate proof. In any attempt to make such an extension, serious limitations arise from the fact that a BF mockup can not be an exact duplicate of a commercial LWR-PV. To illustrate this point, consider the three low power benchmark mockups carried out within the international framework of the LWR-PV-SDIP. In addition to the PCA, the Nestor Shielding and Dosimetry Improvement Program (NESDIP) [13] and the Vulcan Experimental Nuclear Study Facility (VENUS) [14] were established in the UK and Belgium, respectively. While these three BF have provided accurate and comprehensive LWR-PV experimental results, the purpose of each of these low power BF was quite different. The PCA examined the radial variation of the neutron fluence in different LWR-PV configurations, NESDIP studied the neutron fluence in cavity environments and VENUS investigated azimuthal fluence variation as well as effects due to plutonium enriched fuel. It automatically follows that none of these low power BF faithfully duplicated a commercial LWR-PV environment in toto.

CF-1--In low power BF tests, geometric design specifications are accessible to direct measurement, remeasurement and confirmation. This is not the case for commercial NPP. In particular, calculated PV fluence determinations are very sensitive to geometrical, dimensional and positional uncertainties. For example, the PV neutron fluence $\Phi(E>1)$ or displacements per atom (DPA) decrease in the radial direction by more than 10 per cent per cm. Since a PV in a typical NPP has a radius in excess of 2m, deviation between design specifications and as-built NPP dimensions of only a few per cent would introduce geometrical, dimensional or positional uncertainties of at least a few cm. The sensitivity to such uncertainties has already been emphasized in ASTM Standard E560-84, where it is noted that NPP deviations of approximately 3 cm have been observed between design specifications and as-built NPP dimensions. Unfortunately, as-built dimensions are not always accessible for direct measurement. As a consequence, geometrical, dimensional and positional uncertainties can produce large and ill-defined uncertainties for calculated PV fluence determinations.

CF-6--In low power BF, steady state conditions can be readily achieved for the rather limited irradiation duration required by most low power experimental methods. In contrast, a commercial LWR undergoes continuous change over the course of a fuel cycle. At the high power levels attained in commercial LWR, effects such as plutonium burn-in and burn-out of boron in the coolant water create a power distribution that changes spatially and temporally over the fuel cycle. Control rods in a commercial LWR are often moved over the course of any given fuel cycle, which also produces temporal and spatial changes in the LWR-PV neutron field. These high power effects obviously do not exist in low power BF and therefore introduce uncertainties not taken into account in a low power BF test.

CF-7 & CF-10--Steady-state conditions that can be maintained in low power BF enable accurate measurement of power-time history. Run-to-run monitoring can be accurately achieved by judicious location of an active power monitor. Absolute power can then be established through absolute fission rate measurements carried out in one or at most a few runs. These ideal conditions produce accurate power-time history for virtually all low power BF experiments. In contrast, the power-time history over any given fuel cycle of a commercial LWR can not be established with anywhere near the same accuracy. Many inadvertent shutdowns, of indeterminate duration, can arise over the course of a fuel cycle. For commercial NPP absolute power can not be based on direct measurement of absolute fission rate, but on in-direct observation from reactor control room instruments. Furthermore, the power-time history is not always available from NPP documentation, i.e., the complete control room operating records do not always exist. This situation is, unfortunately, not as rare as one might expect, since the draft regulatory guide [1] recommends use of a conservative power-time history to handle this contingency. The complexity of NPP power-time history has been experimentally confirmed for the case of a Boiling Water Reactor (BWR) [15], where dosimetry measurements demonstrated that the total reactor power-time history for the BWR need not be representative of the localized power-time history in any specific region of the BWR-PV environment. In fact, uncertainties of approximately 20 per cent (1σ) can be incurred when total power-time history is used for a specific localized BWR-PV region of interest.

Deep Penetration Limitations

The determination of PV neutron fluence for LWR can be characterized as a deep penetration (DP) problem. DP transport problems are highly sensitive to CF-1, CF-2 and CF-5 and to the inherent elements of uncertainty introduced by these particular CF. The differences exhibited between different computational methods, or even the same method applied at different laboratories, reveals the extreme sensitivity of DP-PV neutron fluence calculations to these inherent elements of uncertainty.

CF-1 & CF-2--A European program of neutron cross section measurements based on single element DP-BF experiments has been in progress for some time [16]. The high sensitivity of DP to the neutron cross section of the single element is exploited in these BF experiments. Advocates claim these integral experiments have a number of advantages over conventional thin sample neutron cross section measurements. Hence it is clear that calculational methods of PV fluence determination will be sensitive not only to compositional and neutron cross section uncertainties, but to cross section processing and preparation codes as well as the group structure that is used in the calculational method.

Recent work with iron filters [17] is an excellent example of the high sensitivity of DP transmission in iron to the fine energy cross section structure that exists in the resonance region below approximately 1 MeV. In this work, it was observed that variation of only 3 to 9 percent in the localized cross section minima that occur at energies just below resonant peaks can change the transmission (at the energy of these localized minima) by typically 20 to 85 per cent, depending on the specific resonance in question.

CF-2--Neutron penetrability into a given medium increases with increasing neutron energy. High energy source term neutrons are particularly important in the DP transport of neutrons. Although these high energy neutrons may represent only an insignificant fraction of the total source, these high energy neutrons can be a significant fraction of the neutron population that survives DP transport. In the case of PV neutron fluence determination, the high energy portion of the ^{235}U fission neutron spectrum, especially above approximately 8 MeV, has not been accurately measured. In fact, recent adjustment of the ^{235}U fission neutron spectrum with integral reaction rates reveals significant spectral changes arise above approximately 4 MeV [18]. The comparable uncertainty of the high energy component of the ^{239}Pu burn-in source term is even larger. These source term uncertainties are a fundamental limitation of the accuracy that can be attained in PV fluence calculations, regardless of the computational method that is employed. Because of this concern, a unique BF study of deep neutron penetration was advanced at the last ASTM-EURATOM symposium in Strasbourg [19].

CF-2, CF-3, CF-4 & CF-5--Neutron spectrum measurements carried out some time ago in low power fast breeder benchmark fields with proton-recoil proportional counters demonstrated that reactor neutron spectra can possess extremely fine energy structure [20]. It was deduced that the fine energy structure in the neutron spectrum is created by resonance neutron scattering in constituents of the environment. Since that time, fine energy structure has been observed in many other low power benchmark fields.

Neutron spectrometry conducted in LWR-PV environments at the PCA and NESDIP BF reveal a fine energy structure that: 1) is due to resonance scattering in iron and 2) becomes more pronounced with increasing penetration into the PV. Fluence calculations that do not duplicate the detail of this fine energy structure can not determine threshold reaction rates accurately, especially for thresholds that rise rapidly in the resonance region of iron, i.e., below approximately 1 MeV. This conclusion has been demonstrated by comparison of calculations with proton-recoil data from J-integral mode scanning of nuclear research emulsions (NRE) in VENUS [21]. The J-integral response of NRE behaves like a threshold reaction, except that the threshold energy can be arbitrarily varied. The calculated-to experimental (C/E) ratio for the J-integral data varied from approximately 0.75 up to 1.5 for different locations in VENUS. Given the limited number of energy groups used in these calculations, i.e., only 17 groups, the fine energy structure in the neutron spectra could not be represented. This inadequate energy resolution must therefore contribute to the poor C/E ratios attained in VENUS. In fact, these NRE measurements demonstrate that J-integral data varies significantly through energy regions that are smaller than the energy groups used in this calculation [21].

Owing to the limited NRE neutron energy resolution, the NRE data from VENUS can not be used to accurately ascertain just how many calculational energy groups will provide an adequate representation of neutron spectra in LWR-PV environments. However from these VENUS NRE data, it is clear that even a few hundred energy groups will not suffice. In this regard, it must be emphasized that the vast majority of resolved resonances in iron possess a neutron level width of at most a few keV.

Since the ^{237}Np fission reaction usually possesses the lowest threshold and one of the most rapidly increasing cross sections used for

LWR-PV surveillance dosimetry, this calculational limitation explains why the C/E ratio for ^{237}Np(n,f) can often be unacceptable, when C/E ratios for most other dosimetry reactions can be acceptable. This result is unfortunate because as stressed in ASTM Standard E1006-89, the ^{237}Np(n,f) threshold reaction is, perhaps, the most important of all dosimetry reactions used for LWR-PV surveillance.

CF-3, CF-4 & CF-5--Failure of calculations to represent the fine energy structure of neutron spectra in LWR-PV environments leads to two additional limitations that are significant for PV fluence determination. Since peaks in the LWR-PV neutron spectra arise at local minima in the iron cross section, the average cross section that is actually attained in the PV will be considerably smaller than the cross section produced with a calculational method of inadequate energy resolution. Recent Monte Carlo calculations in the UK confirm this cross section behavior [22]. As a consequence, calculational methods of inadequate energy resolution will generally underestimate neutron transport through the PV. This underestimation is further exacerbated by the fact that the fine energy structure in the neutron spectrum becomes more pronounced with increasing penetration into the PV. It follows that the C/E ratio for the neutron fluence, attained by a calculational method of inadequate energy resolution, will systematically decrease with increasing penetration into the PV.

A second limitation arises in the calculated DPA exposure unit in iron. There exist two opposing effects that must be considered. The first effect stems from the spatial variation of C/E for the neutron fluence. Since calculational methods of inadequate energy resolution will generally underestimate the fluence, DPA produced with such calculated fluences will be underestimates. Because the C/E ratio for PV fluence systematically decreases with increasing penetration into the PV, the calculated DPA will possess the same systematic behavior. The second effect stems from the DPA cross section in iron, which (as shown in ASTM standard E693-79) possesses the resonant structure of the iron cross section. Folding a calculated neutron spectrum of inadequate energy resolution with this DPA cross section will generally overestimate the DPA, since the peaks in the fine energy structure of the actual spectrum will fall at the local minima in the DPA cross section. Hence using a calculated fluence of inadequate energy resolution to determine DPA in iron creates two radially dependent biases that operate in opposite directions, i.e., one increases and the other decreases with increasing penetration into the PV. For a given computational method that possesses inadequate energy resolution, it is not clear which, if either, of these two biases will dominate or how the net bias varies with increasing penetration into the PV.

AN ASSESSMENT OF DRAFT REGULATORY GUIDE EG-1025

Draft regulatory guide EG-1025 [1] requires that PV neutron fluence determinations be based on: "absolute calculations, rather than extrapolated fluence measurements". EG-1025 further requires that the calculational method be validated in BF tests. The regulatory guide goes on to examine the two possible cases that can arise in BF tests, namely agreement (Case 1) and disagreement (Case 2) between the calculation and the BF test. For Case 1, EG-1025 states that adequately benchmarked calculations possess an accuracy of better than 20 per cent (1σ) for PV neutron fluence determinations. When case 2 arises, EG-1025 recommends that calculations be modified provided the cause of the deviation can be identified. EG-1025 describes a way to accomplish the modification through the introduction of bias factors, which can be obtained from the deviations observed between the calculations and the BF experimental results. These bias factors can then be applied to the calculated PV neutron fluence.

Limitations that exist in PV fluence calculations, described above and in considerably greater detail elsewhere [10], clearly demonstrate that satisfying a BF test, i.e., Case 1, is at best a necessary condition, but not a sufficient condition to conclude that the calculational method is valid to better than 20 per cent (1σ) for PV fluence determinations. As for Case 2, given the number of CF that exist in PV fluence calculations, it may not be possible to uniquely assign the observed bias to a single CF or even a single effect. In fact rather than a single CF or effect, the observed bias factor is more likely to be the result of a number of CF, each possessing a separate bias. The biases of these separate CF could act either in consonance or to offset one another. An explicit example of offsetting biases was described above for the calculated DPA exposure unit in iron, when using a calculational method of inadequate energy resolution.

A more basic difficulty than non-uniqueness exists for Case 2. When a bias factor arises from a BF test, Case 2 assumes that this bias factor can be transferred directly to the PV fluence calculation for a given NPP. However, the invariance of the specific bias factor with respect to such a transformation must be proven. Specific bias factors have been described above and in more detail elsewhere [10], that are not invariant with respect to such a transformation. Indeed, BF and DP limitations explicitly demonstrate that certain biases can arise due to effects in LWR-PV environments that do not exist and are therefore not accounted for in BF tests. Consequently, the invariance of bias factors can not be guaranteed.

Beyond the specific analyses considered so far, the recommendations advanced in EG-1025 contradict two operational axioms that have generally been practiced throughout the history of the physical sciences, namely 1) seek simplicity and 2) quantify by experiment.

The quest for simplicity is a fundamental characteristic of all efforts in natural philosophy. A theory that depends on a few simple postulates is preferred to a theory that relies on many complex assumptions. An experimental method that utilizes a few simple procedures is preferred to an experimental method that relies on many complex steps. The simpler theory and the simpler experimental method almost invariably produce more accurate, reliable and comprehensive results.

As for the second operational axiom, PV fluence is an absolute quantity. In the physical sciences and in nuclear metrology in particular, absolute quantities are almost invariably determined by experiment. All the fundamental physical constants are determined by measurement, such as the velocity of light, the electric charge, elementary particle masses, Planck's constant and Boltzmann's constant. The systematics of nuclear decay, including half-lives, charged and neutral particle energies, nuclear energy levels and branching ratios are all determined by measurement. The same is true for nuclear reactions, including charged and neutral particle cross sections, nuclear masses, Q-values and in particular the systematics of the fission reactions.

To determine PV neutron fluence, measurements can be conducted at either surface or both surfaces of the PV. Surveillance dosimetry can be strategically conducted to concentrate on specific PV locations of concern, such as beltline welds. In contrast, PV fluence calculations can neither start at the PV surface nor focus upon critical locations, but rather must be initiated in a source term that lies at a considerable distance from the PV surface, i.e., in the reactor core. As a consequence, to calculate PV neutron fluence requires many steps, each of which can entail not only assumptions but the need to introduce many physical parameters. These assumptions possess limitations, the physical parameters possess uncertainties and the computational methods employed can possess both limitations and uncertainties. As a consequence, effects created by these calculational limitations are primarily responsible for the wide (and sometimes erratic) variation of the C/E ratio attained in pressure vessel neutron fluence determinations. In spite of the restricted exposition on CF and limitations presented above, it is nevertheless clear that PV fluence calculations are neither simple nor direct when compared with PV fluence measurements.

RECOMMENDATIONS

Given the current limitations that exist in calculations, the only rational way to determine LWR-PV neutron fluence with the necessary accuracy and reliability for evaluating and predicting PV embrittlement, is through reliance upon experiment. This can be accomplished by application of a least squares adjustment code, as described in ASTM standard E944-89, which judiciously combines calculational and experimental results. However, experimental methods also possess limitations. As a consequence, specific and detailed recommendations to improve LWR-PV surveillance dosimetry have been advanced elsewhere [10] and only general areas of emphasis can be indicated here.

Current limitations make complimentary use of experiment and calculation mandatory for PV fluence determination. It has been shown that the absolute scale of PV fluence determination should rest primarily upon experiment. However in any given NPP, dosimetry measurements can not be carried out at all LWR-PV points of interest. Furthermore, integral fluence monitors used in PV surveillance neutron dosimetry do not provide complete energy coverage of the neutron spectrum. Hence to the extent possible, calculations should compliment experiment by focussing upon interpolations/extrapolations in space and neutron energy.

Radiometric (RM) neutron dosimetry forms the backbone of PV surveillance dosimetry in the US. Comparison of RM efforts in the US with those in Europe have shown that the uncertainty levels attained by US laboratories is unacceptable [23]. To remedy this deficiency, an absolute gamma-ray counting facility must be established that is capable of calibrating RM dosimeters to state-of-the-art accuracies, so that counting systems used for RM dosimetry in US surveillance programs can be tested and validated. In conjunction with this gamma-ray counting facility, a quality assurance program must be undertaken that quantifies the isotopic constituents and purity of materials used for RM surveillance dosimetry. This facility can furnish RM dosimeter standards to vendor and service laboratories, so that round-robin comparisons can be conducted on a systematic basis, e.g., annually for certification purposes.

Considerable effort has been expended throughout the world to improve the accuracy of neutron cross sections. It is high time that such efforts focus upon cross sections used for PV neutron surveillance dosimetry, such as: ^{54}Fe(n,p), ^{58}Ni(n,p), ^{63}Cu(n,α), ^{93}Nb(n,n'), ^{237}Np(n,f) and ^{238}U(n,f). The advantage of such efforts would be an immediate payoff through improved accuracy of PV fluence determinations.

To overcome the limitations that exist in calculational methods, an **"Empirical Method of Extrapolation"** has been advanced [24]. Based on benchmark field studies, it has been shown that the radial variation of the fluence (E>1 MeV) or DPA decreases in a simple exponential manner with increasing radial penetration into the PV. Using parameters and associated uncertainties obtained from least squares analyses of benchmark field data, it has been demonstrated that the exponential extrapolation from either the core or cavity side of the PV entails a negligible penalty in increased uncertainty for the extrapolated fluence or DPA. Further study and investigation of this empirical extrapolation method is warranted. The domain of applicability of this simple exponential relation in the PV of NPP should be determined. In particular, effects of both axial and circumferential variation of neutron exposure on the validity/accuracy of this radial extrapolation method must be quantitatively ascertained in actual LWR-PV environments. This effort should be given high priority, since this empirical method provides completely independent extrapolations and thus eliminates biases and the larger uncertainties that can be introduced when calculational methods are used for radial extrapolations of fluence or DPA through the PV. To simplify the determination of the nil-ductility temperature shift at a key location of interest in the PV, one should first extrapolate the neutron fluence or DPA to that location. This accurately extrapolated fluence or DPA value can then be used in a material-dependent trend-curve to determine the value of the nil-ductility temperature shift at the key location of interest.

Rather than revise EG-1025 for promulgation by NRC, it is more appropriate to provide guidance for the US nuclear power industry on PV fluence determination through ASTM standards. Where already established expertise has been demonstrated, such as the ASTM activities for LWR-PV, it would be both prudent and cost effective for NRC to utilize the recognized ASTM capability for establishing objective standards that meet the needs of both industry and the public. In fact, current NRC regulations often cite ASTM standards as an acceptable modus operandi. Hence, it is recommended that standards required for PV fluence determination continue to be developed under ASTM auspices [4,9].

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aspects of LWR-PV embrittlement [2-8]. An ASTM master matrix [9] and ASTM Standards Technology Training course workbook [4] describe the relationships amongst more than twenty standards devoted to LWR-PV surveillance. The present assessment of PV neutron fluence determination is carried out within the perspective of these ASTM standards. Because symposium guidelines require a presentation that is necessarily abridged, a more detailed report has been issued [10] which provides more adequate elaboration upon a number of topics that can not be treated here. In particular, it is shown that the current status of trend curve analysis, which is used to evaluate LWR-PV embrittlement, does not provide any operational implications or requirements for the determination of PV neutron fluence. An important corollary, that follows from this conclusion, is that no preferred neutron exposure unit can be ascertained from the current status trend curve analysis.

LIMITATIONS OF PRESSURE VESSEL FLUENCE CALCULATIONS

Since neutron fluence determinations are essential and the current status of trend curve analysis provides no operational requirements that can be imposed upon the choice of the neutron exposure unit, PV fluence determinations in the US need be responsive mainly to safety criteria specified in NRC regulations. In order to satisfy such safety criteria, the reliability and confidence level of the fluence determination are as important as the accuracy level that is attained. Reliability and confidence level of the fluence determination must be established beyond question. Conversely, it is not sufficient to use a method that merely suggests a certain accuracy level could be attained in fluence determinations without ascertaining the reliability and confidence level of the method.

PV neutron fluence is an <u>absolute</u> quantity. The highly complex nature of neutron transport calculations militates against the use of calculations alone to determine the absolute magnitude of PV neutron fluence. This complexity stems, no doubt, from the vast diversity of factors needed for neutron transport calculations, together with the associated uncertainties of these factors. Consequently, these factors will be called complexity factors (CF). To illustrate the overall complexity of PV fluence calculations, some of the more important CF required in current NPP in- and ex-vessel neutron transport calculations are given below:

CF-1) Environmental, geometrical, and compositional variables.

CF-2) Nuclear constants, including neutron cross sections and fission source term characteristics.

CF-3) Modelling assumptions.

CF-4) Mathematical approximations.

CF-5) Fine energy structure in the neutron spectrum.

CF-6) Temporal and spatial deviations from steady state conditions.

CF-7) Reactor power time-history.

CF-8) Surveillance capsule flux perturbations.

CF-9) Cavity flux perturbations, streaming, etc.

CF-10) Cycle-to-cycle variations, which can be planned such as fuel management schemes or inadvertent shutdowns.