11/7/2000 1:20 PM

Computational Physics and Engineering Division (10)

Issues for Effective Implementation of Burnup Credit

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Submitted to

International Atomic Energy Agency (IAEA)
Technical Committee Meeting
on the Evaluation and Review of the Implementation of
Burnup Credit in Spent Fuel Management Systems

Vienna, Austria
10–14 July 2000

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*Managed by UT-Battelle, LLC, under contract DE-AC05-00OR22725 with the U.S. Department of Energy.

ISSUES FOR EFFECTIVE IMPLEMENTATION OF BURNUP CREDIT

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Abstract

In the United States, burnup credit has been used in the criticality safety evaluation for storage pools at pressurized water reactors (PWRs) and considerable work has been performed to lay the foundation for use of burnup credit in dry storage and transport cask applications and permanent disposal applications. Many of the technical issues related to the basic physics phenomena and parameters of importance are similar in each of these applications. However, the nuclear fuel cycle in the United States has never been fully integrated and the implementation of burnup credit to each of these applications is dependent somewhat on the specific safety bases developed over the history of each operational area. This paper will briefly review the implementation status of burnup credit for each application area and explore some of the remaining issues associated with effective implementation of burnup credit.

1. INTRODUCTION

Since the mid-1980s the domestic utility industry, the U.S. Department of Energy (DOE), and the U.S. Nuclear Regulatory Commission (NRC) have actively considered the incentives, benefits, and obstacles associated with implementing burnup credit in the criticality safety evaluation for storage, transport, and disposal of spent nuclear fuel (SNF). The incentives first emerged with spent fuel storage pools. Lack of off-site alternatives (i.e., reprocessing, permanent disposal, or interim storage) provided significant incentives for utilities to obtain optimum use of the fixed pool storage capacity currently in place. Exacerbating the demand to optimize pool storage space was the trend towards increased initial enrichments, a trend, which continues to the present. Thus the simple, yet conservative, assumption of using unirradiated Afresh fuel@ isotopics for the criticality safety analysis became a significant economic barrier to continued operation of reactor power plants.

By the end of the 1980s several utilities had begun to use burnup credit in the safety analysis for their storage pools at PWRs. Efforts were initiated to evaluate the incentives and seek resolution of technical issues associated with the use of burnup credit in SNF storage and transport casks. In contrast to many countries where burnup credit is desired primarily to increase the allowable enrichment within existing cask designs, the United States nuclear industry is seeking to develop a new fleet of storage and transport casks that are optimized for the anticipated SNF contents. The long cooling times, on the order of 5 years or more, provide considerable flexibility for capacity increase in comparison to the shorter cooling times used in countries that reprocess. Rail casks with capacities of 32 PWR assemblies are being designed—an ~30% increase over existing storage cask concepts. These increased cask capacities can enable a reduction in the number of casks and shipments, and thus have notable economic benefits while providing a risk-based approach to improving safety. Arguments for improvement in safety have noted that the fewer shipments required with burnup credit cask designs will reduce the radiation exposure to both workers and the public as well as reducing the potential for a transport accident involving a cask. Arguments have also been made that the increased capacity per cask increases the potential consequence from any hypothetical transport accident. In either case, from the perspective of criticality safety, it is clear that the use of burnup credit should enable an adequate margin of subcriticality to be maintained while increasing cask capacity.

Incentives for use of burnup credit in boiling water reactor (BWR) applications have not been as significant as for PWR applications. The reason for this reduced incentive is that BWR fuels have less reactivity than PWR fuels and increased use of neutron poisons in intervening regions between assemblies have proven effective for maximizing capacities and allowing fairly high initial enrichments [1]. Thus, the incentives are largely limited to reducing the cost of neutron poison plates and allowance for higher initial enrichment fuel (up to 5.0 wt% ^{235}U).

However, the incentives for implementing burnup credit have really not been a debated issue in the United States. Rather the debated issues have been associated with the ability to demonstrate the technical basis commensurate with the existing expectations of each application area. This paper will briefly review the implementation status of burnup credit for each application area and explore some of the remaining issues associated with effective implementation of burnup credit.

2. APPLICATION AREAS

2.1. Reactor Operations

Accurate prediction and understanding of the changing nuclide inventory as a function of burnup is a necessity to safe and efficient operation of a nuclear reactor. Major efforts have been expended by the nuclear industry to ensure that the changing isotopic compositions of fuel assemblies in an operating reactor are properly accounted for and that effective analysis methods are available to Afollow@ and predict operating conditions for the reactor. Of primary interest is the integral effect (i.e., neutron multiplication) of the changing SNF inventory. The analytic methods used in reactor operations have traditionally been based on geometric and physics approximations (primarily applicability of neutron diffusion theory) to the Boltzmann radiation transport equation, but have been made increasingly reliable with continuous feedback experience (i.e., integral validation) gleaned from a 40-year period of operating commercial light water reactors (LWRs) in a controlled facility. However, the analysis methods used for calculation of the effective neutron multiplication factor (k_{eff}) in commercial LWR operations are typically not applicable for out-of-reactor situations where their geometric and physics approximations are not valid. In addition, the nuclide inventory provided by the reactor core-following codes has historically not included many of the nuclides that are important to the prediction of k_{eff} in out-of-reactor operations because of the build-up of absorbers in the absence of a significant neutron fluence.

2.2. Pool Storage

Storage of spent fuel in underwater racks at reactors has been standard practice in the United States since the start of the nuclear industry. Spent fuel pools (SFPs) at reactors are licensed in the United States under 10 CFR 50 [2]. They represent controlled facilities operated in conjunction with the reactor operations. In lieu of credit for boron in the water, the NRC Office of Nuclear Reactor Regulation has licensed use of burnup credit for many years in borated SFPs at PWR plants. In establishing the safety basis, the general approach used in the United States involves blending the experience and reliability from the reactor core-following codes with the double contingency principle typically applied for out-of-reactor criticality safety. The SNF inventory subsequent to decay of the short-lived ^{135}Xe isotope is typically used within a storage pool geometry to determine a fresh fuel enrichment that provides the same reactivity as the SNF inventory. This Aequivalent@ fresh fuel enrichment is then used within a criticality safety analysis code to perform the actual safety analysis for the pool. Little or no validation of the isotopic inventory prediction via comparison with SNF chemical assays is performed; instead, the reliability of the analysis approach in performing core-following calculations is considered to be adequate. Similarly, validation of the cross-section data, as typically provided by critical experiments, is limited to the fresh fuel nuclide inventory.

The current burnup credit approach for SFPs hinges on the adequacy of the process to determine the SNF-equivalent fresh fuel assembly enrichment as well as the proper use of the equivalence information within environments that provide similar neutronic characteristics. Until recently, this general process had been used to obtain burnup credit in PWR SFPs where credit for the soluble boron is taken only for postulated accident events. Recently, however, credit for soluble boron up to 5% in reactivity has been allowed by the NRC [3]. Credit for reactivity decreases associated with fissile depletion and absorber nuclide increases (i.e., burnup credit) has not been allowed for BWR storage pools (where there is no soluble boron); instead, the approach has been to obtain an equivalent fresh fuel enrichment associated with the peak reactivity anticipated for the BWR fuel during the depletion process (reactivity initially increases early in life due to depletion of the gadolinium absorber in the assembly).

2.3. Transport and Storage Casks

The U.S. regulatory requirements for transport and dry storage (as opposed to wet storage in a pool) of SNF are included in 10 CFR 71 and 72, respectively [4,5]. Both regulations are the responsibility of the NRC Office of Nuclear Material Safety and Safeguards. Neither regulation has any specific requirement that would prevent burnup credit from being implemented in the safety analysis. In the case of dry spent fuel storage, water in-leakage to the cask during storage is not considered credible; thus, burnup credit for PWR fuel is not typically necessary since the only flooded condition corresponds to fuel loading and unloading, where soluble boron in the water may be used for reactivity control. Soluble boron is not present in BWR SFPs, and thus for fuel loading or unloading at a BWR, negative reactivity associated with soluble boron is not available.

The domestic and international practice of assumed upset conditions for transport is that water in-leakage be considered in the evaluation of a single cask. Consequently, spent fuel canisters planned for use in transport must be shown to maintain an adequate subcriticality margin when flooded with fresh water. It is not desirable to have separate spent fuel canisters for storage and transport; thus, canisters designed for use with both storage and transport casks (or overpacks) have become the standard industry practice in the United States. As a result, the regulatory requirements for transport directly impact storage practice. For example, it is not desirable to load spent fuel into a canister and seal-weld the canister for storage if the contents are not allowable for transport. Therefore, the need for burnup credit in casks is driven by the regulatory requirements for transport.

Since 1985 significant effort has been devoted to investigating the operational merits and technical issues associated with burnup credit for cask transport and storage of LWR spent fuel. The efforts have focused on PWR fuel with only scoping studies performed for BWR fuel. To date, there is no regulatory experience in the United States with licensing an LWR cask with burnup credit. However, the NRC has issued interim staff guidance (ISG8) [6] that provides recommendations for implementing burnup credit in the safety analysis of PWR casks. The recommendations within ISG8 limit the burnup credit to that available from actinide-only nuclides for SNF with assembly-average burnup of 40 GWd/MTU or less and a cooling time of 5 years. The ISG8 recommendations allow spent fuel with burnup values greater than 40 GWd/MTU to be loaded in a cask, but burnup to only 40 GWd/MTU can be credited. Initial enrichments up to 5.0 wt % ^{235}U are allowed (special provisions/penalties are required for enrichments beyond 4.0 wt % ^{235}U). However, assemblies with burnable absorbers are not allowed. The approach to implementation of burnup credit in safety analysis for transport packages will involve predicting the nuclide inventory with a code that will provide adequate individual isotopic information for SNF and subsequent use of that inventory to determine the k_{eff} value.

The ISG8 recommends that the analysis methods used to predict the SNF isotopics and k_{eff} value be validated against measured data and that efforts be made to identify and/or bound potential uncertainties caused by variation in reactor operating histories, lack of measured data for validation, and the spatial variation of the burnup within the assembly (axial and horizontal). Further, the ISG recommends the use of a measurement prior to or during the loading procedure to ensure that each assembly is within the loading specifications for the approved contents (e.g., a burnup measurement). The recommendations for a bounding approach and pre-shipment measurements are consistent with the international regulations for transport of fissile material [7], which directly address transport of irradiated nuclear fuel.

2.4. Permanent Disposal

Licensing requirements for permanent disposal of SNF at a proposed repository in the United States are continuing to evolve as the NRC Office of Nuclear Material Safety and Safeguards considers realistic requirements appropriate for demonstrating protection of the public health and safety. Proposed changes to the regulations allow the potential for criticality in the post-closure phase of the repository to be considered in light of the probability of occurrence and the consequences to the total system performance. The quantity of fissile material being considered for disposal together with the uncertainties associated with degradation and movement of the material over geological time frames makes this a practical approach that will provide safety to the public. Thus, the licensing approach [8] being considered seeks to identify credible (above a certain probability of occurrence) configurations with a potential for criticality and explore the consequences that might result from such critical events. For intact fuel, the licensee is seeking to evaluate the configurations using SNF isotopic compositions that include both actinides and stable fission products. Additionally, burnup credit for both PWR and BWR fuel is being considered. The analysis and validation approach for disposal waste packages is more similar to that considered for storage and transport casks than the approach used for SFPs. Excessive conservatism is often used for criticality safety analyses outside reactors as a means to simplify development of the safety basis and the review process. However, recognizing the impact that such excess conservatism will have on the facility design, significant effort is being expended to mitigate any undue conservatism and provide realistic estimates of the potential critical configurations needed for the risk-based approach used in the repository licensing.

3. DISCUSSION OF APPROACHES

The approaches used to resolve a technical problem are typically based on historical precedence and experience in the subject area. The need to consider burnup credit came initially to the SFPs, when the absence of disposal and reprocessing options caused the capacity requirements to progressively exceed initial design expectations. Credit for burnup or soluble boron was needed to extend the pool capacity. At the time, the Advisory Committee on Reactor Safety considered potential loss of soluble boron to be of greater concern than any uncertainties associated with implementing burnup credit. Thus burnup credit was implemented in a fashion consistent with the analysis and operations experience within the reactor industry and NRC Office of Nuclear Reactor Regulation. However, the presence of boron in the pool remains an important component of the safety basis in that it provides support for satisfying the double contingency principle of out-of-reactor criticality safety [3]. Licensing analysis for burnup credit is based on site-specific conditions and assumptions relative to plant operations and fuel inventory.

The second application area to address burnup credit was transport and dry storage. The use of transport casks in the public domain means the operational environment is more unpredictable and the controls less reliable—a fact considered in the existing U.S. [4] and international [7] regulations for transport, which are considerably more prescriptive relative to the assumptions for normal conditions of transport and hypothetical accident conditions. The approach that was used immediately sought to meet the requirements of national consensus standards for criticality safety outside reactors while extending the safety analysis to use a Abounding@ spent fuel inventory. Also, since transport casks have been historically licensed based on specified contents and independent of a specific facility, the need to assume reactor conditions and assumptions that bound all potential plant operations had to be considered. The composite result of all of these constraints was that the technical complexity for using burnup credit increased. In addition, the original applicant seeking a viable approach to burnup credit in transportation (the U.S. DOE) did not have initial success convincing the regulatory office (the NRC Office of Nuclear Material Safety and Safeguards) that there was ample short-term need to focus resources on the issue. This situation changed as the SFP storage availability continued to decrease, and the reactor industry reliance on storage casks increased. Recently, the need for more efficient storage capacity coupled with the potential for dual utilization in the transport mode has made burnup credit a near-term issue that has demanded increased attention from both the U.S. NRC and the domestic nuclear industry.

The latest application area to consider use of burnup credit has been permanent disposal. Being a first-of-its-kind facility, the regulatory requirements and the licensee safety basis are both evolving as information is gained. The applicant is seeking to use a best estimate approach to predicting k_{eff} that considers actinides and fission product nuclides for intact fuel only. The repository is a site-specific application; but the SNF is from all operating plants, and so, conditions and fuel from all reactors must be considered. However, the regulations are far less prescriptive than those for storage and transport and the risk-based approach anticipated for the latest regulatory change allows considerable flexibility in the assumptions and approaches that can be used to assure public safety.

4. COMPARISON OF APPROACHES

The regulatory allowance of burnup credit in SFPs, including credit for fission products, seems to be partly justified [9] by the presence of soluble boron in the spent fuel pool. The reactivity margin associated with the soluble boron is inherently credited in SFP burnup credit analyses to account for uncertainties associated with the utilization of burnup credit. This approach is justified on the basis that there is typically sufficient soluble boron present in PWR SFPs (soluble boron concentrations of ~2000 ppm are common) to maintain subcriticality even if an entire storage rack intended to accommodate burned fuel were misloaded with fresh fuel assemblies of the highest allowable enrichment. Note that recent allowance for partial soluble boron credit (up to 5%) reduces this associated margin. In contrast, guidance for burnup credit criticality safety evaluations for dry storage and transport [6] calls for an assessment of individual sources of uncertainty and consideration of these uncertainties in the safety evaluation—a practice consistent with the national consensus standards for criticality safety outside reactors.

Spent fuel pools provide a protected, controlled environment within the confines of the reactor site and where responsibility for safety resides. This may account for why burnup credit criticality analyses for SFPs do not typically address the numerous issues that have been identified in the context of burnup credit for transportation. The following paragraphs briefly review the three major differences between the requirements for criticality safety analyses for SFPs and cask storage and transport. In the comparison noted below, which highlights the added constraints for burnup credit in transportation, the allowances for SFP analyses are all justified by the presence and control of soluble boron.

The first notable difference between the two NRC guidance documents for pool storage [3] and dry storage/transport [6] is the selection of nuclides used in the implementation of burnup credit. The SFP analyses included credit for all nuclides except ^{135}Xe without explicit consideration of uncertainties in the calculated nuclide concentrations or assurance of their presence (e.g., fission-product gases). To account for uncertainties in fuel depletion calculations and nuclide presence, an uncertainty equivalent to 5% of the reactivity decrement to the burnup of interest (5% of the reactivity reduction from fresh to the burnup of interest) is suggested as an acceptable assumption [3]. In contrast, proposed burnup credit for dry storage and transport [6] may credit only a subset of the available actinides present and must employ conservative isotopic biases determined from benchmarks of applicable fuel assay measurements. In addition, Ref. 6 limits the safety analyses to a single cooling time of 5 years while Ref. 3 allows consideration for all cooling times. Thus, SFP analyses are allowed 95% credit for the reduction in reactivity associated with all of the calculated isotopics (except ^{135}Xe), but analyses for a transport application currently allow only a limited number of actinides and must substantiate the uncertainty in their prediction via comparison with measurement.

In regard to depletion calculations, no clear guidance or requirements for bounding depletion parameters, similar to those suggested in Refs. 10–11, exist for SFP analyses. Assemblies that used fixed burnable absorber rods (e.g., burnable poison rods and axial power shaping rods) are currently allowed to assume burnup credit in SFPs. In addition, assemblies with integral burnable absorbers (e.g., integral fuel burnable absorber and UO_2/Gd_2O_3 rods) are allowed in SFPs. Allowance of burnup credit for assemblies with burnable absorber rods or integral burnable absorbers is not recommended in the current guidance for dry storage and transport [6]. The U.S. NRC is sponsoring work to provide a basis for removing this restriction.

The second major distinction between the approach used in SFPs and that currently proposed for transport and dry storage is that the safety evaluation for SFPs typically uses fresh fuel with a reactivity determined to be equivalent to spent fuel at a specified burnup. Uncertainties are associated with this approach in terms of the effect on the neutron spectrum (and associated reactivity worth of the poison material) and the geometric conditions under which the equivalency may be valid. For example, the fresh fuel equivalent for SNF in unborated water will be different than that in borated water [12]. Other illustrations, perhaps extreme, of the uncertainties and concerns have been documented [13]. The finite geometry of a cask in comparison to the effectively infinite geometry of an SFP leads to significant differences in reactivity depending on the location of the assembly within the cask, thus making the reactivity equivalence approach inadequate for use in cask analysis. Instead, the criticality safety analyses for transport and dry storage are currently required to use SNF nuclides predicted using codes and data validated against measured isotopic information. Furthermore, the analysis methodologies for calculating k_{eff} must be validated for the specific nuclides that are credited.

The recommendations of ISG8 note that the axial and horizontal variation of burnup within an assembly merit special consideration be given to the spatial variation of the SNF nuclide inventory such that conservative estimates of k_{eff} are determined in the analysis. Modeling for SFP analyses typically assume uniform axial burnup (modeled as equivalent fresh fuel), and thus are required to determine and include a reactivity penalty associated with the axial burnup distribution [3]. This penalty is determined based on the comparison of a calculation with uniform axial burnup (using equivalent enrichment) and a calculation with axial distributed burnup (using equivalent enrichments for each axial zone). Unlike analyses for transport and dry storage, use of a bounding axial burnup distribution is not required. Further, there are currently no requirements related to horizontal burnup distributions for SFP burnup credit criticality safety assessments.

The third significant distinction between burnup credit applications in SFPs and transport and storage casks is that verification of assembly burnup through measurement is recommended prior to cask loading, but administrative confirmation procedures are acceptable for SFP storage. In both cases, the assembly burnup value used for comparison to the loading criteria is a percentage of the reactor record burnup value. Although variations among utilities are believed to exist, the assembly burnup value used for establishing acceptance for SFP storage is typically between 90 and 95% of the reactor record value. For transport and dry storage, the percentage of the reactor record burnup value will be determined based on comparisons to measurements that can be related to the burnup.

Industry would like to eliminate the regulatory requirement for pre-shipment measurements of each assembly for cask loading or reduce the burden by performing measurements within the SFP to obtain a statistical sampling that demonstrates the accuracy of the utilities administrative records relative to fuel exposure history. This can be a significant economic benefit to the industry, but its implementation must be done in a manner that does not compromise assurance of the characteristics of the fuel assemblies being loaded in a particular cask. The measurement methods and the various proposed methods for their implementation need to be further reviewed to support development of future regulatory guidance. Such regulatory expectations would include specification of proper measurement criteria needed to corroborate of reactor records. An industry report that discusses the variation in the way that utilities obtain and maintain their records on spent fuel burnup together with a discussion of the anticipated uncertainty in the reported burnup would be beneficial to development of loading curves that are independent of the reactor facility.

The three distinctions discussed above are meant to illustrate the disparity that can arise in the implementation of burnup credit even within a single country. A comparison between the regulatory guidance on burnup credit for SFPs and transport or storage casks is summarized in Table I. These differences can be attributed to the different approaches for demonstrating safety that have evolved within each application area prior to the introduction of burnup credit as an option. In the United States, the industry and regulatory components responsible for each application area have historically sought to develop the basis for burnup credit with little consideration towards developing a consistent and viable approach amenable to all areas. To date the only country that has approved transport casks for use with burnup credit has been France. Unlike the United States, the French have used virtually identical approaches for applying burnup credit in storage pools and in transport casks: the minimum burnup as averaged over any contiguous 50-cm segment of the fuel is applied as a uniform burnup over the entire fuel length, and only the uranium and plutonium isotopes are considered. The advantage of using the same technical approach for all applications (SFPs, transport, storage, etc.) is that it allows an effective interface of the safety evaluations between the application areas.

5. CHALLENGES TO IMPLEMENTATION

From the authors' perspective, the major challenge to the implementation of burnup credit for out-of-reactor applications is the added complexity required for the safety evaluation. Figure 1 provides a schematic that highlights the differences between criticality safety evaluations performed assuming burnup credit and those assuming the fresh fuel assumption. The safety analysis report (SAR) will become more complex, thus increasing the time required for thorough preparation and review. In addition, there is a need to establish technical specifications to ensure that loaded contents are consistent with the allowable contents analyzed in the SARs. Consequently, the technical specifications and operating procedures associated with cask loading will be more complicated. The SAR for a burnup credit cask must assure that the restrictions imposed for certifying the cask contents can be readily understood and implemented at any potential facility that has a license to handle SNF.

A number of technical issues with regard to burnup credit criticality assessments are not fully resolved, and thus, variations in submitted safety assessments, which will prolong the associated review time, should be expected. Notable among the technical issues for burnup credit implementation in transport and disposal are:

(1) selection of the appropriate reactor operating conditions that should be used in the safety analysis;
(2) selection, acquisition and use of measured data for code and data validation; and
(3) clear guidance on requirements and criteria for, or possibly elimination of, pre-shipment burnup measurements, to provide a minimum impact on loading operations.

TABLE I. COMPARISON OF REGULATORY REQUIREMENTS FOR PWR BURNUP CREDIT CRITICALITY SAFETY ASSESSMENTS IN POOL STORAGE, DRY CASK STORAGE, AND TRANSPORT

Issue	**Regulatory guidance**	
	Spent fuel pools[a]	**Transport and dry storage**[b]
Nuclides credited	All nuclides except ^{135}Xe, with depletion uncertainty equal to 5% of the reactivity decrement	Select actinides-only, with conservative biases applied to the concentrations
Modeling **B** fuel	Equivalent fresh fuel enrichments	Explicit isotopic content
Modeling **B** burnup distributions	Consideration of axial burnup distribution	Bounding consideration of axial and horizontal burnup distributions
Validation requirements	Criticality code validation with fresh fuel isotopics	Validation of criticality and depletion methodologies for the specific isotopics credited
Maximum allowable burnup	None specified	No credit for burnup beyond 40 GWd/MTU
Maximum allowable initial enrichment	5.0 wt % ^{235}U	4.0 wt % ^{235}U (5.0 wt % with offset penalty)
Fixed burnable Absorbers	Acceptable	Perhaps unclear from the text of ISG8, but intended to be not acceptable
Integral burnable Absorbers	Acceptable	Not acceptable
Requirement for Burnup Measurements	No	Yes
Cooling time	All cooling times allowed	5-year cooling time

[a]Guidance per Ref. 3.
[b]Guidance per Ref. 6.

Because the inclusion of burnup credit in the criticality safety assessment for casks is a new addition to industry and NRC procedures, diligence will be required in both the preparation and review process. Ready access to the technical information of import to burnup credit and computational tools that expedite the analyses should facilitate preparation and review of SARs. A goal of current research has been to develop sound technical guidance and criteria to be considered in preparation and review of the SARs and to ensure that adequate computational tools and data are readily available.

The operational background and historical bases for safety varies between the different application areas discussed in this paper. Burnup credit is a relatively new approach being used within these various application areas and it involves a number of diverse technical topics (e.g., reactor physics and operations, criticality safety principles and analysis methods, and experiment and measurement technology). A wealth of information exists on each of these technical topics, and the key to effective implementation is successful integration of the information to develop an adequate safety basis for the application of interest. As the various approaches used by different application areas to integrate the technical information become better understood, the effort required for preparation and review of SARs for burnup credit should decrease.

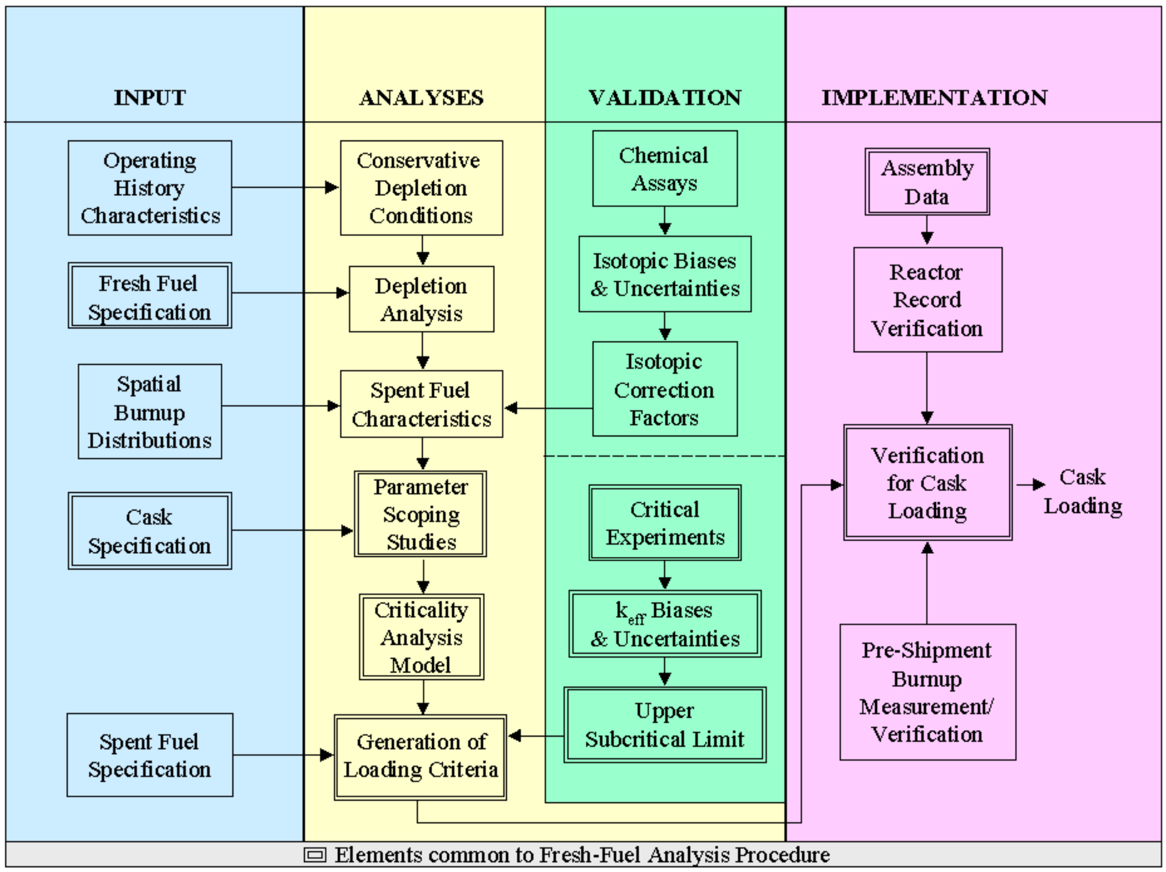

FIG. 1. Procedure for burnup credit criticality safety evaluation and implementation in transport and storage cask applications

ACKNOWLEDGEMENTS

The authors wish to acknowledge the U.S. NRC Office of Nuclear Regulatory Research for sponsoring the efforts necessary to develop this paper and participate in the IAEA Technical Committee Meeting on burnup credit. The authors are grateful to the continued support for D. D. Ebert, R. Y. Lee, and F. Eltawila of the NRC who are leading the NRC program of research on burnup credit.

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