The Use of Burnup Credit for Spent Fuel Cask Design

W.H. Lake

U.S. Department of Energy, Washington, DC, United States of America

INTRODUCTION

The U.S. Department of Energy's (DOE's) Office of Civilian Radioactive Waste Management (DOE/OCRWM) is in the process of developing a new generation of high capacity casks to transport spent fuel from existing commercial nuclear reactor facilities to future federal waste facilities. The DOE's role in the Federal Waste Management System (FWMS) is defined by U.S. Federal law in the 1982 Nuclear Waste Policy Act (NWPA) and its 1987 amendment (NWPAA). The NWPAA requires DOE to use spent fuel and high level radioactive waste casks certified by the U.S. Nuclear Regulatory Commission (USNRC).

Because of the high shipping rates anticipated, and since cooling times of spent fuel that will be shipped significantly exceed the design cooling times of existing casks, a decision was made to develop new higher capacity casks. The potential benefit of higher cask capacities, is fewer shipments. Fewer shipments result in health, safety, and cost benefits. In evaluating the needs of the cask development program a number of technical issues were identified that would further support improved cask capacities. Burnup credit is one of these technical issues (Sanders, et. al., 1987).

The DOE/OCRWM program is currently designing casks for fuel having up to 4.5% initial enrichment of U-235. It is expected that this enrichment level will be exceeded by new fuel designs. Since burnup credit accounts for actual reactivity of fuel, and higher initial enrichments are used to allow greater fuel burnup, discharged fuel is expected to have similar reactivity regardless of initial enrichment (e.g., high initial enrichment with high burnup is similar to low initial enrichment with low burnup). Burnup credit casks permit accommodation of higher initial enrichments without redesign and physical modification of the criticality control system.

The DOE/OCRWM program focuses its efforts on burnup credit on its use in spent fuel transport casks. However, the fundamental technical issues of burnup credit are addressed in a comprehensive manner, so that application of the information developed will be of use in other areas of the DOE/OCRWM program, such as spent fuel storage (Sanders, et. al., 1991).

Burnup credit is the practice of accounting for the reduced reactivity of spent fuel in evaluating criticality safety. In the U.S., the USNRC transportation regulations (USNRC, 10 CFR Part 71) require subcriticality of transport systems. These regulations do not elaborate on how subcriticality should be assured, nor do they prohibit the use of burnup credit for criticality safety. The USNRC transportation regulations are based on those of the International Atomic Energy Agency (IAEA); however, the IAEA regulations and their accompanying guidance (IAEA, 1985 and 1987) do address actual irradiation experience for irradiated fissile material in determining subcriticality.

The USNRC has, in the past, approved one cask which uses burnup credit. This cask, the Model NLI-6502 (NRC certificate of compliance no. 9103) is used to ship highly enriched research reactor fuel (USNRC, 1991). However, in the case of commercial light water reactor (LWR) spent fuel, the USNRC has established a long standing precedent of assuming that spent fuel is unburned or fresh for the purpose of evaluating criticality safety (i.e., the fresh fuel assumption).

Since burnup credit has not been considered in the U.S. for criticality safety analysis of spent LWR fuel casks, DOE/OCRWM has had to develop appropriate analysis methods, and technical data to supplement the information already being used for the fresh fuel assumption. Other technical areas being pursued by DOE/OCRWM are verification of analytic methods and verification of procedures to assure proper loading for casks using burnup credit.

THE DOE/OCRWM BURNUP CREDIT PROGRAM

Although the DOE/OCRWM's pursuit of burnup credit supports cask development activities, the basic technical issues related to burnup credit in cask design are recognized as generic issues that can be resolved independently of the cask development activities. Once the generic criticality safety issues associated with burnup credit are resolved the cask designers can incorporate those results into their specific cask designs. Furthermore, the generic criticality safety methodology developed for casks can be applied elsewhere (e.g., storage).

The DOE/OCRWM burnup credit activities are performed cooperatively by two separate groups. Resolution of generic technical issues for burnup credit is being developed by the Burnup Credit Task Group, lead by Sandia National Laboratories (SNL). The implementation of burnup credit for use in spent fuel cask design is the responsibility of the DOE/OCRWM cask contractors. The two OCRWM cask contractors planning to use burnup credit for criticality safety are General Atomics (GA) and Babcock & Wilcox (B&W). Both use burnup credit for their pressurized water reactor (PWR) spent fuel cask designs, neither for their boiling water reactor (BWR) spent fuel cask designs.

CRITICALITY AND CRITICALITY SAFETY

Criticality is the achievement of a self-sustaining nuclear chain reaction. The measure of criticality is the multiplication factor, k. The multiplication factor is the ratio of the rates of neutron production to neutron loss. When $k < 1$, we say the system is subcritical. Criticality is achieved when $k = 1$, and a system is said to be supercritical if $k > 1$. In theory we may consider an unbounded system of fissile material (i.e., infinite system), in which case k_∞ is used as the measure of criticality. In practice we are interested in real systems which are finite, in which case k_{eff} is used as the measure of criticality.

Nuclear reactors are designed to achieve criticality, and spent fuel is removed from a reactor when its reactivity is too low to effectively contribute to power generation. Spent fuel is eventually transported away from the reactor facility for disposal or reprocessing. The spent fuel is transported in casks which are designed to always be subcritical. Subcriticality is accomplished by using one or more of the following approaches: 1) limit the quantity of fissile material in the system, 2) remove thermal neutrons by using neutron absorbers (poisons), 3) control the population of thermal neutrons by moderator and/or reflector materials, and 4) control the geometry of the system. Although the spent fuel is no longer very effective for power generation it may still contains fissile material and is still somewhat reactive. Furthermore, under the worst case flooded conditions assumed in the regulations (USNRC, 10 CFR Part 71 and IAEA, 1985), and under transport conditions which are cooler than reactor conditions, the spent fuel would be more reactive.

To obtain approval for the use of a spent fuel cask a designer must demonstrate subcriticality of the spent fuel cask under the appropriate regulatory requirements. Criticality safety must be demonstrated for a single package assumed to contain and be surrounded by water (intended to bound moderation and reflection of neutrons). Criticality safety must also be demonstrated for arrays of casks in their most reactive credible condition following both normal and hypothetical accident damage conditions. The DOE/OCRWM casks are designed with dry containment cavities. For dry spent fuel casks which are water tight under normal and hypothetical accident conditions, leakage of water into the casks in an array is not assumed, and the single package which assumes a water flooded cask is most reactive. Furthermore, since water is necessary for criticality in a LWR system only the single package case can achieve criticality for dry cask systems. The analytic conditions described above are intended to represent the worst case conditions, and to assure criticality safety. In addition, it has become a customary practice in the U.S. to design transport casks to a 5% criticality safety margin (i.e., $k_{eff} \leq 0.95$). For OCRWM casks which will be used to transport spent fuel to a repository that will be licensed by NRC under its rules a cask $k_{eff} \leq 0.95$ is required by those regulations (USNRC, 10 CFR Part 60).

CASK DESIGN FOR CRITICALITY SAFETY

Casks are designed and used to specific limits of fissile content and internal configuration. For multi-assembly PWR casks, fuel baskets are used to limit neutron interaction between assemblies by controlling geometry and by the use of external (i.e., outside the fuel) poisons. Baskets may also use flux traps to control neutron interaction between adjacent fuel assemblies. A flux trap is a gap built into a basket which is activated when water floods a cask, forming a layer of water surrounded by neutron poisons within the basket. The flux trap configuration increases the effectiveness of the poisons.

Under the fresh fuel assumption for criticality safety analysis, the fissile content of the spent fuel is assumed to be the same as the unused levels, and fission products that may act as internal poisons are ignored. For casks designed using burnup credit for criticality safety, the reduced fissile content of the fuel is considered along with the internal poisons present in the burned fuel.

In theory, a designer could take full advantage of spent fuel burnup in demonstrating criticality safety, but as a practical matter DOE/OCRWM has chosen to use partial burnup credit along with external poisons for criticality control. That is, a minimum burnup is required for a specified initial enrichment, and loading in a burnup credit configuration is permitted for spent fuel exceeding the specified minimum burnup. Furthermore, the minimum burnups are conservatively determined by overestimating net fissile content, only accounting for the small fraction of fission product poisons that are significant neutron absorbers, and underestimating these fission products.

A substantial amount of data and experience exists for criticality safety in transportation for designs that use the fresh fuel assumption. This information provides a good basis for applying burnup credit, and is directly applicable to criticality safety design for burnup credit casks. However, the use of burnup credit introduces several new variables and issues that require additional information and resolution. These include: 1) spent fuel characteristics and criticality analysis methods, 2) effects of fuel in-core burnup history on average and local characteristics (e.g., axial variations in burnup or the so-called end effects), 3) assurance of loading burnup casks with fuel having sufficient burnup, and 4) uncertainties associated with the new variables.

Computer programs are available to predict isotopic inventories for spent fuel, and to model fuel/cask configurations and perform criticality safety analysis. However, using these programs may require additional benchmarking against experimental or field data. Chemical assay data is being generated by the DOE/OCRWM program to benchmark codes that predict the isotopic inventories of the spent fuel. The assay data is being developed to include all fissile elements, but only the important neutron absorbing fission products (i.e., poisons). Benchmarks for criticality analysis are being developed using reactor restart critical data. The data is being obtained from several sources including reactors that have had cold starts following extended shut-downs, conditions similar to those expected in spent fuel casks. Both sets of benchmark data will be combined to develop a set of benchmark problems that may be used for criticality safety analysis for burnup credit casks (Brady and Sanders, April 1992).

An unavoidable characteristic of spent fuel that is important to criticality safety is the axial distribution of burnup. Because of the neutron leakage at the ends of a reactor core fuel assemblies tend to be underburned at the ends. This is of no importance under the fresh fuel assumption, since all fuel is assumed to be unburned; however, it is an issue for spent fuel. For example, if the burnup of a spent fuel assembly is given as an average the ends will be burned less than the average, while the central region will be burned more than the average. This means that the criticality safety analysis must address the affects of these less than average burned ends (Marotta, 1989). The DOE/OCRWM program is addressing this issue, and has offered approaches to account for it in criticality safety design (Marotta, et. al., 1992)

The above two issues dealt with design and analysis of spent fuel casks. An important issue associated with the use of burnup credit casks is that of assuring sufficient burnup of fuel loaded into a cask. The DOE/OCRWM has identified loading of unburned fuel or underburned spent fuel as the most likely event that could lead to reducing the design criticality safety margins for spent fuel casks (Sanders, et. al., 1991). The approaches being considered to address this issue include using reactor fuel management practices already in place, and verification of loadings by measurement. The advantage of the first approach is that fuel management procedures are already in place and are covered by the USNRC through facility licenses (USNRC, 10 CFR Part 50). The second approach adds confidence to the loading process since the measurement is an independent check on fuel management practice; however, it introduces additional complication into the loading procedures.

The use of burnup credit in criticality safety analysis of spent fuel casks introduces new variables and uncertainties associated with those variables. These uncertainties have been identified and bounded early in the program, at the feasibility stage (Sanders, et. al., 1987). Approaches to obtaining the required data, resolving uncertainties, and assessing their importance were also developed (Sanders, 1989; Sanders and Lake, 1989; and Lake and Sanders, 1989). An independent effort to identify and bound technical issues and uncertainties associated with burnup credit has produced similar conclusions to those of DOE/OCRWM's (Carlson and Fischer, 1990). A general approach to quantifying and dealing with these uncertainties in design of a burnup credit cask has evolved (Sanders, et. al., 1991; Lake, et. al., 1992).

Figure 1 presents a graphical description of an approach to criticality safety design. The graph can provide a useful quantitative description of criticality safety design, including uncertainties, for a cask using either the fresh fuel assumption or burnup credit.

Curve A represents k_∞ for an infinite array (or perfectly reflected finite array) of spent fuel assemblies of specific design with a given geometry. The fuel is assumed to have various initial enrichments, no external criticality controls, and no burnup (i.e., fresh fuel assumption). Curve B represents the k_{eff} for essentially the same system, but of finite size. The difference in k between curves A and B is due to neutron leakage at the

system boundaries. For very large arrays the leakage is small, and for small arrays the leakage would be larger (e.g., a R/B cask vs. a LWT cask).

Curve C_o is the k_{eff} for an externally controlled version of the system represented by curve B (i.e., a specific cask and basket design). The external criticality controls may include poisons as well as flux traps which are part of the fuel basket. The values of k_{eff} represented by curves C_1 through C_5 correspond to the system represented by C_o, but with increasing burnup credit assumed, and corresponding reduced reactivity.

The design multiplication factor for our hypothetical burnup credit cask design, $k_{eff,D}$, is represented by curve C_o up to initial enrichment e_o, and curve D between e_o and e_m. The increasing $k_{eff,D}$ (up to e_o) is the fresh fuel portion of the criticality safety design curve. The decreasing portion between e_o and e_m is the burnup credit portion. If there were no uncertainties associated with burnup credit the burnup portion of the curve would coincide with a design multiplication factor $k_{eff,D} = 0.95$ throughout its range. The difference in k_{eff} between curve D and 0.95 represents the increase in uncertainty as more burnup credit is taken. Basically, for a cask designed using the fresh fuel assumption or burnup credit the peak k_{eff} occurs at the maximum enrichment under the fresh fuel assumption. Although uncertainties can be reduced for burnup credit, they can never be reduced to zero; furthermore, they tend to increase as burnup credit is increased.

A number of observations may be made at this point. If criticality safety is based on the fresh fuel assumption, the point corresponding to $k_{eff} \leq 0.95$ and initial enrichment e_o are known; therefore, burnup credit data may be obtained to develop a cask and fuel specific curve in the form of Figure 1. If criticality safety is already based on burnup credit, then any increase in initial enrichment could be accommodated by extending the burnup credit data of Figure 1 beyond initial enrichment e_m. In the example shown in Figure 1, only partial credit is taken for burnup. That is, the suppression of $k_{eff,o}$ from $k_{eff,B}$ is accomplished by using external poisons (e.g., flux traps or poison plates in the basket). Further suppression of the cask's k_{eff} is accomplished through increased reliance on burnup credit ($B_1 < ... < B_5$, and $k_{eff,1} > ... > k_{eff,5}$). A different fuel design and/or a different cask design would result in a different set of curves. However, a single bounding curve can be used for a given cask design if the most reactive fuel design(s) is(are) identified.

USE OF A BURNUP CREDIT CASK

Operation and use of a burnup credit cask is nearly the same as operation and use of a cask designed using the fresh fuel assumption. The difference is that for fuel falling into the region where criticality safety relies on burnup credit, the loading process must assure that the additional burnup conditions are met. For proper loading of a burnup credit cask we need to know the amount of burnup the fuel has undergone, its age, and initial enrichment. Of those, only the initial enrichment is needed for a fresh fuel cask loading. Figure 1 provides a design curve for a specific fuel type (with various initial enrichments) in a specific cask design along with specific age, initial enrichments, and burnups. The curve representing the cask design k_{eff} in Figure 1 can be used to develop the spent fuel loading curves shown in Figure 2. The family of loading curves, designated L_o, ... L_3, represent loading curves for different fuel types with different reactivities. Curve L_o represents the most reactive of those considered. Curve L_3 represents the least reactive.

Spent fuel with burnup and initial enrichment above and to the left of the curve representing (or bounding) its fuel type in Figure 2, may be loaded to full capacity. Spent fuel with initial enrichment less than the enrichment designated $e_{o,i}$ (where i = 1, 2, 3, or 4) for its fuel type is loaded as a fresh fuel array, and minimum burnup is not a concern. Spent fuel with burnup and initial enrichment below and to the right of the curve representing (or bounding) its fuel type requires additional measures to assure a $k_{eff} \leq 0.95$.

Assurance of proper loading of the DOE/OCRWM burnup credit casks will rely on utility fuel management data which will be verified by a measurement of each assembly to be loaded. The measurement method identified for use is an existing system which passively measures gross gammas and neutrons, and is easy to use (Ewing and Bierman, May 1992). The DOE/OCRWM plan is to use this approach initially while gathering statistical data to enable development of a more efficient loading verification procedure that would measure a portion of spent fuel being loaded as a check on the fuel management data.

CONCLUSIONS

Although LWR spent fuel casks using burnup credit have not been certified by the USNRC, the regulations do not prohibit such an action. Furthermore, the NRC has certified a cask for burnup credit under the condition of verification of the loaded cask by measurement. It is evident that the use of burnup credit as part of the criticality control for a spent fuel cask introduces new variables in evaluating criticality safety. It is also evident that for burnup credit casks, loading is somewhat more important for criticality safety than loading of a cask that is designed and used based on the fresh fuel assumption. For the loading of a fresh fuel cask, only initial enrichment needs to be considered to assure adequate criticality control margins. For a burnup credit cask, initial enrichment, age, and burnup must be considered.

The uncertainties associated with the introduction of burnup credit for criticality control of spent LWR fuel in transportation casks have been identified. These uncertainties are being addressed and quantified, and technical issues are being resolved in a manner that will assure adequate criticality safety margins for burnup credit cask designs. In addition, the use of utility fuel management practices coupled with verification measurements will assure proper loading of burnup credit casks. The DOE/OCRWM believes that a strong basis is being developed for USNRC's eventual approval of spent LWR fuel casks that use burnup credit as part of their criticality safety design.

REFERENCES

Brady, M.C., D. Napolitano, "Code Benchmarking," INMM Spent Fuel Seminar IX, Jan. 15-17, 1992, Washington, DC.

Carlson, R.W., and L.E. Fischer, July 1990, "Safety Implications of Burnup Effects in Criticality Safety Margins for Spent Pressurized Water Reactor Fuel Transport and Storage," UCRL-ID-104572, Lawrence Livermore National Laboratory, Livermore, CA.

Ewing, R., and S. Bierman, "Measurement Techniques for Verifying Burnup," Journal of Nuclear Materials Management, Vol XX, Number 3, May 1992.

International Atomic Energy Agency, "Regulations for the Safe Transport of Radioactive Material," Safety Series No. 6, Vienna, 1985.

International Atomic Energy Agency, "Advisory Material for the IAEA Regulations for the Safe Transport of Radioactive Material (1985 Edition)," Third Edition, Safety Series No. 37, Vienna, 1987.

Lake, W.H. and T.L. Sanders, "Evaluating Alternative Design Philosophies for Spent Fuel Transport Casks Using a Comparative Probabalistic Risk Assessment Approach," Proceedings, PSA '89 International Topical Meeting: Probability, Reliability, and Safety Assessment, Vol 2, April 1989.

Lake, W.H., J.R. Boshoven, and L.A. Hassler, "Strategies for Certifying a Burnup Credit Cask," Journal of Nuclear Materials Management, Vol XX, Number 3, May 1992.

Marotta, C.R., "Bounding Estimates of Criticality Effects of Unburned LWR Fuel Assembly Tips for Casks Assuming Burnup Credit," The 9th International Symposium on the Packaging and Transportation of Radioactive Materials, Washington, DC, 1989.

Marotta, C.R., M.C. Brady, D. Napolitano, "End Effects and Uncertainties," INMM Spent Fuel Seminar IX, Jan. 15-17, 1992, Washington, DC.

Sanders, T.L., R.M. Westfall, and R.H. Jones, 1987, "Feasibility and Incentives for the Consideration of Spent Fuel Operating Histories in the Criticality Analysis of Spent Fuel Shipping Casks," SAND87-0151, Sandia National Laboratories, Albuquerque, NM.

Sanders, T.L., Editor, 1989, "Proceedings of a Workshop on the Use of Burnup Credit in Spent Fuel Transport Casks," SAND89-0018, Sandia National Laboratories, Albuquerque, NM.

Sanders, T.L. and W.H. Lake, "Alternatives for Implementing Burnup Credit in the Design and Operation of Spent Fuel Transport Casks," The 9th International Symposium on the Packaging and Transportation of Radioactive Materials, Washington, DC, 1989.

Sanders, T.L., R.I. Ewing, and W.H. Lake, "Burnup Credit for Transportation and Storage," Journal of Nuclear Materials Management, Vol XIX, Number 2, May 1991.

U.S. Nuclear Regulatory Commission (USNRC), October 1991, "Directory of Certificates of Compliance for Radioactive Materials Packages," NUREG-0383, V2, Rev. 14.

USNRC, Code of Federal Regulations, Title 10, Parts 50, 60, and 71, Washington, DC.

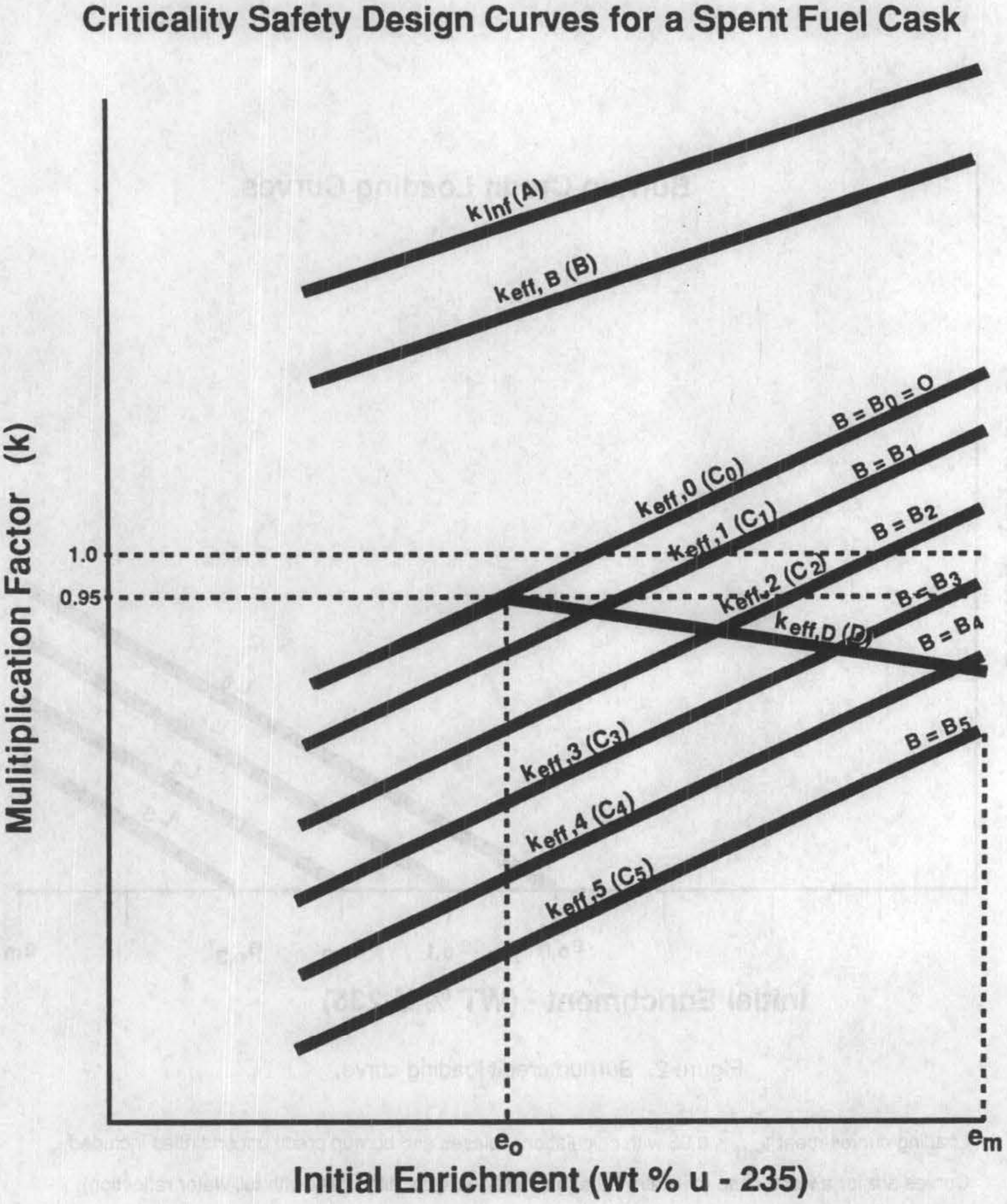

Figure 1. Criticality safety design curve.

Curves are for a worst case (criticality safety) condition (water filled cask with full water reflection).

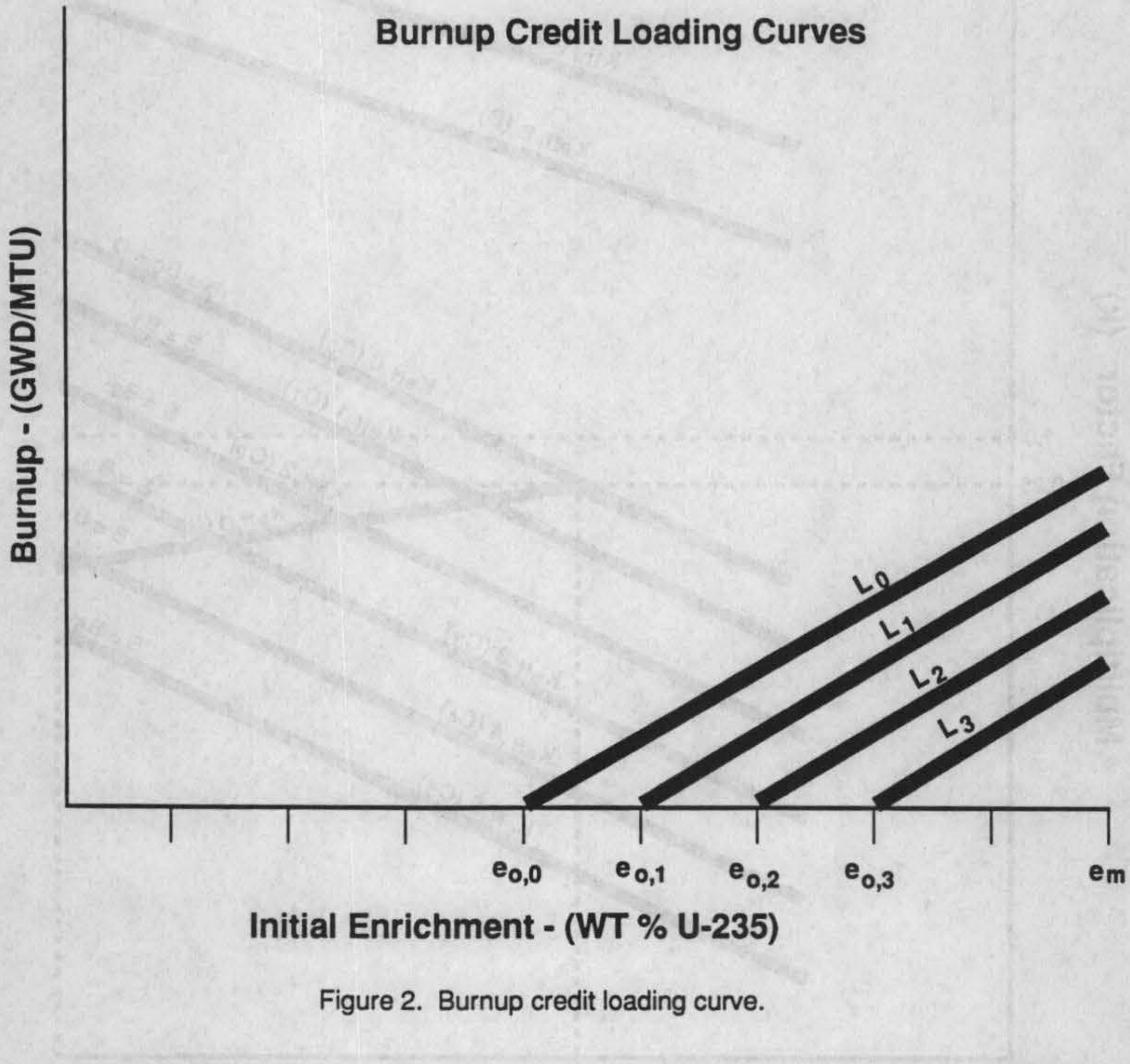

Figure 2. Burnup credit loading curve.

Loading curves meet $k_{eff} \le 0.95$ with calculational biases and burnup credit uncertainties included.

Curves are for a worst case (criticality safety) condition (water filled cask with full water reflection).