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Abstract. This paper presents an assessment of the benefits for extended burnup credit in transporting pressurized-water-reactor (PWR) spent nuclear fuel (SNF) in the United States. A prototypic 32-assembly cask and the current regulatory guidance were used as bases for this assessment. By comparing recently released PWR discharge data with actinide-only-based loading curves, this evaluation shows that additional negative reactivity (through either increased credit for fuel burnup or cask design/utilization modifications) is necessary to accommodate the majority of U.S. SNF assemblies in high-capacity storage and transportation casks. Given sufficient data for validation, the most significant component that would improve accuracy, and subsequently enhance the utilization of burnup credit, is the inclusion of fission products (i.e., extended burnup credit). A simple, conservative assessment of the cost benefits of extended burnup credit is also presented. Based on the estimated reduction in the number of shipments, achievable with extended burnup credit in the criticality safety evaluation, the cost savings for the U.S. Department of Energy (DOE) is estimated to be at least \$150M and is most likely in the \$200M–\$300M range. Evaluation of variations in the relevant input assumptions used to develop these estimates provides confidence that the actual cost savings may be much higher but are not likely to be lower.

1. Introduction

Historically, package designs for spent nuclear fuel (SNF) were constrained by weight, thermal loading, external dose, and structural integrity. With the reduced thermal load and dose provided by a minimum 5-year cooling time for transport of SNF, it became apparent in the 1980s that package capacity would often be limited by the conservative, yet simple fuel assumption of unirradiated fuel (i.e,. no burnup credit) used in criticality safety evaluations[1]. For pressurized-water reactor (PWR) SNF, burnup credit eliminates the need for the relatively wide basket structures (i.e., flux traps) used for separation and criticality control – thus providing an important degree of flexibility to package designers. For a typical rail-type transportation cask, elimination of the flux-traps between assembly storage cells enables an increase in cask capacity from ~24 to ~32 PWR assemblies. Hence, the potential benefit of using 32-assembly casks with burnup credit is a maximum reduction of ~25% in the number of required shipments. Note that due to the smaller cross-sectional area of some PWR assemblies (e.g., 14×14), assembly-specific canisters can be designed with capacities exceeding 32. However, for simplicity in this discussion, a value of 32 is used for the capacity of PWR burnup credit casks.

The use of higher-capacity packages enables a reduction in SNF packages, a reduction in package handling and loading operations, and fewer package shipments—resulting in a reduction in shipment and operational costs, personnel dose, public exposure, and accident risks [1]. After a decade of exploratory work and regulatory evolution, the U.S. Nuclear Regulatory Commission (NRC) issued Interim Staff Guidance 8 (ISG-8) in May 1999, providing the first allowance of burnup credit for PWR fuel. Subsequently, ISG-8 has undergone two revisions [2], which have eliminated or lessened a number of the restrictions. The initial issuance and subsequent revisions of ISG-8 have provided the impetus for industry to proceed with a new generation of high-capacity rail-type cask designs using burnup credit. However, ISG-8 recommends the burnup credit allowance be limited to that provided by the change in actinide composition. As shown in the following section, this restriction significantly

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limits the percentage of the available SNF inventory that can be loaded in a high-capacity cask. To accommodate the majority of the SNF in high-capacity rail casks, extended burnup credit is needed (i.e., credit for the fission product nuclides). This paper presents an assessment of the benefits, in terms of inventory accommodation and cost savings, of extended burnup credit (considering both actinide plus fission product compositions) for transportation of PWR SNF in the United States

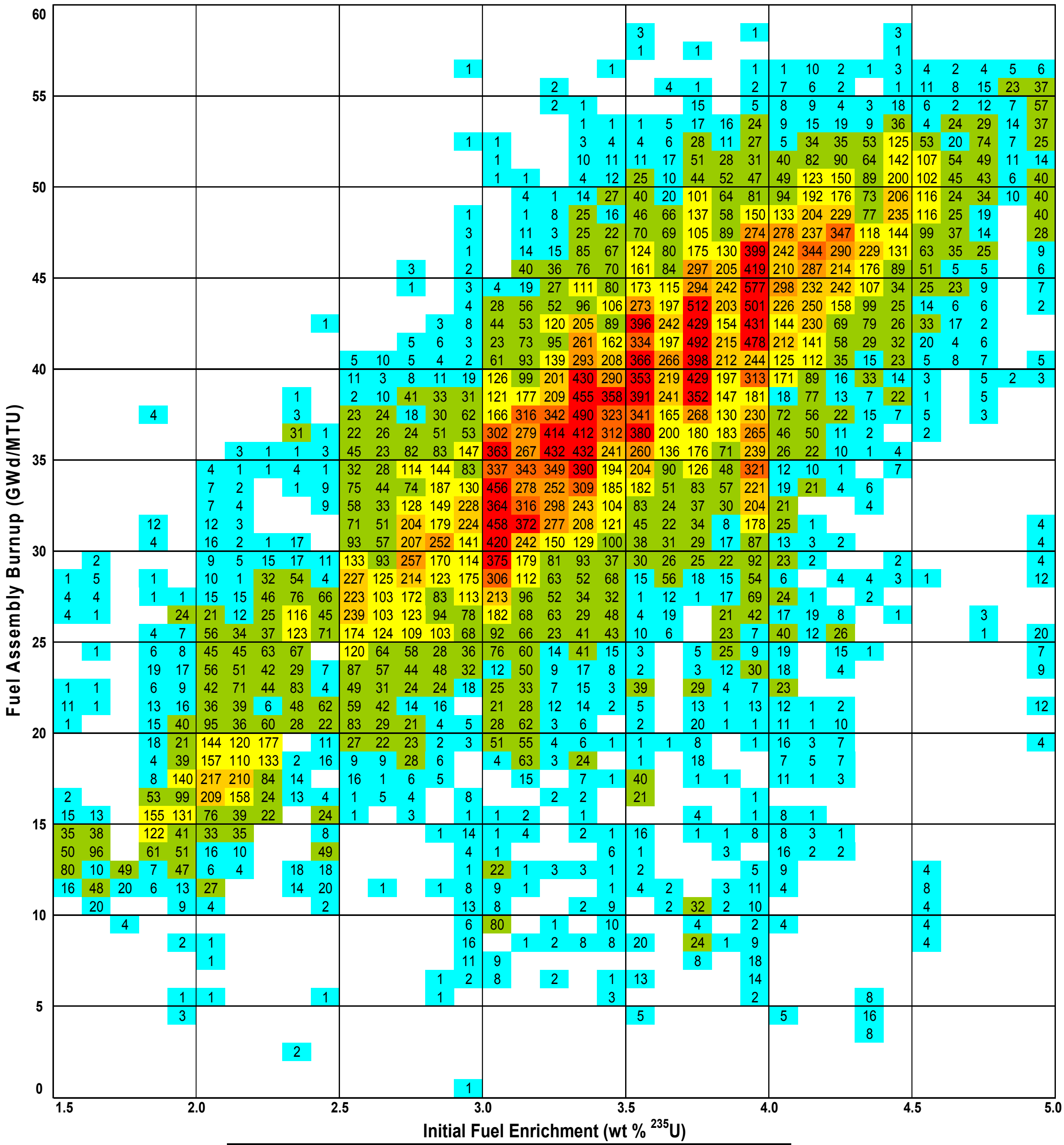
2. Inventory Accommodation for PWR SNF

During 2005, the DOE Energy Information Administration released a Microsoft Access™ data base with an updated version of the RW-859 compilation [3] submitted by U.S. commercial nuclear power plant licensees for PWR SNF through the end of 2002 (see Fig. 1). Six of the PWR fuel assembly types—WE 17 × 17, WE 15 × 15, WE 14 × 14, B&W 15 × 15, CE 16 × 16, and CE 14 × 14—comprise about 94% of the 70,290 PWR SNF assemblies in the data base. These six types of PWR assemblies were investigated to assess the benefits that would be provided by full burnup credit.

A review of the RW-859 (2002) data reveals that the average burnup of discharged PWR fuel assemblies has risen from around 20 GWd/MTU in 1975 to 45.7 GWd/MTU in 2002. This increase in assembly-average burnup represents a significant increase in the amount of criticality safety margin potentially available through burnup credit. Through 2002, 18.1% of the 70,290 discharged PWR fuel assemblies had burnups greater than 45 GWd/MTU. The average initial ^{235}U enrichment of discharged PWR assemblies has risen from about 2.7 wt % in 1975 to 4.2 wt % in 2002. This trend of increasing initial enrichment has made the fresh fuel assumption typically used in criticality safety analyses a more restrictive approach for cask design.

A generic high-capacity (32-assembly) cask, designated GBC-32, was selected as the reference configuration [4] to assess the benefits of full burnup credit for the RW-859 inventory. The GBC-32 cask is representative of burnup-credit rail casks currently being considered by U.S. industry and is therefore a relevant and appropriate configuration for this evaluation. The loading curves (required burnup and initial enrichment combinations) are generated with the STARBUCS sequence of the SCALE code system [5]. The basic assumptions (reactor operating conditions, bias and uncertainty process, axial profiles, etc.) can be found in Ref. [6].

Loading curves, consistent with the regulatory guidance of Ref. [2], are provided in Figs. 2 and 3 for two of the six assembly types. The acceptability of the SNF assemblies for each fuel type is summarized in Table I. Consistent with the regulatory guidance, assemblies that require burnup >50 GWd/MTU are classified as unacceptable. Also, the determination of acceptability does not account for burnup uncertainty, which would reduce the percentage of acceptable assemblies. The results indicate that while burnup credit can enable loading a large percentage of the CE 14 × 14 and WE 14 × 14 assemblies in a high-capacity cask, its effectiveness under the current regulatory guidance is minimal for the other assembly designs considered.



Number of Assy in Group			Total Assy	% of All	Cum. Assy
0	to	20	3,385	4.8	70,128
21	to	100	14,937	21.3	66,743
101	to	200	15,082	21.5	51,806
201	to	250	10,891	15.5	36,724
251	to	300	6,354	9.1	25,833
301	to	350	5,555	7.9	19,479
351	to	577	13,924	19.9	13,924

FIG. 1. PWR spent fuel inventory from RW-859 (2002) nuclear data files.

Table I. Summary of SNF acceptability in the GBC-32 cask with actinide-only burnup credit for the six most prevalent assembly types

Assembly type	Total in discharge data	Number acceptable for loading	Number unacceptable for loading
CE 14 × 14	6,972	4,518 (65%)	2,454 (35%)
CE 16 × 16	6,828	1,731 (25%)	5,097 (75%)
B&W 15 × 15	7,519	166 (2%)	7,353 (98%)
WE 17 × 17	28,704	2,448 (9%)	26,256 (91%)
WE 15 × 15	10,365	475 (5%)	9,890 (95%)
WE 14 × 14	5,448	4,686 (86%)	762 (14%)
Total	65,836	14,024 (21%)	51,812 (79%)

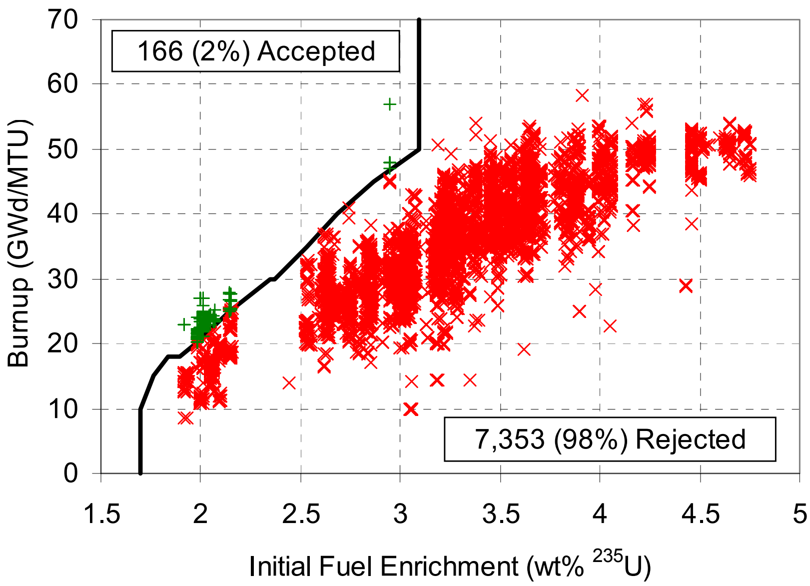


FIG. 2. B&W 15 × 15 inventory shown with ISG-8 burnup credit limit curve.

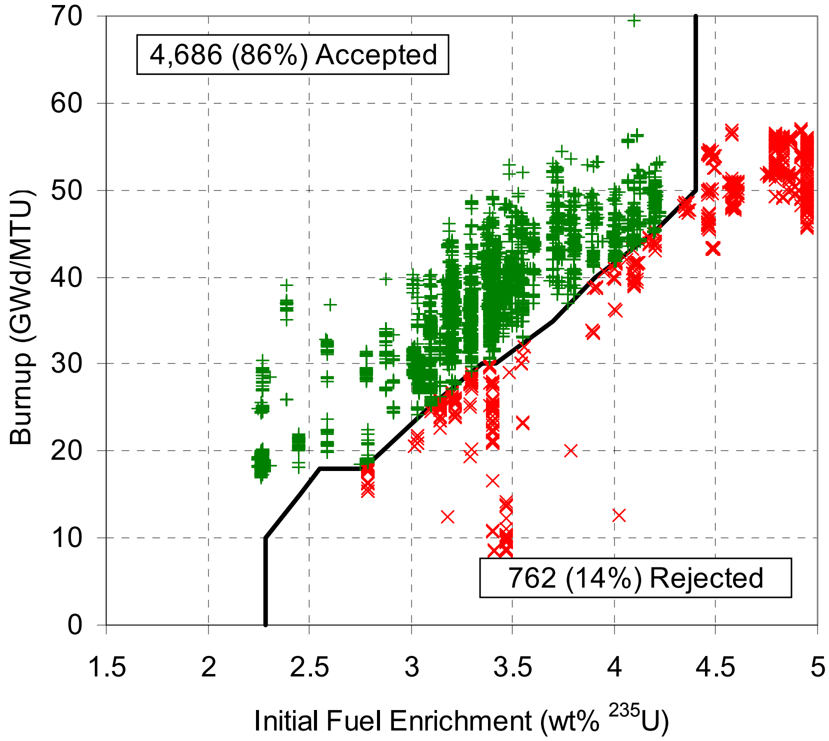


FIG. 3. WE 14 × 14 inventory shown with ISG-8 burnup credit limit curve.

To evaluate the effect of selected calculational assumptions, Fig. 4 compares the reference case loading curve for the WE 17 × 17 assembly with loading curves for the following individual variations:

1. Inclusion of minor actinides (^{236}U, ^{237}Np, ^{243}Am) and five of the principal six fission products (^{149}Sm, ^{143}Nd, ^{151}Sm, ^{133}Cs, and ^{155}Gd), with isotopic correction factors [7] based on comparisons with available assay data. (The fission product ^{103}Rh is excluded due to insufficient measured assay data.)
2. Inclusion of minor actinides and five principal fission products with spent fuel composition bias and uncertainty based on a best-estimate approach [7] for bounding isotopic validation.
3. Inclusion of the principal fission products (^{95}Mo, ^{99}Tc, ^{101}Ru, ^{103}Rh, ^{109}Ag, ^{133}Cs, ^{147}Sm, ^{149}Sm, ^{150}Sm, ^{151}Sm, ^{152}Sm, ^{143}Nd, ^{145}Nd, ^{151}Eu, ^{153}Eu, ^{155}Gd) and minor actinides (^{236}U, ^{237}Np, ^{243}Am), with spent fuel composition bias and uncertainty based on a best-estimate approach for bounding isotopic validation.
4. Inclusion of the principal fission products and minor actinides without any correction for isotopic validation.

Note that for a few of the relevant fission products (e.g., ^{103}Rh), insufficient measured assay data are available to estimate bias and uncertainty. Thus, with the exception of the final case, no credit was taken for their presence in the SNF.

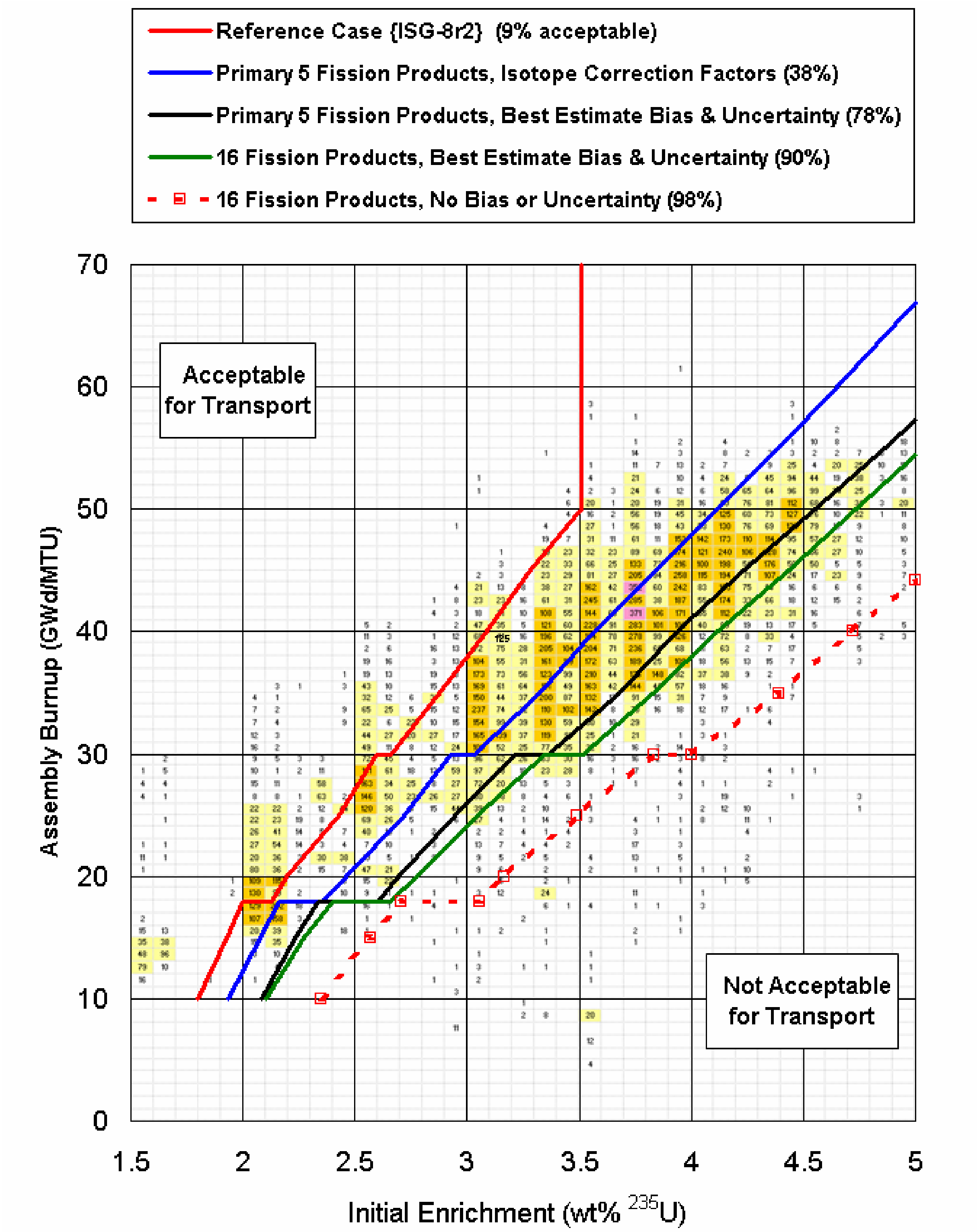


FIG. 4. Comparison of calculational assumptions for WE 17 × 17 fuel assemblies. Percentages of inventory acceptable for the GBC-32 cask are shown in parentheses.

All of the curves in Fig. 4 were prepared assuming a 5-year cooling time. Extending the cooling time up to 20 years makes only a marginal increase in the allowed inventory [6]. A more effective approach is shown in Fig. 4 where inclusion of fission products and/or the use of more realistic approaches to isotopic validation offers significantly larger increases in allowed inventory. For the GBC-32 cask, the percentage of acceptable assemblies increases from 9 to 38% with the inclusion of the primary five fission products and minor actinides (both cases at 5-year cooling), and from 38 to 78% with the use of a bounding best-estimate approach for isotopic validation [7]. The next case includes the remainder of the principle fission products and uses the best-estimate isotopic validation approach. These assumptions allow the percentage of acceptable assemblies to increase to 90%. The final case shown in Fig. 4 corresponds to full credit for the calculated actinide and principal fission product compositions and, given the conditions considered, represents an unattainable limit in terms of the potentially available negative reactivity. For all the cases with fission products included, no explicit consideration of reactivity bias and uncertainty from comparison with critical experiments is included. However, the loading curves are all based on an upper subcritical limit of 0.94 (as opposed to 0.95), which inherently allows 1% Δk for criticality calculational bias and uncertainty.

Comparison of actinide-only-based loading curves for the GBC-32 cask with PWR SNF discharge data (through the end of 2002) leads to the conclusion that additional negative reactivity (through either increased credit for fuel burnup or cask design/utilization modifications) is necessary to accommodate the majority of PWR SNF assemblies in high-capacity casks. The loading curves presented in this paper are such that a notable portion of the SNF inventory would be unacceptable for loading because the burnup value is too low for the initial enrichment. Relatively small shifts in a cask loading curve, which increase or decrease the minimum required burnup for a given enrichment, can have a significant impact on the number of SNF assemblies that are acceptable for loading. Thus, as the uncertainties and corresponding conservatisms in burnup credit analyses are better understood and reduced, the population of SNF acceptable for loading in high-capacity casks will increase. Given appropriate data for validation, the most significant component that would improve accuracy, and subsequently enhance the utilization of burnup credit, is the inclusion of fission products.

3. Cost benefits for PWR SNF transportation

An initial economic analysis of burnup credit for transportation was prepared for the U.S. Department of Energy (DOE) Office of Civilian Radioactive Waste Management (OCRWM) in 1988 and used a life cycle cost model to estimate a potential savings up to $900M [8]. Since that time, a portion of this predicted savings has become obtainable via the actinide-only credit allowed by ISG-8. Under this project, a relatively simple, but more current, cost analysis of the potential benefits of burnup credit was initially completed in 2003. The analysis used the current capacity limit for the Yucca Mountain repository [70,000 metric tons of heavy metal (MTHM)], the percentage of total MTHM from PWRs at the end of 1998 (~64%), and the average number of PWR assemblies per MTHM to predict that ~100,000 PWR assemblies will need to be transported to the repository. Using representative loading curves and assuming assemblies that cannot be accommodated in a 32-assembly cask are transported in a 24-assembly cask, it was estimated that full burnup credit can reduce the number of shipments by ~22% (~940 shipments), while actinide-only-based burnup credit reduces the number of shipments by only ~8% (~315 shipments); a difference of ~625 shipments attributable to credit for fission products in the burnup-credit criticality safety evaluation (see Fig. 5).

A survey of U.S. industry experts suggested an estimated cost per rail cask shipment (freight and operational costs) ranging from $200K to $500K. Although the majority of the experienced opinions supported the $500K/shipment value, a conservative estimate of $250K was adopted. The operational and manufacturing costs will be essentially equivalent between the lower-capacity (24-assembly) and higher-capacity (32-assembly) casks. Consequently, the cost savings associated with burnup credit will be dominated by the reduction in the number of shipments and the cost per shipment. Using the above cost-per-shipment estimate [assuming shipments are reduced by 625 (940 - 315)] provides a resulting costs savings of at least $156M that can be realized from establishing full burnup credit for SNF transportation. This situation is shown graphically in Fig. 6. Note that the cost-savings estimate

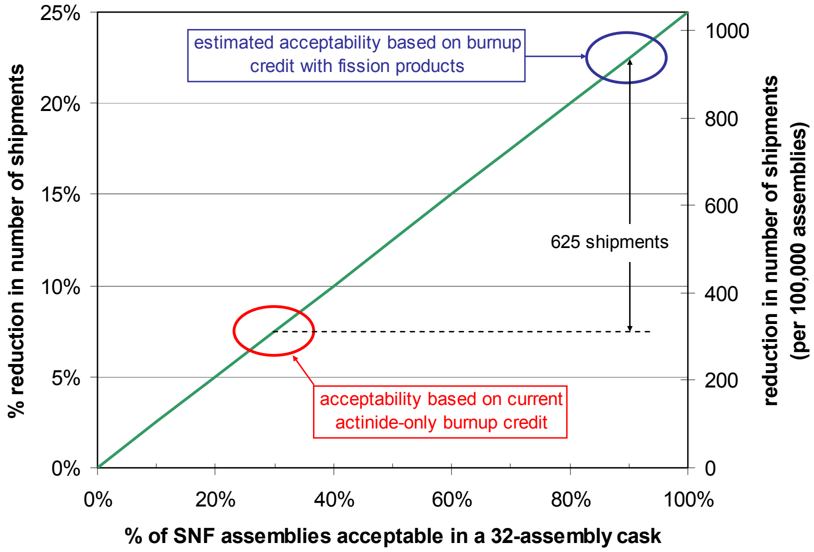


FIG. 5. Graphical representation of the potential reduction in the number of SNF shipments associated with the use of 32-assembly casks, as opposed to the use of 24-assembly casks. (Note that 100,000 assemblies in 24-assembly casks require 4,167 shipments.)

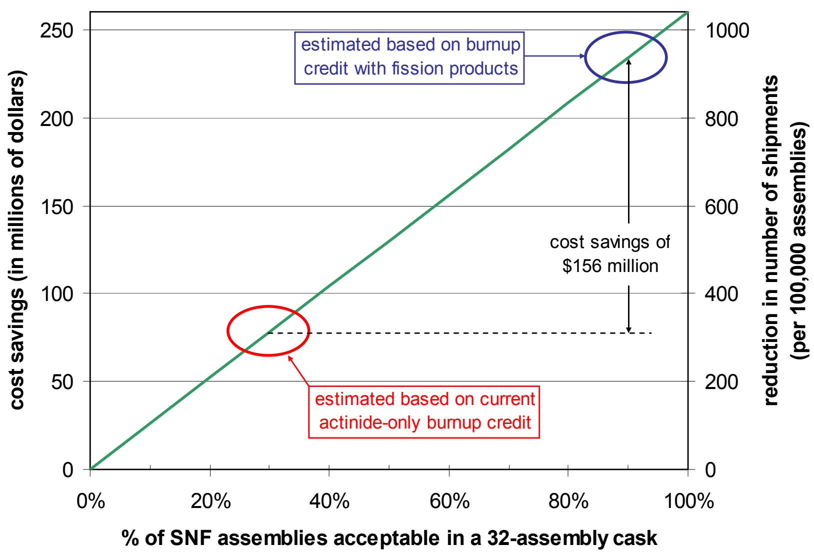


FIG. 6. Graphical representation of the potential cost savings associated with the use of 32-assembly casks, as opposed to the use of 24-assembly casks, assuming a cost of $250K per cask shipment. (Note that the cost savings scale linearly with the cost per shipment.)

scales linearly with the cost per shipment and does not include the difficult-to-quantify, but significant, cost savings associated with the reduction in SNF packages required and the reduction in personnel dose, public exposure, and handling and transportation accident risks.

A significant simplifying assumption used in the above cost analysis is that all assemblies would be loaded and transported in large (i.e., 100 to 125-ton) rail-type casks. In 2005, the cost estimate was updated to remove the simplifying assumption and investigate the impact of using a cask fleet of varying sizes. Discharge data as a function of site capabilities were first obtained (see Table II). For the various cask sizes that could be used, estimates were developed for (1) cost per cask shipment, (2) cask design capacities with and without burnup credit, and (3) fraction of assemblies acceptable for loading with and without burnup credit. These estimates are listed in Table III. Using the discharge data from Table II and the analysis assumptions listed in Table III, the cost savings associated with burnup credit for transportation are estimated (see Table IV) to be ~$638M. Of this total, ~$235M is attributable to credit for fission products. These estimates are consistent with the previous analysis and demonstrate the significant potential cost savings associated with establishing burnup credit that includes credit for the primary fission product compositions. The results are based solely on cost savings associated with the reduction in the number of shipments for PWR SNF; cost savings associated with reduced personnel dose, public exposure, and accident risks are not included.

Limited sensitivity analyses were performed to evaluate the sensitivity of the cost savings estimates to variations in the input assumptions listed in Tables II and III. In general, it was found that increased use of smaller casks will increase the cost savings. This trend is shown in the last column of Table IV, which lists savings due to fission product burnup credit on a per-assembly basis. This savings is due to the increased shipment cost on a per-assembly basis associated with the use of smaller casks. Assuming all 113,109 assemblies are transported in any one of the various cask sizes yields a range of $177M–$424M in estimated cost savings attributable to fission product burnup credit, with the lowest number corresponding to the use of all large rail-type casks and the highest number corresponding to the use of all truck casks. Note that the assumptions listed in Table III account for the fact that the increase in the fraction of acceptable assemblies due to fission product burnup credit is much less for smaller casks.

Although this most recent analysis does not specifically address decay heat constraints that could require a reduction in capacity for the large rail-type casks (e.g., if utilities opt to transport hottest fuel first), it does show that the use of smaller casks (e.g., to transport SNF with high decay heat) results in greater cost savings when burnup credit is applied. Also, there is a considerable portion of the discharged SNF inventory that will not present challenges in terms of decay heat, and the ability to use full burnup credit will provide a significant degree of flexibility to the vendors and utilities seeking to optimize their cask loadings.

Table II. Number of projected discharged SNF assemblies as a function of site capability

Cask size code[a]	Site handling cask weight (tons)	Number of assemblies[b]
LWT	LWT ≤ 25	3,234
OWT	25 < OWT ≤ 35	4,734
RC1	40 < RC1 ≤ 75	8,443
RC2	75 < RC2 ≤ 100	52,333
RC3	100 < RC3 ≤ 125	36,426
RC4	125 < RC4	7,939
	Total	113,109

[a] LWT = Legal Weight Truck, OWT = Over Weight Truck, RC1 = Rail Cask 1.
[b] Data correspond to the number of assemblies discharged through 12/31/1998 plus those projected to be discharged through 12/31/2015 (_Source_: RW-859).

Table III. Analysis assumptions for the various cask sizes

Cask size (tons)	Cost per shipment ($K)[a]	Design capacity (number of assemblies)[b]		Fraction of assemblies acceptable for loading[c]		
		w/o BUC	w/BUC	w/o BUC	w/AO[d] BUC	w/AFP[e] BUC
LWT ≤ 25	150	2	4	1	0.9	1
25 < OWT ≤ 35	200	4	6	1	0.8	1
40 < RC1 ≤ 75	200	7	10	1	0.7	1
75 < RC2 ≤ 100	200	12	18	1	0.5	0.9
100 < RC3 ≤ 125	250	24	32	1	0.3	0.9
125 < RC4	250	24	32	1	0.3	0.9

[a] Values are intended to include freight, operational, and security costs and are based on a review of industry experts/experience and information generated during the process of evaluating the use of dedicated trains. The latter source suggested a cost of ~$200K per cask shipment for freight and security only; no estimate of operational cost was available.

[b] Values developed based on a review of published and unpublished information, as well as consultation with industry experts.

[c] Values based on specific analyses, published results, and analytical experience.

[d] "AO BUC" refers to burnup credit that only accounts for the principal actinide compositions, consistent with current regulatory guidance (ISG-8).

[e] "AFP BUC" refers to burnup credit that includes the actinide and principal fission product compositions. This is also referred to as "full" burnup credit, which is not permitted under current regulatory guidance (ISG-8).

Table IV. Summary of cost savings

Cask size code	Number of assemblies	Number of shipments			Cost savings ($K)		Additional savings due to FP BUC ($K)	
		w/o BUC	w/AO BUC	w/AFP BUC	w/AO BUC	w/AFP BUC	Total	Per assembly
LWT	3,234	1,617	889	809	109,200	121,200	12,000	3.71
OWT	4,734	1,184	868	789	63,200	79,000	15,800	3.34
RC1	8,443	1,206	953	844	50,600	72,400	21,800	2.58
RC2	52,333	4,361	3,634	3,053	145,400	261,600	116,200	2.22
RC3	36,426	1,518	1,404	1,176	28,500	85,500	57,000	1.56
RC4	7,939	331	306	256	6,250	18,750	12,500	1.57
Totals	**113,109**	**10,217**	**8,054**	**6,927**	**403,150**	**638,450**	**235,300**	

4. Conclusions

Comparisons of recently released U.S. PWR discharge data with actinide-only-based loading curves, shows that additional negative reactivity (through either increased credit for fuel burnup or cask design/utilization modifications) is necessary to accommodate the majority of SNF assemblies in high-capacity storage and transportation casks. The impact of varying selected calculational assumptions was investigated, and considerable benefits in terms of inventory accommodation were shown to be possible with extended burnup credit (i.e., credit for the principal fission products). A simple, conservative assessment of the cost savings benefits for extended burnup credit in transporting PWR SNF in the United States was also presented. This assessment indicates that the estimated cost savings is greater than $150M and is most likely in the $200M–$300M range. Evaluation of the variations in the relevant input assumptions used to develop these estimates provides confidence that the actual cost savings may be much higher but are not likely to be lower. This estimate of cost savings does not include cost savings associated with the reduction in personnel dose, public exposure, and handling and transportation accident risks.

5. References

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