METHODOLOGY FOR THE PROJECTION OF SPENT NUCLEAR FUEL DISCHARGES

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ABSTRACT

This paper describes the method that has been developed by the Department of Energy's Office of Civilian Radioactive Waste Management for the projection of future utility spent nuclear fuel discharges in regard to their timing, quantities, and characteristics. The projected discharges are appended to the historic discharges and the next five discharges projected by the utilities in the Energy Information Agency's periodic RW-859 survey. The projections extend these data through the projected lifetime of each nuclear generation plant. The resulting projections of the timing, quantities, and characteristics of spent nuclear fuel discharges are used by the designers of storage and transport casks, the repository and its waste packages. This paper describes the primary assumptions that are made, outlines the principal steps in the projection methodology, and summarizes the results of a recent projection.

INTRODUCTION

The designers of equipment and facilities for the storage, transport and disposal of spent nuclear fuel (SNF) need to know the spectrum of quantities and type, and the thermal and radiological characteristics of the SNF assemblies that will be delivered to the Department of Energy (DOE) for repository disposal. The SNF characteristics at the time of delivery depend upon two factors: (i) the characteristics of the fuel as discharged; and (ii) the selection by the utilities, of specific fuel assemblies from the inventory of previously discharged SNF, at the time of delivery to DOE. In addition to the fuel type, the most important characteristic of a SNF assembly at discharge is its average burnup in Megawatt days per metric ton of uranium (MWd/MTU). The most important SNF characteristic resulting from the utility selection process is the age (cooling time) since its discharge from the reactor, at the time of delivery to DOE. Most of the thermal and radiological characteristics of SNF needed by designers can be determined from the age and burnup, and to some extent from the initial U-235 enrichment of the SNF. This paper describes the methods and assumptions that are used to project the quantities, timing, burnup and initial enrichments of the SNF as discharged. As indicated in Figure 1, the results of this discharge projection (shaded box) are necessary inputs to the process of projecting the selection of specific SNF at the time of delivery. The latter is a separate process and is not discussed further in this paper.

The most important factors underlying the projection of future discharges can be understood via the simple energy balance linkage between those important factors. Specifically, the SNF discharge Quantity in MTU and the Average Burnup of the SNF in MWd/MTU are directly related to the total thermal Nuclear Energy Generation in thermal MWd by:

$$\text{Quantity (MTU)} = \frac{\text{Nuclear Energy Generation (MWd)}}{\text{Average Burnup (MWd/MTU)}} \qquad \text{(Eq 1)}$$

The foregoing indicates that the projected discharge quantities are directly determined (i.e., calculated) as a consequence of assumptions as to the projected total future nuclear energy generation expressed in thermal terms and the projected average burnup of discharged SNF. Because both of these parameters are determined totally by utility future operational decisions and nuclear fuel purchase decisions, assumptions are required as to the nature of those future utility decisions. The remainder of this paper describes, first, the basis for the primary assumptions that are made as to nuclear energy generation and average discharge burnups, and the related usage of historical data and trends. Next, the principal steps in the projection methodology are summarized. The paper concludes with a discussion of the limitations and uncertainties of the projections, and the results of a recent projection.

ASSUMPTIONS REGARDING TOTAL NUCLEAR ENERGY GENERATION

The overall assumption as to total future nuclear energy generation is a consequence of two subsidiary assumptions: the future average capacity factor of operating reactors; and the end-of-life shutdown date of each reactor. DOE's Energy Information Agency (EIA) makes regular projections of energy usage, currently through the year 2020, including nuclear-electric energy generation. These projections include a systematic analysis and evaluation of economic competition among alternative energy sources and reflect the historic and most recent energy costs, usage and trends. The most recent EIA projections for nuclear-electric generation are therefore adopted and used as the principal basis for total nuclear-electric generation. With specific regard to average capacity factors, the projection methodology uses annual average capacity factors developed from the most recent EIA 20-year forecasts of nuclear-electric generation. The average capacity factor for the last year of the EIA projection is assumed to extend for the remainder of the projection period. For the end-of-life reactor shutdown dates, the Nuclear Regulatory Commission (NRC) operating license termination dates are used, in general. However, the recent awarding of 20-year NRC operating life extensions (to the typical 40-year original license) for several plants, and the prospect of additional 20-year extensions, now requires that an important additional assumption be made: the total number of reactors that will receive such extensions and operate for the full extended-license period. For the current base-case projection, the EIA's current assumption that a little less than half of the reactors will receive license extensions is being used (EIA 2001). However, sensitivity cases are also run with higher and lower assumptions for this important new variable.

ASSUMPTIONS REGARDING AVERAGE DISCHARGE BURNUPS

The projection of the timing and level of future discharge burnups involves one of the most important sets of assumptions that is made for a discharge projection. The burnup assumptions directly affect the projected thermal and radiological characteristics of the SNF and thus impact projected storage cask, transport cask and waste package loadings, and ultimately the scheduling and logistics of repository operation and emplacement. For this reason, particular attention has been given to the factors and assumptions underlying the projection of future burnups. In that regard, a number of key factors need to be considered, as follows:

1. There is a well-established historic trend of increasing average SNF discharge burnups, at a recent rate of more than 2 percent/yr. The annual averages of utility projections for their next five discharges continue to show increasing burnups.

2. Because of the continued importance to all nuclear utilities, of continued increases in burnup, the Electric Power Research Institute (EPRI) has established the Robust Fuel Project. This Project has established demonstration targets that support average discharge burnups of 57,000 MWd/MTU for boiling water reactors (BWR) and 62,000 MWd/MTU for pressurized water reactors (PWR). Achievement of these batch-average burnups requires the demonstration of maximum assembly-average burnups of about 71,000 MWd/MTU and maximum rod-average burnups of 75,000 MWd /MTU. Attainment of these batch-average burnups relative to current average burnups in the range of 40,000 MWd/MTU would result in fuel cost savings in the range of 0.15 to 0.3 mills/kWhe, equivalent to $1 to 2 million/yr savings for a 1000 megawatt-electrical (MWe) plant. Under ongoing electric utility deregulation practices, these savings would accrue directly to utilities, giving utilities significant direct incentives to continue to increase discharge burnups at a rate consistent with demonstrating continuing fuel integrity.

3. There is a current limit on attainable burnup, imposed by the current 5 percent maximum enrichment in the NRC licenses for nuclear fuel fabrication plants. The EPRI target burnups are generally compatible with the PWR and BWR burnups attainable with the current 5 percent enrichment limit. Because of the compatibility with enrichment limits and the utility financial incentives to increase burnups, the ultimate attainment of EPRI target burnups appears to be a reasonable assumption for the projection of future discharge burnups. A 1 percent annual increase in average burnups would result in the initial discharges of EPRI target burnups in about 2015, providing considerable time for demonstration of operationally acceptable fuel clad integrity. The 1 percent/yr rate is less than both the historic and the most-recent utility-projected increase rates. However, this appears appropriate in view of the progressive decrease in economic incentive as burnups increase.

4. An increase in the maximum licensed enrichment to 5.5 percent would permit an increase in discharge burnups of 6,000 to 10,000 MWd/MTU, and additional fuel cost savings in the range of $0.3 to $1.0 M/yr for a 1000 MWe plant, under current economic conditions. Such an incentive is probably sufficient to interest at least some utilities, so that there is a possibility that burnups could ultimately go above the current EPRI targets. However, given the relatively long time for getting to, and then beyond the EPRI target burnups, the related technical uncertainties, and the possibility of adverse cost changes that reduce or eliminate the apparent current incentives, it does not appear prudent to project average discharge burnups above the EPRI target burnup levels at this time.

5. The burnups that can be achieved at the 5.5 percent enrichment limit result in fuel costs that are within roughly 1 percent of minimum possible fuel costs under current economic conditions, and could be at or above future minimum fuel costs. The rapidly diminishing incentives and the increased enrichments needed to go to even higher burnups probably mean that the practical upper limit on burnup is the burnup achievable at 5.5 percent enrichment.

6. Burnup assumptions are also of near-term interest for the design of shielding in permanent repository facilities. The maximum assembly-average burnup that is currently projected is 71,000 MWd/MTU, with maximum rod-average burnups of 75,000 MWd /MTU. These values are consistent with the EPRI batch-average PWR target burnup of 62,000 MWd/MTU. Thus, a suitable design-basis maximum assembly burnup for repository facilities would be in the range

> of 71,000 to 75,000 MWd/MTU, with the current 5.0 percent enrichment limit. However, an additional 6,000 to 10,000 MWd/MTU could be achieved in the future, if the enrichment limit were to be raised to 5.5 percent. Because the incremental cost of additional shielding is quite small if included in the original construction, it would be prudent for the current designers of fixed facilities to consider using 80,000 to 85,000 MWD/MTU as the design-basis maximum assembly-average burnup, for the near-term design of fixed repository facilities.

In conclusion, the current fuel fabrication plant license limit of 5 percent enrichment, the related target burnups of the EPRI Robust Fuel Project, and the assumed gradual (1 percent/year) approach to those target burnups appear to provide a reasonable basis for the projection of future spent fuel discharge burnups. Unless and until the 5 percent enrichment limit is increased, it is reasonable to expect only relatively few "outlier" assemblies with burnups above the EPRI maximum assembly-average discharge burnup targets. Only after fuel fabricators re-license their plants for enrichments above 5 percent, and utilities begin higher-burnup demonstration programs, would it be reasonable to begin projecting meaningful quantities of SNF with burnups above the current EPRI target levels. The practical upper limit on burnup is probably the burnup achievable at 5.5 percent enrichment.

CALCULATION STEPS IN THE PROJECTION PROCESS

The objective of the projection process is to provide the timing, quantity (assemblies and MTU), average burnup and initial enrichment of each SNF discharge up to and including the final, full-core discharges at the end of the licensed operating period of each reactor. The total energy produced by all of the discharges is to be consistent with the EIA nuclear generation projection, and the projected burnups are to increase at 1 percent/year until the target burnups of the EPRI Robust Fuel Project are reached. The starting point of the projection is the next five future discharges projected for each reactor by the utility owner and provided to DOE/EIA in the most recent RW-859 utility survey (EIA 2000). The projection methodology is based on energy-balance and simplified reactor physics methods. The alternative, the use of detailed reactor physics-based nuclear fuel cycle methods, also provides an energy balance, but is considerably more complex. In general, these alternative methods are equivalent if the initial enrichments are chosen correctly in the energy-balance method. Since the enrichment correlation that is used to assign enrichments is based on actual historical discharges, there is reasonable assurance that the energy-balance method used for this calculation procedure gives results that are the equivalent of using a reactor-physics-based method. The following paragraph summarizes the steps in the projection process and the subsequent paragraphs provide additional detail on each step in the process.

One of the primary goals of the projection process is to recognize and replicate the principal trends that are evident in the historic utility discharges and in the utility-projected next five discharges. Accordingly, the first step in the projection process is to analyze and characterize the utility-projected next five discharges. The principal data to be obtained from these projections for each reactor includes determination of the cycle time between refuelings. An appropriate burnup reference point from which to project future burnup increases is also developed. And the average plant operating capacity factor that is implied by the discharge quantities, burnups, cycle times and the unit's licensed maximum thermal rating is calculated. The most important of the trends that need to be replicated in the projection include the recent general utility adoption of 18- or 24-month cycle durations between refuelings, and a consistent long-term trend of increasing historical and utility-projected discharge burnups. Accordingly, the next step for each reactor consists of calculating the future discharge dates using the dates of the fifth utility-projected discharges and the cycle durations obtained by inspection of the discharge periods between the five utility-projected discharge dates. An appropriate reference burnup for each reactor is then calculated from the utility-projected burnups, and this value is extrapolated to the time of each future discharge at the assumed 1%/yr global average burnup increase rate until the EPRI target burnups are reached. The discharge quantities are calculated next, assuming the continuation of the reactor-specific average capacity factor implied by the utility five-discharge projection. Then, because it is necessary to assure consistency between the projected energy to be generated by the discharged fuel, and the chosen reference EIA projection of total electric energy, an adjustment factor is applied uniformly to all discharge quantities except the first utility-projected discharge and the final core discharge. This uniform adjustment factor is chosen so that the SNF discharge quantities (MTU) and their burnups (MWd/MTU), produce the total thermal energy (MWd) and related electrical energy that is consistent with the capacity factors of the reference EIA projection of total nuclear-electric energy generation. This uniform adjustment, in effect, makes the same percentage change in all of the individual plant capacity factors that are implied by the utility five-discharge projections, but preserves all of the relative capacity factor differences among the different nuclear units. The initial enrichments required to achieve the projected fuel burnups are then calculated using an EIA-developed correlation of initial enrichment as a function of burnup and refueling fraction, normalized to the utility-projected enrichments. Finally, the distribution of assembly burnups about the batch-average is calculated using a data-based burnup distribution pattern, resulting in a 15% spread of assembly burnups above and below the average burnup of the discharge batch.

GENERAL COMMENT ON THE PROJECTION LIMITATIONS AND UNCERTAINTIES

This section comments on aspects of the projection method in which it is recognized that there is above-average probability of significant differences between the model's projection and what may actually be experienced. Three particular aspects are: burnup distributions; enrichment distributions; and the final, pre-shutdown fuel cycle. Users of the projection data, particularly criticality designers, need to be aware of these limitations of the projection method and the ensuing results, and should evaluate possible impacts for their particular application.

- Historical data on burnup distributions associated with a single discharge show a greater random and skewed variability than is provided by the regular balanced distribution that is assumed in the methodology.
- The historical data on enrichment versus discharge burnup exhibits a wider band of variance from the average enrichments calculated by the methodology.
- It is not clear how the utilities will schedule and control the reload quantities in the one or two refuelings that precede the final shutdown and full-core discharge. The projection method basically maintains the full cycle duration up to the two pre-final refuelings, and then discharges quantities of fuel in proportion to the duration of the last one or two cycles.

By way of summary, it needs to be emphasized that the actual timing, quantity, burnup and burnup distribution projected for a single discharge batch for a particular reactor will not be what is projected. There are too many unknowable future utility operational circumstances that will need to be accommodated by adjustments in the fuel cycle. These circumstances preclude the ability to make reasonably accurate projections at the individual discharge level. However, this realistic fact is of little concern to the repository designer. The principal concern of the designer is with the spectrum of fuel types and characteristics that will need to be accommodated. The projection is anchored in the near term to historical experience, including the spectrum of utility operational and fuel cycle management practices. The projection uses informed extrapolation of identifiable practices and trends in these utility practices, thereby extrapolating the spectrum of those practices and their consequences in terms of the spectrum of SNF characteristics. Because of this approach, and the statistical fact that averages can be projected with much less uncertainty than the individual details, it is believed that the overall projection of the spectrum of SNF discharge characteristics provides a reasonable and realistic input to the repository design process.

Finally, it is noted that uncertainties in SNF characteristics due to projection uncertainties are only a part of the uncertainties that must be addressed by disposal system designers. The other major source of uncertainty in SNF characteristics at the time of transport or disposal is the uncertainty in the waste selection approaches that will be used by utilities at the time of delivery to DOE. In fact, recent work demonstrates that uncertainties due to waste selection dominate among the source of uncertainties that designers need to address. Nonetheless, the fairly rigorous modeling that has been accomplished for both the discharge and the waste selection processes enables designers to bound the SNF characteristics at various levels of extremity. This allows designers to make informed design tradeoffs between (i) the probability and costs (ie risks) of having to handle more above-design-basis SNF than anticipated and (ii) the risks of overdesigning by providing handling capability for extreme fuel that ultimately proves to be little used and unnecessary.

RECENT RESULTS

The detailed results of the projection of life cycle SNF discharges and characteristics includes the number of discharged assemblies, MTU, burnups, enrichments and discharge dates for each discharge and each reactor, and are summarized for each reactor on a calendar year basis. These same results are also provided in the input format required for waste selection and logistics analysis. Table 1 summarizes historical SNF discharges, projected SNF discharges, and the resulting projected total SNF discharges for a recent SNF discharge projection. This reflects a recent EIA nuclear-electric projection which includes assumed 20-year license extensions for somewhat less than half of the current operating reactors, and relatively high average capacity factors based on recent industry experience. Note that the summary totals for MTU and Assemblies do not add horizontally because the projection data and the total data have been rounded to the nearest 100 units. The average burnups are MTU-weighted and thus do not directly add, numerically.

TABLE 1 SUMMARY OF HISTORICAL AND PROJECTED SNF DISCHARGES

Characteristic	Historical Through 12/98	Projected After 12/98	Total
MTU:			
BWR	13,784	22,600	36,400
PWR	24,599	43,500	68,100
Total	38,383	66,100	104,500
Assemblies:			
BWR	76,495	130,600	207,100
PWR	57,255	99,200	156,500
Total	133,750	229,800	363,600
Average Burnup, MWd/MTU			
BWR	26,214	45,200	38,000
PWR	34,127	49,500	43,900
Overall	31,285	48,000	41,900

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FIGURE 1 DESIGN BASIS WASTE INPUT CALCULATION SYSTEM