A Classification of Commercial Nuclear Reactor Sites and the Subsequent Impacts on Preparing Spent Nuclear Fuel for Shipment[1] – 17355

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ABSTRACT

The US Department of Energy is conducting analyses to inform future decisions regarding an integrated waste management system for the acceptance of spent nuclear fuel (SNF) from commercial nuclear reactor sites. The ability to prepare SNF for shipment from reactor sites is likely to be restricted by ongoing operations at those sites. This report examines the extent to which those operations will restrict the reactor sites' availability to prepare SNF for shipment. Specifically, the analysis focuses on the impact and frequency of refueling operations within the commercial reactor sites in the US. In this report, a characterization of reactor sites into families is described. This characterization is based on the number of operating reactors on site, the length of refueling cycles for those reactors, and the configuration of spent fuel pools on site. Each reactor family is analyzed to estimate the amount of time for which each reactor site in the family would be available to prepare SNF shipments. This analysis is a work in progress, and the results are used to inform the development of new models of an integrated waste management system for commercial SNF.

INTRODUCTION

The US Department of Energy is conducting analyses to inform future decisions regarding an integrated waste management system for the acceptance of spent nuclear fuel (SNF) from commercial nuclear reactor sites. Software development efforts for creating detailed models of potential waste management system designs are ongoing [1, 2]. To date, simplifying assumptions of the availability of site operators to prepare SNF for shipment from reactor sites have been made. However, model development has reached a level of detail requiring a greater refinement of site operations and their impact on a site's ability to prepare SNF for shipment.

The work in this paper focuses on constraints in preparing SNF shipments imposed by refueling operations and associated spent fuel pool (SFP) activities at reactor sites. The refueling outages are major efforts at reactor sites and typically preclude the possibility of any other operations at the reactor site. Prior to core refueling, fuel inspection and other activities occupy the SFP and prohibit the availability for SNF to be prepared for direct shipment from the pool. Once the core has been refueled, it is common for maintenance and other activities to take place in the SFPs.

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[1] This technical paper reflects concepts which could support future decision-making by DOE. No inferences should be drawn from this paper regarding future actions by DOE. To the extent this technical paper conflicts with the provisions of the Standard Contract, the Standard Contract provisions prevail.

The activities associated with refueling the reactor core impose restrictions on the availability of the reactor site to prepare SNF shipments. Activities prior to and after refueling outages will restrict loading and transportation of SNF assemblies directly from the SFP. Transportation of the dual purpose canisters or casks in dry storage at the reactor site's independent spent fuel storage installation (ISFSI) may be possible during these periods. However, direct transportation of SNF from SFPs is preferable since it allows reactor sites to maintain the SNF inventory in the SFP without requiring a transfer of assemblies to dry storage. Transportation of SNF from the ISFSI does nothing to directly maintain or reduce SFP inventory.

The refueling outages are likely to restrict availability to transport SNF from both the SFP and the ISFSI. As mentioned previously, the activities associated with refueling the reactor are significant and typically require "all hands" to be available. Furthermore, reactor site operators are intensely focused on getting the reactor core refueled and returning to power generating operations. Permitting other activities (e.g., transportation of SNF from an ISFSI) to take place on site during such a refueling period is unlikely.

The frequency with which a site experiences a refueling outage or pool activities is the result of a number of site characteristics. This paper examines site characteristics that include the number of operating reactors at the site, the number of pools at the site, and the length of time between refueling cycles of reactors. Those characteristics are used to categorize reactor sites into families, and estimates of SFP and ISFSI availability for SNF shipments are generalized across sites within each family.

METHODS

Site categorization

In an effort to better understand the constraints in retrieving SNF at reactor sites, the sites were categorized into 14 families. These families are determined by the following characteristics:

- Number of operating reactors on site: Commercial reactor sites in the US have between 1 and 3 reactors operating on site at a time. Sites where all on-site reactors have been permanently shut down are simply termed "shutdown sites."
- Operating Reactor type: The reactors at commercial sites are either pressurized water reactors (PWRs) or boiling water reactors (BWRs).
- Length of refueling cycle: The amount of time between refueling outages of a reactor. The duration of these cycles is either 18 or 24 months for reactors at commercial reactor sites in the US.
- Number of spent fuel pools: Sites have between 1 and 4 SFPs on site.
- Configuration of spent fuel pools: At some sites multiple reactors discharge SNF into the same SFP (i.e., a "shared" SFP). At other sites, each reactor unit has a dedicated SFP.

Each family represents a different combination of the above characteristics. For example, family II consists of sites with one operating BWR unit that refuels every 24 months and has a single SFP. Operating sites such as Duane Arnold, Oyster

Creek, and River Bend are categorized into this family. Alternatively, family VI consists of sites with one operating BWR unit that refuels every 18 months and has a single SFP. Sites such as Fermi and Hope Creek are included in this family. Note that the two families differ only by the length of the refueling cycle (18 months vs. 24 months). Yet a third family, family VIII, consists of sites with a single PWR unit, but are otherwise identical to the sites in family II.

Single unit sites with single SFPs are straightforward examples of families, but more elaborate configurations exist at US commercial reactor sites. For example, Oconee has three PWR units that each operate on a 24 month cycle. That site also has 2 SFPs, where pool 1 is shared by reactor units Oconee 1 and Oconee 2, and pool 3 is dedicated to unit Oconee 3. This is a unique configuration, and Oconee is the only site in family XIV. Another family consisting of only one site is Family XIII consisting of Palo Verde. Palo Verde has three PWR units on 18 month cycles and three SFPs, each of which are dedicated to one of the operating units.

Table I provides a complete list of the 15 families, including family XV, which consists of sites without an operating reactor (i.e., shutdown sites). The table includes the number and type of reactor at each site in the family, the length of the refueling cycle for those reactors, the number of SFPs and their configuration, and the number of sites in each family.

Note that sites are categorized, in part, based on the number of *operating* reactors on site. As a reactor at a site shuts down, that site will move into a different family. After the final shutdown of the unit at any site with only one operating reactor (i.e., family II, III, VI, VIII, IX, or X), that site then becomes a member of the shutdown sites' family XV.

TABLE I. List of Reactor Families and Defining Characteristics

Family	Number and type of Operating Reactors	Length of Refueling Cycle (months)	Number and Configuration of Spent Fuel Pools	Number of Sites in Family
I	2 PWR	18	2 Dedicated	12
II	1 BWR	24	1 Dedicated	11
III	1 PWR	18	1 Dedicated	10
IV	2 BWR	24	2 Dedicated	9
V	2 PWR	18	1 Shared	9
VI	1 BWR	18	1 Dedicated	2
VII	3 BWR	24	3 Dedicated	1
VIII	1 PWR	24	1 Dedicated	1
IX	1 PWR	24	2 Dedicated to single unit	1
X	1 PWR	18	4 Dedicated to single unit	1
XI	2 PWR	24	2 Dedicated	1
XII	2 PWR	24	1 Shared	1
XIII	3 PWR	18	3 Dedicated	1
XIV	3 PWR	24	1 Shared, 1 Dedicated	1
XV	Shutdown Sites			13

Refueling Operations

Refueling operations at reactor sites are extensive and take multiple weeks to complete. Two sets of estimates for these operations were examined in order to bound the impact of these operations on the availability of reactor sites to prepare SNF for shipment. The first set of operations were provided in [3].

In both estimates it is assumed that activities directly involving the refueling of the reactor prohibit any other operations at the reactor site. Ancillary operations, such as additional pool activities, are assumed to prohibit SNF from being transported from the SFP, but SNF from the ISFSI could be transported. Finally, when none of these activities are taking place, the entire site (SFP and ISFSI) is assumed to be available to prepare SNF for shipment from the reactor site. The operations, duration of those operations, and availability of the ISFSI and SFP are listed in Table II.

In families with multiple reactor units it is assumed that an activity on site affects the entire site. Using these assumptions, a refueling outage to reactor unit 1 at Palo Verde prohibits the availability of operations in all of the SFPs and the ISFSI at Palo Verde.

TABLE II. Conservative estimates for refueling operations

Operations	Duration (weeks)	ISFSI available	SFP available
Pre-outage loading	4	No	No
Repositioning of SNF in SFP in advance of refueling outage	2	Yes	No
Refueling outage	5	No	No
Healthy fuel inspections and special nuclear material physical inventory	2	Yes	No
Post-outage SFP cleanup activities and heavy loads movements	4	No	No
Maintenance, surveillance, and inspection of cask handling crane, ventilation systems, and other equipment	3	Yes	No
Additional pool activities that include control rod movement in SFP, neutron absorber inspections, debris and non-fuel related material cleanup, and seasonal restrictions	4	Yes	No
Scheduled training, vacations, and holidays	4	Yes	No

While the assumptions in [3] provide an initial understanding of the operations required at operating reactor sites, these assumptions are assuredly over conservative. For example, a site in family XIII would never permit access to one of the SFPs on site. The three units, each operating on 18 month refueling cycles, result in a refueling outage on site every 6 months. Combining that refueling frequency, the activities surrounding each outage, and the assumption that outage activates affecting one reactor affect the entire site would result in a site that could never perform pool activities outside of those associated with reactor refueling. However, Palo Verde is in family XIII, and as of May 2016, that site has loaded 133 canisters into dry storage [4].

As the activities derived from [3] are overly conservative, an additional set of activity estimates were used. These estimates for activities are substantially more aggressive in order to serve as a bounding case opposite that of the more conservative estimates. These aggressive estimates assume only the three most crucial activities of the refueling process, and that they can be accomplished sooner. As a result the aggressive set of assumptions are limited to those provided in Table III:

TABLE III. Aggressive estimates for refueling operations

Operations	Duration (weeks)	ISFSI available	SFP available
Pre-outage loading	2	No	No
Refueling outage	4	No	No
Post-outage SFP cleanup activities and heavy loads movements	4	No	No

Timelines / availability for each family

Using each of the activity estimates described above, timelines for site availability were established for each family of sites. Illustrations of such timelines are provided in Figure 1 and Figure 2. In each graphic the green coloring illustrates periods of time where on-site SFPs and the site's ISFSI could be accessed; the yellow coloring indicates periods where only the site's ISFSI can be accessed (e.g., pre-outage loading); and the red coloring indicates periods of time when no SNF can be retrieved from the site (i.e., refueling outages).

Figure 1 illustrates the site availability over the course of two years for two families with on-site reactors using 24 month refueling cycles, and indicates the total number of weeks over two years that at least one portion of the site is available to prepare SNF shipments. The left side of the graphic illustrates site families with one operating reactor unit and one SFP (e.g., families II and VIII). The right side of the graphic illustrates site family XIV. In both cases the timeline assumes that the first fuel outage is in the spring of year one of the two year cycle. Refueling outages are always in either the fall or the spring, but for the purposes of tracking availability among reactor sites, this simplifying assumption of first outage occurring in the spring of the first year in the cycle preserves the generality of the analysis.

In the 1 unit, 1 pool case, the outage occurs in the spring of year one. Under the aggressive assumptions for activity estimates that results in eight weeks of time where the entire site is unavailable to prepare SNF for shipment. Under the more conservative activity estimates the entire site is unable to prepare fuel for shipment for 13 weeks, and the SFP is unavailable for an additional 18 weeks every two years. The entire site is available to prepare SNF shipments for the remaining 73 weeks. The timeline for family XIV is notably more complex. The entire site is down three times throughout the 24 month cycle: once for each of the three operating reactor units. This results in a site that can prepare fuel shipments from the SFP for 21 weeks out of the two year period, and from the ISFSI for an additional 44 weeks.

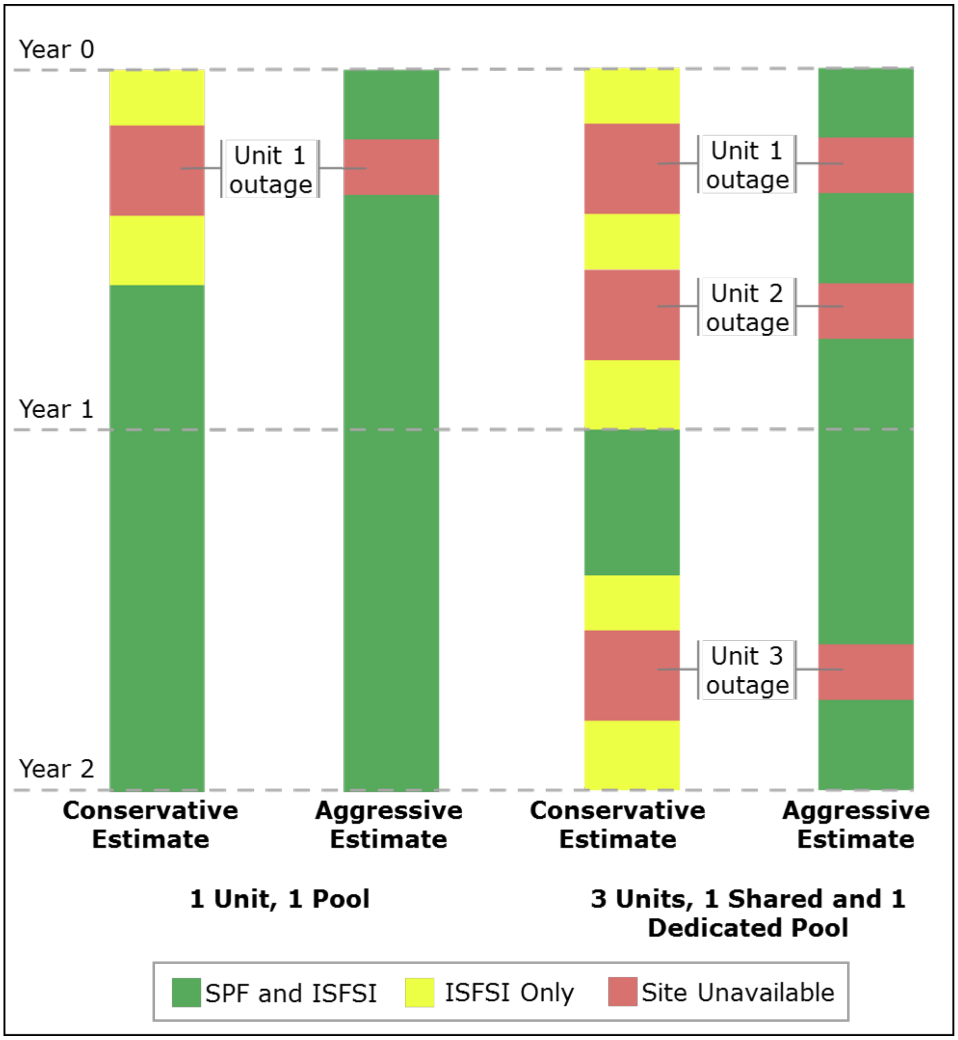

Fig. 1. Examples of 24 Month Refueling Cycle Families Showing Availability Over Two Years

Under the more aggressive estimates for operation durations, the number of weeks for which a site is available to prepare SNF shipments increases dramatically. With only one reactor unit, sites are able to ship SNF from the ISFSI and the SFPs for 96 weeks over the two year period compared to only 73 weeks under the conservative assumptions. For a site in family XIV, the change is even more dramatic as the entire site (ISFSI and SFPs) is available for 80 weeks under the aggressive estimates, but only 21 weeks under the conservative estimates for outage activities.

Figure 2 provides the same information as Figure 1 but does so for families which reactor sites operating under 18 month refueling cycles, and with 3 years illustrated rather than 24 months. The figure on the left illustrates sites with a single unit and a single SFP, demonstrating two refueling outages over the 3 year period. The figure on the right illustrates the availability over the 3 year period for a site in family XIII. As mentioned above, under the conservative estimates, the SFP would never be available to prepare SNF for shipment (green period) for a site in family XIII. However, under the aggressive estimates, the SFPs and ISFSI become available for 108 of the 156 weeks in the 3 year period.

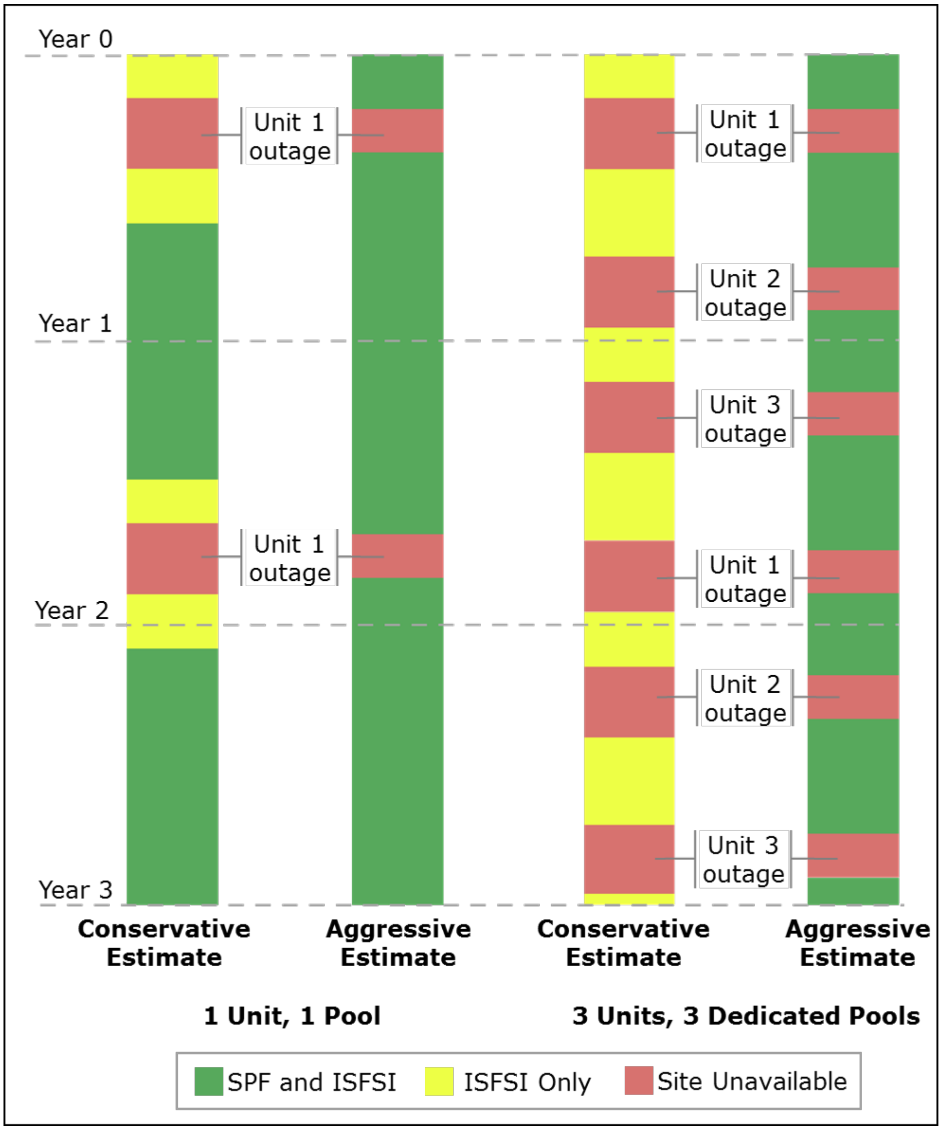

Fig. 2. Examples of 18 Month Refueling Cycle Families Showing Availability over Three years

Table IV provides a detailed breakdown of the number of weeks in a 6 year period that the ISFSI and SFPs are available to prepare SNF shipments at sites within each of the families. The duration of six years was chosen to normalize the repeating periods of 18 and 24 month refueling cycles. Columns indicating the weeks of ISFSI availability for both conservative and aggressive estimates are provided. As the ISFSI is available whenever the SFP is available, there is also a column indicating the number of weeks where both the ISFSI and the SFPs are available.

TABLE IV. Number of Weeks Sites in Each Family are Available to Prepare SNF for Shipment Over a Six Year Period (312 weeks)

		Conservative Estimates		Aggressive Estimates	
Family	**Family Characteristics (reactor units, SFPs, refueling cycle months)**	**ISFSI (weeks)**	**SFP and ISFSI (weeks)**	**ISFSI (weeks)**	**SFP and ISFSI (weeks)**
I	2 PWR, 2 dedicated, 18 mo.	208	84	248	248
II	1 BWR, 1 dedicated, 24 mo.	273	219	288	288
III	1 PWR, 1 dedicated, 18 mo.	260	188	280	280
IV	2 BWR, 2 dedicated, 24 mo.	234	126	264	264
V	2 PWR, 1 shared, 18 mo.	208	92	248	248
VI	1 BWR, 1 dedicated, 18 mo.	260	188	280	280
VII	3 BWR, 3 dedicated, 24 mo.	234	126	264	264
VIII	1 PWR, 1 dedicated, 24 mo.	273	219	288	288
IX	1 PWR, 2 dedicated, 24 mo.	273	219	288	288
X	1 PWR, 4 dedicated, 18 mo.	260	188	280	280
XI	2 PWR, 2 dedicated, 24 mo.	234	126	264	264
XII	2 PWR, 1 shared, 24 mo.	234	126	264	264
XIII	3 PWR, 3 dedicated, 18 mo.	156	0	216	216
XIV	3 PWR, 1 shared & 1 dedicated, 24 mo.	195	63	240	240
XV	Shutdown Site	312	312	312	312

More reactors on site implies more refueling within a cycle, and that trend is evident in the table. Sites with more reactors have fewer weeks of availability when compared to sites with fewer reactors. The length of the refueling cycle has an effect as well since shorter cycles (e.g., 18 months) result in more refueling outages over six years than the longer 24 month cycles. The family with the fewest weeks of availability is family XIII, which has the highest frequency of refueling outages with one occurring every 6 months.

DISCUSSION

The conservative and aggressive estimates for reactor activities provide a wide range in the number of weeks of availability in Table II. The actual number of weeks available for sites in each family is likely to be somewhere between these two sets of results. These results do however provide a set of bounding cases that indicate, among other things, where additional attention should be devoted when incorporating reactor site availability into modeling the waste management system.

Some further elements of consideration are not specifically examined here, but are likely to impact further modeling of the waste management system. There are certain anomaly cases within the fleet that may add additional constraints on the ability of reactor sites to prepare and ship SNF. For example, while the reactor sites of Salem and Hope Creek are independent from one another, they are located within the same fence line, and operational impacts at one of those sites (e.g., refueling operations) are likely to impact the availability of crews at the other site to support SNF shipment preparation. Similarly, sites owned by the same utility may recall crews from nearby sites to assist during refueling outages reducing the availability of those crews at their usual site.

Another issue affecting the ability of reactor operators to prepare shipments of SNF from the site involves the transportation infrastructure around the sites. For example, the proximity of rail lines, barge docks, and the size of marshalling yards from reactor sites will all impact a site's ability to transport SNF off site. Evaluations along these lines has been conducted at shut down reactor sites [5] (i.e., site family XV), but further investigation at the operation US commercial reactor sites is needed.

CONCLUSIONS

Further work is still required to achieve a faithful modeling of the availability at operating reactor sites. However, the work discussed here provides an improved level of modeling addressing the limitations at reactor sites caused by refueling outages and associated activities. The amount of reactor availability in this work are bounding cases under conservative and aggressive estimates for operational activities, and the information provided is currently being implemented into in-development models for the waste management system [1, 2].

REFERENCES

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