Updated Response to Request for Additional Information Specific to the Electric Power Research Institute Report 1025203, "Utilization of the EPRI Depletion Benchmarks for Burnup Credit Validation"

General Response:

One of the major themes consistent through the RAIs on both EPRI Reports 1025203, “Utilization of the EPRI Depletion Benchmarks for Burnup Credit Validation” and 1022909, “Benchmarks for Quantifying Fuel reactivity Depletion Uncertainty” [1] is a need for comparison of the similarity between the benchmark cases and the spent fuel pool applications. EPRI reports 1025203 and 1022909 will be referred as “Utilization report” and “Benchmark report”, respectively from this point forward. This has always been one of the major issues concerning the use of reactor related data (i.e., commercial reactor criticals) in previous benchmarking efforts. Table 8-4 of Benchmark report [1] included a determination of the similarity between the reactor and spent fuel pool conditions using the Correlation Coefficient c_k. With the completion of the EPRI sensitivity studies [2] which included a range of spent fuel storage racks configurations, it is possible to provide an extensive comparison of the benchmark cases and the spent fuel pool storage configurations.

To provide a quantitative evaluation of the similarity, all 11 benchmarks at the six burnups (100 hours cooling) were analyzed with SCALE 6.1 Tsunami-3D-K5 [3]. The modification of the benchmark input files was identical to the input modifications made for the Tsunami inputs given in the “International Handbook of Evaluated Criticality Safety Benchmark Experiments” disk (under DiceData\ornl\inputs\tsunami-3d-k5) [4]. These runs produced .sdf files which will be available at the EPRI web site. Since many criticality applications do not use SCALE, a set of representative spent fuel pool conditions were analyzed for comparison to the benchmarks. The representative spent fuel pool cases are the same 56 rack and fuel configurations used in the EPRI sensitivity studies [2]. (The zero burnup cases were not analyzed.) A Tsunami analysis was performed for each of these cases producing 56 .sdf files. The Tsunami-IP code was then run to find the c_k for each application compared to all 66 benchmarks. Table GR-1 provides the resulting c_k’s comparing the 11 benchmark cases to each of the spent fuel rack configurations.

The lower c_k values seen on Table GR-1 are where the benchmark and the spent fuel rack have significant differences in burnup. This is expected and consistent with previous results published in Reference 5, showing low c_ks when comparing fresh fuel criticals to spent fuel. In order to make the agreement clearer, the maximum c_k was placed at the bottom of the column for each spent fuel configuration. Of the 56 spent fuel pool configurations investigated all but 3 had a c_k greater than 0.9 for at least one of the benchmark cases. The three that had a maximum c_k less than 0.9 were associated with flux trap (Region 1) designs with low burnup (≤ 20 GWd/T) and CE 16x16 fuel (see the bottom of Table GR-1, page 7 of 7). Flux traps add more water to the system than contained in the benchmarks. All of the non-flux trap designs (Region 2) had very good agreement with the minimum of the maximums c_ks being 0.9821 for W 17x17 fuel and 0.9710 for CE 16x16 fuel. Flux trap racks are principally designed to accommodate fresh fuel and therefore do not usually require burnup credit. In fact two of the three cases which had c_k values less than 0.9 were for rack designs which did not need burnup credit. The only spent fuel configuration that is likely to need burnup credit and has a c_k less than 0.90 are flux trap designs that do not credit absorber panels. However, these c_ks are marginally below 0.90.

Table GR-1: c_k Between EPRI Depletion Benchmarks (100 hours cooling) and Typical Spent Fuel Pools (1 of 7)

Fuel	**W17**	**W17**	**W17**	**W17**	**W17**	**W17**	**W17**	**W17**
Region	**2**	**2**	**2**	**2**	**2**	**2**	**2**	**2**
Areal Density ($g^{10}B/cm^2$)	**0**	**0**	**0**	**0**	**0**	**0**	**0.015**	**0.015**
Enrichment (wt%^{235}U)	**3.5**	**3.5**	**3.5**	**5**	**5**	**5**	**3.5**	**3.5**
Burnup (GWd/T)	**20**	**30**	**40**	**30**	**40**	**60**	**10**	**20**
EPRI Benchmark	**c_k**							
BM 1 10 GWD/T	0.9317	0.8822	0.8391	0.9270	0.8882	0.8184	0.9920	0.9417
BM 1 20 GWD/T	0.9810	0.9699	0.9511	0.9781	0.9702	0.9389	0.9730	0.9945
BM 1 30 GWD/T	0.9725	0.9845	0.9812	0.9707	0.9814	0.9748	0.9263	0.9876
BM 1 40 GWD/T	0.9519	0.9791	0.9863	0.9511	0.9739	0.9841	0.8821	0.9680
BM 1 50 GWD/T	0.9314	0.9686	0.9830	0.9313	0.9622	0.9838	0.8464	0.9480
BM 1 60 GWD/T	0.9146	0.9584	0.9777	0.9150	0.9512	0.9806	0.8196	0.9314
BM 2 10 GWD/T	0.8480	0.7743	0.7170	0.8496	0.7903	0.6962	0.9555	0.8570
BM 2 20 GWD/T	0.9513	0.9114	0.8742	0.9538	0.9219	0.8602	0.9947	0.9634
BM 2 30 GWD/T	0.9781	0.9632	0.9420	0.9812	0.9696	0.9335	0.9781	0.9923
BM 2 40 GWD/T	0.9769	0.9808	0.9723	0.9804	0.9841	0.9682	0.9457	0.9924
BM 2 50 GWD/T	0.9636	0.9821	0.9835	0.9672	0.9828	0.9830	0.9091	0.9799
BM 2 60 GWD/T	0.9462	0.9757	0.9849	0.9499	0.9745	0.9872	0.8744	0.9630
BM 3 10 GWD/T	0.8841	0.8186	0.7660	0.8832	0.8310	0.7450	0.9751	0.8934
BM 3 20 GWD/T	0.9689	0.9400	0.9097	0.9692	0.9465	0.8963	0.9927	0.9818
BM 3 30 GWD/T	0.9813	0.9773	0.9632	0.9823	0.9798	0.9555	0.9622	0.9958
BM 3 40 GWD/T	0.9704	0.9843	0.9824	0.9720	0.9839	0.9791	0.9224	0.9861
BM 3 50 GWD/T	0.9515	0.9785	0.9858	0.9535	0.9760	0.9859	0.8834	0.9682
BM 3 60 GWD/T	0.9330	0.9694	0.9833	0.9351	0.9653	0.9860	0.8500	0.9499
BM 4 10 GWD/T	0.8720	0.8026	0.7475	0.8702	0.8151	0.7256	0.9685	0.8792
BM 4 20 GWD/T	0.9648	0.9316	0.8986	0.9639	0.9380	0.8838	0.9946	0.9757
BM 4 30 GWD/T	0.9821	0.9747	0.9585	0.9817	0.9767	0.9494	0.9676	0.9949
BM 4 40 GWD/T	0.9728	0.9846	0.9813	0.9727	0.9832	0.9767	0.9269	0.9866
BM 4 50 GWD/T	0.9534	0.9795	0.9862	0.9535	0.9756	0.9850	0.8852	0.9682
BM 4 60 GWD/T	0.9322	0.9687	0.9828	0.9324	0.9629	0.9843	0.8482	0.9476
BM 5 10 GWD/T	0.8999	0.8401	0.7909	0.9003	0.8523	0.7714	0.9829	0.9122
BM 5 20 GWD/T	0.9714	0.9459	0.9179	0.9725	0.9524	0.9054	0.9899	0.9856
BM 5 30 GWD/T	0.9805	0.9781	0.9651	0.9822	0.9808	0.9580	0.9590	0.9957
BM 5 40 GWD/T	0.9692	0.9837	0.9823	0.9714	0.9838	0.9795	0.9204	0.9854
BM 5 50 GWD/T	0.9522	0.9791	0.9863	0.9547	0.9772	0.9869	0.8834	0.9687
BM 5 60 GWD/T	0.9335	0.9696	0.9833	0.9364	0.9662	0.9863	0.8511	0.9507
BM 6 10 GWD/T	0.8943	0.8322	0.7816	0.8943	0.8446	0.7616	0.9807	0.9056
BM 6 20 GWD/T	0.9702	0.9427	0.9133	0.9709	0.9492	0.9002	0.9920	0.9836
BM 6 30 GWD/T	0.9807	0.9770	0.9632	0.9820	0.9797	0.9557	0.9616	0.9957
BM 6 40 GWD/T	0.9700	0.9838	0.9819	0.9718	0.9837	0.9787	0.9226	0.9860
BM 6 50 GWD/T	0.9525	0.9792	0.9863	0.9546	0.9769	0.9864	0.8845	0.9689

Fuel	**W17**	**W17**	**W17**	**W17**	**W17**	**W17**	**W17**	**W17**
Region	**2**	**2**	**2**	**2**	**2**	**2**	**2**	**2**
Areal Density (g^{10}B/cm^{2})	**0**	**0**	**0**	**0**	**0**	**0**	**0.015**	**0.015**
Enrichment (wt%^{235}U)	**3.5**	**3.5**	**3.5**	**5**	**5**	**5**	**3.5**	**3.5**
Burnup (GWd/T)	**20**	**30**	**40**	**30**	**40**	**60**	**10**	**20**
EPRI Benchmark	**c_k**							
BM 6 60 GWD/T	0.9332	0.9693	0.9831	0.9355	0.9654	0.9857	0.8510	0.9502
BM 7 10 GWD/T	0.9067	0.8503	0.8031	0.9079	0.8625	0.7846	0.9852	0.9209
BM 7 20 GWD/T	0.9731	0.9489	0.9216	0.9745	0.9553	0.9095	0.9893	0.9875
BM 7 30 GWD/T	0.9802	0.9782	0.9654	0.9821	0.9810	0.9585	0.9582	0.9956
BM 7 40 GWD/T	0.9691	0.9835	0.9820	0.9715	0.9838	0.9793	0.9205	0.9854
BM 7 50 GWD/T	0.9520	0.9787	0.9858	0.9547	0.9770	0.9864	0.8841	0.9688
BM 7 60 GWD/T	0.9337	0.9696	0.9831	0.9367	0.9664	0.9862	0.8519	0.9511
BM 8 10 GWD/T	0.8890	0.8250	0.7732	0.8883	0.8371	0.7525	0.9774	0.8986
BM 8 20 GWD/T	0.9711	0.9437	0.9144	0.9716	0.9501	0.9013	0.9918	0.9841
BM 8 30 GWD/T	0.9810	0.9784	0.9652	0.9824	0.9809	0.9578	0.9598	0.9960
BM 8 40 GWD/T	0.9703	0.9851	0.9837	0.9722	0.9849	0.9808	0.9202	0.9860
BM 8 50 GWD/T	0.9522	0.9796	0.9870	0.9545	0.9773	0.9874	0.8825	0.9686
BM 8 60 GWD/T	0.9338	0.9703	0.9842	0.9364	0.9666	0.9872	0.8501	0.9506
BM 9 10 GWD/T	0.8877	0.8233	0.7712	0.8869	0.8355	0.7505	0.9767	0.8972
BM 9 20 GWD/T	0.9695	0.9417	0.9122	0.9701	0.9483	0.8992	0.9915	0.9829
BM 9 30 GWD/T	0.9802	0.9771	0.9637	0.9816	0.9798	0.9564	0.9600	0.9954
BM 9 40 GWD/T	0.9693	0.9838	0.9822	0.9713	0.9837	0.9793	0.9205	0.9854
BM 9 50 GWD/T	0.9511	0.9784	0.9858	0.9534	0.9762	0.9863	0.8822	0.9679
BM 9 60 GWD/T	0.9321	0.9687	0.9828	0.9348	0.9650	0.9857	0.8492	0.9494
BM 10 10 GWD/T	0.8836	0.8229	0.7735	0.8853	0.8364	0.7546	0.9739	0.8997
BM 10 20 GWD/T	0.9612	0.9370	0.9101	0.9638	0.9444	0.8987	0.9842	0.9806
BM 10 30 GWD/T	0.9690	0.9691	0.9581	0.9723	0.9724	0.9522	0.9504	0.9900
BM 10 40 GWD/T	0.9571	0.9743	0.9749	0.9608	0.9747	0.9732	0.9103	0.9788
BM 10 50 GWD/T	0.9379	0.9675	0.9768	0.9418	0.9658	0.9783	0.8714	0.9600
BM 10 60 GWD/T	0.9179	0.9564	0.9722	0.9220	0.9532	0.9759	0.8377	0.9404
BM 11 10 GWD/T	0.8915	0.8278	0.7763	0.8907	0.8399	0.7556	0.9787	0.9009
BM 11 20 GWD/T	0.9717	0.9451	0.9162	0.9723	0.9514	0.9032	0.9912	0.9848
BM 11 30 GWD/T	0.9810	0.9790	0.9662	0.9825	0.9815	0.9591	0.9586	0.9960
BM 11 40 GWD/T	0.9696	0.9848	0.9837	0.9717	0.9846	0.9810	0.9189	0.9855
BM 11 50 GWD/T	0.9516	0.9793	0.9870	0.9542	0.9772	0.9876	0.8813	0.9682
BM 11 60 GWD/T	0.9330	0.9697	0.9838	0.9360	0.9662	0.9869	0.8493	0.9502
Max c_k	0.9821	0.9851	0.9870	0.9825	0.9849	0.9876	0.9947	0.9960

Table GR-1: c_k Between EPRI Depletion Benchmarks (100 hours cooling) and Typical Spent Fuel Pools (2 of 7)

Fuel	**W17**	**W17**	**W17**	**W17**	**W17**	**W17**	**W17**	**W17**
Region	**2**	**2**	**2**	**2**	**2**	**2**	**2**	**2**
Areal Density (g^{10}B/cm^2)	**0.015**	**0.015**	**0.015**	**0.015**	**0.015**	**0.015**	**0.03**	**0.03**
Enrichment (wt%^{235}U)	**3.5**	**3.5**	**5**	**5**	**5**	**5**	**3.5**	**3.5**
Burnup (GWd/T)	**30**	**40**	**20**	**30**	**40**	**60**	**10**	**20**
EPRI Benchmark	c_k							
BM 1 10 GWD/T	0.8885	0.8438	0.9736	0.9354	0.8946	0.8229	0.9917	0.9416
BM 1 20 GWD/T	0.9793	0.9582	0.9829	0.9896	0.9791	0.9451	0.9725	0.9942
BM 1 30 GWD/T	0.9954	0.9896	0.9514	0.9836	0.9916	0.9820	0.9259	0.9872
BM 1 40 GWD/T	0.9910	0.9957	0.9165	0.9648	0.9849	0.9921	0.8817	0.9675
BM 1 50 GWD/T	0.9811	0.9930	0.8866	0.9454	0.9737	0.9923	0.8460	0.9475
BM 1 60 GWD/T	0.9713	0.9880	0.8638	0.9294	0.9630	0.9894	0.8192	0.9310
BM 2 10 GWD/T	0.7801	0.7216	0.9266	0.8569	0.7960	0.7008	0.9555	0.8571
BM 2 20 GWD/T	0.9196	0.8806	0.9915	0.9640	0.9299	0.8659	0.9943	0.9632
BM 2 30 GWD/T	0.9733	0.9499	0.9918	0.9933	0.9792	0.9404	0.9777	0.9921
BM 2 40 GWD/T	0.9921	0.9810	0.9709	0.9936	0.9946	0.9758	0.9452	0.9920
BM 2 50 GWD/T	0.9941	0.9930	0.9428	0.9812	0.9940	0.9912	0.9087	0.9795
BM 2 60 GWD/T	0.9883	0.9950	0.9140	0.9643	0.9861	0.9958	0.8740	0.9626
BM 3 10 GWD/T	0.8245	0.7705	0.9495	0.8909	0.8368	0.7495	0.9750	0.8934
BM 3 20 GWD/T	0.9489	0.9166	0.9945	0.9801	0.9551	0.9025	0.9923	0.9816
BM 3 30 GWD/T	0.9876	0.9712	0.9804	0.9947	0.9895	0.9624	0.9617	0.9955
BM 3 40 GWD/T	0.9958	0.9914	0.9515	0.9854	0.9946	0.9868	0.9219	0.9857
BM 3 50 GWD/T	0.9910	0.9958	0.9202	0.9678	0.9876	0.9945	0.8830	0.9678
BM 3 60 GWD/T	0.9821	0.9936	0.8920	0.9496	0.9770	0.9947	0.8497	0.9495
BM 4 10 GWD/T	0.8066	0.7503	0.9387	0.8761	0.8192	0.7283	0.9681	0.8792
BM 4 20 GWD/T	0.9387	0.9037	0.9918	0.9731	0.9448	0.8882	0.9940	0.9755
BM 4 30 GWD/T	0.9835	0.9649	0.9817	0.9926	0.9850	0.9547	0.9669	0.9945
BM 4 40 GWD/T	0.9942	0.9884	0.9524	0.9844	0.9922	0.9824	0.9262	0.9862
BM 4 50 GWD/T	0.9901	0.9942	0.9189	0.9661	0.9854	0.9916	0.8846	0.9677
BM 4 60 GWD/T	0.9800	0.9915	0.8876	0.9455	0.9732	0.9914	0.8476	0.9471
BM 5 10 GWD/T	0.8487	0.7980	0.9632	0.9107	0.8607	0.7784	0.9830	0.9123
BM 5 20 GWD/T	0.9560	0.9259	0.9952	0.9845	0.9620	0.9127	0.9897	0.9853
BM 5 30 GWD/T	0.9890	0.9737	0.9791	0.9951	0.9911	0.9655	0.9586	0.9953
BM 5 40 GWD/T	0.9957	0.9918	0.9509	0.9853	0.9950	0.9877	0.9200	0.9851
BM 5 50 GWD/T	0.9915	0.9961	0.9210	0.9689	0.9887	0.9952	0.8830	0.9683
BM 5 60 GWD/T	0.9827	0.9939	0.8938	0.9511	0.9783	0.9954	0.8508	0.9503
BM 6 10 GWD/T	0.8399	0.7878	0.9588	0.9037	0.8521	0.7677	0.9807	0.9056
BM 6 20 GWD/T	0.9521	0.9206	0.9952	0.9823	0.9582	0.9068	0.9916	0.9834
BM 6 30 GWD/T	0.9878	0.9717	0.9804	0.9948	0.9898	0.9631	0.9612	0.9954
BM 6 40 GWD/T	0.9956	0.9911	0.9520	0.9855	0.9946	0.9867	0.9222	0.9857
BM 6 50 GWD/T	0.9914	0.9960	0.9211	0.9686	0.9882	0.9947	0.8841	0.9685
BM 6 60 GWD/T	0.9822	0.9935	0.8929	0.9501	0.9773	0.9946	0.8507	0.9498

Fuel	**W17**	**W17**	**W17**	**W17**	**W17**	**W17**	**W17**	**W17**
Region	**2**	**2**	**2**	**2**	**2**	**2**	**2**	**2**
Areal Density (g^{10}B/cm^2)	**0.015**	**0.015**	**0.015**	**0.015**	**0.015**	**0.015**	**0.03**	**0.03**
Enrichment (wt%^{235}U)	**3.5**	**3.5**	**5**	**5**	**5**	**5**	**3.5**	**3.5**
Burnup (GWd/T)	**30**	**40**	**20**	**30**	**40**	**60**	**10**	**20**
EPRI Benchmark	**c_k**							
BM 7 10 GWD/T	0.8605	0.8117	0.9690	0.9199	0.8723	0.7931	0.9855	0.9210
BM 7 20 GWD/T	0.9592	0.9297	0.9958	0.9867	0.9651	0.9169	0.9890	0.9873
BM 7 30 GWD/T	0.9894	0.9743	0.9790	0.9953	0.9916	0.9663	0.9579	0.9953
BM 7 40 GWD/T	0.9956	0.9916	0.9512	0.9855	0.9950	0.9877	0.9202	0.9850
BM 7 50 GWD/T	0.9914	0.9959	0.9217	0.9692	0.9887	0.9951	0.8837	0.9684
BM 7 60 GWD/T	0.9828	0.9938	0.8946	0.9516	0.9785	0.9954	0.8516	0.9507
BM 8 10 GWD/T	0.8311	0.7780	0.9532	0.8962	0.8433	0.7572	0.9773	0.8987
BM 8 20 GWD/T	0.9527	0.9213	0.9950	0.9826	0.9587	0.9075	0.9914	0.9838
BM 8 30 GWD/T	0.9891	0.9735	0.9795	0.9951	0.9910	0.9652	0.9594	0.9956
BM 8 40 GWD/T	0.9965	0.9926	0.9505	0.9856	0.9955	0.9884	0.9197	0.9856
BM 8 50 GWD/T	0.9918	0.9967	0.9202	0.9686	0.9887	0.9956	0.8820	0.9682
BM 8 60 GWD/T	0.9830	0.9944	0.8929	0.9508	0.9783	0.9958	0.8497	0.9502
BM 9 10 GWD/T	0.8293	0.7759	0.9521	0.8948	0.8416	0.7551	0.9766	0.8972
BM 9 20 GWD/T	0.9511	0.9196	0.9946	0.9815	0.9573	0.9058	0.9912	0.9827
BM 9 30 GWD/T	0.9881	0.9723	0.9795	0.9946	0.9901	0.9640	0.9597	0.9951
BM 9 40 GWD/T	0.9956	0.9916	0.9506	0.9851	0.9947	0.9874	0.9201	0.9850
BM 9 50 GWD/T	0.9910	0.9960	0.9197	0.9679	0.9879	0.9950	0.8819	0.9675
BM 9 60 GWD/T	0.9819	0.9934	0.8918	0.9496	0.9771	0.9949	0.8489	0.9490
BM 10 10 GWD/T	0.8350	0.7839	0.9545	0.8990	0.8480	0.7651	0.9746	0.8999
BM 10 20 GWD/T	0.9520	0.9230	0.9919	0.9805	0.9585	0.9109	0.9846	0.9805
BM 10 30 GWD/T	0.9856	0.9723	0.9740	0.9904	0.9879	0.9654	0.9507	0.9899
BM 10 40 GWD/T	0.9915	0.9898	0.9442	0.9795	0.9908	0.9868	0.9106	0.9786
BM 10 50 GWD/T	0.9854	0.9923	0.9123	0.9609	0.9823	0.9924	0.8717	0.9598
BM 10 60 GWD/T	0.9748	0.9882	0.8836	0.9415	0.9701	0.9906	0.8381	0.9402
BM 11 10 GWD/T	0.8339	0.7809	0.9547	0.8985	0.8459	0.7601	0.9785	0.9009
BM 11 20 GWD/T	0.9542	0.9232	0.9951	0.9834	0.9600	0.9095	0.9908	0.9846
BM 11 30 GWD/T	0.9898	0.9747	0.9789	0.9953	0.9916	0.9664	0.9581	0.9957
BM 11 40 GWD/T	0.9965	0.9928	0.9498	0.9853	0.9955	0.9888	0.9184	0.9851
BM 11 50 GWD/T	0.9917	0.9968	0.9196	0.9683	0.9887	0.9959	0.8809	0.9677
BM 11 60 GWD/T	0.9827	0.9943	0.8926	0.9506	0.9782	0.9958	0.8489	0.9497
Max c_k	0.9965	0.9968	0.9958	0.9953	0.9955	0.9959	0.9943	0.9957

Table GR-1: c_k Between EPRI Depletion Benchmarks (100 hours cooling) and Typical Spent Fuel Pools (3 of 7)

Fuel	W17	W17	W17	W17	W17	W17	W17	W17
Region	**2**	**2**	**2**	**2**	**2**	**2**	**1**	**1**
Areal Density ($g^{10}B/cm^2$)	**0.03**	**0.03**	**0.03**	**0.03**	**0.03**	**0.03**	**0.0**	**0.0**
Enrichment (wt%^{235}U)	**3.5**	**3.5**	**5**	**5**	**5**	**5**	**3.5**	**3.5**
Burnup (GWd/T)	**30**	**40**	**20**	**30**	**40**	**60**	**20**	**40**
EPRI Benchmark	c_k							
BM 1 10 GWD/T	0.8889	0.8440	0.9734	0.9353	0.8946	0.8233	0.8673	0.7937
BM 1 20 GWD/T	0.9793	0.9581	0.9823	0.9893	0.9789	0.9452	0.9147	0.9034
BM 1 30 GWD/T	0.9952	0.9894	0.9506	0.9832	0.9913	0.9819	0.9067	0.9330
BM 1 40 GWD/T	0.9908	0.9955	0.9155	0.9643	0.9846	0.9919	0.8871	0.9383
BM 1 50 GWD/T	0.9809	0.9928	0.8856	0.9449	0.9733	0.9921	0.8679	0.9355
BM 1 60 GWD/T	0.9711	0.9878	0.8628	0.9289	0.9627	0.9891	0.8524	0.9309
BM 2 10 GWD/T	0.7807	0.7219	0.9264	0.8570	0.7962	0.7014	0.7860	0.6733
BM 2 20 GWD/T	0.9198	0.8806	0.9913	0.9639	0.9298	0.8662	0.8859	0.8276
BM 2 30 GWD/T	0.9733	0.9498	0.9913	0.9931	0.9790	0.9405	0.9108	0.8931
BM 2 40 GWD/T	0.9920	0.9809	0.9703	0.9932	0.9944	0.9758	0.9100	0.9229
BM 2 50 GWD/T	0.9940	0.9928	0.9419	0.9807	0.9937	0.9911	0.8971	0.9339
BM 2 60 GWD/T	0.9882	0.9948	0.9131	0.9638	0.9858	0.9956	0.8810	0.9359
BM 3 10 GWD/T	0.8250	0.7708	0.9493	0.8909	0.8369	0.7500	0.8212	0.7217
BM 3 20 GWD/T	0.9491	0.9166	0.9941	0.9799	0.9549	0.9027	0.9021	0.8618
BM 3 30 GWD/T	0.9875	0.9710	0.9799	0.9944	0.9893	0.9624	0.9146	0.9147
BM 3 40 GWD/T	0.9956	0.9912	0.9508	0.9850	0.9943	0.9867	0.9042	0.9335
BM 3 50 GWD/T	0.9909	0.9957	0.9191	0.9672	0.9873	0.9943	0.8856	0.9364
BM 3 60 GWD/T	0.9820	0.9934	0.8910	0.9491	0.9767	0.9944	0.8689	0.9351
BM 4 10 GWD/T	0.8070	0.7504	0.9388	0.8762	0.8192	0.7288	0.8143	0.7077
BM 4 20 GWD/T	0.9387	0.9036	0.9916	0.9729	0.9446	0.8884	0.9022	0.8545
BM 4 30 GWD/T	0.9833	0.9647	0.9813	0.9923	0.9847	0.9547	0.9191	0.9134
BM 4 40 GWD/T	0.9939	0.9881	0.9519	0.9840	0.9918	0.9823	0.9109	0.9365
BM 4 50 GWD/T	0.9898	0.9939	0.9182	0.9656	0.9850	0.9914	0.8920	0.9412
BM 4 60 GWD/T	0.9796	0.9913	0.8867	0.9450	0.9728	0.9911	0.8719	0.9383
BM 5 10 GWD/T	0.8493	0.7983	0.9627	0.9107	0.8609	0.7788	0.8330	0.7430
BM 5 20 GWD/T	0.9562	0.9259	0.9946	0.9843	0.9619	0.9128	0.9026	0.8680
BM 5 30 GWD/T	0.9890	0.9736	0.9785	0.9948	0.9909	0.9655	0.9128	0.9155
BM 5 40 GWD/T	0.9957	0.9917	0.9501	0.9849	0.9948	0.9877	0.9018	0.9322
BM 5 50 GWD/T	0.9913	0.9959	0.9201	0.9685	0.9884	0.9951	0.8867	0.9373
BM 5 60 GWD/T	0.9825	0.9937	0.8928	0.9506	0.9780	0.9952	0.8685	0.9342
BM 6 10 GWD/T	0.8405	0.7881	0.9584	0.9037	0.8522	0.7681	0.8292	0.7354
BM 6 20 GWD/T	0.9522	0.9206	0.9947	0.9820	0.9580	0.9070	0.9029	0.8648
BM 6 30 GWD/T	0.9878	0.9716	0.9797	0.9944	0.9896	0.9631	0.9129	0.9137
BM 6 40 GWD/T	0.9955	0.9910	0.9511	0.9850	0.9943	0.9866	0.9030	0.9322
BM 6 50 GWD/T	0.9913	0.9958	0.9202	0.9681	0.9879	0.9945	0.8873	0.9376
BM 6 60 GWD/T	0.9821	0.9933	0.8918	0.9495	0.9770	0.9944	0.8684	0.9342

Fuel	W17	W17	W17	W17	W17	W17	W17	W17
Region	2	2	2	2	2	2	1	1
Areal Density (g^{10}B/cm^{2})	0.03	0.03	0.03	0.03	0.03	0.03	0.0	0.0
Enrichment (wt%^{235}U)	3.5	3.5	5	5	5	5	3.5	3.5
Burnup (GWd/T)	30	40	20	30	40	60	20	40
EPRI Benchmark	c_k							
BM 7 10 GWD/T	0.8612	0.8121	0.9683	0.9198	0.8726	0.7934	0.8377	0.7534
BM 7 20 GWD/T	0.9594	0.9298	0.9953	0.9865	0.9650	0.9170	0.9051	0.8724
BM 7 30 GWD/T	0.9894	0.9742	0.9783	0.9949	0.9913	0.9663	0.9119	0.9153
BM 7 40 GWD/T	0.9955	0.9915	0.9503	0.9850	0.9948	0.9876	0.9013	0.9316
BM 7 50 GWD/T	0.9913	0.9958	0.9208	0.9687	0.9884	0.9949	0.8855	0.9359
BM 7 60 GWD/T	0.9827	0.9937	0.8936	0.9511	0.9782	0.9952	0.8683	0.9336
BM 8 10 GWD/T	0.8317	0.7782	0.9530	0.8963	0.8434	0.7577	0.8255	0.7283
BM 8 20 GWD/T	0.9528	0.9213	0.9946	0.9824	0.9585	0.9077	0.9046	0.8667
BM 8 30 GWD/T	0.9891	0.9734	0.9788	0.9948	0.9907	0.9651	0.9136	0.9159
BM 8 40 GWD/T	0.9963	0.9924	0.9498	0.9852	0.9952	0.9883	0.9048	0.9354
BM 8 50 GWD/T	0.9916	0.9964	0.9193	0.9681	0.9883	0.9954	0.8873	0.9386
BM 8 60 GWD/T	0.9828	0.9942	0.8919	0.9503	0.9780	0.9955	0.8702	0.9364
BM 9 10 GWD/T	0.8298	0.7762	0.9520	0.8949	0.8417	0.7556	0.8245	0.7266
BM 9 20 GWD/T	0.9513	0.9196	0.9941	0.9813	0.9572	0.9060	0.9016	0.8632
BM 9 30 GWD/T	0.9881	0.9722	0.9788	0.9943	0.9899	0.9640	0.9118	0.9135
BM 9 40 GWD/T	0.9955	0.9914	0.9498	0.9846	0.9944	0.9873	0.9023	0.9325
BM 9 50 GWD/T	0.9909	0.9958	0.9188	0.9674	0.9876	0.9949	0.8851	0.9363
BM 9 60 GWD/T	0.9817	0.9933	0.8908	0.9491	0.9768	0.9947	0.8670	0.9335
BM 10 10 GWD/T	0.8359	0.7846	0.9535	0.8989	0.8484	0.7654	0.8139	0.7229
BM 10 20 GWD/T	0.9526	0.9233	0.9907	0.9802	0.9587	0.9109	0.8880	0.8561
BM 10 30 GWD/T	0.9861	0.9726	0.9726	0.9899	0.9880	0.9653	0.8957	0.9032
BM 10 40 GWD/T	0.9919	0.9900	0.9427	0.9789	0.9908	0.9867	0.8853	0.9206
BM 10 50 GWD/T	0.9857	0.9926	0.9108	0.9603	0.9823	0.9922	0.8674	0.9229
BM 10 60 GWD/T	0.9751	0.9885	0.8819	0.9408	0.9701	0.9903	0.8484	0.9186
BM 11 10 GWD/T	0.8343	0.7811	0.9546	0.8986	0.8460	0.7606	0.8288	0.7322
BM 11 20 GWD/T	0.9543	0.9232	0.9946	0.9832	0.9599	0.9097	0.9050	0.8683
BM 11 30 GWD/T	0.9898	0.9745	0.9782	0.9950	0.9914	0.9664	0.9138	0.9171
BM 11 40 GWD/T	0.9963	0.9927	0.9491	0.9848	0.9952	0.9887	0.9036	0.9349
BM 11 50 GWD/T	0.9915	0.9966	0.9187	0.9678	0.9883	0.9958	0.8867	0.9385
BM 11 60 GWD/T	0.9825	0.9941	0.8916	0.9501	0.9779	0.9956	0.8688	0.9354
Max c_k	0.9963	0.9966	0.9953	0.9950	0.9952	0.9958	0.9191	0.9412

Table GR-1: c_k Between EPRI Depletion Benchmarks (100 hours cooling) and Typical Spent Fuel Pools (4 of 7)

Fuel	**W17**	**W17**	**W17**	**W17**	**CE16**	**CE16**	**CE16**	**CE16**
Region	**1**	**1**	**1**	**1**	**2**	**2**	**2**	**2**
Areal Density ($g^{10}B/cm^2$)	**0.0**	**0.0**	**0.015**	**0.015**	**0**	**0**	**0**	**0**
Enrichment (wt%^{235}U)	**5**	**5**	**3.5**	**5**	**3.5**	**3.5**	**3.5**	**5**
Burnup (GWd/T)	**20**	**40**	**10**	**10**	**20**	**30**	**40**	**30**
EPRI Benchmark	c_k							
BM 1 10 GWD/T	0.8829	0.8318	0.9103	0.8883	0.9295	0.8783	0.8332	0.9247
BM 1 20 GWD/T	0.8875	0.9107	0.8926	0.8245	0.9696	0.9620	0.9436	0.9670
BM 1 30 GWD/T	0.8557	0.9216	0.8463	0.7550	0.9565	0.9748	0.9732	0.9554
BM 1 40 GWD/T	0.8216	0.9144	0.8020	0.6973	0.9335	0.9686	0.9784	0.9334
BM 1 50 GWD/T	0.7932	0.9034	0.7678	0.6554	0.9114	0.9576	0.9752	0.9121
BM 1 60 GWD/T	0.7719	0.8934	0.7429	0.6258	0.8937	0.9472	0.9700	0.8950
BM 2 10 GWD/T	0.8385	0.7362	0.8709	0.8920	0.8504	0.7715	0.7105	0.8518
BM 2 20 GWD/T	0.8974	0.8635	0.9162	0.8901	0.9447	0.9044	0.8658	0.9473
BM 2 30 GWD/T	0.8941	0.9086	0.8971	0.8407	0.9659	0.9538	0.9327	0.9695
BM 2 40 GWD/T	0.8731	0.9228	0.8653	0.7884	0.9614	0.9703	0.9628	0.9654
BM 2 50 GWD/T	0.8451	0.9214	0.8276	0.7362	0.9456	0.9707	0.9741	0.9501
BM 2 60 GWD/T	0.8178	0.9138	0.7941	0.6924	0.9267	0.9641	0.9758	0.9312
BM 3 10 GWD/T	0.8605	0.7760	0.8924	0.8977	0.8849	0.8155	0.7597	0.8839
BM 3 20 GWD/T	0.8983	0.8868	0.9103	0.8671	0.9603	0.9325	0.9015	0.9609
BM 3 30 GWD/T	0.8837	0.9192	0.8829	0.8116	0.9676	0.9678	0.9544	0.9691
BM 3 40 GWD/T	0.8547	0.9232	0.8421	0.7527	0.9536	0.9737	0.9736	0.9558
BM 3 50 GWD/T	0.8231	0.9150	0.8002	0.6988	0.9325	0.9672	0.9770	0.9354
BM 3 60 GWD/T	0.7973	0.9057	0.7704	0.6611	0.9127	0.9579	0.9748	0.9158
BM 4 10 GWD/T	0.8583	0.7652	0.8967	0.9075	0.8757	0.8015	0.7430	0.8737
BM 4 20 GWD/T	0.9028	0.8825	0.9209	0.8825	0.9590	0.9262	0.8922	0.9583
BM 4 30 GWD/T	0.8910	0.9200	0.8953	0.8271	0.9710	0.9673	0.9516	0.9710
BM 4 40 GWD/T	0.8627	0.9268	0.8569	0.7691	0.9585	0.9761	0.9745	0.9589
BM 4 50 GWD/T	0.8293	0.9192	0.8136	0.7124	0.9367	0.9703	0.9795	0.9375
BM 4 60 GWD/T	0.7990	0.9072	0.7765	0.6664	0.9140	0.9591	0.9764	0.9150
BM 5 10 GWD/T	0.8659	0.7934	0.8891	0.8868	0.8980	0.8352	0.7832	0.8984
BM 5 20 GWD/T	0.8953	0.8906	0.9024	0.8554	0.9612	0.9374	0.9088	0.9626
BM 5 30 GWD/T	0.8806	0.9191	0.8774	0.8047	0.9658	0.9679	0.9557	0.9680
BM 5 40 GWD/T	0.8522	0.9218	0.8377	0.7480	0.9516	0.9725	0.9727	0.9545
BM 5 50 GWD/T	0.8247	0.9165	0.8046	0.7037	0.9328	0.9674	0.9771	0.9361
BM 5 60 GWD/T	0.7979	0.9056	0.7705	0.6620	0.9127	0.9575	0.9742	0.9165
BM 6 10 GWD/T	0.8648	0.7875	0.8906	0.8914	0.8937	0.8282	0.7746	0.8937
BM 6 20 GWD/T	0.8978	0.8889	0.9079	0.8633	0.9611	0.9349	0.9048	0.9621
BM 6 30 GWD/T	0.8818	0.9181	0.8777	0.8061	0.9667	0.9673	0.9542	0.9686
BM 6 40 GWD/T	0.8538	0.9221	0.8393	0.7502	0.9530	0.9730	0.9728	0.9556
BM 6 50 GWD/T	0.8253	0.9166	0.8049	0.7040	0.9336	0.9680	0.9775	0.9365
BM 6 60 GWD/T	0.7973	0.9051	0.7691	0.6602	0.9129	0.9576	0.9744	0.9161

Fuel	W17	W17	W17	W17	CE16	CE16	CE16	CE16
Region	1	1	1	1	2	2	2	2
Areal Density ($g^{10}B/cm^2$)	0.0	0.0	0.015	0.015	0	0	0	0
Enrichment ($wt\%^{235}U$)	5	5	3.5	5	3.5	3.5	3.5	5
Burnup (GWd/T)	20	40	10	10	20	30	40	30
EPRI Benchmark	c_k							
BM 7 10 GWD/T	0.8670	0.8014	0.8842	0.8777	0.9034	0.8445	0.7947	0.9048
BM 7 20 GWD/T	0.8966	0.8942	0.9052	0.8570	0.9625	0.9402	0.9124	0.9642
BM 7 30 GWD/T	0.8794	0.9188	0.8745	0.8015	0.9652	0.9677	0.9558	0.9677
BM 7 40 GWD/T	0.8519	0.9214	0.8364	0.7470	0.9513	0.9721	0.9724	0.9545
BM 7 50 GWD/T	0.8240	0.9154	0.8017	0.7011	0.9324	0.9668	0.9763	0.9360
BM 7 60 GWD/T	0.7980	0.9054	0.7697	0.6615	0.9129	0.9574	0.9739	0.9168
BM 8 10 GWD/T	0.8630	0.7815	0.8931	0.8964	0.8893	0.8215	0.7667	0.8885
BM 8 20 GWD/T	0.8992	0.8906	0.9114	0.8665	0.9620	0.9360	0.9060	0.9628
BM 8 30 GWD/T	0.8815	0.9196	0.8775	0.8048	0.9667	0.9685	0.9561	0.9687
BM 8 40 GWD/T	0.8548	0.9247	0.8429	0.7529	0.9531	0.9743	0.9747	0.9557
BM 8 50 GWD/T	0.8248	0.9173	0.8041	0.7026	0.9329	0.9681	0.9780	0.9361
BM 8 60 GWD/T	0.7989	0.9074	0.7730	0.6639	0.9132	0.9585	0.9755	0.9168
BM 9 10 GWD/T	0.8625	0.7801	0.8954	0.8993	0.8879	0.8197	0.7646	0.8869
BM 9 20 GWD/T	0.8966	0.8874	0.9072	0.8626	0.9600	0.9336	0.9034	0.9610
BM 9 30 GWD/T	0.8801	0.9176	0.8760	0.8036	0.9656	0.9669	0.9543	0.9676
BM 9 40 GWD/T	0.8525	0.9220	0.8392	0.7494	0.9518	0.9726	0.9728	0.9545
BM 9 50 GWD/T	0.8226	0.9151	0.8012	0.6998	0.9316	0.9666	0.9766	0.9347
BM 9 60 GWD/T	0.7956	0.9043	0.7676	0.6583	0.9113	0.9566	0.9737	0.9148
BM 10 10 GWD/T	0.8488	0.7747	0.8616	0.8614	0.8818	0.8179	0.7654	0.8838
BM 10 20 GWD/T	0.8802	0.8784	0.8735	0.8258	0.9499	0.9277	0.9001	0.9533
BM 10 30 GWD/T	0.8616	0.9055	0.8411	0.7664	0.9527	0.9577	0.9476	0.9570
BM 10 40 GWD/T	0.8337	0.9085	0.8051	0.7137	0.9379	0.9620	0.9644	0.9426
BM 10 50 GWD/T	0.8036	0.9004	0.7677	0.6653	0.9168	0.9546	0.9665	0.9219
BM 10 60 GWD/T	0.7761	0.8883	0.7340	0.6243	0.8955	0.9432	0.9620	0.9009
BM 11 10 GWD/T	0.8659	0.7851	0.8982	0.9009	0.8917	0.8244	0.7699	0.8908
BM 11 20 GWD/T	0.8989	0.8916	0.9099	0.8642	0.9624	0.9372	0.9077	0.9633
BM 11 30 GWD/T	0.8810	0.9203	0.8767	0.8034	0.9665	0.9690	0.9571	0.9686
BM 11 40 GWD/T	0.8532	0.9240	0.8397	0.7493	0.9521	0.9738	0.9745	0.9549
BM 11 50 GWD/T	0.8240	0.9171	0.8029	0.7013	0.9321	0.9677	0.9779	0.9356
BM 11 60 GWD/T	0.7975	0.9064	0.7696	0.6605	0.9122	0.9577	0.9748	0.9161
Max c_k	0.9028	0.9268	0.9209	0.9075	0.9710	0.9761	0.9795	0.9710

Table GR-1: c_k Between EPRI Depletion Benchmarks (100 hours cooling) and Typical Spent Fuel Pools (5 of 7)

Fuel	**CE16**	**CE16**	**CE16**	**CE16**	**CE16**	**CE16**	**CE16**	**CE16**
Region	**2**	**2**	**2**	**2**	**2**	**2**	**2**	**2**
Areal Density ($g^{10}B/cm^2$)	**0**	**0**	**0.015**	**0.015**	**0.015**	**0.015**	**0.015**	**0.015**
Enrichment (wt%^{235}U)	**5**	**5**	**3.5**	**3.5**	**3.5**	**3.5**	**5**	**5**
Burnup (GWd/T)	**40**	**60**	**10**	**20**	**30**	**40**	**20**	**30**
EPRI Benchmark	**C_k**							
BM 1 10 GWD/T	0.8865	0.8133	0.9937	0.9501	0.8930	0.8448	0.9800	0.9439
BM 1 20 GWD/T	0.9632	0.9322	0.9571	0.9947	0.9806	0.9585	0.9760	0.9904
BM 1 30 GWD/T	0.9719	0.9677	0.9014	0.9832	0.9950	0.9896	0.9372	0.9802
BM 1 40 GWD/T	0.9631	0.9770	0.8518	0.9608	0.9895	0.9955	0.8978	0.9587
BM 1 50 GWD/T	0.9505	0.9768	0.8128	0.9391	0.9790	0.9928	0.8653	0.9377
BM 1 60 GWD/T	0.9391	0.9737	0.7841	0.9215	0.9688	0.9878	0.8408	0.9206
BM 2 10 GWD/T	0.7904	0.6904	0.9678	0.8688	0.7845	0.7211	0.9402	0.8688
BM 2 20 GWD/T	0.9169	0.8525	0.9904	0.9682	0.9218	0.8798	0.9936	0.9694
BM 2 30 GWD/T	0.9614	0.9249	0.9630	0.9921	0.9735	0.9486	0.9855	0.9939
BM 2 40 GWD/T	0.9741	0.9595	0.9235	0.9888	0.9912	0.9798	0.9590	0.9910
BM 2 50 GWD/T	0.9715	0.9743	0.8817	0.9737	0.9923	0.9917	0.9265	0.9761
BM 2 60 GWD/T	0.9624	0.9788	0.8433	0.9550	0.9859	0.9938	0.8947	0.9574
BM 3 10 GWD/T	0.8305	0.7395	0.9838	0.9042	0.8291	0.7707	0.9608	0.9017
BM 3 20 GWD/T	0.9406	0.8888	0.9837	0.9847	0.9506	0.9161	0.9929	0.9837
BM 3 30 GWD/T	0.9710	0.9475	0.9431	0.9940	0.9877	0.9705	0.9711	0.9938
BM 3 40 GWD/T	0.9735	0.9710	0.8966	0.9810	0.9946	0.9906	0.9368	0.9813
BM 3 50 GWD/T	0.9644	0.9778	0.8530	0.9607	0.9888	0.9948	0.9012	0.9613
BM 3 60 GWD/T	0.9532	0.9782	0.8168	0.9409	0.9796	0.9928	0.8708	0.9417
BM 4 10 GWD/T	0.8170	0.7220	0.9811	0.8926	0.8132	0.7520	0.9540	0.8896
BM 4 20 GWD/T	0.9345	0.8783	0.9895	0.9813	0.9423	0.9048	0.9940	0.9792
BM 4 30 GWD/T	0.9703	0.9434	0.9518	0.9956	0.9855	0.9659	0.9758	0.9941
BM 4 40 GWD/T	0.9751	0.9708	0.9042	0.9840	0.9952	0.9895	0.9410	0.9828
BM 4 50 GWD/T	0.9663	0.9793	0.8574	0.9629	0.9902	0.9953	0.9030	0.9618
BM 4 60 GWD/T	0.9528	0.9787	0.8169	0.9405	0.9794	0.9926	0.8686	0.9395
BM 5 10 GWD/T	0.8498	0.7644	0.9872	0.9204	0.8514	0.7967	0.9704	0.9190
BM 5 20 GWD/T	0.9452	0.8970	0.9785	0.9869	0.9565	0.9245	0.9912	0.9865
BM 5 30 GWD/T	0.9713	0.9494	0.9386	0.9929	0.9884	0.9724	0.9686	0.9933
BM 5 40 GWD/T	0.9727	0.9707	0.8938	0.9796	0.9940	0.9904	0.9352	0.9806
BM 5 50 GWD/T	0.9652	0.9783	0.8528	0.9610	0.9892	0.9950	0.9022	0.9623
BM 5 60 GWD/T	0.9535	0.9779	0.8174	0.9413	0.9797	0.9926	0.8722	0.9429
BM 6 10 GWD/T	0.8430	0.7553	0.9869	0.9149	0.8434	0.7872	0.9677	0.9132
BM 6 20 GWD/T	0.9429	0.8925	0.9821	0.9860	0.9533	0.9198	0.9927	0.9853
BM 6 30 GWD/T	0.9707	0.9474	0.9420	0.9935	0.9874	0.9706	0.9704	0.9934
BM 6 40 GWD/T	0.9731	0.9704	0.8967	0.9807	0.9941	0.9901	0.9368	0.9812
BM 6 50 GWD/T	0.9654	0.9784	0.8544	0.9616	0.9895	0.9952	0.9027	0.9624
BM 6 60 GWD/T	0.9531	0.9778	0.8177	0.9411	0.9795	0.9925	0.8715	0.9421

Fuel	**CE16**	**CE16**	**CE16**	**CE16**	**CE16**	**CE16**	**CE16**	**CE16**
Region	**2**	**2**	**2**	**2**	**2**	**2**	**2**	**2**
Areal Density (g^{10}B/cm^2)	**0**	**0**	**0.015**	**0.015**	**0.015**	**0.015**	**0.015**	**0.015**
Enrichment (wt%^{235}U)	**5**	**5**	**3.5**	**3.5**	**3.5**	**3.5**	**5**	**5**
Burnup (GWd/T)	**40**	**60**	**10**	**20**	**30**	**40**	**20**	**30**
EPRI Benchmark	**C_k**							
BM 7 10 GWD/T	0.8588	0.7768	0.9870	0.9275	0.8622	0.8097	0.9737	0.9268
BM 7 20 GWD/T	0.9479	0.9011	0.9772	0.9886	0.9597	0.9284	0.9915	0.9885
BM 7 30 GWD/T	0.9712	0.9497	0.9374	0.9926	0.9885	0.9728	0.9679	0.9932
BM 7 40 GWD/T	0.9725	0.9704	0.8938	0.9794	0.9937	0.9901	0.9353	0.9806
BM 7 50 GWD/T	0.9648	0.9776	0.8533	0.9609	0.9888	0.9945	0.9025	0.9623
BM 7 60 GWD/T	0.9536	0.9776	0.8182	0.9415	0.9797	0.9924	0.8729	0.9433
BM 8 10 GWD/T	0.8363	0.7467	0.9852	0.9089	0.8354	0.7779	0.9637	0.9066
BM 8 20 GWD/T	0.9439	0.8937	0.9819	0.9866	0.9542	0.9207	0.9928	0.9858
BM 8 30 GWD/T	0.9717	0.9495	0.9397	0.9935	0.9887	0.9725	0.9692	0.9936
BM 8 40 GWD/T	0.9742	0.9726	0.8940	0.9806	0.9953	0.9918	0.9356	0.9814
BM 8 50 GWD/T	0.9656	0.9792	0.8518	0.9610	0.9897	0.9957	0.9014	0.9621
BM 8 60 GWD/T	0.9542	0.9792	0.8165	0.9415	0.9804	0.9935	0.8716	0.9429
BM 9 10 GWD/T	0.8345	0.7446	0.9846	0.9076	0.8337	0.7759	0.9629	0.9053
BM 9 20 GWD/T	0.9417	0.8911	0.9815	0.9851	0.9522	0.9185	0.9919	0.9843
BM 9 30 GWD/T	0.9703	0.9477	0.9399	0.9927	0.9874	0.9710	0.9689	0.9928
BM 9 40 GWD/T	0.9726	0.9707	0.8941	0.9797	0.9939	0.9903	0.9351	0.9804
BM 9 50 GWD/T	0.9641	0.9777	0.8515	0.9600	0.9886	0.9948	0.9006	0.9611
BM 9 60 GWD/T	0.9523	0.9773	0.8153	0.9399	0.9788	0.9922	0.8700	0.9412
BM 10 10 GWD/T	0.8336	0.7471	0.9780	0.9071	0.8365	0.7815	0.9600	0.9066
BM 10 20 GWD/T	0.9361	0.8892	0.9707	0.9800	0.9505	0.9198	0.9845	0.9807
BM 10 30 GWD/T	0.9613	0.9421	0.9269	0.9847	0.9824	0.9689	0.9589	0.9860
BM 10 40 GWD/T	0.9621	0.9631	0.8808	0.9705	0.9874	0.9865	0.9244	0.9723
BM 10 50 GWD/T	0.9522	0.9683	0.8377	0.9497	0.9805	0.9890	0.8891	0.9517
BM 10 60 GWD/T	0.9389	0.9661	0.8011	0.9284	0.9693	0.9849	0.8577	0.9307
BM 11 10 GWD/T	0.8391	0.7500	0.9863	0.9113	0.8384	0.7810	0.9655	0.9091
BM 11 20 GWD/T	0.9450	0.8955	0.9809	0.9871	0.9555	0.9225	0.9925	0.9863
BM 11 30 GWD/T	0.9722	0.9507	0.9381	0.9934	0.9893	0.9736	0.9683	0.9936
BM 11 40 GWD/T	0.9738	0.9726	0.8922	0.9798	0.9949	0.9918	0.9344	0.9807
BM 11 50 GWD/T	0.9653	0.9793	0.8504	0.9603	0.9894	0.9958	0.9006	0.9617
BM 11 60 GWD/T	0.9536	0.9787	0.8154	0.9407	0.9798	0.9931	0.8709	0.9423
Max c_k	0.9751	0.9793	0.9937	0.9956	0.9953	0.9958	0.9940	0.9941

Table GR-1: c_k Between EPRI Depletion Benchmarks (100 hours cooling) and Typical Spent Fuel Pools (6 of 7)

Fuel	CE16	CE16	CE16	CE16	CE16	CE16	CE16	CE16
Region	2	2	2	2	2	2	2	2
Areal Density ($g^{10}B/cm^2$)	0.015	0.015	0.03	0.03	0.03	0.03	0.03	0.03
Enrichment (wt%^{235}U)	5	5	3.5	3.5	3.5	3.5	5	5
Burnup (GWd/T)	40	60	10	20	30	40	20	30
EPRI Benchmark	c_k							
BM 1 10 GWD/T	0.9006	0.8240	0.9925	0.9500	0.8929	0.8446	0.9795	0.9433
BM 1 20 GWD/T	0.9812	0.9458	0.9557	0.9943	0.9804	0.9582	0.9754	0.9897
BM 1 30 GWD/T	0.9915	0.9825	0.8999	0.9828	0.9948	0.9892	0.9367	0.9793
BM 1 40 GWD/T	0.9834	0.9926	0.8502	0.9603	0.9893	0.9951	0.8974	0.9578
BM 1 50 GWD/T	0.9712	0.9929	0.8113	0.9386	0.9788	0.9924	0.8649	0.9367
BM 1 60 GWD/T	0.9600	0.9900	0.7825	0.9209	0.9686	0.9874	0.8404	0.9197
BM 2 10 GWD/T	0.8027	0.7004	0.9665	0.8689	0.7846	0.7210	0.9397	0.8683
BM 2 20 GWD/T	0.9336	0.8654	0.9893	0.9680	0.9217	0.8797	0.9932	0.9689
BM 2 30 GWD/T	0.9804	0.9396	0.9617	0.9918	0.9733	0.9484	0.9851	0.9933
BM 2 40 GWD/T	0.9944	0.9751	0.9221	0.9884	0.9910	0.9795	0.9586	0.9903
BM 2 50 GWD/T	0.9925	0.9905	0.8802	0.9733	0.9921	0.9914	0.9260	0.9752
BM 2 60 GWD/T	0.9837	0.9953	0.8418	0.9545	0.9858	0.9935	0.8943	0.9565
BM 3 10 GWD/T	0.8435	0.7497	0.9826	0.9042	0.8291	0.7706	0.9603	0.9012
BM 3 20 GWD/T	0.9580	0.9022	0.9824	0.9845	0.9505	0.9159	0.9924	0.9830
BM 3 30 GWD/T	0.9903	0.9622	0.9418	0.9937	0.9875	0.9703	0.9706	0.9930
BM 3 40 GWD/T	0.9938	0.9866	0.8952	0.9806	0.9944	0.9903	0.9363	0.9805
BM 3 50 GWD/T	0.9855	0.9942	0.8513	0.9602	0.9887	0.9945	0.9008	0.9604
BM 3 60 GWD/T	0.9743	0.9947	0.8152	0.9404	0.9795	0.9925	0.8704	0.9408
BM 4 10 GWD/T	0.8280	0.7301	0.9802	0.8925	0.8130	0.7519	0.9534	0.8891
BM 4 20 GWD/T	0.9500	0.8896	0.9884	0.9809	0.9421	0.9045	0.9934	0.9786
BM 4 30 GWD/T	0.9879	0.9562	0.9507	0.9951	0.9852	0.9656	0.9752	0.9934
BM 4 40 GWD/T	0.9937	0.9842	0.9031	0.9834	0.9949	0.9892	0.9404	0.9820
BM 4 50 GWD/T	0.9855	0.9934	0.8561	0.9623	0.9898	0.9950	0.9025	0.9610
BM 4 60 GWD/T	0.9724	0.9934	0.8155	0.9399	0.9791	0.9923	0.8682	0.9386
BM 5 10 GWD/T	0.8655	0.7773	0.9856	0.9205	0.8516	0.7967	0.9700	0.9184
BM 5 20 GWD/T	0.9637	0.9116	0.9770	0.9866	0.9565	0.9243	0.9907	0.9857
BM 5 30 GWD/T	0.9912	0.9647	0.9372	0.9926	0.9883	0.9722	0.9681	0.9925
BM 5 40 GWD/T	0.9936	0.9870	0.8923	0.9792	0.9938	0.9901	0.9348	0.9797
BM 5 50 GWD/T	0.9864	0.9947	0.8514	0.9605	0.9890	0.9947	0.9018	0.9615
BM 5 60 GWD/T	0.9751	0.9949	0.8158	0.9408	0.9796	0.9923	0.8718	0.9419
BM 6 10 GWD/T	0.8577	0.7672	0.9854	0.9149	0.8435	0.7871	0.9672	0.9126
BM 6 20 GWD/T	0.9607	0.9063	0.9807	0.9858	0.9533	0.9196	0.9922	0.9846
BM 6 30 GWD/T	0.9902	0.9625	0.9405	0.9931	0.9873	0.9703	0.9699	0.9926
BM 6 40 GWD/T	0.9935	0.9862	0.8951	0.9803	0.9940	0.9898	0.9364	0.9803
BM 6 50 GWD/T	0.9863	0.9946	0.8529	0.9612	0.9893	0.9949	0.9023	0.9616
BM 6 60 GWD/T	0.9744	0.9945	0.8160	0.9406	0.9794	0.9922	0.8711	0.9411

Fuel	**CE16**	**CE16**	**CE16**	**CE16**	**CE16**	**CE16**	**CE16**	**CE16**
Region	**2**	**2**	**2**	**2**	**2**	**2**	**2**	**2**
Areal Density (g^{10}B/cm^2)	**0.015**	**0.015**	**0.03**	**0.03**	**0.03**	**0.03**	**0.03**	**0.03**
Enrichment (wt%^{235}U)	**5**	**5**	**3.5**	**3.5**	**3.5**	**3.5**	**5**	**5**
Burnup (GWd/T)	**40**	**60**	**10**	**20**	**30**	**40**	**20**	**30**
EPRI Benchmark	**c_k**							
BM 7 10 GWD/T	0.8760	0.7912	0.9852	0.9276	0.8625	0.8096	0.9733	0.9261
BM 7 20 GWD/T	0.9668	0.9158	0.9759	0.9884	0.9597	0.9282	0.9911	0.9878
BM 7 30 GWD/T	0.9914	0.9653	0.9359	0.9922	0.9884	0.9726	0.9675	0.9924
BM 7 40 GWD/T	0.9934	0.9867	0.8922	0.9790	0.9935	0.9898	0.9348	0.9797
BM 7 50 GWD/T	0.9862	0.9943	0.8517	0.9604	0.9887	0.9942	0.9021	0.9614
BM 7 60 GWD/T	0.9752	0.9948	0.8165	0.9411	0.9795	0.9921	0.8725	0.9423
BM 8 10 GWD/T	0.8496	0.7572	0.9839	0.9089	0.8355	0.7778	0.9632	0.9061
BM 8 20 GWD/T	0.9615	0.9072	0.9807	0.9863	0.9541	0.9205	0.9923	0.9851
BM 8 30 GWD/T	0.9913	0.9646	0.9382	0.9931	0.9885	0.9722	0.9687	0.9928
BM 8 40 GWD/T	0.9946	0.9882	0.8926	0.9802	0.9951	0.9915	0.9351	0.9806
BM 8 50 GWD/T	0.9866	0.9954	0.8504	0.9605	0.9895	0.9954	0.9010	0.9612
BM 8 60 GWD/T	0.9755	0.9957	0.8150	0.9410	0.9802	0.9932	0.8712	0.9420
BM 9 10 GWD/T	0.8479	0.7551	0.9835	0.9076	0.8337	0.7758	0.9624	0.9048
BM 9 20 GWD/T	0.9597	0.9051	0.9801	0.9848	0.9522	0.9184	0.9914	0.9836
BM 9 30 GWD/T	0.9901	0.9631	0.9384	0.9923	0.9873	0.9707	0.9684	0.9920
BM 9 40 GWD/T	0.9934	0.9867	0.8926	0.9793	0.9938	0.9900	0.9347	0.9796
BM 9 50 GWD/T	0.9855	0.9945	0.8499	0.9596	0.9885	0.9944	0.9001	0.9602
BM 9 60 GWD/T	0.9739	0.9944	0.8137	0.9394	0.9787	0.9918	0.8696	0.9402
BM 10 10 GWD/T	0.8517	0.7628	0.9757	0.9073	0.8370	0.7815	0.9597	0.9057
BM 10 20 GWD/T	0.9585	0.9080	0.9683	0.9800	0.9509	0.9196	0.9841	0.9797
BM 10 30 GWD/T	0.9855	0.9625	0.9244	0.9845	0.9827	0.9687	0.9585	0.9850
BM 10 40 GWD/T	0.9871	0.9841	0.8783	0.9703	0.9877	0.9862	0.9240	0.9712
BM 10 50 GWD/T	0.9776	0.9898	0.8353	0.9494	0.9808	0.9888	0.8888	0.9506
BM 10 60 GWD/T	0.9645	0.9880	0.7986	0.9281	0.9696	0.9846	0.8575	0.9295
BM 11 10 GWD/T	0.8524	0.7604	0.9852	0.9113	0.8384	0.7810	0.9650	0.9086
BM 11 20 GWD/T	0.9627	0.9091	0.9797	0.9868	0.9554	0.9223	0.9920	0.9857
BM 11 30 GWD/T	0.9919	0.9658	0.9366	0.9930	0.9891	0.9733	0.9678	0.9928
BM 11 40 GWD/T	0.9943	0.9884	0.8908	0.9793	0.9947	0.9915	0.9339	0.9798
BM 11 50 GWD/T	0.9864	0.9956	0.8489	0.9598	0.9893	0.9954	0.9001	0.9608
BM 11 60 GWD/T	0.9751	0.9955	0.8137	0.9402	0.9796	0.9928	0.8705	0.9414
Max c_k	0.9946	0.9957	0.9925	0.9951	0.9951	0.9954	0.9934	0.9934

Table GR-1: c_k Between EPRI Depletion Benchmarks (100 hours cooling) and Typical Spent Fuel Pools (7 of 7)

Fuel	**CE16**	**CE16**	**CE16**	**CE16**	**CE16**	**CE16**	**CE16**	**CE16**
Region	**2**	**2**	**1**	**1**	**1**	**1**	**1**	**1**
Areal Density (g^{10}B/cm^2)	**0.03**	**0.03**	**0.0**	**0.0**	**0.0**	**0.0**	**0.015**	**0.015**
Enrichment (wt%^{235}U)	**5**	**5**	**3.5**	**3.5**	**5**	**5**	**3.5**	**5**
Burnup (GWd/T)	**40**	**60**	**20**	**40**	**20**	**40**	**10**	**10**
EPRI Benchmark	c_k							
BM 1 10 GWD/T	0.9002	0.8237	0.8631	0.7890	0.8656	0.8281	0.8861	0.8459
BM 1 20 GWD/T	0.9807	0.9453	0.9015	0.8966	0.8579	0.9017	0.8516	0.7676
BM 1 30 GWD/T	0.9908	0.9819	0.8888	0.9254	0.8204	0.9098	0.7977	0.6922
BM 1 40 GWD/T	0.9826	0.9919	0.8665	0.9302	0.7830	0.9010	0.7491	0.6316
BM 1 50 GWD/T	0.9705	0.9922	0.8458	0.9273	0.7530	0.8892	0.7127	0.5885
BM 1 60 GWD/T	0.9593	0.9893	0.8293	0.9226	0.7307	0.8786	0.6865	0.5585
BM 2 10 GWD/T	0.8024	0.7000	0.7861	0.6684	0.8289	0.7344	0.8574	0.8598
BM 2 20 GWD/T	0.9333	0.8652	0.8780	0.8210	0.8760	0.8573	0.8863	0.8429
BM 2 30 GWD/T	0.9800	0.9392	0.8973	0.8852	0.8650	0.8989	0.8569	0.7844
BM 2 40 GWD/T	0.9939	0.9746	0.8930	0.9145	0.8393	0.9111	0.8188	0.7272
BM 2 50 GWD/T	0.9918	0.9900	0.8774	0.9251	0.8081	0.9082	0.7767	0.6717
BM 2 60 GWD/T	0.9831	0.9947	0.8596	0.9270	0.7787	0.8997	0.7405	0.6264
BM 3 10 GWD/T	0.8431	0.7494	0.8199	0.7170	0.8483	0.7737	0.8752	0.8619
BM 3 20 GWD/T	0.9576	0.9018	0.8918	0.8549	0.8733	0.8791	0.8756	0.8154
BM 3 30 GWD/T	0.9898	0.9617	0.8995	0.9070	0.8521	0.9089	0.8392	0.7526
BM 3 40 GWD/T	0.9932	0.9861	0.8856	0.9252	0.8188	0.9108	0.7927	0.6894
BM 3 50 GWD/T	0.9847	0.9935	0.8643	0.9276	0.7841	0.9010	0.7470	0.6326
BM 3 60 GWD/T	0.9736	0.9940	0.8465	0.9264	0.7570	0.8911	0.7153	0.5942
BM 4 10 GWD/T	0.8277	0.7300	0.8161	0.7047	0.8499	0.7653	0.8839	0.8764
BM 4 20 GWD/T	0.9495	0.8893	0.8948	0.8493	0.8811	0.8772	0.8902	0.8348
BM 4 30 GWD/T	0.9874	0.9559	0.9065	0.9074	0.8622	0.9117	0.8549	0.7713
BM 4 40 GWD/T	0.9931	0.9838	0.8950	0.9302	0.8296	0.9168	0.8108	0.7090
BM 4 50 GWD/T	0.9849	0.9929	0.8734	0.9345	0.7931	0.9076	0.7634	0.6493
BM 4 60 GWD/T	0.9717	0.9928	0.8516	0.9314	0.7607	0.8946	0.7237	0.6018
BM 5 10 GWD/T	0.8650	0.7768	0.8282	0.7365	0.8495	0.7885	0.8665	0.8455
BM 5 20 GWD/T	0.9632	0.9111	0.8904	0.8601	0.8681	0.8815	0.8649	0.8010
BM 5 30 GWD/T	0.9907	0.9643	0.8967	0.9073	0.8478	0.9080	0.8325	0.7446
BM 5 40 GWD/T	0.9929	0.9864	0.8825	0.9233	0.8155	0.9088	0.7874	0.6838
BM 5 50 GWD/T	0.9858	0.9942	0.8657	0.9285	0.7860	0.9026	0.7516	0.6380
BM 5 60 GWD/T	0.9744	0.9942	0.8458	0.9251	0.7572	0.8907	0.7151	0.5946
BM 6 10 GWD/T	0.8573	0.7667	0.8258	0.7295	0.8501	0.7836	0.8701	0.8522
BM 6 20 GWD/T	0.9603	0.9059	0.8919	0.8576	0.8720	0.8808	0.8721	0.8106
BM 6 30 GWD/T	0.9896	0.9620	0.8971	0.9055	0.8495	0.9071	0.8331	0.7462
BM 6 40 GWD/T	0.9929	0.9856	0.8840	0.9236	0.8175	0.9093	0.7895	0.6863
BM 6 50 GWD/T	0.9857	0.9940	0.8666	0.9291	0.7869	0.9030	0.7522	0.6384
BM 6 60 GWD/T	0.9737	0.9937	0.8458	0.9253	0.7568	0.8904	0.7138	0.5930

Fuel	**CE16**	**CE16**	**CE16**	**CE16**	**CE16**	**CE16**	**CE16**	**CE16**
Region	**2**	**2**	**1**	**1**	**1**	**1**	**1**	**1**
Areal Density (g^{10}B/cm^2)	**0.03**	**0.03**	**0.0**	**0.0**	**0.0**	**0.0**	**0.015**	**0.015**
Enrichment (wt%^{235}U)	**5**	**5**	**3.5**	**3.5**	**5**	**5**	**3.5**	**5**
Burnup (GWd/T)	**40**	**60**	**20**	**40**	**20**	**40**	**10**	**10**
EPRI Benchmark	**c_k**							
BM 7 10 GWD/T	0.8755	0.7905	0.8309	0.7457	0.8483	0.7950	0.8585	0.8332
BM 7 20 GWD/T	0.9664	0.9154	0.8929	0.8646	0.8693	0.8851	0.8674	0.8025
BM 7 30 GWD/T	0.9908	0.9648	0.8954	0.9068	0.8462	0.9073	0.8290	0.7408
BM 7 40 GWD/T	0.9928	0.9861	0.8817	0.9226	0.8150	0.9081	0.7859	0.6825
BM 7 50 GWD/T	0.9855	0.9937	0.8641	0.9268	0.7848	0.9011	0.7482	0.6348
BM 7 60 GWD/T	0.9745	0.9940	0.8454	0.9243	0.7572	0.8902	0.7141	0.5939
BM 8 10 GWD/T	0.8492	0.7569	0.8235	0.7233	0.8500	0.7788	0.8748	0.8595
BM 8 20 GWD/T	0.9611	0.9068	0.8940	0.8598	0.8738	0.8828	0.8760	0.8143
BM 8 30 GWD/T	0.9907	0.9641	0.8976	0.9078	0.8489	0.9086	0.8327	0.7447
BM 8 40 GWD/T	0.9941	0.9877	0.8862	0.9272	0.8187	0.9123	0.7933	0.6895
BM 8 50 GWD/T	0.9859	0.9948	0.8663	0.9299	0.7860	0.9035	0.7509	0.6367
BM 8 60 GWD/T	0.9748	0.9950	0.8478	0.9276	0.7586	0.8928	0.7178	0.5969
BM 9 10 GWD/T	0.8477	0.7549	0.8229	0.7218	0.8499	0.7777	0.8776	0.8630
BM 9 20 GWD/T	0.9592	0.9047	0.8905	0.8559	0.8707	0.8792	0.8714	0.8098
BM 9 30 GWD/T	0.9896	0.9626	0.8957	0.9052	0.8473	0.9063	0.8310	0.7433
BM 9 40 GWD/T	0.9928	0.9862	0.8832	0.9238	0.8160	0.9091	0.7892	0.6855
BM 9 50 GWD/T	0.9849	0.9938	0.8638	0.9274	0.7836	0.9010	0.7479	0.6336
BM 9 60 GWD/T	0.9732	0.9937	0.8441	0.9243	0.7548	0.8892	0.7119	0.5908
BM 10 10 GWD/T	0.8510	0.7618	0.8070	0.7146	0.8308	0.7679	0.8368	0.8173
BM 10 20 GWD/T	0.9577	0.9070	0.8722	0.8457	0.8496	0.8663	0.8317	0.7665
BM 10 30 GWD/T	0.9847	0.9614	0.8749	0.8919	0.8246	0.8905	0.7905	0.7001
BM 10 40 GWD/T	0.9862	0.9830	0.8619	0.9091	0.7932	0.8921	0.7499	0.6443
BM 10 50 GWD/T	0.9767	0.9887	0.8420	0.9113	0.7608	0.8828	0.7094	0.5941
BM 10 60 GWD/T	0.9636	0.9868	0.8214	0.9066	0.7317	0.8698	0.6736	0.5519
BM 11 10 GWD/T	0.8521	0.7601	0.8272	0.7275	0.8531	0.7827	0.8801	0.8644
BM 11 20 GWD/T	0.9622	0.9087	0.8941	0.8612	0.8730	0.8836	0.8740	0.8116
BM 11 30 GWD/T	0.9913	0.9653	0.8976	0.9089	0.8482	0.9092	0.8315	0.7430
BM 11 40 GWD/T	0.9937	0.9878	0.8844	0.9264	0.8167	0.9112	0.7895	0.6854
BM 11 50 GWD/T	0.9858	0.9950	0.8655	0.9298	0.7851	0.9032	0.7494	0.6352
BM 11 60 GWD/T	0.9744	0.9947	0.8459	0.9263	0.7568	0.8914	0.7138	0.5930
Max c_k	0.9941	0.9950	0.9065	0.9345	0.8811	0.9168	0.8902	0.8764

NRC Questions and Responses:

1. In Section 2, it is stated that, "In particular, it is important to assure that the neutron energy spectrum for the critical system is bounded by the neutron energy spectrum in benchmarks used for the determination of Δk_d." With the large variation in possible Spent Fuel Pool (SFP) configurations, how is it ensured that the neutron energy spectrum in benchmarks used for the determination of Δk_d are similar (or bound) the neutron energy spectrum for all possible critical systems?

Response:

The term "bounded by" in Section 2 should be replaced with "representative of" as it is not likely that all the possible spectrums in the SFP will be strictly bounded by the set of 11 benchmarks. However, the particular benchmarks included were selected to provide a range of spectra that are representative of the spent fuel pool environment. Figure 1.1 demonstrates this pictorially, where the Energy of the Average Lethargy causing Fission (EALF) for the benchmarks is compared to the EALF from a range of typical SFP racks as a function of burnup. It is observed that the hardest spectrum is from Benchmark 10, which contains 1500 ppm soluble boron as it has the highest EALF of all benchmark cases at all burnups. The softest spectrum is from Benchmark 4, which uses the OFA fuel pin design as it has the lowest EALF of all benchmark cases at all burnups. The same rack and fuel configurations, 56 cases in total, used in the previous EPRI sensitivity studies [2] are used for the analysis. The key parameters for rack descriptions are provided in the first few rows of Table GR-1. As evident from the points plotted in Figure 1.1, the benchmarks bound the majority of the spent fuel rack configurations and are representative of all configurations. The prime exception where the benchmarks do not necessarily "bound" the typical rack configurations is in the fresh fuel cases (zero burnup), where the spectrum is much softer than what the benchmark cases represent. However, the benchmarks where chosen with the intent to represent the spectrum associated with spent fuel for quantification of the depletion uncertainty and the fresh fuel configuration is already covered by the fresh fuel benchmarks that are addressed in NEI 12-16 [6].

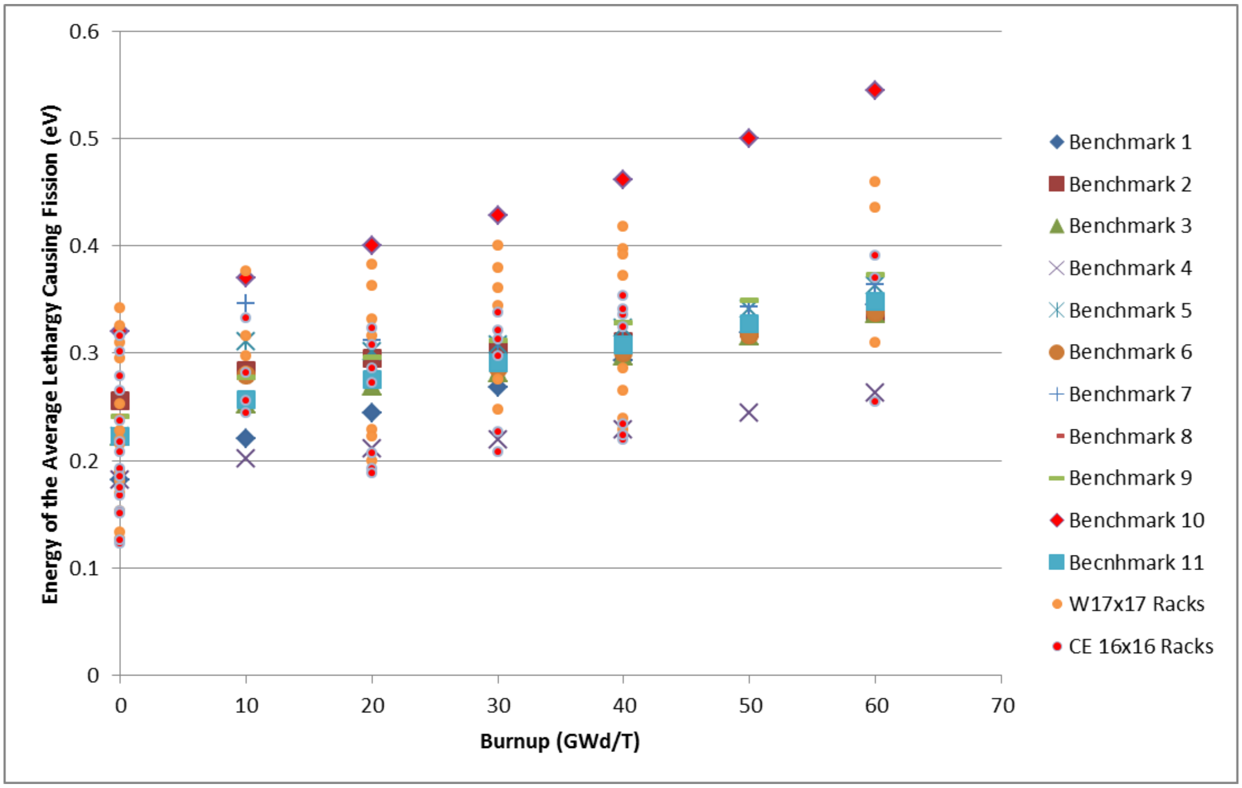

Figure 1-1: Energy Spectrum Index (EALF) of the Benchmarks and Typical Racks as a Function of Burnup

Question 1 continued:

a. In order to justify the bias and bias uncertainty analysis based on the 3-D reactor environment, there should be sufficient similarity to a sufficient range of 3-D SFP environments (rather than 2-D). If sufficient similarity does not exist, then applying depletion bias and bias uncertainty from the reactor benchmarks to the SFP environment becomes questionable.

   A limited similarity assessment has been performed in Electric Power Research Institute (EPRI) Report 1025203, "Utilization of the EPRI Depletion Benchmarks for Burnup Credit Validation," looking at correlation coefficients (or c_k values) to justify the treatment of cross-section uncertainties when going from hot full power (HFP) in-core conditions to cold in-rack SFP conditions. How do c_k values compare between the 3-D reactor environment and the 3-D SFP environment and how sensitive are these c_k values to differences in the 3-D reactor environment, differences in the 3-D SFP environment, or both?

Response:

The depletion reactivity bias and uncertainty is related to cross sections, yields, and decay constants not spatial distribution. The ability to correctly predict spatial effects is covered by the fresh fuel critical experiments. However, since burnup is not uniform, if a burnup dependent bias were used, one would need to correctly average the burnups. In the SFP environment, the flux is higher at the top where the burnup is smaller. A volume averaged burnup over-predicts the effective burnup. For biases that increase the predicted reactivity, using a higher (volume averaged) burnup would be conservative (assuming the magnitude of the bias increases with burnup). Section 6 of the Utilization report recommends using a constant conservative bias, rather than a burnup dependent bias, so that correct averaging would not be an issue.

In order to confirm that the benchmarks cover the 3D effects, a 3-D model of the EPRI Benchmark 3 at 50 GWd/T (100 hours cooling) was created. The analysis was performed using the axial burnup profile provided in Table 5 of Reference 7.The c_k values, as a function of burnup for Benchmark 3, from the 3D analysis were compared against the 2D analysis and shown in Table 1-1. The 3D 50 GWd/T 3D case matches best with the 30 and 40 GWd/T 2D cases, indicating the importance of the lower burnup regions near the ends of the assembly.

To confirm that the conclusion does not change when the rack features are included in the benchmark cases, the same node-wise atom densities were put into a Region 2 style rack (see Reference 2 for rack features) with absorber panels having an areal density of 0.015 $g^{10}B/cm^2$. Table 1-1 shows the c_k comparison of Benchmark 3 with the rack included to the 2D benchmark for Benchmark 3 as a function of burnup. When the results in Table 1-1 are compared, it is observed that the rack features change the c_k values slightly; however, there is still good agreement with the benchmark case (i.e., c_k greater than 0.9 in all but the low burnup case).

Table 1-1: c_k Comparison between 2D and 3D analysis

Benchmark 3 Burnup (GWd/T)	**c_k Comparing 3D Benchmark 3 at 50 GWd/T to 2D Benchmarks**	**c_k Comparing 3D Benchmark 3 at 50 GWd/T with Rack included to 2D Benchmarks**
10	0.8415	0.8356
20	0.9507	0.9473
30	0.9813	0.9791
40	0.9822	0.9811
50	0.9710	0.9709
60	0.9599	0.9604

Question 1 continued:

b. In Table 8-4 of EPRI Report 1025203, there is only a single “spent nuclear fuel rack” where c_k relative to HFP in-core conditions is calculated. This rack is described as “a simplified uniform rack...with a 0.0625 cm thick borated aluminum poison sheet having a width of 19 cm, and a B-10 areal density of 0.006 g/cm^2.” What is the c_k sensitivity to different areal density, poison width, poison thickness, soluble boron, temperatures, low power density (rather than high), etc.? At what c_k would the bias and bias uncertainty estimates begin to breakdown in terms of applicability?

Response:

The c_k analysis presented in the General Response and Table GR-1 demonstrates the effect of changing various rack and fuel design features. Each of the individual parameters included in the RAI are addressed below:

Areal density

Table GR-1 shows the change in c_k for three areal densities; 0, 0.015, and 0.03 g^{10}B/cm^2. The areal density of the absorber panel in the rack makes a difference in the c_k but not enough to challenge the similarity criteria. Table 1-2, using data from Table GR-1, shows how the c_k changes with areal density for two points on a typical loading curve.

Table 1-2: c_k Changes with Areal Density

EPRI Benchmark Case	Spent Fuel In Rack		Areal Density (g^{10}B/cm^2)		
	Enrichment (wt% ^{235}U)	Burnup (GWd/T)	0	0.015	0.030
			Similarity between Benchmark and Rack (c_k)		
BM1 30 GWd/T	3.5	30	0.9845	0.9954	0.9952
BM2 40 GWd/T	5.0	40	0.9841	0.9946	0.9944

Neutron absorber (poison) width and thickness

For a given areal density, neutron absorber width and thickness have only a small impact on reactivity in the spent fuel storage racks as demonstrated in multiple license applications. The areal density is the only significant parameter when considering absorber panels. Additionally, the neutron absorber width tolerance is analyzed in criticality analysis. Because of the small impact of the neutron absorber width and thickness, c_k's would not change significantly with a change in width or thickness.

Soluble boron

While soluble boron would have direct impact on the c_k, the limiting condition in spent fuel pool criticality analysis is the unborated condition. Normally large margin exists for borated cases and this margin would cover any concern. It is possible to quantify the impact of boron on the c_k when comparing Benchmark 3 to Benchmark 10. The differences in these two benchmarks is that Benchmark 3 has 0.0 ppm and Benchmark 10 has 1500 ppm of soluble boron. Table 1-3 shows that adding the soluble boron has a small effect on the c_k, but the minimum c_k for adding the soluble boron is 0.9646, which is still good similarity.

Table 1-3: c_k Comparison between 0 Boron and 1500 ppm Benchmarks

Benchmark Burnup (GWd/T)	c_k Comparing Benchmark 3 To Benchmark 10 (same burnup)
10	0.9762
20	0.9722
30	0.9679
40	0.9651
50	0.9646
60	0.9650

Temperature

Temperature (including the change in water density) in the rack has a small impact. As for the soluble boron, the c_k impact of changing the temperature from room temperature (293 K) to a hot pool condition of 150 F (338.7 K) is shown in Table 1-4.

Table 1-4: c_k Comparison between Pools at 293 K and 338.7 K

Benchmark Burnup (GWd/T)	c_k Comparing Benchmark 3 To Benchmark 9 (same burnup)
10	0.9999
20	0.9998
30	0.9998
40	0.9998
50	0.9998
60	0.9998

Low power density

Low power density is one of the uncertainties covered in the benchmarks. The uncertainties stated in the benchmark are power related, with higher power having a higher uncertainty. Lower power would actually have a smaller uncertainty since the fuel temperature is lower and the fuel temperature is driving the uncertainty.

Minimum c_k

It is recommended in the Utilization Report that the uncertainty to be applied to the criticality analysis is the uncertainty in the experimental benchmarks. This uncertainty was derived conservatively and a single value is applied to all the benchmarks. Further it is recommended that the bias to be used is the maximum difference from all the benchmarks. So long as there is good similarity with some of the benchmarks, including low c_k benchmarks is conservative.

Table GR-1 shows that there is good similarity for all the pools investigated to date.

2. The suggested bias uncertainty values are not reported as being based on a 95% confidence interval that bounds 95% of the population. Provide additional information/discussion on the confidence interval associated with the reported bias values.

    a. The 11 supplied independent benchmarks in EPRI Report 1025203 are not sufficient in number or diversity to establish a statistically based confidence interval that bounds 95% of all reactivity decrement error bias with 95% confidence. Discuss the limitations or acceptance criteria on the accuracy and precision of the calculated results relative to the benchmark results that would ensure that a licensee or applicant who would use this methodology will satisfy the regulatory requirements of Title 10 of the Code of Federal Regulations, Part 50, Section 50.68 (10 CFR 50.68).

Response:

The RAI implies that a licensee would use the 11 benchmarks to establish a statistically-based uncertainty in the depletion reactivity. This would not be an appropriate use of the benchmarks as there are too few comparisons to provide meaningful statistics. This approach is not what is contained in the Utilization Report. Instead, the worst bias of the 66 benchmark cases (11 benchmarks at 6 different burnups) is used for the bias. The recommended bias and uncertainty treatment is similar to the treatment associated with a single experiment (the single experiment which resulted in the worst difference). If one only has a single experiment, the difference between the experiment and the prediction is a bias and the uncertainty in that bias is the uncertainty in the experiment. The "experiment" is derived from a collection of a large number of measurements. The result of the "experiment" is a reactivity decrement bias for CASMO-5. Although there are eleven benchmarks at six different burnups (and three cooling times), they are all derived from the same "experiment." The difference between the "experiment" and the calculated prediction is not statistical in nature. The 11 benchmarks allow estimation of this difference. The eleven cases were selected to test the key parameters that could affect the bias (initial enrichment and energy spectra during depletion and in the SFP). Using the worst case for the bias from the eleven cases provides a level of assurance that it is conservative.

The uncertainty in the "experiment" is difficult to determine using normal statistical approaches since many of these measurements are highly correlated. Section 7.5 of the EPRI Benchmark Report [1] discusses the problems associated in a statistical analysis of the measured data. Section 7.6 of the Benchmark Report describes an approach to estimate the uncertainty in the "experiment." This approach demonstrates the Hot Full Power (HFP) uncertainty is less than 250 pcm which is then carried forward in the uncertainty analysis. A conservative approach is also used to estimate the uncertainty in the benchmarks due to conversion between HFP conditions and cold conditions. This approach is described in Section 8 of the Benchmark Report.

In summary, the uncertainty is established in both the Benchmark and Utilization Reports using a bounding rather than a statistical approach. Bounding approaches are a conservative alternative when incorporated into safety analysis for simplicity as a method to satisfy the 95/95 requirements for certain elements of a methodology.

Question 2 continued:

b. A dependency in the bias is reported with respect to specific power – 38.1 Watts/gram (W/g) and 57.2 W/g. The assembly ends may have a specific power well below 38.1 W/g, however, the provided benchmarks do not cover the power range necessary to assess a calculation's performance at lower specific powers. Provide additional benchmarks at fuel conditions important to SFP criticality safety analyses to demonstrate applicability within the specific power range of concern.

Response:

The dependency with respect to specific power is in the uncertainty shown on Table C-1 of the Benchmark report, not the bias. That dependency in the uncertainty is due to the fuel temperature. The last sentence of Section 8.2 of the Benchmark report [1] states:

> *"To be conservative, we statistically combine the maximum computed changes in HFP reactivity and cold reactivity and treat this as a 2-sigma burnup decrement uncertainty of 255 pcm arising from HFP fuel temperature uncertainties – independent of sub-batch burnup."*

Table 8-1 of the benchmark report provides more details. At higher power the HFP temperature of the fuel is higher, hence the resultant increase in the uncertainty. At lower power, the fuel temperature would be lower and this would produce a lower uncertainty. The Utilization Report does not address the change in uncertainty with specific power extensively. The last paragraph of Section 3 recommends to "*use the uncertainty from the specific power that bounds the average operation of the fuel*." This approach is clearly conservative for the ends which are at lower power.

Benchmark Case 11 allows the user to determine if the specific power is significant to the calculated bias. If it is significant the analyst can use the two specific powers to extrapolate to low power conditions. While it would be possible to generate an additional benchmark at a lower power, it would rely on prediction in CASMO rather than measured data. Additionally, a benchmark with low moderator density and low fuel temperatures may convey a precision beyond what is available from the measured data. For these reasons an additional low power benchmark provides no additional benefit.

3. EPRI Report 1025203 bases the 11 benchmark criticality case bias and uncertainty estimates, intended to cover reactivity calculations in SFP conditions, on bias and uncertainty estimates inferred from HFP operating reactor measurements. Application of bias and uncertainty in this manner requires bias and uncertainty extrapolation in time (decay), fuel temperature, moderator temperature, etc. Provide additional discussion on the basis for the bias and uncertainty, and justification for the limitations and assumptions associated with the following conditions:

    a. an extension of operating reactivity measurements to 100 hours (Were restart critical configurations considered?),

Response:

The uncertainty in going from HFP to cold rack conditions at 100 hours is conservatively assessed as 452 pcm (Table 8-10 of the Benchmark report) as presented in Section 8.5 and 8.6 of the Benchmark report [1]. This assessment was made assuming the uncertainty is dominated by the uncertainty in the cross section library and TSUNAMI was used to propagate the cross section uncertainty.

Although agreement with HZP startup data was not used directly in the assessment of the bias and uncertainty in going from HFP to cold conditions at 100 hours, the performance of CASMO-4/SIMULATE-3 in predicting reactor conditions are shown in Section 5.4 of the Benchmark report. Tables 5-3 through 5-6 of the Benchmark report show the agreement between measured and predicted BOC HZP and HFP critical soluble boron concentrations and the agreement between measured and predicted EOC HFP critical soluble boron concentrations. The difference between the third from the last column and the second from the last column is a HZP to HFP bias in the CASMO-4/SIMULATE-3 system. Figure 3.1 below plots this bias as a function of the BOC core average burnup. There is a HFP to HZP bias of about 17 ppm. It is assumed that this bias is not burnup dependent. Using the general rule of thumb equating 1 ppm to 9 pcm, 17 ppm results in about 150 pcm effect in reactivity. This ~150 pcm is well within the claimed total hot to cold uncertainty of 453 pcm.

The restart critical configurations were not considered in the determination of the bias and uncertainty.

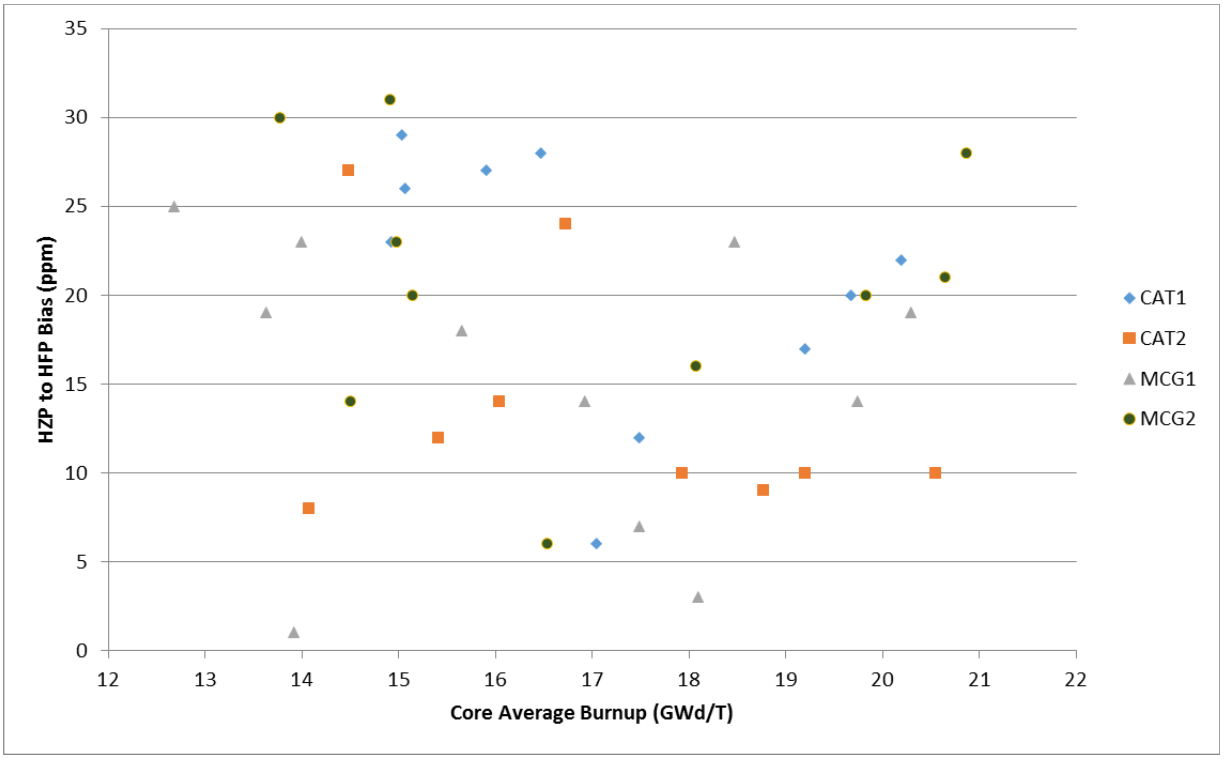

Figure 3-1 HZP to HFP Bias as a Function of Burnup

b. an increased bias/uncertainty (of 0.0025) for cooling times beyond 100 hours,

Response:

The determination of a bias starts with the comparison between the predicted and measured Δk of depletion determined from the benchmarks. For cooling times beyond 100 hours, this comparison is shown in Tables 5-3 and 5-4 of Utilization report. The largest bias given in these two tables for any case, where ignored IFBA absorbers do not compensate (i.e., Cases 6 and 7 for burnups 10, 20, and 30) is 0.0017 for Case 5 at 10 GWd/T with 15 years cooling (Table 5-4). Higher enrichments produce a higher bias (difference between Case 2 and Case 3). After adding the enrichment effect, there are several cases where the bias would be 0.0022 (Case 7 at 40 GWd/T and 15 years cooling for example). This 0.0022 was rounded up to 0.0025.

The uncertainty for all cooling times is the uncertainty of the benchmark experiments which is given as 0.00576 for 38.1 W/g U or 0.00643 for 57.1 W/g U.

The main contributor to cooling time reactivity changes is due to the decay of Pu-241 to Am-241. The reactivity worth of the change from the decay of Pu-241 into Am-241 has been confirmed by validation against the MOX critical experiments. MOX experiments reuse the same MOX pins over many years. By comparing the calculated reactivity of experiments with newer MOX pins to experiments with older MOX pins, it is possible to show that the reactivity associated with the decay of Pu-241 to Am-241 is well predicted. It is theoretically possible to correctly predict the Δk of depletion at 100 hours cooling but be incorrect about the Pu-241 content. However, it is more likely that the Pu-241 content is correct and that there is no a compensating error that varies little with burnup. Furthermore, the Pu-241 content has been tested by comparisons to measured chemical assay data. As shown in Table 6.1 of Reference 8, the Pu-241 measured/prediction ratio has the best agreement of all the plutonium isotopes for burnups greater than 15 GWd/T.

The response to RAI-12 also provides additional detail on the justification of the bias value of 0.0025 for cooling times up to 15 years.

c. consideration of fuel temperature sensitivities,

Response:

Fuel temperature sensitivities are discussed in Section 8.2 of the Benchmark Report. The uncertainty in the fuel temperature represents a significant portion (255 pcm given on page 8-2 of the Benchmark Report) of the total uncertainty (576 pcm from Table C-1 of the benchmark report). Case 11 has a higher fuel temperature than the base case (Case 3). Subsequently, the difference in the bias between Case 3 and Case 11 helps to quantify dependence of the depletion reactivity bias on fuel temperature. If the application temperature is different than the Case 3 temperature, the difference between the Case 3 and Case 11 bias should be used to determine the appropriate bias for the application if needed.

d. consideration of moderator temperature and density sensitivities, and

Response:

The moderator temperature and density changes from hot full power to cold conditions were considered by using TSUNAMI to determine the uncertainty due to this change. The hot full power to cold condition bias was assumed to be independent of burnup. Please see the answer to part (a) of this RAI.

e. the use of storage rack absorber materials.

Response:

The storage rack absorbers harden the spectrum. The higher temperature in the reactor also hardens the spectrum. The best way to determine if the storage rack absorbers make the rack conditions dis-similar to the core conditions is via c_k. Table 8-4 of the Benchmark Report shows c_k's of greater than 0.95 for all depletion conditions. The uncertainty used for the benchmarks conservatively ignores the absorber materials. For more information, reader is referred to Tables 8-7 and 8-8 and the discussion of these tables in Section 8.6 of the Benchmark Report.

4. Provide a list of all of the significant isotopes that were included in the benchmark analyses. Additionally, since volatile fission products are not typically credited in SFP criticality safety analyses, an assessment of the change in the bias and uncertainty when volatile and soluble nuclides are excluded is necessary.

<u>Response:</u>

The analysis was performed using addnux=4 in SCALE 6.1. Therefore, 388 nuclides were followed in the analysis and used in the determination of the depletion reactivity. The 388 nuclides are listed on Tables T1.3.2 through T1.3.7 of the SCALE manual [3] and include volatile fission products. The statement in the RAI that volatile fission products are not typically credited in SFP criticality safety analysis is not accurate. Normally, all the fission products used in fuel management are credited in SFP criticality analysis. The assessment of the bias and uncertainty needs to include all isotopes to determine an accurate bias and uncertainty since all isotopes are included in the measured data.

5. In Section 4, the following is stated: “SCALE 6.1 TRITON has no branching capability, unlike most fuel management tools.” NUREG/CR-7041, “SCALE/TRITON Primer: A Primer for Light Water Reactor Lattice Physics Calculations,” discusses the type of branch calculations that SCALE 6.1 TRITON can perform. Revise the statement in Section 4 accordingly.

<u>Response:</u>

The statement about branching capability was far too broad and will be replaced in the next revision of the report. However, the “BRANCH” block in SCALE 6.1 TRITON is not supported with 3D KENO depletion sequences. It should be noted that much of the work for the Utilization Report used 3D KENO depletion sequences. Additionally, the TRITON Primer was issued November, 2012 while the Utilization Report was issued earlier in April, 2012 and therefore was not available at the time the Utilization Report was written. The paragraph will be rewritten to describe only what was performed.

The paragraph in Section 4 which started with, “SCALE 6.1 TRITON has no branching…” will be replaced with:

Separate SCALE 6.1 TRITON cases were run for each of the 10, 20, 30, 40, 50 and 60 GWD/MTU benchmarks and cooled for 100 hours. The same input decks were used for the 5 and 15 year cases but the fuel atom densities were inserted using the “StdCmpMix” file for the fuel collected from the 100 hour cooling case. The burndata cards were replaced with:

power=0.1 burn=.0002 nlib=1 down=X end

where x= 1822.08 for 5 years cooling and x= 3652.50 for 15 years cooling. This approach burns the fuel at 0.1 MW/MTU for 0.0002 days beyond the desired burnup. The low power and short burnup had no impact on the final number density after cooling. Other methods could have been used but this *approach matched the atom densities generated from a test case where the full depletion and cooling time was done from the fresh fuel.*

6. In Section 4, it is stated that “ENDF/B-VII has only one group wise library and it uses 238 groups.” ENDF/B-VII data is not restricted to 238 groups. Revise the statement accordingly.

Response:

The statement will be revised to read “The only ENDF/B-VII group cross section library provided with SCALE 6.1 uses 238 energy groups.”

7. Section 6 states, “Care must be taken to cover all the depletion and rack conditions.” How will the criticality safety analyst know if all rack conditions are covered? What if the safety analysis rack conditions are not similar to one of the 11 benchmark conditions?

Response:

The statement “*Care must be taken to cover all the depletion and rack conditions.*” is part of the introduction to Section 6 which then explores the depletion and rack conditions. This statement will be revised to read “*Care must be taken to adequately represent the depletion and rack conditions*”. The General Response to these RAIs provides a similarity analysis to a range of rack and fuel designs and shows excellent agreement with non-flux trap racks designs and good agreement with flux trap designs with low burnup fuel. The criticality safety analyst can rely on the similarity analysis given in the general response and only needs to do further analysis if the rack or fuel is significantly different than current racks and fuel. If there is a new rack or fuel design significantly different that the current generation racks or fuels then the analyst should confirm similarity or use alternate methods to establish a bias and uncertainty for burned fuel in the spent fuel rack.

8. Section 6 states the following:

> However, a quick review of the biases shown in Section 5 reveals a slight trend to more negative biases as one goes down in enrichment. Therefore, a bias from the high enrichments would be conservative for the low enrichments. Note that other cross-section libraries could have a trend in the opposite direction, and in that case, the trend would have to be projected and conservatism added.

It is not clear, from the limited discussion above, how bias trends are to be handled. Provide specific guidance for handling of bias trends amongst benchmarks (e.g. When is extrapolation appropriate? How much extrapolation is appropriate? How much conservatism should be added when extrapolating?).

Response:

It is desirable that the application be within the range of benchmarks for enrichment (key material property), spectrum during depletion (key parameter for isotopic production), and spectrum at application (key parameter for isotopic worth). Clearly there are a number of less important parameters that affect the depletion reactivity. If the application is within the range of experiments then **the most limiting bias is to be applied**. The most limiting bias is not merely the largest of the calculated biases but could include perturbations off of case 3 when a number of these perturbations simultaneously exist in the application. For example, the application could be 5 wt% enriched fuel run at 150% power. For this example, the application bias would be the case 3 bias (4.25% ^{235}U, 100% power) plus the difference between case 3 and case 2 (5 wt% ^{235}U, 100% power) plus the difference between case 3 and case 11 (4.25 wt% ^{235}U, 150% power). If any of the differences were negative (i.e., non-conservative), then that difference would be set to zero. This example was chosen to provide a clear explanation; however, for the actual implementation, it is recommended to start with case 3 and then conservatively add all the biases from all the deltas off of case 3 to determine a single bounding bias for the range of benchmarks.

Some applications may have enrichment less than 3.25 wt% ^{235}U from first core fuel, so extrapolation of the bias may be necessary. No general method for extrapolation is provided. It is expected that the applicant will use a conservative extrapolation consistent with their available margin. The extrapolation will be reviewed by the NRC and can be used to judge the acceptability of the extrapolation in the totality of the margin to criticality. In the Utilization report, analysis of the trend with enrichment produced higher biases with enrichment. Therefore, the bias from the highest enrichment would be sufficient to cover enrichments below 3.25 wt% ^{235}U.

Since application margin is part of the decision on the extrapolation method and the amount of conservatism to add, no generic approach is proposed.

9. Section 6 states the following:

   "The maximum difference in the biases in Table 5-2 between Case 11 and Case 3 is 0.0004. Since the bias is the difference between two Monte Carlo cases each with a 0.0002 uncertainty, the difference in the bias due to a large change in power is insignificant."

   Explain why a difference of 0.0004 is insignificant and provide guidance for determining significance. When taking the difference between two numbers, each with its own uncertainty, why wouldn't propagation of error apply?

Response:

This portion of Section 6 quoted in this RAI does not relate to the treatment of the results but rather to understanding the results. "*Insignificant*" will be removed in the next revision and the wording follows:

> *Next, are the depletion parameters adequately covered? Cases 5, 6, 7, 8, and 11 vary depletion parameters from the base case (Case 3). The Monte Carlo uncertainty used in this analysis is 0.0002. Case 11 increases the power by 50%. The maximum difference in the biases in Table 5-2 between Case 11 and Case 3 is 0.0004. This difference is small enough that it can be attributed to the statistical uncertainty of the Monte Carlo analysis. Similarly the differences between Case 8 and Case 3, in which boron concentration is changed by 600 ppm (from 900 ppm to 1500 ppm), are too small to be statistically significant.*

There is no discussion of the handling of the Monte Carlo uncertainty in the rack up of the bias. It is assumed that the applicant will either include a sufficiently converged eigenvalues (i.e., a sufficient number of cycles, with a sufficient number of neutrons per cycle) such that the impact of the Monte Carlo uncertainty has little impact on the final results or that the Monte Carlo uncertainty is included in the uncertainty analysis.

10. Section 6 states the following:

    > The wet annular burnable absorbers (WABAs) are typically not credited in the criticality analysis, so the criticality analysis is actually done with only the change in reactivity of the fuel being taken into account. The difference in bias is still small with the maximum difference being 0.0007. Adjusted to cover 24 WABA pins instead of the 20 in the analysis would only be about 0.0001.

    How is the adjustment referred to above being made and what is the basis for the adjustment? Provide specific guidance for the types of bias adjustments that are appropriate, when they are to be applied, and how they are to be applied.

<u>Response:</u>

The example provided in Section 6 that is quoted in the RAI response is not an adjustment, but an extrapolation of the bias determined for 20 WABA rods to a WABA with 24 rods. For small effects, it is acceptable to assume a linear extrapolation. In the case of the 20 WABA fingers versus the maximum 24 WABA fingers, it was assumed that the effect was linearly dependent on the number of WABA fingers. Therefore, this extrapolation was calculated as:

$$(0.0007/20)*24 - 0.0007 = 0.00014$$

For this example, the extrapolation is required to be conservative if 24 WABA fingers were going to be used in the application. Similar extrapolations could be required if the specific power or soluble boron of the application is not between the benchmark conditions. It is not expected that an extrapolation on specific power or soluble boron is needed.

11. Section 6 states the following:

> It should be noted that the geometric parameters of the rack need to be covered in the selection of the fresh fuel critical experiments. The rack condition changes are to explore if the delta k of depletion is impacted by rack conditions. Since this is a fuel effect, the most important concerns are changes in the fuel, so the rack condition changes are a change in the water temperature and density and a change in the boron ppm.

It is not clear that the bias and uncertainty in the “delta k of depletion” does not change as a function of the rack material and rack geometry. Provide quantitative evidence that the rack material and conditions are not important enough to be considered as “rack condition changes”.

Response:

The rack material and rack geometry change the spectrum which will indeed change the Δk of depletion. In the response to RAI question 1, he spectral index, EALF, as a function of burnup for a large number of rack designs was shown in Figure 1-1. The absorber material in PWR racks is typically composed of boron and aluminum. Case 10 uses a higher boron content (1500 ppm) to assure that the effect of boron on the Δk of depletion is observed. Case 9 changes the water density, which isolates another rack feature. None of the 11 benchmarks include the stainless steel structure of the racks because the measured data (HFP PWR cores) does not contain any stainless steel. A benchmark with a stainless steel structure would be merely a code-to-code comparison. However, the uncertainty due to cross sections has been analyzed covering rack features including stainless steel and absorber panels. This uncertainty development is presented in Sections 8.5 and 8.6 of the Benchmark report. Finally, the similarity coefficient, c_k, has been analyzed showing the similarity of the benchmarks for a range of rack designs as described in the General Response. Those c_k values are presented in Table GR-1 of this RAI response (the General Response section) and it is clear that the benchmarks have very good similarity to actual racks. Finally, the approach recommended for establishing the bias uses the most limiting bias. This approach conservatively covers spectral effects such as would be created by rack materials.

12. Page 6-3 in Section 6 suggests “that the bias be increased by 0.001 to 0.0025 for cooling time credit.” What is the basis for increasing the bias by 0.001? What bias would be applicable beyond 15 years cooling?

Response:

The Utilization report suggests using conservatively rounded up biases. It rounded up a calculated bias of 0.0012 to 0.0015 then suggested adding a 0.001 to cover the cooling time. Following the procedure used to arrive at a 0.012 bias at 100 hours cooling time, the 5 year cooling time bias would be 0.0022 (Case 5 20 GWd/MTU plus 0.0007 for the Case 3/2 difference). For 15 years cooling time the raw bias similarly calculated is 0.0022. Using a 0.0025 bias covers all cooling times.

As further clarification of the value of 0.0025 used for the bias, Table 5.3 provides the value 0.0025 as the bias for Case 7 with 20 GWd/MTU burnup. However, this bias is attributed to the residual IFBA boron left in the fuel, and therefore is not applied. Table 6.1 shows the worth of the residual IFBA boron remaining in the fuel. Since the residual IFBA boron worth is greater than the biases for Cases 6 and 7 for low burnups, those biases are neglected.

13. Section 6 references Tables 5-2, 5-3 and 5-4 relative to “depletion spectrum” and “wetness”. Extrapolation to fuel that wasn’t considered in the EPRI depletion benchmark work is not appropriate. A trend found on “wetness” is not a defensible basis for extrapolating to other fuel types as it is not known that “wetness” is fundamentally causing the trend and if the trend actually holds in the region of extrapolation.
    a. Define the difference between “wetness” and the more commonly used H/X parameter.
    b. Why is “wetness” an appropriate figure of merit to show depletion spectrum coverage?
    c. What is the basis for the 0.001 additional bias to be applied for W14x14 Standard and W16x16 fuel (also mentioned on page 9-1)?
    d. Provide appropriate tables with spectra along with a quantitative illustration of a spectrum comparison.

Response (all parts):

The paragraph on wetness has been re-written to be more precise on spectrum. A column giving the depletion averaged EALF at 60 GWd/T burnup for each fuel type is now given. In addition, two new Tables are added (Tables 13-2 and 13-3 of this response) which shows the depletion averaged EALF for all the benchmark cases as a function of burnup (Table 13-2) and the depletion averaged EALF as a function of burnup for all the PWR fuel types with 4.25 wt% enrichment and no burnable absorbers (Case 3).

Table 13-2 shows the EALF of fuel types as a function of the burnup over which the EALF is averaged. Most of the fuel types shown in Table 13.2 are within this range of spectra except the W 14x14 OFA fuel which sees a spectrum that is slightly softer than all the benchmarks and W14x14 and W16x16 which see a slightly harder spectrum. Table 13-3 shows that the benchmark experiments cover a range of spectra during depletion.

A 0.001 additional bias was suggested for two fuel types, W14x14 Standard and W 16x16. This was intended to be a conservative increase in the bias to cover the potential spectral differences. The bias determined in the initial release of the report was around 0.002 and this would represent a 50% increase. This recommendation will be removed in the next revision of the report. Instead it will be recommended that the applicant compare the burnup averaged EALF from their depletion analysis to the benchmarks and if it is outside of the range of the benchmarks in a non-conservative direction, add an additional bias determined by extrapolation of the bias as a function of EALF.

All of the fuel designs are very similar and the key parameter that determines the difference is the amount of moderation. Using a spectral index is sufficient for showing the benchmarks are applicable to other fuels. Since all the materials (UO_2, Zircaloy, and water) are the same for all the fuels and the measurements, it is clear that a trend would be due to the relative proportion of these materials which is measured by the spectral index (i.e., EALF).

Some historical figures of merit to show depletion spectrum coverage are H/X and H/U ratios. The fuel to moderator ratio is a spectral index which is easy to determine with publically available data. H/X requires the knowledge of the enrichment which makes this index less useful for fuel with varying enrichment. Conversion between the fuel-to-moderator ratio to H/U is straightforward since the fuel is UO_2. However, the more precise EALF will be emphasized in the revised report and is added to Table 6-3.

Below is the rewritten portion of Section 6 with the newly added tables. Note that the table numbers are 13-x rather than 6-x to prevent confusion with other figures in the response to the RAI. In the revised Utilization Report the Table numbers will be changed to be consistent with Section 6.

> *So far the analysis has not addressed the range of applicability for fuel designs. The measured data came from Westinghouse type 17X17 fuel. The benchmarks cover both Standard (Std) and Optimized Fuel Assembly (OFA) fuel designs. This gives the benchmarks a range of depletion spectrum that covers most PWR fuel designs. Table 13-1 shows the fuel design parameters of major PWR fuel designs. The last column shows the average EALF over 60 GWd/T depletion. Table 13-2 shows the EALF for each fuel type as a function of the burnup over which it is averaged. As can be seen from Tables 13-1 and 13-2, the range of the benchmarks covers the W 15X15, B&W and CE fuel. The Westinghouse 14X14 and 16X16 products will require some extrapolation. As can be seen in Tables 5-2, 5-3, and 5-4, the softer spectrum is slightly more conservatively predicted; so the W 14X14 OFA design is covered. For fuel types that have a harder depletion spectrum, it is recommended to add a bias, based on extrapolation, to cover the impact due to spectral differences. The extrapolation can be done by using the 17x17 and 17x17 OFA cases but this can be supplemented by using the spectral differences between the other cases. Table 13-3 shows the average depletion EALF for all the benchmark cases. As can be seen from Table 13-3, there is a significant range of depletion spectra.*

Table 13-1 Fuel Design Dimensions and Spectra

Fuel Design	Pellet OD (inches)	Clad OD (inches)	Pitch (inches)	Water to Pellet Volume Ratio	Depletion EALF averaged over GWd/T (eV)
W 17X17 Std	0.323	0.374	0.496	1.67	1.011
W 17x17 OFA	0.309	0.360	0.496	1.93	0.765
W 16X16	0.323	0.374	0.485	1.53	1.209
W 15X15	0.366	0.422	0.563	1.68	1.000
W 14X14 Std	0.366	0.422	0.556	1.61	1.100
W 14X14 OFA	0.344	0.400	0.556	1.97	0.734
B&W 15X15	0.369	0.430	0.568	1.66	1.000
B&W 17X17	0.323	0.379	0.502	1.70	0.956
CE 14X14	0.377	0.440	0.580	1.66	0.957
CE 16x16	0.325	0.382	0.506	1.70	0.941

Table 13-2 Burnup Averaged Energy of the Average Lethargy Causing Fission (EALF) For Various Fuel Types (4.25 wt% U-235 Case 3 conditions)

	Energy of the Average Lethargy Causing Fission (EALF) (eV)					
	Burnup (GWd/T)					
Fuel	**10**	**20**	**30**	**40**	**50**	**60**
W 14x14	0.849	0.913	0.965	1.011	1.055	1.100
W 14x14 OFA	0.591	0.625	0.652	0.678	0.704	0.734
W 15x15	0.782	0.837	0.882	0.921	0.960	1.000
W 16x16	0.909	0.986	1.050	1.105	1.157	1.209
W 17x17	0.781	0.839	0.887	0.929	0.970	1.011
W 17x17 OFA	0.608	0.646	0.678	0.706	0.734	0.765
B&W 15x15	0.782	0.837	0.882	0.921	0.960	1.000
B&W 17x17	0.745	0.798	0.842	0.880	0.918	0.956
CE 14x14	0.757	0.807	0.848	0.884	0.919	0.957
CE 16x16	0.737	0.789	0.830	0.867	0.903	0.941

Table 13-3 Burnup Averaged Energy of the Average Lethargy Causing Fission (EALF) from the Depletion Analysis of the Benchmark Cases

		Energy of the Average Lethargy Causing Fission (EALF) (eV)					
		Burnup (GWd/T)					
Case	**Lattice Description**	**10**	**20**	**30**	**40**	**50**	**60**
1	**3.25% enrichment depletion**	0.664	0.734	0.796	0.854	0.910	0.965
2	**5.00% enrichment depletion**	0.891	0.943	0.984	1.017	1.048	1.079
3	**4.25% enrichment depletion**	0.781	0.839	0.887	0.929	0.970	1.011
4	**off-nominal pin depletion**	0.608	0.646	0.678	0.706	0.734	0.765
5	**20 WABA depletion**	1.084	1.081	1.086	1.103	1.129	1.160
6	**104 IFBA depletion**	1.006	0.987	0.994	1.013	1.038	1.069
7	**104 IFBA, 20 WABA depletion**	1.381	1.276	1.226	1.212	1.217	1.235
8	**high boron depletion = 1500 ppm**	0.876	0.943	1.001	1.052	1.100	1.148
11	**high power density depletion**	0.877	0.951	1.013	1.066	1.116	1.166

14. Regarding Appendix B reactivity benchmark specification descriptions (pp. B-2 to B-13):

    a. Revise the descriptions to include units for all specifications.

Response:

Appendix B will be updated to add the few missing units where needed. All temperatures are in degrees K and all number densities are in atoms/cc.

    b. Some descriptions contain missing sections (e.g. “Structural Material Description” and “Coolant Description” for Figure B-2); revise the descriptions accordingly so that each description stands alone.

Response:

Appendix B structural material descriptions for Case 1 are common for all other cases and they have simply been restated Case 5 (the small diameter fuel pin case) where the physical geometry has been altered from the other cases.

The Coolant Description for Depletion is the same for all cases except for Case 8 (the high boron depletion case where the boron number density in the coolant has been stated explicitly).

The Coolant Description, Cold for Case 9 corresponds to 150F (338.7K) rather than 293K used for all the other cases. The Coolant Description, Cold for Case 10 (branch to high rack boron) corresponds to the higher boron number density.

If these explanations are deemed to be insufficient, the report can be updated to explicitly state the conditions for each case separately.

c. The title for Case 9 in Figure B-10 is ambiguous. For clarity, include a more complete description explaining the purpose of each benchmark. Also, explain why the eleven benchmarks proposed provide sufficient coverage to validate all PWR depletion analyses for any SFP storage configuration.

Response:

Case 9 is the same depletion as Case 3, but it has been branched to 150F (338.7K) rather than 293K used for all the other cases. A more accurate title for this case would be 'Case 3 Branched to SFP Hot Isothermal Temperatures = 150F", as there is no rack geometry for this case. This case was added to represent the hottest anticipated temperatures in a SFP rack.

A more accurate title for Case 10 would be "Case 3 Branched to SFP High Boron Concentration = 1500 ppm", as there is no rack geometry for this case. This case was added to represent a high boron concentration in a SFP rack.

The intention of Table B-1 is to convey a range of: enrichment, pin diameters, burnable absorbers, depletion boron concentration, depletion power density, SFP coolant density and boron concentrations. Table B-1 will be revised to implement the changes in the titles for Case 9 and 10 and the revised Table is shown below:

Table ***Error! No text of specified style in document.***-*1*
Benchmark Lattice Cases

1	3.25% Enrichment
2	5.00% Enrichment
3	4.25% Enrichment
4	off-nominal pin diameter depletion
5	20 WABA depletion
6	104 IFBA depletion
7	104 IFBA plus 20 WABA depletion
8	high boron depletion = 1500 ppm
9	Case3 Branched to SFP Hot Isothermal Temperatures = 150F
10	Case 3 Branched to SFP High Boron Concentration = 1500 ppm
11	high power depletion (power, coolant/fuel temp)

The justification that the benchmark cases provide an adequate representation of the spent fuel pool has been addressed in the responses to the preceding RAI questions, especially in the General Response.

References:

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7. J. C. Wagner, M. D. DeHart, C. V. Parks, Recommendations for Addressing Axial Burnup in PWR Burnup Credit Analyses, NUREG/CR-6801 (ORNL/TM-2001/273), U.S. Nuclear regulatory Commission, March 2003.
8. G. Radulescu and I.C. Gauld, *An Approach for Validating Actinide and Fission Product Burnup Credit Criticality Safety Analyses – Isotopic Composition Predictions*, NUREG/CR-7108 (ORNL/TM-2011/509),U.S. Nuclear Regulatory Commission, Oak Ridge National Laboratory, April 2012.