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MARTIN MARIETTA

Comparison of Radiation Spectra from Selected Source-Term Computer Codes

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MASTER

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ABSTRACT

This report compares the radiation spectra and intensities predicted by three radionuclide inventory/depletion codes, ORIGEN2, ORIGEN-S, and CINDER-2. The comparisons were made for a series of light-water reactor models [including three pressurized-water reactors (PWR) and two boiling-water reactors (BWR)] at cooling times ranging from 30 d to 100 years. The work presented here complements the results described in an earlier report that discusses in detail the three depletion codes, the various reactor models, and the comparison by nuclide of the inventories, activities, and decay heat predictions by nuclide for the three codes.

In this report, the photon production rates from fission product nuclides and actinides were compared as well as the total photon production rates and energy spectra. Very good agreement was observed in the photon source terms predicted by ORIGEN2 and ORIGEN-S. The absence of bremsstrahlung radiation in the CINDER-2 calculations resulted in large differences in both the production rates and spectra in comparison with the ORIGEN2 and ORIGEN-S results. A comparison of the CINDER-2 photon production rates with an ORIGEN-S calculation neglecting bremsstrahlung radiation showed good agreement. An additional discrepancy was observed in the photon spectra predicted from the CINDER-2 calculations and has been attributed to the absence of spectral data for ^{144}Pr in those calculations.

Neutron production rates from (alpha,n) reactions and spontaneous fission sources predicted by the three depletion codes are also compared. Although the ORIGEN2 calculations do not predict neutron spectra, a comparison of the neutron spectra from the ORIGEN-S and CINDER-2 calculations was made. Agreement was good for neutron production rates in the decay-only case. The differences observed for the other cases reflect the disagreement seen in the actinide inventories (particularly ^{244}Cm) as noted in the companion report.

Both the neutron and photon source spectra were applied to a shielding problem involving a thick-walled spent fuel storage cask. Dose rates from neutrons and primary photons were calculated and compared at the cask surface. The agreement observed in the dose rates calculated from the ORIGEN-S and CINDER-2 results was generally as good or better than that seen in the source strengths. The same is true for the comparisons of ORIGEN2 and ORIGEN-S at 5 years. However, at 50 years the photon dose rates are in poorer agreement than the respective production rate comparisons.

1. INTRODUCTION

A study to assess the performance of various source-term computer codes under a variety of conditions was begun in 1986 in order to provide the Department of Energy/Office of Civilian Radioactive Waste Management (DOE/OCRWM) with information to assist them in selecting such a code to be used in licensing procedures for the siting, design and construction of transportation, storage and disposal systems for reactor spent fuel and high-level radioactive wastes. The codes chosen for this comparative assessment study were ORIGEN2,[1] ORIGEN-S,[2] and CINDER-2.[3] In general, these codes compute the time-dependent inventories and source terms of a large number of radionuclides as they are simultaneously generated or depleted by various physical, chemical, and nuclear processes. Five test cases involving both PWRs and BWRs with normal and extended exposure rates (burnup) were developed through a joint effort by staff members of Oak Ridge National Laboratory (ORNL), who were responsible for the ORIGEN2 and ORIGEN-S calculations, and Los Alamos National Laboratory (LANL), who were responsible for performing the CINDER-2 calculations. The test cases are summarized in Sect. 2 for convenience. Detailed descriptions of the codes themselves and the five test problems are given in an earlier report[4] describing the initial results of the code comparison study. That report compares results from ORIGEN2, ORIGEN-S and CINDER-2 in units of mass (gram-atoms), radioactivity (Ci) and decay heat (W) for 52 radionuclides as well as aggregate decay heat rates (total W). (The original request had been to compare results for each of 66 nuclides determined by Kelmers et al.[5] to be important to the analysis of reactor waste systems, however, 14 of these nuclides were not included in the CINDER-2 output, resulting in the final comparisons being made for only 52 nuclides.)

In this report aggregate photon and neutron production rates are compared at cooling times ranging from 30 d to 100 years, and their associated source spectra are compared for decay times of 5 and 50 years. The source spectra are also used in a one-dimensional calculation using the SAS1 shielding analysis sequence from the SCALE[6] computational system to calculate the photon dose rates from a typical rail cask.

This report will emphasize trends in the data and will attempt to resolve major discrepancies in the results. The relative performance of each of the codes in predicting radiation source terms will be evaluated. A typical shielding problem will be used to illustrate the effect the various source spectra might have in calculating dose rates.

2. SUMMARY DESCRIPTION OF TEST CASES

The data from the five test cases whose results are to be compared are summarized below.

2.1. THE DECAY-ONLY CASE

In this case, data calculated by ORIGEN2 for the discharge of a PWR of 33 GWd/MTU (3.443 atom % fissions) with 0.029, 3.2,and 96.771 wt % ^{234}U, ^{235}U, and ^{238}U, respectively, at 37.5 MW/MTU were used to define initial nuclide inventories in gram-atoms per metric ton of initial uranium (MTU). Each of the three codes used the ORIGEN2 data as input and calculated the "decay-only" results at various cooling times (times after discharge) from 30 d to 10,000 years. The exact ORIGEN2 data as used for input are given as Appendix B in the previous report.[4] The significance of this case was to provide a means of comparing results dependent only on decay characteristics, thereby emphasizing differences in the basic decay data (decay constants, branching fractions, etc.).

2.2. THE TYPICAL PWR EXPOSURE CASE

A detailed description of the 17 x 17 Westinghouse assembly used to represent the "typical PWR" is given in the initial report describing the multicode comparisons.[4] Case problems 2 and 3 were chosen as representative of the range of exposure experienced in PWRs. The first of these is a typical exposure case where the exposure time is 880 d with a burnup equivalent to about 33 GWd/MTU (3.443 at. % fissions). The fuel in this case is 3.1 wt % ^{235}U, 0.0275 wt % ^{234}U, and 96.8725 wt % ^{238}U.

2.3. THE EXTENDED PWR EXPOSURE CASE

This case represents an extended burnup with an exposure time of 1333.33 d at a rate of approximately 50 GWd/MTU (5.206 at. % fissions). The ^{235}U wt % is correspondingly higher in this situation at 4.5%. Weight percents of 0.0400 and 95.460 were taken for ^{234}U and ^{238}U respectively.

2.4. THE TYPICAL BWR EXPOSURE CASE

An 8 x 8 General Electric assembly was taken as the "typical BWR" and is also described in detail in the earlier comparison report. The range of exposure experienced in typical BWRs is represented by cases 4 and 5. The typical exposure case has an exposure time of 1061.777 d with a burnup of about 27.5 GWd/MTU (2.866 at. % fissions). Point depletion codes require a single enrichment and therefore the fuel composition was taken as 2.64 wt % ^{235}U, 0.0234 wt % ^{234}U and 97.3366 wt % ^{238}U in place of the usual mixed enrichments.

2.5. THE EXTENDED BWR EXPOSURE CASE

This extended exposure case has a burnup of approximately 40 GWd/MTU (4.172 at. % fissions) and an exposure time of 1544.400 d. The fuel composition was again taken to be all of one enrichment with 4.15 wt % ^{235}U, 0.0386 wt % ^{234}U and 95.8132 wt % ^{238}U.

3. AGGREGATE PRODUCTION RATES

The results from each of the three depletion codes were produced as both printed output and computer datasets. In order to eliminate the possibility of errors in transcribing the data, a short program (CMPROR) was written to read the individual datasets and make the appropriate comparisons. Consistent with methods used in the earlier report, the various production rates were compared both directly and as ratios. These ratios illustrate the results between each combination of two codes OR2/ORS, OR2/CIN, and ORS/CIN (where the code names ORIGEN2, ORIGEN-S, and CINDER-2 have been abbreviated OR2, ORS, and CIN respectively).

3.1. PHOTON PRODUCTION RATES

The three groups responsible for the depletion codes were to calculate photon production rates from both fission product nuclides and actinides. These values as well as the aggregate (total) photon production rates, in units of photons per second per metric ton initial uranium, and their ratios are given in Tables 1—5 for case studies one thur five. Comparisons are made at cooling times of 30 d, 5, 10, 20, 50, and 100 years. It was felt that comparisons at longer cooling times were unnecessary because of the dramatic decrease in production rates (>10,000) after 100 years of decay.

In the decay-only case (Table 1), the ORIGEN2 and ORIGEN-S results are in very good agreement at all decay times, with maximum deviations of 1.3% for fission product photons, 1.9% in the photon production rates from actinides, and 1.3% for aggregate production rates. (Use of the term "deviation" in this report should be taken to mean the absolute value of the fractional or percentage difference between two results.) The agreement between these two codes appears to improve as cooling time is increased, and at 100 years the photon production rates are within 0.7%. The decay-only case represents the closest overall agreement between ORIGEN2 and ORIGEN-S. In the subsequent cases the agreement is still good, with deviations typically on the order of 1 to 2% for fission product and total photon production rates. The actinide photon production rates exhibit the largest differences consistent with the decay-only case results. However, the deviations are much larger for the succeeding cases [as great as 17.6% for case five at 100 years (Table 5)]. In the PWR exposure cases (Tables 2 and 3) and the extended BWR exposure case (Table 5), the deviations in the photon production rates from actinides increase with increasing cooling times with ORIGEN2 consistently predicting the lower of the two production rates. The typical BWR exposure case (Table 4) displays almost the reverse tendency with deviations in the photon production rates from actinides having a maximum at 5 years (9.9%) and then decreasing with increasing cooling times. In this case, the ORIGEN2 result is consistently higher than that of ORIGEN-S. There appears to be a gross discrepancy between the CINDER-2 results and both the ORIGEN2 and ORIGEN-S results for all five cases examined, especially for the fission product photon production rates

TABLE 1. Decay-only (PWR, 33 GWd/MTU) photon production rates (photons/s)

Source	OR2	ORS	CIN	OR2/ORS	OR2/CIN	ORS/CIN
			30 d			
Fission prod	4.127E+17	4.090E+17	2.548E+17	1.009	1.620	1.605
Actinides	3.590E+15	3.660E+15	3.144E+15	0.981	1.142	1.164
Total	4.163E+17	4.127E+17	2.580E+17	1.009	1.614	1.599
			5 years			
Fission prod	1.335E+16	1.320E+16	6.831E+15	1.011	1.954	1.932
Actinides	5.369E+13	5.330E+13	4.754E+13	1.007	1.129	1.121
Total	1.340E+16	1.325E+16	6.878E+15	1.011	1.949	1.927
			10 years			
Fission prod	7.574E+15	7.480E+15	3.765E+15	1.013	2.012	1.987
Actinides	6.702E+13	6.640E+13	6.548E+13	1.009	1.024	1.014
Total	7.641E+15	7.546E+15	3.831E+15	1.013	1.995	1.970
			20 years			
Fission prod	5.350E+15	5.280E+15	2.446E+15	1.013	2.187	2.159
Actinides	8.498E+13	8.420E+13	9.011E+13	1.009	0.943	0.934
Total	5.435E+15	5.364E+15	2.536E+15	1.013	2.143	2.115
			50 years			
Fission prod	2.556E+15	2.530E+15	1.148E+15	1.010	2.226	2.204
Actinides	1.025E+14	1.020E+14	1.164E+14	1.005	0.881	0.876
Total	2.658E+15	2.632E+15	1.264E+15	1.010	2.103	2.082
			100 years			
Fission prod	7.882E+14	7.830E+14	3.597E+14	1.007	2.191	2.177
Actinides	9.851E+13	9.850E+13	1.147E+14	1.000	0.859	0.859
Total	8.867E+14	8.815E+14	4.745E+14	1.006	1.869	1.858

TABLE 2. Typical PWR exposure (33 GWd/MTU) photon production rates (photons/s)

Source	OR2	ORS	CIN	OR2/ORS	OR2/CIN	ORS/CIN
			30 d			
Fission prod	4.128E+17	4.110E+17	2.554E+17	1.004	1.616	1.609
Actinides	3.588E+15	3.670E+15	2.829E+15	0.978	1.268	1.297
Total	4.164E+17	4.147E+17	2.582E+17	1.004	1.613	1.606
			5 years			
Fission prod	1.339E+16	1.300E+16	6.774E+15	1.030	1.977	1.919
Actinides	5.552E+13	5.900E+13	5.369E+13	0.941	1.034	1.099
Total	1.345E+16	1.306E+16	6.828E+15	1.030	1.969	1.913
			10 years			
Fission prod	7.560E+15	7.430E+15	3.781E+15	1.017	1.999	1.965
Actinides	6.898E+13	7.460E+13	7.442E+13	0.925	0.927	1.002
Total	7.629E+15	7.505E+15	3.855E+15	1.017	1.979	1.947
			20 years			
Fission prod	5.330E+15	5.260E+15	2.493E+15	1.013	2.138	2.110
Actinides	8.710E+13	9.580E+13	1.029E+14	0.909	0.846	0.931
Total	5.417E+15	5.356E+15	2.595E+15	1.011	2.088	2.064
			50 years			
Fission prod	2.545E+15	2.510E+15	1.179E+15	1.014	2.159	2.129
Actinides	1.047E+14	1.170E+14	1.334E+14	0.895	0.785	0.877
Total	2.650E+15	2.627E+15	1.312E+15	1.009	2.020	2.002
			100 years			
Fission prod	7.846E+14	7.780E+14	3.700E+14	1.008	2.121	2.103
Actinides	1.005E+14	1.140E+14	1.318E+14	0.882	0.763	0.865
Total	8.851E+14	8.920E+14	5.018E+14	0.992	1.764	1.778

TABLE 3. Extended PWR exposure (50 GWd/MTU) photon production rates (photons/s)

Source	OR2	ORS	CIN	OR2/ORS	OR2/CIN	ORS/CIN
			30 d			
Fission prod	4.425E+17	4.400E+17	2.787E+17	1.006	1.588	1.579
Actinides	4.612E+15	4.880E+15	3.906E+15	0.945	1.181	1.249
Total	4.471E+17	4.449E+17	2.826E+17	1.005	1.582	1.574
			5 years			
Fission prod	2.013E+16	1.940E+16	1.092E+16	1.038	1.843	1.777
Actinides	1.037E+14	1.080E+14	9.579E+13	0.960	1.083	1.127
Total	2.023E+16	1.951E+16	1.102E+16	1.037	1.836	1.770
			10 years			
Fission prod	1.155E+16	1.130E+16	5.880E+15	1.022	1.964	1.922
Actinides	1.188E+14	1.250E+14	1.206E+14	0.950	0.985	1.036
Total	1.157E+16	1.142E+16	6.001E+15	1.021	1.944	1.904
			20 years			
Fission prod	8.030E+15	7.910E+15	3.764E+15	1.015	2.133	2.101
Actinides	1.384E+14	1.480E+14	1.542E+14	0.935	0.898	0.960
Total	8.168E+15	8.058E+15	3.918E+15	1.014	2.085	2.057
			50 years			
Fission prod	3.814E+15	3.760E+15	1.761E+15	1.014	2.166	2.135
Actinides	1.541E+14	1.670E+14	1.879E+14	0.923	0.820	0.889
Total	3.968E+15	3.927E+15	1.949E+15	1.010	2.036	2.015
			100 years			
Fission prod	1.175E+15	1.160E+15	5.517E+14	1.013	2.130	2.103
Actinides	1.433E+14	1.570E+14	1.815E+14	0.913	0.790	0.865
Total	1.318E+15	1.317E+15	7.332E+14	1.001	1.798	1.796

TABLE 4. Typical BWR exposure (27.5 GWd/MTU) photon production rates (photons/s)

Source	OR2	ORS	CIN	OR2/ORS	OR2/CIN	ORS/CIN
			30 d			
Fission prod	2.921E+17	2.890E+17	1.766E+17	1.011	1.654	1.636
Actinides	2.326E+15	2.210E+15	1.575E+15	1.052	1.477	1.403
Total	2.944E+17	2.912E+17	1.781E+17	1.011	1.653	1.635
			5 years			
Fission prod	1.057E+16	1.020E+16	5.091E+15	1.036	2.076	2.004
Actinides	4.636E+13	4.220E+13	3.386E+13	1.099	1.369	1.246
Total	1.062E+16	1.024E+16	5.125E+15	1.037	2.071	1.998
			10 years			
Fission prod	6.172E+15	6.070E+15	3.001E+15	1.017	2.057	2.023
Actinides	5.897E+13	5.440E+13	4.755E+13	1.084	1.240	1.144
Total	6.231E+15	6.124E+15	3.049E+15	1.017	2.044	2.009
			20 years			
Fission prod	4.394E+15	4.350E+15	2.037E+15	1.010	2.157	2.135
Actinides	7.603E+13	7.100E+13	6.638E+13	1.071	1.145	1.070
Total	4.470E+15	4.421E+15	2.104E+15	1.011	2.125	2.101
			50 years			
Fission prod	2.103E+15	2.090E+15	9.724E+14	1.006	2.163	2.149
Actinides	9.309E+13	8.830E+13	8.679E+13	1.054	1.073	1.017
Total	2.196E+15	2.178E+15	1.059E+15	1.008	2.074	2.057
			100 years			
Fission prod	6.486E+14	6.480E+14	3.057E+14	1.001	2.122	2.120
Actinides	9.008E+13	8.600E+13	8.598E+13	1.047	1.048	1.000
Total	7.387E+14	7.340E+14	3.917E+14	1.006	1.886	1.874

TABLE 5. Extended BWR exposure (40 GWd/MTU) photon production rates (photons/s)

Source	OR2	ORS	CIN	OR2/ORS	OR2/CIN	ORS/CIN
			30 d			
Fission prod	3.071E+17	3.070E+17	1.860E+17	1.000	1.651	1.651
Actinides	3.145E+15	2.900E+15	2.090E+15	1.084	1.505	1.388
Total	3.102E+17	3.099E+17	1.881E+17	1.001	1.649	1.648
			5 years			
Fission prod	1.482E+16	1.440E+16	7.599E+15	1.029	1.950	1.895
Actinides	6.371E+13	6.950E+13	5.370E+13	0.917	1.186	1.294
Total	1.488E+16	1.447E+16	7.653E+15	1.029	1.945	1.891
			10 years			
Fission prod	9.088E+15	8.900E+15	4.405E+15	1.021	2.063	2.020
Actinides	7.699E+13	8.460E+13	7.083E+13	0.910	1.087	1.194
Total	9.165E+15	8.985E+15	4.476E+15	1.020	2.048	2.007
			20 years			
Fission prod	6.482E+15	6.350E+15	2.938E+15	1.021	2.206	2.161
Actinides	9.475E+13	1.050E+14	9.426E+13	0.902	1.005	1.114
Total	6.577E+15	6.455E+15	3.032E+15	1.019	2.169	2.129
			50 years			
Fission prod	3.099E+15	3.040E+15	1.392E+15	1.019	2.226	2.184
Actinides	1.112E+14	1.250E+14	1.188E+14	0.890	0.936	1.052
Total	3.210E+15	3.165E+15	1.511E+15	1.014	2.125	2.095
			100 years			
Fission prod	9.551E+14	9.410E+14	4.372E+14	1.015	2.185	2.152
Actinides	1.055E+14	1.190E+14	1.160E+14	0.887	0.909	1.026
Total	1.061E+15	1.060E+15	5.532E+14	1.001	1.917	1.916

which are the primary source of photons at cooling times less than 100 years. It is important at this point to refer to the precursory report in which inventories (masses) and energy production on the basis of individual nuclides were compared as well as the total energies (watts per metric ton initial uranium) from fission product, actinide, and total photon production. Average deviations of less than 1% in the total energies were observed among the three codes in the decay-only case. This suggests that the differences seen in the current comparisons may reflect dissimilarities in how each code calculates the number of photons and perhaps in the basic line data used by each code. An attempt to reconcile a major portion of these differences will be made in the following section.

3.2 MAJOR DIFFERENCES IN PHOTON PRODUCTION RATES

The photon production rates in units of photons per second per metric ton initial uranium were calculated directly by both ORIGEN2 and ORIGEN-S, but in the CINDER-2 calculations an auxiliary code supplied by the user (in this case staff members at LANL used a code called READ13[7]) is required to combine the radionuclide inventories with the appropriate photon production data for each nuclide. It was found that the LANL calculations did not include bremsstrahlung radiation in this step of the calculation although they certainly could have. In order to determine quantitatively the influence of bremsstrahlung radiation in the calculation of photon production rates (ORSNB), the ORIGEN-S calculations were repeated with an option not to include bremsstrahlung. These calculations were performed for the decay-only case and are given in Table 6 in comparison with the CINDER-2 results. The differences are dramatically reduced for the fission product and total photon production rates at all decay times. The agreement in the production rates from actinides at 5 and 10 years was improved whereas the differences in these values at longer cooling times remained relatively unchanged. A major part of the deviations between the CINDER-2 calculations and the ORIGEN calculations is thus attributed to the exclusion of bremsstrahlung radiation. The remaining differences range from 0.3 to 14.2% for the actinides and are typically about 10% for the fission product and total photon production rates and are assumed to reflect differences in the basic line data. Calculations by ORIGEN2 that do not include bremsstrahlung

TABLE 6. Decay-only ORIGEN-S results without bremsstrahlung; photon production rates (photons/s)

Source	ORSNB	CIN	ORSNB/CIN
	5 years		
Fission prod	7.222E+15	6.831E+15	1.057
Actinides	5.180E+13	4.754E+13	1.090
Total	7.274E+15	6.878E+15	1.058
	10 years		
Fission prod	4.105E+15	3.765E+15	1.090
Actinides	6.530E+13	6.548E+13	0.997
Total	4.170E+15	3.831E+15	1.088
	20 years		
Fission prod	2.716E+15	2.446E+15	1.110
Actinides	8.350E+13	9.011E+13	0.927
Total	2.800E+15	2.536E+15	1.104
	50 years		
Fission prod	1.284E+15	1.148E+15	1.118
Actinides	1.018E+14	1.164E+14	0.875
Total	1.386E+15	1.264E+15	1.097
	100 years		
Fission prod	4.031E+14	3.597E+14	1.121
Actinides	9.836E+13	1.147E+14	0.858
Total	5.015E+14	4.745E+14	1.057

radiation would show similar dramatic improvements in comparisons with CINDER-2.

3.3 NEUTRON PRODUCTION RATES

Neutron production rates from (alpha,n) reactions, spontaneous fission and their sums as calculated from each of the three depletion codes (or in the case of the CINDER-2 results, an auxiliary calculation using the READ13[7] code) were compared via the CMPROR code. The results of those comparisons are given in Tables 7—11.

In the decay-only case there is very good agreement between the ORIGEN2 and ORIGEN-S results for cooling times greater than 30 d with differences less than 1%. At 30 d the agreement between these two codes is excellent for neutron production rates from spontaneous fission (<0.1%); however, the (alpha,n) production calculated by ORIGEN2 is 2.6% less than that predicted by ORIGEN-S. Agreement between the CINDER-2 results and the ORIGEN results is reasonably good. The deviations in the neutron production rates from spontaneous fission are approximately 2.5% at thirty days and decrease to slightly less than 2% at 50 and 100 years. Neutron production rates from (alpha,n) reactions as calculated from ORIGEN-S and CINDER-2 exhibit an almost constant percent difference of 7.5% over all cooling times. The ORIGEN2 and CINDER-2 results for (alpha,n) production vary from 4.7% at 30 d cooling to 8.2% at 20 years and thereafter remain constant.

In the subsequent exposure cases the percentage deviations between the ORIGEN2 and ORIGEN-S results are greater than those observed in the decay only case. Differences in the PWR exposure cases for neutron production rates from (alpha,n) reactions increase with increasing cooling time to values as large as 9.3% at 100 years. Spontaneous fission neutron production rates remain in relatively good agreement at about 2.5% or less. The worst agreement between ORIGEN2 and ORIGEN-S was observed in the BWR exposure cases, where the fractional deviations were found as large as 0.163 (Table 11, 5 years) for (alpha,n) neutrons and 0.301 (Table 10, 5 years) for spontaneous fission neutrons. The previously observed trend of the deviations in (alpha,n) production rates increasing with increased cooling time was reversed in the typical BWR exposure case, and in the extended BWR exposure case those deviations were nearly constant with cooling time. In

TABLE 7. Decay-only (PWR, 33 GWd/MTU) neutron production rates (neutrons/s)

Source	OR2	ORS	CIN	OR2/ORS	OR2/CIN	ORS/CIN
			30 d			
Alpha,n	4.762E+07	4.887E+07	4.547E+07	0.974	1.047	1.075
Spontaneous	4.999E+08	5.000E+08	4.879E+08	1.000	1.025	1.025
Total	5.475E+08	5.488E+08	5.334E+08	0.998	1.026	1.029
			5 years			
Alpha,n	5.178E+06	5.192E+06	4.824E+06	0.997	1.073	1.076
Spontaneous	2.250E+08	2.250E+08	2.200E+08	1.000	1.023	1.023
Total	2.302E+08	2.302E+08	2.248E+08	1.000	1.024	1.024
			10 years			
Alpha,n	5.394E+06	5.385E+06	5.006E+06	1.002	1.078	1.076
Spontaneous	1.864E+08	1.864E+08	1.824E+08	1.000	1.022	1.022
Total	1.918E+08	1.918E+08	1.874E+08	1.000	1.023	1.023
			20 years			
Alpha,n	5.639E+06	5.607E+06	5.214E+06	1.006	1.082	1.075
Spontaneous	1.285E+08	1.285E+08	1.258E+08	1.000	1.021	1.021
Total	1.341E+08	1.341E+08	1.310E+08	1.000	1.024	1.024
			50 years			
Alpha,n	5.542E+06	5.498E+06	5.116E+06	1.008	1.083	1.075
Spontaneous	4.351E+07	4.352E+07	4.288E+07	1.000	1.015	1.015
Total	4.905E+07	4.901E+07	4.800E+07	1.001	1.022	1.021
			100 years			
Alpha,n	4.856E+06	4.820E+06	4.485E+06	1.007	1.083	1.075
Spontaneous	9.793E+06	9.808E+06	9.971E+06	0.998	0.982	0.984
Total	1.465E+07	1.463E+07	1.446E+07	1.001	1.013	1.012

TABLE 8. Typical PWR exposure (33 GWd/MTU) neutron production rates (neutrons/s)

Source	OR2	ORS	CIN	OR2/ORS	OR2/CIN	ORS/CIN
			30 d			
Alpha,n	4.957E+07	5.110E+07	4.758E+07	0.970	1.042	1.074
Spontaneous	5.346E+08	5.277E+08	5.903E+08	1.013	0.906	0.894
Total	5.842E+08	5.788E+08	6.378E+08	1.009	0.916	0.907
			5 years			
Alpha,n	5.405E+06	5.642E+06	5.369E+06	0.958	1.007	1.051
Spontaneous	2.462E+08	2.398E+08	2.979E+08	1.027	0.826	0.805
Total	2.516E+08	2.455E+08	3.032E+08	1.025	0.830	0.810
			10 years			
Alpha,n	5.601E+06	5.906E+06	5.545E+06	0.948	1.010	1.065
Spontaneous	2.040E+08	1.986E+08	2.467E+08	1.027	0.827	0.805
Total	2.096E+08	2.045E+08	2.523E+08	1.025	0.831	0.811
			20 years			
Alpha,n	5.818E+06	6.221E+06	5.736E+06	0.935	1.014	1.085
Spontaneous	1.405E+08	1.368E+08	1.698E+08	1.027	0.827	0.806
Total	1.463E+08	1.430E+08	1.756E+08	1.023	0.833	0.814
			50 years			
Alpha,n	5.670E+06	6.188E+06	5.583E+06	0.916	1.016	1.108
Spontaneous	4.745E+07	4.621E+07	5.718E+07	1.027	0.830	0.808
Total	5.312E+07	5.240E+07	6.276E+07	1.014	0.846	0.835
			100 years			
Alpha,n	4.950E+06	5.456E+06	4.905E+06	0.907	1.009	1.112
Spontaneous	1.053E+07	1.026E+07	1.248E+07	1.026	0.844	0.822
Total	1.548E+07	1.572E+07	1.739E+07	0.985	0.890	0.904

TABLE 9. Extended PWR exposure (50 GWd/MTU) neutron production rates (neutrons/s)

Source	OR2	ORS	CIN	OR2/ORS	OR2/CIN	ORS/CIN
			30 d			
Alpha,n	9.139E+07	9.810E+07	9.327E+07	0.932	0.980	1.052
Spontaneous	1.247E+09	1.265E+09	1.515E+09	0.986	0.823	0.835
Total	1.339E+09	1.363E+09	1.608E+09	0.982	0.833	0.848
			5 years			
Alpha,n	1.161E+07	1.222E+07	1.241E+07	0.950	0.936	0.985
Spontaneous	6.814E+08	6.765E+08	8.940E+08	1.007	0.762	0.757
Total	6.930E+08	6.887E+08	9.064E+08	1.006	0.765	0.760
			10 years			
Alpha,n	1.134E+07	1.199E+07	1.193E+07	0.946	0.951	1.005
Spontaneous	5.640E+08	5.594E+08	7.403E+08	1.008	0.762	0.756
Total	5.753E+08	5.713E+08	7.522E+08	1.007	0.765	0.760
			20 years			
Alpha,n	1.081E+07	1.151E+07	1.112E+07	0.939	0.972	1.035
Spontaneous	3.875E+08	3.843E+08	5.088E+08	1.008	0.762	0.755
Total	3.983E+08	3.958E+08	5.199E+08	1.006	0.766	0.761
			50 years			
Alpha,n	9.277E+06	1.000E+07	9.204E+06	0.928	1.008	1.086
Spontaneous	1.289E+08	1.284E+08	1.697E+08	1.004	0.760	0.757
Total	1.382E+08	1.384E+08	1.789E+08	0.999	0.772	0.774
			100 years			
Alpha,n	7.506E+06	8.144E+06	7.361E+06	0.922	1.020	1.106
Spontaneous	2.640E+07	2.683E+07	3.524E+07	0.984	0.749	0.761
Total	3.390E+07	3.497E+07	4.261E+07	0.969	0.796	0.821

TABLE 10. Typical BWR exposure (27.5 GWd/MTU) neutron production rates (neutrons/s)

Source	OR2	ORS	CIN	OR2/ORS	OR2/CIN	ORS/CIN
			30 d			
Alpha,n	4.367E+07	3.874E+07	3.515E+07	1.127	1.242	1.102
Spontaneous	4.176E+08	3.410E+08	3.439E+08	1.225	1.214	0.992
Total	4.612E+08	3.797E+08	3.790E+08	1.215	1.217	1.002
			5 years			
Alpha,n	4.210E+06	3.795E+06	3.130E+06	1.109	1.345	1.212
Spontaneous	1.697E+08	1.304E+08	1.396E+08	1.301	1.216	0.934
Total	1.740E+08	1.342E+08	1.427E+08	1.297	1.219	0.940
			10 years			
Alpha,n	4.468E+06	4.069E+06	3.311E+06	1.098	1.349	1.229
Spontaneous	1.407E+08	1.082E+08	1.158E+08	1.300	1.215	0.934
Total	1.452E+08	1.122E+08	1.191E+08	1.294	1.219	0.942
			20 years			
Alpha,n	4.790E+06	4.422E+06	3.542E+06	1.083	1.352	1.248
Spontaneous	9.705E+07	7.475E+07	8.006E+07	1.298	1.212	0.934
Total	1.018E+08	7.917E+07	8.361E+07	1.286	1.218	0.947
			50 years			
Alpha,n	4.865E+06	4.578E+06	3.603E+06	1.063	1.350	1.271
Spontaneous	3.311E+07	2.578E+07	2.771E+07	1.284	1.195	0.930
Total	3.797E+07	3.036E+07	3.131E+07	1.251	1.213	0.970
			100 years			
Alpha,n	4.345E+06	4.120E+06	3.233E+06	1.055	1.344	1.274
Spontaneous	7.730E+06	6.332E+06	6.924E+06	1.221	1.116	0.915
Total	1.207E+07	1.045E+07	1.016E+07	1.155	1.188	1.029

TABLE 11. Extended BWR exposure (40 GWd/MTU) neutron production rates (neutrons/s)

Source	OR2	ORS	CIN	OR2/ORS	OR2/CIN	ORS/CIN
			30 d			
Alpha,n	5.916E+07	6.696E+07	5.777E+07	0.884	1.024	1.159
Spontaneous	6.008E+08	6.501E+08	6.596E+08	0.924	0.911	0.986
Total	6.600E+08	7.171E+08	7.173E+08	0.920	0.920	1.000
			5 years			
Alpha,n	6.385E+06	6.980E+06	5.843E+06	0.915	1.093	1.195
Spontaneous	2.632E+08	2.790E+08	3.122E+08	0.943	0.843	0.894
Total	2.695E+08	2.859E+08	3.180E+08	0.943	0.847	0.899
			10 years			
Alpha,n	6.532E+06	7.150E+06	5.881E+06	0.914	1.111	1.216
Spontaneous	2.180E+08	2.310E+08	2.586E+08	0.944	0.843	0.893
Total	2.245E+08	2.382E+08	2.645E+08	0.942	0.849	0.901
			20 years			
Alpha,n	6.668E+06	7.319E+06	5.876E+06	0.911	1.135	1.246
Spontaneous	1.501E+08	1.590E+08	1.781E+08	0.944	0.843	0.893
Total	1.568E+08	1.664E+08	1.840E+08	0.942	0.852	0.904
			50 years			
Alpha,n	6.332E+06	6.995E+06	5.439E+06	0.905	1.164	1.286
Spontaneous	5.069E+07	5.367E+07	6.011E+07	0.944	0.843	0.893
Total	5.702E+07	6.066E+07	6.555E+07	0.940	0.870	0.925
			100 year			
Alpha,n	5.409E+06	5.997E+06	4.621E+06	0.902	1.171	1.298
Spontaneous	1.121E+07	1.183E+07	1.329E+07	0.948	0.843	0.890
Total	1.662E+07	1.783E+07	1.791E+07	0.932	0.928	0.996

the PWR exposure cases, comparison of the OR2/CIN (alpha,n) production rates revealed differences on the order of 10% or less. Predictions for spontaneous fission neutrons showed much higher deviations, typically from 15 to 20% and as great as 25.1% (Table 9, 100 years). The largest differences in the OR2/CIN (alpha, n) neutron production rates were observed in extended PWR exposure case (Table 9) for decay times greater than 30 d, and in the typical BWR exposure case (Table 10), at all times. As with the OR2/ORS comparisons, the largest deviations in the comparison of the OR2 (alpha,n) production rates with the CINDER-2 results were observed in the BWR exposure cases. The (alpha,n) neutron production rates for the typical BWR exposure case (Table 10) agreed no better than 24.2% at any decay time, were typically 35% in the OR2/CIN comparisons, and ranged from 10.2 to 27.4% in the ORS/CIN comparisons. Comparisons of the spontaneous fission neutron production rates in Table 10 revealed deviations from 11.6% to 22.5% for the OR2/CIN results, whereas the ORS/CIN results agreed to within approximately 10% at all cooling times. In the extended BWR exposure case the ratio OR2/CIN for spontaneous fission neutron production is a constant, 0.843, for all cooling times greater than 30 d. The ORS/CIN ratios for spontaneous fission neutrons decrease slightly with decay time but are in fair agreement with values near 0.89; however, the corresponding ratios for the (alpha,n) neutron production rates increase much faster with increasing cooling time from 1.159 at 30 d to 1.298 at 100 years. The primary mechanism for neutron production, particularly at the decay times of interest in this report (< 100 years), is spontaneous fission. These production rates are dominated by three nuclides, ^{242}Cm, ^{244}Cm and ^{246}Cm. Curium -242, -244, and plutonium -239 are the prevalent contributors to (alpha,n) neutron production. Large differences were observed in the inventories of these nuclides and are discussed in Sect. 6.2 of the earlier report concerning these code comparisons. The deviations in the neutron production rates of Tables 8--11 reflected the basic differences in nuclide inventories for these actinides as predicted by each of the point depletion codes.

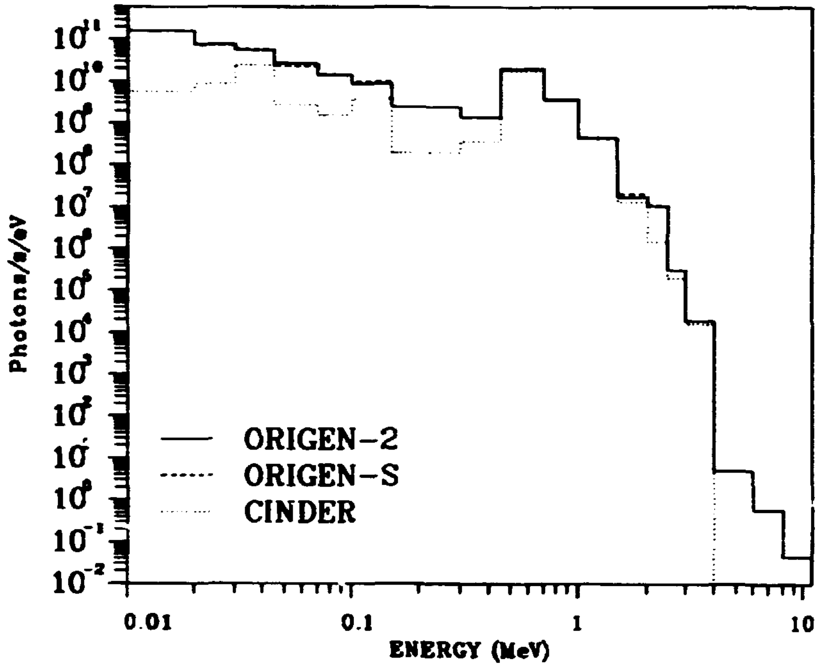
The largest deviations in the OR2/ORS comparisons for total neutron production rates are seen in the typical BWR exposure case (29.7%), and the best agreement is in the decay-only case (<1%). In the situations where there are the greatest differences in the OR2/ORS results, the agreement between ORS/CIN is at its best (other than for the decay-only case) at <6%.

4. COMPARISON OF TOTAL PHOTON SPECTRA

The aggregate photon spectra in units of photons/s/eV per metric ton initial uranium are compared in graphical (Figs. 1—10) and tabular (Tables 12—21) form. These spectra were calculated by dividing the intensity (photons/s) by the energy width (eV) for each group. The 18-group energy structure was chosen to be consistent with the ORIGEN2 results (although ORIGEN-S has the ability to calculate the photon spectra in any group structure) and is given in the comparison tables. The CINDER-2 spectra for photons, like the production rates, are calculated by an auxiliary code, SPEC5,[8] which combines the CINDER-calculated inventories with photon spectral data for each nuclide and, like ORIGEN-S, is capable of calculating these spectra in any specified group structure.

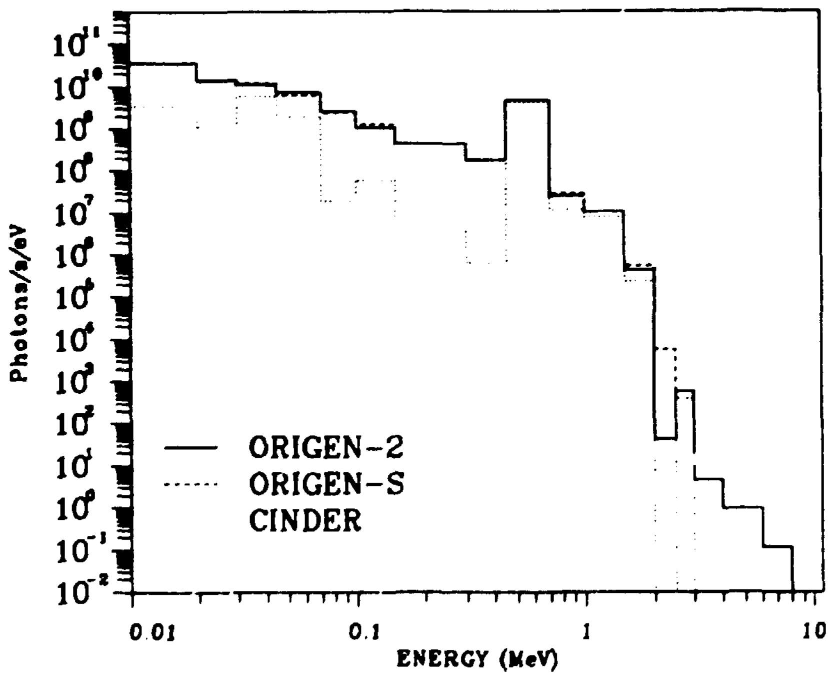
4.1 GENERAL COMMENTS ON THE PHOTON SPECTRA COMPARISONS

The photon spectra produced by ORIGEN2 and ORIGEN-S are in good agreement at energies less than 2 MeV. Above this energy there is some disagreement at 5-years cooling, particularly in the BWR exposure cases, and large disagreement (usually an order of magnitude or better) for all cases at 50-years cooling. The primary differences that have been observed in these comparisons are consistently seen in energy groups 13 (2—2.5 MeV) and 14 (2.5—3 MeV). In all cases the ORIGEN-S value in group 13 is larger than the corresponding ORIGEN2 value, and the reverse is true for group 14. Differences of this type, where ORIGEN-S (relative to ORIGEN2) predicts lower intensities in one group and higher intensities in an adjacent group, are partly due to the method ORIGEN-S uses to bin the spectra. The photon spectra are initially calculated as point data based on nuclide inventories and appropriate line data for each nuclide. These point energy spectra are then binned into the desired energy group structure. In ORIGEN-S and ORIGEN2 photons are binned such that energy is conserved (i.e., the product of the group intensity and the group mean energy summed over all groups yields the same value of total energy as does the point data). The method used by ORIGEN-S treats the boundaries in a manner slightly more complicated than that of ORIGEN2. In ORIGEN-S, photons produced within a certain energy



CASE 1 ; 5-YR COOLING TIME

Fig. 1: Case 1, Decay-only (PWR, 33 GWd/MTU) photon spectra (photons/s/eV); 5-year cooling.



CASE 1 ; 50-YR COOLING TIME

Fig. 2: Case 1, Decay-only (PWR, 33 GWd/MTU) photon spectra (photons/s/eV); 50-year cooling.

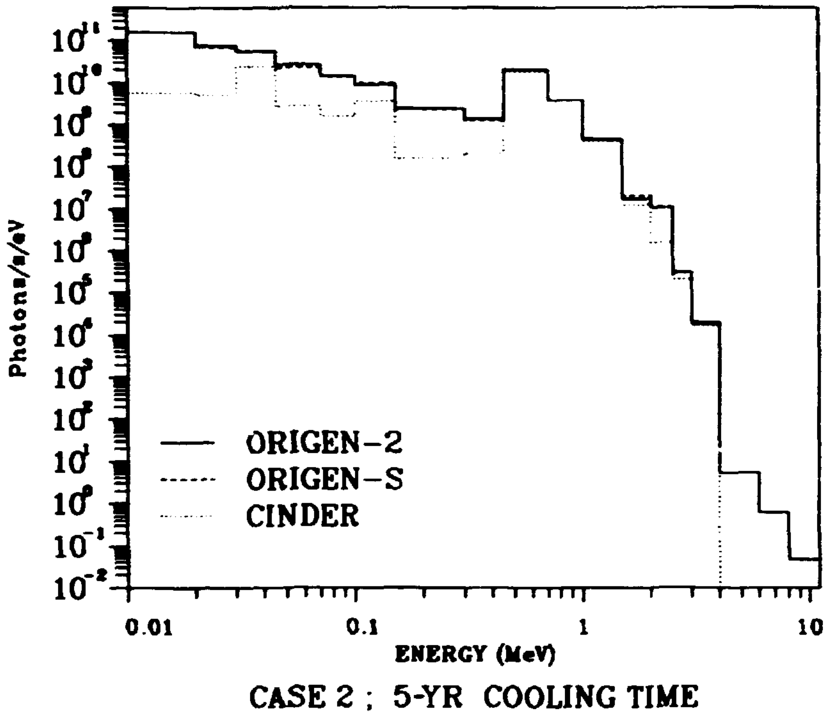


Fig. 3: Case 2, Typical PWR exposure (33 GWd/MTU) photon spectra (photons/s/eV); 5-year cooling.

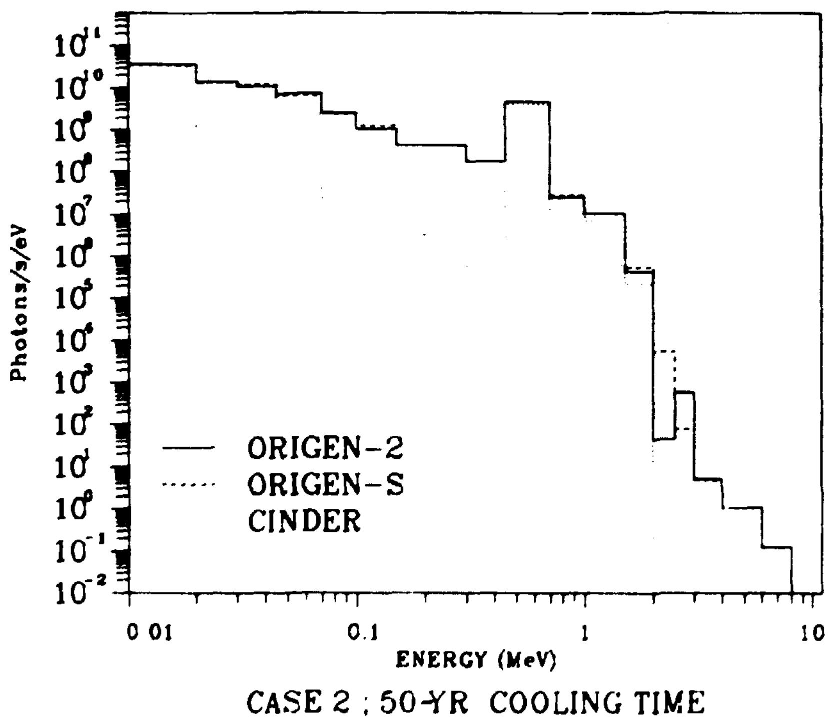


Fig. 4: Case 2, Typical PWR exposure (33 GWd/MTU) photon spectra (photons/s/eV); 50-year cooling.

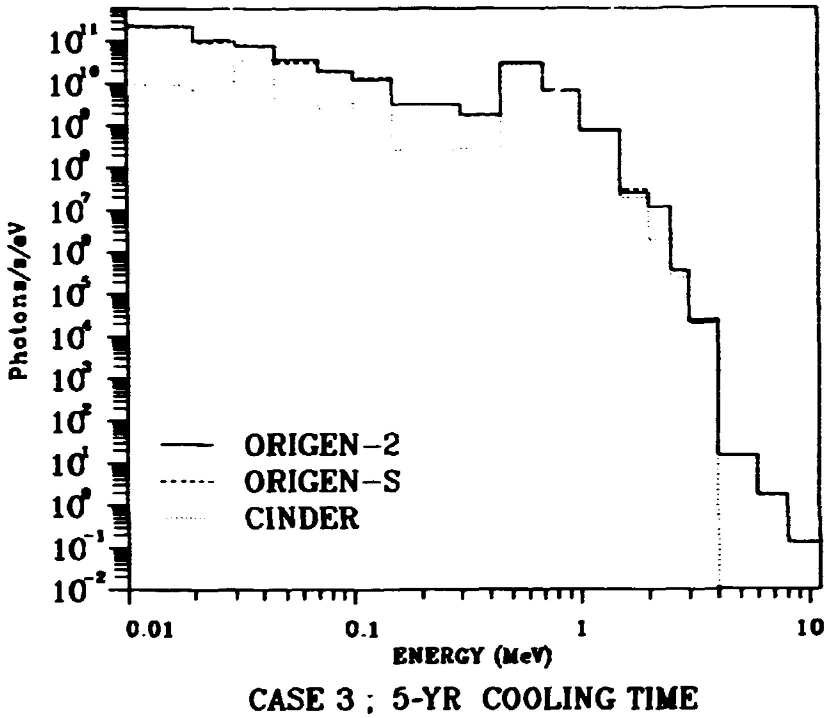


Fig. 5: Case 3, Extended PWR exposure (50 GWd/MTU) photon spectra (photons/s/eV); 5-year cooling.

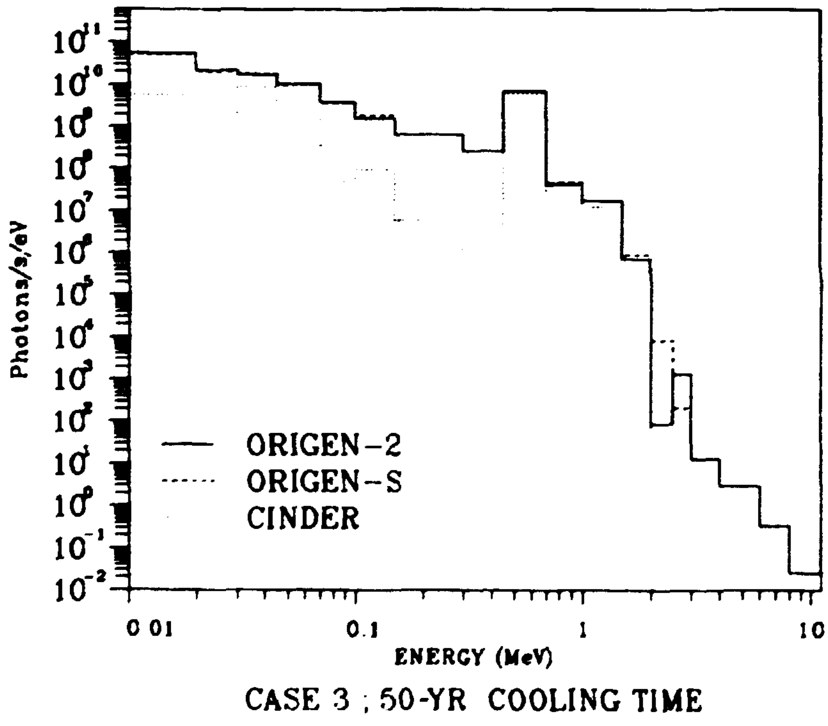
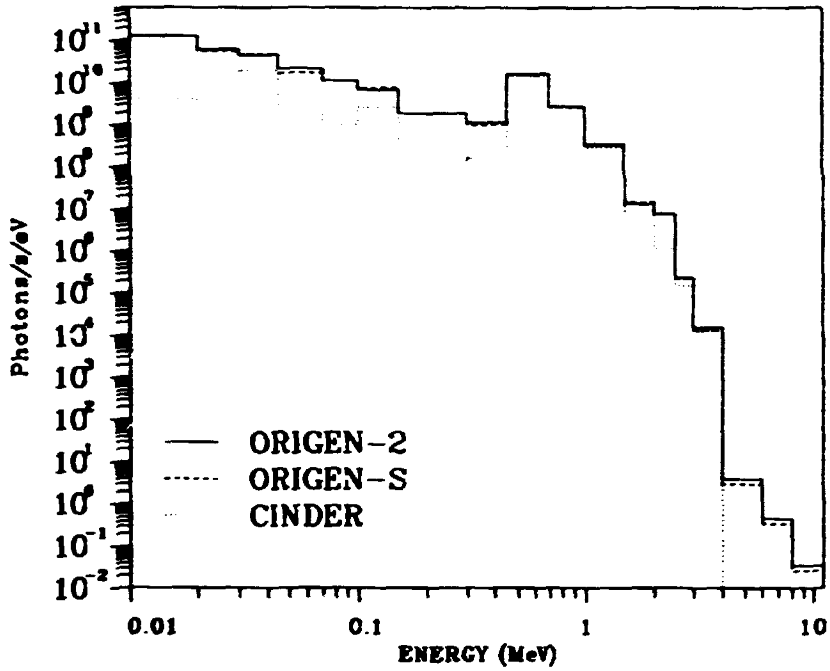
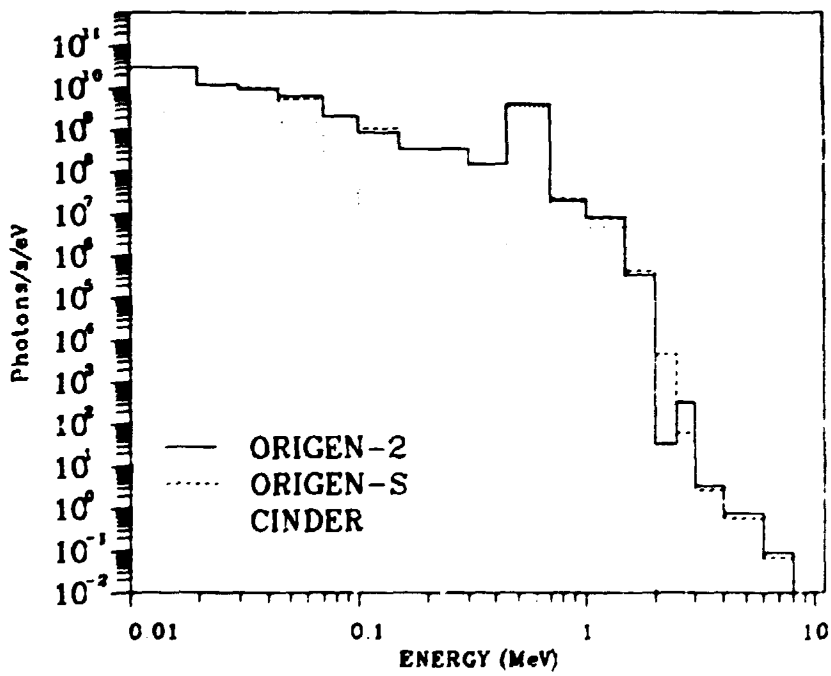


Fig. 6: Case 3, Extended PWR exposure (50 GWd/MTU) photon spectra (photons/s/eV); 50-year cooling.



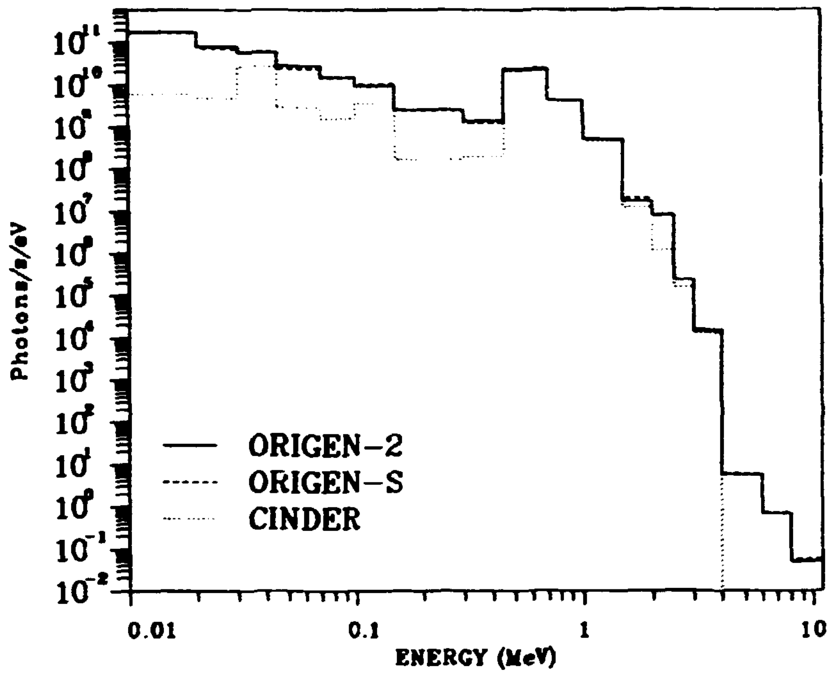
CASE 4 ; 5-YR COOLING TIME

Fig. 7: Case 4, Typical BWR exposure (27.5 GWd/MTU) photon spectra (photons/s/eV); 5-year cooling.



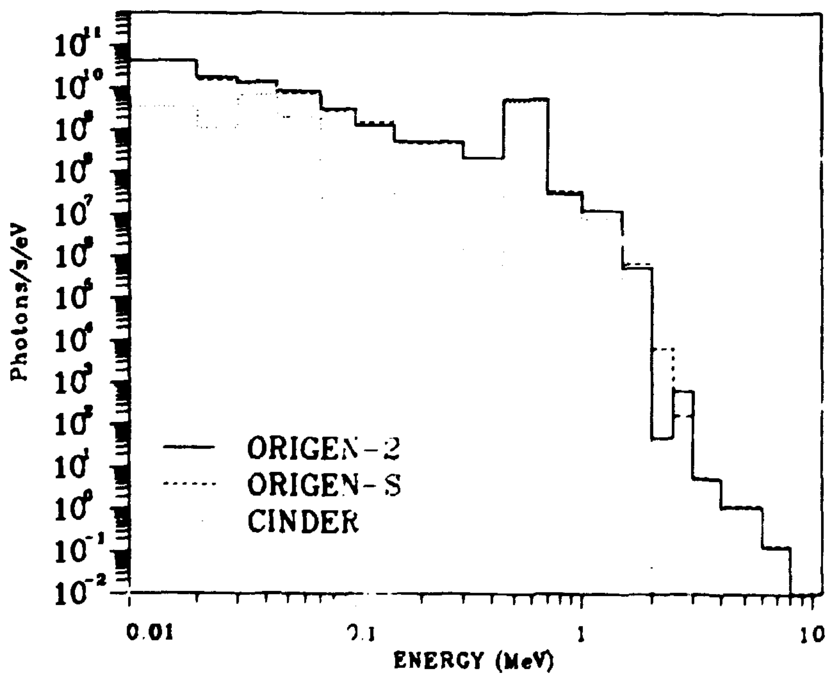
CASE 4 ; 50-YR COOLING TIME

Fig. 8: Case 4, Typical BWR exposure (27.5 GWd/MTU) photon spectra (photons/s/eV); 50-year cooling.



CASE 5 ; 5-YR COOLING TIME

Fig. 9: Case 5, Extended BWR exposure (40 GWd/MTU) photon spectra (photons/s/eV); 5-year cooling.



CASE 5 ; 50-YR COOLING TIME

Fig. 10: Case 5, Extended BWR exposure (40 GWd/MTU) photon spectra (photons/s/eV); 50-year cooling.

TABLE 12. Decay-only photon spectra (photons/s/eV) at a 5-year decay time

Energy (MeV)	ORIGEN2	ORIGEN-S	CINDER-2
0.000- 0.020	1.634E+11	1.574E+11	5.685E+09
0.020- 0.030	7.716E+10	7.339E+10	8.700E+09
0.030- 0.045	5.483E+10	5.868E+10	2.445E+10
0.045 0.070	2.615E+10	2.238E+10	2.774E+09
0.070- 0.100	1.415E+10	1.375E+10	1.569E+09
0.100- 0.150	8.655E+09	9.692E+09	3.824E+09
0.150- 0.300	2.399E+09	2.403E+09	2.047E ^8
0.300- 0.450	1.410E+09	1.407E+09	3.641E+08
0.450- 0.700	2.045E+10	2.040E+10	1.818E+10
0.700- 1.000	3.683E+09	3.733E+09	3.810E+09
1.000- 1.500	4.542E+08	4.380E+08	4.428E+08
1.500- 2.000	1.682E+07	2.000E+07	1.294E+07
2.000- 2.500	1.030E+07	1.082E+07	1.502E+06
2.500- 3.000	3.053E+05	3.085E+05	1.997E+05
3.000- 4.000	1.945E+04	1.922E+04	1.653E+04
4.000- 6.000	4.960E+00	4.965E+00	0.000E+00
6.000- 8.000	5.720E-01	5.700E-01	0.000E+00
8.000-11.000	4.380E-02	4.400E-02	0.000E+00

TABLE 13. Decay-only photon spectra (photons/s/eV) at a 50-year decay time

Energy (MeV)	ORIGEN2	ORIGEN-S	CINDER-2
0.000- 0.020	3.663E+10	3.536E+10	3.395E+09
0.020- 0.030	1.444E+10	1.365E+10	1.121E+09
0.030- 0.045	1.121E+10	1.202E+10	5.779E+09
0.045 0.070	7.234E+09	6.432E+09	2.002E+09
0.070- 0.100	2.576E+09	2.497E+09	1.912E+07
0.100- 0.150	1.045E+09	1.255E+09	5.980E+07
0.150- 0.300	4.302E+08	4.305E+08	3.603E+06
0.300- 0.450	1.813E+08	1.815E+08	6.442E+05
0.450- 0.700	4.796E+09	4.800E+09	4.148E+09
0.700- 1.000	2.554E+07	2.910E+07	1.131E+07
1.000- 1.500	1.019E+07	1.032E+07	7.688E+06
1.500- 2.000	4.419E+05	5.561E+05	2.416E+05
2.000- 2.500	4.219E+01	5.578E+03	5.480E-08
2.500- 3.000	5.640E+02	5.620E+02	3.938E+02
3.000- 4.000	4.583E+00	4.580E+00	6.028E-10
4.000- 6.000	9.780E-01	9.800E-01	0.000E+00
6.000- 8.000	1.125E-01	1.125E-01	0.000E+00
8.000-11.000	8.603E-03	8.633E-03	0.000E+00

TABLE 14. Typical PWR exposure (33 GWd/MTU) photon spectra (photons/s/eV) at a 5-year decay time

Energy (MeV)	ORIGEN2	ORIGEN-S	CINDER-2
0.000- 0.020	1.632E+11	1.560E+11	5.530E+09
0.020- 0.030	7.723E+10	6.911E+10	5.141E+09
0.030- 0.045	5.492E+10	5.795E+10	2.388E+10
0.045 0.070	2.614E+10	2.223E+10	2.721E+09
0.070- 0.100	1.417E+10	1.369E+10	1.553E+09
0.100- 0.150	8.693E+09	9.671E+09	3.602E+09
0.150- 0.300	2.402E+09	2.349E+09	1.565E+08
0.300- 0.450	1.416E+09	1.267E+09	2.127E+08
0.450- 0.700	2.055E+10	2.028E+10	1.843E+10
0.700- 1.000	3.737E+09	3.767E+09	3.780E+09
1.000- 1.500	4.620E+08	4.440E+08	4.162E+08
1.500- 2.000	1.713E+07	2.000E+07	1.229E+07
2.000- 2.500	1.030E+07	1.076E+07	1.567E+06
2.500- 3.000	3.123E+05	3.001E+05	2.078E+05
3.000- 4.000	1.993E+04	1.862E+04	1.724E+04
4.000- 6.000	5.425E+00	5.300E+00	0.000E+00
6.000- 8.000	6.255E-01	6.100E-01	0.000E+00
8.000-11.000	4.790E-02	4.667E-02	0.000E+00

TABLE 15. Typical PWR exposure (33 GWd/MTU) photon spectra (photons/s/eV) at a 50-year decay time

Energy (MeV)	ORIGEN2	ORIGEN-S	CINDER-2
0.000- 0.020	3.637E+10	3.521E+10	3.770E+09
0.020- 0.030	1.431E+10	1.350E+10	1.279E+09
0.030- 0.045	1.116E+10	1.196E+10	5.940E+09
0.045 0.070	7.225E+09	6.732E+09	2.318E+09
0.070- 0.100	2.552E+09	2.466E+09	2.418E+07
0.100- 0.150	1.037E+09	1.240E+09	5.432E+07
0.150- 0.300	4.260E+08	4.238E+08	3.274E+06
0.300- 0.450	1.794E+08	1.782E+08	5.694E+05
0.450- 0.700	4.796E+09	4.800E+09	4.264E+09
0.700- 1.000	2.559E+07	2.910E+07	1.019E+07
1.000- 1.500	1.030E+07	1.044E+07	6.928E+06
1.500- 2.000	4.437E+05	5.581E+05	2.176E+05
2.000- 2.500	4.349E+01	5.479E+03	5.716E-08
2.500- 3.000	5.710E+02	7.580E+01	7.576E-09
3.000- 4.000	4.989E+00	4.860E+00	6.287E-10
4.000- 6.000	1.065E+00	1.040E+00	0.000E+00
6.000- 8.000	1.225E-01	1.195E-01	0.000E+00
8.000-11.000	9.370E-03	9.133E-03	0.000E+00

TABLE 16. Extended PWR exposure (50 GWd/MTU) photon spectra (photons/s/eV) at a 5-year decay time

Energy (MeV)	ORIGEN2	ORIGEN-S	CINDER-2
0.000- 0.020	2.294E+11	2.181E+11	9.190E+09
0.020- 0.030	1.062E+11	9.565E+10	7.052E+09
0.030- 0.045	7.876E+10	8.336E+10	3.523E+10
0.045 0.070	3.654E+10	3.096E+10	4.440E+09
0.070- 0.100	1.999E+10	1.930E+10	2.639E+09
0.100- 0.150	1.256E+10	1.394E+10	5.614E+09
0.150- 0.300	3.316E+09	3.238E+09	2.573E+08
0.300- 0.450	1.878E+09	1.700E+09	2.869E+08
0.450- 0.700	3.217E+10	3.132E+10	2.899E+10
0.700- 1.000	6.750E+09	6.500E+09	6.860E+09
1.000- 1.500	7.900E+08	7.540E+08	7.270E+08
1.500- 2.000	2.532E+07	2.960E+07	1.962E+07
2.000- 2.500	1.132E+07	1.176E+07	1.905E+06
2.500- 3.000	3.741E+05	3.524E+05	2.526E+05
3.000- 4.000	2.391E+04	2.197E+04	2.095E+04
4.000- 6.000	1.498E+01	1.490E+01	0.000E+00
6.000- 8.000	1.727E+00	1.715E+00	0.000E+00
8.000-11.000	1.323E-01	1.313E-01	0.000E+00

TABLE 17. Extended PWR exposure (50 GWd/MTU) photon spectra (photons/s/eV) at a 50-year decay time

Energy (MeV)	ORIGEN2	ORIGEN-S	CINDER-2
0.000- 0.020	5.485E+10	5.301E+10	5.530E+09
0.020- 0.030	2.146E+10	2.023E+10	1.808E+09
0.030- 0.045	1.674E+10	1.791E+10	8.873E+09
0.045 0.070	1.057E+10	9.616E+09	3.124E+09
0.070- 0.100	3.846E+09	3.704E+09	4.927E+07
0.100- 0.150	1.578E+09	1.881E+09	9.684E+07
0.150- 0.300	6.429E+08	6.383E+08	6.029E+06
0.300- 0.450	2.701E+08	2.684E+08	9.533E+05
0.450- 0.700	7.152E+09	7.160E+09	6.360E+09
0.700- 1.000	4.127E+07	4.701E+07	1.804E+07
1.000- 1.500	1.732E+07	1.756E+07	1.227E+07
1.500- 2.000	7.224E+05	9.101E+05	3.854E+05
2.000- 2.500	8.792E+01	8.251E+03	6.948E-08
2.500- 3.000	1.358E+03	2.120E+02	9.210E-09
3.000- 4.000	1.337E+01	1.330E+01	7.643E-10
4.000- 6.000	2.857E+00	2.850E+00	0.000E+00
6.000- 8.000	3.291E-01	3.275E-01	0.000E+00
8.000-11.000	2.518E-02	2.510E-02	0.000E+00

TABLE 18. Typical BWR exposure (27.5 GWd/MTU) photon spectra (photons/s/eV) at a 5-year decay time

Energy (MeV)	ORIGEN2	ORIGEN-S	CINDER-2
0.000- 0.020	1.298E+11	1.239E+11	3.956E+09
0.020- 0.030	6.099E+10	5.498E+10	3.853E+09
0.030- 0.045	4.367E+10	4.588E+10	1.886E+10
0.045 0.070	2.081E+10	1.761E+10	1.832E+09
0.070- 0.100	1.119E+10	1.075E+10	9.913E+08
0.100- 0.150	6.763E+09	7.427E+09	2.510E+09
0.150- 0.300	1.892E+09	1.848E+09	1.123E+08
0.300- 0.450	1.102E+09	9.935E+08	1.611E+08
0.450- 0.700	1.639E+10	1.600E+10	1.428E+10
0.700- 1.000	2.748E+09	2.653E+09	2.546E+09
1.000- 1.500	3.528E+08	3.220E+08	2.876E+08
1.500- 2.000	1.320E+07	1.478E+07	8.586E+06
2.000- 2.500	7.496E+06	7.800E+06	1.110E+06
2.500- 3.000	2.383E+05	2.201E+05	1.471E+05
3.000- 4.000	1.523E+04	1.361E+04	1.221E+04
4.000- 6.000	3.745E+00	2.885E+00	0.000E+00
6.000- 8.000	4.317E-01	3.320E-01	0.000E+00
8.000-11.000	3.306E-02	2.547E-02	0.000E+00

TABLE 19. Typical BWR exposure (27.5 GWd/MTU) photon spectra (photons/s/eV) at a 50-year decay time

Energy (MeV)	ORIGEN2	ORIGEN-S	CINDER-2
0.000- 0.020	3.006E+10	2.919E+10	2.564E+09
0.020- 0.030	1.181E+10	1.131E+10	8.330E+08
0.030- 0.045	9.215E+09	9.954E+09	4.897E+09
0.045 0.070	6.126E+09	5.444E+09	1.510E+09
0.070- 0.100	2.099E+09	2.059E+09	1.467E+07
0.100- 0.150	8.507E+08	1.031E+09	3.776E+07
0.150- 0.300	3.502E+08	3.545E+08	2.267E+06
0.300- 0.450	1.475E+08	1.495E+08	4.128E+05
0.450- 0.700	3.978E+09	3.992E+09	3.524E+09
0.700- 1.000	2.057E+07	2.314E+07	7.130E+06
1.000- 1.500	8.155E+06	8.021E+06	4.846E+06
1.500- 2.000	3.553E+05	4.400E+05	1.522E+05
2.000- 2.500	3.347E+01	4.591E+03	4.048E-08
2.500- 3.000	3.244E+02	6.100E+01	5.366E-09
3.000- 4.000	3.506E+00	2.740E+00	4.452E-10
4.000- 6.000	7.480E-01	5.850E-01	0.000E+00
6.000- 8.000	8.600E-02	6.750E-02	0.000E+00
8.000-11.000	6.573E-03	5.133E-03	0.000E+00

TABLE 20. Extended BWR exposure (40 GWd/MTU) photon spectra (photons/s/eV) at a 5-year decay time

ENERGY (MeV)	ORIGEN-2	ORIGEN-S	CINDER
0.000- 0.020	1.777E+11	1.690E+11	5.960E+09
0.020- 0.030	8.121E+10	7.362E+10	4.781E+09
0.030- 0.045	5.983E+10	6.322E+10	2.649E+10
0.045- 0.070	2.823E+10	2.388E+10	2.827E+09
0.070 0.100	1.516E+10	1.462E+10	1.554E+09
0.100- 0.150	9.177E+09	1.023E+10	3.656E+09
0.150- 0.300	2.529E+09	2.469E+09	1.704E+08
0.300- 0.450	1.390E+09	1.280E+09	1.983E+08
0.450- 0.700	2.350E+10	2.320E+10	2.095E+10
C.700- 1.000	4.197E+09	4.200E+09	4.193E+09
1.000- 1.500	5.210E+08	5.020E+08	4.628E+08
1.500- 2.000	1.705E+07	2.000E+07	1.256E+07
2.000- 2.500	7.940E+06	8.280E+06	1.180E+06
2.500- 3.000	2.429E+05	2.343E+05	1.564E+05
3.000- 4.000	1.548E+04	1.443E+04	1.297E+04
4.000- 6.000	5.800E+00	6.150E+00	0.000E+00
6.000- 8.000	6.685E-01	7.100E-01	0.000E+00
8.000- 11.000	5.120E-02	5.433E-02	0.000E+00

TABLE 21. Extended BWR exposure (40 GWd/MTU) photon spectra (photons/s/eV) at a 50-year decay time

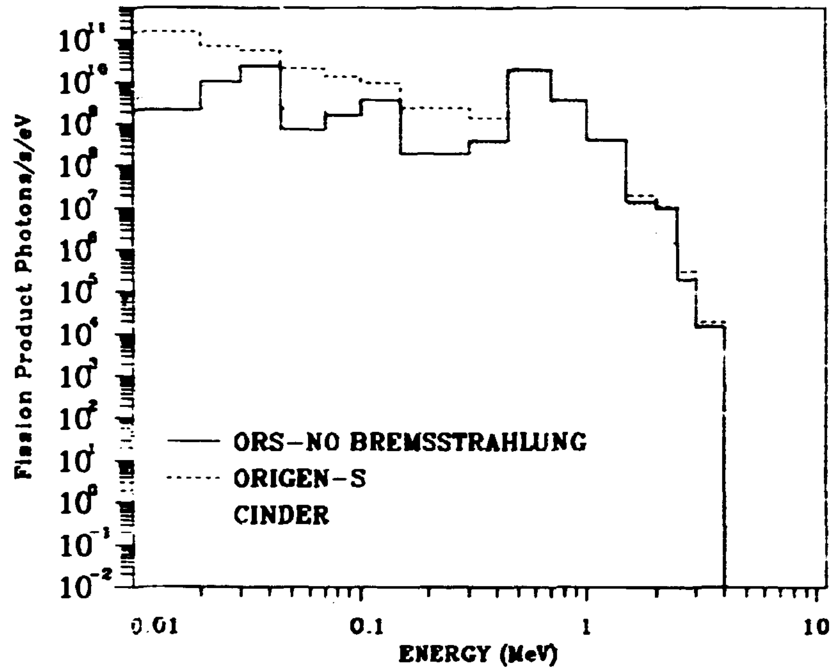
ENERGY (MeV)	ORIGEN-2	ORIGEN-S	CINDER
0.000- 0.020	4.500E+10	4.310E+10	3.609E+09
0.020- 0.030	1.778E+10	1.661E+10	1.143E+09
0.030- 0.045	1.361E+10	1.450E+10	7.013E+09
0.045- 0.070	8.566E+09	7.776E+09	2.014E+09
0.070- 0.100	3.190E+09	3.044E+09	2.485E+07
0.100- 0.150	1.294E+09	1.531E+09	6.258E+07
0.150- 0.300	5.346E+08	5.253E+08	3.819E+06
0.300- 0.450	2.258E+08	2.216E+08	6.416E+05
0.450- 0.700	5.696E+09	5.720E+09	5.040E+09
0.700- 1.000	3.141E+07	3.567E+07	1.179E+07
1.000- 1.500	1.242E+07	1.262E+07	8.014E+06
1.500- 2.000	5.423E+05	6.801E+05	2.518E+05
2.000- 2.500	5.112E+01	6.802E+03	4.302E-08
2.500- 3.000	6.612E+02	1.712E+02	5.702E-09
3.000- 4.000	5.328E+00	5.630E+00	4.732E-10
4.000- 6.000	1.137E+00	1.205E+00	0.000E+00
6.000- 8.000	1.308E-01	1.385E-01	0.000E+00
8.000- 11.000	1.000E-02	1.060E-02	0.000E+00

interval (taken to be 3% of the energy width of the group) of a group boundary are divided among the two groups adjacent to that boundary such that energy is conserved. The magnitude of the intensities in these two groups (10^1 to 10^3) predicted by either code being substantially less than that observed for the peak values (10^{10} to 10^{11}) helps put these seemingly large differences into perspective. Results of the photon dose calculations (Sect. 6.2) will further allay concerns about these differences. The auxiliary code used for the CINDER-2 calculations uses a simple method of binning the photon spectra which is independent of the group mean energies and conserves photon number.

The CINDER-2 photon spectra agree relatively well with the ORIGEN calculations from 0.45 to 1.5 MeV for decay times of 5 years. At cooling times of 50 years, there is poor agreement in all energy intervals other than group 9 (0.45 to 0.7 MeV).

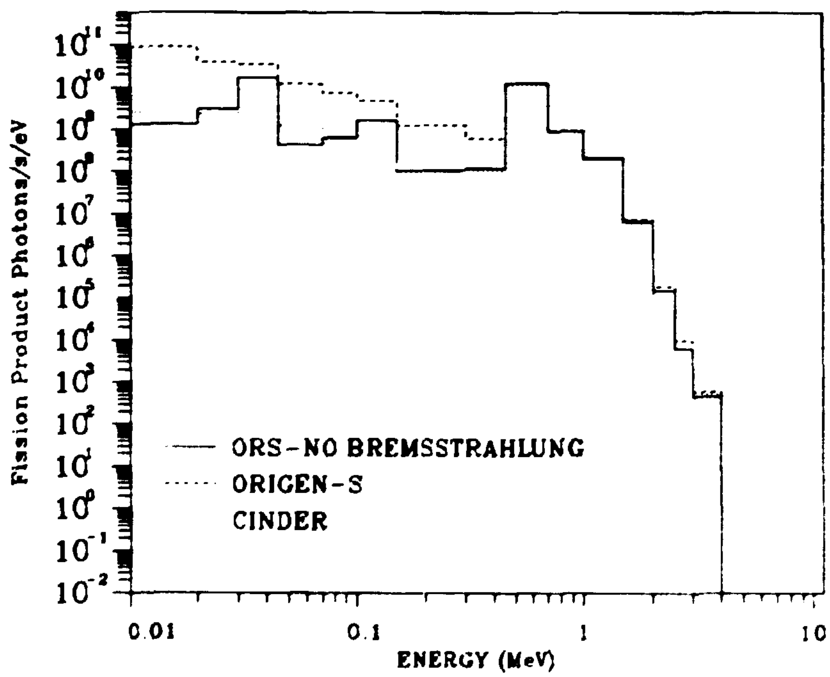
4.2 RECONCILING MAJOR DIFFERENCES IN THE PHOTON SPECTRA

As was the case with the photon production rates, the large differences between the CINDER-2 spectra and those calculated by the ORIGEN-type codes are suspected to be the result of the inclusion of bremsstrahlung radiation in both the ORIGEN2 and ORIGEN-S calculations but not in the CINDER-2 results. Figs. 11—13 are plots of the energy spectra of photons from fission products as produced from ORIGEN-S, CINDER-2, and a second ORIGEN-S calculation in which bremsstrahlung were purposefully neglected for the decay-only case at cooling times of 5, 10, and 50 years, respectively. The original ORIGIN-S results are included in the figures as a reference and to illustrate the effect of the bremsstrahlung radiation. The spectra for total photons are given in a similar fashion in Figs. 14—16 and in Tables 22—24. The agreement between the ORIGEN-S calculation without bremsstrahlung (ORSNB) and the CINDER-2 results is greatly improved. Ratios of ORSNB/CIN for total photon production rates at 5, 10, and 50 years were calculated as 1.0576, 1.0885 and 1.0966. The spectra over the energy range 0.45 to 2.0 MeV exhibit very good agreement at all cooling times. Energy group 13 (2.0 to 2.5 MeV) displays poor agreement at all decay times; however, the magnitude of the intensity in this group relative to the total is significant only for the 5-year cooling time.



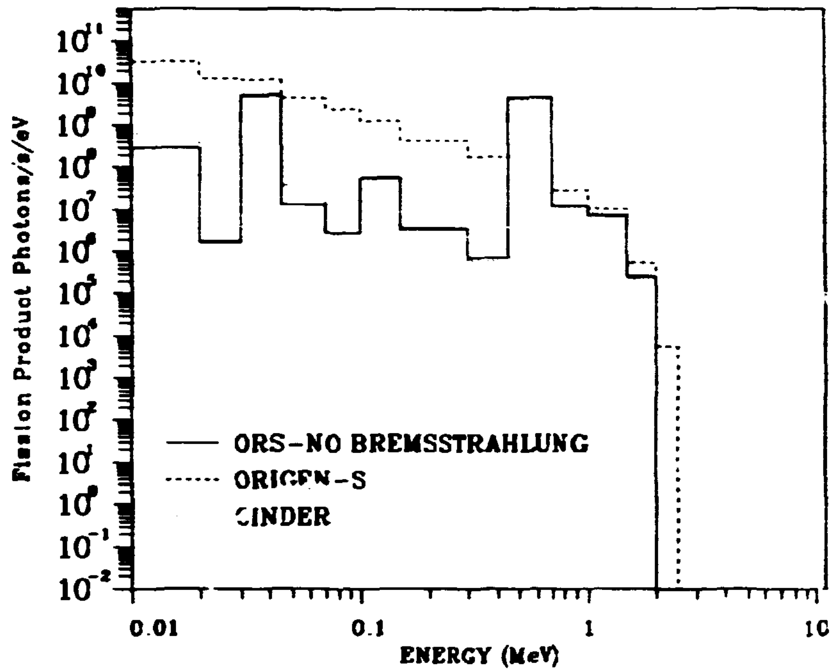
DECAY ONLY; 5-YEAR COOLING TIME

Fig. 11: Decay-only fission product photon spectra; 5-year cooling time.



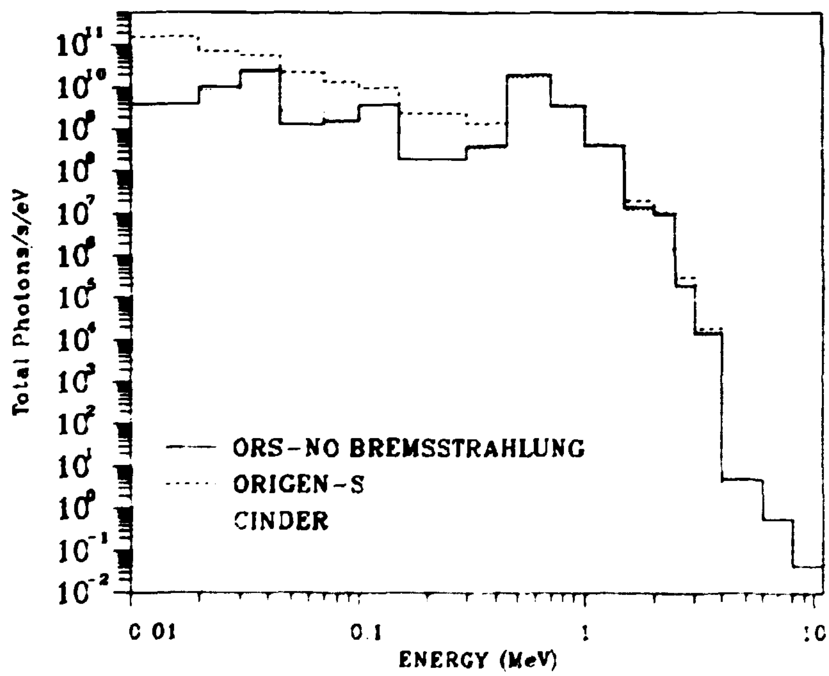
DECAY ONLY; 10-YEAR COOLING TIME

Fig. 12: Decay-only fission product photon spectra; 10-year cooling time.



DECAY ONLY; 50-YEAR COOLING TIME

Fig. 13: Decay-only fission product photon spectra; 50-year cooling time.



DECAY ONLY; 5-YEAR COOLING TIME

Fig. 14. Decay-only total photon spectra; 5-year cooling time.

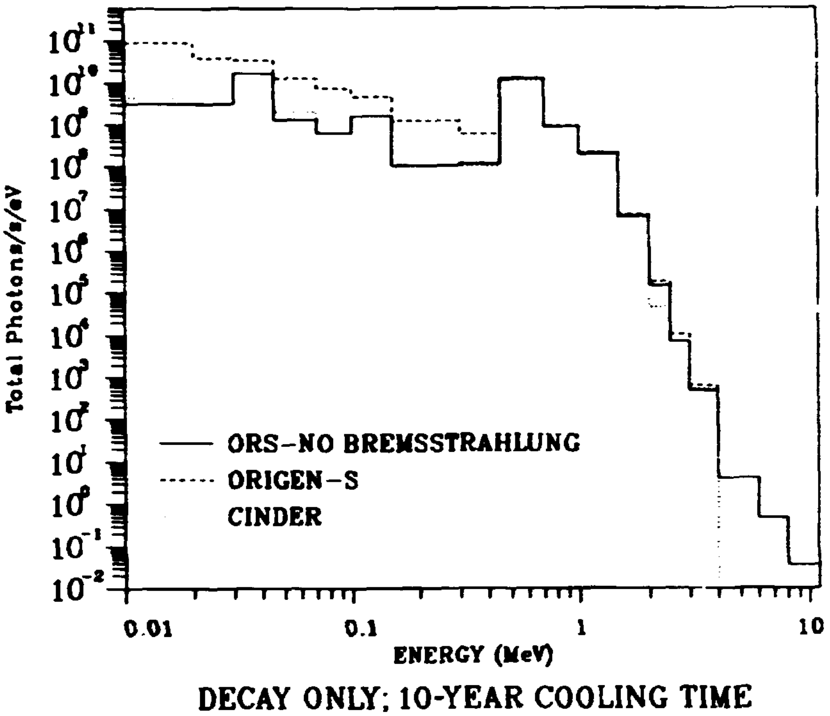


Fig. 15: Decay-only total photon spectra; 10-year cooling time.

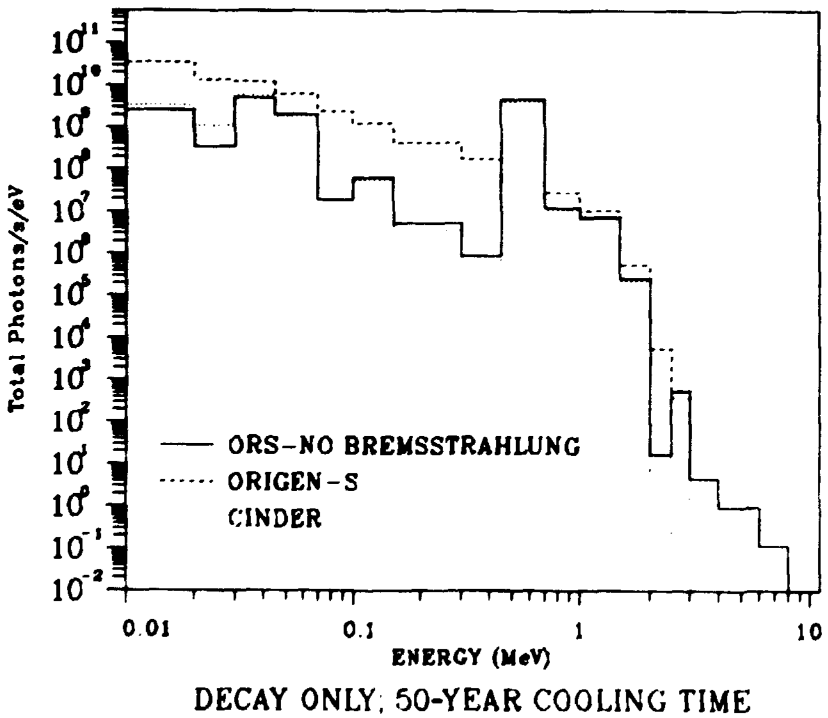


Fig. 16: Decay-only total photon spectra; 50-year cooling time.

TABLE 22. Comparisons without bremsstrahlung; total photons (photons/s/eV) at 5-year cooling time

ENERGY (MeV)	CINDER-2	ORIGEN-S NO BREM	ORIGEN-S	ORSNB/CIN
0.000- 0.020	5.6850E+09	4.0206E+09	1.5735E+11	0.7072
0.020- 0.030	8.7000E+09	1.0681E+10	7.3393E+10	1.2277
0.030- 0.045	2.4447E+10	2.5993E+10	5.8679E+10	1.0632
0.045 0.070	2.7736E+09	1.3083E+09	2.2380E+10	0.4717
0.070- 0.100	1.5693E+09	1.6962E+09	1.3751E+10	1.0809
0.100- 0.150	3.8240E+09	3.7858E+09	9.6919E+09	0.9900
0.150- 0.300	2.0473E+08	1.9951E+08	2.4028E+09	0.9745
0.300- 0.450	3.6413E+08	4.1070E+08	1.4069E+09	1.1279
0.450- 0.700	1.8184E+10	2.0098E+10	2.0400E+10	1.1053
0.700- 1.000	3.8100E+09	3.6347E+09	3.7333E+09	0.9540
1.000- 1.500	4.4280E+08	4.1018E+08	4.3800E+08	0.9263
1.500- 2.000	1.2940E+07	1.4682E+07	2.0000E+07	1.1346
2.000- 2.500	1.5024E+06	9.8024E+06	1.0820E+07	6.5245
2.500- 3.000	1.9968E+05	2.0164E+05	3.0850E+05	1.0098
3.000- 4.000	1.6530E+04	1.4533E+04	1.9223E+04	0.8792
4.000- 6.000	0.0000E+00	4.9670E+00	4.9650E+00	0.0000
6.000- 8.000	0.0000E+00	5.7195E-01	5.7000E-01	0.0000
8.000- 11.000	0.0000E+00	4.3860E-02	4.4000E-02	0.0000

TABLE 23. Comparisons without bremsstrahlung; total photons (photons/s/eV) at 10-year cooling time

ENERGY (MeV)	CINDER-2	ORIGEN-S NO BREM	ORIGEN-S	ORSNB/CIN
0.000- 0.020	4.3985E+09	3.2847E+09	9.2510E+10	0.7468
0.020- 0.030	2.9910E+09	3.1947E+09	3.9357E+10	1.0681
0.030- 0.045	1.6873E+10	1.6743E+10	3.5416E+10	0.9923
0.045- 0.070	2.1028E+09	1.3591E+09	1.3276E+10	0.6463
0.070- 0.100	6.3867E+08	6.5087E+08	7.3509E+09	1.0191
0.100- 0.150	1.6836E+09	1.6336E+09	4.8315E+09	0.9703
0.150- 0.300	1.0513E+08	1.0904E+08	1.2493E+09	1.0372
0.300- 0.450	1.0833E+08	1.2236E+08	6.0552E+08	1.1295
0.450- 0.700	1.1548E+10	1.3130E+10	1.3280E+10	1.1370
0.700- 1.000	9.1133E+08	8.9003E+08	9.3667E+08	0.9766
1.000- 1.500	2.1740E+08	1.9668E+08	2.0600E+08	0.9047
1.500- 2.000	6.1820E+06	6.6266E+06	7.5202E+06	1.0719
2.000- 2.500	4.8260E+04	1.4774E+05	1.9087E+05	3.0613
2.500- 3.000	6.9640E+03	7.1240E+03	1.0488E+04	1.0230
3.000- 4.000	5.3090E+02	4.8525E+02	6.3420E+02	0.9140
4.000- 6.000	0.0000E+00	4.1197E+00	4.1200E+00	0.0000
6.000- 8.000	0.0000E+00	4.7434E-01	4.7450E-01	0.0000
8.000- 11.000	0.0000E+00	3.6370E-02	3.6333E-02	0.0000

TABLE 24. Comparisons without bremsstrahlung total photons (photons/s/eV) at 50-year cooling time

ENERGY (MeV)	CINDER-2	ORIGEN-S NO BREM	ORIGEN-S	ORSNB/CIN
0.000- 0.020	3.3950E+09	2.5936E+09	3.5360E+10	0.7639
0.020- 0.030	1.1210E+09	3.4712E+08	1.3647E+10	0.3097
0.030- 0.045	5.7793E+09	5.1289E+09	1.2025E+10	0.8875
0.045- 0.070	2.0020E+09	2.0455E+09	6.4320E+09	1.0217
0.070- 0.100	1.9117E+07	1.9518E+07	2.4969E+09	1.0210
0.100- 0.150	5.9800E+07	6.5628E+07	1.2553E+09	1.0975
0.150- 0.300	3.6033E+06	5.3418E+06	4.3051E+08	1.4825
0.300- 0.450	6.4420E+05	9.1827E+05	1.8152E+08	1.4254
0.450- 0.700	4.1480E+09	4.7628E+09	4.8000E+09	1.1482
0.700- 1.000	1.1313E+07	1.2073E+07	2.9103E+07	1.0672
1.000- 1.500	7.6880E+06	6.8792E+06	1.0321E+07	0.8948
1.500- 2.000	2.4160E+05	2.5876E+05	5.5610E+05	1.0710
2.000- 2.500	0.0000E+00	1.7686E+01	5.5777E+03	0.0000
2.500- 3.000	3.9380E+02	5.6132E+02	5.6200E+02	1.4254
3.000- 4.000	0.0000E+00	4.5798E+00	4.5800E+00	0.0000
4.000- 6.000	0.0000E+00	9.7985E-01	9.8000E-01	0.0000
6.000- 8.000	0.0000E+00	1.1257E-01	1.1250E-01	0.0000
8.000- 11.000	0.0000E+00	0.0000E+00	0.0000E+00	0.0000

Using information tabulated in the ORIGEN-S output, ^{144}Pr was identified as an important contributor to group 13. The radionuclide photon spectra data used by SPEC5 (CINDER-2 calculations) and supplied by the group at LANL did not include spectra for this nuclide. Praseodymium-144 is not calculated explicitly in CINDER-2 as it is in secular equilibrium with ^{144}Ce. The spectral data for ^{144}Ce were examined to determine if a correction for the ^{144}Pr spectra had been made there; none was found. A rough calculation of the contribution of ^{144}Pr to group 13 (based on the ^{144}Ce activity calculated by CINDER-2 and the group 13 data from the ORIGEN-S Photon Library) was made. This value when added to the group 13 intensity calculated by SPECS without ^{144}Pr reduces the ratio ORSNB/CIN for group 13 from 6.5245 (Table 22) to approximately 0.98.

5. COMPARISON OF TOTAL NEUTRON SPECTRA

ORIGEN-S is the only one of the three depletion codes to directly calculate neutron spectra. The CINDER-2 results were combined with neutron spectral data for the individual nuclides (produced by the SOURCES[9] code) externally to provide total neutron spectra. At this time ORIGEN2 does not calculate neutron spectra. The 20-group energy structure used for the spectral calculations and comparisons was chosen arbitrarily and is given with the spectra in Tables 25—34.

Comparisons of the ORIGENS and CINDER-2 neutron spectra at 5- and 50-year cooling times are given graphically in Figures 17—26 for the five test cases. The spectral shapes were found to be almost identical for all cases and all cooling times, with the largest differences between the two source codes being observed at very low energies and again at the very high energies. The neutron spectra are considered to generally be in good overall agreement. The large differences in the group-1 value are due to the data used by ORIGEN-S to calculate neutron spectra; the (alpha,n) neutron spectra are cut off at the low-energy end at 0.1 MeV, and similarly the spontaneous fission data begin at 0.3 MeV.[10] Therefore, the group-1 value for the ORIGEN-S result is actually the contribution from (alpha,n) production from 0.1 to 0.202 MeV, whereas the value calculated from the CINDER-2 data includes both (alpha,n) and spontaneous fission neutrons from 0 to 0.202 MeV.

TABLE 25. Decay-only neutron spectra (neutrons/s/eV) at a 5-year decay time

Energy (MeV)	ORIGEN-S	CINDER-2
0.000- 0.202	1.565E-02	3.545E+01
0.202- 0.408	4.562E+01	5.902E+01
0.408- 0.608	8.993E+01	6.878E+01
0.608- 0.781	9.201E+01	7.267E+01
0.781- 1.003	8.088E+01	7.358E+01
1.003- 1.225	8.203E+01	7.221E+01
1.225- 1.423	8.031E+01	6.951E+01
1.423- 1.572	7.148E+01	6.649E+01
1.572- 1.827	6.478E+01	6.234E+01
1.827- 2.019	7.851E+01	5.744E+01
2.019- 2.466	4.260E+01	5.031E+01
2.466- 3.012	3.913E+01	3.960E+01
3.012- 3.679	2.843E+01	2.822E+01
3.679- 4.066	2.147E+01	2.021E+01
4.066- 4.966	1.283E+01	1.333E+01
4.966- 6.065	6.916E+00	6.796E+00
6.065- 8.187	2.246E+00	2.279E+00
8.187-10.000	3.862E-01	4.931E-01
10.000-14.918	5.828E-02	5.392E-02
14.918-19.640	0.000E+00	8.778E-04

TABLE 26. Decay-only neutron spectra (neutrons/s/eV) at a 50-year decay time

Energy (MeV)	ORIGEN-S	CINDER-2
0.000- 0.202	1.718E-02	7.021E+00
0.202- 0.408	8.894E+00	1.182E+01
0.408- 0.608	1.754E+01	1.400E+01
0.608- 0.781	1.803E+01	1.493E+01
0.781- 1.003	1.603E+01	1.527E+01
1.003- 1.225	1.652E+01	1.518E+01
1.225- 1.423	1.651E+01	1.496E+01
1.423- 1.572	1.507E+01	1.450E+01
1.572- 1.827	1.410E+01	1.369E+01
1.827- 2.019	1.793E+01	1.279E+01
2.019- 2.466	1.011E+01	1.145E+01
2.466- 3.012	9.674E+00	9.145E+00
3.012- 3.679	6.568E+00	6.349E+00
3.679- 4.066	4.479E+00	4.257E+00
4.066- 4.966	2.528E+00	2.619E+00
4.966- 6.065	1.337E+00	1.307E+00
6.065- 8.187	4.344E-01	4.343E-01
8.187-10.000	7.470E-02	9.318E-02
10.000-14.918	1.127E-02	1.011E-02
14.918-19.640	0.000E+00	1.623E-04

TABLE 27. Typical PWR exposure (33 GWd/MTU) neutron spectra (neutrons/s/eV) at a 5-year decay time

Energy (MeV)	ORIGEN-S	CINDER-2
0.000- 0.202	1.701E-02	4.796E+01
0.202- 0.408	4.862E+01	7.982E+01
0.408- 0.608	9.586E+01	9.297E+01
0.608- 0.781	9.809E+01	9.820E+01
0.781- 1.003	8.625E+01	9.932E+01
1.003- 1.225	8.748E+01	9.743E+01
1.225- 1.423	8.561E+01	9.369E+01
1.423- 1.572	7.622E+01	8.958E+01
1.572- 1.827	6.906E+01	8.396E+01
1.827- 2.019	8.377E+01	7.732E+01
2.019- 2.466	4.546E+01	6.767E+01
2.466- 3.012	4.175E+01	5.321E+01
3.012- 3.679	3.033E+01	3.798E+01
3.679- 4.066	2.289E+01	2.729E+01
4.066- 4.966	1.367E+01	1.805E+01
4.966- 6.065	7.370E+00	9.214E+00
6.065- 8.187	2.394E+00	3.089E+00
8.187-10.000	4.115E-01	6.692E-01
10.000-14.918	6.212E-02	7.320E-02
14.918-19.640	0.000E+00	1.192E-03

TABLE 28. Typical PWR exposure (33 GWd/MTU) neutron spectra (neutrons/s/eV) at a 50-year decay time

Energy (MeV)	ORIGEN-S	CINDER-2
0.000- 0.202	1.932E-02	9.323E+00
0.202- 0.408	9.449E+00	1.566E+01
0.408- 0.608	1.863E+01	1.849E+01
0.608- 0.781	1.916E+01	1.967E+01
0.781- 1.003	1.706E+01	2.007E+01
1.003- 1.225	1.759E+01	1.990E+01
1.225- 1.423	1.761E+01	1.953E+01
1.423- 1.572	1.610E+01	1.888E+01
1.572- 1.827	1.509E+01	1.780E+01
1.827- 2.019	1.926E+01	1.659E+01
2.019- 2.466	1.088E+01	1.478E+01
2.466- 3.012	1.044E+01	1.177E+01
3.012- 3.679	7.060E+00	8.219E+00
3.679- 4.066	4.784E+00	5.591E+00
4.066- 4.966	2.689E+00	3.490E+00
4.966- 6.065	1.421E+00	1.751E+00
6.065- 8.187	4.614E-01	5.829E-01
8.187-10.000	7.933E-02	1.254E-01
10.000-14.918	1.197E-02	1.364E-02
14.918-19.640	0.000E+00	2.196E-04

TABLE 29. Extended PWR exposure (50 GWd/MTU) neutron spectra (neutrons/s/eV) at a 5-year decay time

Energy (MeV)	ORIGEN-S	CINDER-2
0.000- 0.202	3.666E-02	1.438E+02
0.202- 0.408	1.371E+02	2.392E+02
0.408- 0.608	2.703E+02	2.784E+02
0.608- 0.781	2.765E+02	2.939E+02
0.781- 1.003	2.429E+02	2.972E+02
1.003- 1.225	2.462E+02	2.913E+02
1.225- 1.423	2.407E+02	2.800E+02
1.423- 1.572	2.140E+02	2.675E+02
1.572- 1.827	1.936E+02	2.506E+02
1.827- 2.019	2.341E+02	2.306E+02
2.019- 2.466	1.267E+02	2.016E+02
2.466- 3.012	1.160E+02	1.585E+02
3.012- 3.679	8.463E+01	1.133E+02
3.679- 4.066	6.428E+01	8.167E+01
4.066- 4.966	3.855E+01	5.419E+01
4.966- 6.065	2.079E+01	2.768E+01
6.065- 8.187	6.753E+00	9.288E+00
8.187-10.000	1.161E+00	2.012E+00
10.000-14.918	1.752E-01	2.204E-01
14.918-19.640	0.000E+00	3.592E-03

TABLE 30. Extended PWR exposure (50 GWd/MTU) neutron spectra (neutrons/s/eV) at a 50-year decay time

Energy (MeV)	ORIGEN-S	CINDER-2
0.000- 0.202	3.113E-02	2.749E+01
0.202- 0.408	2.614E+01	4.594E+01
0.408- 0.608	5.152E+01	5.382E+01
0.608- 0.781	5.285E+01	5.705E+01
0.781- 1.003	4.675E+01	5.794E+01
1.003- 1.225	4.784E+01	5.712E+01
1.225- 1.423	4.735E+01	5.548E+01
1.423- 1.572	4.273E+01	5.332E+01
1.572- 1.827	3.943E+01	5.012E+01
1.827- 2.019	4.911E+01	4.641E+01
2.019- 2.466	2.723E+01	4.098E+01
2.466- 3.012	2.563E+01	3.242E+01
3.012- 3.679	1.789E+01	2.290E+01
3.679- 4.066	1.276E+01	1.604E+01
4.066- 4.966	7.394E+00	1.032E+01
4.966- 6.065	3.945E+00	5.224E+00
6.065- 8.187	1.281E+00	1.746E+00
8.187-10.000	2.203E-01	3.767E-01
10.000-14.918	3.325E-02	4.107E-02
14.918-19.640	0.000E+00	6.648E-04

TABLE 31. Typical BWR exposure (27.5 GWd/MTU) neutron spectra (neutrons/s/eV) at a 5-year decay time

Energy (MeV)	ORIGEN-S	CINDER-2
0.000- 0.202	1.150E-02	2.250E+01
0.202- 0.408	2.646E+01	3.748E+01
0.408- 0.608	5.217E+01	4.368E+01
0.608- 0.781	5.338E+01	4.616E+01
0.781- 1.003	4.698E+01	4.671E+01
1.003- 1.225	4.766E+01	4.586E+01
1.225- 1.423	4.672E+01	4.413E+01
1.423- 1.572	4.165E+01	4.222E+01
1.572- 1.827	3.782E+01	3.958E+01
1.827- 2.019	4.600E+01	3.648E+01
2.019- 2.466	2.501E+01	3.195E+01
2.466- 3.012	2.304E+01	2.515E+01
3.012- 3.679	1.667E+01	1.790E+01
3.679- 4.066	1.251E+01	1.282E+01
4.066- 4.966	7.449E+00	8.454E+00
4.966- 6.065	4.009E+00	4.308E+00
6.065- 8.187	1.302E+00	1.443E+00
8.187-10.000	2.239E-01	3.122E-01
10.000-14.918	3.379E-02	3.414E-02
14.918-19.640	0.000E+00	5.551E-04

TABLE 32. Typical BWR exposure (27.5 GWd/MTU) neutron spectra (neutrons/s/eV) at a 50-year decay time

Energy (MeV)	ORIGEN-S	CINDER-2
0.000- 0.202	1.433E-02	4.550E+00
0.202- 0.408	5.288E+00	7.671E+00
0.408- 0.608	1.043E+01	9.107E+00
0.608- 0.781	1.075E+01	9.716E+00
0.781- 1.003	9.612E+00	9.946E+00
1.003- 1.225	9.982E+00	9.896E+00
1.225- 1.423	1.007E+01	9.778E+00
1.423- 1.572	9.292E+00	9.486E+00
1.572- 1.827	8.817E+00	8.962E+00
1.827- 2.019	1.144E+01	8.382E+00
2.019- 2.466	6.537E+00	7.519E+00
2.466- 3.012	6.349E+00	6.008E+00
3.012- 3.679	4.203E+00	4.158E+00
3.679- 4.066	2.750E+00	2.768E+00
4.066- 4.966	1.512E+00	1.690E+00
4.966- 6.065	7.923E-01	8.406E-01
6.065- 8.187	2.574E-01	2.785E-01
8.187-10.000	4.424E-02	5.958E-02
10.000-14.918	6.678E-03	6.448E-03
14.918-19.640	0.000E+00	1.031E-04

TABLE 33. Extended BWR exposure (40 GWd/MTU) neutron spectra (neutrons/s/eV) at a 5-year decay time

ENERGY (MeV)	ORIGEN-S	CINDER
0.000- 0.202	2.115E-02	5.025E+01
0.202- 0.408	5.658E+01	8.367E+01
0.408- 0.608	1.115E+02	9.746E+01
0.608- 0.781	1.141E+02	1.030E+02
0.781- 1.003	1.004E+02	1.041E+02
1.003- 1.225	1.018E+02	1.022E+02
1.225- 1.423	9.970E+01	9.828E+01
1.423- 1.572	8.878E+01	9.399E+01
1.572- 1.827	8.050E+01	8.809E+01
1.827- 2.019	7.258E+01	8.111E+01
2.019- 2.466	6.385E+01	7.101E+01
2.466- 3.012	4.876E+01	5.585E+01
3.012- 3.679	3.537E+01	3.984E+01
3.679- 4.066	2.665E+01	2.861E+01
4.066- 4.966	1.592E+01	1.892E+01
4.966- 6.065	8.574E+00	9.651E+00
6.065- 8.187	2.785E+00	3.238E+00
8.187- 10.000	4.787E-01	7.012E-01
10.000- 14.918	7.224E-02	7.670E-02
14.918- 19.640	0.000E+00	1.249E-03

TABLE 34. Extended BWR exposure (40 GWd/MTU) neutron spectra (neutrons/s/eV) at a 50-year decay time

ENERGY (MeV)	ORIGEN-S	CINDER
0.000- 0.202	2.189E-02	9.792E+00
0.202- 0.408	1.097E+01	1.644E+01
0.408- 0.608	2.164E+01	1.938E+01
0.608- 0.781	2.225E+01	2.061E+01
0.781- 1.003	1.979E+01	2.101E+01
1.003- 1.225	2.041E+01	2.081E+01
1.225- 1.423	2.041E+01	2.038E+01
1.423- 1.572	1.865E+01	1.969E+01
1.572- 1.827	1.747E+01	1.856E+01
1.827- 2.019	1.644E+01	1.727E+01
2.019- 2.466	1.506E+01	1.537E+01
2.466- 3.012	1.203E+01	1.223E+01
3.012- 3.679	8.142E+00	8.550E+00
3.679- 4.066	5.539E+00	5.841E+00
4.066- 4.966	3.119E+00	3.664E+00
4.966- 6.065	1.649E+00	1.840E+00
6.065- 8.187	5.358E-01	6.126E-01
8.187- 10.000	9.207E-02	1.318E-01
10.000- 14.918	1.390E-02	1.433E-02
14.918- 19.640	0.000E+00	2.308E-04

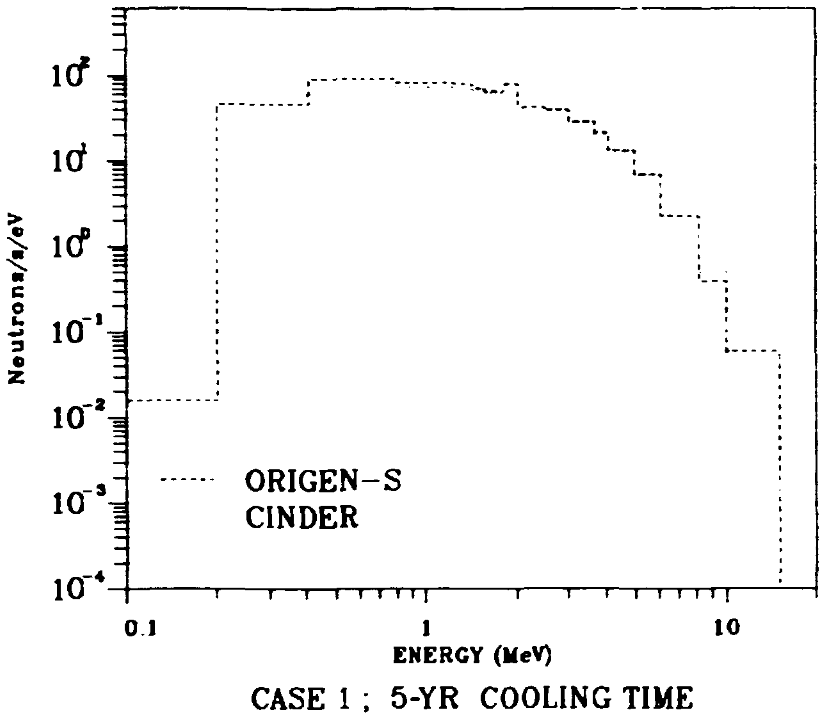


Fig. 17: Case 1, Decay-only (PWR, 33 GWd/MTU) neutron spectra (neutrons/s/eV); 5-year cooling.

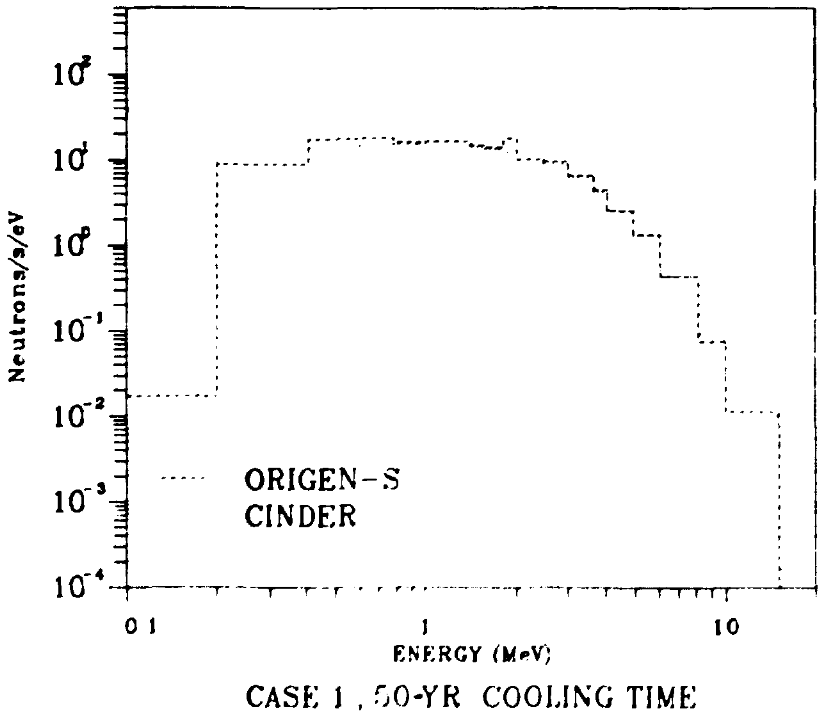


Fig. 18: Case 1, Decay-only (PWR, 33 GWd/MTU) neutron spectra (neutrons/s/eV); 50-year cooling.

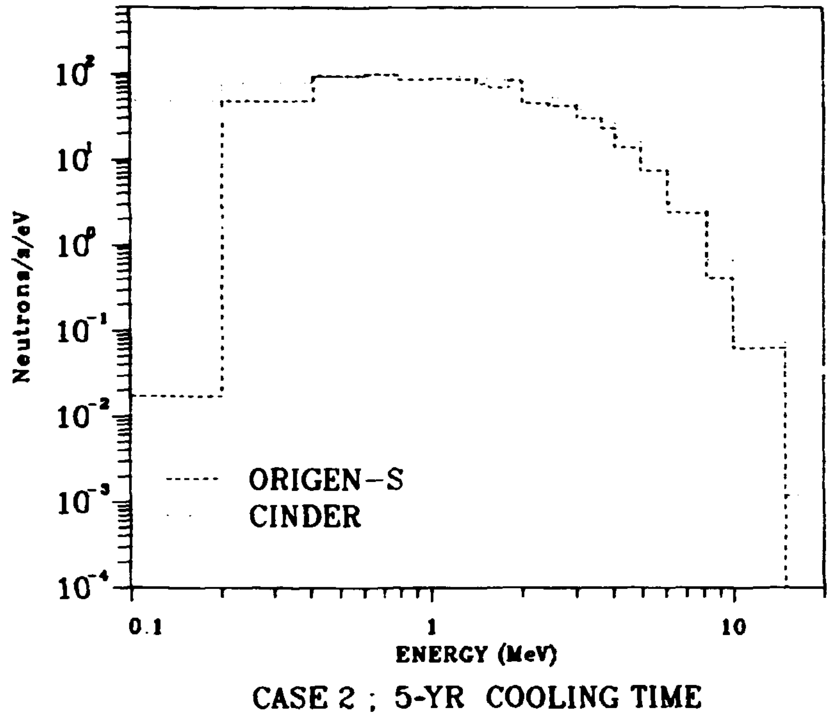


Fig. 19: Case 2, Typical PWR exposure (33 GWd/MTU) neutron spectra (neutrons/s/eV); 5-year cooling.

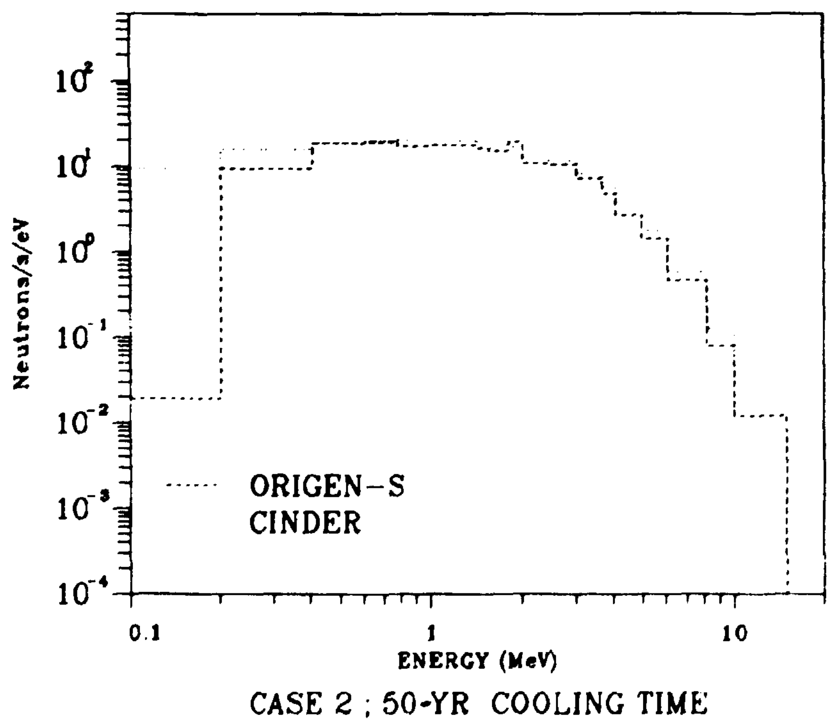


Fig. 20: Case 2, Typical PWR exposure (33 GWd/MTU) neutron spectra (neutrons/s/eV); 50-year cooling.

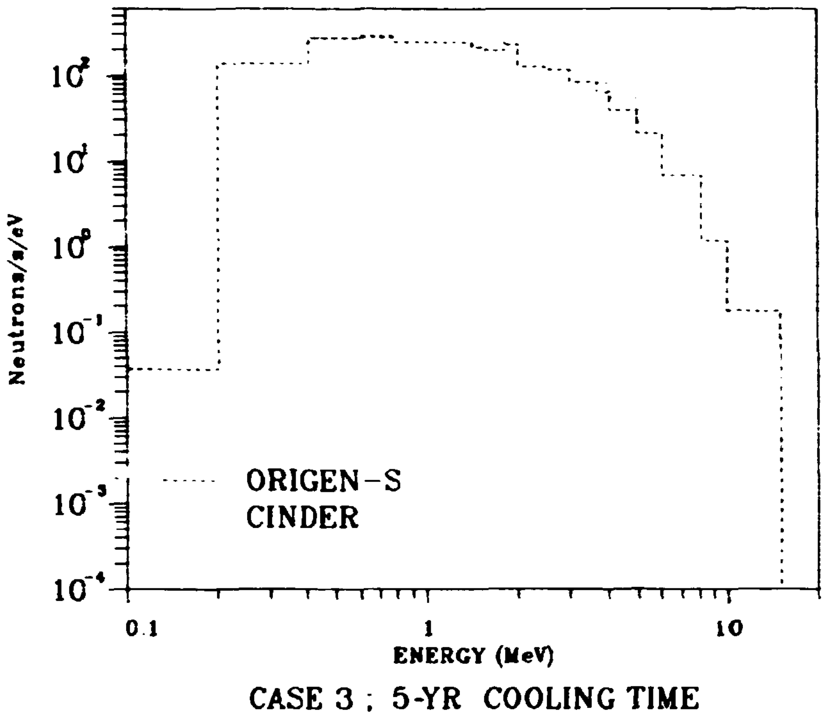


Fig. ?1: Case 3, Extended PWR exposure (50 GWd/MTU) neutron spectra (neutrons/s/ev); 5-year cooling.

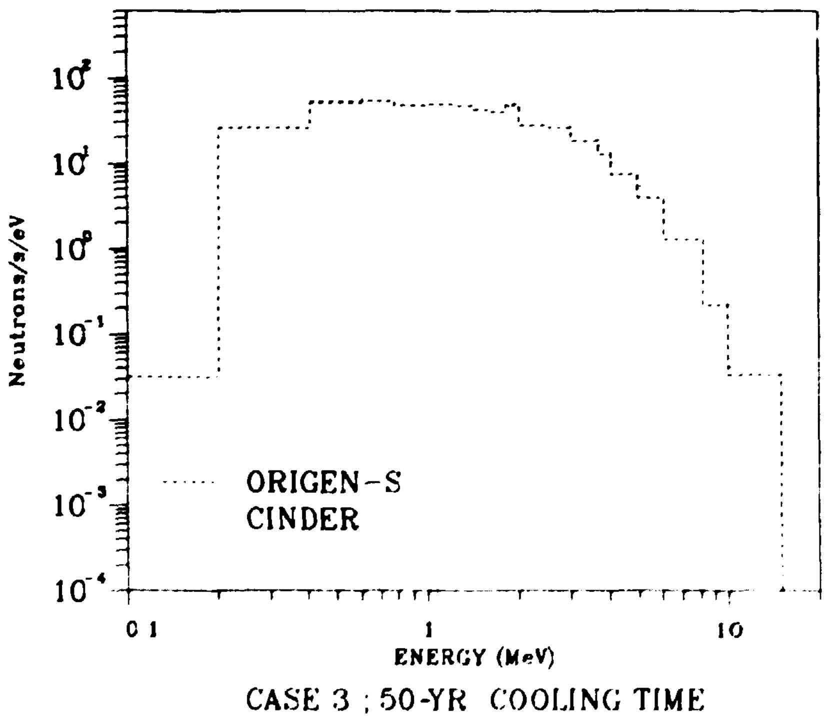
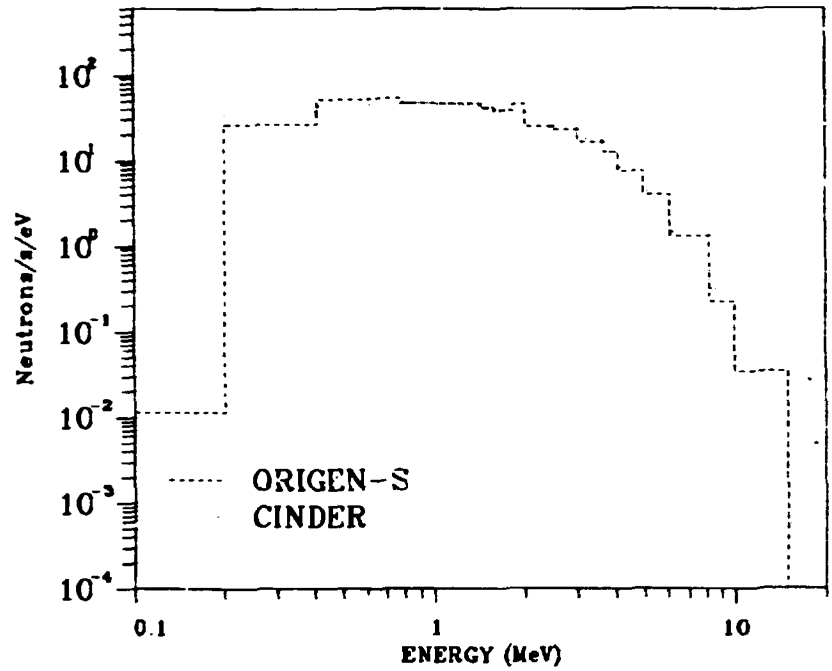
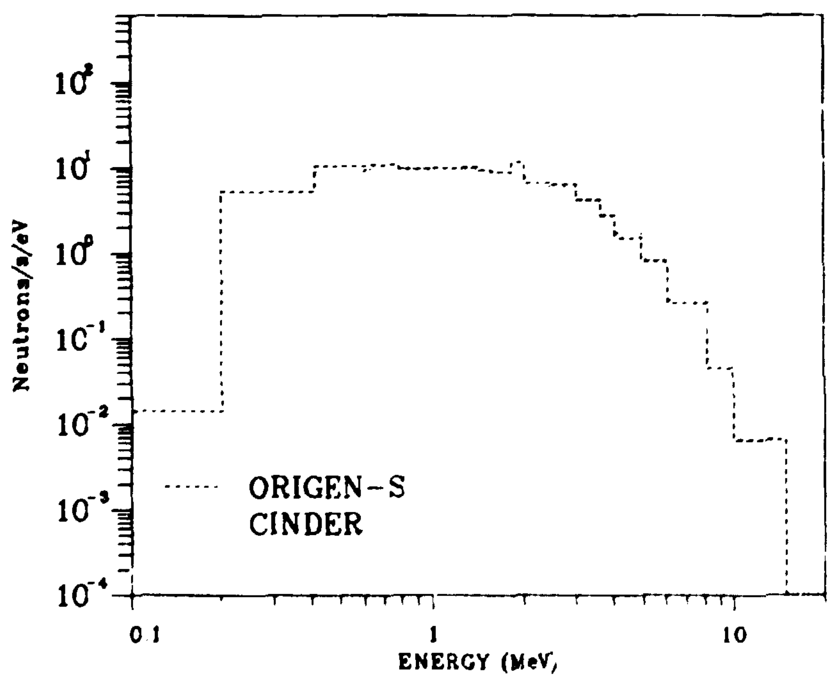


Fig. 22: Case 3, Extended PWR exposure (50 GWd/MTU) neutron spectra (neutrons/s/eV); 50-year cooling.



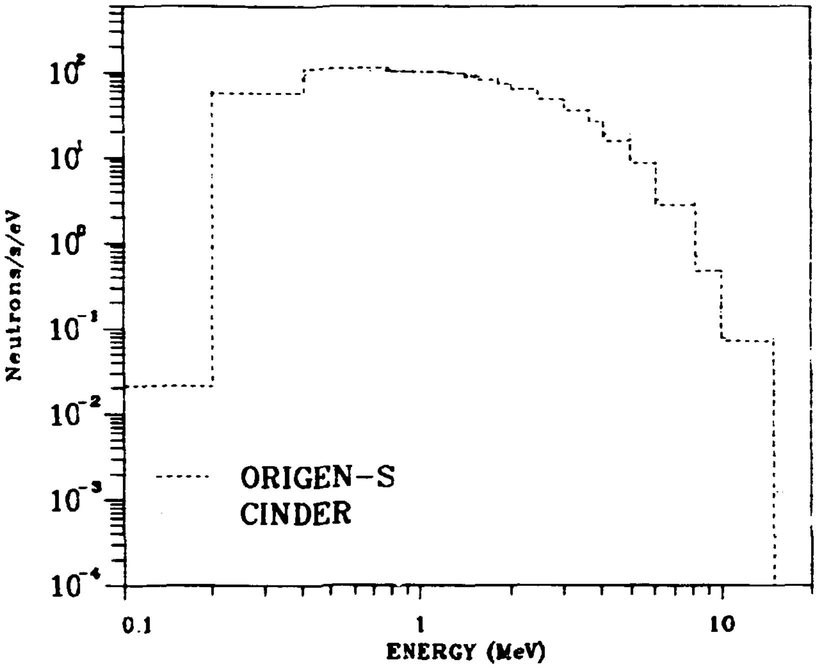
CASE 4 ; 5-YR COOLING TIME

Fig. 23: Case 4, Typical BWR exposure (27.5 GWd/MTU) neutron spectra (neutrons/s/eV); 5-year cooling.



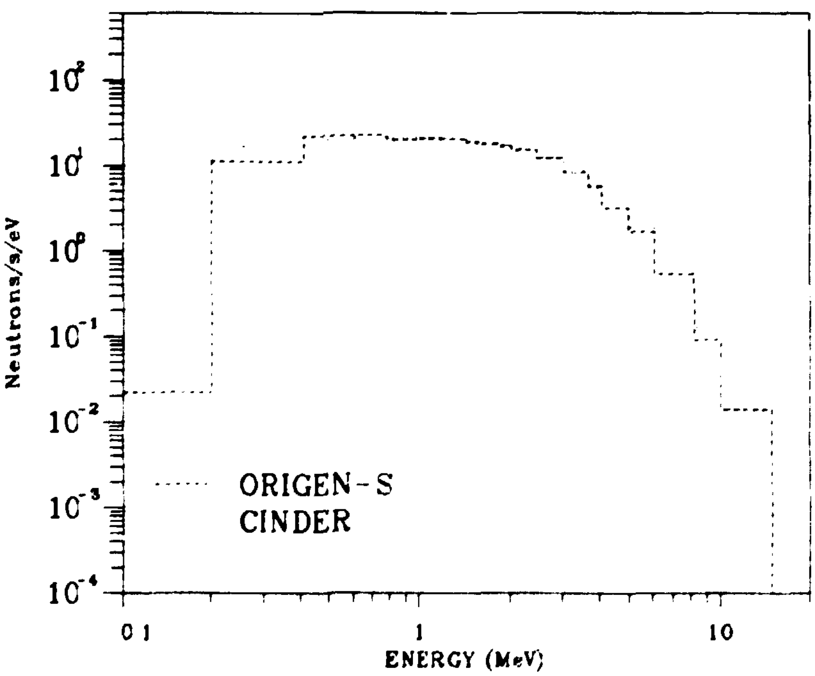
CASE 4 ; 50-YR COOLING TIME

Fig. 24: Case 4, Typical BWR exposure (27.5 GWd/MTU) neutron spectra (neutrons/s/eV); 50-year cooling.



CASE 5 ; 5-YR COOLING TIME

Fig. 25: Case 5, Extended BWR exposure (40 GWd/MTU) neutron spectra (neutrons/s/eV); 5-year cooling.



CASE 5 ; 50-YR COOLING TIME

Fig. 26: Case 5, Extended BWR exposure (40 GWd/MTU) neutron spectra (neutrons/s/eV); 50-year cooling.

6. TYPICAL CASK PHOTON DOSE RATE

The photon spectra produced by each of the codes were used as source terms in a shielding calculation as a practical test of their relative performance.

6.1 SHIELDING PROBLEM DEFINITION

A typical thick-walled dry cask was chosen for the shielding problem. The model used was based on the Castor-V/21 spent fuel storage cask.[11] This cast iron cask is a one-piece, cylindrical structure with overall dimensions of 4886 mm in height and a diameter of 2385 mm. The external surface has 73 heat transfer fins that were modeled as a region of low-density cast iron. The wall thickness (excluding fins) is 380 mm. Two concentric rows of 60-mm-diam polyethylene rods are contained in the wall. A spent fuel basket of stainless steel (OD, 1524 mm) fits snuggly into the 1527-mm inner cavity of the cask.

In the PWR cases (including the decay-only case) the source region was modeled with 21 fuel assemblies, and a loading of 52 BWR assemblies was used in evaluating case 4 and 5 data. Other than the source regions, the same cask model was used in all five cases. Photon dose rates at the surface of the cask were calculated for all cases at cooling times of 5 and 50 years using the SAS1 sequence[12] from the SCALE code system.[6] A multigroup cross-section library generated using ENDF/B-V photon data was used in all gamma dose rate calculations.

6.2 PHOTON DOSE RATE RESULTS

The results of these dose calculations are given in Table 35 in millirem per hour and as ratios. The ORIGEN2/ORIGEN-S results for the decay-only and PWR exposure cases agree within 1.8% at the 5-year cooling time and 5% at 50 years. In the BWR exposure cases, the agreement between these two codes is slightly higher at 2.86% for the 5-year cooling time, but remains at 4 to 6% at the longer decay time.

These calculations and comparisons were performed with the original results; therefore, differences seen in the CINDER-2 data due to the omission of bremsstrahlung are again apparent. Comparing the OR2/CIN and ORS/CIN ratios of Table 35 to those in Tables 1—5 reveals that the deviations in the calculated dose rates are much less than the differences observed in the absolute source strength. The photon spectra calculated using ORIGEN-S and neglecting bremsstrahlung for the decay-only case were also used in the shielding calculation. The dose rates predicted using these source spectra were 19.4335 mrem/h at 5 years cooling and 0.34688 mrem/h at 50 years. Agreement with the CINDER-2 result given in Table 35 at 50 years, 1.37%, is excellent; however, the comparison at 5 years was 20.6%. A significant part of this difference is likely due to the failure to include the ^{144}Pr spectra in the CINDER-2 calculations.

6.3 NEUTRON DOSE RATE RESULTS

The neutron source spectra calculated by ORIGEN-S and SOURCES (an auxiliary code used in the CINDER-2 calculations) were also used in shielding calculations involving the same cask model. Note earlier that the neutron spectra predicted by the two codes (ORIGEN2 does not produce neutron spectra) display the greatest difference in the first energy group. These low-energy source neutrons should have little effect on the external neutron dose rate because they will be absorbed as they are transported through the cask. The results of the neutron dose calculations are given in Table 36. The agreement appears to be very good in the decay-only case. However, the almost 4% difference observed in these dose rate comparisons is slightly worse than the 2 to 2.5% difference that was observed in the total production rates for this case. In the remaining reactor cases, the neutron dose rates are in slightly better agreement (about 1% closer) than the neutron production rates. The large difference observed in the dose rate for the PWR cases reflect the differences in the source strengths that are representative of deviations observed in the actinide inventories (see Sect. 3.3).

TABLE 35. Sidewall gamma dose rates (mrem/h): thick-walled dry cask

Decay Time (years)	OR2	ORS	CIN	OR2/ORS	OR2/CIN	ORS/CIN
			Case 1. Decay Only			
5	21.1077	21.4900	16.1115	0.9822	1.3101	1.3338
50	0.4571	0.4824	0.3422	0.9475	1.3358	1.4097
			Case 2. Typical PWR			
5	21.3859	21.5142	15.4547	0.9940	1.3838	1.3921
50	0.4601	0.4840	0.3244	0.9506	1.4183	1.4920
			Case 3. Extended PWR			
5	32.2348	31.9590	25.6680	1.0086	1.2558	1.2451
50	0.7249	0.7631	0.5259	0.9499	1.3784	1.4510
			Case 4. Typical BWR			
5	15.8758	15.4338	10.5456	1.0286	1.5054	1.4635
50	0.3653	0.3778	0.2403	0.9669	1.5202	1.5722
			Case 5. Extended BWR			
5	21.5921	21.8445	16.4119	0.9884	1.3156	1.3310
50	0.5455	0.5738	0.3732	0.9507	1.4617	1.5375

7. SUMMARY AND CONCLUSIONS

The primary purpose of this report was to provide an accurate and concise comparison of the photon and neutron production rates and spectra produced by selected source-term computer codes. A major difference in the photon production rates and spectra from CINDER-2 and the ORIGEN codes has been attributed to the omission of bremsstrahlung in the CINDER-2 calculations, although the modifications required to include bremsstrahlung would be minor. An additional discrepancy observed in the CINDER-2 photon spectra revealed that spectral data for ^{144}Pr had been omitted in those calculations. Differences observed in the neutron production rates were on the same order as the previously observed[4] deviations in the inventories of actinides important to neutron production (especially ^{244}Cm). The primary difference in the ORIGEN-S and CINDER-2 neutron spectra was in the first energy group where the ORIGEN-S neutron spectral data are limited. ORIGEN2 does not currently produce neutron spectra but changes to incorporate calculations of that type could be made.

The photon source spectra from ORIGEN2 and ORIGEN-S, when applied to a typical shielding cask problem, predict dose rates at the surface within 5% of one another. Comparisons of the dose rates calculated using the photon source spectra from CINDER-2 and those produced from ORIGEN-S neglecting bremsstrahlung showed excellent agreement at 50 years and poor agreement at 5 years. The discrepancy at 5 years is due to the large differences in the group-13 intensity that has been attributed to the absence of ^{144}Pr spectral data in the CINDER-2 calculations. Neutron dose rates calculated using the ORIGEN-S and CINDER-2 neutron spectra continued to reflect the deviations in actinide inventories predicted by the two codes.

In summary, a comparison of photon and neutron source strengths and spectra as predicted by the three point depletion codes has been made and the calculated source spectra applied in a typical shielding problem. The results of this comparison tend to substantiate the findings of the earlier report[4] and suggest that the differences among the codes may be attributed to differences in the data libraries and not the methodology applied in each of these codes.

TABLE 36. Sidewall neutron dose rates (mrem/h) thick-walled dry cask

Decay Time (years)	ORS	CIN	ORS/CIN
	<u>Case 1. Decay-Only</u>		
5	18.5477	17.8483	1.0392
50	3.9721	3.8254	1.0384
	<u>Case 2. Typical PWR</u>		
5	19.8185	24.1165	0.8218
50	4.2566	5.0079	0.8500
	<u>Case 3. Extended PWR</u>		
5	52.8C50	68.4601	0.7713
50	10.6512	13.5356	0.7869
	<u>Case 4. Typical BWR</u>		
5	10.7863	11.2994	0.9546
50	2.4596	2.4890	0.9882
	<u>Case 5. Extended BWR</u>		
5	24.0191	24.4743	0.9814
50	5.1216	5.0596	1.0123

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