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Reactor Safety Study

An Assessment of Accident Risks in U.S. Commercial Nuclear Power Plants

Appendix VI

United States Nuclear Regulatory Commission

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Section 3

Radioactive Inventory of Reactor Core

3.1 METHOD OF CALCULATING BURNUP

The potential radioactive source (fission products, transuranics, and activation products) in the reactor immediately preceding the initiation of an an accident was obtained from analyses performed with the ORIGEN computer program (Bell, 1973). The set of equations describing the formation, transmutation, and decay of nuclides within an operating nuclear reactor is approximated by ORIGEN as a homogeneous set of simultaneous first-order ordinary differential equations with constant coefficients. Rigorously, the set of equations is nonlinear since the neutron flux varies as the composition of the fuel changes at constant power. However, this variation with time is small, and the neutron flux can be considered constant over short time intervals, thus permitting the linear approximation.

ORIGEN solves this set of equations by the matrix-exponential method. Most computer programs solve this set of equations by the method of Bateman (1910), which involves direct solution of the governing differential equations in a general form. In general, programs utilizing this technique have not been able to treat the full range of transmutations that might occur. They also have experienced difficulties in computing nuclide concentrations for decay chains in which (1) a nuclide decays to produce one of its precursors (e.g., neutron capture followed by alpha decay) or (2) a nuclide decays to produce a daughter that is present in another decay chain. The matrix-exponential method eliminates these difficulties.

3.2 REACTOR COMPOSITION, DESIGN, AND OPERATING HISTORY

Radionuclide inventories were calculated by means of the ORIGEN program for a 3200-MWt three-region PWR core with a composition that is representative of PWRs (Bell, 1973). (This composition represents a typical four-loop Westinghouse PWR.) It was assumed that the three regions of the core operate at a constant specific power density of 40 kW/kg of uranium charged. Inventories were calculated for an equilibrium core initially charged with 3.3% enriched uranium at a time when the three regions have average burnups of 880, 17,600, and 26,400 megawatt-days per metric ton of uranium charged.

Pressurized water reactors generally operate with power densities in the range of 30 to 35 kW/kg. Calculations based on a power density of 40 kW/kg will overestimate the inventory of short-lived radionuclides by 14 to 33% since the inventory of isotopes that reach equilibrium during irradiation is directly proportional to the power density (neutron flux). The inventory of the long-lived radionuclides, however, is proportional to burnup (i.e., neutron flux times time) and is not sensitive to power density at any given exposure.

Boiling water reactors typically operate at a lower specific power density (approximately 23 kW/kg of uranium charged) and with less enriched fuel (approximately 2.2%). However, because of the lower enrichment of BWR, the average thermal neutron flux for both PWRs and BWRs is approximately the same. Thus fission-product generation and transmutation by neutron absorption are equivalent in both types of reactors when operating at the same power densities. There may be some differences in the inventory of activation products between PWRs and BWRs because the atom densities of the various constituents of core structural and cladding material differ. However, activation products are not significant in comparison to the fission products and transuranics, and, in general, the variations in the quantity of activation products between the two types of reactor can be ignored.

3.3 SELECTION OF RADIONUCLIDES

The ORIGEN program calculates the time-dependent concentration of a very large number of nuclides: 246 activation products, 461 fission products, and 82 transuranics. Although many of these nuclides are not radioactive, the total number of radionuclides is quite large and significant amounts of computer storage and computational time would be required to handle all of them in the consequence model. At a very small sacrifice in the precision of the radiation dose calculations, the number of radionuclides considered can be reduced to a manageable size.

The elimination of radionuclides from consideration in radiation dose calculations was based on a number of parameters, such as quantity (curies), release fraction, radioactive half-life, emitted radiation type and energy, and chemical characteristics. The precise method of elimination is explained in section 8.2.1. In addition, it is possible to eliminate radionuclides with half-lives shorter than 25.7 minutes (decay constants greater than 4.5×10^{-4} sec^{-1}) because, as explained in Appendix V, the minimum delay time between termination of the chain-reaction (start of the accident) and the release of radioactive material to the atmosphere would be at least 0.5 hour and could be as long as 30 hours.

These eliminations resulted in the list of 54 radionuclides presented in Table VI 3-1, which also gives their activity at the time the accident is assumed to be initiated.

REFERENCES

Bell, M. J., 1973, ORIGEN, the ORNL Isotope Generation and Depletion Code, ORNL-4628, Oak Ridge National Laboratory.

Bateman, H., 1910, Proc. Cambridge Phil. Soc., 15, p. 423.

TABLE VI 3-1 INITIAL ACTIVITY OF RADIONUCLIDES IN THE NUCLEAR REACTOR CORE AT THE TIME OF THE HYPOTHETICAL ACCIDENT

No.	Radionuclide	Radioactive Inventory Source (curies x 10^{-8})	Half-Life (days)
1	Cobalt-58	0.0078	71.0
2	Cobalt-60	0.0029	1,920
3	Krypton-85	0.0056	3,950
4	Krypton-85m	0.24	0.183
5	Krypton-87	0.47	0.0528
6	Krypton-88	0.68	0.117
7	Rubidium-86	0.00026	18.7
8	Strontium-89	0.94	52.1
9	Strontium-90	0.037	11,030
10	Strontium-91	1.1	0.403
11	Yttrium-90	0.039	2.67
12	Yttrium-91	1.2	59.0
13	Zirconium-95	1.5	65.2
14	Zirconium-97	1.5	0.71
15	Niobium-95	1.5	35.0
16	Molybdenum-99	1.6	2.8
17	Technetium-99m	1.4	0.25
18	Ruthenium-103	1.1	39.5
19	Ruthenium-105	0.72	0.185
20	Ruthenium-106	0.25	366
21	Rhodium-105	0.49	1.50
22	Tellurium-127	0.059	0.391
23	Tellurium-127m	0.011	109
24	Tellurium-129	0.31	0.048
25	Tellurium-129m	0.053	0.340
26	Tellurium-131m	0.13	1.25
27	Tellurium-132	1.2	3.25
28	Antimony-127	0.061	3.88
29	Antimony-129	0.33	0.179
30	Iodine-131	0.85	8.05
31	Iodine-132	1.2	0.0958
32	Iodine-133	1.7	0.875
33	Iodine-134	1.9	0.0366
34	Iodine-135	1.5	0.280
35	Xenon-133	1.7	5.28
36	Xenon-135	0.34	0.384
37	Cesium-134	0.075	750
38	Cesium-136	0.030	13.0
39	Cesium-137	0.047	11,000
40	Barium-140	1.6	12.8
41	Lanthanum-140	1.6	1.67
42	Cerium-141	1.5	32.3
43	Cerium-143	1.3	1.38
44	Cerium-144	0.85	284
45	Praseodymium-143	1.3	13.7
46	Neodymium-147	0.60	11.1
47	Neptunium-239	16.4	2.35
48	Plutonium-238	0.00057	32,500
49	Plutonium-239	0.00021	8.9×10^6
50	Plutonium-240	0.00021	2.4×10^6
51	Plutonium-241	0.034	5,350
52	Americium-241	0.000017	1.5×10^5
53	Curium-242	0.0050	163
54	Curium-244	0.00023	6,630