④ NA ⑤ 626 900 63-4-1

Scale 2

USNRDL-TR-642
⑪ 4 April 1963

⑥ ESTIMATES OF FISSION PRODUCT YIELDS OF A THERMONUCLEAR EXPLOSION

(7-9) NA

⑩ by
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⑫ 24p.
(13-17) NA
⑱ NRDL
⑲ TR 642
⑳ 2
㉑ NA

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#2.60

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ADMINISTRATIVE INFORMATION

The work reported was requested specifically by the Fallout Studies Branch, Division of Biology and Medicine, U. S. Atomic Energy Commission, in addition to that already sponsored under AEC Contract No. AT(49-7)-1963. The project is described in USNRDL Technical Program Summary for Fiscal Years 1963, 1964, and 1965, 1 November 1962. It is designated as Problem 7, Program A-1.

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ABSTRACT

Chain yields and independent yields of the U^{238} fission products from a thermonuclear explosion ~~have been~~ were estimated. Since unclassified data for this kind of process are scanty, some features of the mass yield curve were inferred from published data on U^{238} fission by neutrons ranging from fission-spectrum energies to 14 Mev. Independent yields of the fission products were then calculated by application of the equal charge displacement ~~(ECD)~~ theory of nuclear charge distribution in fission processes.

SUMMARY

Fallout studies require a knowledge of the amounts of each fission product radionuclide produced in a thermonuclear explosion. Such yield values are fairly well known for certain kinds of fission processes. However, their determination is difficult for thermonuclear events, and, in any case, not much unclassified information on the subject is available. In this report U^{238} thermonuclear fission product yields have been estimated by theoretical methods based on observed correlations of the yields of other fission processes.

INTRODUCTION

The use of fallout formation models, such as C. F. Miller's[1] fractionation model (which is being employed at NRDL), requires a knowledge of the independent yields of the fission product radionuclides for the fission process under consideration. In the case of a thermonuclear explosion, the only available unclassified data of this kind are a number of chain yields.[2] In order to use the model to make predictions for comparison with field-collected data, it was necessary to make some kind of estimate of the fission product independent yields of a thermonuclear explosion.

The chain yield for any mass number, which is the average number of radionuclides of that mass number produced per fission, depends on the nature of the fissile material and the identity and energy of the fissioning projectile. The total yields of the fission product decay chains for various fission processes involving uranium and plutonium isotopes are fairly accurately known.[3,4] However, these data all pertain to fission processes initiated either by thermal neutrons, fission neutrons, or neutrons having a narrow, well-defined energy range. In thermonuclear explosions the energy spectrum of the neutrons is not well-defined. No theoretical or empirical method for extrapolating the known yield data to the thermonuclear fission process is known.

The independent yields, i.e., the yields of the individual radionuclides, are much less well known than the chain yields. Many experimental determinations have been made for thermal neutron fission of U^{235} but the data are still incomplete. On the basis of the available information Glendenin and others[5] have developed a method, based on the hypothesis of equal charge displacement (ECD), for correlating independent yield with the most probable nuclear charge of fission fragments.

In this report, chain yields for thermonuclear fission were estimated from a curve drawn on the basis of a few reported values. Independent yields were then calculated according to the ECD method.

ESTIMATION OF CHAIN YIELDS

A yield curve was constructed from the 21 mass-chain yield values for thermonuclear fission published by Hallden, et al.[2] Inspection shows that these points are very nearly symmetrical around an axis drawn through mass number 118. This axis of symmetry corresponds to the prompt emission of 3 neutrons per fission. In 14-Mev neutron fission of U^{238}, reported values for the number of prompt neutrons per fission range from 4.13 to 4.55.[6,7,8,9] The value of three prompt neutrons per fission lies between the values observed for 14-Mev fission and for fission-neutron fission[10] of U^{238}.

The given points and their reflections outline fairly well the wings of the curve and the light- and heavy-fragment peaks, and they indicate the location of the valley. However, none of the points fall in the transition regions between the valley and the two peaks. Observed yields in this region for 14-Mev neutron and fission-neutron fission of U^{238} were examined with the intention of choosing intermediate values for the thermonuclear yield estimates. However, intermediate values are too low to permit a smooth joining of the reported thermonuclear yields. The values used in this region, which closely resemble the 14-Mev neutron U^{238} fission yields, provide a smooth fit.

A smooth curve was drawn through the outline provided by the points thus obtained. The curve was then normalized to yield 200 fragments for 100 U^{238} fissions. The final form of the curve is presented in Fig. 1. The light-fragment part of the curve is quite similar to the yield curve for 14-Mev fission of U^{238}, but the heavy-fragment portion is shifted about one mass unit to the right. The yields in the valley are intermediate to those reported for 14-Mev fissions and fission-neutron fission of U^{238}, and they correspond fairly well to those determined by Levy, et al.[11] for U^{238} fission by neutrons from the Al (α, n) reaction.

The studies of Levy and co-workers of the yields of U^{238} fission by broad energy spectrum neutron fluxes suggest a means of testing the estimates from the curve. It has been established that, with neutron fluxes of mean energies in the range from 2 to 3 Mev to about 10 Mev, the yields y_i and y_j of any two mass chains i and j (produced at the same neutron energy) fit the linear relationship:

$$y_i = c_{ij}y_j + d_{ij} \qquad (1)$$

where c_{ij} and d_{ij} are independent of the energy. Thus, if one plots y_i versus y_j for U^{238} fission by neutron fluxes of several different energy spectra, all the points should fall on the same straight line. However, the relationship is not completely general, as Levy, et al.,[12] have shown by experiments on U^{235} fission.

The yield curve for thermonuclear fission in Fig. 1 has been tested according to this equation. The fit is not as good as that of the experimental data of Levy, et al., but compares favorably with the fit of published data for 14-Mev fission and fission-neutron fission of U^{238}. The measure of agreement with this relationship shown by the estimates lends some degree of support to the estimates. This is particularly welcome in the case of the intermediate mass chains, where only three published yield values were available for constructing the curve.

CALCULATION OF INDEPENDENT YIELDS

In any fission process, direct determination of the independent yield of any particular radionuclide is not usually possible, and recourse must be made to empirical or theoretical methods of calculating these yields. The status of this subject has been well reviewed in the literature.[13] At least three different theoretical approaches have been suggested and investigated. In spite of the difficulty of making direct experimental determinations of the independent yields, sufficient data has been accumulated to make a strong case for the ECD method of Glendenin and Coryell. We have therefore used this method to calculate the charge distribution, i.e., the partition of the chain yields among the members of the chain.

A most stable charge number, Z_A, can be associated with any nucleus of mass number A. Z_A is an essentially linear function of A within a given nucleon-shell region but undergoes upward discontinuity on crossing a neutron-shell edge and downward discontinuity on crossing a proton-shell edge. Values of Z_A as a function of A are given by Coryell.[14] Now, suppose a compound nucleus having charge number Z_c and mass number A_c undergoes fission into two fragments of masses A_1 and A_2. The two fragments will release ν_1 and ν_2 prompt neutrons respectively. In the absence of better information we will assume that ν_1 and ν_2 are on the average each equal to half the total number of prompt neutrons observed in the fission event. As remarked above, this total number is assumed to be three for thermonuclear fission. According to Coryell,[13] we can calculate the most probable charge number, $Z_p(A_1)$, associated with the fragment of mass A_1 by:

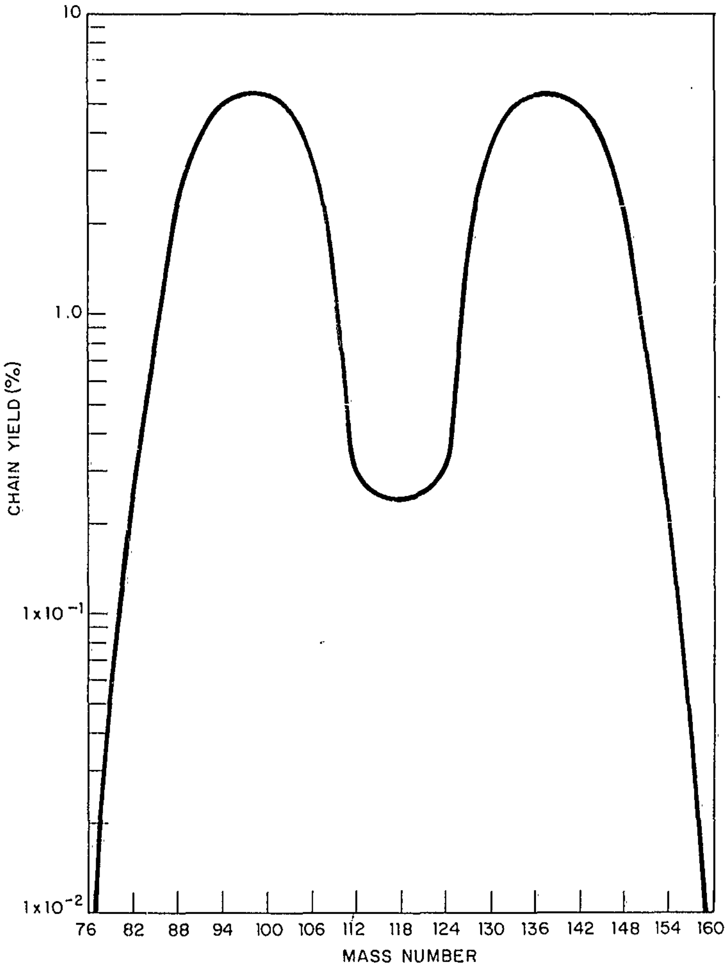

Fig. 1 Mass Yield Curve

$$Z_p(A_1) = Z_{(A_1 + \nu_1)} - \frac{1}{2}\left[Z_{(A_1 + \nu_1)} + Z_{(A_c - A_1 - \nu_1)} - Z_c\right] \qquad (2)$$

Note that the first three subscripted Z's on the right-hand side are the most stable charge numbers associated with the subscripted mass values as given by Reference 14. The most probable charge number for the second fragment, $Z_p(A_2)$, can be calculated, of course, by substituting the value of A_2 and ν_2 for A_1 and ν_1 in Eq. (2).

Generally Z_p will be a non-integral number and will have a value more or less intermediate to the actual series of atomic numbers in the decay chain. The probability of formation, hence the yield, of any nuclide in the chain is determined by the difference between its atomic number Z and the calculated Z_p. The correlation we have used, originally due to Glendenin, is presented in Fig. 2. This curve has been constructed from values tabulated by Wahl,[15] which were normalized so that the fractional yields given by a series of values of Z_p - Z differing by one would add up to one. The curve is very nearly Gaussian for values of Z_p - Z less than about 2; for larger values it is more nearly exponential. The fraction corresponding to Z_p - Z is multiplied by the chain yield for any mass number A to give the independent yield of the radionuclide having mass A and atomic number Z.

RESULTS

The independent yields and the chain yields of the fission product radionuclides for a thermonuclear explosion are given in Table 1. The yields are expressed in terms of atoms of radionuclide produced per 10,000 U^{238} fissions. Table 2 presents the chain yields in terms of atoms per 1.45×10^{23} fissions which, according to the Effects of Nuclear Weapons, is the number of fissions required to release a kiloton equivalent of TNT (10^{12} calories). For thermonuclear detonations a somewhat lower value for the number of fissions is really more accurate.

Although these yield values are to be regarded merely as estimates, since they are based on a mass yield curve constructed on very fragmentary experimental data, they are the most refined estimates available at the present time. It should be borne in mind that the neutron energy spectrum of a thermonuclear explosion is not well-defined, but varies from one explosion to another. **Variations as large as a factor of two greater or smaller than the estimated yields would not be unexpected in the sensitive regions of the curve.**

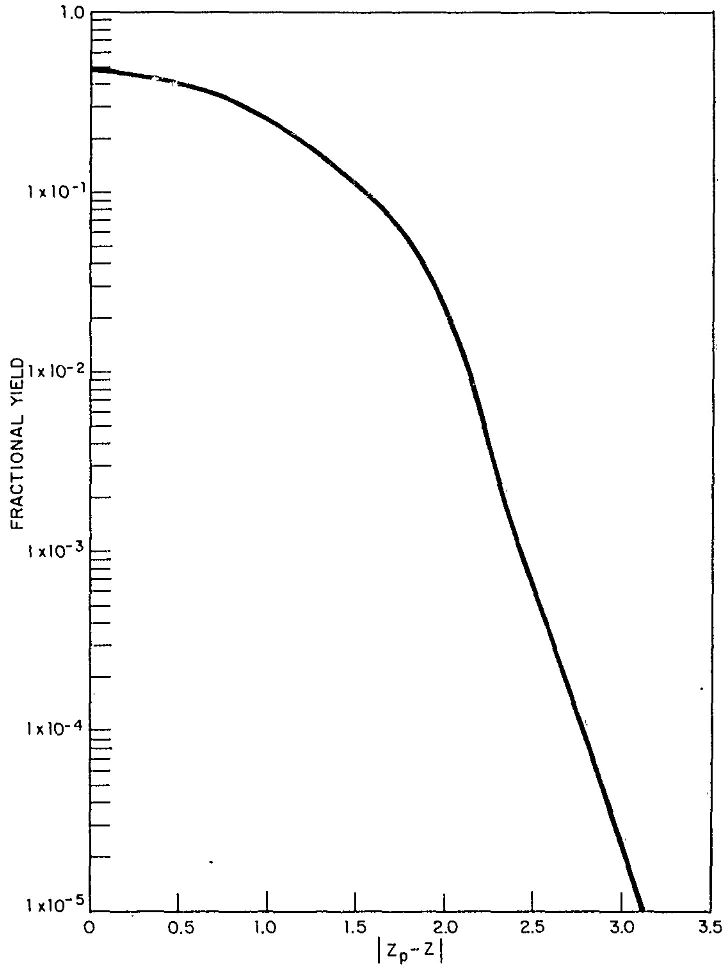

Fig. 2 Charge Distribution

TABLE 1

Yields of Fission Products Expressed as Atoms of Radionuclide Per 10,000 U^{238} Fissions

A	Element	Z	Yield	A	Element	Z	Yield
77	Ni	28	0.007	82	Zn	30	0.247
77	Cu	29	0.189	82	Ga	31	4.708
77	Zn	30	0.483	82	Ge	32	10.43
77	Ga	31	0.315	82	As	33	6.278
77	Ge	32	0.048	82	Se	34	0.807
77	Chain Yield		1.05	82	Chain Yield		22.42
78	Cu	29	0.182	83	Zn	30	0.050
78	Zn	30	0.768	83	Ga	31	5.914
78	Ga	31	0.828	83	Ge	32	20.80
78	Ge	32	0.236	83	As	33	18.90
78	As	33	0.002	83	Se	34	4.461
78	Chain Yield		2.02	83	Chain Yield		50.12
79	Cu	29	0.022	84	Ga	31	4.223
79	Zn	30	0.677	84	Ge	32	24.64
79	Ga	31	1.665	84	As	33	35.19
79	Ge	32	1.116	84	Se	34	13.69
79	As	33	0.176	84	Br	35	0.313
79	Chain Yield		3.66	84	Chain Yield		78.21
80	Zn	30	0.627	85	Ga	31	0.110
80	Ga	31	2.649	85	Ge	32	13.02
80	Ge	32	2.858	85	As	33	45.78
80	As	33	0.815	85	Se	34	41.59
80	Se	34	0.006	85	Br	35	9.818
80	Chain Yield		6.97	85	Chain Yield		110.3
81	Zn	30	0.420	86	Ge	32	10.17
81	Ga	31	3.027	86	As	33	50.13
81	Ge	32	4.835	86	Se	34	62.33
81	As	33	2.123	86	Br	35	22.38
81	Se	34	0.090	86	Kr	36	0.363
81	Chain Yield		10.51	86	Chain Yield		145.3

Continued

TABLE 1 (Cont'd)

Yields of Fission Products Expressed as Atoms of Radionuclide per 10,000 U^{238} Fissions

A	Element	Z	Yield	A	Element	Z	Yield
87	Ge	32	1.417	93	Br	35	38.51
87	As	33	35.25	93	Kr	36	174.2
87	Se	34	84.86	93	Rb	37	197.8
87	Br	35	55.95	93	Sr	38	59.70
87	Kr	36	8.206	93	Y	39	0.565
87	Chain Yield		186.5	93	Chain Yield		470.9
88	As	33	17.46	94	Br	35	12.60
88	Se	34	81.61	94	Kr	36	126.6
88	Br	35	96.57	94	Rb	37	237.2
88	Kr	36	30.60	94	Sr	38	119.0
88	Rb	37	0.408	94	Y	39	8.57
88	Chain Yield		226.7	94	Chain Yield		504.0
89	As	33	3.404	95	Br	35	0.919
89	Se	34	58.69	95	Kr	36	71.76
89	Br	35	123.3	95	Rb	37	221.1
89	Kr	36	74.24	95	Sr	38	180.1
89	Rb	37	8.844	95	Y	39	36.44
89	Chain Yield		268.0	95	Chain Yield		510.4
90	As	33	0.278	96	Kr	36	33.39
90	Se	34	34.59	96	Rb	37	177.5
90	Br	35	126.6	96	Sr	38	229.6
90	Kr	36	119.5	96	Y	39	79.82
90	Rb	37	27.79	96	Zr	40	1.304
90	Chain Yield		308.8	96	Chain Yield		521.7
91	Se	34	11.00	97	Kr	36	5.856
91	Br	35	100.9	97	Rb	37	114.5
91	Kr	36	168.7	97	Sr	38	250.2
91	Rb	37	80.70	97	Y	39	143.7
91	Sr	38	4.40	97	Zr	40	18.10
91	Chain Yield		366.8	97	Chain Yield		532.4
92	Se	34	1.86	98	Rb	37	46.66
92	Br	35	72.13	98	Sr	38	200.4
92	Kr	36	185.7	98	Y	39	227.4
92	Rb	37	129.9	98	Zr	40	65.02
92	Sr	38	21.37	98	Nb	41	0.540
92	Chain Yield		411.0	98	Chain Yield		540.2

Continued

TABLE 1 (Cont'd)

Yields of Fission Products Expressed as Atoms of Radionuclide per 10,000 U^{238} Fissions

A	Element	Z	Yield	A	Element	Z	Yield
99	Rb	37	5.48	105	Zr	40	19.85
99	Sr	38	112.0	105	Nb	41	120.7
99	Y	39	256.7	105	Mo	42	176.6
99	Zr	40	152.9	105	Tc	43	70.06
99	Nb	41	20.82	105	Ru	44	2.06
99	Chain Yield		547.9	105	Chain Yield		389.2
100	Sr	38	42.32	106	Zr	40	2.01
100	Y	39	195.3	106	Nb	41	61.99
100	Zr	40	233.3	106	Mo	42	154.4
100	Nb	41	70.53	106	Tc	43	100.7
100	Mo	42	0.814	106	Ru	44	16.08
100	Chain Yield		542.5	106	Chain Yield		335.1
101	Sr	38	2.40	107	Nb	41	24.80
101	Y	39	93.44	107	Mo	42	106.7
101	Zr	40	240.3	107	Tc	43	113.0
101	Nb	41	168.2	107	Ru	44	30.87
101	Mo	42	27.87	107	Rh	45	0.248
101	Chain Yield		532.2	107	Chain Yield		275.6
102	Y	39	33.73	108	Nb	41	7.286
102	Zr	40	176.3	108	Mo	42	61.16
102	Nb	41	223.1	108	Tc	43	101.6
102	Mo	42	76.67	108	Ru	44	48.36
102	Tc	43	1.226	108	Rh	45	2.80
102	Chain Yield		511.1	108	Chain Yield		220.8
103	Y	39	7.356	109	Nb	41	0.420
103	Zr	40	112.0	109	Mo	42	24.72
103	Nb	41	230.5	109	Tc	43	67.95
103	Mo	42	127.5	109	Ru	44	52.09
103	Tc	43	13.24	109	Rh	45	10.42
103	Chain Yield		490.4	109	Chain Yield		155.5
104	Y	39	0.295	110	Mo	42	5.62
104	Zr	40	45.49	110	Tc	43	28.01
104	Nb	41	174.3	110	Ru	44	33.93
104	Mo	42	169.9	110	Rh	45	11.71
104	Tc	43	42.89	110	Pd	46	0.159
104	Chain Yield		433.2	110	Chain Yield		79.37

Continued

TABLE 1 (Cont'd)

Yields of Fission Products Expressed as Atoms of Radionuclide per 10,000 U^{238} Fissions

A	Element	Z	Yield	A	Element	Z	Yield
111	Mo	42	0.527	117	Ru	44	0.270
111	Tc	43	9.36	117	Rh	45	5.16
111	Ru	44	19.48	117	Pd	46	11.42
111	Rh	45	11.51	117	Ag	47	6.87
111	Pd	46	1.18	117	Cd	48	0.884
111	Chain Yield		42.17	117	Chain Yield		24.55
112	Mo	42	0.030	118	Ru	44	0.530
112	Tc	43	3.57	118	Rh	45	5.90
112	Ru	44	12.36	118	Pd	46	11.52
112	Rh	45	11.34	118	Ag	47	5.90
112	Pd	46	2.67	118	Cd	48	0.530
112	Chain Yield		29.99	118	Chain Yield		24.09
113	Tc	43	1.51	119	Ru	44	0.883
113	Ru	44	8.33	119	Rh	45	6.87
113	Rh	45	11.71	119	Pd	46	11.41
113	Pd	46	4.40	119	Ag	47	5.15
113	Ag	47	0.107	119	Cd	48	0.270
113	Chain Yield		26.03	119	Chain Yield		24.53
114	Tc	43	0.198	120	Ru	44	0.273
114	Ru	44	4.92	120	Rh	45	5.26
114	Rh	45	11.84	120	Pd	46	11.50
114	Pd	46	7.81	120	Ag	47	6.83
114	Ag	47	1.15	120	Cd	48	0.869
114	Chain Yield		26.02	120	Chain Yield		24.83
115	Ru	44	2.48	121	Ru	44	0.018
115	Rh	45	10.01	121	Rh	45	2.68
115	Pd	46	10.31	121	Pd	46	10.01
115	Ag	47	2.75	121	Ag	47	9.89
115	Cd	48	0.018	121	Cd	48	2.50
115	Chain Yield		25.02	121	Chain Yield		25.03
116	Ru	44	0.872	122	Rh	45	1.11
116	Rh	45	6.85	122	Pd	46	7.54
116	Pd	46	11.53	122	Ag	47	11.83
116	Ag	47	5.28	122	Cd	48	4.59
116	Cd	48	0.274	122	In	49	0.177
116	Chain Yield		24.90	122	Chain Yield		25.23

Continued

TABLE 1 (Cont'd)

Yields of Fission Products Expressed as Atoms of Radionuclide per 10,000 U^{238} Fissions

A	Element	Z	Yield	A	Element	Z	Yield
123	Rh	45	0.104	129	Ag	47	0.195
123	Pd	46	4.60	129	Cd	48	31.12
123	Ag	47	11.71	129	In	49	112.8
123	Cd	48	8.23	129	Sn	50	107.4
123	In	49	1.35	129	Sb	51	26.40
123	Chain Yield		25.96	129	Chain Yield		277.9
124	Pd	46	2.62	130	Cd	48	15.04
124	Ag	47	11.18	130	In	49	102.0
124	Cd	48	12.57	130	Sn	50	155.4
124	In	49	3.70	130	Sb	51	59.49
124	Sn	50	0.036	130	Te	52	2.34
124	Chain Yield		30.09	130	Chain Yield		334.2
125	Pd	46	1.14	131	Cd	48	1.95
125	Ag	47	10.64	131	In	49	69.60
125	Cd	48	19.78	131	Sn	50	178.4
125	In	49	9.86	131	Sb	51	120.1
125	Sn	50	0.716	131	Te	52	19.88
125	Chain Yield		42.12	131	Chain Yield		389.9
126	Pd	46	0.158	132	In	49	38.24
126	Ag	47	11.12	132	Sn	50	165.1
126	Cd	48	33.29	132	Sb	51	179.1
126	In	49	27.86	132	Te	52	51.71
126	Sn	50	6.01	132	I	53	0.391
126	Chain Yield		79.04	132	Chain Yield		434.5
127	Ag	47	10.11	133	In	49	13.26
127	Cd	48	51.35	133	Sn	50	129.6
127	In	49	68.78	133	Sb	51	229.4
127	Sn	50	25.05	133	Te	52	111.4
127	Sb	51	0.467	133	I	53	7.37
127	Chain Yield		155.6	133	Chain Yield		491.0
128	Ag	47	2.43	134	In	49	1.03
128	Cd	48	46.39	134	Sn	50	76.03
128	In	49	102.4	134	Sb	51	222.4
128	Sn	50	61.75	134	Te	52	176.0
128	Sb	51	7.95	134	I	53	36.89
128	Chain Yield		220.9	134	Chain Yield		512.3

Continued

TABLE 1 (Cont'd)

Yields of Fission Products Expressed as Atoms of Radionuclide per 10,000 U^{238} Fissions

A	Element	Z	Yield	A	Element	Z	Yield
135	Sn	50	27.65	141	I	53	38.24
135	Sb	51	168.6	141	Xe	54	179.4
135	Te	52	239.3	141	Cs	55	219.7
135	I	53	94.13	141	Ba	56	71.37
135	Xe	54	2.13	141	La	57	1.02
135	Chain Yield		531.8	141	Chain Yield		509.8
136	Sn	50	1.09	142	I	53	8.46
136	Sb	51	74.91	142	Xe	54	116.0
136	Te	52	230.8	142	Cs	55	234.0
136	I	53	192.8	142	Ba	56	126.4
136	Xe	54	42.86	142	La	57	12.94
136	Chain Yield		542.5	142	Chain Yield		497.8
137	Sb	51	19.64	143	I	53	0.567
137	Te	52	152.8	143	Xe	54	57.62
137	I	53	252.6	143	Cs	55	197.4
137	Xe	54	114.6	143	Ba	56	176.2
137	Cs	55	6.00	143	La	57	40.62
137	Chain Yield		545.6	143	Chain Yield		472.5
138	Sb	51	0.430	144	Xe	54	21.35
138	Te	52	59.58	144	Cs	55	130.2
138	I	53	222.1	144	Ba	56	184.8
138	Xe	54	208.5	144	La	57	72.68
138	Cs	55	51.45	144	Ce	58	1.64
138	Chain Yield		541.6	144	Chain Yield		410.7
139	Te	52	18.10	145	Xe	54	2.18
139	I	53	146.4	145	Cs	55	67.25
139	Xe	54	247.6	145	Ba	56	165.8
139	Cs	55	114.5	145	La	57	110.9
139	Ba	56	6.39	145	Ce	58	17.45
139	Chain Yield		532.4	145	Chain Yield		363.6
140	Te	52	1.57	146	Cs	55	25.94
140	I	53	79.88	146	Ba	56	112.7
140	Xe	54	229.7	146	La	57	130.9
140	Cs	55	177.0	146	Ce	58	38.91
140	Ba	56	34.98	146	Pr	59	0.309
140	Chain Yield		522.1	146	Chain Yield		308.8

Continued

TABLE 1 (Cont'd)

Yields of Fission Products Expressed as Atoms of Radionuclide per 10,000 U^{238} Fissions

A	Element	Z	Yield	A	Element	Z	Yield
135	Sn	50	27.65	141	I	53	38.24
135	Sb	51	168.6	141	Xe	54	179.4
135	Te	52	239.3	141	Cs	55	219.7
135	I	53	94.13	141	Ba	56	71.37
135	Xe	54	2.13	141	La	57	1.02
135	Chain Yield		531.8	141	Chain Yield		509.8
136	Sn	50	1.09	142	I	53	8.46
136	Sb	51	74.91	142	Xe	54	116.0
136	Te	52	230.8	142	Cs	55	234.0
136	I	53	192.8	142	Ba	56	126.4
136	Xe	54	42.86	142	La	57	12.94
136	Chain Yield		542.5	142	Chain Yield		497.8
137	Sb	51	19.64	143	I	53	0.567
137	Te	52	152.8	143	Xe	54	57.62
137	I	53	252.6	143	Cs	55	197.4
137	Xe	54	114.6	143	Ba	56	176.2
137	Cs	55	6.00	143	La	57	40.62
137	Chain Yield		545.6	143	Chain Yield		472.5
138	Sb	51	0.430	144	Xe	54	21.35
138	Te	52	59.58	144	Cs	55	130.2
138	I	53	222.1	144	Ba	56	184.8
138	Xe	54	208.5	144	La	57	72.68
138	Cs	55	51.45	144	Ce	58	1.64
138	Chain Yield		541.6	144	Chain Yield		410.7
139	Te	52	18.10	145	Xe	54	2.18
139	I	53	146.4	145	Cs	55	67.25
139	Xe	54	247.6	145	Ba	56	165.8
139	Cs	55	114.5	145	La	57	110.9
139	Ba	56	6.39	145	Ce	58	17.45
139	Chain Yield		532.4	145	Chain Yield		363.6
140	Te	52	1.57	146	Cs	55	25.94
140	I	53	79.88	146	Ba	56	112.7
140	Xe	54	229.7	146	La	57	130.9
140	Cs	55	177.0	146	Ce	58	38.91
140	Ba	56	34.98	146	Pr	59	0.309
140	Chain Yield		522.1	146	Chain Yield		308.8

Continued

TABLE 1 (Cont'd)

Yields of Fission Products Expressed as Atoms of Radionuclide per 10,000 U^{238} Fissions

A	Element	Z	Yield	A	Element	Z	Yield
147	Cs	55	8.02	152	La	57	0.781
147	Ba	56	73.80	152	Ce	58	16.31
147	La	57	123.5	152	Pr	59	35.75
147	Ce	58	58.8	152	Nd	60	21.86
147	Pr	59	3.21	152	Pm	61	2.97
147	Chain Yield		267.4	152	Chain Yield		78.06
148	Cs	55	0.455	153	Ce	58	4.17
148	Ba	56	30.69	153	Pr	59	18.38
148	La	57	97.06	153	Nd	60	20.86
148	Ce	58	80.92	153	Pm	61	6.11
148	Pr	59	18.18	153	Sm	62	0.050
148	Chain Yield		227.3	153	Chain Yield		49.67
149	Ba	56	8.22	154	Ce	58	0.787
149	La	57	56.07	154	Pr	59	6.25
149	Ce	58	85.04	154	Nd	60	10.46
149	Pr	59	35.32	154	Pm	61	4.79
149	Nd	60	1.50	154	Sm	62	0.022
149	Chain Yield		186.9	154	Chain Yield		22.49
150	Ba	56	0.291	155	Ce	58	0.094
150	La	57	21.69	155	Pr	59	2.18
150	Ce	58	64.21	155	Nd	60	4.80
150	Pr	59	49.80	155	Pm	61	2.96
150	Nd	60	9.61	155	Sm	62	0.409
150	Chain Yield		145.6	155	Chain Yield		10.48
151	La	57	5.75	156	Ce	58	0.006
151	Ce	58	34.73	156	Pr	59	0.817
151	Pr	59	49.99	156	Nd	60	2.86
151	Nd	60	19.58	156	Pm	61	2.65
151	Pm	61	0.553	156	Sm	62	0.628
151	Chain Yield		110.6	156	Chain Yield		6.98

Continued

TABLE 1 (Cont'd)

Yields of Fission Products Expressed as Atoms of Radionuclide Per 10,000 U^{238} Fissions

A	Elements	Z	Yield
157	Pr	59	0.180
157	Nd	60	1.13
157	Pm	61	1.67
157	Sm	62	0.67
157	Eu	63	0.022
157	Chain Yield		3.68
158	Pr	59	0.010
158	Nd	60	0.370
158	Pm	61	0.919
158	Sm	62	0.628
158	Eu	63	0.101
158	Chain Yield		2.02
159	Nd	60	0.093
159	Pm	61	0.398
159	Sm	62	0.440
159	Eu	63	0.126
159	Gd	64	0.001
159	Chain Yield		1.06

TABLE 2

Chain Yields Expressed as Atoms per 1.45 x 10^{23} Fissions

Mass No.	$\frac{\text{Atoms}}{\text{KT}}$ x 10^{-19}	Mass No.	$\frac{\text{Atoms}}{\text{KT}}$ x 10^{-19}	Mass No.	$\frac{\text{Atoms}}{\text{KT}}$ x 10^{-19}
77	1.52	105	564.3	133	712.0
78	2.93	106	485.9	134	742.8
79	5.31	107	399.6	135	771.1
80	10.1	108	320.2	136	786.6
81	15.2	109	225.5	137	791.1
82	32.5	110	115.1	138	785.3
83	72.7	111	61.1	139	772.0
84	113.4	112	43.5	140	757.0
85	159.9	113	37.7	141	739.2
86	210.7	114	37.7	142	721.8
87	270.4	115	36.3	143	685.1
88	328.7	116	36.1	144	595.4
89	388.6	117	35.6	145	527.1
90	447.8	118	34.9	146	447.8
91	531.9	119	35.6	147	387.7
92	596.0	120	36.0	148	329.6
93	682.8	121	36.3	149	271.0
94	730.8	122	36.6	150	211.1
95	740.1	123	37.6	151	160.4
96	756.5	124	43.6	152	113.2
97	772.0	125	61.1	153	72.0
98	783.3	126	114.6	154	32.6
99	794.5	127	225.6	155	15.2
100	786.6	128	320.3	156	10.1
101	771.7	129	403.3	157	5.34
102	741.1	130	484.6	158	2.93
103	711.1	131	565.3	159	1.54
104	628.1	132	630.0		

REFERENCES

1. C. F. Miller. A Theory of Formation of Fallout From Land Surface Nuclear Detonations and Decay of Fission Products. U. S. Naval Radiological Defense Laboratory Technical Report, USNRDL-TR-425, 27 May 1960.

2. N. A. Hallden, I. M. Fisenne, L. D. Y. Ong and J. H. Harley. Health and Safety Laboratory Fallout Program Quarterly Summary Report. HASL-117, p. 194, 30 December 1961.

3. S. Katcoff, Nucleonics 16:78 (1958) and 18:201 (1960).

4. L. E. Weaver, P. O. Strom, P. A. Killeen. Estimated Total Chain and Independent Fission Yield for Several Neutron-Induced Fission Processes. U. S. Naval Radiological Defense Laboratory Technical Report, USNRDL-TR-633, 5 March 1963.

5. L. E. Glendenin, C. D. Coryell, R. R. Edwards. National Nuclear Energy Series. Div. IV, Vol. 9, Paper 52. McGraw-Hill Book Co., New York, 1951.

6. N. N. Flerov, V. M. Taltzin. Atomnaya Energiya 5:653 (1958).

7. Yu. A. Vasil'ev. Zhur. Eksptl. i. Teoret. Fiz. 38:671 (1960). C. A. 56:8249.

8. G. Vendoyes, et al., Proc. Int. Conf. on Neutron Interaction with Nucleus. (Columbia University, Sept. 9-13, 1957. USAES, TISE Oak Ridge, Tennessee), TID-7547.

9. N. N. Flerov, E. A. Tamanov. J. Nucl. Energy, Part A: Reactor Science 12:101 (1960).

10. R. Sher, J. Leroy. J. Nucl. Energy, Part A: Reactor Science 12:101 (1960).

11. H. B. Levy, H. G. Hicks, W. E. Nervik, P. C. Stevenson, J. B. Niday, J. C. Armstrong, Jr. Phys. Rev. 124:544(1961).

12. H. B. Levy, H. G. Hicks, W. E. Nervik, P. C. Stevenson, J. B. Niday, J. C. Armstrong, Jr. Phys. Rev. 128:700 (1962).

13. C. D. Coryell, M. Kaplan, R. D. Fink. Can. J. Chem. 39:646 (1961).

14. C. D. Coryell. MIT Lab. Nuclear Sci. Ann. Progress Report, 1 June 1956-31 May 1957.

15. A. Wahl. J. Inorg. Nucl. Chem. 6:263 (1958).

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