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Kerma factors for use in 37-group neutron spectrum calculations

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Research was conducted according to the principles enunciated in the "Guide for the Care and Use of Laboratory Animals," prepared by the Institute of Laboratory Animal Resources, National Research Council.

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Neutron kerma factors have been regrouped from the format of the International Commission on Radiation Units and Measurements Report 26 (ICRU-26) to supplement those available in the 37-group format of the Oak Ridge Data Library Collection 31 (DLC-31). Lists of regrouped neutron kerma factors are presented for eight elements and for seven compounds and mixtures. For several elements, disagreements in excess of 15% were observed between those neutron kerma factors available in DLC-31 and the regrouped neutron kerma factors of ICRU-26.

CONTENTS

INTRODUCTION

Kerma factors* are used in neutron dosimetry to interpret the readings of ionization chambers or other dosimeters and to calculate total neutron kerma from the known neutron fluence and spectrum. The International Commission on Radiation Units and Measurements (ICRU) compiled and published detailed listings[1] of recommended kerma factors for materials of interest in neutron dosimetry. These ICRU-26 kerma factors are listed for thermal neutrons (0.0253 eV) and for 116 contiguous energy intervals extending from 0.026 eV to 30 MeV.

Neutron spectra for the AFRRI TRIGA reactor have been calculated, and in selected cases measured, for 18 different exposure configurations.[2,3] All of the calculated and measured neutron spectra were compiled in the DLC-31 format,[4] consisting of 37 intervals covering the neutron energy range from 1×10^{-5} eV to 19.6 MeV. This 37-energy-group structure is one commonly used in radiation effects work.[4]

To perform spectrum-weighted averaging of neutron kerma factors, it is necessary to assign a single kerma factor to each of the 37 energy intervals in which the neutron spectrum is compiled. This entails averaging and interpolating between the 117 various ICRU-26 kerma factors to arrive at a set of 37 representative factors for each material of interest. This report presents the procedures used to perform this averaging and interpolation, and lists in detail the resultant 37-group kerma factors.

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*Kerma factor is defined as the product of the mass energy transfer coefficient, (μ_{tr}/ρ), and neutron energy E_N, i.e., $K = E_N(\mu_{tr}/\rho)$.

METHODS

ICRU-26 kerma factors were regrouped to the DLC-31 format by averaging with weights proportional to the logarithms of the widths of the respective energy groups. Logarithmic weighting was used to preserve proper energy dependence of the kerma factors over the several orders of magnitude of energy involved. The weighting procedure is illustrated in Figure 1, and symbols are defined below.

E_u = Upper bound energy of a DLC-31 group

E_L = Lower bound energy of a DLC-31 group

K_j = Regrouped kerma factor for the jth DLC-31 group bounded by E_u and E_L

E_α = Upper bound energy of the ICRU-26 group that includes E_L

E_ω = Upper bound energy for the ICRU-26 group that includes E_u

k_i = Kerma factor for the i^{th} ICRU-26 group bounded by E_i and E_{i-1}.

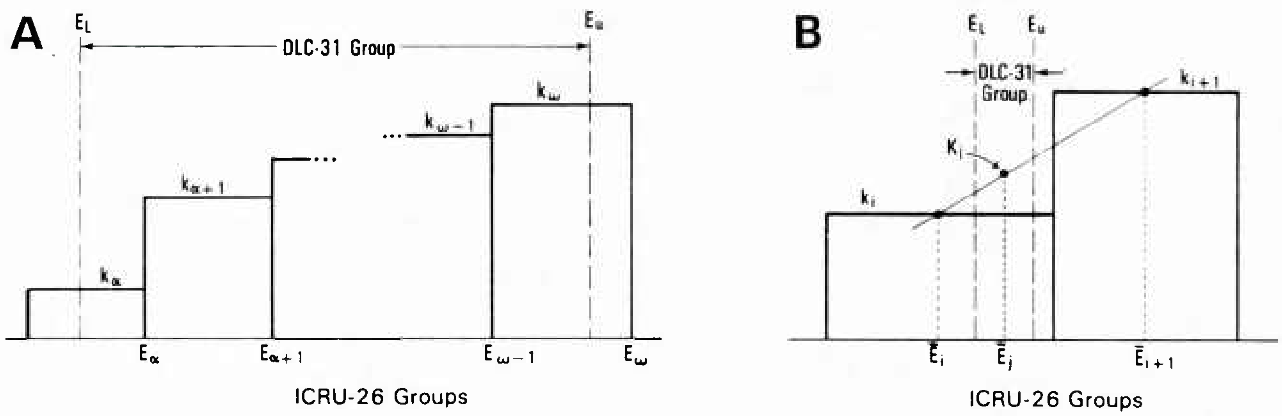


Figure 1. Kerma factor-regrouping scheme. A. When one DLC-31 group included two or more ICRU-26 groups, weighted averaging of kerma factors followed equation 1. B. Where a DLC-31 group was spanned by a single ICRU-26 group, equation 2 was used for interpolation of kerma factors.

Regrouped DLC-31 kerma factors K_j were calculated from the ICRU-26 kerma factors k_i as follows:

$$K_j = \frac{k_\alpha \ln(E_\alpha/E_L) + \sum_{i=\alpha+1}^{\omega-1} k_i \ln(E_i/E_{i-1}) + k_\omega \ln(E_u/E_{\omega-1})}{\ln(E_u/E_L)} \qquad (1)$$

Table 1 gives the upper bound energies E_u and E_ω for each of the DLC-31 and ICRU-26 groups. In Table 1, the group numbering for DLC-31 groups follows the customary order, while group numbers for ICRU-26 groups were arbitrarily chosen, beginning with thermal neutrons as group number 1. In this regard, note that the ICRU-26 "point" kerma factors for thermal neutrons (0.025 eV) were applied equally to a group extending from the lower bound of DLC-31 group 37 (10^{-5} eV) to the lower bound of ICRU-26 group 2 (0.026 eV).

The collated energy group listings in Table 1 show that in four cases, a DLC-31 group was not partitioned by one or more ICRU-26 groups. In these cases (DLC-31 group numbers 3, 6, 18, and 26), a single ICRU-26 group spanned an entire DLC-31 group. Thus, equation 1 was not applied in these cases; rather, the value of the regrouped DLC-31 kerma factor K_j was determined by linear interpolation using the midpoint energies E_j of the DLC-31 group and E_i and E_{i+1} of the applicable ICRU-26 groups, as follows (see Figure 1B):

$$K_j = k_i + \frac{\ln(\bar{E}_j / \bar{E}_i)}{\ln(\bar{E}_{i-1} / \bar{E}_i)} (k_{i+1} - k_i) \qquad (2)$$

Table 2 gives the equations used to regroup the kerma factors. The weight factors in the equations were evaluated from equations 1 and 2.

The above procedures apply directly to the regrouping of elemental kerma factors given in ICRU-26. For compounds and mixtures of elements, the ICRU-26 kerma factors extend only to a lower energy of 8 eV. Thus, for energies below 8 eV, it was necessary to perform special evaluation of DLC-31 kerma factors. Table 3 shows the elemental compositions of the compounds and mixtures of concern. High-energy (over 8 eV) DLC-31 kerma factors for these materials were determined as described above. Low-energy (groups 34-37) DLC-31 kerma factors were determined by first computing the DLC-31 kerma factors for the elements H, C, N, and O, and then averaging these H, C, N, and O kerma factors with weights equal to the percent elemental composition of each substance. In this procedure, trace elements other than H, C, N, and O present in tissue, muscle, and A-150 plastic were ignored. Errors from this omission were found to be less than 0.6% (in K_j) when the same procedure was applied to DLC-31 groups 32 and 33, and would presumably be even less for the lower energy groups.

Calculations involved in the above-described kerma factor regrouping were performed using FORTRAN computer program REDUCE, which was run on the AFRRI PDP 1170 computer system.

RESULTS AND DISCUSSION

Regrouped neutron kerma factors are listed in Table 4 for eight elements and in Table 5 for seven compounds and mixtures. Figure 2 shows a graph of regrouped DLC-31 kerma factors and the respective ICRU-26 kerma factors for hydrogen, for comparative purposes. It is seen that the regrouped kerma factors provide an excellent approximation to the more detailed ICRU-26 listings. The values in Tables 4 and 5 can be used as direct input for neutron spectrum-averaging calculations using neutron spectra represented in the 37-energy-group format of DLC-31.

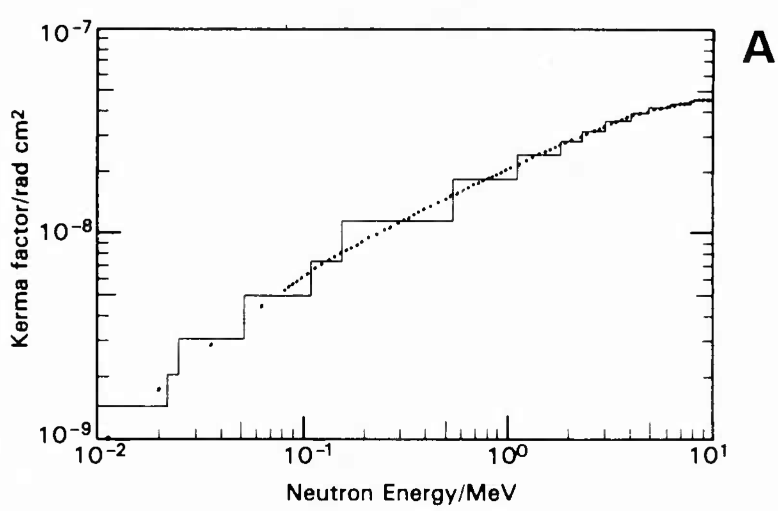
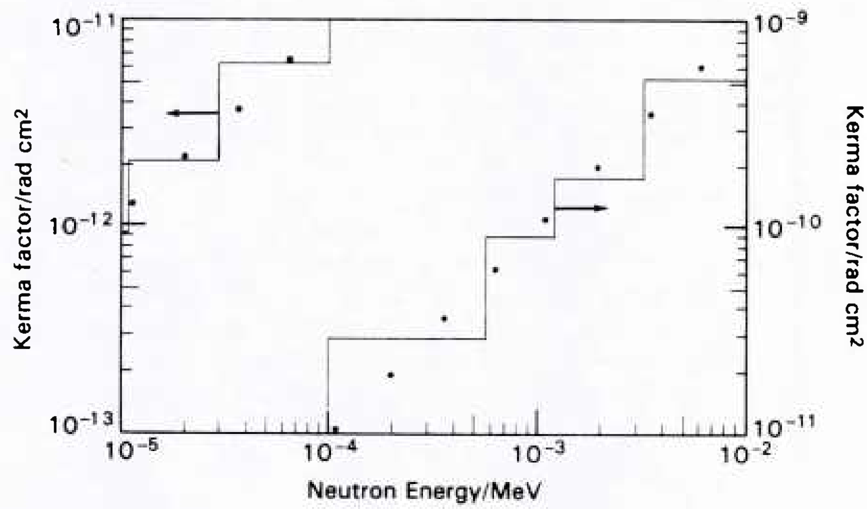
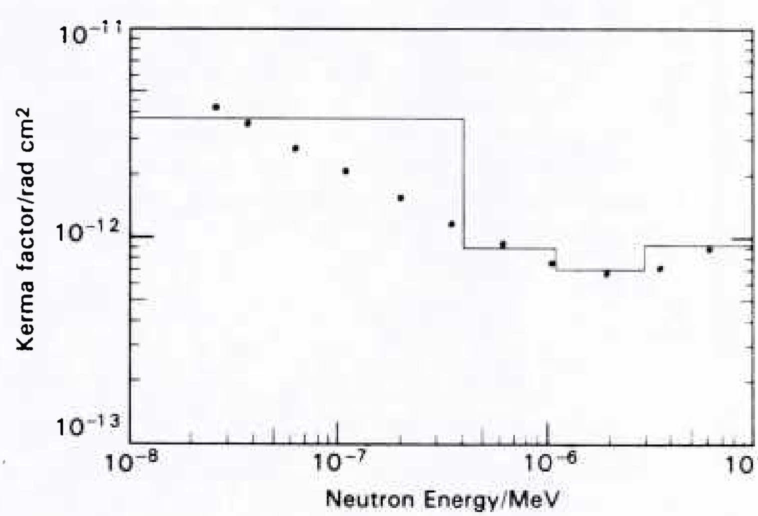


Figure 2. ICRU-26 and regrouped kerma factors for hydrogen. Points represent ICRU-26 kerma factors plotted at group midpoint energies. Solid lines are the regrouped kerma factors for DLC-31 energy groups. Parts A, B, and C portray different regions of the neutron energy spectrum.

B



C



The neutron kerma factors for compounds and mixtures presented in Table 5 represent an extension of the ICRU-26 data to neutron energies below 8 eV. In this range where neutron energy is comparable to chemical bond energy, chemical compositions may exert a substantial effect on neutron cross sections and kerma factors. All of the kerma factor data included in ICRU-26 and in this report represent isolated atoms and ignore effects due to chemical composition. Due to lack of published information on the magnitudes of these chemical effects, the isolated-atom assumption remains the only reasonable approach for estimation of low-energy neutron kerma factors for compounds and mixtures.

The DLC-31 data library contains elemental neutron kerma factors in the 37-group format that can be directly compared to many of the regrouped ICRU-26 kerma factors derived in this report. Table 6 shows such a comparison for representative neutron energies (DLC-31 groups 4, 13, 21, 24, and 37). Close agreement is to be expected between the DLC-31 and regrouped ICRU-26 kerma factors because both sources reference the same Evaluated Nuclear Data File, ENDF B-IV. For several elements, disagreements in excess of 15% were observed. In one case (oxygen, thermal neutrons), the disagreement may have been due to the use of different weighting schemes for a function with strong energy dependence. However, for other elements with disagreements over 15%, the DLC-31 kerma factors were clearly different from those listed in ICRU-26. The reason for these differences remains unknown.

Also listed in Table 6 is a comparison of the DLC-31 neutron free-in-air tissue kerma factors and the regrouped ICRU-26 kerma factors for muscle. Except for thermal neutrons, the kerma factors for DLC-31 tissue correspond closely to those for ICRU-26 muscle. The large difference in kerma factors for thermal neutrons is due to the differing nitrogen content of the two materials: 3.5% for ICRU-26 muscle and 2.9% for DLC-31 tissue. This difference emphasizes the importance of precise knowledge of tissue chemical compositions for use in dose calculations. This is particularly true for neutron spectra including large numbers of thermal neutrons, such as found at depth within phantoms[3] or experimental animals.

REFERENCES

1. Neutron Dosimetry for Biology and Medicine. Report 26, International Commission on Radiation Units and Measurements. Washington, DC, 15 January 1977.

2. Verbinski, V. V., Cassapakis, C. G., and Hagan, W. K. Radiation Field Characterization for the AFRRI TRIGA Reactor, Volume 1, Baseline Data and Evaluation of Calculational Data. DNA Report 5793F-1. Defense Nuclear Agency, Washington, DC, 1 June 1981.

3. Verbinski, V. V., and Cassapakis, C. G. Calculation of the Neutron and Gamma-Ray Environment In and Around the TRIGA Reactor, Volume II. DNA Report 5793F-2. Defense Nuclear Agency, Washington, DC, 1 June 1981.

4. DLC-31/(DPL-1/FEWG1), 37 Neutron, 21 Gamma Ray Coupled, P3, Multigroup Library in ANISN Format. Radiation Shielding Information Center, Oak Ridge National Laboratory, Oak Ridge, TN, July 1979.

Table 1. Upper Bound Neutron Energies for ICRU-26 and DLC-31 Spectrum Groups

ICRU-26		**DLC-31**	
Group Number	Energy (MeV)	Group Number	Energy (MeV)
1	0.260 -07		
2	0.460 -07		
3	0.800 -07		
4	0.140 -06		
5	0.260 -06		
		37	0.414 -06
6	0.460 -06		
7	0.800 -06		
		36	0.113 -05
8	0.140 -05		
9	0.260 -05		
		35	0.306 -05
10	0.460 -05		
11	0.800 -05		
		34	0.107 -04
12	0.140 -04		
13	0.260 -04		
		33	0.290 -04
14	0.460 -04		
15	0.800 -04		
		32	0.101 -03
16	0.140 -03		
17	0.260 -03		
18	0.460 -03		
		31	0.583 -03
19	0.800 -03		
		30	0.123 -02
20	0.140 -02		
21	0.260 -02		
		29	0.335 -02
22	0.460 -02		
23	0.800 -02		
		28	0.103 -01
24	0.140 -01		
		27	0.219 -01
		26	0.248 -01
25	0.260 -01		
26	0.460 -01		
		25	0.525 -01
27	0.800 -01		
28	0.840 -01		
29	0.880 -01		
30	0.920 -01		
31	0.960 -01		
32	0.100 +00		
33	0.110 +00		
		24	0.111 +00
34	0.120 +00		
35	0.130 +00		
36	0.140 +00		
37	0.150 +00		
		23	0.158 +00

(continued next page)

Table 1—*Continued*

ICRU-26		DLC-31	
Group Number	Energy (MeV)	Group Number	Energy (MeV)
38	0.160 +00		
39	0.170 +00		
40	0.180 +00		
41	0.190 +00		
42	0.200 +00		
43	0.220 +00		
44	0.240 +00		
45	0.260 +00		
46	0.280 +00		
47	0.300 +00		
48	0.320 +00		
49	0.340 +00		
50	0.360 +00		
51	0.380 +00		
52	0.400 +00		
53	0.440 +00		
54	0.480 +00		
55	0.520 +00		
		22	0.550 +00
56	0.560 +00		
57	0.600 +00		
58	0.640 +00		
59	0.680 +00		
60	0.720 +00		
61	0.760 +00		
62	0.800 +00		
63	0.840 +00		
64	0.880 +00		
65	0.920 +00		
66	0.960 +00		
67	0.100 +01		
68	0.110 +01		
		21	0.111 +01
69	0.120 +01		
70	0.130 +01		
71	0.140 +01		
72	0.150 +01		
73	0.160 +01		
74	0.170 +01		
75	0.180 +01		
		20	0.183 +01
76	0.190 +01		
77	0.200 +01		
78	0.220 +01		
		19	0.231 +01
		18	0.239 +01
79	0.240 +01		
80	0.260 +01		
81	0.280 +01		
82	0.300 +01		
		17	0.301 +01
83	0.320 +01		
84	0.340 +01		
85	0.360 +01		
86	0.380 +01		
87	0.400 +01		

(continued next page)

Table 1—*Continued*

ICRU-26		DLC-31	
Group Number	Energy (MeV)	Group Number	Energy (MeV)
		16	0.407 +01
88	0.440 +01		
		15	0.472 +01
89	0.480 +01		
		14	0.497 +01
90	0.520 +01		
91	0.560 +01		
92	0.600 +01		
		13	0.638 +01
93	0.640 +01		
94	0.680 +01		
95	0.720 +01		
		12	0.741 +01
96	0.760 +01		
97	0.800 +01		
		11	0.819 +01
98	0.840 +01		
99	0.880 +01		
		10	0.905 +01
100	0.920 +01		
101	0.960 +01		
		9	0.100 +02
102	0.100 +02		
103	0.110 +02		
		8	0.111 +02
104	0.120 +02		
		7	0.122 +02
		6	0.128 +02
105	0.130 +02		
		5	0.138 +02
106	0.140 +02		
		4	0.142 +02
		3	0.149 +02
107	0.150 +02		
108	0.160 +02		
		2	0.169 +02
109	0.170 +02		
110	0.180 +02		
111	0.190 +02		
		1	0.196 +02
112	0.200 +02		

Table 2. Weights for Regrouping Kerma Factors*

$K_{37} = 0.740k_1 + 0.0537k_2 + 0.0521k_3 + 0.0526k_4 + 0.0582k_5 + 0.0438k_6$

$K_{36} = 0.105k_6 + 0.551k_7 + 0.344k_8$

$K_{35} = 0.215k_8 + 0.621k_9 + 0.164k_{10}$

$K_{34} = 0.326k_{10} + 0.442k_{11} + 0.232k_{12}$

$K_{33} = 0.270k_{12} + 0.621k_{13} + 0.110k_{14}$

$K_{32} = 0.370k_{14} + 0.443k_{15} + 0.187k_{16}$

$K_{31} = 0.186k_{16} + 0.353k_{17} + 0.325k_{18} + 0.135k_{19}$

$K_{30} = 0.424k_{19} + 0.576k_{20}$

$K_{29} = 0.129k_{20} + 0.618k_{21} + 0.253k_{22}$

$K_{28} = 0.282k_{22} + 0.493k_{23} + 0.225k_{24}$

$K_{27} = 0.407k_{24} + 0.593k_{25}$

$K_{26} = 0.737k_{25} + 0.263k_{26}$

$K_{25} = 0.0630k_{25} + 0.761k_{26} + 0.176k_{27}$

$K_{24} = 0.563k_{27} + 0.0652k_{28} + 0.0621k_{29} + 0.0594k_{30} + 0.0568k_{31} + 0.0545k_{32} + 0.127k_{33} + 0.0121k_{34}$

$K_{23} = 0.221k_{34} + 0.227k_{35} + 0.210k_{36} + 0.195k_{37} + 0.147k_{38}$

$K_{22} = 0.0101k_{38} + 0.0486k_{39} + 0.0458k_{40} + 0.0433k_{41} + 0.0411k_{42} + 0.0373k_{43} + 0.0698k_{44} + 0.0642k_{45} + 0.0594k_{46} + 0.0553k_{47} + 0.0517k_{48} + 0.0486k_{49} + 0.0458k_{50} + 0.0433k_{51} + 0.0411k_{52} + 0.0764k_{53} + 0.0698k_{54} + 0.0642k_{55} + 0.0450k_{56}$

$K_{21} = 0.0257k_{56} + 0.0983k_{57} + 0.0919k_{58} + 0.0863k_{59} + 0.0814k_{60} + 0.0770k_{61} + 0.0730k_{62} + 0.0695k_{63} + 0.0662k_{64} + 0.0633k_{65} + 0.0606k_{66} + 0.0581k_{67} + 0.136k_{68} + 0.0129k_{69}$

$K_{20} = 0.156k_{69} + 0.160k_{70} + 0.148k_{71} + 0.138k_{72} + 0.129k_{73} + 0.121k_{74} + 0.114k_{75} + 0.0331k_{76}$

$K_{19} = 0.161k_{76} + 0.220k_{77} + 0.409k_{78} + 0.209k_{79}$

$K_{18} = 0.742k_{79} + 0.258k_{80}$

$K_{17} = 0.0181k_{79} + 0.347k_{80} + 0.321k_{81} + 0.299k_{82} + 0.0144k_{83}$

$K_{16} = 0.203k_{83} + 0.201k_{84} + 0.189k_{85} + 0.179k_{86} + 0.170k_{87} + 0.0575k_{88}$

$K_{15} = 0.526k_{88} + 0.474k_{89}$

$K_{14} = 0.326k_{89} + 0.674k_{90}$

$K_{13} = 0.181k_{90} + 0.297k_{91} + 0.276k_{92} + 0.246k_{93}$

(Continued next page)

Table 2–*Continued*

$K_{12} =$	$0.0209k_{93} + 0.405k_{94} + 0.382k_{95} + 0.192k_{96}$
$K_{11} =$	$0.253k_{96} + 0.513k_{97} + 0.235k_{98}$
$K_{10} =$	$0.254k_{98} + 0.466k_{99} + 0.281k_{100}$
$K_9 =$	$0.165k_{100} + 0.426k_{101} + 0.409k_{102}$
$K_8 =$	$0.913k_{103} + 0.0867k_{104}$
$K_7 =$	$0.825k_{104} + 0.175k_{105}$
$K_6 =$	k_{105}
$K_5 =$	$0.206k_{105} + 0.794k_{106}$
$K_4 =$	$0.504k_{106} + 0.496k_{107}$
$K_3 =$	$0.948k_{107} + 0.052k_{108}$
$K_2 =$	$0.053k_{107} + 0.512k_{108} + 0.434k_{109}$
$K_1 =$	$0.0398k_{109} + 0.386k_{110} + 0.365k_{111} + 0.210k_{112}$

*Lower case kerma factors k_i represent ICRU-26 values. Upper case factors K_j represent regrouped kerma factors for DLC-31 energy groups. Indices i and j are group designators defined by Table 1. Weight factors were calculated as described in the text.

Table 3. Elemental Composition of Compounds and Mixtures*

	Percent Elemental Weight				
	H	C	N	O	Other
Tissue approximation	10.0	14.9	3.5	71.6	
Tissue, muscle	10.2	12.3	3.5	72.9	1.1 (Na + Mg + P + S + K + Ca)
A-150 plastic	10.1	77.6	3.5	5.2	1.8 Ca, 1.7 F
Polymethyl methacrylate	8.0	60.0	—	32.0	
Muscle-equivalent liquid (without sucrose)	10.2 —	12.0	3.6	74.2	
Muscle-equivalent gas (with methane)	10.2 —	45.6	3.5	40.7	
Carbon dioxide	—	27.3	—	72.7	

* Taken from ICRU-26 (reference 1)

Table 4. Elemental Kerma Factors (Rad Cm^2)

DLC-31 Group	Hydrogen	Carbon	Nitrogen	Oxygen	Magnesium	Argon	Silicon	Calcium
1	0.470 E-07	0.318 E-08	0.308 E-08	0.236 E-08	0.164 E-08	0.492 E-09	0.160 E-08	0.150 E-08
2	0.471 E-07	0.283 E-08	0.273 E-08	0.208 E-08	0.926 E-09	0.397 E-09	0.142 E-08	0.162 E-08
3	0.471 E-07	0.241 E-08	0.253 E-08	0.194 E-08	0.148 E-08	0.297 E-09	0.131 E-08	0.164 E-08
4	0.470 E-07	0.223 E-08	0.243 E-08	0.180 E-08	0.141 E-08	0.245 E-09	0.126 E-08	0.164 E-08
5	0.469 E-07	0.203 E-08	0.229 E-08	0.162 E-08	0.130 E-08	0.192 E-09	0.121 E-08	0.163 E-08
6	0.467 E-07	0.182 E-08	0.211 E-08	0.141 E-08	0.117 E-08	0.167 E-09	0.118 E-08	0.160 E-08
7	0.464 E-07	0.147 E-08	0.183 E-08	0.143 E-08	0.102 E-08	0.155 E-09	0.112 E-08	0.151 E-08
8	0.459 E-07	0.126 E-08	0.158 E-08	0.117 E-08	0.829 E-09	0.140 E-09	0.101 E-08	0.138 E-08
9	0.452 E-07	0.145 E-08	0.129 E-08	0.910 E-09	0.613 E-09	0.124 E-09	0.864 E-09	0.127 E-08
10	0.445 E-07	0.922 E-09	0.115 E-08	0.769 E-09	0.500 E-09	0.111 E-09	0.776 E-09	0.119 E-08
11	0.438 E-07	0.107 E-08	0.120 E-08	0.689 E-09	0.396 E-09	0.996 E-10	0.718 E-09	0.111 E-08
12	0.427 E-07	0.528 E-09	0.998 E-09	0.655 E-09	0.301 E-09	0.872 E-10	0.456 E-09	0.998 E-09
13	0.406 E-07	0.599 E-09	0.107 E-08	0.456 E-09	0.224 E-09	0.791 E-10	0.213 E-09	0.853 E-09
14	0.391 E-07	0.525 E-09	0.120 E-08	0.517 E-09	0.230 E-09	0.823 E-10	0.172 E-09	0.770 E-09
15	0.378 E-07	0.650 E-09	0.154 E-08	0.431 E-09	0.210 E-09	0.828 E-10	0.148 E-09	0.692 E-09
16	0.350 E-07	0.869 E-09	0.128 E-08	0.475 E-09	0.151 E-09	0.776 E-10	0.106 E-09	0.459 E-09
17	0.316 E-07	0.605 E-09	0.677 E-09	0.166 E-09	0.139 E-09	0.709 E-10	0.101 E-09	0.200 E-09
18	0.300 E-07	0.437 E-09	0.487 E-09	0.117 E-09	0.116 E-09	0.650 E-10	0.879 E-10	0.119 E-09
19	0.284 E-07	0.414 E-09	0.384 E-09	0.201 E-09	0.954 E-10	0.593 E-10	0.918 E-10	0.808 E-10
20	0.241 E-07	0.321 E-09	0.312 E-09	0.248 E-09	0.786 E-10	0.358 E-10	0.676 E-11	0.370 E-10
21	0.183 E-07	0.242 E-09	0.156 E-09	0.202 E-09	0.548 E-10	0.134 E-10	0.491 E-10	0.180 E-10
22	0.115 E-07	0.129 E-09	0.851 E-10	0.109 E-09	0.502 E-10	0.450 E-11	0.318 E-10	0.829 E-11
23	0.732 E-08	0.647 E-10	0.471 E-10	0.345 E-10	0.173 E-10	0.232 E-11	0.183 E-11	0.555 E-11
24	0.508 E-08	0.391 E-10	0.327 E-10	0.196 E-10	0.301 E-10	0.138 E-11	0.269 E-11	0.250 E-11
25	0.308 E-08	0.209 E-10	0.209 E-10	0.101 E-10	0.514 E-11	0.747 E-12	0.142 E-11	0.183 E-11
26	0.204 E-08	0.129 E-10	0.146 E-10	0.612 E-11	0.286 E-11	0.368 E-11	0.713 E-12	0.163 E-11
27	0.144 E-08	0.876 E-11	0.110 E-10	0.413 E-11	0.311 E-11	0.451 E-12	0.836 E-12	0.149 E-11
28	0.615 E-09	0.356 E-11	0.603 E-11	0.166 E-11	0.670 E-12	0.775 E-13	0.310 E-12	0.124 E-11
29	0.220 E-09	0.124 E-11	0.442 E-11	0.578 E-12	0.234 E-12	0.214 E-13	0.113 E-12	0.112 E-11
30	0.877 E-10	0.490 E-12	0.501 E-11	0.228 E-12	0.927 E-13	0.815 E-14	0.448 E-13	0.108 E-11
31	0.287 E-10	0.160 E-12	0.847 E-11	0.740 E-13	0.304 E-13	0.315 E-14	0.150 E-13	0.106 E-11
32	0.614 E-11	0.336 E-13	0.171 E-10	0.156 E-13	0.676 E-14	0.225 E-14	0.401 E-14	0.106 E-11
33	0.205 E-11	0.106 E-13	0.301 E-10	0.488 E-14	0.267 E-14	0.244 E-14	0.264 E-14	0.106 E-11
34	0.919 E-12	0.370 E-14	0.527 E-10	0.164 E-14	0.186 E-14	0.358 E-14	0.325 E-14	0.107 E-11
35	0.694 E-12	0.141 E-14	0.922 E-10	0.525 E-15	0.229 E-14	0.589 E-14	0.524 E-14	0.110 E-11
36	0.880 E-12	0.882 E-15	0.151 E-09	0.198 E-15	0.348 E-14	0.931 E-14	0.846 E-14	0.117 E-11
37	0.368 E-11	0.213 E-14	0.688 E-09	0.400 E-16	0.154 E-13	0.424 E-13	0.382 E-13	0.123 E-11

Table 5. Kerma Factors (Rad Cm^2) for Seven Compounds or Mixtures*

DLC-31 Group	Tissue Approx.	Tissue, Muscle	A150 Plastic	Polymethyl Methacrylate	CO_2	Muscle Equivalent Liquid (without sucrose)	Muscle Equivalent Gas (with methane)
1	0.698 E-08	0.703 E-08	0.755 E-08	0.645 E-08	0.258 E-08	0.704 E-08	0.731 E-08
2	0.674 E-08	0.679 E-08	0.726 E-08	0.616 E-08	0.228 E-08	0.679 E-08	0.704 E-08
3	0.655 E-08	0.662 E-08	0.691 E-08	0.586 E-08	0.207 E-08	0.662 E-08	0.677 E-08
4	0.641 E-08	0.648 E-08	0.675 E-08	0.570 E-08	0.192 E-08	0.648 E-08	0.662 E-08
5	0.624 E-08	0.631 E-08	0.656 E-08	0.551 E-08	0.173 E-08	0.631 E-08	0.644 E-08
6	0.603 E-08	0.610 E-08	0.636 E-08	0.530 E-08	0.152 E-08	0.610 E-08	0.623 E-08
7	0.596 E-08	0.603 E-08	0.605 E-08	0.507 E-08	0.144 E-08	0.603 E-08	0.604 E-08
8	0.568 E-08	0.575 E-08	0.581 E-08	0.483 E-08	0.120 E-08	0.576 E-08	0.579 E-08
9	0.544 E-08	0.551 E-08	0.585 E-08	0.480 E-08	0.106 E-08	0.551 E-08	0.569 E-08
10	0.519 E-08	0.526 E-08	0.536 E-08	0.438 E-08	0.811 E-09	0.526 E-08	0.531 E-08
11	0.508 E-08	0.514 E-08	0.538 E-08	0.438 E-08	0.793 E-09	0.514 E-08	0.527 E-08
12	0.486 E-08	0.494 E-08	0.485 E-08	0.396 E-08	0.620 E-09	0.494 E-08	0.489 E-08
13	0.452 E-08	0.459 E-08	0.468 E-08	0.378 E-08	0.495 E-09	0.459 E-08	0.464 E-08
14	0.440 E-08	0.447 E-08	0.446 E-08	0.362 E-08	0.520 E-09	0.447 E-08	0.447 E-08
15	0.424 E-08	0.431 E-08	0.444 E-08	0.357 E-08	0.491 E-09	0.431 E-08	0.438 E-08
16	0.402 E-08	0.408 E-08	0.431 E-08	0.349 E-08	0.582 E-09	0.408 E-08	0.421 E-08
17	0.340 E-08	0.345 E-08	0.372 E-08	0.296 E-08	0.286 E-09	0.345 E-08	0.359 E-08
18	0.317 E-08	0.321 E-08	0.341 E-08	0.271 E-08	0.206 E-09	0.321 E-08	0.332 E-08
19	0.306 E-08	0.310 E-08	0.323 E-08	0.260 E-08	0.259 E-09	0.310 E-08	0.318 E-08
20	0.266 E-08	0.270 E-08	0.238 E-08	0.222 E-08	0.268 E-09	0.270 E-08	0.272 E-08
21	0.202 E-08	0.205 E-08	0.203 E-08	0.168 E-08	0.213 E-09	0.205 E-08	0.206 E-08
22	0.125 E-08	0.127 E-08	0.128 E-08	0.104 E-08	0.115 E-09	0.127 E-08	0.128 E-08
23	0.769 E-09	0.781 E-09	0.797 E-09	0.639 E-09	0.427 E-10	0.782 E-09	0.791 E-09
24	0.530 E-09	0.538 E-09	0.549 E-09	0.438 E-09	0.249 E-10	0.538 E-09	0.544 E-09
25	0.320 E-09	0.325 E-09	0.330 E-09	0.264 E-09	0.130 E-10	0.325 E-09	0.328 E-09
26	0.259 E-09	0.215 E-09	0.217 E-09	0.174 E-09	0.797 E-11	0.215 E-09	0.216 E-09
27	0.149 E-09	0.152 E-09	0.153 E-09	0.122 E-09	0.540 E-11	0.152 E-09	0.153 E-09
28	0.636 E-10	0.647 E-10	0.655 E-10	0.522 E-10	0.218 E-11	0.647 E-10	0.653 E-10
29	0.228 E-10	0.232 E-10	0.236 E-10	0.187 E-10	0.758 E-12	0.232 E-10	0.234 E-10
30	0.921 E-11	0.937 E-11	0.947 E-11	0.742 E-11	0.299 E-12	0.937 E-11	0.945 E-11
31	0.325 E-11	0.330 E-11	0.336 E-11	0.243 E-11	0.972 E-13	0.330 E-11	0.332 E-11
32	0.123 E-11	0.125 E-11	0.127 E-11	0.520 E-12	0.205 E-13	0.125 E-11	0.125 E-11
33	0.126 E-11	0.128 E-11	0.130 E-11	0.173 E-12	0.644 E-14	0.128 E-11	0.128 E-11
34	0.194 E-11	0.194 E-11	0.194 E-11	0.763 E-13	0.221 E-14	0.199 E-11	0.194 E-11
35	0.330 E-11	0.330 E-11	0.330 E-11	0.565 E-13	0.766 E-15	0.339 E-11	0.330 E-11
36	0.537 E-11	0.537 E-11	0.537 E-11	0.710 E-13	0.385 E-15	0.552 E-11	0.537 E-11
37	0.244 E-10	0.244 E-10	0.244 E-10	0.296 E-12	0.610 E-15	0.251 E-11	0.245 E-10

*See Table 3 for elemental compositions.

Table 6. Comparison of DLC-31 and Regrouped ICRU-26 Kerma Factors

Material	Neutron Energy 14 MeV	5 MeV	1 MeV	0.1 MeV	Thermal
H	—	—	—	—	—
C	-31%	—	—	—	+6%
N	+4%	+3%	—	—	-8%
O	—	+5%	—	—	+70%
Mg	+46%	+7%	—	+4%	+88%
Si	+29%	—	—	+5%	+66%
Ca	+23%	+37%	—	—	-16%
Tissue	-2.4%	—	—	—	-23%

Entries are percentage differences between DLC-31 kerma factors and regrouped ICRU-26 kerma factors. Dash indicates less than 2%. For tissue, DLC-31 neutron free-in-air tissue kerma factors were compared to regrouped ICRU-26 kerma factors for muscle. DLC-31 tissue contains 10% H, 24% C, 2.9% N, 60% O, 0.20% Na, 0.30% Mg, 1.1% P, 0.24% S, 0.20% K, 1.2% Ca, and 0.20% Cl.

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