

**CALCULATION OF INTERNAL RADIATION EXPOSURES AT  
A HIGH-ENERGY ELECTRON ACCELERATOR\***

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**ABSTRACT**

Estimates are made of the internal radiation exposures at a high-energy electron accelerator, relative to the external exposures received by machine-shop workers during cutting, grinding and welding operations performed on activated beamline components.

Using conservative assumptions, it is shown that for these operations the external radiation exposure is higher than the corresponding internal exposures by at least a factor of  $10^6$ .

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## INTRODUCTION

Induced activity is created in accelerator components after being exposed to the primary electron beam or high-energy secondary particles. Since this activity is created within the metallic matrix, it represents a stable, nondispersible source which results in no internal exposure during normal operations. However, there is a potential for internal exposures from these components if machining operations are performed which may produce respirable particulates. Machinshop workers at the Stanford Linear Accelerator Center (SLAC) occasionally perform machining operations on accelerator components containing induced radioactivity. The dose rates are typically in the range of a few hundreds of  $\mu\text{Sv hr}^{-1}$  (tens of  $\text{mrem hr}^{-1}$ ) and seldom, if ever, above  $1 \text{ mSv hr}^{-1}$  ( $100 \text{ mrem hr}^{-1}$ ) at 30 cm from the component. The 30 cm distance is important because this represents the approximate working distance between worker and source.

The machining operations primarily involve drilling or cutting and may occasionally involve grinding or welding. It is these operations which may produce respirable radioactive particulates leading to a potential internal dose. This paper will examine the magnitude of these internal exposures. The approach taken is a slightly more analytic one than presented by Busick.<sup>(1)</sup> The significant isotopes present in these components and their relative concentrations will be determined. From this, a comparison will be made between the estimated internal exposure and the corresponding external exposure.

## SIGNIFICANT RADIONUCLIDES

Most machining operations are performed on accelerator components such as valves, vacuum flanges, collimators, vacuum pipes and bellows. These components typically are made of aluminum, copper and iron. When a high-energy electron beam hits an accelerator component, high-energy photons are created during the electromagnetic cascade. These photons have large photonuclear cross sections in the Giant Resonance region, roughly 6-25 MeV where the photon has exceeded

the separation energy of a neutron or photon. These cross sections are small when compared to the photoatomic cross sections of Compton scattering or pair production (see Fig. 1). Regardless, it has been estimated<sup>(2)</sup> that in most cases the Giant Resonance reactions account for the majority of the induced activity.

The photon-induced activity produced (per incident electron) by the giant resonance reactions can be estimated by integrating the differential photon track length and Giant Resonance cross section over the energy range of the Giant Resonance;

$$Y = \frac{N_0 \varphi}{A} \int_{E_{cut}}^{E_0} \sigma_{GR}(k) \frac{d\ell}{dk} dk \quad (1)$$

where

$N_0$  is Avogadro's Number,

$\rho$  is the material density,

$\sigma_{GR}(k)$  is the Giant Resonance cross section at photon energy,  $k$ , and

$d\ell/dk$  is the differential photon track length.

Approximation *A* of shower theory<sup>(3)</sup> states that the differential photon track length may be estimated as

$$\frac{d\ell}{dk} \simeq \frac{0.572 X_0 E_0}{k^2} \quad (2)$$

where

$X_0$  is the target thickness in radiation lengths ,

$E_0$  is the incident electron energy and

$K$  is the photon energy .

Substituting, we have

$$Y = \left[ \frac{N_0 \varphi}{A} \right] 0.572 X_0 E_0 \int_{E_{cut}}^{E_0} \frac{\sigma_{GR}(k)}{k^2} dk \quad (3)$$

This is the approach taken by DesStaebler<sup>(9)</sup> and is called the Saturation Activity (when expressed in terms of Becquerels or Curies). This assumes a thick target so that all of the beam power is absorbed. The Saturation Activity is the amount of activity to be found immediately after the accelerator is turned off, assuming the accelerator had been running for a long time compared to the half-life of the isotope considered. Swanson<sup>(4)</sup> has tabulated the Saturation Activities as a function of beam power, for various elements induced by high-energy electrons. These are shown for aluminum, iron and copper in Table 1.

One problem with this approach is that some isotopes may never reach Saturation Activity. For example, <sup>60</sup>Co has a half-life of 5.26 years. This means that the component would be exposed to the electron beam continuously for 15–20 years, which is very unlikely. A more reasonable approach is taken. An assumption is made that the component is exposed to the beam continuously for one year and then allowed to decay for one day. Under this assumption, if an isotope has a half-life less than one hour, it will be neglected, since it will be decayed by at least 24 half-lives.

The number of radioactive nuclei with half-life ( $T_{1/2}$ ), and Saturation Activity ( $A_s$ ) which are created after an exposure period of ( $T$ ) is

$$n = \frac{A_s T_{1/2}}{0.693} [1 - e^{-(0.693 T)/T_{1/2}}] \quad (4)$$

Assuming a decay time  $t$ , the remaining number is

$$n(t) = \frac{A_s T_{1/2}}{0.693} [1 - e^{-(0.693 T)/T_{1/2}}] e^{-(0.693 t)/T_{1/2}} \quad (5)$$

Therefore, the activity is

$$A(t) = - \frac{dn}{dt} = A_s (1 - e^{-(0.693 T)/T_{1/2}}) e^{-(0.693 t)/T_{1/2}} \quad (6)$$

This equation is used to determine the  $A(t)$  shown in Table 1. The activity is then normalized to the most abundant isotope for each material, in terms of activity.

As will be demonstrated, the absolute concentrations are not significant, *i.e.*, whether 0.46 GBq s kJ<sup>-1</sup> (similar to Ci kW<sup>-1</sup>) of <sup>22</sup>Na or whether 0.46 Bq s kJ<sup>-1</sup> of <sup>22</sup>Na is produced. What is important here are the relative concentrations, *i.e.*, for every 0.46 GBq of <sup>22</sup>Na produced, 0.72 GBq of <sup>24</sup>Na and 1.0 GBq of <sup>7</sup>Be will be produced.

The next step is to determine the amount of activity as a function of external dose rate.

### RADIONUCLIDE CONCENTRATION

After determining the significant isotopes and their relative concentrations, the absolute concentration for a fixed dose rate and a fixed geometry can be tabulated. It is conservatively assumed that the worker is machining (cutting/grinding/ welding) a component which is  $7.17 \times 10^{-9}$  C kg<sup>-1</sup> s<sup>-1</sup> (or, 100 mR hr<sup>-1</sup>) at 30 cm from the source. As a first approximation, a disk source is assumed as in Ref. 1. This approximation ignores self-shielding, which is appropriate since the accelerator components being machined are relatively thin.

$$R_\gamma = \frac{q\Gamma}{a^2} \ln \left( \frac{h^2 + a^2}{h^2} \right) \text{ C kg}^{-1} \text{ s}^{-1} , \quad (7)$$

where

$$R_\gamma = \text{dose rate, C kg}^{-1} \text{ s}^{-1} ,$$

$$q = \text{MBq} ,$$

$$a = \text{disk radius} ,$$

$$h = \text{distance from center of disk to receiver point (worker)} ,$$

$$\Gamma = \text{dose rate constant} \left( \frac{\text{C kg}^{-1} \text{ s}^{-1}}{\text{MBq m}^{-2}} \right) .$$

If we assume

$$a = 10 \text{ cm} ,$$

$$h = 30 \text{ cm} ,$$

$$R_\gamma = 7.17 \times 10^{-9} \text{ C kg}^{-1} \text{ s}^{-1} \text{ (or, 100 mR hr}^{-1}\text{)} ,$$

then

$$q\Gamma = \frac{7.17 \times 10^{-9} \times 10^{-2}}{\ln\left(\frac{30^2+10^2}{30^2}\right)} = 6.8 \times 10^{-10} \text{ C m}^2 \text{ kg}^{-1} \text{ s}^{-1} . \quad (8)$$

Since we have more than one isotope and only know the relative concentrations, some multiple,  $m$ , of this will give  $7.17 \times 10^{-9} \text{ C kg}^{-1} \text{ s}^{-1}$  (or, 100 mR hr<sup>-1</sup>). The above expression is rewritten:

$$m \sum_{i=1}^N q_i \Gamma_i = 6.80 \times 10^{-10} \text{ C m}^2 \text{ kg}^{-1} \text{ s}^{-1} . \quad (9)$$

### Example – Aluminum

From Table 2 we assume that for every 1 MBq of <sup>7</sup>Be produced, we produce 0.46 MBq of <sup>22</sup>Na and 0.72 MBq of <sup>24</sup>Na. We then have:

$$\begin{aligned} m &= \frac{6.80 \times 10^{-10}}{\sum_{i=1}^N q_i \Gamma_i} \\ &= \frac{6.80 \times 10^{-10}}{[(1 \times 0.6) + (0.72 \times 35.6) + (0.46 \times 23.2)] \times 10^{-9}} \\ &= 1.85 \times 10^{-2} . \end{aligned} \quad (10)$$

Therefore, to get  $7.17 \times 10^{-9} \text{ C kg}^{-1} \text{ s}^{-1}$  (or,  $100 \text{ mR hr}^{-1}$ ) at 30 cm, an aluminum disk source, we need:

- $^{22}\text{Na} - 1.85 \times 10^{-2} \times 0.46 \text{ MBq} = 8.51 \times 10^{-3} \text{ MBq}$
- $^{24}\text{Na} - 1.85 \times 10^{-2} \times 0.72 \text{ MBq} = 1.33 \times 10^{-2} \text{ MBq}$
- $^7\text{Be} - 1.85 \times 10^{-2} \times 1.0 \text{ MBq} = 1.85 \times 10^{-2} \text{ MBq}$

Knowing the volume and density of the source, we can determine the concentration; this is shown in Table 3 for all three materials.

### SUSPENDED RESPIRIBLE CONCENTRATIONS

We now know the radionuclide concentration of the aluminum, iron and copper sources. Next we determine the radionuclide concentration in air.

Busick and Warren<sup>(1)</sup> state that dust or particulate concentrations for rain, fog, smoke, etc., vary from  $0.1\text{--}1 \text{ mg m}^{-3}$ . Also,  $1\text{--}10 \text{ mg m}^{-3}$  are typical values for very dusty operations, such as foundry shakeout and mine atmospheres during drilling operations. Reference 8 is a study of the characterization of aerosols from metal-cutting operations. (See Table 4.)

The most common machining operation at SLAC which involves suspended respirables is probably accelerator beampipe machining. This operation may include cutting a piece of activated beampipe, grinding down the end and then welding on a vacuum flange. An operation such as this may be performed ten times a year on an activated beampipe with a radiation level of, at the most,  $100\text{--}200 \mu\text{Sv hr}^{-1}$  ( $10\text{--}20 \text{ mrem hr}^{-1}$ ) at 30 cm.

The welding of the vacuum flange may be performed with either an oxyacetylene or plasma torch. As seen in Table 4, the plasma torch creates four times the aerosol concentration of the oxyacetylene torch but only requires one-sixth the welding time; therefore, this results in a larger inhaled fraction when using the oxyacetylene torch.

If we assume that this operation involves two minutes of cutting with a band saw ( $\sim 3 \text{ mg m}^{-3}$ ), one minute of grinding ( $\sim 3 \text{ mg m}^{-3}$ ) and four minutes of welding with an oxyacetylene torch, we have an average respirable aerosol concentration of

$$\frac{(3 \text{ min} \times 3 \text{ mg m}^{-3}) + (4 \text{ min} \times 15 \text{ mg m}^{-3})}{3 \text{ min} + 4 \text{ min}} = 10 \text{ mg m}^{-3} \quad (12)$$

This is equivalent to  $10^{-8} \text{ g ml}^{-1}$ . This is now multiplied by the radionuclide concentrations given in Table 3. The results are shown in Table 5. These calculated concentrations are then compared<sup>(5)</sup> with the Derived Air Concentrations (DAC's) taken from Department of Energy (DOE) Order 5480.11.

Table 7 shows the contributions from each isotope to the calculated external and internal doses. The external contribution can be found by weighting the product  $q_i \Gamma_i$  of each isotope of the material by the  $q_i \Gamma_i$  of all isotopes. The internal contribution can be determined by weighting the fraction of the DAC's for each isotope by the total fraction.

## DISCUSSION

As shown in Table 5, all calculated concentrations are less than the respective DAC's, even after using conservative assumptions. Remember that DAC's are defined as concentrations which, if continuously inhaled for one working year (2000 hrs), yield an internal exposure corresponding to the DOE annual limit of 50 mSv (5 rem). Assuming the worker has machined an activated piece of aluminum continuously for one year, his internal exposure would be  $(5 \times 10^{-5}) \times 50 \text{ mSv} = 2.5 \text{ } \mu\text{Sv}$  (0.25 mrem).

More importantly, the corresponding external exposure would be  $1 \text{ mSv hr}^{-1} \times 2000 \text{ hrs}$ , or 2 Sv (200 rem).

A better comparison is made by evaluating realistic machining operations. If one conservatively assumes that a cutting/grinding/welding operation will take

one hour and will occur ten times a year, this gives 10 machining-hrs yr<sup>-1</sup> versus the 2000 assumed above, and will reduce the dose by a factor of 10/2000, or  $5 \times 10^{-3}$ . Table 6 reports this exposure in comparison with the DAC's averaged over a year. Note that for this operation the worker will have received  $1 \text{ mSv hr}^{-1} \times 10 \text{ hrs}$ , or 10 mSv (1 rem).

Table 6 shows that the internal exposures are extremely low, and that they are at least a factor of  $10^6$  lower than the corresponding external exposure. When a machinist is working on a piece of equipment, much of his time is spent setting up the job at hand. This will tend to increase his external exposure while having no affect on any internal exposure. It is therefore reasonable to state that this ratio may be even greater.

## CONCLUSION

It has been shown that machining of thin aluminum, iron and copper accelerator components will result in negligible internal exposures. Additionally, internal exposure is bounded by the corresponding external exposure by at least a factor of  $10^6$ . The machine-shop workers at SLAC typically receive annual external whole body exposures of less than 1 mSv (or, 100 mrem), and the majority of this dose is from machining operations which do not involve grinding or welding and therefore produce no measurable respirable particulate concentration.

## ACKNOWLEDGMENT

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## TABLE CAPTIONS

Table 1(a). Important isotopes and properties (SI units).

Table 1(b). Important isotopes and properties (useful units).

Table 2(a). Activities of important isotopes (SI units).

Table 2(b). Activities of important isotopes (useful units).

Table 3(a). Concentration to give  $1 \text{ mSv hr}^{-1}$  at 30 cm (SI units).

Table 3(b). Concentration to give  $100 \text{ mrem hr}^{-1}$  at 30 cm (useful units).

Table 4. Aerosol particle size distribution, cutting time and aerosol concentration for metal cutting tools used on 2-inch (5 cm), schedule 40, type 304L stainless steel pipe.

Table 5(a). Comparison of calculated concentrations and Derived Air Concentrations (DAC's) in SI units.

Table 5(b). Comparison of calculated concentrations and DAC's in useful units.

Table 6. Comparison of DAC's over a one-year period.

Table 7. Relative contributions to internal and external doses.

**Table 1(a).** Important isotopes and properties (SI units).

Material	Isotope	Half-Life	$\Gamma$ ( $\frac{C \text{ kg}^{-1} \text{ s}^{-1}}{MBq \text{ m}^{-2}}$ )
Aluminum	$^{22}\text{Na}$	2.62y	23.2
	$^{24}\text{Na}$	14.96h	35.6
	$^7\text{Be}$	53.6d	0.6
Iron	$^{46}\text{Sc}$	83.9d	21.1
	$^{48}\text{V}$	16.0d	29 <sup>(*)</sup>
	$^{51}\text{Cr}$	27.8d	0.31 <sup>(*)</sup>
	$^{54}\text{Mn}$	303d	9.1 <sup>(*)</sup>
	$^{52}\text{Fe}$	8.2h	13.9
	$^{55}\text{Fe}$	2.60y	13.4
	$^{56}\text{Mn}$	2.58h	16.7
Copper	$^{58}\text{Co}$	71.3d	10.7
	$^{60}\text{Co}$	5.26y	25.6
	$^{64}\text{Cu}$	12.8h	2.3 <sup>(*)</sup>

<sup>(\*)</sup> Taken from Ref. 6, all others from Ref. 4. Multiplied by  $10^9$ .

**Table 1(b).** Important isotopes and properties (useful units).

Material	Isotope	Half-Life	$\Gamma \left( \frac{R \cdot m^2}{mCi \cdot hr} \right)$
Aluminum	$^{22}\text{Na}$	2.62y	12.0
	$^{24}\text{Na}$	14.96h	18.4
	$^7\text{Be}$	53.6d	0.3
Iron	$^{46}\text{Sc}$	83.9d	10.9
	$^{48}\text{V}$	16.0d	15 <sup>(*)</sup>
	$^{51}\text{Cr}$	27.8d	0.16 <sup>(*)</sup>
	$^{54}\text{Mn}$	303d	4.7 <sup>(*)</sup>
	$^{52}\text{Fe}$	8.2h	7.2
	$^{55}\text{Fe}$	2.60y	6.9
	$^{56}\text{Mn}$	2.58h	8.6
Copper	$^{58}\text{Co}$	71.3d	10.7
	$^{60}\text{Co}$	5.26y	13.2
	$^{64}\text{Cu}$	12.8h	1.2 <sup>(*)</sup>

<sup>(\*)</sup> Taken from Ref. 6, all others from Ref. 4. Multiplied by  $10^9$ .

**Table 2(a).** Activities of important isotopes (SI units).

Material	Isotope	$A_s$ (*) (GBq s kJ <sup>-1</sup> )	$A(t)$ (†) (GBq s kJ <sup>-1</sup> )	Normalized $A(t)$ (GBq s J <sup>-1</sup> )
Aluminum	<sup>22</sup> Na	9.25	2.1	0.46
	<sup>24</sup> Na	10.4	3.4	0.72
	<sup>7</sup> Be	4.8	4.7	1.0
Iron	<sup>46</sup> Sc	7.4	7.0	.061
	<sup>48</sup> V	14.8	14.1	0.12
	<sup>51</sup> Cr	14.8	14.1	0.13
	<sup>54</sup> Mn	21.8	12.2	0.11
	<sup>52</sup> Fe	2.1	0.27	0.0024
	<sup>55</sup> Fe (‡)	492	115	1.0
	<sup>56</sup> Mn	1.2	—	—
Copper	<sup>58</sup> Co	24.4	23.3	.46
	<sup>60</sup> Co	24.1	3.0	0.06
	<sup>64</sup> Cu	185	50.3	1.0

(\*) Saturation activity.

(†) Assumes one-year exposure time and one-day decay.

(‡) <sup>55</sup>Fe has  $E_\gamma \sim 6$  keV; therefore, neglect for external exposure but not for internal exposure.

**Table 2(b).** Activities of important isotopes (useful units).

Material	Isotope	$A_s$ (*) (Ci kW <sup>-1</sup> )	$A(t)$ (†) (Ci kW <sup>-1</sup> )	Normalized $A(t)$ (Ci kW <sup>-1</sup> )
Aluminum	<sup>22</sup> Na	0.25	0.058	0.46
	<sup>24</sup> Na	0.28	0.092	0.72
	<sup>7</sup> Be	0.13	0.13	1.0
Iron	<sup>46</sup> Sc	0.20	0.19	.061
	<sup>48</sup> V	0.40	0.38	0.12
	<sup>51</sup> Cr	0.40	0.39	0.13
	<sup>54</sup> Mn	0.59	0.33	0.11
	<sup>52</sup> Fe (‡)	0.056	0.0074	0.0024
	<sup>55</sup> Fe <sup>c</sup>	13.3	3.11	1.0
	<sup>56</sup> Mn	0.032	—	—
Copper	<sup>58</sup> Co	0.66	0.63	.46
	<sup>60</sup> Co	0.65	0.082	0.06
	<sup>64</sup> Cu	5.0	1.36	1.0

(\*) Saturation activity.

(†) Assumes one-year exposure time and one-day decay.

(‡) <sup>55</sup>Fe has  $E_\gamma \sim 6$  keV; therefore, neglect for external exposure but not for internal exposure.

**Table 3(a).** Concentration to give 1 mSv hr<sup>-1</sup> at 30 cm (SI units).

Material	Multiplying Factor, <i>m</i>	Isotope	kBq	Concentration Bq g <sup>-1</sup>
Aluminum	5	<sup>22</sup> Na	8.51	10.0
		<sup>24</sup> Na	13.3	15.9
		<sup>7</sup> Be	18.5	21.8
Iron	4	<sup>46</sup> Sc	0.89	0.37
		<sup>48</sup> V	1.78	0.70
		<sup>51</sup> Cr	1.92	0.78
		<sup>54</sup> Mn	1.63	0.67
		<sup>52</sup> Fe	0.037	0.015
		<sup>55</sup> Fe	14.8	5.9
Copper	21	<sup>58</sup> Co	36.0	13.0
		<sup>60</sup> Co	4.81	1.70
		<sup>64</sup> Cu	77.7	27.8

**Table 3(b).** Concentration to give 100 mrem hr<sup>-1</sup> at 30 cm (useful units).

Material	Multiplying Factor, <i>m</i>	Isotope	$\mu\text{Ci}$	Concentration nCi g <sup>-1</sup>
Aluminum	5	<sup>22</sup> Na	0.23	0.27
		<sup>24</sup> Na	0.36	0.43
		<sup>7</sup> Be	0.50	0.59
Iron	4	<sup>46</sup> Sc	0.024	0.010
		<sup>48</sup> V	0.048	0.019
		<sup>51</sup> Cr	0.052	0.021
		<sup>54</sup> Mn	0.044	0.018
		<sup>52</sup> Fe	0.001	0.0004
		<sup>55</sup> Fe	0.40	0.16
Copper	21	<sup>58</sup> Co	0.97	0.35
		<sup>60</sup> Co	0.13	0.046
		<sup>64</sup> Cu	2.10	0.75

**Table 4.** (\*) Aerosol particle size distribution, cutting time and aerosol concentration for metal cutting tools used on 2-inch (5 cm), schedule 40, type 304L stainless steel pipe.

Tool	Range of MMAD (†) ( $\mu\text{m}$ )	Typical $\sigma_R$	Cutting Time (minutes)		Measured Concentration ( $\text{mg m}^{-3}$ )
			Range	Mean	
Pipe cutter	N.D. (‡)	N.A. (§)	0.9–1.1	1.0	N.D.
Reciprocating saw	Bimodal	N.A.	1.8–4.5	3.1	$1.0 \pm 0.8$
Band saw	0.1–0.5	2.3	0.9–1.9	1.5	$2.5 \pm 1$
Side arm grinder	Bimodal	N.A.	N.A.	N.A.	$2.7 \pm 1.6$
Chop saw	1.5–9.0	4.6	1.1–1.7	1.5	$12 \pm 3$
Oxyacetylene torch	0.1–10.3	2.3	2.0–4.2	3.6	$15 \pm 11$
Cut rod	0.4–0.8	1.8	0.7–1.0	0.8	$42 \pm 29$
Plasma torch	0.2–0.3	2.7	0.5–0.7	0.6	$62 \pm 38$

(\*) From Ref. 8.

(†) Mass Median Aerodynamic Diameter by cascade impactor.

(‡) N.D. = None detected.

(§) N.A. = Not applicable.

**Table 5(a).** Comparison of calculated concentrations and Derived Air Concentrations (DAC's) in SI units.

Material	Isotope	Calculated (MBq/ml)	DAC's (GBq/ml)	Normalized Calculated/DAC's
Aluminum	<sup>22</sup> Na	0.10	$1.1 \times 10^1$	$9.1 \times 10^{-6}$
	<sup>24</sup> Na	0.16	$7.4 \times 10^1$	$2.1 \times 10^{-6}$
	<sup>7</sup> Be	0.22	$3.0 \times 10^{+2}$	$7.4 \times 10^{-7}$
Iron	<sup>46</sup> Sc	$3.7 \times 10^{-3}$	3.7	$1 \times 10^{-6}$
	<sup>48</sup> V	$7.0 \times 10^{-3}$	$1.1 \times 10^1$	$6.3 \times 10^{-7}$
	<sup>51</sup> Cr	$7.8 \times 10^{-3}$	$3.0 \times 10^2$	$2.6 \times 10^{-10}$
	<sup>54</sup> Mn	$6.7 \times 10^{-3}$	$1.1 \times 10^1$	$6.0 \times 10^{-7}$
	<sup>52</sup> Fe	$1.5 \times 10^{-3}$	$3.7 \times 10^1$	$4.0 \times 10^{-10}$
	<sup>55</sup> Fe	$5.9 \times 10^{-2}$	$3.0 \times 10^1$	$2.0 \times 10^{-6}$
Copper	<sup>58</sup> Co	0.13	$1.1 \times 10^1$	$1.3 \times 10^{-5}$
	<sup>60</sup> Co	$1.7 \times 10^{-2}$	$3.7 \times 10^{-1}$	$5.0 \times 10^{-5}$
	<sup>64</sup> Cu	0.28	$3.3 \times 10^2$	$8.3 \times 10^{-7}$

**Table 5(b).** Comparison of calculated concentrations and DAC's in useful units.

Material	Isotope	Calculated ( $\mu\text{Ci ml}^{-1}$ )	DAC's ( $\mu\text{Ci ml}^{-1}$ )	Normalized Calculated/DAC's.
Aluminum	$^{22}\text{Na}$	$3.7 \times 10^{-12}$	$4.1 \times 10^{-7}$	$9.1 \times 10^{-6}$
	$^{24}\text{Na}$	$5.9 \times 10^{-12}$	$2.7 \times 10^{-6}$	$2.1 \times 10^{-6}$
	$^7\text{Be}$	$8.1 \times 10^{-12}$	$1.1 \times 10^{-5}$	$7.4 \times 10^{-7}$
Iron	$^{46}\text{Sc}$	$1.4 \times 10^{-13}$	$1.4 \times 10^{-7}$	$1 \times 10^{-6}$
	$^{48}\text{V}$	$2.6 \times 10^{-13}$	$4.1 \times 10^{-7}$	$6.3 \times 10^{-7}$
	$^{51}\text{Cr}$	$2.9 \times 10^{-13}$	$1.1 \times 10^{-5}$	$2.6 \times 10^{-10}$
	$^{54}\text{Mn}$	$2.5 \times 10^{-13}$	$4.1 \times 10^{-7}$	$6.0 \times 10^{-7}$
	$^{52}\text{Fe}$	$5.5 \times 10^{-14}$	$1.4 \times 10^{-6}$	$4.0 \times 10^{-10}$
	$^{55}\text{Fe}$	$2.2 \times 10^{-12}$	$1.1 \times 10^{-6}$	$2.0 \times 10^{-6}$
Copper	$^{58}\text{Co}$	$1.8 \times 10^{-12}$	$4.1 \times 10^{-7}$	$1.3 \times 10^{-5}$
	$^{60}\text{Co}$	$6.3 \times 10^{-13}$	$1.4 \times 10^{-8}$	$5.0 \times 10^{-5}$
	$^{64}\text{Cu}$	$3.8 \times 10^{-12}$	$1.2 \times 10^{-5}$	$8.3 \times 10^{-7}$

**Table 6.** Comparison of DAC's over a one-year period.

	Fraction of DAC's for Ten Hour Machining Operation	Fraction of DAC's Averaged Over One Year	Ratio of Internal/External Exposures
Aluminum	$1.3 \times 10^{-5}$	$6.3 \times 10^{-8}$	$3.1 \times 10^{-7}$
Iron	$4.4 \times 10^{-6}$	$2.2 \times 10^{-8}$	$1.1 \times 10^{-7}$
Copper	$5.0 \times 10^{-5}$	$2.5 \times 10^{-7}$	$1.3 \times 10^{-6}$

**Table 7.** Relative contributions to internal and external doses.

Material	Isotope	External Dose	Internal Dose
Aluminum	$^{22}\text{Na}$	29%	76%
	$^{24}\text{Na}$	69%	18%
	$^7\text{Be}$	2%	6%
Iron	$^{46}\text{Sc}$	22%	23%
	$^{48}\text{V}$	60%	15%
	$^{51}\text{Cr}$	1%	1%
	$^{54}\text{Mn}$	16%	14%
	$^{52}\text{Fe}$	1%	1%
	$^{55}\text{Fe}$	–	46%
	$^{56}\text{Mn}$	–	–
Copper	$^{58}\text{Co}$	56%	20%
	$^{60}\text{Co}$	18%	79%
	$^{64}\text{Cu}$	26%	1%

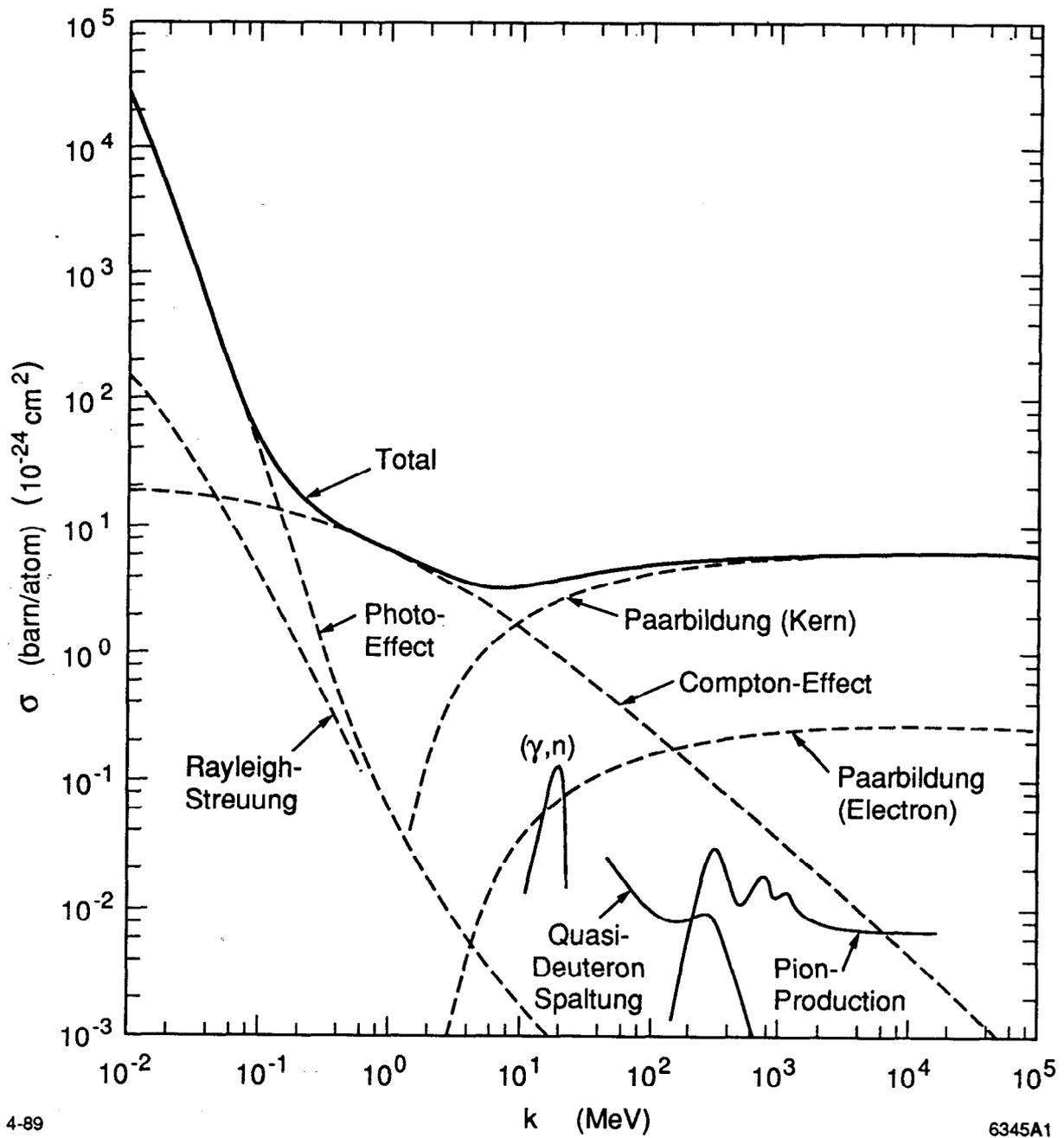


Fig. 1. Photon cross sections [taken from Freytag<sup>(1)</sup>].