

REJECTION CRITERIA FOR DEFECTS IN LEAD APPAREL USED FOR RADIATION PROTECTION OF X-RAY WORKERS

PURPOSE

The purpose of this report is to provide a rationale for the rejection of lead protective apparel for use by x-ray facility operators and to present the basis on which the criteria was developed for radiation protection purposes.

INTRODUCTION

Lead protective apparel for x-ray shielding such as lead aprons, thyroid shields and gauntlets is recommended in the Health Canada safety codes. Its purpose is to help keep occupational exposures from radiation within applicable limits and **as low as reasonably achievable (ALARA)** below these limits. Optimization of protection by applying some form of cost-benefit analysis implies that the cost of protection and cost of detriment should be minimized. At doses approaching the whole-body equivalent limit of 20 mSv/y for workers, the detriment will not result in deterministic effects so only the risks of stochastic effects need to be considered. Thus for the lead apron, which protects many of the major organs and tissues that are sensitive to radiation, the risks considered are cancer-induction and hereditary effects. For thyroid shields and gauntlets, only cancer induction is considered. The rejection criteria for lead aprons therefore is based not only on the cancer risk but pays particular attention to the reproductive region, where the concern is the risk of hereditary effects. This report identifies the criteria for rejecting the use of the apparel (lead apron, thyroid shield, and gauntlets) as a result of damage or degradation, based on an optimization approach that considers the incremental doses and costs of replacement of the apparel. Consideration has to be given to the relative radiation sensitivity of the particular organs and tissues at risk under the apparel by applying the tissue weighting factors in ICRP 60, to determine the maximum area of the holes or defects permitted for each type of apparel used.

RATIONALE

Lead aprons (with or without built-in thyroid shield) are the most expensive item of the range of apparel and cost from \$200-600. If we apply an additional 20% shipping costs and taxes, we can assume an average cost of a new apron to be about \$500. If an apron is to be replaced at about half way through its useful life (i.e. replaced at 5 years instead of 10) due to damage or defect, then the incremental cost would be half the value of an apron or \$250. Regarding the benefit gained for money spent, the price to avert additional dose can be considered. Applying the practice in the nuclear industry (Lambert and McKeon, 2001) of assigning a cost of protection equivalent to \$1000 per mSv averted, the incremental dose associated with \$250 would then be 0.25 mSv, which would be received over 5 years or 0.05 mSv per year. In the medical x-ray field, the cost to avert dose may be considerably lower, since optimization of protection, through facility design/operations and personal protection, against x-rays will generally require lower costs than for the higher-energy gamma radiation from sources such as the nuclear industry. However, in the absence of an integrated cost-of-protection value used in the medical X-ray field, the practice in the nuclear industry was adopted here. This would most likely result to a more conservative dose criteria.

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The detriment associated with an additional 0.05 mSv/y to the average doses actually received by medical X-ray personnel has been determined using the doses received by personnel in 1999 from the National Dose Registry in its annual report on occupational radiation exposures in Canada (Health Canada, 2000). The job categories considered are the medical radiation technologists, radiologists (diagnostic), physicians (e.g. cardiologists, orthopedic surgeons, anesthetists), and nurses since these are the job categories where lead aprons may be required at least for some, if not all of the workers. The average of positive doses for these different categories range from 0.54 mSv/y (nurse) to 1.06 mSv/y (radiologist/diagnostic) to the whole body. The average doses are much lower, i.e. from 0.04 (nurse) to 0.13 mSv/y (radiologist/diagnostic), since most of the doses are below reportable doses (<0.2 mSv). If we base our dose criteria on the average of positive doses and choose 1.06 mSv/y which is the highest average, the incremental dose of 0.05 mSv/y is equivalent to about 5% of the average dose. The effect of incremental 5% dose to the 1999 collective doses is shown in Table 1 below (Health Canada, 2001):

Table 1 Additional Collective Dose due to Defects in Lead Apron at 5% Incremental Dose

Job category	Number of workers	Collective dose (year 1999)	5% incremental dose	Resultant per capita dose
Medical radiation technologist	10,538	507.20 mSv	25.36 mSv	0.0505 mSv/y
Nurse	3,733	156.92 mSv	7.85 mSv	0.0441 mSv/y
Physician	1,646	194.40 mSv	9.72 mSv	0.1240 mSv/y
Radiologist (Diagnostic)	1,521	193.21 mSv	9.66 mSv	0.1334 mSv/y
TOTAL	17,438	1,051.73 mSv	52.59 mSv	0.0633 mSv/y

Applying the nominal probability coefficient for stochastic effects in ICRP 60 (5.6×10^{-5} per mSv), the detriment to this worker group for a 5% incremental dose is 3×10^{-3} per year or 1.5×10^{-2} over 5 years. This detriment may be even lower since not all of the workers in these job categories wear lead aprons. The case where the dose under the apron approaches the dose limit of 20 mSv/y or 100 mSv/5 years was also considered. There are only 16 out of 17,438 workers that received doses in 1999 in the >5 to 20 mSv category and only 2 in the >20-50 mSv category. The detriment to this worker sub-group due to the 5% incremental dose is small, i.e., 6.2×10^{-4} per year or 3.1×10^{-3} over 5 years. In terms of cancer risk, the probability of developing (fatal) cancer associated with 5% of 20 mSv over 5 years (or total of 5 mSv) is 0.02%. The typical lifetime probability of developing cancer is 40% for males and 35.5% for females (Statistics Canada, 2001).

The same cost-benefit optimization approach can be followed in the case of thyroid shields and gauntlets. However, the cost of protection and dose criteria will differ. Since the costs of these protective apparel are lower than for lead aprons, the corresponding percentage increase in dose due to defects which can be considered as tolerable will be lower. If we apply the average cost of a thyroid shield to be \$75, the dose criteria is then 0.075 mSv, or 0.015 mSv per year over 5 years. For gauntlets, if \$200 is the average cost, then the additional dose associated with its continued use despite defects would be 0.2 mSv, or 0.04 mSv per year over 5 years. Further, the whole-body effective dose of 1.06 mSv/y cannot also be used. Unlike the lead apron which covers different organs or tissues of varying radiation sensitivity, the stand-alone thyroid shield and gauntlet protects specifically only the thyroid and hands, respectively. In the absence of

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data on the equivalent dose to the hands or thyroid received by X-ray workers per year, we can assume that the relative contribution of the equivalent dose received by these tissues to the effective dose is given by the weighting factors from ICRP 60. Thus, from ICRP 60:

$$E = \sum w_t E_t$$

where E is the effective or whole-body dose
 w_t is the tissue weighting factor
 E_t is the equivalent dose to different tissues

Adopting the average whole-body dose $E = 1.06$ mSv/y (Health Canada 2000) for the job categories considered and applying $w_t = 0.025$ (ICRP 60) for the hands, we can estimate the equivalent dose to the hands (since the other tissues or organs are not the relevant organs for the gauntlet) by:

$$E_t = 1.06/0.025 = 42 \text{ mSv}$$

The percent incremental dose for the gauntlet is thus:

$$0.04 \text{ mSv}/42 \text{ mSv} = 0.1\%$$

For the thyroid, applying $w_t = 0.05$ (ICRP 60):

$$E_t = 1.06/0.05 = 21 \text{ mSv}$$

The percent incremental dose for the thyroid shield is thus:

$$0.015 \text{ mSv}/21 \text{ mSv} \times 100 = 0.07\%$$

The sizes of the holes or cracks in the thyroid shield that is built into a lead apron is higher than the stand-alone thyroid shield, since the approach is based on cost-benefit analysis, and lead aprons with built-in thyroid shields will cost more to replace than stand-alone thyroid shields. In either case, however, the detriment associated with the defect is low, as discussed above.

COMPUTATIONAL APPROACH

1. Lead Aprons

From above, if we accept a 5% increase in dose under the apron due to the presence of these holes or cracks, then:

$$d_i = 0.05 D_u T$$

where: d_i is the additional dose due to holes in the apron
 D_u is the unattenuated dose through the apron
 T is the transmission factor through the lead apron

$$d_i = 0.05 D_u T = \sum_t w_t D_u \frac{H_t}{A_t} - w_t D_u T \frac{H_t}{A_t} \quad (1)$$

where: w_t is the tissue weighting factor for the organ or region of interest
 H_t is the aggregate area of holes over the organ or region of interest
 A_t is the surface area of the organ or region of interest

Uniform distribution of holes over the entire frontal area covered by the apron

In this case,

$$w_t = w_{wb} = 1$$

$$A_t = A_{wb} = \text{frontal area of the lead apron}$$

$$0.05 D_u T = D_u \frac{H_{wb}}{A_{wb}} - D_u T \frac{H_{wb}}{A_{wb}}$$

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$$0.05 T = \frac{H_{wb}(1-T)}{A_{wb}}$$

As discussed in **RPS RIN#10** , the transmission factors for lead aprons decreases with kVp. RIN#10 recommends lead aprons that are 0.3 mm Pb equivalent for procedures requiring <100 kVp and 0.5 mm Pb equivalent for procedures requiring >100 kVp. If we take 70 kVp as a common setting for procedures requiring <100 kVp (transmission is 3% with 0.3 mm Pb apron) and 120 kVp as a common setting for procedures >100 kVp (transmission is 5% with 0.5 mm Pb), we can adopt an average transmission factor of 4%; then

$$H_{wb} = \frac{(0.05)(0.04)A_{wb}}{1-0.04}$$

$$H_{wb} = 0.002A_{wb} \quad (2)$$

From ICRP (2001) and EPA (1997) reports and available sizes of aprons (commercial literature), we can estimate average $A_{wb} = 5000 \text{ cm}^2$, then:

$$H_{wb} = (0.002)(5000) = 10 \text{ cm}^2$$

In addition to reducing the stochastic risks associated with exposure of different regions of the body, another limiting condition is to reduce the risks of hereditary effects by protecting the reproductive region. The maximum size of holes or cracks over the reproductive region is determined as follows:

Holes/cracks are over the reproductive region only

From equation (1):

$$d_i = 0.05D_u T = \sum_t w_t D_u \frac{H_t}{A_t} - w_t D_u T \frac{H_t}{A_t}$$

$$d_j = 0.05D_u T = w_{t,g} D_u \frac{H_{t,g}}{A_{t,g}} - w_{t,g} D_u T \frac{H_{t,g}}{A_{t,g}} + w_{t,r} D_u \frac{H_{t,r}}{A_{t,r}} - w_{t,r} D_u T \frac{H_{t,r}}{A_{t,r}} \quad (3)$$

where: $w_{t,g}$ = tissue weighting factor for the gonads = 0.2 (ICRP 60)
 $w_{t,r}$ = tissue weighting factor for remainder of tissues/region = 0.8
 $A_{t,g}$ = area of the gonad region
 $A_{t,r}$ = area of the remainder of tissues/region
 $H_{t,g}$ = area of the holes over the gonad region
 $H_{t,r}$ = area of holes over the remainder of tissues/region

but $H_{t,r} = 0$ since the holes are only over the gonad region, then equation 3 reduces to:

$$d_j = 0.05D_u T = w_{t,g} D_u \frac{H_{t,g}}{A_{t,g}} - w_{t,g} D_u T \frac{H_{t,g}}{A_{t,g}} \quad (4)$$

$$0.05T = w_{t,g} \frac{H_{t,g}}{A_{t,g}} - w_{t,g} T \frac{H_{t,g}}{A_{t,g}}$$

$$H_{t,g} = 0.05 \frac{A_{t,g}}{w_{t,g}} \frac{T}{(1-T)} \quad (5)$$

applying $T = 4\%$, $w_{t,g} = 0.2$ (ICRP 60)

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$$H_{t,g} = 0.05A_{t,g} \frac{0.04}{(0.2)(1 - 0.04)}$$

$$H_{t,g} = 0.010A_{t,g} \tag{6}$$

From ICRP (2001), average $A_{t,g}$ is approximately 20 cm², then:

$$\mathbf{H_{t,g} = (0.010)(20 \text{ cm}^2) = 0.2 \text{ cm}^2}$$

Some lead apron designs already include a thyroid shield. To reduce the risks of stochastic effects to the thyroid, an additional limiting condition in this case will be the size of defect over the thyroid region.

Holes/cracks are over the thyroid region only:

From equation 5:

$$H_{t,tha} = 0.05 \frac{A_{t,tha}}{w_{t,tha}} \frac{T}{(1 - T)}$$

applying T=4%, $w_{t,tha} = 0.05$ (ICRP 60)

$$H_{t,tha} = 0.042A_{t,tha} \tag{7}$$

Gray (1912) describes the thyroid gland as consisting of the right and left lobes, situated at the front and sides of the neck. Each lobe is about 5 cm long and its greatest width is 3 cm. Based on this, it is estimated roughly that $A_{t,th} = 30 \text{ cm}^2$, then:

$$\mathbf{H_{t,tha} = (0.042)(30 \text{ cm}^2) = 1.2 \text{ cm}^2 \approx 1 \text{ cm}^2}$$

2. Stand-alone Thyroid Shields

As discussed in the Rationale, if we accept a 0.07% increase in dose under the thyroid shield due to holes or cracks, then from equation 4 the additional dose to the thyroid is given by:

$$d_{i,ths} = 0.0007D_u T = w_{t,ths} D_u \frac{H_{t,ths}}{A_{t,ths}} - w_{t,ths} D_u T \frac{H_{t,ths}}{A_{t,ths}} \tag{8}$$

$$0.0007T = \frac{w_{t,ths} H_{t,ths}}{A_{t,ths}} (1 - T)$$

$$H_{t,ths} = 0.0007 \frac{A_{t,ths}}{w_{t,ths}} \frac{T}{(1 - T)}$$

applying T=4%, $w_{t,ths} = 0.05$ (ICRP 60)

$$H_{t,ths} = 0.0007 \frac{A_{t,ths}}{0.05} \frac{0.04}{(1 - 0.04)}$$

$$H_{t,ths} \approx 0.001A_{t,ths} \tag{9}$$

Assuming $A_{t,ths} = 30 \text{ cm}^2$ (Gray, 1912), then:

$$\mathbf{H_{t,ths} \approx (0.001)(30) \approx 0.03 \text{ cm}^2}$$

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3. Gauntlets (Gloves/Mittens)

For gauntlets, if we accept a 0.1% incremental dose under the gauntlet due to holes or cracks, then from equation 8 the additional dose to the hands is given by:

$$d_{i,h} = 0.001D_u T = w_{t,h} D_u \frac{H_{t,h}}{A_{t,h}} - w_{t,h} D_u T \frac{H_{t,h}}{A_{t,h}} \quad (10)$$

$$H_{t,h} = 0.001 \frac{A_{t,h}}{w_{t,h}} \frac{T}{(1-T)}$$

For the hands, the applicable weighting factors from ICRP 60 can either be the weighting factor for the skin, $w_t = 0.01$ or the weighting factor for a single one of the remainder tissues that is selectively irradiated, $w_t = 0.025$. Since the hands are selectively irradiated in this case, the $w_t = 0.025$ is applied, and assuming $T = 4\%$ then:

$$H_{t,h} = 0.001 \frac{A_{t,h}}{0.025} \frac{0.04}{(1-0.04)}$$

$$H_{t,h} \approx 0.002A_{t,h} \quad (11)$$

From EPA (1997), the average surface area of the hands is 795 cm². We should add to this the part of the arm that is also protected by the gauntlet. If we estimate the part of the arms covered by gauntlets to be 1/4 of the whole arm, then from EPA (1997), this corresponds to an additional average area of 547 cm². Thus, total $A_{t,h} = 1342$ cm².

$$H_{t,h} \approx (0.002)(1342) \approx 2.684 \text{ cm}^2 \approx 3 \text{ cm}^2$$

SUMMARY

An approach to establishing rejection criteria for lead protective apparel based on the cost of the apparel and the cost of detriment was presented. In summary, lead apparel which contain defects such as holes or cracks should be decommissioned if the aggregate area of the holes or cracks exceed those in Table 2 below:

Table 2 Maximum Aggregate Area of Holes or Cracks in Lead Protective Apparel

Type of Apparel	Total or Aggregate Area
Lead apron with built-in thyroid shield	10 cm ² whole-body 0.2 cm ² or 20 mm ² reproductive region 1 cm ² neck region
Separate Thyroid Shield	0.03 cm ² or 3 mm ²
Gauntlet	3 cm ²

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