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## ANALYSIS OF POTENTIAL RADIOBIOLOGICAL EFFECTS RELATED TO A UNIFIED SKIN DOSE LIMIT

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**Abstract**—A unified skin dose limit of 0.5 Sv at a depth of 70  $\mu\text{m}$  averaged over the highest 10  $\text{cm}^2$  of skin exposed was evaluated to replace the existing limit of 0.5 Sv averaged over 1  $\text{cm}^2$ . This limit would apply to all exposures including non-uniform exposures such as from hot particles on or off skin, skin contamination, or beams of charged particles or photons. The probabilities and severity of both stochastic and deterministic risks were estimated for a wide range of worst-case exposure scenarios using published radiobiological data and calculations of radial- and depth-dose distributions. Results indicate that exposures at the unified dose limit have the potential to cause effective doses of about 17  $\mu\text{Sv}$  (1.7 mrem), estimated stochastic risks of  $<3.3 \times 10^{-7}$  fatal skin cancers, and  $<1.6 \times 10^{-4}$  non-fatal skin cancers. The worst deterministic effects were estimated to be (a) based on a 2 Gy threshold, transient erythema induction to an area of 2.5  $\text{cm}^2$  for uniform skin contamination over this same area and 0.65  $\text{cm}^2$  for a  $^{60}\text{Co}$  hot particle 3 mm off of skin, (b) based on data for pig skin, 50% probability that 0.5  $\text{cm}^2$  of skin would suffer 20% dermal thinning for uniform contamination with  $^{106}\text{Rh}$  spread over the same area, and (c) 10% probability of barely detectable transient acute necrosis or ulceration for  $^{60}\text{Co}$  or activated fuel particles 0.4 mm off of skin. It was concluded that the unified limit would provide a more logical system of dose control with possible savings of whole-body dose and other benefits.

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**Key words:** radiation risk; health effects; hot particles; skin dose

### INTRODUCTION

THE RECENT NCRP Report 130 on hot particles (NCRP 1999) recommends "The dose to skin at a depth of 70  $\mu\text{m}$  from hot particles on skin (including ear), hair or clothing be limited to no more than 0.5 Gy averaged over the most highly exposed 10  $\text{cm}^2$  of skin." This recommendation, if incorporated into regulations, would provide a significant regulatory relief to the nuclear power industry because the current regulations only allow 0.5 Sv dose equivalent averaged over the highest exposed 1  $\text{cm}^2$  of skin (CFR 2000). The change would also be expected to make

possible significant reductions in whole-body exposures in situations where workers must incur unproductive dose as they stop work and make checks to ensure that they do not exceed the current limit.

In support of the NRC rulemaking process on "Protection Against Discrete Radioactive Particle Exposures," information has been gathered and analyzed to evaluate the pros and cons of various options for achieving regulatory relief and optimum safety. During this effort suggestions were received from nuclear power plant health physicists<sup>†</sup> indicating a need for a unified skin dose limit that would apply not only to hot particle exposures on the skin but also to other non-uniform exposures such as from hot particles on clothing or hair, localized skin contaminations, localized x-ray exposures, and exposures from x-ray or charged particle beams. The NRC has asked the NCRP to provide recommendations on such a harmonized approach to skin dose limits.

This report summarizes data and analyses of risks that may be encountered for 0.5 Gy doses averaged over 10  $\text{cm}^2$  at 70  $\mu\text{m}$  depth in skin. Comparisons are also made to risks from effective doses due to whole-body exposures and exposures to skin of the whole body at the current skin dose limit.

### MATERIALS AND METHODS

Skin exposures may lead to both stochastic and deterministic risks. The former include both fatal and non-fatal skin cancers, which are assumed to have no threshold for production and have an increasing probability of occurrence with increasing dose. The probabilities of induction of fatal and non-fatal skin cancers were estimated using recent data published in NCRP Report 130 (NCRP 1999) and ICRP Publication 59 (ICRP 1991a).

In the range of doses near the dose limits considered here, the most likely deterministic effects include acute erythema (slight reddening or tinting of skin), epidermal necrosis (cell killing), acute ulceration (a tiny break in the skin which quickly forms a small scab and heals), and dermal thinning (a slight depression in the skin). The epidermal necrosis and acute ulceration are likely to be barely detectable as small scabs. The probabilities of

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<sup>†</sup> Personal communications with Michael W. Lantz and Michael J. Russell; 2000.

induction for these effects were estimated based on experimental data obtained from irradiated pig skin (Kaurin et al. 1997; NCRP 1999) and dose calculations obtained using an updated version<sup>‡</sup> of the VARSKIN Mod2 computer code (Durham and Bell 1992). This updated version employs 50 points for integration instead of 25 and includes a backscatter correction factor for all target areas (not just 1 cm<sup>2</sup>).

Based on data from patients receiving x- and gamma-ray therapy, the threshold for early transient erythema induction from uniform skin irradiations is about 2 Gy at a depth of 70 μm in skin (NCRP 1999; ICRP 1991a). Three phases of erythema have been identified (Potten 1985). The first phase is observed within a few hours of irradiation and is probably a capillary dilation and leakage. The second phase begins about the tenth day, reaches a peak after about the fourteenth day, declines after about 4 wk, and has intensity which is dose dependent. The third phase has a beginning about 35 d after irradiation and has an intensity that is largely independent of dose.

Although higher threshold doses can be found in the literature, to be conservative, the 2 Gy threshold cited by both the NCRP and the ICRP was employed for estimated effects evaluated in this study. For each exposure scenario, the code was used to determine the radius at which a 2 Gy dose was predicted at 70 μm depth, and from this radius the estimated erythema area was calculated.

Dose-effect relationships for dermal thinning due to cell atrophy in humans are available only from studies on patients receiving fractionated radiotherapy treatments (ICRP 1991a; NCRP 1999). Thresholds for atrophy in large fields after doses given in 30 fractions were about 40 Gy for visible effects in humans and about 35 Gy for >12.5% linear contraction of skin fields on the pig (NCRP 1999). Assuming the applicability of the LQ model of cell survival and an alpha/beta ratio in that model of 3 Gy for late damage to the skin, the NCRP estimated an acute dose of about 17 Gy for 50% probability of visible damage to the skin and a threshold of 10.5 Gy. Extrapolation of data for thinning of dermis after the <sup>90</sup>Sr/<sup>90</sup>Y irradiation of pig skin suggested a similar threshold dose of about 10 Gy (NCRP 1999).

Twenty percent dermal thinning was produced with 50% probability following large area exposures to <sup>90</sup>Sr/<sup>90</sup>Y beta rays that produced doses above 12 Gy at a depth of 16 μm in pig skin (Hopewell 1991; NCRP 1999). Higher doses were required for lower energy beta particles. From this it was concluded that the critical depth in tissue for this effect was 300–500 μm (ICRP 1991a). For doses from large area <sup>90</sup>Sr/<sup>90</sup>Y beta ray sources, the 12 Gy dose at 16 μm depth is reduced to about 3.75 Gy at 400 μm depth. Using this depth and dose, and radial dose predictions from the modified VARSKIN Mod2 code, an upper limit on the size of such an effect was estimated. It is recognized that repair processes such as cell division

and migration may fill in the small lesions predicted here and reduce their size and probability of occurrence.

## RESULTS

### Analysis of stochastic risks

The National Council on Radiation Protection and Measurements and the International Commission on Radiological Protection have reviewed the risks of cancer induction due to exposure of the skin to ionizing radiation (NCRP 1989, 1999; ICRP 1991a). In Report 130, the NCRP projected lifetime risks based on the excess relative risk model, since that model gives more conservative (i.e., larger) risk projections than the excess additive risk model. The updated risks given in NCRP Report 130 (1999) are very similar to those reported earlier in NCRP Report 106 (1989) and ICRP Publication 59 (1991a), from which the ICRP derived its tissue weighting factor for skin. The ICRP estimated an excess relative risk (ERR) of 61% per Sv for UVR-exposed skin (face, neck, and arms) and 0.5% per Sv for UVR-shielded skin. In Report 130, the NCRP also estimated an ERR of 61% per Sv for UVR-exposed skin and 1.4% per Sv for UVR-shielded skin. The natural incidence rates for total skin cancers to which these relative rates apply are 90% occurrence at UVR-exposed areas of skin and 10% at UVR-shielded areas of skin.

The ICRP (1991b) and NCRP (1993) also indicated that the weighting factor of 0.01 used to convert skin dose equivalent to effective dose was still appropriate. This factor was applied by the NCRP to estimate effective dose and stochastic effects from hot particles. Thus, the estimated effective dose for a 0.5 Sv exposure to the skin of the whole body is

$$\text{Effective dose} = 0.5 \text{ Sv} \times 0.01 = 5 \times 10^{-3} \text{ Sv.}$$

Based on life-table analyses and an assumed minimum cancer-induction period of 10 y, the ICRP (1991a) estimated an excess fatal cancer probability of  $2 \times 10^{-4}$  per Sv for doses evenly spread over ages 18–64 y. Thus, the mortality risk estimate for skin cancers due to a 0.5 Sv exposure to the skin of the whole body is

$$\begin{aligned} \text{Fatal skin cancer risk} &= (0.5 \text{ Sv}) \times (2 \times 10^{-4} \text{ Sv}^{-1}) \\ &= 1 \times 10^{-4}. \end{aligned}$$

Both ICRP Publication 59 (ICRP 1991a) and ICRP Publication 60 (ICRP 1991b) indicate that the ratio of non-fatal skin cancers to fatal skin cancers is a factor of about 490; thus the estimate of non-fatal cancers due to a 0.5 Sv exposure to the skin of the whole body is

$$\begin{aligned} \text{Non-fatal skin cancer risk} &= 490 \times 1 \times 10^{-4} \\ &= 4.9 \times 10^{-2}. \end{aligned}$$

It is important to note that the UVR-exposed areas of skin are much more susceptible to radiation induced skin cancer than are the UVR-shielded areas. Using the NCRP (1999) updated analysis of relative risks to exposed and shielded areas of skin, the ratio of relative

<sup>‡</sup> Personal communication, J. S. Durham; 1999.

increases is 61% (exposed) to 1.4% (shielded) = 44. In addition, the relative natural rates are 90% (exposed) and 10% (shielded). Finally, the ratio of areas exposed, for uniform skin of the whole body exposures, is  $15,000/3,000 = 5$ . Thus, for uniform exposures the ratio of excess cancer induced in  $1 \text{ cm}^2$  UVR-exposed skin to that in  $1 \text{ cm}^2$  UVR-shielded skin is the product of these three ratios or  $44 \times 9 \times 5 = 1,980$ . These ratios also indicate that the risks due to exposure to skin of the whole body are almost entirely due to risks to UVR-exposed skin. Therefore, the effective dose and risks due to exposure of the  $3,000 \text{ cm}^2$  of UVR exposed skin are approximately the same as the effective dose and risks for exposure to skin of the whole body. These effective doses and risks are summarized in rows one and two of Table 1.

The ICRP and NCRP also used relative areas of skin of the whole body ( $18,000 \text{ cm}^2$ ), UVR-exposed skin ( $3,000 \text{ cm}^2$ ) and UVR-shielded skin ( $15,000 \text{ cm}^2$ ) to arrive at area-weighted risks. The weighting factor for average dose to  $10 \text{ cm}^2$  of skin is the ratio of that area to the area of the skin of the whole body. Thus the area-weighted effective dose and risks due to a uniform dose of  $0.5 \text{ Sv}$  to  $10 \text{ cm}^2$  of average (UVR-exposed and UVR-shielded) skin are

$$\begin{aligned} \text{Effective dose} &= 0.5 \text{ Sv} \times (10/18,000) \times 0.01 \\ &= 2.8 \times 10^{-6} \text{ Sv}. \end{aligned}$$

$$\begin{aligned} \text{Fatal skin cancer risk} &= 0.5 \text{ Sv} \times 2 \times 10^{-4} \text{ Sv}^{-1} \\ &\quad \times 10/18,000 \\ &= 5.6 \times 10^{-8}. \end{aligned}$$

$$\begin{aligned} \text{Non fatal skin cancer risk} &= 490 \times 5.6 \times 10^{-8} \\ &= 2.7 \times 10^{-5}. \end{aligned}$$

The effective dose and risks for a uniform dose of  $0.5 \text{ Sv}$  to the  $10 \text{ cm}^2$  of UVR-exposed skin are

$$\begin{aligned} \text{Effective dose} &= 0.5 \text{ Sv} \times (10/3,000) \times 0.01 \\ &= 1.7 \times 10^{-5} \text{ Sv}. \end{aligned}$$

$$\begin{aligned} \text{Fatal skin cancer risk} &= 0.5 \text{ Sv} \times 2 \times 10^{-4} \text{ Sv}^{-1} \\ &\quad \times 10/3,000 \\ &= 3.3 \times 10^{-7}. \end{aligned}$$

$$\begin{aligned} \text{Non-fatal skin cancer risk} &= 490 \times 3.3 \times 10^{-7} \\ &= 1.6 \times 10^{-4}. \end{aligned}$$

The effective dose and risks for a uniform dose of  $0.5 \text{ Sv}$  to  $10 \text{ cm}^2$  of UVR-shielded skin are a factor of 1,980 less than for UVR-exposed skin, or

$$\begin{aligned} \text{Effective dose} &= 1.7 \times 10^{-5} \text{ Sv} \times 1/1,980 \\ &= 8.6 \times 10^{-9} \text{ Sv}. \end{aligned}$$

$$\text{Fatal cancer risk} = 3.3 \times 10^{-7} \times 1/1,980 = 1.7 \times 10^{-10}.$$

$$\begin{aligned} \text{Non-fatal cancer risk} &= 1.6 \times 10^{-4} \times 1/1,980 \\ &= 8.1 \times 10^{-8}. \end{aligned}$$

When expressed as risk per unit area exposed the risks for UVR-exposed skin are

$$\begin{aligned} \text{Fatal cancer risk} &= 2 \times 10^{-4} \text{ Sv}^{-1}/3,000 \text{ cm}^2 \\ &= 6.7 \times 10^{-8} \text{ Sv}^{-1} \text{ cm}^{-2}. \end{aligned}$$

$$\begin{aligned} \text{Non-fatal cancer risk} &= 6.7 \times 10^{-8} \text{ Sv}^{-1} \text{ cm}^{-2} \times 490 \\ &= 3.3 \times 10^{-5} \text{ Sv}^{-1} \text{ cm}^{-2}. \end{aligned}$$

When expressed as risk per unit area exposed, the risks for UVR-shielded skin are

$$\begin{aligned} \text{Fatal cancer risk} &= 6.7 \times 10^{-8}/1,980 \\ &= 3.4 \times 10^{-11} \text{ Sv}^{-1} \text{ cm}^{-2}. \end{aligned}$$

$$\begin{aligned} \text{Non-fatal cancer risk} &= 3.3 \times 10^{-5}/1,980 \\ &= 1.7 \times 10^{-8} \text{ Sv}^{-1} \text{ cm}^{-2}. \end{aligned}$$

Results from the above estimates are summarized in Table 1.

#### Analysis of deterministic risks

Deterministic risks were estimated for  $0.5 \text{ Sv}$  to (a) skin of the whole body, (b) UVR-exposed skin, (c) average dose to  $1 \text{ cm}^2$  from a hot particle or uniform skin contamination on either UVR-exposed or UVR-shielded skin, and (d) to  $10 \text{ cm}^2$  from uniform skin contamination on UVR-exposed or UVR-shielded skin. In none of these cases was the  $2 \text{ Gy}$  (at  $70 \mu\text{m}$  depth) erythema threshold exceeded. Therefore, no erythema was predicted.

For a skin dose of  $0.5 \text{ Sv}$  averaged over  $10 \text{ cm}^2$  from fuel or  $^{60}\text{Co}$  hot particles, erythema areas of from  $0.15 \text{ cm}^2$  (for  $^{60}\text{Co}$  hot particles,  $0.65 \text{ cm}^2$  (for  $^{60}\text{Co}$ , 3 mm off skin) were estimated. The only absorption included in this and subsequent evaluations is that of air. These results are shown in Table 1.

Maximum likely erythema areas predicted by this method for point sources of  $^{60}\text{Co}$ , activated fuel particles, and  $^{106}\text{Rh}$  (average beta particle energy =  $1.46 \text{ MeV}$ ) at distances of 0 to 30 mm off of skin were also calculated. These results are shown in Table 2 along with comparisons of results for a dose of  $5 \text{ Sv}$  averaged over  $1 \text{ cm}^2$ . Note that a limit based on  $5 \text{ Sv}$  ( $500 \text{ rad}$ ) averaged over  $1 \text{ cm}^2$  could result in much larger skin erythemas than a limit based on  $0.5 \text{ Sv}$  ( $50 \text{ rad}$ ) averaged over  $10 \text{ cm}^2$  for particles off the skin. This is because, for particles off the skin, the areas surrounding the  $1 \text{ cm}^2$  area that receives the highest dose ( $500 \text{ rad}$  averaged over  $1 \text{ cm}^2$ ) also receive very high doses. These areas would need to be restricted by the  $50 \text{ rad}$  limit for skin of the whole body in order to avoid large areas of erythema induction.

The largest expected erythema area ( $2.5 \text{ cm}^2$ ) would be produced by contamination that was spread uniformly

**Table 1.** Estimated risks and effective doses for exposures of skin at current and proposed unified skin dose limits.

Exposure, skin dose equivalent	Probability of effect	Effective dose <sup>a</sup>
0.5 Sv to skin of the whole body (18,000 cm <sup>2</sup> )	4.9 × 10 <sup>-2</sup> non-fatal cancers 1 × 10 <sup>-4</sup> fatal cancers No erythema, dermal thinning, acute necrosis or ulceration	5 × 10 <sup>-3</sup> Sv  (500 mrem)
0.5 Sv to UVR-exposed skin (3,000 cm <sup>2</sup> )	4.9 × 10 <sup>-2</sup> non-fatal cancers 1 × 10 <sup>-4</sup> fatal cancers No erythema, dermal thinning, acute necrosis or ulceration	5 × 10 <sup>-3</sup> Sv  (500 mrem)
0.5 Sv to 1 cm <sup>2</sup> from a hot particle or uniform skin contamination on UVR-exposed skin	<1.6 × 10 <sup>-5</sup> non-fatal cancers <3.3 × 10 <sup>-8</sup> fatal cancers 0.25 cm <sup>2</sup> erythema, <0.15 cm <sup>2</sup> dermal thinning, no acute necrosis or ulceration	1.7 × 10 <sup>-6</sup> Sv  (0.17 mrem)
0.5 Sv to 1 cm <sup>2</sup> from a hot particle or uniform skin contamination on UVR-exposed skin	<8.3 × 10 <sup>-9</sup> non-fatal cancers <1.7 × 10 <sup>-11</sup> fatal cancers 0.25 cm <sup>2</sup> erythema, <0.15 cm <sup>2</sup> dermal thinning, no acute necrosis or ulceration	8.6 × 10 <sup>-10</sup> Sv  (8.6 × 10 <sup>-5</sup> mrem)
2 Sv to 2.5 cm <sup>2</sup> from uniform skin contamination on UVR-exposed skin (0.5 Sv average over 10 cm <sup>2</sup> )	<1.6 × 10 <sup>-4</sup> non-fatal cancers <3.3 × 10 <sup>-7</sup> fatal cancers <2.5 cm <sup>2</sup> erythema, no dermal thinning, acute necrosis or ulceration	1.7 × 10 <sup>-5</sup> Sv  (1.7 mrem)
0.5 Sv to 10 cm <sup>2</sup> from a <sup>106</sup> Rh hot particle or uniform skin contamination on UVT-exposed skin	<1.6 × 10 <sup>-4</sup> non-fatal cancers <3.3 × 10 <sup>-7</sup> fatal cancers <2.5 cm <sup>2</sup> erythema, <0.15 cm <sup>2</sup> dermal thinning, <0.05 acute necrosis or ulceration	1.7 × 10 <sup>-5</sup> Sv  (1.7 mrem)
0.5 Sv to 10 cm <sup>2</sup> from a fuel hot particle on UVT-exposed skin	<1.6 × 10 <sup>-4</sup> non-fatal cancers <3.3 × 10 <sup>-7</sup> fatal cancers 0.15 cm <sup>2</sup> erythema, <0.06 cm <sup>2</sup> dermal thinning, 0.05 acute necrosis or ulceration	1.7 × 10 <sup>-5</sup> Sv  (1.7 mrem)
0.5 Sv to 10 cm <sup>2</sup> from activated fuel hot particle 0.4 mm off UVR-exposed skin	<1.6 × 10 <sup>-4</sup> non-fatal cancers <3.3 × 10 <sup>-7</sup> fatal cancers 0.28 cm <sup>2</sup> erythema <0.08 cm <sup>2</sup> dermal thinning 0.1 acute necrosis or ulceration	1.7 × 10 <sup>-5</sup> Sv  (1.7 mrem)
0.5 Sv to 10 cm <sup>2</sup> from a <sup>60</sup> Co hot particle 0.4 mm off UVR-exposed skin	<1.6 × 10 <sup>-4</sup> non-fatal cancers <3.3 × 10 <sup>-7</sup> fatal cancers 0.18 cm <sup>2</sup> erythema <0.01 cm <sup>2</sup> dermal thinning 0.1 acute necrosis or ulceration	1.7 × 10 <sup>-5</sup> Sv  (1.7 mrem)

<sup>a</sup> Based on stochastic risks due to beta particles relative to stochastic risks for exposure of skin of the whole body.

over an area such that the entire area received the 2 Gy threshold dose, i.e., 0.5 Gy × 10 cm<sup>2</sup>/2 Gy = 2.5 cm<sup>2</sup>. For doses spread over smaller areas, the erythema would be somewhat more pronounced but not likely to extend much beyond the irradiated area.

For dermal thinning, the threshold was assumed to be 3.75 Gy at depth 400 μm based on data in NCRP Report 130 (NCRP 1999) and ICRP 59 (ICRP 1991a). Using the updated version of VARSKIN Mod2 calculations were made for each exposure scenario to determine the radius at which dose at 400 μm depth would be 3.75 Gy. From this radius the maximum likely diameter for dermal thinning was estimated. Dermal thinning estimates were made for point sources of <sup>60</sup>Co, activated fuel, and <sup>106</sup>Rh particles at distances 0 to 30 mm off the skin. For <sup>90</sup>Sr-<sup>90</sup>Y, 10% probability (ED<sub>10</sub>) and 90% probability (ED<sub>90</sub>) doses were about 1/2 and two times, respectively, the values for 50% probability (ED<sub>50</sub>)

(NCRP 1999). Assuming these same ratios apply for other radionuclides, the skin areas predicted to experience dermal thinning for doses of 5 Gy averaged over 1 cm<sup>2</sup> and 0.5 Gy averaged over 10 cm<sup>2</sup> at depth 70 μm were calculated. For a dose limit of 0.5 Gy averaged over 10 cm<sup>2</sup>, the maximum estimated dermal thinning area at ED<sub>50</sub> was 0.15 cm<sup>2</sup> for point sources of <sup>106</sup>Rh at 0 to 0.2 mm off the skin; 0.01 cm<sup>2</sup> for <sup>60</sup>Co particles 0.2 to 0.4 mm off the skin, and about 0.06 to 0.08 cm<sup>2</sup> for activated fuel particles 0 to 1 mm off the skin. Somewhat larger areas are predicted for a dose of 5 Gy averaged over 1 cm<sup>2</sup>. These results are summarized in Table 3.

For uniform contamination the maximum size of dermal thinning would occur for high energy beta particle emissions on the skin. For contamination with <sup>106</sup>Rh, an area of skin of about 0.5 cm<sup>2</sup> could suffer dermal thinning for contamination uniformly spread over 0.5 cm<sup>2</sup> using the unified dose limit of 0.5 Sv averaged over

**Table 2.** Estimated maximum likely erythema areas.<sup>a</sup> (Uniform skin contamination yields erythema areas up to 2.5 cm<sup>2</sup> for contamination on skin spread uniformly over the same area for a dose of 0.5 Gy averaged over 10 cm<sup>2</sup>.)

Source	Air gap (mm)	Erythema For 5 Gy cm <sup>-2</sup> Limit	Area (cm <sup>2</sup> ) For 0.5 Gy (10 cm <sup>2</sup> ) <sup>-1</sup> Limit
<sup>60</sup> Co	0	0.01	0.01
	0.2	0.09	0.09
	0.4	0.18	0.18
	1	0.41	0.40
	3	2.92	0.65
	10	4.37	0.00
	15	8.04	0.00
Fuel	30	26.41	0.00
	0	0.15	0.15
	0.2	0.21	0.21
	0.4	0.32	0.28
	1	0.50	0.38
	3	1.13	0.56
	10	4.91	0.00
<sup>106</sup> Rh	15	9.62	0.00
	30	26.41	0.00
	0	0.28	0.28
	0.2	0.41	0.31
	3	1.37	0.41
	10	6.07	0.00
	15	11.82	0.00
	30	44.16	0.00

<sup>a</sup> Based on assumed 2 Gy at 70 μm depth erythema threshold (NCRP 1999).

10 cm<sup>2</sup>. With the present limit of 0.5 Sv averaged over 1 cm<sup>2</sup>, the maximum dermal thinning estimated for uniform <sup>106</sup>Rh contamination is about 0.17 cm<sup>2</sup> for contamination spread over the same area.

Dermal thinning areas for ED<sub>10</sub> were generally about two times those for ED<sub>50</sub>, but as much as 20 times higher for <sup>106</sup>Rh at 3 mm off the skin (0.41 cm<sup>2</sup> compared to 0.02 cm<sup>2</sup>). Conversely, the results for ED<sub>90</sub> were generally about 1/2 those for ED<sub>50</sub>, as shown in Table 3.

The probability of acute necrosis or acute ulceration was determined from data in NCRP Report 130 (NCRP 1999) and work of Kaurin et al. (1997). No acute necrosis or ulceration was predicted for any of the uniform exposure scenarios, or for doses of 0.5 Sv at 70 μm depth, averaged over 10 cm<sup>2</sup>, from fuel or <sup>60</sup>Co hot particles 3 mm off of skin. For this dose from activated fuel particles on skin the probability of an acute necrosis or ulcer was 0.05. For <sup>106</sup>Rh hot particles on skin the probability is expected to be somewhat less since the energy is spread over a somewhat larger area due to the higher average beta particle energy. For <sup>60</sup>Co or activated fuel particles 0.4 mm off skin, the probability was 0.1. These results are summarized in Table 1.

Effective doses were calculated using the skin weighting factor of 0.01 for skin of the whole body and area weighted values for 10 cm<sup>2</sup> exposure scenarios. Results for exposures of 0.5 Sv average dose to 10 cm<sup>2</sup> of skin are 17 μSv (1.7 mrem). These results can be compared to the value of 5 mSv (500 mrem) effective

dose for exposure to skin of the whole body at the limit of 0.5 Sv.

### Risks for higher LET particles

A limit expressed in Sv implies that it applies to various types of radiation after use of appropriate radiation weighting quality factors (Q values) for converting dose in Gy (or rad) to Sv (or rem). The ICRP (1989) has reviewed data on the relative biological effectiveness (RBE) of various radiations. For early responses to 2 and 2.5 MeV neutrons incident on pig and mouse skin, the maximum RBE (RBE<sub>m</sub>) was 6.5 to 8.7. The RBE<sub>m</sub> for early response in humans for 7.5–20 MeV neutrons was 4.5 to 4.6 based on linear quadratic extrapolations to low doses. If dose is multiplied by the usual Q of 10 to 20 to arrive at a value in Sv, it will overestimate the risk since the RBE would have been less than 10 to 20.

Since for heavy ions the highest RBE occurs at the lowest doses, the non-uniform exposures from hot particles and other sources would yield a lower average or effective RBE than would apply for the same energy spread uniformly over a larger area. Also, for doses averaged over 10 cm<sup>2</sup>, the more non-uniform the dose in that area, the lower the expected RBE. For this reason it is safe to express the limit in Sv and have it apply to all types of ionizing radiation.

## DISCUSSION

The stochastic risks and the effective dose for uniform or non-uniform exposures of 0.5 Sv averaged over 10 cm<sup>2</sup> are about a factor of 300 lower than the stochastic risks and the effective dose attributable to receiving dose to the skin of the whole body at the present skin dose limit. The possible detriment due to a 2.5 cm<sup>2</sup> area of erythema from uniform skin contamination or at most a 0.5 cm<sup>2</sup> area of dermal thinning should be considered with reference to the stochastic risks associated with this dose (<1.6 × 10<sup>-4</sup> non-fatal cancers and <3.3 × 10<sup>-7</sup> fatal cancers). Assuming the probability of the erythema and dermal thinning is 0.5 at the dose limit, occurrence of these effects would be about 312 times more frequent than occurrence of non-fatal skin cancers at the dose limit, and much less for doses below the limit.

At nuclear power plants experiencing hot particle problems, workers are often required to leave their work on an hourly basis to check for hot particle contamination. When work is in areas with whole-body dose rates above about 100 μSv per hour (10 mrem h<sup>-1</sup>), this may lead to unproductive effective doses of many rem for each hot particle exposure avoided. With a limit based on averaging dose over 10 cm<sup>2</sup> instead of 1 cm<sup>2</sup> many fewer exits and reentries would be needed. Based on the likely savings of much more than 17 μSv (1.7 mrem) unproductive whole-body dose per hot particle exposure avoided at nuclear power plants, the proposed unified skin dose limit seems clearly worthwhile for minimizing risk in the control of hot particles.

**Table 3.** Estimated dermal thinning areas (cm<sup>2</sup>) based on doses at 400 μm depth in skin.<sup>a</sup>

Source	Air gap (mm)	ED <sub>50</sub> For 5 Gy cm <sup>-2</sup> Limit	ED <sub>50</sub> For 0.5 Gy (10 cm <sup>2</sup> ) <sup>-1</sup> Limit	ED <sub>10</sub> For 5 Gy cm <sup>-2</sup> Limit	ED <sub>10</sub> For 0.5 Gy (10 cm <sup>2</sup> ) <sup>-1</sup> Limit	ED <sub>90</sub> For 5 Gy cm <sup>-2</sup> Limit	ED <sub>90</sub> For 0.5 (10 cm <sup>2</sup> ) <sup>-1</sup> Limit
Point sources							
<sup>60</sup> Co	0	0.00	0.00	0.01	0.01	0.00	0.00
	0.2	0.01	0.01	0.01	0.01	0.00	0.00
	0.4	0.01	0.01	0.01	0.01	0.00	0.00
	1	0.00	0.00	0.02	0.02	0.00	0.00
	3	0.00	0.00	0.00	0.00	0.00	0.00
	10	0.00	0.00	0.00	0.00	0.00	0.00
	15	0.00	0.00	0.00	0.00	0.00	0.00
	30	0.00	0.00	0.00	0.00	0.00	0.00
Fuel	0	0.06	0.06	0.11	0.11	0.03	0.03
	0.2	0.08	0.07	0.14	0.13	0.04	0.03
	0.4	0.09	0.08	0.15	0.14	0.05	0.04
	1	0.09	0.07	0.23	0.18	0.03	0.02
	3	0.04	0.00	0.31	0.08	0.00	0.00
	10	0.00	0.00	0.45	0.00	0.00	0.00
	15	0.00	0.00	0.37	0.00	0.00	0.00
	30	0.00	0.00	1.54	0.00	0.00	0.00
<sup>106</sup> Rh	60	0.00	0.00	0.00	0.00	0.00	0.00
	0	0.15	0.15	0.28	0.28	0.07	0.07
	0.2	0.21	0.15	0.38	0.29	0.10	0.08
	3	0.56	0.02	1.49	0.41	0.10	0.00
	10	1.39	0.00	0.00	0.00	0.00	0.00
1 cm <sup>2</sup> uniform contamination	15	2.95	0.00	0.00	0.00	0.00	0.00
	30	2.33	0.00	0.00	0.00	0.00	0.00
<sup>60</sup> Co	10	0.00	0.00	0.00	0.00	0.00	0.00
Fuel	10	0.00	0.00	0.00	0.00	0.00	0.00
<sup>106</sup> Rh	10	1.66	0.00	7.35	0.00	0.00	0.00

<sup>a</sup> ED<sub>50</sub> = 50% probability of 20% reduction in dermal thickness.

ED<sub>10</sub> = 10% probability of 20% reduction in dermal thickness.

ED<sub>90</sub> = 90% probability of 20% reduction in dermal thickness.

Normal dermal thickness is about 10 times the related epidermal thickness, or 1 to 2 mm.

Results are based on extrapolations from results of Hopewell (1991) for <sup>90</sup>Sr/<sup>90</sup>Y sources of 5 to 40 mm diameter and calculations with an updated VARSKIN Mod2 code.

For 0.5 Gy (10 cm<sup>2</sup>)<sup>-1</sup>, dermal thinning of areas up to 0.5 cm<sup>2</sup> are estimated for uniform contamination with <sup>106</sup>Rh on skin over the same area, and smaller dermal thinning areas for contamination off the skin.

In addition to benefits to workers who avoid unproductive whole-body dose, or who are less likely to need transfer due to exposures above the skin dose limit, there are other benefits to licensees. These include more time to devote to other safety issues; less unproductive surveying, analysis and reporting of work areas; and less concerns over liability issues related to contamination and hot particle exposures. It would be interesting to compare the regulations and restrictions imposed on industry in other than nuclear activities to determine how minor deterministic effects such as small paper cuts or bruises are regulated and enforced. This comparison may aid in judging the justification of a limit which permits minor effects without serious regulatory consequences.

Comparisons of unproductive doses that were received before the implementation of the U.S. Nuclear Regulatory Commission regulatory enforcement policy (NRC 1990), which permits an exposure of 75 μCi h (about 10<sup>10</sup> beta particles), with those being received more recently may provide an indication of the unproductive dose that is currently being avoided and might be avoided in the future if the proposed limit of 0.5 Sv

averaged over 10 cm<sup>2</sup> is implemented. The gain should be similar because the dose to 10 cm<sup>2</sup> of skin is approximately 0.5 Sv for an exposure of 75 μCi h for a hot particle on skin.

For workers who are threatened with job layoff or transfer to less productive work due to exposure to hot particles or skin contamination, the monetary value of dose averted may be considered in evaluating tradeoffs. The monetary value of the 17 μSv effective dose attributed to stochastic risks, for exposures at the unified skin dose limit, is only valued at about \$3.40 (at \$200,000/person-Sv). This cost seems trivial in comparison to the value of a person's job, or even the costs and social impacts of having to work in a less productive or desirable activity for months or years if the limit is exceeded.

An important feature of the new regulation should be the conversion of skin doses to equivalent doses based on proportion of skin exposed compared to skin of the whole body, or to UVR-exposed area of skin, as was done above. Thus, the exposure of 10 cm<sup>2</sup> of UVR-exposed skin to 0.5 Sv would be assigned an effective

dose of about 17  $\mu\text{Sv}$  for stochastic effects plus an equivalent dose for deterministic effects that may be a few times this value. This would make it clear that these partial body exposures are much less detrimental than an equal exposure to the whole body or to the skin of the whole body.

### CONCLUSION

Risks due to exposures to skin for a unified skin dose limit of 0.5 Sv average dose over 10  $\text{cm}^2$  from hot particles and other sources of non uniform exposure were analyzed. Results show that the effective dose from these exposures would be approximately 17  $\mu\text{Sv}$  (1.7 mrem) at the unified skin dose limit. This effective dose would imply an estimated risk of  $<3.3 \times 10^{-7}$  fatal skin cancers,  $<1.6 \times 10^{-4}$  non-fatal skin cancers, erythema induction to an area of  $<2.5 \text{ cm}^2$  of skin, dermal thinning to  $<0.5 \text{ cm}^2$  of skin, and 0.1 probability of barely detectable acute necrosis or ulceration.

It is concluded that non-uniform dose exposures at the unified skin dose limit would entail much less (about a factor of 300) stochastic risk than the risks at the current limit for skin of the whole body, and would allow in addition only minor deterministic detriments. The present skin dose limit has the potential for induction in skin of 0.25  $\text{cm}^2$  of erythema and  $<0.15 \text{ cm}^2$  of dermal thinning for uniform contamination spread over comparable areas. The added potential deterministic detriment using the unified dose limit is judged to be less serious than the potential detriment due to whole-body dose that could be avoided with the unified limit at nuclear power plants experiencing hot particle problems.

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