Inclusion of Bragg-Gray stopping-power ratios in the EGSnrc user-code SPRRZnrc

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Abstract

This report describes the inclusion of Bragg-Gray stopping-power ratios in the EGSnrc user-code SPRRZnrc which already calculates Spencer-Attix stopping-power ratios in cylindrical geometries. In addition it describes a minor change in the calculation of Spencer-Attix stopping-power ratios due to changes in EGSnrc in July 2005. The report includes a description of the inputs needed to use the new option and a variety of tests done to verify the new coding.

Table 3 was revised in July 2008 due to previous use of an incorrect I value for one material, but relative values are unchanged.

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I. Introduction

The EGSnrc-based[1] user-code SPRRZnrc,[2] which is distributed along with EGSnrcMP system, calculates Spencer-Attix restricted mass collision stopping-power ratios in each region in a cylindrical RZ geometry. This code utilizes an "on-the-fly" scoring technique.[3] Although Spencer-Attix cavity theory[4,5] is considered more accurate than Bragg-Gray cavity theory, the latter is sometimes still applied in radiation dosimetry studies.[6–10] We have therefore modified the SPRRZnrc code to include the Bragg-Gray stopping-power ratio.

In this report, we describe the implementation of Bragg-Gray theory in the existing SPRRZnrc code and the basic tests carried out to ensure that the code is working, including comparisons to published results to confirm that the existing coding of the Spencer-Attix stopping-power ratio is undisturbed.

II. Bragg-Gray cavity theory

The Bragg-Gray stopping-power ratio of medium m_1 to medium m_2 is given by:

$$\left(\frac{\overline{S}}{\rho}\right)^{m_1}_{m_2} = \frac{\int_0^{E_{max}} \Phi_P [S/\rho]_{m_1} dE}{\int_0^{E_{max}} \Phi_P [S/\rho]_{m_2} dE} \tag{1}$$

where Φ_P is the differential fluence spectrum of primary charged particles in medium m_1 in the region of interest (i.e.Φ_PdE is the fluence of primary charged particles in medium m_1 with energies between E and E+dE) and $[S/\rho]_{m_1}$ and $[S/\rho]_{m_2}$ are the unrestricted mass collision stopping-powers of media m_1 and m_2 respectively.

In a photon beam, Φ_P includes photon-generated electrons and positrons. The knock-on electrons (δ-rays) produced by these charged particles are not part of Φ_P. In a charged particle beam, the δ-rays are not part of Φ_P. In a given incident beam (electron, positron or photon), bremsstrahlung photons can always be created by charged particles. Bremsstrahlung photons can be those generated by both primary charged particles and δ-rays. Φ_P includes charged particles generated by bremsstrahlung photons generated by primary charged particles. In general, irrespective of the incident beam, the knock-on electrons (δ-rays) produced by charged particles are not part of Φ_P. The definition of primary fluence is not strictly unique since there is some dependence, in the calculations at least, on what is the lowest energy knock-on electron considered explicitly in the calculation (variable AE, which is total energy). Fortunately, as will be shown in section V.A., the effect of these variations is negligible in the calculation of the Bragg-Gray stopping-power ratios.

Sometimes in the literature (for example the ISO beta report[6]) it is assumed that in Bragg-Gray theory the δ-rays stop where they are generated. Actually, in Bragg-Gray theory all that is needed is charged particle equilibrium of the δ-rays. Strictly speaking the integral in eqn(1) extends to zero kinetic energy but the fluence of charged particle primaries below energy AE=ECUT is negligible and in practice the integral starts from AE-0.511.

III. The new coding

III.A. Bragg-Gray stopping-power ratio calculation in the SPRRZnrc code

The basic approach of scoring the total dose deposited in two different media, as represented by the numerator and denominator in equation (1) is as follows. The transport of particles takes place in the transport medium, m_1, not in the detector medium, m_2 i.e. there is no cavity in the calculation. Photons and charged particles are transported down to the energies of AP=PCUT and AE=ECUT respectively. Modes of energy deposition considered in the Spencer-Attix SPRRZnrc code are from 4 distinct types of events, called, α, β, γ and δ events (this δ is different from δ-rays) in the SPRRZnrc manual.[2]

α **events** are those events in which energy is deposited by a charged particle in a step with the total energy entirely above ECUT.

γ **events** are those events in which the charged particle starts a step with its energy greater than ECUT and ends with an energy below ECUT. Recent changes in EGSnrc (July 2005) mean that charged particles basically stop their step when their energy is 0.99*AE, which is always 0.99*ECUT in SPRRZnrc. In the past these events ended at whatever energy below ECUT that the transport had determined.

δ **events** are those events in which a charged particle or photon is being terminated because its energy is below the cutoffs ECUT (total energy) or PCUT (kinetic energy).

β **events** are a subset of δ events, namely those events in which charged particles and photons are being discarded after being created with their energy initially below ECUT or PCUT. The β events are not scored in the B-G or S-A integrals but are included in the total dose. This is somewhat problematic when calculating stopping-power ratios (for example for low-energy photon beams) as discussed by Borg et al.[11]

While scoring energy deposition, for Spencer-Attix stopping-power ratios no distinction is made between the primary and secondary electrons as opposed to Bragg-Gray stopping-power ratios.

We describe below how energy deposition is scored for Bragg-Gray stopping-power ratios from different events. We introduce the subscript 'P' to indicate quantities associated with primary charged particles.

Let $\text{EDEP}_{m_1,P}$ be the energy deposited by a primary charged particle in the medium m_1 from α_P, γ_P or δ_P events. For α and γ events, the code initially calculates EDEP_{m_1} for each step based on the linear restricted stopping powers of the medium m_1, L(E)_{m1}. The total pathlength on that step is given by $\text{EDEP}_{m_1}/\text{L(E)}_{m1}$ and hence, if considering primary particles only, the energy deposition is given by:

$$EDEP_{m1,P} = S(E)_{m1}(EDEP_{m_1}/L(E)_{m1}) \tag{2}$$

where S(E)_{m1} is the linear unrestricted stopping-power of medium m_1. To calculate the energy deposition in medium m_2 from primaries we sum $\text{EDEP}_{m1,P}$ times the ratio of unrestricted collision stopping-powers of m_2 to m_1:

$$EDEP_{m_2,P} = EDEP_{m_1,P}\frac{S(E)_{m_2}}{S(E)_{m_1}} \tag{3}$$

where we have not yet defined the energy E at which to evaluate the stopping powers.

For α events, E is taken as the mid-point energy of the step, which very nearly matches the energy used by EGSnrc to establish EDEP_{m_1} (although EGSnrc uses a more complex algorithm, the differences in the stopping powers is negligible). For γ events, E is similarly the mid-point energy of the step to Δ, since these steps stop at 0.99*AE.

For the same medium, the values of restricted and unrestricted stopping-powers are the same when evaluated at E=Δ. Therefore, for δ_P events, ie, discards or stoppers, $\text{EDEP}_{m_1,P}$=$\text{EDEP}_{m_1} = E_\delta$ where E_δ is the kinetic energy of the primary charged particle which is being discarded. The value of E used in equation 3 in this case is Δ. The ratio of stopping-powers reflects the fact that of the number of particles actually stopping would be different in the two media. As discussed elsewhere (see section III.E in ref[12]) there are conceptual problems on this point concerning electrons created below Δ but the effects are not critical for beams in which we are interested in the stopping-power ratios.

When doing stopping-power ratio calculations it is imperative not to use range rejection in any region where the stopping-power ratio is wanted since range rejection seriously distorts the electron fluence spectrum. The SPRRZnrc code ensures this is the case, even if the user asks for range rejection.

III.B. Changes to S-A calculations in SPRRZnrc

For γ events, ie, events in which the electron energy falls across AE (Δ), EGSnrc gives (since July 2005) the energy deposition in material m_1 as $\mathrm{EDEP}_{m_1,\gamma} = E_\gamma - 0.99 \times \Delta$, where E_γ is the initial kinetic energy of the charged particle of the γ events. In other words, the electron step length is arranged to terminate at an energy of $0.99\times\Delta$ (ie the kinetic energy of AE) rather than falling further below the cutoff as it used to do.

In the original version of SPRRZnrc, the energies deposited above and below Δ were handled differently from each other, but with the change in algorithm in EGSnrc, SPRRZnrc has been simplified and now just ignores the small amount of energy deposition below Δ and treats these steps as if they were α events.

As seen below, this appears to make no difference to the calculated stopping-power ratios.

III.C. New media input for the SPRRZnrc code

Preparation of input files for running the new version of the SPRRZnrc code is not significantly different from that of previous version of the SPRRZnrc code although there is a new input value needed:
Include Bragg-Gray spr= yes or no
This is part of the Monte Carlo inputs block of inputs. If it is left out, the default is for just the Spencer-Attix calculation to be done (ie old input files should work).

The previous version of the SPRRZnrc code works with PEGS4 data for n media input with the second medium being the detector material, m_2. The new version of the SPRRZnrc code requires PEGS4 data for $2n$ media to be input. The first set of n media datasets provides restricted stopping-power data for each medium which is used for normal transport and for calculating Spencer-Attix stopping-power ratios. The second medium is still for the detector material, m_2. The second set of datasets for n media includes unrestricted stopping-power data and is used for calculating Bragg-Gray stopping-power ratios. Thus the second set of n media has the same material and density information as that of the first set and differs only in the stopping-power data. Medium (n+2) includes the unrestricted stopping power for the detector material for the Bragg-Gray calculation corresponding to the data for material m_2. The user must provide the media input appropriately in the input file.

A sample input file is given in Appendix A. It calculates on-axis Spencer-Attix and Bragg-Gray stopping-power ratios in water when a broad parallel beam (BPB) of 1 MeV photons is incident on a 1000 cm radius$\times$ 30 cm deep cylinder of water.

In preparation of PEGS4 data sets for Bragg-Gray stopping-power ratios the user must explicitly set IUNRST=1 in the PEGS4 input file. This can not be done from the `egsgui` and so the file must be created manually. The IUNRST=1 option provides a cross section data set (PEGS4 output) that includes just the unrestricted collision stopping powers rather than the sum of the restricted collision and radiative stopping powers generated when IUNRST = 0. The material name must uniquely identify it as having unrestricted stopping powers. The IUNRST=1 input is part of the namelist input for INP (along with NE, AE etc). For more details regarding the IUNRST options, see the EGSnrc manual, chapter 6.[1]

The IUNRST=1 option produces exactly the collision stopping powers required for the Bragg-Gray stopping-power ratio calculation. However, the IUNRST=0 option produces the sum of the restricted radiative and collision stopping powers whereas strictly what we need is the restricted collision stopping power. However, as shown in Appendix B, in water the restricted radiative stopping power is negligible as long as AP = 10 keV or less is used. It is advisable to use AP = 1 keV for all such calculations just to be on the safe side since for high-Z materials there can be a systematic error.

III.D. Input checks in the code

Before the simulation is initiated, SPRRZnrc makes the following checks:

1. Does the PEGS4 cross section data set cover the ranges of energies incident?
2. Is the value of AE the same for the first n media? This is important for Spencer-Attix stopping-power ratios.
3. If Bragg-Gray sprs are requested, are the total number of media an even number? The minimum value of NMED is 4 (2 each for Spencer-Attix and Bragg-Gray).
4. Is IUNRST = 0 (restricted stopping power) and is IUNRST = 1 (unrestricted stopping power) for the first and second set of n media respectively (if Bragg-Gray sprs are requested)?
5. Does the density information of the first and second set of n media match with each other (if Bragg-Gray sprs are requested)?

If any of the above conditions is not fulfilled the program stops, prompting the user to provide proper input.

For different Spencer-Attix stopping-power ratio calculations we may be using PEGS4 data sets with different AE values. However, for the Bragg-Gray part of the calculation one can use an unrestricted stopping power PEGS4 data set with any value of AE less than that being used for the Spencer-Attix calculation (thus it makes sense to use AE=512 keV). This is because the unrestricted stopping power is independent of AE(=ECUT). The program uses the AE(=ECUT) value of the first medium for the Bragg-Gray stopping-power ratio calculations.

At the time of writing this report, the GUI `egsinprz` does not handle the case for Bragg-Gray stopping-power ratios, but if there is sufficient interest it may be implemented.

IV. Verification

IV.A. Comparison to previous results

There are many published studies regarding calculation of water-to-air stopping-power ratios for radiotherapy photon and electron beams.[3,13–17] The work of Malamut et al,[16] Andreo and Brahme[14] and Nahum (quoted in Ref. 3) are based on the electron collision stopping-powers from ICRU Report 35.[5] Malamut *et al.*[16] performed Spencer-Attix and Bragg-Gray water-to-air stopping-power ratio calculations for a variety of photon and electron beam energies for a broad parallel beam geometry using the EGS4[18] user-code SPR. Their approach to calculating stopping power ratios was in two steps. First, the particle fluence spectrum was calculated using the EGS4 user-code FLURZ. Secondly, the stopping-power ratios were calculated off-line by using the code SPR which used EGS4 cross sections.

The studies carried out by Kosunen and Rogers[3] and Andreo[17] are based on the electron collision stopping-powers reported in ICRU Report 37.[19] Kosunen and Rogers used the EGS4 user-code SPRRZ(V5) which is a forerunner of the present SPRRZnrc user-code. SPRRZ was written by Rogers and Bielajew and utilizes the “on-the-fly” technique for stopping-power ratio calculations (quoted in Ref. 3). Duane et al[20] implemented the ICRU Report 37/NBS stopping-powers in the EGS4 code system[18] to use with the above-mentioned user-code.

As we utilize the stopping-powers based on ICRU Report 37[19] in the new version of the SPRRZnrc code, we repeated one particular part of the work done by Kosunen and Rogers, and by Andreo.[17] In the present calculations broad parallel beams of photon with energies between 1 and 40 MeV are incident on a water phantom and on-axis Spencer-Attix and Bragg-Gray water-to-air stopping-power ratios are calculated at a depth of 10 cm. We also repeated these calculations by using the previous version of the SPRRZnrc code so as to ensure that the Spencer-Attix aspect of coding is undisturbed by the introduction of Bragg-Gray coding. In both the investigations AE=ECUT=521 keV is used. Table 1 compares Table 1 the stopping-power ratio values obtained in the present study and the corresponding values calculated by Kosunen and Rogers[3] and Andreo.[17] The agreement is excellent. The values of the Spencer-Attix stopping-power ratio calculated by the new version of the SPRRZnrc code (see Table 1) did not alter the values at all.

Table 2 compares the differences between Spencer-Attix and Bragg-Gray stopping-power ratios as published by Malamut *et al.*[16] using ICRU Report 35 stopping powers to the present differences calculated using ICRU Report 37 stopping powers. These differences should be independent of the stopping powers used. The values presented for 40 MeV are at 15 cm depth in water whereas for the remaining beam energies the values are at 10 cm depth. The differences between the Bragg-Gray and Spencer-Attix stopping-power ratios that are based on ICRU Report 35 stopping-powers are within 0.1% of the corresponding differences that are based on ICRU Report 37 stopping-powers. This implies that the new version of the SPRRZnrc code calculates the Bragg-Gray stopping-power ratios correctly for photon beams. Table 2

Figure 1, presents, as a function of depth, the values of water-to-air Spencer-Attix and Bragg-Gray stopping-power ratios and Spencer-Attix stopping-power ratios based on new and old versions of the SPRRZnrc codes respectively for a broad parallel beam of 20-MeV electrons incident on water. The present values of Bragg-Gray stopping-power ratios are in good agreement with those calculated by Malamut *et al.*[16] which are based on ICRU Report 37[19] electron collision stopping powers. This once again confirms that we have implemented Bragg-Gray theory correctly. The new and old versions of the SPRRZnrc codes produce the same values of Spencer-Attix stopping-power ratios. This confirms that the existing Spencer-Attix coding is undisturbed. However, at the surface the present value of Spencer-Attix stopping-power ratio is greeater than calculated by Malamut *et al.*[16] The difference probably is due to a binning artifact or to the differences in boundary crossing algorithms. Fig 1

V. Discussion

V.A. B-G and S-A sprs for a ^{90}Sr/^{90}Y source

The National Research Council of Canada (NRC) has a primary standard for a ^{90}Sr/^{90}Y beta source based on an extrapolation chamber. In a published study, we benchmarked the experimental response of this primary standard against the Monte Carlo-calculated response.[21] The tissue-to-air stopping-power ratio is needed to establish the primary standard. We have calculated on-axis Spencer-Attix and Bragg-Gray tissue-to-air stopping-power ratios at a depth of z=70 μm in a uniform unit density ICRU tissue phantom. The ^{90}Sr/^{90}Y beta source irradiated the phantom at a distance of 30 cm. Table 3 presents the values of stopping-power ratios as a function of AE=ECUT. Table 3

The first thing to note is that the Spencer-Attix and Bragg-Gray stopping-power ratios differ, with the greater differences being for lower values of Δ. For the often used value of 10 keV, the difference is 0.7% but by 189 keV the two formulations are almost identical.

We have calculated the Bragg-Gray stopping-power ratios with the various values of AE, which in principle could lead to a slight variation in the value as the primary fluence changes and/or as the integral involved is stopped at different values. However, in practice, as the values in the table demonstrate, there is virtually no difference as AE changes. The variation is less than 0.03% as AE goes from 512 to 525 keV and is still less than 0.07% when AE is extended to 700 keV.

VI. Conclusions

We have included the Bragg-Gray stopping-power ratio calculation in the existing EGSnrc user-code SPRRZnrc. We carried out some basic tests to ensure that the new version of the SPRRZnrc code utilizes the appropriate PEGS4 data sets while calculating Bragg-Gray and Spencer-Attix stopping-power ratios. We also repeated some previously published studies so as to ensure that there is no overlap between the existing Spencer-Attix and Bragg-Gray coding. The results suggest that this new version of the SPRRZnrc code may safely be used for calculating Bragg-Gray and Spencer-Attix stopping-power ratios.

Acknowledgments

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Tables

Table 1: Comparison of Spencer-Attix water-to-air stopping-power ratios based on the old and new versions of the EGSnrc user-code SPRRZnrc and those calculated by Kosunen and Rogers[3](and obtained from the database created) and by Andreo[17] for broad parallel beams of monoenergetic photons on a uniform water medium. The values are at a depth of 10 cm in water. The AE=ECUT value used in the calculations is 521 keV. The statistical uncertainties associated with the SPRRZnrc-based stopping-power ratios are less than ±0.01%. Electron collision stopping powers are from ICRU Report 37.[19]

Photon energy MeV	Kosunen and Rogers	Andreo	old SPRRZnrc	new SPRRZnrc
1	1.134	1.135	1.135	1.135
5	1.099	1.098	1.100	1.100
10	1.068	1.067	1.069	1.069
20	1.034	1.035	1.035	1.035
40	0.993	0.995	0.994	0.994

Table 2: Comparison of Spencer-Attix and Bragg-Gray water-to-air stopping-power ratios calculated based on new version of the EGSnrc user-code SPRRZnrc and those calculated by Malamut et al[16] for broad parallel beams of monoenergetic photons on a uniform water medium. The values are at a depth of 10 cm in water. The SPRRZnrc code used electron collision stopping powers based on ICRU Report 37.[19] Malamut et al used EGS4 code and the stopping-powers are based on ICRU Report 35.[5] The values are therefore not directly comparable but the differences between B-G and S-A values should be the same. The values presented for the 40 MeV beam are at a depth of 15 cm. The AE=ECUT value used in the calculations is 521 keV. The statistical uncertainties associated with the SPRRZnrc-based stopping-power ratios are less than ±0.01%.

Photon energy MeV	Malamut et al			new SPRRZnrc code		
	Bragg-Gray	Spencer-Attix	% diff	Bragg-Gray	Spencer-Attix	% diff
1	1.132	1.136	0.4	1.132	1.135	0.3
5	1.101	1.107	0.6	1.095	1.100	0.5
10	1.074	1.079	0.5	1.064	1.069	0.5
20	1.042	1.046	0.4	1.031	1.035	0.4
40	1.007	1.011	0.4	0.999	1.002	0.3

Table 3: On-axis Bragg-Gray and Spencer-Attix mean collision stopping-power ratio of tissue-to-air calculated in a 22 cm-radius and 5 cm-thick uniform unit density ICRU tissue phantom as a function of AE=ECUT at a depth of z=70 μm in the phantom. The phantom is irradiated by a ^{90}Sr/^{90}Y beta source at a distance of 30 cm. The fluence-weighted mean energy of the source at 30 cm in air is 827±0.1% keV.[21] The stopping-power ratio values are scored in a cylindrical slab of radius 1.5027 cm and thickness of 1 μm. The statistical uncertainties associated with these values are less than ±0.02%.

AE=ECUT (keV)	Bragg-Gray	Spencer-Attix
512	1.1104	1.1224
515	1.1102	1.1167
521	1.1102	1.1143
525	1.1102	1.1138
700	1.1096	1.1100

Figures

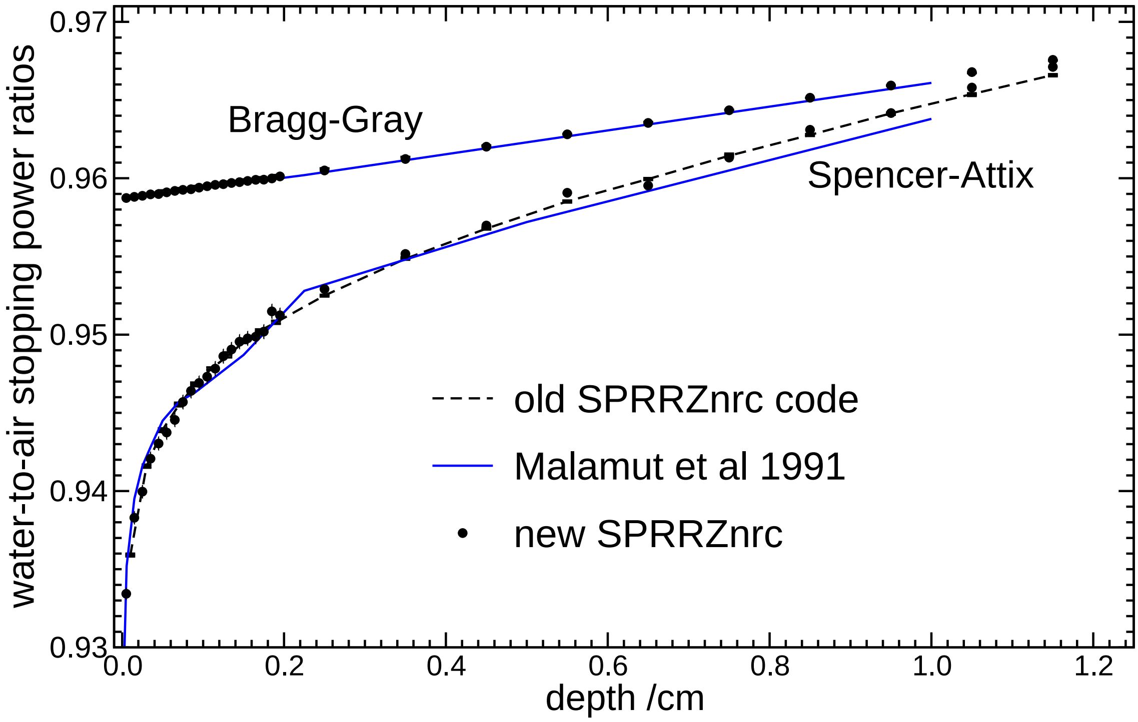

Figure 1: Water-to-air Spencer-Attix and Bragg-Gray stopping-power ratios for a broad parallel beam of 20 MeV electrons incident on a water phantom. The solid lines show the published results of Malamut et al.[16] The dashed line shows the values calculated by the original SPRRZnrc code before changes and the closed symbols are Spencer-Attix and Bragg-Gray values with the new code. The codes utilized electron collision stopping powers that are based on ICRU Report 37.[19] The AE=ECUT value used in the calculations is 521 keV. The statistical uncertainties associated with the SPRRZnrc-based stopping-power ratios are less than ±0.05%.

Appendix A: Sample input file

```
TITLE= BPB 1~MeV photons on water - central axis S-A and B-G sprs

# # # # # # # # # #
:start I/O control:
IWATCH= off
STORE INITIAL RANDOM NUMBERS= no
IRESTART= first
STORE DATA ARRAYS= yes
SPR OUTPUT= regions
SPR START REGION= 2
SPR STOP REGION= 33
:stop I/O control:

# # # # # # # # # #
:start Monte Carlo inputs:
NUMBER OF HISTORIES= 1000000
INITIAL RANDOM NO. SEEDS= 1, 33
MAX CPU HOURS ALLOWED= 60
IFULL= dose and stoppers
STATISTICAL ACCURACY SOUGHT= 0.1
PHOTON REGENERATION= no
Include Bragg-Gray spr= yes
:stop Monte Carlo inputs:

# # # # # # # # # #
# # # # # # # # # #
:start geometrical inputs:
METHOD OF INPUT= groups
Z OF FRONT FACE= 0
NSLAB= 1, 29, 1
SLAB THICKNESS= 0.5, 1.0, 0.5
RADII= 1000.
MEDIA= WAT521,
 AIR521,
 WAT521_UN,
 AIR521_UN;
DESCRIPTION BY= regions
MEDNUM= 1
START REGION= 2
STOP REGION=31
:stop geometrical inputs:

# # # # # # # # # #
```

```
# # # # # # # # # #
:start source inputs:

INCIDENT PARTICLE= photon
SOURCE NUMBER= 4
SOURCE OPTIONS= 0.5, 0, 0, 0
INCIDENT ENERGY= monoenergetic
INCIDENT KINETIC ENERGY(MEV)= 1.0

:stop source inputs:
# # # # # # # # # #

# # # # # # # # # #
:start MC transport parameter:

Global ECUT= 0.521
Global PCUT= 0.001
Global SMAX= 0.5
ESTEPE= 0.25
XImax= 0.50
Skin depth for BCA= 3.0
Boundary crossing algorithm= EXACT
Electron-step algorithm= PRESTA-II
Spin effects= on
Brems angular sampling= KM
Brems cross sections= BH
Bound Compton scattering= On
Pair angular sampling= Simple
Photoelectron angular sampling= On
Rayleigh scattering= Off
Atomic relaxations= On
Set PCUT= 0
Set PCUT start region= 1
Set PCUT stop region= 1
Set ECUT= 0
Set ECUT start region= 1
Set ECUT stop region= 1
Set SMAX= 0
Set SMAX start region= 1
Set SMAX stop region= 1

:stop MC transport parameter:
# # # # # # # # # #
```

```
# # # # # # # # # # #
:start variance reduction:

ELECTRON RANGE REJECTION= on
ESAVEIN= 40.0
RUSSIAN ROULETTE DEPTH= 0.0
RUSSIAN ROULETTE FRACTION= 0.0
EXPONENTIAL TRANSFORM C= 0.0
PHOTON FORCING= off
START FORCING= 0
STOP FORCING AFTER= 0

:stop variance reduction:
```

Appendix B: Conceptual problem with S-A calculations

In the equation for the Spencer-Attix stopping-power ratio, one needs to use the restricted collision stopping power when evaluating the integral. However, in the SPRRZnrc code, the standard EGSnrc restricted stopping powers are used in evaluating the integral and these are the sum of the collision and radiative stopping powers. Thus the method used for the evaluation is, in principle, incorrect.

However, the restricted radiative cross-sections are very small for the values of AP (low energy threshold for production of explicit bremsstrahlung photons) typically used in these calculations. Unfortunately, one does not have easy access to the restricted stopping power in PEGS4 but one can get an estimate of its size by comparing the total restricted stopping powers for AP = 100 keV and AP = 10 keV to those for AP = 1 keV. Figures 2 and 3 show that the difference in the total restricted stopping power as AP is raised from 1 to 10 keV is less than 0.02% and 0.4% for water and lead respectively. As one increases AP to 100 keV the ratio changes by up to 0.26% and 3.7% respectively.

These data suggest that even an AP value of 100 keV would not cause a serious error in an spr calculation for water (or any other low-Z material) whereas it might be a problem for the high-Z materials. These figures suggest that if one is using AP=1 keV for the data sets, then the error introduced by the conceptual problem in the SPRRZnrc code would be completely negligible.

One is therefore strongly encouraged to always use AP=1 keV in calculations of Spencer-Attix stopping-power ratios although 10 keV would also be acceptable.

This problem does not affect the Bragg-Gray calculations since the code explicitly uses the unrestricted collision stopping power for the calculations.

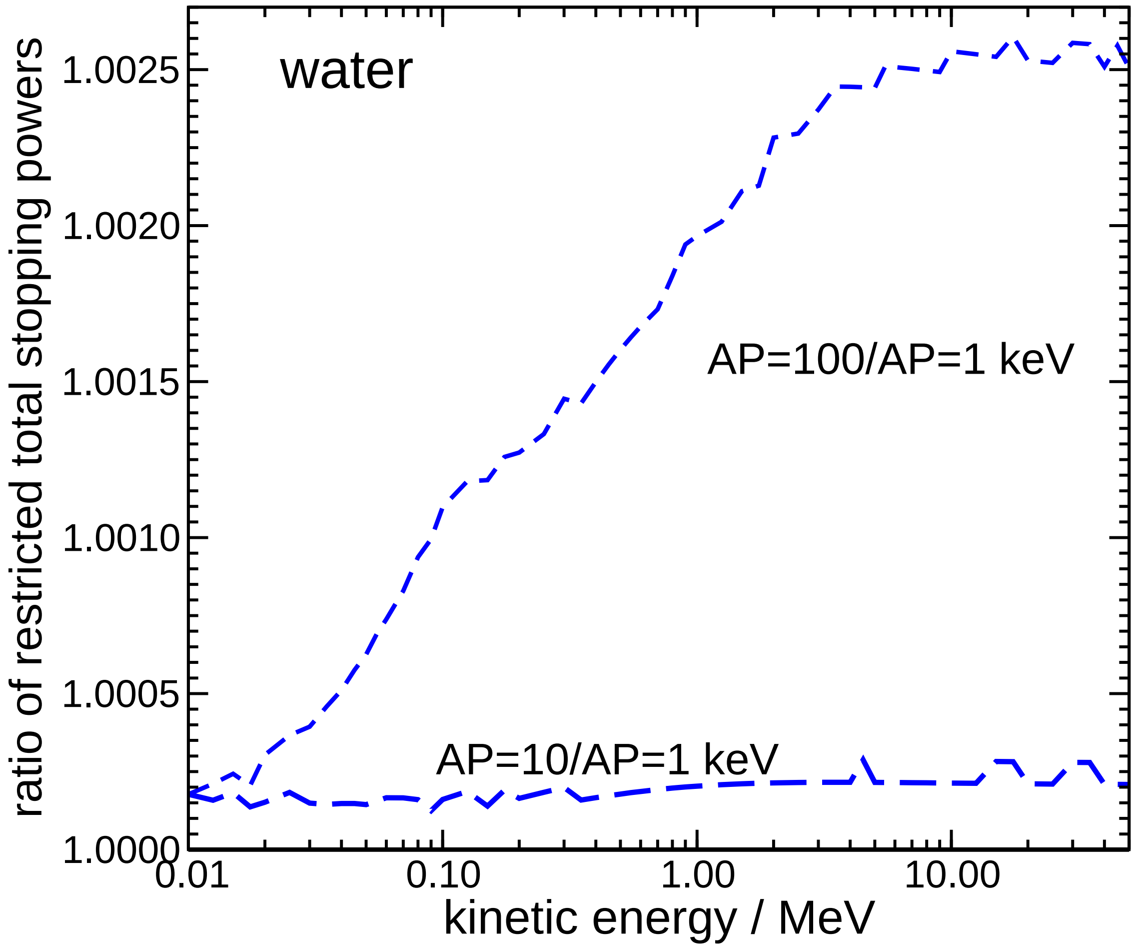

Figure 2: The ratio of water restricted total stopping powers which include collision and radiative restricted stopping powers. The plotted curves show the relative amount of the cross-sections due to the restricted radiative cross section for thresholds of 100 keV and 10 keV relative to a 1 keV threshold. This figure shows that as long as one uses AP=10 keV or less, the restricted radiative stopping power is completely negligible although if one were to use AP = 100 keV, the inclusion of the radiative restricted stopping power would cause an error of up to 0.25%.

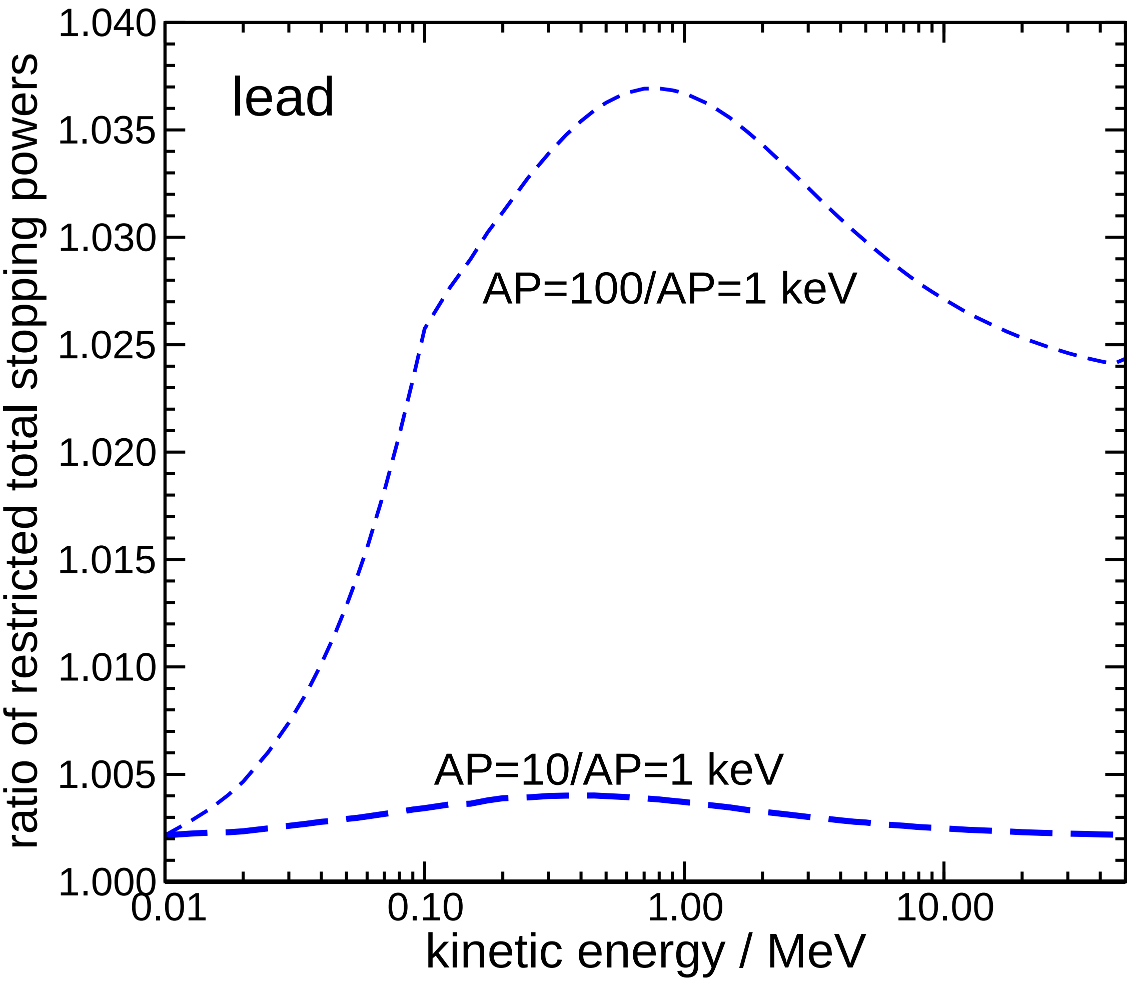

Figure 3: The same as figure 2 but for lead. In this case the 100 keV threshold would lead to errors up to 3.5% whereas the threshold of 10 keV might lead to 0.4% errors.

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e-mail: drogers@physics.carleton.ca

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