SKYCONES: A Code for Neutron and Photon Skyshine Calculations From Annular Conical Sources

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1 Summary

SKYCONES evaluates the skyshine doses produced by a point neutron or gamma-photon source emitting, into the atmosphere, radiation that is collimated into an upward conical annulus between two arbitrary polar angles. The source is assumed to be axially (azimuthally) symmetric about a vertical axis through the source and can have an arbitrary polyenergetic spectrum. Nested contiguous annular cones can thus be used to represent the energy and polar-angle dependence of a skyshine source emitting radiation into the atmosphere. The calculation of the skyshine doses uses the integral line-beam method which is based on a three-parameter approximation of the neutron and gamma-ray line-beam response functions.

Source neutron energies must be between 0.01 and 14 MeV. For energies above 1 MeV, source-to-detector distances can be as great as 2500 m. For source energies below 1 MeV, the maximum source-to-detector distance is somewhat less. For gamma photons, the maximum source-to-detector distance is 3000 m for photon energies between 0.02 and 10 MeV and 1500 m for photon energies between 10 and 100 MeV. For neutron sources, both the neutron skyshine dose and the secondary photon dose from neutron interactions in the air are computed separately.

The neutron skyshine doses are expressed in units of dose equivalents (Sv) per source neutron based on one of the following three response functions: (1) the effective dose equivalent for AP irradiation of an anthropomorphic phantom, (2) the dose equivalent at 10 mm into the ICRU sphere for isotropic (ISO) irradiation, and (3) the ambient dose equivalent on the principal axis at 10 mm depth for irradiation of the ICRU sphere by a plane parallel beam (PAR). Gamma-photon skyshine doses are expressed in terms of air-absorbed dose (Gy) and roentgens.

2 Theory and Methods

The theory and validation for the methods used by SKYCONES are described in detail in other references [1–5]. In this section a brief overview of the integral line-beam method used by SKYCONES is presented. There are companion codes available which use the line-beam methodology for gamma-skyshine calculations [6, 7] and for neutron-skyshine calculations [8] in geometries other than the conical geometry used in SKYCONES.

2.1 The Integral Line-Beam Method

The integral line-beam method for skyshine analysis is based on the availability of a line-beam response function (LBRF) $\Re(x, E, \phi)$, which is the dose per source particle (photon or neutron) at a distance x from a point source that emits radiation of energy E into an infinite air medium at an angle ϕ relative to the source-detector axis. The skyshine dose (or *detector response*) $R(x)$ arising from a collimated point source that emits $S(E, \mathbf{\Omega})\, dE\, d\Omega$ particles with energies in dE about E into directions $d\Omega$ about $\mathbf{\Omega}$ is found by integrating the LBRF over all source energies and over all neutron emission directions allowed by the source collimation, namely [1]

$$R(x) = \int_0^\infty dE \int_{\mathbf{\Omega}_s} d\Omega\, S(E, \mathbf{\Omega})\, \Re(x, E, \phi(\mathbf{\Omega})). \tag{1}$$

Here $\mathbf{\Omega}_s$ represents those directions in which radiation can stream directly from the source into the atmosphere.

The above formulation is based on three implicit approximations. First, the walls of the source collimation are assumed to be "black" i.e., any particles that hit the collimating walls are assumed to be absorbed. This assumption allows one to neglect the dose contribution at the detector from radiation that penetrates the source containment walls or that is scattered from the walls before escaping into the atmosphere.

Second, the source containment structure is assumed to have a negligible perturbation on the skyshine radiation field; i.e., once radiation enters the atmosphere, it does not interact again with the source structure. With this assumption, the calculation of the energy and angular distribution of source particles penetrating any overhead source shield or escaping from the containment structure is independent of the subsequent transport of the particles through the air to the detector. In most far-field skyshine calculations, the source and its containment have a negligible effect on the transport of the radiation through the air once the radiation has left the source structure [12]. However, for near-field calculations, this second assumption may not always be valid.

The third assumption in the integral line-beam method is that the ground may be replaced by a continuation of the air medium. Thus, for such an infinite air medium, the LBRF $\Re$ depends on only three variables: the source-to detector distance x, the source particle energy E, and the angle ϕ between the particle emission direction and the source-detector axis. As shown later, the infinite-air approximation has negligible effect for gamma-photon skyshine. However, for neutron sources, the ground tends to depress the neutron skyshine doses at large source-detector distances compared to dose in an infinite air medium. At small source-detector distances, soil acts as a reflector compared to an infinite air medium and, thus, increases the neutron skyshine doses. SKYCONES can correct the neutron skyshine doses for the air-ground interface by use of optional *ground correction factors*.

When the source energy distribution is represented by a multigroup approximation of G energy groups, the multigroup source spectrum can be incorporated into Eq. (1) as

$$R(x) = \sum_{g=1}^{G} \int_{\mathbf{\Omega}_s} d\Omega \, S(E_g, \mathbf{\Omega}) \, \Re(x, E_g, \phi(\mathbf{\Omega})), \tag{2}$$

where E_g is the midpoint energy of group g.

In SKYCONES, the point source is assumed to be isotropic within the range of conical collimation $[\theta_{\rm min}, \theta_{\rm max}]$ and is assumed to emit radiation into G groups such that, in group g, $S_p f_g$ particles are emitted with the group midpoint energy E_g. Here S_p is the total number of particles of all energies emitted by the source into 4π sr and f_g is the probability a particle is emitted with an energy in group g. Thus the energy and angular dependence of the source can be represented as

$$S(E, \mathbf{\Omega}) = \begin{cases} S_p \displaystyle\sum_{g=1}^{G} \frac{f_g}{4\pi} \, \delta(E - E_g), & \theta_{\rm min} \le \theta \le \theta_{\rm max} \\ 0, & \text{otherwise.} \end{cases} \tag{3}$$

Then, in terms of a spherical polar coordinate system with the source at the origin and the polar axis directed vertically upwards, Eq. (1) reduces to

$$R(x) = S_p \sum_{g=1}^{G} \frac{f_g}{4\pi} \int_0^{2\pi} d\psi \int_{\omega_{\rm min}}^{\omega_{\rm max}} d\omega \, \Re(x, E_g, \phi(\omega, \psi)), \tag{4}$$

where ω is the cosine of the polar angle θ, and the azimuthal angle ψ is defined with respect to the projection on the horizontal plane through the source. Here $\omega_{\rm min} = \cos\theta_{\rm max}$ and $\omega_{\rm max} = \cos\theta_{\rm min}$ define the permissible range of the cosine of polar angle for particle emission allowed by the source collimation.

SKYCONES assumes the detector is located at an arbitrary vertical distance h_d above (h_d positive) or below (h_d negative) the source elevation and at a radial distance x from the vertical (polar) axis through the source. The source-to-detector distance d for this geometry is

$$d = \sqrt{x^2 + {h_d}^2}, \tag{5}$$

Then, because of the assumed azimuthal symmetry of the source, Eq. (4) can be written as

$$R(d) = S_p \sum_{g=1}^{G} \frac{f_g}{2\pi} \int_{\omega_{\rm min}}^{\omega_{\rm max}} d\omega \left[\int_0^{\pi} d\psi \, \Re(d, E_g, \phi(\omega, \psi)) \right], \tag{6}$$

The emission angle ϕ for this geometry is given by [1]

$$\cos\phi = \sin\theta\cos\psi\cos\zeta + \cos\theta\sin\zeta, \tag{7}$$

where $\zeta = \tan^{-1}(h_d/x)$.

Finally, the integrals in Eq. (6) are readily evaluated numerically using standard Gaussian quadrature methods for both integrals. In SKYCONES the skyshine doses are normalized to a per-source-particle basis, i.e., $S_p = 1$.

2.2 Approximation of the LBRF

An analytical approximation of the LBRF in an infinite air medium is used to evaluate efficiently the integrand in Eq. (6). As originally proposed for the SKYSHINE code [13, 14] and later confirmed by Shultis and Faw [2] and by Gui [10], the LBRF may be accurately approximated for gamma-ray sources, neutron sources, and secondary gamma-ray skyshine by the following three-parameter function:

$$\Re(x, E, \phi) \simeq E(\rho/\rho_o)^2[x(\rho/\rho_o)]^c e^{a+bx(\rho/\rho_o)}, \tag{8}$$

where ρ is the air density g/cm^3 and ρ_o is the reference air density (= 0.0012 g/cm^3). The coefficients a, b and c depend on the source particle energy E, the emission direction ϕ, and the selected dose unit. Values of these coefficients have been determined by fitting Eq. (8) to calculated values of the LBRF for a given source energy and emission direction. Many compilations of the coefficients a, b and c are available for photons, neutrons, and secondary photons produced by neutron interactions in the air [15, 16, 17]. By using a double interpolation scheme [10, 2], the approximate LBRF can be made a continuous function of E and ϕ as well as x.

Earlier compilations of coefficients for the neutron and secondary gamma-ray LBRFs [14, 18] used the absorbed air dose to describe the LBRF. For gamma photons, the air-gray is a reasonable approximation for the tissue-gray and the ambient dose equivalent. However, for neutrons, an air-absorbed dose cannot be converted into dose equivalent units, which are needed for modern radiological assessments. Recently Gui [10] used the MCNP code [11] to evaluate the LBRFs for neutrons and the neutron-induced secondary gamma radiation based on modern dose equivalent units. Specifically, the following three effective dose equivalents [19] (Sv/neutron) were used to evaluate the LBRFs for neutron skyshine and for skyshine from secondary gamma photons produced in the air: (1) the effective dose equivalent (EDE) for AP irradiation of an anthropomorphic phantom, (2) the dose equivalent (DE) at 10 mm into the ICRU sphere for isotropic (ISO) irradiation, and (3) the dose equivalent (DE) on the principal axis at 10-mm depth for irradiation of the ICRU sphere by a plane parallel beam (PAR).[1] The user of SKYCONES may specify which of the three dose units are to be used in the skyshine calculations. From his MCNP calculated values of

[1]ICRP Publication 45 [20] recommends that the neutron dose equivalent be multiplied by a factor of two. However, this recommendation has been rejected by the USNRC and corresponding

the LBRFs, Gui developed a comprehensive tabulation of the fit coefficients for use with Eq. (8) [10, 16], and it is this compilation that is used in SKYCONES.

The approximate neutron LBRFs used by SKYCONES cover a range of neutron energies from 0.01 to 14 MeV, and are generally valid for source-to-detector distances out to 2500 m. However, for the lower neutron energies, the approximate LBRFs were obtained from LBRF data over a considerably smaller source-to-detector range. The maximum ranges for the approximate LBRFs used in SKYCONES are summarized in the table below. The maximum range generally depends on the emission angle, the maximum fit range being smaller for larger angles (e.g., > 90 degrees) and larger for smaller angles (e.g, > 5 degrees). For most skyshine problems, neutrons emitted at large angles are far less important than those emitted at small angles, and, unless the source is collimated to very small polar angles, the maximum source-to-detector ranges tabulated below are conservative.

Energy (MeV)	Maximum Range (m)
0.01	500
0.05	600
0.10	1000
0.50	1500
1.00	2200
1.50	2300
>2.00	2500

The approximate gamma-ray LBRFs used by SKYCONES cover a range of photon energies from 0.02 to 100 MeV. These LBRFs are generally accurate for source-to-detector distances from 50 m to about 3000 m for photon energies below 10 MeV. For photon energies between 10 and 100 MeV, the maximum range is about 1500 m.

2.3 Ground Correction Factors

A LBRF $\Re(x, E, \phi)$ for an infinite air medium can be corrected for the air-ground interface by an appropriate multiplicative ground correction factor (GCF). In general, the GCF depends on many problem parameters: distance x, source energy E, emission direction $\mathbf{\Omega}(\theta, \psi)$, and elevations of source and detector above the air-ground interface. However, for conical beams about the vertical and for both source and detector near (within several meters of) the air-ground interface, the GCF is a function of only distance x, polar angle θ, particle energy E, and the neutron dose unit.

US state regulators. The neutron doses calculated by SKYCONES do *not* include this factor of two. The "deep dose" used by the USNRC and other state regulatory agencies most closely corresponds to the 10-mm DE in the ICRU sphere in PAR geometry.

Both gamma photons and neutrons are affected by the air-ground interface; however, the effect is generally quite small for gamma rays and no GCF is needed. Neutron skyshine doses, by contrast, are more severely affected by the air-ground interface and GCFs are provide by SKYCONES to account for its presence. Examples of skyshine doses with and without an air-ground interface are shown in Figs. 1 and 2, as calculated by SKYCONES and MCNP [11]. From Fig. 1 it is seen that the skyshine doses from gamma sources are quite insensitive to the air-ground interface, and no attempt is made by SKYCONES to correct for the interface. However, from Fig. 2 the air-ground interface is seen to depress significantly the neutron skyshine dose at large source-detector distances.

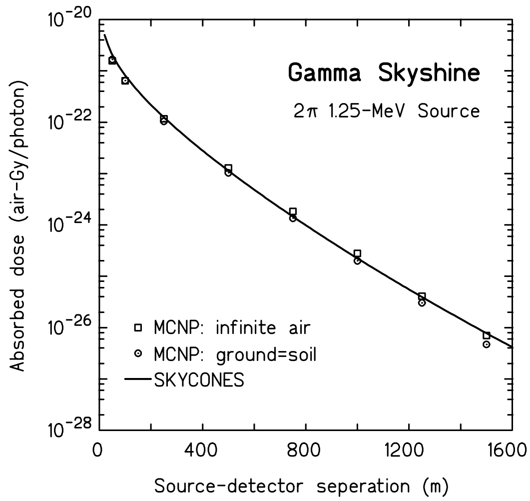

Figure 1. Gamma skyshine doses with and without an air ground interface. Symbols are from an MCNP calculation, and the thick line is from SKYCONES.

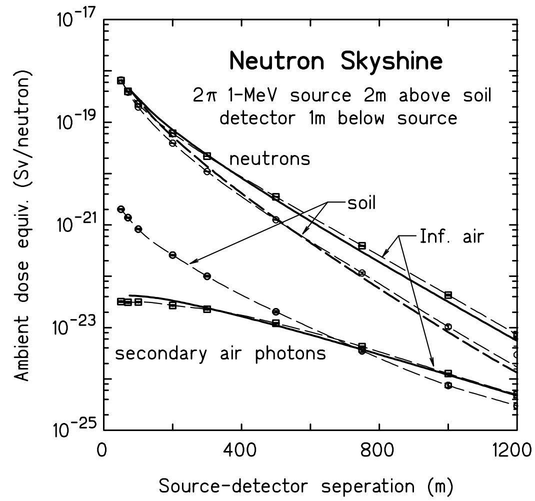

Figure 2. Neutron skyshine doses with and without an air ground interface. Symbols and dashed lines are from MCNP calculations, and the solid lines are SKYCONES results.

In Fig. 2 the SKYCONES calculated neutron skyshine doses for the air-ground interface use the optional ground correction factor as devised by Gui [10]. Gui found, from his MCNP calculations, that the conical-beam GCF for the neutron skyshine dose could be represented by

$$GCF(x, E, \theta) = a + bx + cx \ln x + dx^{1.5} \tag{9}$$

where the coefficients a, b, c, and d depend on the neutron source energy E and the conical half-angle θ. Gui's compilation of these GCF coefficients are used by SKYCONES to correct the infinite-air neutron skyshine doses for the air-ground interface.

2.4 Secondary-Photon Skyshine Doses for Neutron Sources

In any neutron skyshine calculation, the secondary photons skyshine dose arising from neutron interactions in the air (and the ground) may be of interest. However, this dose is usually more than an order of magnitude less than the neutron skyshine dose, except at distances greater than 2000 m, and is usually ignored. For an infinite air medium, the neutron-induced secondary photon skyshine dose is calculated by SKYCONES based on the approximation of Eq. 8 developed by Gui [10] for secondary photons. From Fig. 2, the SKYCONES calculated secondary-photon dose is seen to agree well with the MCNP calculated secondary-photon dose in an infinite-air medium.

However, unlike the neutron skyshine dose, the secondary-photon skyshine dose depends sensitively on the soil composition when an air-ground interface is considered. From Fig. 2, it is seen that the soil can significantly raise the secondary-photon dose at distances near the source, although at levels still well below the primary neutron skyshine dose. At distances far from the source, the soil depresses the secondary-photon dose compared to that in an infinite air medium. At large distances (greater than 2000 m), the secondary-photon dose may even become greater than the primary neutron skyshine dose. For this extreme case, the infinite-air secondary-photon dose is conservative (i.e., overpredicts the dose). SKYCONES makes no attempt to correct the secondary-photon skyshine dose for the air-ground interface, and calculates only the secondary-photon dose for an infinite air medium, even when optional ground correction factors are specified for neutron sources.

3 Required Input Data

SKYCONES obtains its input data from an input file whose name is entered by the user in response to a program prompt. While modest checking of input data is attempted by SKYCONES, the program is not totally "bullet-proof" and the user must bear some responsibility to enter meaningful data.

The input data consist of two blocks: the first defines the desired output file name and type of source particle and dose unit. The second block specifies program and geometry parameters as well as the energy spectrum of the source. Multiple second blocks, separated by a blank line, can be used to analyze multiple annular conical sources of the same radiation/dose type.

3.1 Block One

The first block occupies the first two lines of the input data file. Specifically, the following data is entered.

`OUTFIL` The first line gives the specification for the output file, e.g., `SKYCONES.OUT`. The name of the output file must be left justified, i.e. begin in the first column of the line.

`PART` The first column of the second line contains a single alphabetic character to denote the source particle type and the dose units to be used. Permissible values are:

`p` or `P` for photons with dose in air-rads and roentgens
`e` or `E` for neutrons with the AP-phantom effective dose equivalent
`n` or `N` for neutrons with the PAR-sphere (ambient) dose equivalent
`i` or `I` for neutrons with the ISO-sphere dose equivalent

For neutron sources (`e`, `n`, or `i`), a suffix `g` may be appended to apply a ground correction factor to the neutron skyshine dose. Thus to correct for the air-ground interface, specify `eg` (or `EG`), `ng` (or `NG`), `ig` (or `IG`).

3.2 Block Two

Each *Block Two* set of input data is precedent by a blank line. In this block, information about the conical geometry, program options, and source spectrum is provided. A single input file can contain multiple sets of *Block Two* data. In this way a set of annular conical sources can be analyzed and the results summed to provide a skyshine analysis for a skyshine source whose strength varies with the polar angle.

3.2.1 Start of Block Two

The first line of *Block Two* is a comment line to identify the data of the block. The comment is restricted to columns 1 through 80.

The second line of this block contains the five input parameters tabulated below. Free format may be used with each value separated by at least one blank.

`RHO` The air mass density in g/cm^3. The line-beam response function approximation used by SKYCONES assumes an air density of 0.0012 g/cm^3, but the skyshine dose is corrected to the density specified by `RHO`.

`NPTS` The number of intermediate source-to-detector distances to be used for evaluation of the skyshine dose. If `NPTS` > 0 then, intermediate distances are equally spaced out to the maximum distance `XD` specified later in the input. If `NPTS` < 0, then the intermediate distances are separated by equi-logarithmic intervals between 5m and `XD`.

`NGAU` The order of the Gaussian quadrature used for the numerical integrations over the source emission directions in Eq. (6). Permissible values are 4, 8, 16, or 32. The higher the order, the longer the calculations take but the more precise are the predicted skyshine doses.

`NE` The number of energy groups used to define the multigroup source spectrum (`NE` ≤ 30).

`IADD` A parameter to specify if results from multiple *Block Two* data sets are to be summed for each source-to-detector distance. If `IADD`$= 0$ no final summation is performed. To sum results from multiple *Block Two* sets, set `IADD`= 1 for all sets. If any one of the `IADD` parameters is zero, no final summation is performed.

3.2.2 Source Energy Spectrum

The third line of *Block Two* specifies the energy spectrum of the source radiation, one energy group per line. For each of the `NE` groups, the midpoint energy and frequency of the group are entered. Thus for the ith group the following two quantities are entered with at least one space between the entries:

`E(i)` The midpoint energy (MeV) of group `i`, `i` $= 1, \ldots,$`NE`.

`F(i)` The probability (or frequency) that a source particle is emitted in group `i`. The sum over all `F(i)` should equal unity for the skyshine dose to be normalized to a per-source-particle basis. This normalization is assumed in the labeling of the output skyshine dose table.[2]

3.2.3 Geometry Information

The final line of *Block Two* contains information about the skyshine geometry. Specifically, the following data are entered on a single line with at least one space between adjacent items.

`HD` Elevation of the detector above the source elevation (m). If this entry is positive, the detector is higher than the source, and the user must insure that the conical collimations (defined by `THETA1` and `THETA2`) is such that no radiation can reach the detector directly. The program does not check that only scattered radiation reaches the detector.

`XD` The horizontal source-to-detector distance (m) along an axis perpendicular to the vertical through the source. The skyshine dose is estimated at `NPTS` intermediate points distributed between the source and this maximum distance.

`THETA1` The minimum polar angle (in degrees) of the conical source collimation.
0 <= `THETA1` < `THETA2` <= 90 degrees.

`THETA2` The maximum polar angle (in degrees) of the conical source collimation.
0 <= `THETA1` < `THETA2` <= 90 degrees.

[2]Alternatively, the `F(i)` can be set equal to the source emission rate (number per unit time) to yield the calculated skyshine doses in units of dose per unit time even though the output table heading still indicates a dose per source particle.

4 Example Input and Output Files

4.1 Example 1:

The first example is for an uncollimated, monoenergetic, isotropic, gamma-ray source emitting photons into a 2π hemisphere of air. The input file, TEST1.INP, for this problem is

```
test1.out                          OUTPUT FILE NAME
p                                  PARTICLE/DOSE TYPE
                                   BLANK LINE FOLLOWED BY PROBLEM CAPTION
2pi 1.25-MeV (Co-60) gamma skyshine source
0.00122    9  32  1   0            RHO NPTS NGAU NE IADD
   1.250   1.00                    SOURCE SPECTRUM: Ei(MeV), Fi
-1.500   2000.0   0.00  90.0       Geometry: DELH(m) Xmax(m) Theta1 Theta2
```

The optional annotations to the right of most input lines are ignored by SKYCONES and serve only to remind the user of the data contained on each line. With this input file, the following output file TEST1.OUT is obtained.

```
2pi 1.25-MeV (Co-60) gamma skyshine source
****** SKYCONES 1.1: Annular Conical Geometry with Photon  Source
  Air density (g/cm^3)       =   .001220
  Dist. src above detect (m) =     -1.50
  Source angle 1 (degrees)   =       .00
  Source angle 2 (degrees)   =     90.00
  Source collimation (sr)    =    6.2832
  Source-detector dist. (m)  =    2000.0
  Gauss quadrature order     =        32
  3-parm. approx. LBRF used

  Energy Spectrum: Emid (MeV)   Frequency:
                     1.2500      1.000

          SKYSHINE DOSE: air-Gy and roentgen
  ------------------------------------------------------
      S-D(m)      g/cm^2     Gy/photon     R/photon
  ------------------------------------------------------
       200.0       24.40     2.1399E-22   2.4502E-20
       400.0       48.80     2.7024E-23   3.0943E-21
       600.0       73.20     4.5959E-24   5.2623E-22
       800.0       97.60     9.1587E-25   1.0487E-22
      1000.0      122.00     2.0418E-25   2.3378E-23
      1200.0      146.40     4.9760E-26   5.6975E-24
      1400.0      170.80     1.3051E-26   1.4943E-24
      1600.0      195.20     3.6352E-27   4.1623E-25
      1800.0      219.60     1.0627E-27   1.2168E-25
      2000.0      244.00     3.2270E-28   3.6949E-26
  ------------------------------------------------------
```

In the above table of calculated skyshine doses, columns 1 and 2 are the source-to-detector distances in units of meters and mass thickness, respectively. Columns 3 and 4 give the skyshine doses in units of air-grays and roentgens, respectively.

4.2 Example 2:

The second example is for a polyenergetic neutron source which has slightly different energy spectra for neutrons emitted into the atmosphere between 0 and 45 degrees and for neutrons emitted between 45 and 88 degrees. Two *Block Two* data sets are used to represent this source. Neutron skyshine doses, corrected for the effect of the air-ground interface and in units of ambient dose equivalent, are specified by setting `PART` to `ng`. In this example, the energy group frequencies `F(i)` have been multiply by the neutron hourly emission rate (times 10^5) so that calculated skyshine dose will be in units of mrem/h. The `IADD` parameter in both *Block Two*s is set to `1` so that the results from each Block will be summed. Finally, doses at 5 intermediate equi-logarithmic distances out to 1000 m are desired, so that `NPTS` parameter is specified as -5.

For most problems in which radiation escapes into the atmosphere through a source containment structure, more polar angle ranges are usually needed to represent the polar-angle dependence of the source strength and energy spectrum.

The input file, `TEST2.INP`, for this problem is

```
test2.out                          OUTPUT FILE NAME
ng                                 PARTICLE/DOSE TYPE

Cone between 0 and 45:  Read Sv/neutron as mrem/h (amb. dose equiv.)
0.0013   -5  32  7  1              RHO NPTS NGAU NE IADD
   0.1500000  0.34153E+16          SOURCE SPECTRUM: Ei(MeV)  Fi
   0.4000000  0.47119E+16
   0.8000000  0.11973E+16
   1.2500000  0.45812E+15
   1.7500000  0.23014E+15
   2.5000000  0.23663E+15
   4.0000000  0.10022E+15
1.5  1000.0   0.0  45.0            Geometry: DELH Xmax Theta1 Theta2

Cone between 45 and 88:  Read Sv/neutron as mrem/h (amb. dose equiv.)
0.0013   -5  32  7  1              RHO NPTS NGAU NE IADD
   0.1500000  0.23897E+16          SOURCE SPECTRUM: Ei(MeV)  Fi
   0.4000000  0.33123E+16
   0.8000000  0.12225E+16
   1.2500000  0.56345E+15
   1.7500000  0.38623E+15
   2.5000000  0.47135E+15
   4.0000000  0.17398E+15
1.5  1000.0  45.0  90.0            Geometry: DELH Xmax Theta1 Theta2
```

The following output is obtained.

```
Cone between 0 and 45:  Read Sv/neutron as mrem/h (amb. dose equiv.)
****** SKYCONES 1.1: Annular Conical Geometry with Neutron Source
  Air density (g/cm^3)       =   .001300
  Dist. src above detect (m) =      1.50
  Source angle 1 (degrees)   =       .00
  Source angle 2 (degrees)   =     45.00
  Source collimation (sr)    =    1.8403
  Source-detector dist. (m)  =    1000.0
  Gauss quadrature order     =        32
  3-parm. approx. LBRF used
  Ground correction factors applied to neutron dose

  Energy Spectrum: Emid (MeV)   Frequency:
                    .1500      .3415E+16
                    .4000      .4712E+16
                    .8000      .1197E+16
                   1.2500      .4581E+15
                   1.7500      .2301E+15
                   2.5000      .2366E+15
                   4.0000      .1002E+15

          SKYSHINE DOSE: ADE - ICRU Sphere (PAR)
  ------------------------------------------------------
        S-D          S-D        Neutron      Sec. Gamma
        (m)        (g/cm^2)    (Sv/neut)    (Sv/neut)
  ------------------------------------------------------
        12.2         1.58      5.3432E-03   4.0625E-07
        29.3         3.81      1.9886E-03   4.0705E-07
        70.7         9.19      5.5778E-04   3.7749E-07
       171.0        22.23      7.9055E-05   2.5564E-07
       413.5        53.76      2.6678E-06   7.5930E-08
      1000.0       130.00      7.4688E-09   3.0178E-09
  ------------------------------------------------------


Cone between 45 and 88:  Read Sv/neutron as mrem/h (amb. dose equiv.)
****** SKYCONES 1.1: Annular Conical Geometry with Neutron Source
  Air density (g/cm^3)       =   .001300
  Dist. src above detect (m) =      1.50
  Source angle 1 (degrees)   =     45.00
  Source angle 2 (degrees)   =     90.00
  Source collimation (sr)    =    4.4429
  Source-detector dist. (m)  =    1000.0
  Gauss quadrature order     =        32
  3-parm. approx. LBRF used
  Ground correction factors applied to neutron dose

  Energy Spectrum: Emid (MeV)   Frequency:
                    .1500      .2390E+16
                    .4000      .3312E+16
                    .8000      .1223E+16
```

```
                1.2500       .5635E+15
                1.7500       .3862E+15
                2.5000       .4714E+15
                4.0000       .1740E+15

         SKYSHINE DOSE: ADE - ICRU Sphere (PAR)
------------------------------------------------------
      S-D         S-D        Neutron      Sec. Gamma
      (m)       (g/cm^2)    (Sv/neut)     (Sv/neut)
------------------------------------------------------
      12.2        1.58      2.0156E-02   1.1863E-06
      29.3        3.81      7.0983E-03   9.8378E-07
      70.7        9.19      1.9688E-03   8.0609E-07
     171.0       22.23      2.9140E-04   5.1102E-07
     413.5       53.76      1.1645E-05   1.4869E-07
    1000.0      130.00      4.9990E-08   6.2089E-09
------------------------------------------------------


         SUM OF ABOVE SKYSHINE DOSES
------------------------------------------------------
      S-D         S-D        Neutron      Sec. Gamma
      (m)       (g/cm^2)    (Sv/neut)     (Sv/neut)
------------------------------------------------------
      12.2        1.58      2.5499E-02   1.5926E-06
      29.3        3.81      9.0869E-03   1.3908E-06
      70.7        9.19      2.5266E-03   1.1836E-06
     171.0       22.23      3.7046E-04   7.6666E-07
     413.5       53.76      1.4313E-05   2.2462E-07
    1000.0      130.00      5.7459E-08   9.2267E-09
------------------------------------------------------
```

In the above tables of calculated skyshine doses, columns 1 and 2 are the source-to-detector distances in units of meters and mass thickness, respectively. Columns 3 and 4 give the skyshine doses from neutrons and secondary gamma radiation produced in air, respectively. In this example, the dose unit is the ambient dose equivalent for a plane parallel neutron beam illuminating the 30-cm diameter tissue-equivalent ICRP sphere. Because the `F(i)` have been multiplied by 10^5 times the source emission rate, the indicated doses (Sv/neutron) are actually in units of (mrem/h).

5 Auxiliary Files

SKYCONES requires that three auxiliary data files be present in the same directory as `SKYCONES.EXE`. Two of these files contain the coefficients a, b, and c for the approximate line-beam response function of Eq. (8), and the third contains coefficients a, b, c, and d for the neutron ground correction factor of Eq. (9). The three auxiliary data files are

`GAMLBRF.DAT` This file contains two sets of LBRF coefficients for gamma photons. One set is for photons with energies between 0.02 and 15 MeV; the second set is for high energy photons with energies between 10 and 100 MeV The dose unit for the LBRF, when calculated with these coefficients, is the air-rad.

`NEUTLBRF.DAT` This file contains LBRF coefficients for neutrons with energies between 0.01 and 14 MeV. Six sets of coefficients are contained in this file, three for the neutron LBRF and three for the secondary-photon LBRF. The three sets correspond to the three dose units available in SKYCONES for neutron skyshine problems, namely (1) the effective dose equivalent for AP irradiation of the ICRP anthropomorphic human phantom. (2) the ambient dose equivalent, i.e., the dose equivalent for PAR neutron irradiation of the 30-cm diameter ICRP tissue sphere at 10 mm depth on the principal axis, and (3) the dose equivalent for isotropic (ISO) neutron irradiation of the 30-cm diameter ICRP tissue-equivalent sphere at 10 mm depth.

`NEUTGCF.DAT` This file contains three sets of coefficients for the ground correction factor of Eq. (9). Two sets are for the neutron LBRF (one for effective dose equivalent and the ISO dose equivalent) and the other for the ambient dose equivalent). The third set of coefficients is for a secondary-photon GCF and is not used by SKYCONES.

`GAMLBRF.DAT` and `NEUTLBRF.DAT` contain the LBRF coefficients a, b, and c for the approximate line-beam response function of Eq. (8). For example, `GAMLBRF.DAT` begins as

```
Data for the low-E LBRF approximation for gamma photons
! E=    .02
     .5     -3.2260   -1.010082    .0827326
    1.5     -4.3262   -1.025872    .0829719
    2.5     -4.8423   -1.037587    .0831220
    4.0     -5.3226   -1.051969    .0832978
     .... (lines omitted)
  130.0     -8.9319   -1.398953    .0991899
  150.0     -8.9420   -1.382705    .1012927
  170.0     -8.9415   -1.373270    .1024275
! E=    .03
     .5     -4.4477    -.992174    .0366235
    1.5     -5.5594    -.986039    .0364442
    2.5     -6.0823    -.981497    .0363890
     ....
```

The first line identifies the set. The line beginning with "`!  E=` " gives the photon energy and is followed by 19 lines giving the values of a, b, and c for 19 ϕ angles at that energy. The first column is the angle ϕ (in degrees), and columns 2 through 4 give the value of a, b, and c, respectively.

From the data in these files, SKYCONES uses interpolation procedures to evaluate the line-beam response function at any energy between the minimum and maximum particle energies (0.01 to 14 MeV for neutrons, and 0.02 and 100 MeV for photons), and for any emission direction between 0 and 180 degrees. If any source group has an energy below the minimum, the group energy is set to the minimum allowed energy. Similarly, if a group energy is above the maximum energy, it is set to the maximum.

Finally, it should be noted that the neutron (but not the secondary-photon) dose calculated from the data in the file `NEUTLBRF.DAT` includes the multiplicative factor of 2 recommended by the ICRP [20]. However, because this recommendation has been rejected by US regulators, the neutron skyshine doses calculated by SKYCONES have been reduced by 50% to remove this factor of 2.

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