SKYNEUT: A Code for Neutron Skyshine Calculations Using the Integral Line-Beam Method

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published as

Report 9503

INSTITUTE FOR COMPUTATIONAL RESEARCH IN ENGINEER AND SCIENCE

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June 1995
(revised 4/96 and 1/97)

User Notes for
SKYNEUT

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1 Summary

SKYNEUT evaluates the neutron and neutron-induced secondary gamma-ray skyshine doses from an isotropic, point, neutron source collimated by three simple geometries: an open silo, a vertical black (perfectly absorbing) wall, and a rectangular building. The source may emit monoenergetic neutrons or neutrons with an arbitrary spectrum of energies. The calculation of the skyshine doses uses the integral line-beam method which is based on a newly developed three-parameter approximation of the neutron 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.

The 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 dose equivalent on the principal axis at 10 mm depth for irradiation of the ICRU sphere by a plane parallel beam (PAR).

2 Theory and Methods

The theory and validation for the methods used by SKYNEUT are described in detail in other references [1, 2, 3]. In this section a brief overview of the integral line-beam method used by SKYNEUT is presented. For gamma-ray skyshine sources there are companion codes available that use a similar methodology [4, 5].

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 neutron at a distance x from a point source that emits neutrons of energy E into an infinite air medium at an angle ϕ relative to the source-detector axis. The skyshine dose

$R(x)$ arising from a collimated point source which emits $S(E, \mathbf{\Omega})\, dE\, d\Omega$ neutrons 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 [2]

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

Here $\mathbf{\Omega}_s$ represents those directions in which radiation can stream directly from the source into the atmosphere. Implicit in this approach is the assumption that the ground can be treated as an infinite air medium. This assumption has proven to be quite reasonable for most gamma and neutron skyshine problems [6, 1]. Although *ground correction factors* are available to correct the infinite air results for the presence of an air-ground interface [1], SKYNEUT makes no such correction for the air-ground interface.

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

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

The above results are based on two implicit approximations. First, the walls of the source collimation are assumed to be "black;" i.e., any neutrons that hit the walls are assumed to be absorbed. This assumption allows one to neglect the dose contribution at the detector of neutrons that penetrate the source containment walls or that 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 neutrons enter the atmosphere, they do not interact again with the source structure. With this assumption, the calculation of the energy and angular distribution of source neutrons penetrating any overhead source shield or escaping from the containment structure is independent of the subsequent transport of the neutrons 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 neutrons through the air once the neutrons have left the source structure [7]. However, for near-field calculations, this second assumption is not always true.

If the point source is isotropic and monoenergetic, as is assumed in SKYNEUT, emitting S_p neutrons of energy E_o, the energy and angular distribution of the source can be represented as

$$S(E, \mathbf{\Omega}) = \frac{S_p}{4\pi}\, \delta(E - E_o). \tag{3}$$

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

$$R(x) = \frac{S_p}{4\pi} \int_0^{2\pi} d\psi \int_{\omega_{min}}^{\omega_{max}} d\omega\, \Re(x, E_o, \phi), \tag{4}$$

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 of the source-to-detector axis. Here ω_{min} and ω_{max} define the permissible range of the cosine of polar angles for neutron emission allowed by the source collimation. Generally, these limits are functions of the azimuthal angle ψ.

The above formulation can be used to calculate the skyshine dose for any point skyshine source. Explicit expressions for the limits ω_{min} and ω_{max} can be obtained for some simple skyshine geometries such as the three geometries used in SKYNEUT. In any event, the integrals in Eq. (1) or (4) can be evaluated readily using standard numerical integration techniques.

2.2 Approximation of the LBRF

An analytical approximation of the LBRF is used to evaluate efficiently the integral in Eq. (4). As originally proposed for the SKYSHINE code [8, 9] and later confirmed by Shultis et al. [3] and by Gui [1], the LBRF may be accurately approximated for both neutron and secondary gamma-ray skyshine by the following three-parameter function:

$$\Re(x, E, \phi) \simeq E(\rho/\rho_o)^2[x(\rho/\rho_o)]^c e^{a+bx(\rho/\rho_o)}, \tag{5}$$

where ρ is the air density g/cm^3 and ρ_o is the reference air density (= 0.0012 g/cm^3). The parameters a, b and c depend on the source neutron energy E, the emission direction ϕ, and the selected dose unit. Values of these parameters are determined by fitting Eq. (5) to calculated values of the LBRF for a given source energy and emission direction. By using a double interpolation scheme [1, 3], the approximate LBRF can be a continuous function of E and ϕ as well as x.

Earlier compilations of parameters for the neutron and secondary gamma-ray LBRFs [9, 10] used the absorbed air dose to describe the LBRF. Such a dose for neutrons cannot be converted into dose equivalent units which are needed for modern radiological assessments. Recently Gui [1] used the MCNP code 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 [11] (Sv/neutron) were used to evaluate the LBRFs for neutron skyshine and for skyshine from secondary gamma photons: (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] In SKYNEUT the user may specify which of the three dose units are to be used in the skyshine calculations. From his MCNP calculated values of the

[1] ICRP Publication 45 [12] recommends that the neutron dose equivalent be multiplied by a factor of two. However, this recommendation has been rejected by the USNRC and corresponding US state regulators. The neutron doses calculated by SKYNEUT 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.

LBRFs, Gui [1] developed a comprehensive tabulation of the fit parameters for use with Eq. (5), and it is this compilation that is used in SKYNEUT.

The approximate LBRFs used by SKYNEUT 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 SKYNEUT are summarized in the table below. The maximum range generally depends on the emission angle, being smaller for large angles (e.g., $>$ 90 degrees) and larger for small 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 large angles, the maximum source-to-detector ranges 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

2.3 Geometries Used in SKYNEUT

Three skyshine geometries are available in SKYNEUT, and are summarized in the sections below. In each, the source is assumed to be bare, i.e., exposed directly to the atmosphere. To account for shielding over a neutron source, the total upward flow of neutrons escaping any source shield is used as an effective bare neutron skyshine source whose neutron energy spectrum is that of the neutrons escaping the shield into the atmosphere [7]. Calculation of the energy and angular distribution of neutrons escaping through a source shield, generally requires a transport calculation prior to the use of SKYNEUT.

2.3.1 Open Silo Geometry

In this geometry, a point, isotropic, neutron source is placed on the axis a distance h_s below the top of a roofless cylindrical silo of inner radius r as shown in Fig. 1. The source emits S neutrons with a fraction f_g being emitted in energy group g whose midpoint energy is E_g. A detector is located at a vertical distance h_d below the silo top and at a radial distance x from the silo axis. For this problem, a positive h_s (or h_d) denotes the source (or detector) is below the silo top while a negative h_s (or h_d)

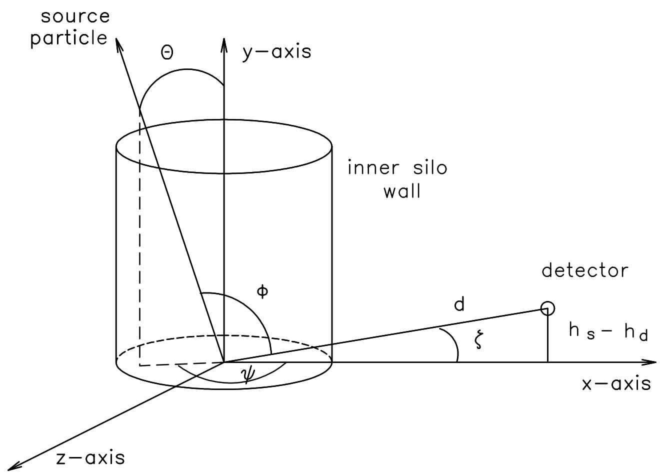

Figure 1. Geometry for the open silo skyshine problem. The point source is on the silo axis at the origin of the spherical coordinate system and at a vertical distance h_s below the silo top. A detector is located at $(x, h_s - h_d, 0)$. The silo wall is assumed to be black.

denotes the source (or detector) is above the silo top. For this geometry, the skyshine dose of Eq. (2) reduces to

$$R_i(d) = \frac{S}{2\pi} \sum_{g=1}^{G} f_g \int_0^{\pi} d\psi \int_{\omega_0}^{1} d\omega\, \Re_i(d, E_g, \phi). \tag{6}$$

Here the subscript i refers to either the neutron skyshine dose or the dose from neutron-induced secondary gamma rays. For this silo geometry,

$$d = \sqrt{x^2 + (h_s - h_d)^2}, \tag{7}$$

$$\zeta = \tan^{-1}[(h_s - h_d)/x], \tag{8}$$

$$\omega_0 \equiv \cos\theta_{max} = h_s/\sqrt{r^2 + {h_s}^2}, \tag{9}$$

and

$$\cos\phi = \sin\theta\cos\psi\cos\zeta + \cos\theta\sin\zeta. \tag{10}$$

2.3.2 Infinite Wall Geometry

Figure 2 depicts the geometry of the skyshine problem for a point, isotropic, neutron source located at a perpendicular distance r behind an infinite black wall and at a vertical distance h_s measured from the horizontal plane touching the top of the wall. The source emits S neutrons with a fraction f_g being emitted in energy group g whose midpoint energy is E_g. A detector, located on the opposite side of the wall, is at a horizontal distance z_d measured normally from the x-axis and at a vertical distance h_d beneath the same horizontal plane through the top of the wall.

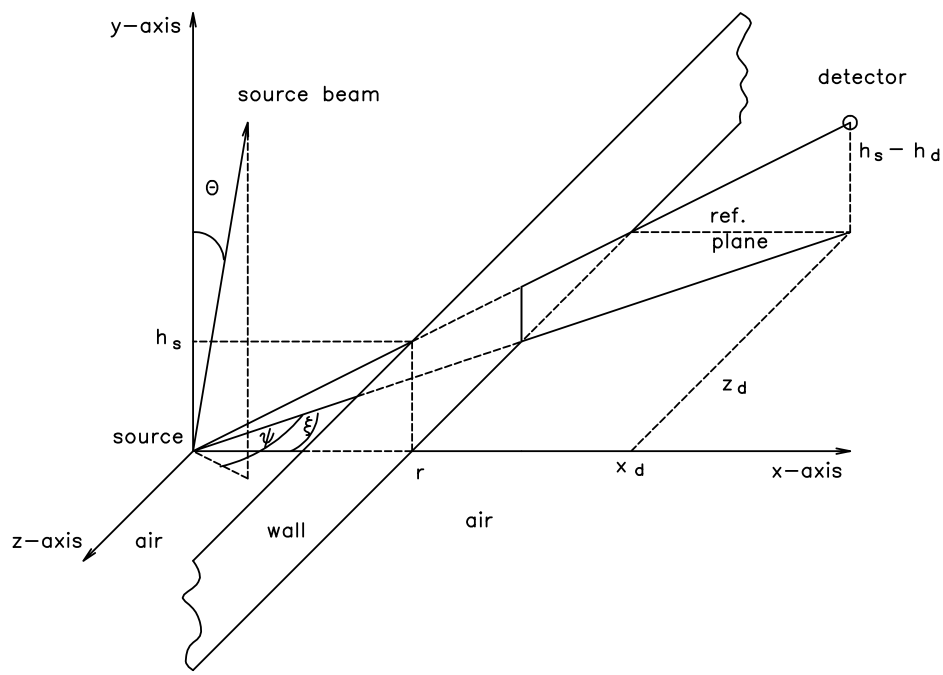

Figure 2. Geometry for the infinite black wall problem. A point isotropic source is located at a distance r behind the wall and a vertical distance h_s beneath the top of the wall. A detector is located at $(x_d, h_s - h_d, z_d)$ while the source is located at the origin of the coordinate system.

For this geometry, Eq. (4) reduces to

$$R_i(d) = \frac{S}{4\pi} \sum_{g=1}^{G} f_g \int_0^{2\pi} d\psi \int_{\omega_{min}}^{1} d\omega \, \Re_i(d, E_g, \phi). \tag{11}$$

Again, the subscript i refers to either the neutron skyshine dose or the dose from neutron-induced secondary gamma rays. For this geometry

$$d = \sqrt{x_d^2 + (h_s - h_d)^2 + z_d^2}, \tag{12}$$

$$\zeta = \tan^{-1}\left(\frac{h_s - h_d}{\sqrt{x_d^2 + z_d^2}}\right), \tag{13}$$

$$\xi = \tan^{-1}(z_d/x_d), \tag{14}$$

and

$$\cos\phi = \cos\psi \sin\theta \cos\zeta + \cos\theta \sin\zeta. \tag{15}$$

Since the minimum value of θ is 0^0, the upper limit of ω, $\omega_{max} = \cos\theta_{min}$, is equal to 1. The determination of $\omega_{min} = \cos\theta_{max}$ is slightly more involved. When the radiations are emitted in the direction towards the detector, that is, for the intervals $(0 \leq \psi \leq \pi/2+\xi)$ and $(3\pi/2+\xi \leq \psi \leq 2\pi)$, θ_{max} occurs when the beam just grazes the top of the wall. For these ranges, $\theta_{max} = \tan^{-1}(r/[h_s \cos(\psi-\xi)])$. When the radiations are emitted away from the detector, that is, for the range $(\pi/2 + \xi \leq \psi \leq 3\pi/2 + \xi)$, it is assumed that all radiations emitted contribute to the skyshine dose and θ_{max} is $\pi/2$ (or $\omega_{min} = 0$). Thus, the θ_{max} for the infinite wall geometry is given by

$$\theta_{max} = \begin{cases} \tan^{-1}\left(\dfrac{r}{h_s \cos(\psi - \xi)}\right), & 0 \leq \psi \leq \pi/2 + \xi,\ 3\pi/2 + \xi \leq \psi \leq 2\pi, \\ \pi/2, & \pi/2 + \xi \leq \psi \leq 3\pi/2 + \xi. \end{cases} \tag{16}$$

The assumption that all of the neutrons emitted in the direction away from the wall contribute to the skyshine dose tends to overestimate the actual skyshine dose because the initial portion of these backward beams will be shielded by the infinite wall. However, since the contribution of the shielded portion of the backward beams is much smaller than the contribution from beams that are emitted towards the detector, the error due to the above assumption is usually small [13].

2.4 Open Rectangular Building Geometry

Normally, most radiation facilities are well shielded on the sides. Much less shielding against radiations is, however, provided by the roof. Hence, the geometry analyzed here is of practical significance. The geometry of the problem is depicted in Fig. 3. A point, isotropic, neutron source is located on the z-axis at a vertical distance h_s below the horizontal plane through the top of the roof. The front and rear walls are, respectively, located at distances x_2 and x_1 from the source. The right wall of the building is located at a distance y_1 from the source along the y-axis while the left wall is located at a distance y_2 from the source. A detector is placed at the coordinate $(x_d, y_d, h_s - h_d)$. The source emits S neutrons with a fraction f_g being emitted in energy group g whose midpoint energy is E_g. For this geometry the skyshine dose at the detector is given by

$$R_i(d) = \frac{S}{4\pi} \sum_{g=1}^{G} f_g \int_0^{2\pi} d\psi \int_{\omega_{min}(\psi)}^{1} d\omega\, \Re_i(d, E_g, \phi). \tag{17}$$

The subscript i again refers to either the neutron skyshine dose or the dose from neutron-induced secondary gamma rays.

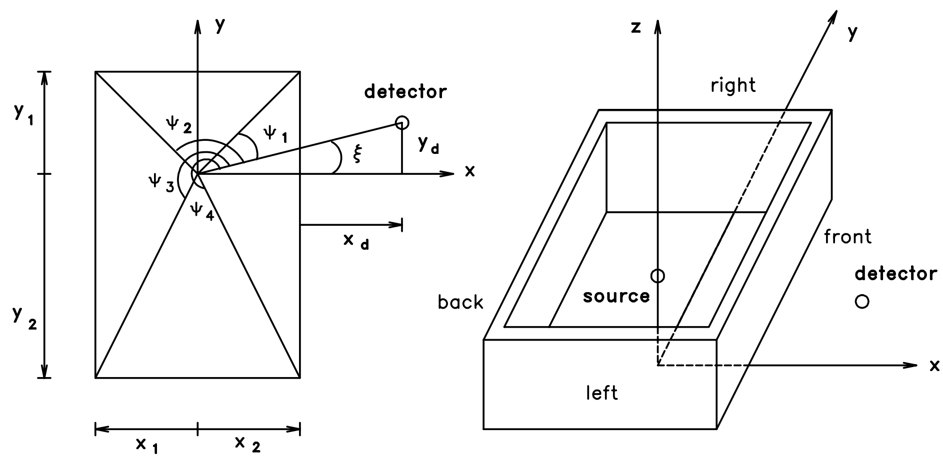

Figure 3. Geometry for roofless rectangular building. The source is on the z-axis at a vertical distance h_s below the horizontal plane through the top of the building. A detector is placed at the coordinates $(x_d, y_d, h_s - h_d)$.

In Eq. (17), ω_{min} is a function of the azimuthal angle ψ. It can be shown that the following relations hold [13]

$$d = \sqrt{(x_2 + x_d)^2 + (h_s - h_d)^2 + y_d^2}, \tag{18}$$

$$\xi = \tan^{-1}\left(\frac{y_d}{x_2 + x_d}\right), \tag{19}$$

and

$$\zeta = \tan^{-1}\left(\frac{h_s - h_d}{\sqrt{(x_2 + x_d)^2 + y_d^2}}\right). \tag{20}$$

The angle between the emission direction and the source-detector-axis, ϕ, is given by Eq. (15).

As for the infinite wall case, it is obvious that the minimum value of the polar angle θ is 0^0, thus $\omega_{max} = 1$. There are four possible values for θ_{max}, which occur when the source beam just clears the top corners of the rectangular room. The azimuthal angles corresponding to these four values are denoted by ψ_1, ψ_2, ψ_3, and ψ_4 which can be shown to be [13]

$$\psi_1 = \tan^{-1}(y_1/x_2) - \xi, \tag{21}$$

$$\psi_2 = \tan^{-1}(x_1/y_1) + \pi/2 - \xi, \tag{22}$$

$$\psi_3 = \tan^{-1}(y_2/x_1) + \pi - \xi, \tag{23}$$

$$\psi_4 \quad = \quad \tan^{-1}(x_2/y_2) + 3\pi/2 - \xi, \tag{24}$$

and the maximum polar angle is

$$\theta_{max} = \begin{cases} \tan^{-1}\left(\dfrac{x_2}{h_s \cos(\psi + \xi)}\right), & \psi_4 - 2\pi \le \psi \le \psi_1, \\ \tan^{-1}\left(\dfrac{y_1}{h_s \cos(\psi + \xi - \pi/2)}\right), & \psi_1 \le \psi \le \psi_2, \\ \tan^{-1}\left(\dfrac{x_1}{h_s \cos(\psi + \xi - \pi)}\right), & \psi_2 \le \psi \le \psi_3, \\ \tan^{-1}\left(\dfrac{y_2}{h_s \cos(\psi + \xi - 3\pi/2)}\right), & \psi_3 \le \psi \le \psi_4. \end{cases} \tag{25}$$

3 Required Input Data

Data may be entered either interactively from the keyboard, or from a previously prepared input file. While modest checking of input data is attempted by SKYNEUT, the program is not totally "bullet-proof" and the user must bear some responsibility to enter meaningful data.

The nature of the input data depends on which of the three geometries is to be used. The input data consist of three blocks: the first defines the output file name and the energy spectrum of the source. The second block specifies the type of skyshine geometry and the geometry-independent parameters while the third block specifies geometry variables for the geometry selected in the second block. The input parameters for each block are specified below.

3.1 Source Energy

If the problem data are entered from the keyboard and if the source is monoenergetic, the source energy is simply entered at the appropriate screen prompt. However, if the source is polyenergetic, the source spectrum is first specified in a data file which SKYNEUT reads. (The format of input data files is discussed in the next section.) To specify a polyenergetic source spectrum, a multigroup formulation is used and is specified by the following parameters.

`NE` The number of energy groups to be used (`NE` ≤ 30).

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

`P(i)` The probability a neutron is emitted in group `i`, `i` $= 1, ...,$`NE`. The sum over all `P(i)` should equal unity.

3.2 Geometry-Independent Parameters:

`OUTFIL` File specification for the output file, e.g., SKYNEUT.OUT

`IPROB` Indicates the skyshine source geometry. Permissible values are
= 1 for the source on the axis of a circular silo (*"silo geometry"*)
= 2 for the source behind an infinitely long wall (*"wall geometry"*)
= 3 for the source in a rectangular building (*"box geometry"*)

`RHO` The air mass density in g/cm^3. The line-beam response function approximation used by SKYNEUT 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. The intermediate distances are equally spaced out to the maximum distance specified later in the input.

`INDX` Index to specify the type of neutron and secondary gamma-ray doses. Permissible values are
= 1 for AP effective dose equivalent in a phantom
= 2 for PAR (ambient) dose equivalent (10 mm depth)
= 3 for ISO dose equivalent (10 mm depth)

`NGAU` The order of the Gaussian quadrature used for the numerical integration over the source emission directions. Permissible values are 4, 8, 16, or 32. The higher the order, the longer the calculations will take but the more precise will be the predicted skyshine doses.

3.3 Geometry-Dependent Parameters

3.3.1 Silo Geometry (`IPROB` = 1)

In this geometry, a point, isotropic, neutron source is on the axis of a silo with a circular cross section. The top of the silo is assumed to be in a horizontal plane and the source is below the silo top. The source location and silo radius define the effective collimation of the radiation emitted into the atmosphere. The silo walls are assumed to be impenetrable and any in-silo scattering is ignored. The following input parameters are required:

`HS` Displacement or elevation of the source below the top of the silo (m). This must be positive, i.e., the source must be below the silo top.

`HD` Detector elevation with respect to the top of the silo (m). This elevation may be positive (for the detector below the silo top) or negative (for the source above the silo top).

R Radius of the circular silo (m). Must be positive.

XD The maximum horizontal distance from the source at which the skyshine dose is to be evaluated. Doses will also be estimated at NPTS intermediate points, equally distributed between the source and the maximum distance XD. XD must be greater than the silo radius R.

3.3.2 Wall Geometry (IPROB = 2)

In this geometry a point, isotropic, neutron source is placed behind and below an infinitely-long, vertical, black wall. The detector is located at some location on the other side of the wall. The following input parameters are required:

HS Displacement or elevation of the source below the top of the wall (m). This must be positive, i.e., the source must be below the top of the wall.

HD Detector elevation with respect to the top of the wall (m). This elevation may be positive (for the detector below the wall top) or negative (for the source above the wall top).

R The distance (m) between the source and the wall along a perpendicular from the source to the wall. This distance must be positive.

ZD The lateral horizontal displacement (m) of the detector from a vertical plane through the perpendicular line from the source to the wall, i.e., the perpendicular distance from the detector to this vertical plane. ZD may be positive or negative.

XD The horizontal source-to-detector distance (m) along axis formed by the normal from the source to the wall. Doses will also be estimated at NPTS intermediate points, equally distributed between the source and the maximum distance XD. XD must be greater than the source to wall distance R.

3.3.3 Box Geometry (IPROB = 3)

In this geometry a point, isotropic, neutron source is placed at an arbitrary position inside a rectangular building whose four vertical sides are assumed to be black. The detector is located outside the building. The "front" wall of the building is that wall through which a line between the source and detector passes. The following input parameters are required:

HS Displacement or elevation of the source below the top of the walls (m). This must be positive, i.e., the source must be below the top of the building.

`HD` Detector elevation with respect to the top of the walls (m). This elevation may be positive (for the detector below the building top) or negative (for the source above the building top).

`X1` The perpendicular distance (m) from the source to the "rear" wall, i.e., the wall opposite the "front" wall. Must be positive.

`X2` The perpendicular distance (m) from the source to the "front" wall. Must be positive.

`Y1` The perpendicular distance (m) from the source to the "left" wall as viewed from the detector position. Must be positive.

`Y2` The perpendicular distance (m) from the source to the "right" wall as viewed from the detector position. Must be positive.

`YD` Horizontal offset (m) of the detector from vertical plane through normal from the source to the front wall. Note: $-\texttt{Y2} \leq \texttt{YD} \leq \texttt{Y1}$.

`XD` Horizontal distance (m) from the detector along a normal to the front wall. It is required that the detector be outside the building, i.e., $\texttt{XD} > 0$.

4 Data Files

4.1 Keyboard Data Entry

If all problem data are to be entered interactively from the keyboard in response to program prompts, there is no need for an input data files *unless* a polyenergetic source spectrum is to be used. In this case, an ASCII file defining the multigroup nature of the source must be created prior to starting SKYNEUT. During entry of keyboard data you will be prompted for the name of the source spectrum file.

The format of the spectrum input file is as follows:

```
Line 1:   NE
Line 2:   E(1), E(2), ..., E(NE)
Line 3:   P(1), P(2), ..., P(NE)
```

The data is entered in "free format" with spaces and/or commas separating the values. Multiple lines may be used for the `E(i)` and `P(i)` values provided that `E(1)` and `P(1)` each begin a new line.

4.2 Data Entry From a File

Rather than enter input data interactively with SKYNEUT, it is often more convenient, especially if many similar cases are to be analyzed, to place the input data into separate input files and have SKYNEUT read these files. If you indicate to SKYNEUT that the input data is to be read from a file, SKYNEUT will ask you to enter the file name (e.g., `SKYNEUT.INP`). The file will then be opened and the input data read.

The ASCII input file must contain the input data in the order specified above. The structure of an input file is thus

```
Output file name (OUTFIL)
NE
E(1), E(2), ..., E(NE)
P(1), P(2), ..., P(NE)
geometry-independent parameters
geometry-dependent parameters
```

The output file name (e.g., `SKYNEUT.OUT`, into which the analysis results are written, is entered as the first item in each input file. If the file already exists, SKYNEUT will overwrite it.

The source energy spectrum data is entered as shown (although multiple lines may be used to enter the `E(i)` and the `P(i)` values. Note, even if the source is monoenergetic, this multigroup format must be used with `NE = 1`, `E(1) =` the source energy, and `P(1) = 1` with each value entered on a separate line.

Geometry-independent parameters are: `IPROB, RHO, NPTS, INDX, NGAU`. They may appear on a single input line or occupy several lines of the input file. However, these parameters must appear in the order indicated.

The geometry-dependent parameters needed depend on the value of `IPROB` for each case.

For `IPROB` = 1 (silo geometry) specify `HS, HD, R, XD`

For `IPROB` = 2 (wall geometry) specify `HS, HD, R, ZD, XD`

For `IPROB` = 3 (box geometry) specify `HS, HD, X1, X2, Y1, Y2, YD, XD`

These parameters must begin on a new line of the input file, and each can be placed several to a line, or each on its own line in the input file.

A typical input file for two separate cases might be

```
silo2.out                        | output filename
1                                | NE = 1 monoenergetic source
5.00                             | E(1) source energy (MeV)
1                                | P(1) = 1 for monoenergetic source
1   0.0012   5   1   32          | IPROB RHO NPTS INDX NGAU
.00001  .00001  1.0  3000.       | HS HD R XD
```

5 Examples

Example output for the three different geometries are shown below. Although three different geometries are illustrated, each case is for the same problem, namely a 2π collimation of a point isotropic source with neutrons emitted in five energy groups. The source and detector are just below the collimation structure so that the detector response is for skyshine arising from source neutrons collimated vertically into a hemisphere. For all three geometries, the predicted skyshine dose are thus the same.

5.1 Silo Geometry

For the input file

```
silo2pi.out
5
0.50 1.00 1.50 2.00 2.50
0.05 0.20 0.50 0.20 0.05
1   0.0012   5   1   32
.00001  .00001  1.0  3000.
```

the following output is obtained.

```
****** SKYNEUT: Silo Geometry
  Air density (g/cm^3)        =        .001200
  Source elevation (m)        =            .00
  Detector elevation (m)      =            .00
  Silo radius (m)             =           1.00
  Source collimation (sr)     =         6.2831
  Source-detector dist. (m)   =         3000.0
  Gauss quadrature order      =             32
  Source energy type          =       Spectrum
  3-parm. approx. LBRF used

        ENERGIES       PROBABILITIES
         .50000           .05000
        1.00000           .20000
        1.50000           .50000
        2.00000           .20000
        2.50000           .05000


          SKYSHINE DOSE: EDE - ICRP Phantom (AP)
  -------------------------------------------------------
        S-D         S-D         Neutron      Sec. Gamma
        (m)       (g/cm^2)    (Sv/neut)     (Sv/neut)
  -------------------------------------------------------
        500.        60.00     2.0544E-21    8.9254E-24
       1000.       120.00     3.6028E-23    1.1188E-24
       1500.       180.00     8.3852E-25    1.2132E-25
       2000.       240.00     2.3706E-26    1.2618E-26
       2500.       300.00     8.0159E-28    1.3079E-27
       3000.       360.00     3.1864E-29    1.3751E-28
  -------------------------------------------------------
```

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 from neutrons and secondary gamma radiation, respectively. In this example the dose units are the effective dose equivalent for AP irradiation of the ICRP anthropomorphic phantom.

5.2 Wall Geometry

For the input file

```
wall2pi.out
5
0.50 1.00 1.50 2.00 2.50
0.05 0.20 0.50 0.20 0.05
2    0.0012    5    1   32
.0001  .0001  1.0  0.0  3000.
```

the following output is obtained.

```
****** SKYNEUT: Wall Geometry
  Air density (g/cm^3)         =        .001200
  Source elevation (m)         =            .00
  Detector elevation (m)       =            .00
  Source-to-wall distance(m)   =           1.00
  Detector horiz. offset (m)   =            .00
  Source-detector dist. (m)    =         3000.0
  Gauss quadrature order       =             32
  Source energy type           =       Spectrum
  3-parm. approx. LBRF used

        ENERGIES       PROBABILITIES
         .50000           .05000
        1.00000           .20000
        1.50000           .50000
        2.00000           .20000
        2.50000           .05000


          SKYSHINE DOSE: EDE - ICRP Phantom (AP)
  -------------------------------------------------------
        X          S-D        Neutron      Sec. Gamma
       (m)         (m)       (Sv/neut)     (Sv/neut)
  -------------------------------------------------------
       500.       500.00     2.0487E-21    8.9024E-24
      1000.      1000.00     3.5897E-23    1.1172E-24
      1500.      1500.00     8.3512E-25    1.2129E-25
      2000.      2000.00     2.3612E-26    1.2633E-26
      2500.      2500.00     7.9882E-28    1.3113E-27
      3000.      3000.00     3.1776E-29    1.3806E-28
  -------------------------------------------------------
```

In the above table of calculated skyshine doses, columns 1 is the *horizontal* source-to-detector distance. Column 2 is the straight-line source-to-detector distance which will be slightly different from that of column 1 if the source and detector are at different elevations. Columns 3 and 4 give the skyshine dose from neutrons and secondary gamma photons, respectively.

5.3 Box Geometry

For the input file

```
box2pi.out
5
0.50 1.00 1.50 2.00 2.50
0.05 0.20 0.50 0.20 0.05
3  0.0012  5  1  32
.0001 .0001  1.0  1.0  1.0  1.0  0.0  3000.
```

the following output is obtained.

```
****** SKYNEUT: Rectangular Building Geometry
  Air density (g/cm^3)              =       .001200
  Source elevation (m)              =           .00
  Detector elevation (m)            =           .00
  Source-rear wall distance (m)     =          1.00
  Source-front wall distance (m)    =          1.00
  Source-left wall distance (m)     =          1.00
  Source-right wall distance (m)    =          1.00
  Detector offset from normal (m)   =           .00
  Detector-front wall distance(m)   =       3000.00
  Gauss quadrature order            =            32
  Source energy type                =      Spectrum
  3-parm. approx. LBRF used

        ENERGIES       PRPBABILITIES
         .50000           .05000
        1.00000           .20000
        1.50000           .50000
        2.00000           .20000
        2.50000           .05000


          SKYSHINE DOSE: EDE - ICRP Phantom (AP)
  ------------------------------------------------------
         X          S-D       Neutron      Sec. Gamma
        (m)         (m)      (Sv/neut)    (Sv/neut)
  ------------------------------------------------------
        500.      500.00     2.0519E-21   8.9247E-24
       1000.     1000.00     3.5995E-23   1.1187E-24
       1500.     1500.00     8.3782E-25   1.2130E-25
       2000.     2000.00     2.3687E-26   1.2617E-26
       2500.     2500.00     8.0105E-28   1.3083E-27
       3000.     3000.00     3.1846E-29   1.3761E-28
  ------------------------------------------------------
```

In the above table of calculated skyshine doses, columns 1 is the *horizontal* source-to-detector distance. Column 2 is the straight-line source-to-detector distance which will be slightly different from that of column 1 if the source and detector are at different elevations. Columns 3 and 4 give the skyshine dose from neutrons and secondary gamma photons, respectively.

6 Auxiliary Files

SKYNEUT requires that the following six auxiliary files be present in the same directory as SKYNEUT.

> `NEDE.DAT` and `GEDE.DAT` for AP effective dose equivalent
> `NEDP.DAT` and `GEDP.DAT` for PAR (ambient) dose equivalent
> `NEDI.DAT` and `GEDI.DAT` for ISO dose equivalent

These ASCII files contain the parameters a, b, and c for the approximate line-beam response function of Eq. (5) for the neutron dose (`NEDE.DAT, NEDP.DAT, NEDI.DAT`) and the secondary gamma-photon dose (`GEDE.DAT, GEDP.DAT, GEDI.DAT`). For example, `NEDE.DAT` begins as

```
! E=  0.01
    1.0   -29.3941911  -.01120174 -1.65967789
    2.0   -30.5019234  -.01093641 -1.50215539
    4.0   -31.3923481  -.00976258 -1.41024703
     .... (lines omitted)
  130.0   -36.5126591  -.01027047  -.61246592
  150.0   -36.6357915  -.01033351  -.59729537
  170.0   -36.6346405  -.01045805  -.60534996
! E= 0.05
    1.0   -30.7384219  -.01203893 -1.49820353
    2.0   -31.5764538  -.01098943 -1.44712132
    4.0   -32.6653884  -.01076011 -1.30236275
     ....
```

The line beginning with "`!  E=` " gives the neutron energy and is followed by 18 lines giving the values of a, b, and c for 18 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, SKYNEUT uses interpolation procedures to evaluate the line-beam response function at any energy between 0.01 and 14 MeV and for any emission direction between 0 and 180 degrees.

Finally, it should be noted that the neutron (but not the secondary-photon) doses calculated from the data in these files include the multiplicative factor of 2 recommended by the ICRP [12]. However, because this recommendation has been rejected by US regulators, the neutron skyshine doses calculated by SKYNEUT have been reduced by 50% to remove this factor of 2.

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ACKNOWLEDGMENTS

The development of the basic methodology and early versions of the integral line-beam method were partially supported by Grove Engineering, Inc., and later by Sandia National Laboratory. The present code, which extends the earlier effort for gamma photons to neutrons, was made possible by support from the Engineering Experiment Station of Kansas State University.