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The SHIELD11 Computer Code

W. R. Nelson* and T. M. Jenkins†

Radiation Physics Group
Stanford Linear Accelerator Center
Stanford University
Stanford, CA 94309

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*Department Associate in the Radiation Physics Group (retired)
†Former Deputy Head of the Radiation Physics Group (retired)

Summary

SHIELD11 is a computer code for performing shielding analyses around a high-energy electron accelerator. It makes use of simple analytic expressions for the production and attenuation of photons and neutrons resulting from electron beams striking thick targets, such as dumps, stoppers, collimators, and other beam devices.

The formulae in SHIELD11 are somewhat unpretentious in that they are based on the extrapolation (scaling) of experimental data using rather simple physics ideas. Because these scaling methods have only been tested over a rather limited set of conditions—namely, 1-15 GeV electrons striking 10-20 radiation lengths of iron—a certain amount of care and judgment must be exercised whenever SHIELD11 is used. Nevertheless, for many years these scaling methods have been applied rather successfully to a large variety of problems at SLAC, as well as at other laboratories throughout the world, and the SHIELD11 code has been found to be a fast and convenient tool.

In this paper we present, without extensive theoretical justification or experimental verification, the five-component model on which the SHIELD11 code is based. Our intent is to demonstrate **how to use the code** by means of a few simple examples. References are provided that are considered to be essential for a full understanding of the model. The code itself contains many comments to provide some guidance for the *informed* user, who may wish to improve on the model.

Contents

1 Introduction

Many of the shielding methods currently used at SLAC are based on fundamental concepts that have been published in Chapter 26 of the book that documents the creation of the Stanford Two-Mile Accelerator[1]. For an electron accelerator, the underlying process involved in the production of the various radiation fields is the electromagnetic (EM) cascade shower. Although the intrinsic interactions of electrons and photons with matter were reasonably well understood during the early 1960s when SLAC was being constructed, a fully comprehensive treatment of both EM and hadronic shower theory had to wait a few more years for the development of Monte Carlo codes, such as EGS[2] and FLUKA[3], respectively.

Nevertheless, even at that time, the basic features of EM showers could be found in textbooks, most notably Rossi's *High-Energy Particles*[4], and the thick-target shielding problem for an electron accelerator reduced to one of developing a reasonable method for determining the energy-angle distribution of the **secondary radiation** as it emanates from the core of a fully-developed EM cascade in a typical beam device.

Early in the design of the Two-Mile Accelerator and its associated beam lines, it became apparent that neutron and photon radiation emanating from thick targets can be grouped (roughly) into five distinct components:

- Giant-Resonance Neutron (GRN): Neutrons having energies in the $0.1 < E < 20$ MeV range. These so-called *fast-neutrons* are photo-produced in the core of the shower by means of the mechanism known as giant-resonance excitation[5, 6, 7].
- High-Energy Neutron (HEN): Neutrons with energies above 100 MeV that are an integral part of the hadronic cascade that is initiated by high-energy photons in the EM cascade. Although the HEN component is the radiation field that dominates for thick shields (*i.e.*, 4 or more feet of concrete), high-energy neutrons themselves are difficult to observe experimentally. What is usually measured are evaporation neutrons (< 20 MeV) produced in high-energy hadronic events (called "stars"). These low-energy neutrons are sometimes referred to as the "camp followers" of the hadronic cascade[8].
- Mid-Energy Neutron (MID): Neutrons having energies between the GRNs and HENs ($20 < E < 100$ MeV), including those produced by means of the quasi-deuteron reaction[5].
- Direct Gamma (GamD): Photons escaping directly from the core of the EM shower with energies in the $0.1 < E < 20$ MeV range, as characterized by thick-target penetration through the so-called "Compton window" (*i.e.*, the minimum of the mass attenuation coefficient). The angular distribution consists of a slowly decreasing level from $0°$–$180°$, superimposed onto which is a very forward ($0°$–$5°$) bremsstrahlung core[1, 9].
- Indirect Gamma (GamI): Photons and directly ionizing particles (*e.g.*, charged pions) that accompany the attenuation of the HEN field in the shield. This component has been experimentally determined to be slightly more than 25% of the HEN dose rate[10].

Each of these components can be described by an empirical model that is experimentally based on what we have traditionally called the *standard-target* arrangement—namely, a *12-inch long cylinder of iron, having a radius of 2-inches, that is struck by a 10 GeV electron beam*. Further details about the *standard-target* model, together with methods for scaling each of the five components to other beam energies, targets and shielding materials, is described in Appendix A.

2 Organization of the SHIELD11 code

SHIELD11 is a Fortran77 code that is distributed as a compressed file (`shield11.tar.gz`) that can be uncompressed using either Winzip or gtar. An `include/` subdirectory contains the various `COMMON` files (*e.g.*, `beam.fh`), as well as a header file (`shield11_h.fh`) that defines the array sizes. SHIELD11 is to a large extent self-documenting and is organized as follows.

- `MAIN`: Driver program to
  - read in the user-supplied data (*e.g.*, geometry, beam energy, etc.),
  - loop over (and sum) the five source components,
  - output the results.
- `BLOCK DATA`: Definitions for target and shield constants (*e.g.*, densities, removal mean-free paths, etc.).
- `SUBROUTINE DataIO`: Subprogram to read and echo-print the input data (as well as the various constants in `BLOCK DATA`).
- `SUBROUTINE DosOut`: Subprogram to print out the dose equivalent (rate) for each of the five components (and their sum) in a convenient format.
- `FUNCTION Sorc`: Subprogram to determine each of the five components described above.

2.1 Input and output

The input and output files required by SHIELD11 are defined at the beginning of `MAIN` by means of the following statements:

```
!     ----------
!     Open files
!     ----------
      open(UNIT= 5,FILE='shield11.in5',STATUS='OLD')
      open(UNIT= 6,FILE='shield11.out6',STATUS='UNKNOWN')
```

2.1.1 User input file (`shield11.in5`)

The following is an example of a `shield11.in5` input file (based on the *standard target*).

```
2                                IOSW (0=none,1=input,2=media/input) (I1)
      10.0                       Ebeam (GeV) (F10.0)
FE                               NamTar (A4)
      12.0       2.0             TarLen (inch), TarRad (inch) (2F10.0)
0                                IattSW (1=target n-atten., 0=none) (I1)
CONC                             NamShl (A4)
      90.0     39.37             AngShl (deg), DisShl (inch) (2F10.0)
       0.0                       ThkShl (inch) (F10.0)
         1       0.0      90.0   NTheta, dTheta, Theta0 (deg) (I10,2F10.0)
       0.0                       ThkCON (inch) (F10.0)
       0.0                       ThkFE (inch) (F10.0)
       0.0                       ThkPB (inch) (F10.0)
       0.0                       ThkMIS (inch) (F10.0)
```

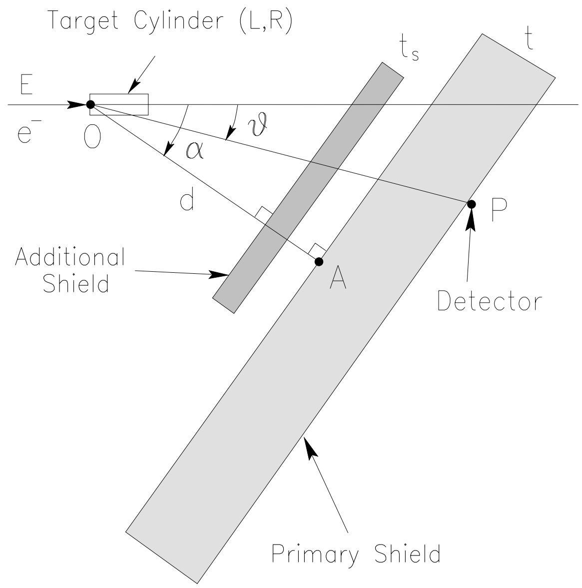

Figure 1: SHIELD11 geometry.

Referring to the above geometry sketch (Fig. 1) the various parameters in `shield11.in5` are:

- `IOSW`: Switch for additional output to the file called `shield11.out6` (0=none, 1=input data, 2=media and input data).
- `Ebeam`: Incident electron beam energy (E) (GeV).
- `NamTar`: Target material (choices: `'CONC'`, `'FE '`, `'PB '`, or `'MISC'`.
- `TarLen`: Target length (L) (inches) (converted to cm in the code).
- `TarRad`: Target radius (R) (inches) (converted to cm in the code).
- `IattSW`: Switch for including neutron attenuation by the target itself (0=no, 1=yes)[1] .
- `NamShl`: Primary (*i.e.*, outer) shield material (same choices as for `NamTar`).
- `AngShl`: Angle of primary shield relative to beam direction (α) (degrees).
- `DisShl`: Primary shield distance from target ($d = \overline{OA}$) (inches) (converted to cm in the code).
- `ThkShl`: Primary shield thickness (t) (inches) (converted to cm in the code).
- `NTheta`: Number of detectors (each located at point P).
- `dTheta`: Angular increment between detectors (degrees).
- `Theta0`: Angle of first detector (ϑ) (degrees).
- `ThkPB`, `ThkFE`, `ThkCON` and `ThkMIS`: Additional (inner) shielding thicknesses (t_S) (inches) (same choices as for `NamTar`).

Note: Although the target has dimensions (*i.e.*, L and R), it should be clearly understood that the *model* we use in the SHIELD11 code assumes that the radiation emanates from a *point-like source* located at O.

[1]To err on the conservative side, it is advised that zero be selected for `IattSW`, unless the target-attenuation model described in Appendix C is fully understood.

2.1.2 SHIELD11 output file (`shield11.out6`)

The following was created by SHIELD11 using the *standard-target* input example shown above.

```
*********************************************************************
                         MATERIAL DATA
*********************************************************************
MatID                      CONC      FE        PB       MISC

Zmat                      13.00     26.00     82.00     82.00
Amat                      26.98     55.85    207.19    207.19
RHOmat (g/cu.cm)           2.35      7.87     11.35     11.35

RLmat  (g/sq.cm)          26.70     13.84      6.37      6.37
XMUmat (g/sq.cm)          11.10     10.70     14.20     14.20
                                                                  Isorc
Xmfp   (g/sq.cm)          30.00     47.00     97.00    135.00   1 (GRNs)
                          55.00    145.00    200.00    200.00   2 (MIDs)
                         120.00    145.00    200.00    200.00   3 (HENs)
                          42.00     33.60     24.00     24.00   4 (GamD)
                         120.00    145.00    200.00    200.00   5 (GamI)

*********************************************************************
                           INPUT DATA
*********************************************************************
2                                   IOsw (0=none,1=input,2=media/input)
    10.000                          Ebeam (GeV)
FE                                  NamTar
    12.000     2.000                TarLen (inch),TarRad (inch)
0                                   IattSW (1=target n-atten., 0=none)
CONC                                NamShl
    90.000    39.370                AngShl (deg),DisShl (inch)
     0.000                          ThkShl (inch)
         1     0.000    90.000      NTheta,dTheta,Theta0 (deg)
     0.000                          AddCON (inch)
     0.000                          AddFE (inch)
     0.000                          AddPB (inch)
     0.000                          AddMIS (inch)

*********************************************************************
                     RESULTS OF CALCULATION
*********************************************************************
      ---------------------------------------------------------
      Production angle=  90.000     degrees    [G/N= 1.1387    ]
      ---------------------------------------------------------
         GRN          MID          HEN          Neutron
       .42615E-12  .99099E-13  .10027E-13  .53527E-12  rem/e
       958.83      222.97      22.560      1204.4      rem/h/kW

         GamD         GamI        Gamma         TOTAL
       .60686E-12  .26771E-14  .60954E-12  .11448E-11  rem/e
       1365.4      6.0235      1371.5      2575.8      rem/h/kW
                                           ==========
```

The first two parts of the output echo the material data available in `BLOCK DATA` and the input data provided by the user, respectively. Note that the user has the choice of printing more or less output by means of the switch, IOSW, described above.

For this *standard-target* example we placed a primary concrete shield (NamShl=CONC) at an angle of 90-degrees relative to the beam direction (AngShl=90.0) and at a distance from the target of one meter (DisShl=39.37 inches). We also chose the thickness of the primary shield to be zero (ThkShl=0.0 inches) and asked SHIELD11 to output the results for a single detector located at an angle of 90-degrees (NTheta=1, dTheta=0.0, Theta0=90.0).

The results are given in two sets of units: a) *dose-equivalent rate* (rem / h) normalized to an incident beam power of one kW, and b) *dose equivalent per incident electron* (rem / e). The columns labeled GRN, MID, HEN, GamD and GamI are the five components in the model. The columns labeled Neutron and Gamma correspond to the sum of those components, respectively. The column labeled TOTAL is the grand sum of all components. The ratio of gamma-to-neutron is also shown (*i.e.*, G/N=1.1387).

2.1.3 Restrictions on primary *vs.* secondary shield materials

As explained in the commentary at the beginning of BLOCK DATA, and as a general rule when using SHIELD11, concrete should be chosen as the primary (*i.e.*, outer) shield material. The reason for this is that the *fast-neutron* removal mean-free paths that are defined in BLOCK DATA for iron and lead[12] are really only applicable when there is at least 6 g / cm^2 of hydrogenous moderator in front of the detector.

Accordingly, SHIELD11 studies should normally start with a primary concrete shield that is at least two feet thick, thereby allowing high-Z material to be added *between the target and primary shield* as part of the overall shield design, if needed.

The 'MISC' indentifer (see NamTar) has been included in SHIELD11 in order to allow users to define special materials whose attenuation properties are known. For example, at SLAC we occasionally use a lead (or iron) shield without following it with the preferred two feet of concrete (or appropriate hydrogenous layer), but we are careful to choose a different mean-free path for the *fast-neutron* component. A close inspection of BLOCK DATA (see code listing in Appendix D.2) will show that 135 g / cm^2 has been chosen for Xmfp(4,1), the *fast-neutron* mean-free path for 'MISC', whereas 97 g / cm^2 is the standard value that is used with lead (*i.e.*, 'PB ') that is followed by moderator (note: the other parameters for 'MISC' remain the same as those for 'PB ').

3 The five components of SHIELD11

The five radiation components in the model are evaluated in the MAIN program of SHIELD11 through a series of calls to FUNCTION Sorc. Specifically, the following section of code

```
!       ----------------------------------
!       Get dose (rem/e) for each component
!       ----------------------------------
        do Isorc=1,5
          Dose(Isorc) = Sorc                             ! rem/e (at 1 cm)
     +    (Isorc,IDtar,TarLen,TarRad,IattSW,Ebeam,Theta)*
     +      exp(-SltShl/Xmfp(IDshl,Isorc))*             ! Primary shield
     +      exp(-SltCON/Xmfp(1,Isorc))*                 ! Added CONCrete
     +      exp(-SltFE/Xmfp(2,Isorc))*                        ! Added FE
```

```
     +      exp(-SltPB/Xmfp(3,Isorc))*                          ! Added PB
     +      exp(-SltMIS/Xmfp(4,Isorc))/                       ! Added MISC
     +      Rsq                                  ! rem/e (actual distance)
        end do
```

fills the five elements of the `Dose` array with the dose equivalent (rem / electron) at a distance of one cm from the front face of the target (point O in Fig. 1). Attenuation due to shielding is than taken into account and the results are scaled to the actual distance from the source to the detector.

The following commentary, which appears at the beginning of `FUNCTION Sorc`, describes each of the parameters and what restrictions apply when using SHIELD11.

```
!***********************************************************************
!********************************   STANFORD LINEAR ACCELERATOR CENTER *
!
      FUNCTION Sorc(Isorc,IDtar,TarLen,TarRad,IattSW,Energy,Angle)
!
!********************************   Version:           1 FEB 2005/0800 *
!***********************************************************************
! This subprogram returns the dose equivalent (rem/e) at 1 cm.
!***********************************************************************
!    Isorc    Source Type:  1 = Giant Resonance Neutrons (GRNs)
!                           2 = Mid-Energy Neutrons (MIDs)
!                           3 = High-Energy Neutrons (HENs)
!                           4 = Gamma Direct (EM cascade) (GamD)
!                           5 = Gamma Indirect (hadron cascade) (GamI)
!
!    IDtar    Target ID:    1 = CONC   (concrete)
!                           2 = FE     (iron)
!                           3 = PB     (lead)
!                           4 = MISC   (default is lead w/o moderator)
!    TarLen   Target length (cm).  Restrictions: Should be larger than
!             0.01 r.l. for photons & larger than 17.3 r.l. for neutron
!             attenuation by the target itself (i.e., when IattSW=1).
!    TarRad   Target radius (cm).  Restrictions: Should be larger than
!             2-in for Fe (or an equivalent number of GamD relaxation
!             lengths for other materials) for neutrons.  Also, should
!             be at least 3.74 Moliere Units in radius for neutron
!             attenuation by the target itself (i.e., when IattSW=1).
!    IattSW   Switch for neutron attenuation by the target material
!             itself (0=no attenuation, 1=attenuation).
!             [Note: Target length must be .GE. 17.3 r.l. and target
!                    radius must be .GE. 3.74 Moliere Units].
!    Energy   Energy of electron beam (GeV)
!             [Note: Below 1 GeV, approximation schemes (based on data
!                    fitting, etc.) are applied to the MID and HEN
!                    neutron terms.]
!    Angle    Production angle (degrees)
!***********************************************************************
```

Other data required by `FUNCTION Sorc`, such as material densities, mean-free paths, general constants, etc., are defined in `BLOCK DATA` (see Appendix D.2) and passed by means of `common/MATDTA/`, `common/MISCON/` and `common/SORCON/`, which in turn are brought into the SHIELD11 code via Fortran77 ‘`include`’ statements.

4 Examples to demonstrate how to use SHIELD11

4.1 Lateral shielding of a beam dump

Assume that a 1 kW beam of 10 GeV electrons strikes a beam dump that we model as a *standard target*. The primary shield is a 5-ft thick concrete tunnel, the inside surface of which runs parallel to the beam line at a distance of 4-ft. In this example we consider three detector angles between 70°–90°. The following is the SHIELD11 output and the input data necessary to produce it.

```
**********************************************************************
                              INPUT DATA
**********************************************************************
1                                  IOsw (0=none,1=input,2=media/input)
    10.000                         Ebeam (GeV)
FE                                 NamTar
    12.000     2.000               TarLen (inch),TarRad (inch)
0                                  IattSW (1=target n-atten., 0=none)
CONC                               NamShl
    90.000    48.000               AngShl (deg),DisShl (inch)
    60.000                         ThkShl (inch)
         3    10.000    70.000     NTheta,dTheta,Theta0 (deg)
     0.000                         AddCON (inch)
     0.000                         AddFE (inch)
     0.000                         AddPB (inch)
     0.000                         AddMIS (inch)

**********************************************************************
                        RESULTS OF CALCULATION
**********************************************************************
      ----------------------------------------------------------
      Production angle=  70.000     degrees    [G/N= .33410    ]
      ----------------------------------------------------------
         GRN         MID         HEN         Neutron
       .15194E-18  .15303E-16  .86462E-16  .10192E-15  rem/e
       .34187E-03  .34433E-01  .19454      .22931      rem/h/kW

         GamD        GamI       Gamma        TOTAL
       .10965E-16  .23085E-16  .34051E-16  .13597E-15  rem/e
       .24672E-01  .51942E-01  .76615E-01  .30593      rem/h/kW
                                           ==========
      ----------------------------------------------------------
      Production angle=  80.000     degrees    [G/N= .36902    ]
      ----------------------------------------------------------
         GRN         MID         HEN         Neutron
       .29865E-18  .19736E-16  .81509E-16  .10154E-15  rem/e
       .67196E-03  .44406E-01  .18340      .22847      rem/h/kW

         GamD        GamI       Gamma        TOTAL
       .15708E-16  .21763E-16  .37471E-16  .13902E-15  rem/e
       .35344E-01  .48967E-01  .84310E-01  .31278      rem/h/kW
                                           ==========
      ----------------------------------------------------------
      Production angle=  90.000     degrees    [G/N= .38892    ]
      ----------------------------------------------------------
         GRN         MID         HEN         Neutron
       .37020E-18  .19570E-16  .67373E-16  .87313E-16  rem/e
       .83295E-03  .44032E-01  .15159      .19645      rem/h/kW

         GamD        GamI       Gamma        TOTAL
       .15969E-16  .17989E-16  .33958E-16  .12127E-15  rem/e
       .35931E-01  .40475E-01  .76405E-01  .27286      rem/h/kW
                                           ==========
```

The highest level is 313 mrem / h (see value .31278) at the detector angle of 80°. It should be clearly noted that the high-energy neutron component (HEN=183 mrem / h) dominates, which is most typically the case whenever lateral concrete shielding gets larger than 4 feet.

However, let's now assume that our design criteria requires that we lower the total dose rate to about 1 mrem / h. We have two options available to us with SHIELD11: a) increase the thickness of the primary concrete (which also increases the inverse-square distance), and / or b) add additional shielding in the 4-ft space between the target and the primary wall. The first option is probably not a good one – the concrete would have to be 12 feet thick! (prove it to yourself with SHIELD11). Alternatively, as we see in the following output, adding 38 inches of lead inside the enclosure (AddPB=38) will bring the level down to about 1 mrem / h (see value .10631E-02 below), and this may be a more practical way of reaching our design criteria.

```
**********************************************************************
                              INPUT DATA
**********************************************************************
1                                  IOsw (0=none,1=input,2=media/input)
    10.000                         Ebeam (GeV)
FE                                 NamTar
    12.000     2.000               TarLen (inch),TarRad (inch)
0                                  IattSW (1=target n-atten., 0=none)
CONC                               NamShl
    90.000    48.000               AngShl (deg),DisShl (inch)
    60.000                         ThkShl (inch)
         3    10.000    70.000     NTheta,dTheta,Theta0 (deg)
     0.000                         AddCON (inch)
     0.000                         AddFE (inch)
    38.000                         AddPB (inch)
     0.000                         AddMIS (inch)

**********************************************************************
                        RESULTS OF CALCULATION
**********************************************************************
      ----------------------------------------------------------
      Production angle=  70.000     degrees    [G/N= .22685    ]
      ----------------------------------------------------------
         GRN         MID         HEN         Neutron
       .91630E-24  .45006E-19  .25428E-18  .29928E-18  rem/e
       .20617E-08  .10126E-03  .57212E-03  .67339E-03  rem/h/kW

         GamD        GamI        Gamma       TOTAL
       .87905E-38  .67892E-19  .67892E-19  .36717E-18  rem/e
       .19779E-22  .15276E-03  .15276E-03  .82614E-03  rem/h/kW
                                           ==========
      ----------------------------------------------------------
      Production angle=  80.000     degrees    [G/N= .21495    ]
      ----------------------------------------------------------
         GRN         MID         HEN         Neutron
       .31235E-23  .75807E-19  .31308E-18  .38889E-18  rem/e
       .70279E-08  .17057E-03  .70443E-03  .87501E-03  rem/h/kW

         GamD        GamI        Gamma       TOTAL
       .11656E-36  .83593E-19  .83593E-19  .47248E-18  rem/e
       .26226E-21  .18808E-03  .18808E-03  .10631E-02  rem/h/kW
                                           ==========
      ----------------------------------------------------------
      Production angle=  90.000     degrees    [G/N= .20690    ]
      ----------------------------------------------------------
         GRN         MID         HEN         Neutron
       .46088E-23  .81796E-19  .28160E-18  .36340E-18  rem/e
       .10370E-07  .18404E-03  .63361E-03  .81766E-03  rem/h/kW

         GamD        GamI        Gamma       TOTAL
       .23962E-36  .75188E-19  .75188E-19  .43859E-18  rem/e
       .53913E-21  .16917E-03  .16917E-03  .98683E-03  rem/h/kW
                                           ==========
```

4.2 Shielding a beam dump in the forward direction

Experience tells us that using the *standard-target* model for *lateral*-shield studies, as we did in the above example, quite often results in a conservative design. The reasoning goes as follows. Since the primary shield is 5-ft of concrete, the HEN component dominates. But HENs are created by *high-energy* photons which, in turn, are mostly near the beginning of the EM shower, not the end. The 12-inch (17.3 r.l.) iron target represents three shower maxima at 12 GeV[2], which is more than adequate in length for producing a maximum number of HENs. In addition, the radial extent of the EM shower is well within the 2-inch radius of the target[3] .

However, experience with EM cascades[4] also tells us that it may not be at all conservative to design 0° shielding using a *standard target*. Nevertheless, in order to give the reader an idea of what we are talking about, we will do just that. We will start with almost the same SHIELD11 input that we used for the lateral-shield problem (*i.e.*, 4-ft distance from target to inside of a 5-ft thick concrete shield), but we will choose AngShl=0.0 and Theta0=0.0 with Ntheta=2, since two detector angles (0° and 10°) will suffice for our demonstration. SHIELD11 gives us

```
**********************************************************************
                              INPUT DATA
**********************************************************************
1                                  IOsw (0=none,1=input,2=media/input)
    10.000                         Ebeam (GeV)
FE                                 NamTar
    12.000     2.000               TarLen (inch),TarRad (inch)
0                                  IattSW (1=target n-atten., 0=none)
CONC                               NamShl
     0.000    48.000               AngShl (deg),DisShl (inch)
    60.000                         ThkShl (inch)
         2    10.000     0.000     NTheta,dTheta,Theta0 (deg)
     0.000                         AddCON (inch)
     0.000                         AddFE (inch)
     0.000                         AddPB (inch)
     0.000                         AddMIS (inch)

**********************************************************************
                        RESULTS OF CALCULATION
**********************************************************************
      ----------------------------------------------------------
      Production angle=  0.0000     degrees    [G/N= 2.6622    ]
      ----------------------------------------------------------
         GRN         MID         HEN         Neutron
       .37020E-18  .78279E-16  .85936E-15  .93800E-15  rem/e
       .83295E-03  .17613      1.9335      2.1105      rem/h/kW

         GamD        GamI       Gamma        TOTAL
       .22677E-14  .22945E-15  .24971E-14  .34351E-14  rem/e
       5.1023      .51626      5.6185      7.7290      rem/h/kW
                                           ==========
      ----------------------------------------------------------
      Production angle=  10.000     degrees    [G/N= .40837    ]
      ----------------------------------------------------------
         GRN         MID         HEN         Neutron
       .29865E-18  .65670E-16  .73722E-15  .80318E-15  rem/e
       .67196E-03  .14776      1.6587      1.8072      rem/h/kW

         GamD        GamI       Gamma        TOTAL
       .13116E-15  .19684E-15  .32800E-15  .11312E-14  rem/e
       .29511      .44288      .73800      2.5452      rem/h/kW
                                           ==========
```

[2] $t_{max} = \ln(E/E_c) - 0.5$, where E is the electron beam energy and E_c is the critical energy [11].

[3] It should no longer come as a surprise why we chose the *standard target* for our experiments in the late 1960s, the results of which are currently used in this five-component model of SHIELD11.

[4] For example, running Monte Carlo codes like EGS[2] and FLUKA[3].

As expected, the total dose rate at $0°$, 7.73 rem / h (see value 7.7290 above), is much higher than our previous lateral-shield number at $80°$ (313 mrem / h), and the dominating component is now Direct Gamma, `GamD`=5.10 rem / h (see value 5.1023)—*i.e.*, the photons that escape directly from the core of the shower, which then get attenuated in the 5-ft concrete shield.

At this point in the shielding design it is important to know what the actual beam dump looks like. Maybe it's a large tank of water flowing around copper plates that get increasingly thicker as the EM cascade develops and attenuates, or maybe it's simply a large solid cylinder of aluminum. The point here is that our *standard-target* model may be too conservative, or not conservative enough, but there's a method that quite often we can apply to remedy this .

As an example of how to approach a problem like this, let's assume that the beam dump is similar to the one that was actually used at SLAC during the SLC project[13]; namely, a solid cylinder of aluminum, 56 inches long with a 6.9-inch iron plate at the end to help attenuate the EM cascade. Here are the steps to take in order to find out which parameters to use in `shield11.in5`.

- We determine the total thickness of dump material in the forward direction in units of g / cm^2, which turns out in this case to be 522 g / cm^2 (*i.e.*, 56(2.54)(2.70) + 6.9(2.54)(7.87)).
- Since the length of the 12-inch *standard target* is 240 g / cm^2 of iron, we can simply add an additional amount of ("ficticious") iron shielding at the end of our *standard target* input. That is, we can set `AddFe`=$(522 - 240)/7.87/2.54$=14.1 inches.

With this minor addition, and limiting the detector angle to 0° (to save space in this paper), we get the following results from SHIELD11.

```
***********************************************************************
                              INPUT DATA
***********************************************************************
1                                  IOsw (0=none,1=input,2=media/input)
    10.000                         Ebeam (GeV)
FE                                 NamTar
    12.000     2.000               TarLen (inch),TarRad (inch)
0                                  IattSW (1=target n-atten., 0=none)
CONC                               NamShl
     0.000    48.000               AngShl (deg),DisShl (inch)
    60.000                         ThkShl (inch)
         1    10.000     0.000     NTheta,dTheta,Theta0 (deg)
     0.000                         AddCON (inch)
    14.100                         AddFE (inch)
     0.000                         AddPB (inch)
     0.000                         AddMIS (inch)

***********************************************************************
                        RESULTS OF CALCULATION
***********************************************************************
      -----------------------------------------------------------
      Production angle=  0.0000     degrees    [G/N= .24855    ]
      -----------------------------------------------------------
         GRN         MID         HEN         Neutron
       .92045E-21  .11206E-16  .12302E-15  .13423E-15  rem/e
       .20710E-05  .25213E-01  .27679      .30201      rem/h/kW

         GamD        GamI       Gamma        TOTAL
       .51578E-18  .32846E-16  .33362E-16  .16759E-15  rem/e
       .11605E-02  .73904E-01  .75065E-01  .37707      rem/h/kW
                                           ==========
```

Clearly, the tail of the EM cascade has been dramatically reduced (probably why 6.9 inches of iron was added by the designers [13] of the beam dump!) and, in order to reach our design limit, it remains for us to add additional shielding (not "ficticious" this time). From experience, it is preferable to place high-Z material in the 4-ft space between the target and the primary concrete wall. As in the case of our previous lateral-shield problem, SHIELD11 tells us that the HEN component, 277 mrem / h (see value .27679 above), again dominates and a quick back-of-the-envelope estimate[5] tells us that we probably will need to add at least 39 inches of lead just to attenuate that component. However, when we actually run SHIELD11 we see (below) that it actually takes a total of 41 inches to get us down to about 1 mrem / h (see value .10196E-02).

```
**********************************************************************
                              INPUT DATA
**********************************************************************
1                                  IOsw (0=none,1=input,2=media/input)
    10.000                         Ebeam (GeV)
FE                                 NamTar
    12.000     2.000               TarLen (inch),TarRad (inch)
0                                  IattSW (1=target n-atten., 0=none)
CONC                               NamShl
     0.000    48.000               AngShl (deg),DisShl (inch)
    60.000                         ThkShl (inch)
         1    10.000     0.000     NTheta,dTheta,Theta0 (deg)
     0.000                         AddCON (inch)
    14.100                         AddFE (inch)
    41.000                         AddPB (inch)
     0.000                         AddMIS (inch)

**********************************************************************
                        RESULTS OF CALCULATION
**********************************************************************
      ----------------------------------------------------------
      Production angle=  0.0000     degrees    [G/N= .24471    ]
      ----------------------------------------------------------
         GRN         MID         HEN         Neutron
       .46981E-26  .30394E-19  .33367E-18  .36407E-18  rem/e
       .10571E-10  .68387E-04  .75076E-03  .81915E-03  rem/h/kW

         GamD        GamI       Gamma         TOTAL
       .21070E-39  .89090E-19  .89090E-19  .45316E-18  rem/e
       .47407E-24  .20045E-03  .20045E-03  .10196E-02  rem/h/kW
                                           ==========
```

Voila! It looks like we have designed the shielding for a 1 kW beam dump struck by 10 GeV electrons. Well, not quite. Question: Had we directly chosen 56 inches of aluminum for the "target", instead of using the 12-inch *standard target* and applying "corrections", would we have gotten a significantly different result? Answer: Most likely yes.

To demonstrate this, we have rerun SHIELD11 using NamTar=MISC, TarLen=56 inches, TarRad=8 inches and AddFE=6.90 (*i.e.*, the iron plate at the end of the aluminum dump). Before doing this, however, we had to edit the shield11.f code itself in order to redefine the MISC parameters in BLOCK DATA so that they correspond to *aluminum*. And this, in turn, required us to recompile the code.

The results are shown below, where we have yet to add the necessary high-Z wall. (Note: we also set the output switch IOsw to 2 in order to make sure that the changes we made to MISC in BLOCK DATA were correctly used following recompilation of shield11.f).

[5] By looking at the MATERIAL DATA output in Section 2.1.2, we see that the attenuation mean-free path for high-energy neutrons in lead is 200 g / cm^2. Therefore, $\exp(-2.54(11.35)t/200) = 1/277$ gives us $t = 39$ inches.

```
**********************************************************************
                             MATERIAL DATA
**********************************************************************
MatID                   CONC      FE        PB       MISC

Zmat                   13.00    26.00    82.00    13.00
Amat                   26.98    55.85   207.19    26.98
RHOmat (g/cu.cm)        2.35     7.87    11.35     2.70

RLmat  (g/sq.cm)       26.70    13.84     6.37    26.70
XMUmat (g/sq.cm)       11.10    10.70    14.20    11.10
                                                            Isorc
Xmfp   (g/sq.cm)       30.00    47.00    97.00    30.00   1 (GRNs)
                       55.00   145.00   200.00    55.00   2 (MIDs)
                      120.00   145.00   200.00   120.00   3 (HENs)
                       42.00    33.60    24.00    42.00   4 (GamD)
                      120.00   145.00   200.00   120.00   5 (GamI)

**********************************************************************
                               INPUT DATA
**********************************************************************
2                                   IOsw (0=none,1=input,2=media/input)
    10.000                          Ebeam (GeV)
MISC                                NamTar
    56.000     8.000                TarLen (inch),TarRad (inch)
0                                   IattSW (1=target n-atten., 0=none)
CONC                                NamShl
     0.000    48.000                AngShl (deg),DisShl (inch)
    60.000                          ThkShl (inch)
         1    10.000     0.000      NTheta,dTheta,Theta0 (deg)
     0.000                          AddCON (inch)
     6.900                          AddFE (inch)
     0.000                          AddPB (inch)
     0.000                          AddMIS (inch)

**********************************************************************
                         RESULTS OF CALCULATION
**********************************************************************
      ----------------------------------------------------------
      Production angle=  0.0000     degrees    [G/N= .25852    ]
      ----------------------------------------------------------
         GRN         MID         HEN         Neutron
       .12435E-19  .39577E-16  .53265E-15  .57224E-15  rem/e
       .27979E-04  .89047E-01  1.1985      1.2875      rem/h/kW

         GamD        GamI        Gamma        TOTAL
       .57175E-17  .14222E-15  .14794E-15  .72018E-15  rem/e
       .12864E-01  .31999      .33285      1.6204      rem/h/kW
                                           ==========
```

The total dose rate is now 1.62 rem / h, a factor of 4.3 higher than the earlier *standard-target* design (without a lead wall), where the total dose rate had been determined to be 377 mrem / h. The message here is that it's best to model the target an closely as you can.

Finally, after playing around with different thicknesses for the lead wall (`AddPB`), we end up with 51 inches for the final design. The SHIELD11 results for the forward shielding are shown below.

```
*********************************************************************
                              INPUT DATA
*********************************************************************
1                                  IOsw (0=none,1=input,2=media/input)
    10.000                         Ebeam (GeV)
MISC                               NamTar
    56.000     8.000               TarLen (inch),TarRad (inch)
0                                  IattSW (1=target n-atten., 0=none)
CONC                               NamShl
     0.000    48.000               AngShl (deg),DisShl (inch)
    60.000                         ThkShl (inch)
         1    10.000     0.000     NTheta,dTheta,Theta0 (deg)
     0.000                         AddCON (inch)
     6.900                         AddFE (inch)
    51.000                         AddPB (inch)
     0.000                         AddMIS (inch)

*********************************************************************
                        RESULTS OF CALCULATION
*********************************************************************
      ----------------------------------------------------------
      Production angle=  0.0000     degrees    [G/N= .24853    ]
      ----------------------------------------------------------
         GRN         MID         HEN         Neutron
       .32495E-26  .25396E-19  .34180E-18  .36720E-18  rem/e
       .73114E-11  .57141E-04  .76905E-03  .82619E-03  rem/h/kW

         GamD        GamI       Gamma        TOTAL
       .14178E-43  .91261E-19  .91261E-19  .45846E-18  rem/e
       .31901E-28  .20534E-03  .20534E-03  .10315E-02  rem/h/kW
                                           ==========
```

However, for completeness, we also have to repeat the lateral-shield problem (Section 4.1) using the actual dimensions of the aluminum dump, which we do in the next section.

4.3 Lateral shielding of a beam dump—revisted

In order to repeat the lateral-shield calculation, to account for the actual SLC beam dump dimensions, we simply have to edit the `shield11.in5` file that we just used for the forward direction by changing the angle of the primary concrete shield to 90 degrees and also changing the detector angle to 80 degrees (since we discovered earlier that this is where the radiation level peaks). Also, we must change `AddFE` back to zero because the 6.9-inch iron end-plate certainly is not expected to attenuate *lateral* radiation emanating from point O (see Fig. 1).

Accordingly, SHIELD11 tells us (see below) that the 38-inch lead wall that we used in the original *standard-target* case had to be increased to 41 inches for the actual aluminum beam dump geometry—had we used 38 inches of lead the total dose rate would have been 1.7 mrem / h, as the reader can easily verify.

```
*********************************************************************
                              INPUT DATA
*********************************************************************
1                                   IOsw (0=none,1=input,2=media/input)
    10.000                          Ebeam (GeV)
MISC                                NamTar
    56.000     8.000                TarLen (inch),TarRad (inch)
0                                   IattSW (1=target n-atten., 0=none)
CONC                                NamShl
    90.000    48.000                AngShl (deg),DisShl (inch)
    60.000                          ThkShl (inch)
         1    10.000    80.000      NTheta,dTheta,Theta0 (deg)
     0.000                          AddCON (inch)
     0.000                          AddFE (inch)
    41.000                          AddPB (inch)
     0.000                          AddMIS (inch)

*********************************************************************
                        RESULTS OF CALCULATION
*********************************************************************
      ----------------------------------------------------------
      Production angle=  80.000     degrees    [G/N= .22296    ]
      ----------------------------------------------------------
         GRN         MID         HEN         Neutron
       .79829E-24  .63962E-19  .32385E-18  .38781E-18  rem/e
       .17962E-08  .14391E-03  .72866E-03  .87258E-03  rem/h/kW

         GamD        GamI       Gamma        TOTAL
       .26207E-38  .86468E-19  .86468E-19  .47428E-18  rem/e
       .58965E-23  .19455E-03  .19455E-03  .10671E-02  rem/h/kW
                                           ==========
```

As a final note, in all of the examples above we purposely did *not* set `IattSW=1`, for to do so would have required a full understanding of the *target-attenuation* model, and its associated algorithms, described in Appendix C. Instead, we took the recommended, more conservative, approach and simply ignored differences between the *actual-target* and *standard-target* geometry that could result in additional neutron attenuation.

5 Concluding remarks

This document was written with the following three ideas in mind:

- to illustrate by example *how to use* the SHIELD11 code,
- to provide enough guidance so that the code is *not used outside it's intended purpose*, and
- to provide adequate references and information to aid *informed users* in their effort to *improve* the code.

The descriptions and examples given in this report are meant to serve as guides for using SHIELD11 and, while not complete, will at least aid the user in adapting the abilities of the code to their own particular needs. It should be noted that Monte Carlo methods, while more universal and complete, are most often quite time consuming. When using such codes, the user should first do back-of-the-envelope calculations... which SHIELD11 provides. The accuracy and / or precision of SHIELD11 may not be as good as the more rigorous Monte Carlo methods, yet still should be, and often have been shown to be, good enough for most shielding studies, since uncertainties in beam targeting, materials, angles, and especially *beam loss*, usually are greater than any imprecisions in the SHIELD11 code itself.

Finally, we note that new experiments and Monte Carlo studies can provide the means for improving the models which are employed in SHIELD11. We hope that such studies will be undertaken in the near future.

References

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[7] V. I. Antonesoc, "Photonuclear Reactions", *Bibliographical Series No. 10*, International Atomic Energy Agency (1964).

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[9] A hereto unpublished experiment, performed at SLAC in 1968 using a 10 GeV beam of positrons, currently provides us with our best knowledge of the *ionizing radiation* component (`GamD`) in the very-forward direction from a *standard target*. In this experiment, a fine-mesh matrix of tiny TLD rods (0.5 mm dia.), covering an angular interval of 0°–5°, was centered 10-ft downstream of the target.

[10] T. M. Jenkins, "Neutron and photon measurements through concrete for a 15 GeV electron beam on a target—comparison with models and calculations", Nucl. Instr. Meth. 159 (1979) 265.

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[12] A. B. Chilton, J. K. Shultis and R. E. Faw, *Principles of Radiation Shielding* (Prentice-Hall, New Jersey, 1984); see Chapter 8, Section 3.

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[14] W. P. Swanson, "Improved calculation of photoneutron yields released by incident electrons", Health Physics 37 (1979) 347; see Table 1.

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APPENDIX

A Components of the *Standard-Target* Model

During the early days of SLAC (1966-1979), the authors of this paper had the opportunity to perform a series of radiation shielding experiments using the Stanford Two-Mile Accelerator beam as it passed through End Station A and terminated in Beam Dump East. One particular experiment[9] used 10-GeV positrons to measure neutron and photon radiation emanating from a 12-inch long cylinder of iron, having a radius of 2-inches—what we today commonly refer to as the *standard target*. A second, more refined set of neutron measurements, was later published by Jenkins[10].

The choice of dimensions for the *standard target* was important. We wanted to make sure that the electromagnetic cascade shower was reasonably *well developed* within the device, thereby ensuring that the maximum number of neutrons, both low and high-energy, would be produced. In addition, we wanted the *standard target* to be similar in size and material to the beam stoppers that were then being incorporated into the Personnel Protection System (PPS) at SLAC.

At the time, as a result of on-going shield-design efforts at SLAC, it had become rather clear that radiation coming out of a *standard target* could be roughly grouped into five distinct components, each of which had specific attenuation properties in shielding. In fact, a significant portion of what we already knew and were applying, had been published as Chapter 26 (“Shielding and Radiation”) in what became known as the SLAC Big Book[1]. All of this provided the impetus to create the five-component shielding model that is the basis of SHIELD11.

In SHIELD11 each component is calculated through five consecutive calls to `FUNCTION Sorc`. The parameter `Isorc` takes on values 1 through 5 and the following *branching code*

```
!      =====================================
!      Branch to the appropriate source term
!      =====================================
!              GRN  MID  HEN  GamD  GamI
!             -------------------------
 1000 go to (  1,   2,   3,   4,    3   ) Isorc
!             -------------------------
```

redirects each calculation to labeled sections, which are described in the following subsections of this appendix.

A.1 `Isorc=1`: Giant-Resonance Neutron (`GRN`)

Photoproduction of neutrons by the mechanism known as giant-resonance excitation has been well studied[5, 6, 7]. These neutrons are quite often referred to as *fast neutrons* because their energies lie in the range $0.1 < E_n < 20$ MeV. They are, for the most part, emitted isotropically in angle.

The experiment by Jenkins[10] provides us with our basic model for the `GRN` component that's used in SHIELD11. However, the formula that we are currently using is based on a yield-vs-Z study by Swanson[14]. In Fig. A.1.1 we plot Swanson's *calculated* GRN yield as a function of atomic number, Z.

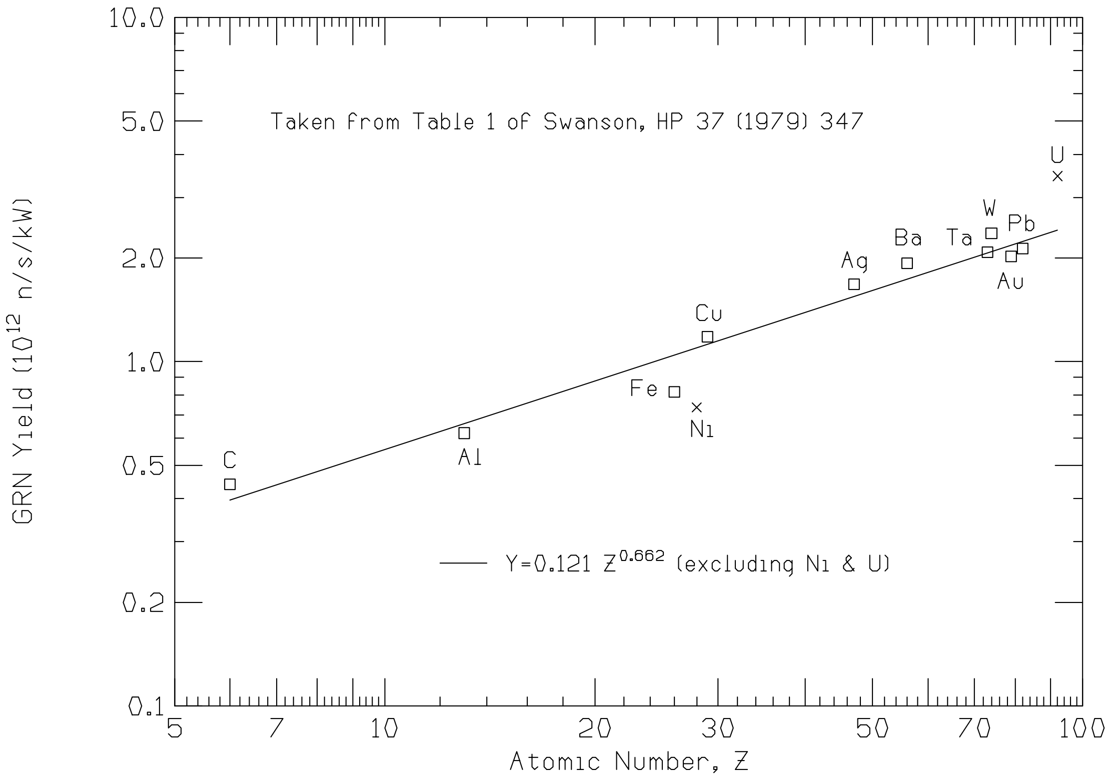

Fig. A.1.1 Giant resonance neutron yield as a function of the atomic number

The straight line in Fig. A.1.1 is a linear least-squares fit of this data (excluding Ni and U[6]) to the functional form $Y = aZ^b$, where we obtain $a = 0.121$ and $b = 0.662$. Using a fluence to dose-equivalent factor of 3.2×10^{-8} rem-cm^2/n, we arrive at the following formulation currently being used in `SUBROUTINE Sorc`:

$$D_{\mathrm{GRN}} = 4.93 Z^{0.662} \, (E \times 10^{-11}) \, (\mathrm{rem/e}), \tag{A.1.1}$$

for a source-to-detector distance of 1 cm, where the beam energy, E(GeV), is required for the

[6]Nickel is known to have an anomalously low yield, whereas the neutron yield for uranium is high due to the competing process of photofission[15].

conversion from kWs to electrons[7] . Note that there is no angular dependence in the above formula. Also, depending on the setting of switch `IattSW` (0=off, 1=on), additional *target attenuation* may be applied (see Appendix C).

The code listing for the `GRN` component is given below.

```
!      ==============================
!      GIANT-RESONANCE NEUTRONS (GRN)
!      ==============================
 1     Sorc = 4.93D0*Zmat(IDtar)**0.662D0
       Sorc=Sorc*Energy*1.D-11                              ! rem/e at 1 cm
       if (IattSW.eq.1) then                   ! Apply target attenuation
         Sorc = Sorc*exp(-SltSor/Xmfp(IDtar,Isorc))
       end if
```

A.2 `Isorc`=2: Mid-Energy Neutron (`MID`)

The neutron measurements made at SLAC through thick concrete shields[10] aren't conveniently fit by only *two* energy groups, *i.e.*, GRN and HEN, as has been done by Tesch at DESY[16]. Instead, we include a *third* shape, which we call the mid-energy neutron component (`MID`), and which can be justified as arising from quasi-deuteron (pseudo-deuteron) produced neutrons[5, 10] (also see: Fig. 26-7 of Reference [1] and p.88 of Reference [15]).

The fit to a third shape results in the following expression for the yield:

$$Y = \frac{3.1 \times 10^{-3}}{1 - 0.75\cos\theta} \quad \text{(n/sr/GeV)}.$$

Because the *standard target* is iron, we make allowance for other materials by assuming the yield varies according to $(A_{\rm Fe}/A)^{0.37} = 4.43/A^{0.37}$, as recommended by Stapleton[17]. Also, we use the same fluence to dose-equivalent factor as for giant-resonance neutrons, 3.2×10^{-8} rem-cm^2 / n, to arrive at the following formulation currently being used in `SUBROUTINE Sorc`:

$$D_{\rm MID} = \frac{43.9A^{-0.37}}{1 - 0.75\cos\theta} \left(E \times 10^{-11}\right) \text{(rem/e)}, \tag{A.2.1}$$

for a source-to-detector distance of 1 cm, where the beam energy, E(GeV), is required for the conversion from kWs to electrons[8] . The code listing for the `MID` component is given below.

```
!       =========================
!       MID-ENERGY NEUTRONS (MID)
!       =========================
 2     Sorc = 43.9D0/Amat(IDtar)**0.37D0/(1.D0 - 0.75D0*CosThe)
       if (Energy.le.0.5D0) then
         Sorc = Sorc*1.6D0*Energy**1.5D0
       else if (Energy.gt.0.5D0 .and. Energy.lt.1.D0) then
         Sorc = Sorc*(0.566D0 + 0.434D0*(Energy - 0.5D0)/0.5D0)
       end if
       Sorc = Sorc*Energy*1.D-11                            ! rem/e at 1 cm
       if (IattSW.eq.1) then                   ! Apply target attenuation
         Sorc = Sorc*exp(-SltSor/Xmfp(IDtar,Isorc))
       end if
```

[7] For the dose equivalent (rem / e) at 1 cm, the factor $E \times 10^{-11}$ is explicitly separated out in the formulae for all five components of the SHIELD11 model.

[8] An approximation scheme based on data fits is used for beam energies below 1 GeV.

As in the GRN case, additional *target attenuation* may be applied (see Appendix C) depending on the setting of switch `IattSW` (0=off, 1=on).

A.3 `Isorc`=3: High-Energy Neutron (`HEN`)

The yield of high-energy neutrons ($E_n > 100$ MeV) from high-energy electrons striking a thick copper target as a function of production angle was fit by DeStaebler et al[1], resulting in the following expression:

$$Y = \frac{1.5 \times 10^{-4}}{(1 - 0.72\cos\theta)^2} \quad \text{(n/sr/GeV)}.$$

Because the *standard target* is iron, we make allowance for other materials by assuming the yield varies according to $(A_{\rm Fe}/A)^{0.65} = 13.66/A^{0.65}$ [8].

Using a fluence to dose-equivalent factor of 6.7×10^{-8} rem-cm^2/n [8], we arrive at the following expression currently being used in `SUBROUTINE Sorc` for the high-energy neutron component:

$$D_{\rm HEN} = \frac{13.7A^{-0.65}}{(1 - 0.72\cos\theta)^2}\,(E \times 10^{-11})\ \text{(rem/e)}, \tag{A.3.1}$$

for a source-to-detector distance of 1 cm, where the beam energy, E(GeV), is required for the conversion from kWs to electrons.

In SHIELD11 we arbitrarily set a threshold on the electron beam energy at 0.150 GeV, below which $D_{\rm HEN} = 0$, and in the energy range $0.150 < E < 1.0$ GeV, we allow $D_{\rm HEN}$ to rise in a smooth, step-wise linear fashion until it reaches the value given by Eqn. A.3.1[9] . The code listing for the `HEN` component is given below.

```
!      ==========================
!      HIGH-ENERGY NEUTRONS (HEN)
!      ==========================
 3     if (Energy.le.ThrHEN) then                       ! Below threshold
         Sorc = 0.D0
       else
         Sorc = 13.7D0/Amat(IDtar)**0.65D0/(1.D0 - 0.72D0*CosThe)**2D0
       end if

       if (Energy.lt.1.D0) then   ! Loop over the energy bins below 1 GeV
         do k=2,23
           if (Energy.lt.E_HEN(k)) then
             DelCS = (CS_HEN(k) - CS_HEN(k-1))*(Energy - E_HEN(k-1))/
     +               (E_HEN(k) - E_HEN(k-1))
             Sorc = (CS_HEN(k-1) + DelCS)*Sorc
             go to 1100
           end if
         end do
       end if
```

As in the GRN and MID cases, additional *target attenuation* may be applied (see Appendix C) depending on the setting of switch `IattSW` (0=off, 1=on).

[9] In this manner, we account (approximately) for the rise above the threshold in the total photoneutron cross section illustrated in Fig. 26-7 of Reference [1].

A.4 `Isorc=4`: Direct Gamma (`GamD`)

The Direct Gamma (`GamD`) component in the SHIELD11 code is based on the combined results from two *standard-target* experiments performed at SLAC in the late 1960's; namely,

- TLD measurements in the very-forward (0°–5°) direction using a fine-mesh matrix of tiny crystalline rods of LiF[9].
- TLD measurements between 30°–180° using conventional LiF powder poured into small polystyrene capsules (see Fig. 26-3 in the SLAC Big Book[1]).

The combined results from these two *standard-target* experiments are plotted in Fig. A.4.1, along with an EGS4 calculation (histogram) for the angular region 0°–5°.

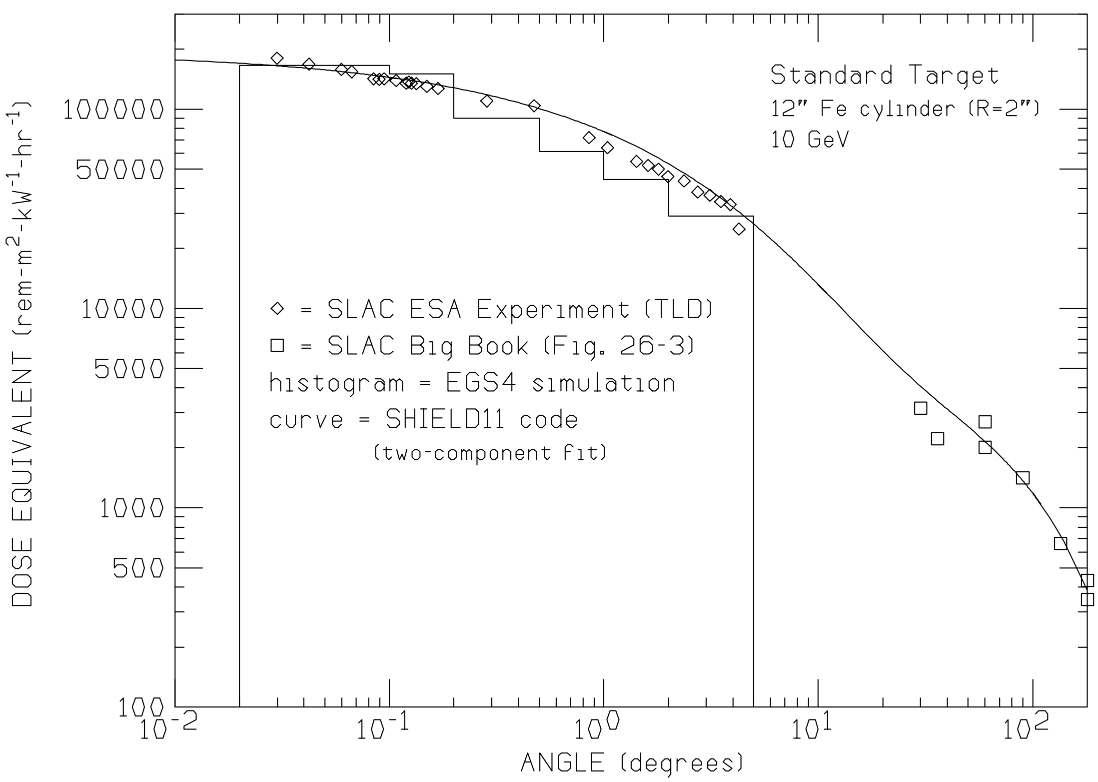

Fig. A.4.1 Angular distribution of x-ray dose from a *standard target* struck by 10 GeV electrons

As described in the Introduction to this paper, the angular distribution for the Direct Gamma component can be viewed as consisting of a slowly decreasing level from 0°–180°, superimposed onto which is a more intense and forward-directed bremsstrahlung core. With this in mind, the following analysis was performed.

A linear least-squares fit of the 0°–5° data was done assuming a functional form, $Y = Ae^{-a\sqrt{\theta}}$, which resulted in the following equation:

$$D(0^\circ - 5^\circ) = 1.8943 \times 10^5 e^{-0.959\sqrt{\theta}} \text{ (rem/kWh)} . \qquad \text{(A.4.1)}$$

A separate fit was also done using the 30°–180° data with the functional form, $Y = Be^{-b\theta}$, which gave the following:

$$D(30^\circ - 180^\circ) = 4.6764 \times 10^3 e^{-\theta/72.2} \text{ (rem/kWh)} . \qquad \text{(A.4.2)}$$

In an attempt to bridge the gap between 5° and 30°, these two equations were simply added and applied across the entire angular interval; namely,

$$D(0^\circ - 180^\circ) = 1.8943 \times 10^5 e^{-0.959\sqrt{\theta}} + 4.6764 \times 10^3 e^{-\theta/72.2} \text{ (rem/kWh)}. \qquad \text{(A.4.3)}$$

Equation A.4.3 is plotted as a smooth curve in Fig. A.4.1, where it seems to represent all of the experimental data rather well and, in addition, provides a reasonably smooth transition through the 5°–30° region.

Now, it is a well-known fact based on the build up of particle number (*i.e.*, the progeny) in an EM cascade shower that, for constant beam current, the bremsstrahlung intensity in the forward direction (0°) varies rapidly with incident beam energy (*e.g.*, see p. 52 in Reference [15]). Therefore, if we multiply the *first* term of Eqn. A.4.3 by the factor $E/10$, we should be able to apply it to higher (or lower) energies. Rewritten in units of rem / e, we then get

$$D(0^\circ - 180^\circ) = [841.91\, E\, e^{-0.959\sqrt{\theta}} + 207.84 e^{-\theta/72.2}](E \times 10^{-11}) \text{ (rem/e)}\ , \qquad \text{(A.4.4)}$$

where the source-to-detector distance has also been set at 1 cm.

What remains to be completed in our Direct Gamma (`GamD`) model is a reasonable generalization that conservatively accounts for the difference in material composition and dimensions between the *standard target* and the actual one. We treat the forward-directed photon radiation (*first* term in Eqn. A.4.4) differently than the lateral radiation (*second* term in Eqn. A.4.4), as described in the following sections.

Generalization of the *first* (forward-directed radiation) term in Eqn. A.4.4

As shown in Fig. A.4.1, we have a reasonably good agreement between the EGS4 calculation (histogram) and the TLD data for the angular region 0°–5°. The EGS4 simulation also provides an explanation as to where the x-rays are produced and how they are able to remain in such a very small forward angle subtended by the matrix of LiF rods downstream. Here is the scenario.

- The x-rays that are produced at small forward angles, and still manage to reach the detector, are those that are generated by the primary electron beam in the very *initial layer of the target*—*i.e.*, before multiple scattering significantly spreads the electron beam.
- In order for these *early-produced* x-rays to maintain their small angle, they must pass through nearly all of the target without interacting (note: those that do interact become part of the overall EM cascade and contribute to the lateral (*second*) term in Eqn. A.4.4).
- The dose in the forward direction is then caused by the combination (*i.e.*, sum) of
    1. x-rays that pass completely through the thick target and the air path and then *interact within the detector* (*i.e.*, the LiF rods and the plastic sheet in which they are imbedded),
    2. electrons that enter the detector after being *generated in the air path* by x-rays exiting the target, and
    3. electrons created at the *very end of the thick target* (*e.g.*, by pair production) that reach the detector.

A rough estimate of the *initial layer* can be estimated by setting the RMS angle for multiple scattering equal to the the characteristic angle for producing bremsstrahling. Namely,

$$\frac{15\sqrt{t_{\rm rl}}}{E} = \frac{mc^2}{E}\ .$$

Solving for $t_{\rm rl}$ we find

$$t_{\rm rl} = \left(\frac{0.511}{15}\right)^2 \approx 0.001 \text{ rl} .$$

Admittedly, this is a very small thickness and is probably not of much use other than as a rough measure to demonstrate how quickly the shower spreads in angle[10] .

Our generalization for target length is actually rather simple. First remove the x-ray attenuation caused by the *standard target* (*i.e.*, 12-inches of Fe), and then put it back in using the length of the actual target—that is, multiply by the factor $e^{12(2.54)7.87/33.6}e^{-L/\lambda}$. The *first* term of Eqn. A.4.4 then reduces to

$$D = 1.06 \times 10^6 \; E \; e^{-0.959\sqrt{\theta}} \; e^{-L\rho/\lambda} \; (E \times 10^{-11}) \;\; (\text{rem/e}) \; . \qquad \text{(A.4.5a)}$$

In this expression, we make use of the λ values listed in `BLOCK DATA`, which is a conservative approach because they correspond to Compton minima in the mass attenuation curves.

A Rule of Thumb by Swanson (see p. 53 of Reference [15]) provides us with a quick way of checking the above model. According to Swanson, the 0° bremsstrahlung dose rate from an "optimized" thick target can be approximated using

$$D \approx 30,000 E_0 \;\; (\text{rem/kWh}) \text{ at 1 meter} \; ,$$

where E_0 is in MeV. Applying an attenuation factor of $e^{-12(2.54)7.87/33.6}$, to account for the thickness of the *standard target*, and using a beam energy of 10 GeV, the above expression gives us 2.4×10^5 rem / h, which is only 25% higher than 1.9×10^5 rem / h, the value we get for the `GamD` component when we run SHIELD11.

Generalization of the *second* (lateral radiation) term in Eqn. A.4.4

We first set a restriction on the minimum target radius based on the *standard target*. Specifically, two inches of iron calculates to be

$$R_{min} = 2.0(2.54)\rho/\lambda = 2.0(2.54)7.87/33.6 = 1.189869,$$

relaxation lengths for photons. In order to make sure that the lateral spread of the shower is well established, we require all targets to have a radius (in relaxation lengths), that is at least this large. Then, in a manner similar to what we did above with the *first* term of Eqn. A.4.4, we remove the x-ray attenuation caused by the *standard target* using the multiplying factor, $e^{1.189869}$. Target attenuation is then accounted for in one of two ways, depending on angle. The *second* term of Eqn. A.4.4 finally reduces to

$$D = 683 e^{-\theta/72.2} e^{-R\rho/\lambda} (E \times 10^{-11}) \;\; (\text{rem/e}) \quad \text{for } \; 0^\circ \leq \theta \leq 90^\circ \; , \qquad \text{(A.4.5b)}$$

or

$$D = 683 e^{-\theta/72.2} e^{-R_{min}} (E \times 10^{-11}) \;\; (\text{rem/e}) \quad \text{for } \; 90^\circ < \theta \leq 180^\circ \; , \qquad \text{(A.4.5b)}$$

where $R_{min} = 1.189869$ (*i.e.*, to be conservative, we limit ourselves to the *standard target* attenuation for angles greater than 90°).

Equations A.4.4a and A.4.4b are combined to give $D_{\rm GamD}$, which is shown below in the code listing.

[10] Because this estimate for $t_{\rm rl}$ is so small, we have set an arbitrary limit of 0.01 r.l. for the minimum allowed target thickness for the `GamD` component (in `SUBROUTINE Sorc` look for `if(TarLenRL.le.TarLenG)`).

```
!     =================================================
!     DIRECT PHOTONS FROM ELECTROMAGNETIC SHOWER (GamD)
!     =================================================
 4    if (TarLenRL.le.TarLenG) then        ! TarLenG=0.01=minimum target
                                           !          length for photons

        write(6,'(/,''Stopped in FUNCTION Sorc with TarLenRL'',
     +    G15.7,'' r.l. <= TarLenG ='',G15.7,'' r.l.'')')
     +    TarLenRL,TarLenG
        stop
      end if

      if (TarRadRelax.lt.TarRadG) then      ! TarRadG=1.189869D0=minimum
                                            !  target radius for photons
        write(6,'(/,''Stopped in FUNCTION Sorc with TarRadRelax='',
     +    G15.7,'' < TarRadG='',G15.7)')
     +    TarRadRelax,TarRadG
        stop
      end if

!     ------------------------------------------------------------------
!     The GamD model is based on fitting experimental data (vs. theta)
!     for the standard target (12" long cylinder of Fe (R=2")) using two
!     functional forms:    y=a*exp(b*sqrt(theta)) for 0 thru   5 degrees
!                      and y=a*exp(b*theta)       for 5 thru 180 degrees
!     After normalization, the two source terms are summed.  However,
!     as shown below, two different attenuation factors are applied to
!     the 5-180 degree source term.  Namely,
!
!       exp(-TarRadRelax) for     0 < theta <  90 degrees
!       exp(-TarRadG)     for    90 < theta < 180 degrees
!     ------------------------------------------------------------------
      Sorc1 = 1.06D6*Energy*exp(-TarLenGCM/Xmfp(IDtar,4))*
     +          exp(-0.959D0*AbsAng**0.5D0)

      if (AbsAng.le.90.D0) then
        Sorc2 = 683.D0*exp(-TarRadRelax)*exp(-AbsAng/72.2D0)
      else
        Sorc2 = 683.D0*exp(-TarRadG)*exp(-AbsAng/72.2D0)
      end if

      Sorc = Sorc1 + Sorc2
      Sorc = Sorc*Energy*1.D-11                          ! rem/e at 1 cm
```

It should be noted that there are two target-size limitations imposed at the beginning of the `GamD` portion of the code shown above. Namely, the target *length* must be greater than 0.01 radiation lengths, and the *radius* must be at least as large as that of the *standard target*, when expressed in *relaxation-length* units.

A.5 `Isorc=5`: Indirect Gamma (`GamI`)

Following the startup of the Two-Mile Accelerator, ion chamber measurements behind thick (>4 ft) earth and/or concrete shields revealed that an ionizing-radiation component always tracked fast-neutron measurements made with BF3 counters. It was clear from theoretical studies that these fast neutrons were the so-called “camp followers” described at the beginning of this paper. This ionizing-radiation component was, therefore, presumed to be due to a combination of things: charged-pions from hadron interactions (“stars”), photons from pi-zero decays, neutron-capture gamma rays, etc. For lack of a better name, we simply refer to this ionizing radiation in the SHIELD11 model as the Indirect Gamma (`GamI`) component and, based on the 1979 experiment by Jenkins[10], we assign to it a fixed factor 0.267 relative to the `HEN` term. That is, $D_{\rm GamI} = 0.267 D_{\rm HEN}$, as shown below in the code listing for the `GamI` component.

```
                           ! ========================================
 1100 if (Isorc.eq.5) then  ! INDIRECT PHOTONS FROM HADRON SHOWER (GamI)
                           ! ========================================
        Sorc = 0.267D0*Sorc          ! Sorc on the right is for the HENs
      end if
      Sorc = Sorc*Energy*1.D-11                            ! rem/e at 1 cm
      if (IattSW.eq.1) then                     ! Apply target attenuation
        Sorc = Sorc*exp(-SltSor/Xmfp(IDtar,Isorc))
      end if
```

B Removal mean-free paths used in SHIELD11

The attenuation factors that are applied for both primary and the secondary (*i.e.*, add-on) shielding are simple exponentials of the form $e^{-t/\lambda}$, where t is the slant distance through the shield and λ is the appropriate removal mean-free path (MFP). The MFPs are passed in `common/MATDTA/` in a 4×5 array, `Xmfp(MXMAT,MXSOR)`, which is defined in the `include` file called `matdta.fh`. Specific values are assigned by means of `DATA` statements in `BLOCK DATA` as follows:

```
      DATA MatID /'CONC',  'FE  ', 'PB  ','MISC'/          ! Material ID

      DATA Xmfp  /  30.0,  47.0,   97.0,  135.0,  ! MFP (g/sq.cm) - GRNs
     +              55.0, 145.0,  200.0,  200.0,  !               - MIDs
     +             120.0, 145.0,  200.0,  200.0,  !               - HENs
     +              42.0,  33.6,   24.0,   24.0,  !               - GamD
     +             120.0, 145.0,  200.0,  200.0 / !               - GamI
```

The following explains where these MFPs were obtained:

- 30.0, 55.0 and 120.0 g / cm^2 are from Jenkins [10] (see Fig. 17 therein).
- 47.0 and 97.0 g / cm^2 are from Chilton et al [12] (see Table 8.3 therein).
- 24.0, 33.6 and 42.0 g / cm^2 are from Dinter and Tesch [20] (see Figs. 13 and 14 therein).
- 145.0 g / cm^2 comes from applying the scaling formula, $\lambda \approx 38A^{1/3}$ in Jenkins [10] (which references Patterson and Thomas [8] as its source). The 200.0 g / cm^2 number also comes from Jenkins [10] (see Fig. 28 therein). Note, however, that applying $\lambda \approx 38A^{1/3}$ yields 225.0 g / cm^2.
- The MFPs for the `GamI` component are the same as those for the `HEN` component, since the Indirect Gamma field has been shown to attenuate in direct proportion with the removal of high-energy neutrons.

- And to be conservative, we simply use 145 and 200 g/^{2} for the `MID` component.
- The MFPs for `'MISC'` has been arbitraily set up for `'PB  '`, but with 135.0 used instead of 97.0 g/cm^2 to represent a lead shield not followed by hydrogeneous material.

C Attenuation of neutrons by the target itself (`IattSW`=1)

In this section we describe a very rudimentary method to account for neutron attenuation by targets that are larger than the *standard target*. The algorithm is based on the assumption that the "core" of an electromagnetic shower is well-contained within the dimensions of the target, thereby assuring that most of the neutrons (of all energies) have been produced. The algorithm is invoked in SHIELD11 by turning on switch `IattSW` (0=no, 1=yes), which is part of the input data in the `shield11.in5` file (see Section 2.1.1).

Consider a cylindrical iron target of length L and radius R as shown in Fig. C.1 which contains the core (red cylinder) of an EM shower. To be conservative, we purposely choose the dimensions of the core to be the same as the *standard target*. Namely $L_C = 12$ inches and $R_C = 2$ inches.

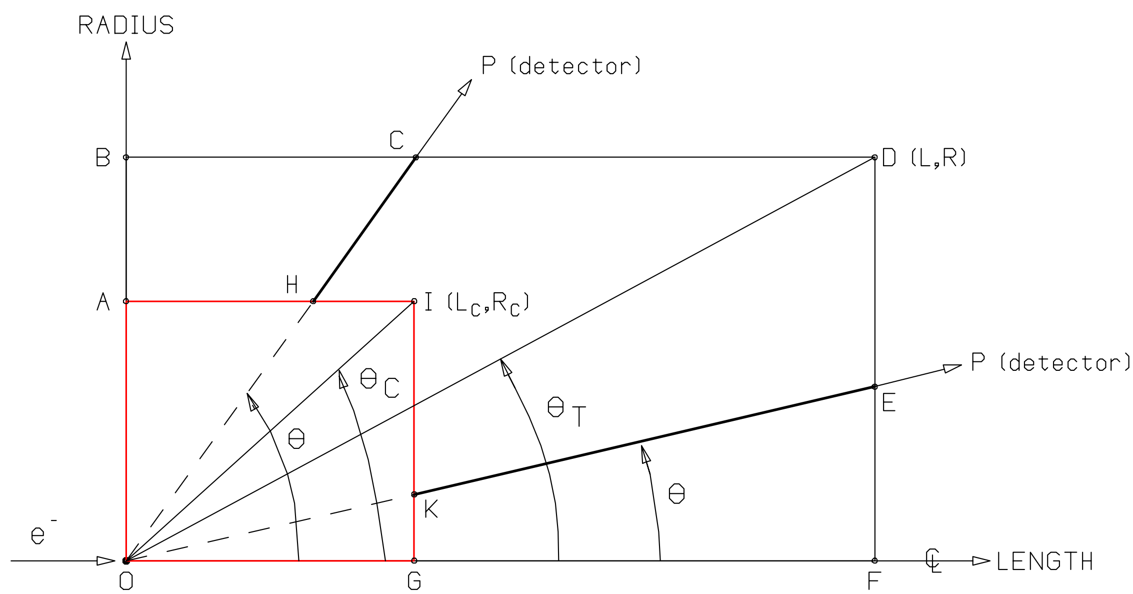

Fig. C.1 Target with shower core (red cylinder)

The two vectors $\overrightarrow{OP}$ point to detectors located at P in the same way that vector $\overrightarrow{OP}$ does in Fig. 1 of Section 2.1.1. The rays $\overline{HC}$ and $\overline{KE}$ need to be determined in order to calculate attenuation[11]. First we define what we call the *critical angles* subtended by the target and the core

$$\theta_T = \angle\, FOD = \texttt{CritTar} = \tan^{-1}(R/L)$$

and

$$\theta_C = \angle\, GOI = \texttt{CritCor} = \tan^{-1}(R_C/L_C)\ ,$$

[11] However, it's important to note that in SHIELD11 all radiation emanates from a single point located at O, so we cannot apply target attenuation at angles greater than 90 degrees.

respectively. Then

$$\begin{aligned} t_T &= \text{total slant distance in the target} = \texttt{SltTar} \\ &= \overline{OC} = R/\sin\theta \quad (\text{for } \theta \geq \theta_T) \\ &= \overline{OE} = L/\cos\theta \quad (\text{for } \theta < \theta_T)\ , \end{aligned}$$

and

$$\begin{aligned} t_C &= \text{total slant distance in the core} = \texttt{SltCor} \\ &= \overline{OH} = R_C/\sin\theta \quad (\text{for } \theta \geq \theta_C) \\ &= \overline{OK} = L_C/\cos\theta \quad (\text{for } \theta < \theta_C)\ . \end{aligned}$$

The added thickness of material that is inside the target, but outside the core, is then given by

$$t = t_T - t_C = \texttt{SltTar} - \texttt{SltCor}\ .$$

for either of the representative vectors $\overrightarrow{OP}$ in Fig. C.1. The corresponding attenuation factor is then calculated using $e^{-t/\lambda}$, where λ is the appropriate MFP for each of the three neutron components in SHIELD11.

Now, to extend our target-attenuation model to materials *other than iron*, we need to redefine the dimensions of the core, L_C and R_C, in such a way that the shower is still well-contained within the dimensions of the target. In the forward direction the energy deposited in the target increases with thickness, goes through a maximum, and then drops again in a smooth manner. It is well known that showers are fairly universal in shape when scaled in terms of the radiation length of the material. Furthermore, the *shower maximum* increases only slowly with the logarithm of the energy of the beam[11]. The shower maximum for a 10 GeV beam in iron is 5.6 r.l. and since the length of the *standard target* is 17.3 r.l., most of the energy of the beam already has been expended in the target, so most of the neutrons already have been produced. Accordingly, to extend our target-attenuation model in a conservative fashion, we require targets to be at least 17.3 r.l. in length (see parameter `TarLenN` in `BLOCK DATA`).

However, in the radial direction the situation is slightly more complex. The model we follow in this case is based on an EM shower concept first published in a 1966 study by Nelson et al[18] and later incorporated into Chapter 26 of the SLAC Big Book[1]. In the mid 1960's a series of electron-photon shower calculations had been published by three independent laboratories. In these Monte Carlo calculations, electrons with energies between 100 MeV and 20 GeV were directed into large cylinders of aluminum, copper and lead and energy deposition was scored into bins as a function of depth, z, and radius, r. Nelson et al[18] demonstrated that there was a useful way to combine all of the *Monte Carlo* results into a single plot by considering the energy absorbed per unit volume, dw/dv, and they defined the *fraction* of the total energy, E_0, absorbed beyond radius, r_0, by

$$\frac{U(r_0)}{E_0} = \int_0^\infty \int_{r_0}^\infty \frac{dw}{dv}\, 2\pi dr dz \Bigg/ \int_0^\infty \int_0^\infty \frac{dw}{dv}\, 2\pi dr dz$$

and plotted U/E_0 as a function of r_0 in Molière units[12], as shown in Fig. C.2 (figure taken from the SLAC Big Book[1])[13] .

[12] A Molière unit, X_m, is the characteristic measure for radial distributions in analytic shower theory[19] and is equal to $X_m = X_0 E_s/\epsilon_0$, where X_0 is the radiation length, ϵ_0 is the critical energy of the material and $E_s = 21.2$ MeV. The values used in SHIELD11 for X_0, ϵ_0 and X_m are in `BLOCK DATA` and are taken from Swanson's book [15].

[13] We appologise that the r_0/X_m units are difficult to read in Fig. C.2. They are 1.0, 2.0, etc.

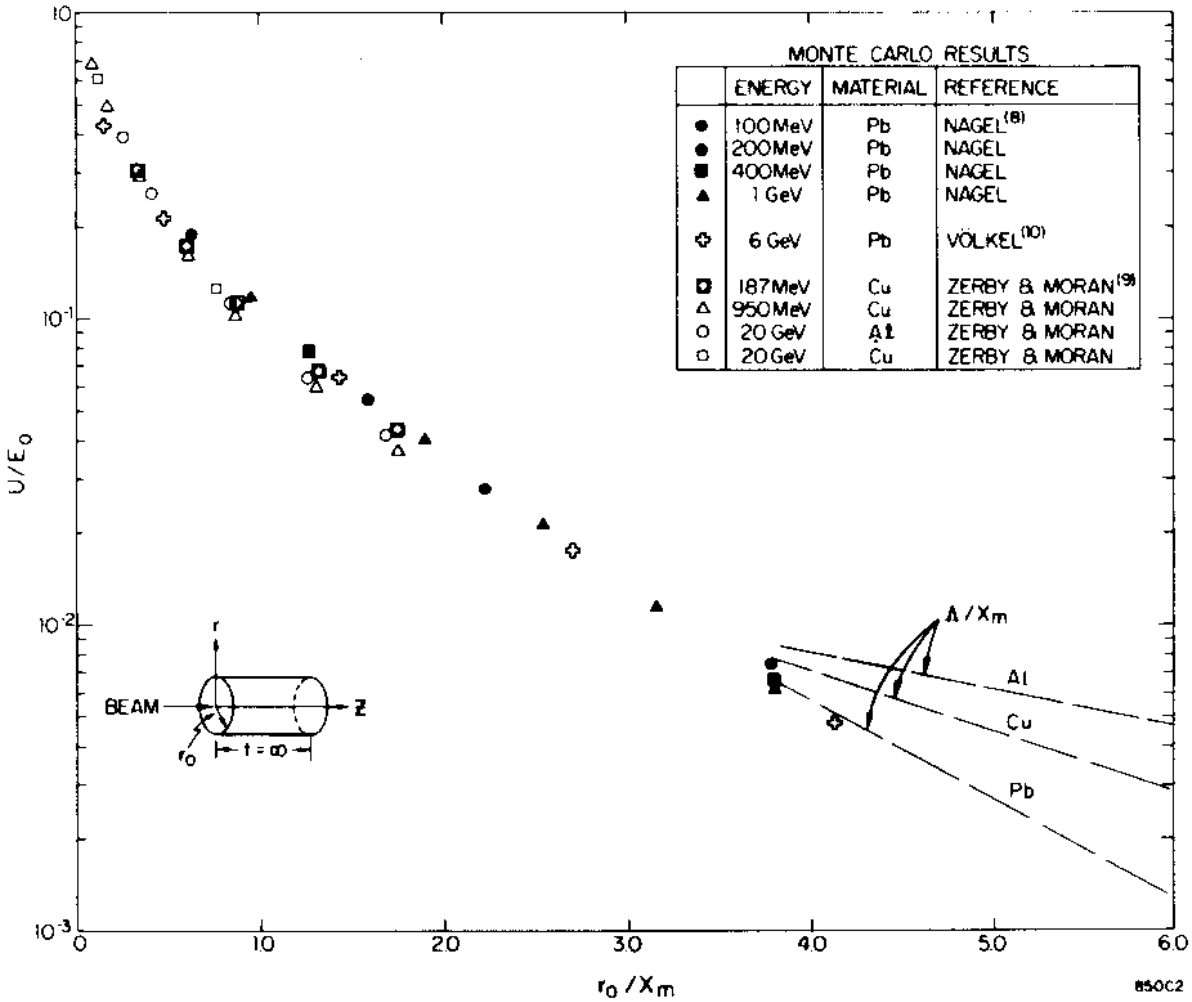

Fig. C.2 Energy deposition fraction as a function of the Molière radius

From a shielding perspective, the significance of Fig. C.2 is that a universal curve is formed. Specifically, the energy fraction, U/E_0, that escapes laterally from cylinders in which the shower is fully developed longitudinally, is independent both of *incident energy* and *target material*, at least out to four Molière radii.

The 2-inch radius for the *standard target* turns out to be equivalent to 3.74 Molière units. Accordingly, to again extend our target-attenuation model in a conservative way, we require targets to have a radius that is at least 3.74 Molière units (see parameter `TarRadN` in `BLOCK DATA`).

The code listing for neutron attenuation by the target is listed below.

```
!      ---------------------------------------
!      Check for neutron attenuation by target
!          (GRN, MID, HEN, and GamI only)
!      ---------------------------------------
       if (IattSW.eq.1 .and. Isorc.ne.4) then
         if (TarLenRL.lt.TarLenN) then
           write(6,'(/,''Stopped in FUNCTION Sorc with TarLenRL='',G15.7,
     +       '' r.l. < TarLenN='',G15.7,'' r.l.)'')')
     +       TarLenRL,TarLenN
```

```
          stop
        end if

        if (TarRadMU.lt.TarRadN) then
          write(6,'(/,''Stopped in FUNCTION Sorc with TarRadMU '',G15.7,
     +      '' m.u.) < TarRadN ('',G15.7,'' m.u.)'')')
     +      TarRadMU,TarRadN
          stop
        end if

        if (AbsAng.gt.90.D0) then                ! NO target attenuation
          SltSor = 0.0                           ! in backward direction
          go to 1000
        end if

!       ----------------------------------------------------
!       Find critical angle and SltTar for cylindrical target
!       ----------------------------------------------------
        CritTar = atan(TarRad/TarLen)/DegRad                 ! (degrees)
        if (AbsAng.ge.CritTar) then
          SltTar = TarRadGCM/SinThe                          ! (g/sq.cm)
        else
          SltTar = TarLenGCM/CosThe                          ! (g/sq.cm)
        end if

!       --------------------------------------------------
!       Find critical angle and SltCor for cylindrical core
!       --------------------------------------------------
        CritCor = atan(TarRadN*XMUmat(IDtar)/TarLenN/RLmat(IDtar))/
     +            DegRad                                     ! (degrees)
        if (AbsAng.ge.CritCor) then
          SltCor = TarRadN*XMUmat(IDtar)/SinThe              ! (g/sq.cm)
        else
          SltCor = TarLenN*RLmat(IDtar)/CosThe               ! (g/sq.cm)
        end if

        SltSor = SltTar - SltCor                             ! (g/sq.cm)

      end if                  ! End of IattSW.eq.1 .and. Isorc.ne.4 loop
```

D SHIELD11 Code Listing

D.1 MAIN program

```
!***********************************************************************
!********************************   STANFORD LINEAR ACCELERATOR CENTER *
!***     S H I E L D 1 1     ***                                       *
!********************************   Version:           1 FEB 2005/0800 *
!***********************************************************************
!                      ----------------------
!                      COPYRIGHT (C) 1988-2005
!                      ----------------------
!    By the Board of Trustees of the Leland Stanford Junior University
!                        All Rights Reserved
!
!***********************************************************************
!                            ----------
!                            DISCLOSURE
!                            ----------
!   The SHIELD11 code has been developed at SLAC under the sponsorship
!   of the U.S. Government.  Neither the U.S. nor the U.S.D.O.E., nor
!   the Leland Stanford Junior University, nor their employees, nor
!   their respective contractors, subcontractors, or their employees,
!   makes any warranty, express or implied, or assumes any liability or
!   responsibility for accuracy, completeness or usefulness of any
!   information, apparatus, product or process disclosed, or represents
!   that its use will not infringe privately-owned rights.  Mention of
!   any product, its manufacturer, or suppliers shall not, nor is it
!   intended to, imply approval, disapproval, or fitness for any par-
!   ticular use.  A royalty-free, non-exclusive right to use and dis-
!   seminate same for any purpose whatsoever is expressly reserved to
!   the U.S. and the University.
!
!***********************************************************************
!                         ---------------
!                         ACKNOWLEDGEMENT
!                         ---------------
!   The contributors acknowledge T. M. Jenkins for his part in develop-
!   ing the original versions leading up to (and including) SHIELD11.
!
!***********************************************************************
!                      --------------------
!                      DISTRIBUTION CONTACT
!                      --------------------
!               Walter R. Nelson
!               Department Associate (retired)
!               Radiation Physics Group, MS/48
!               Stanford Linear Accelerator Center
!               Stanford, CA 94309
!               U.S.A.
!
!               Email: wrnrp@slac.stanford.edu
!
!***********************************************************************
!                            ------------
!                            CODE HISTORY
!                            ------------
!  SHIELD11 is a code for performing shielding analysis around a high-
!  energy electron accelerator.  It makes use of simple analytic
!  expressions for the production of photons and neutrons by electron
!  beams striking thick targets (e.g., dumps, stoppers, etc.), and the
!  attenuation of these photons and neutrons.  The code, originally
!  written by T. M. Jenkins and W. R. Nelson, makes use of experimental
!  data from a number of sources and involves extrapolation (scaling)
!  based on rather simple physics concepts described in these sources
!  (e.g., see references listed below).
!
!  Because these scaling methods have only been tested over a rather
```

```
!  limited set of conditions (1-10 GeV electrons striking 10-20 r.l.
!  Fe and Pb targets), careful judgement should be exercised when using
!  SHIELD11.  To be more specific, users of SHIELD11 would be well
!  advised to fully understand the models used in the code before
!  trusting the results, particularly outside the range of design.
!
!***********************************************************************
!                          ---------------------
!                          PRIMARY DOCUMENTATION
!                          ---------------------
!
!       W. R. Nelson and T, M. Jenkins, "The SHIELD11 Computer Code",
!       SLAC-Report-737, February 2005.
!
!                            ------------------
!                            RELATED REFERENCES
!                            ------------------
!
!    1) H. DeStaebler, T. M. Jenkins and W. R. Nelson, "Shielding and
!       Radiation", Chapter 26 in THE STANFORD TWO-MILE ACCELERATOR,
!       R. B. Neal, Editor (Benjamin, 1968).
!    2) T. M. Jenkins, "Neutron and Photon Measurements through Con-
!       crete for a 15 GeV Electron Beam on a Target -- Comparison with
!       Models and Calculations", Nucl. Instr. Meth. 159 (1979) 265.
!    3) W. P. Swanson and R. H. Thomas, "Dosimetry for Radiological
!       Protection at High-Energy Particle Accelerators", Chapter 1
!       in THE DOSIMETRY OF IONIZING RADIATION, Volume III, K. R. Kase,
!       B. E. Bjarngard and F. H. Attix, Editors (Academic Press, 1990).
!    4) W. P. Swanson, RADIOLOGICAL SAFETY ASPECTS OF THE OPERATION OF
!       ELECTRON LINEAR ACCELERATORS, IAEA Technical Reports Series
!       No. 188 (Vienna, 1979).
!    5) A. Fasso, K. Goebel, M. Hoefert, J. Ranft, G. Stevenson,
!       "Shielding Against High-Energy Radiation", in Volume 11
!       Landolt-Bornstein - Numerical Data and Functional Relationships
!       in Science and Technology (Springer-Verlag, 1990).
!    6) H. Hirayama and S. Ban, "Review of Shielding Problems Concern-
!       ing Electron Accelerators", p.107-132 in Proceedings of the
!       Specialists' Shielding Meeting on SHIELDING ASPECTS OF ACCELERA-
!       TORS, TARGETS AND IRRADIATION FACILITIES, held in Arlington,
!       Texas (28-29 April 1994); Nuclear Energy Agency OECD Document.
!
!***********************************************************************
!23456789|123456789|123456789|123456789|123456789|123456789|123456789|12

!=======================================================================
!                            MAIN program
!=======================================================================

      implicit none

      include 'include/shield11_h.fh'     ! "Header" file for parameters

!     ----------------
!     SHIELD11 COMMONs
!     ----------------
      include 'include/beam.fh'                              ! Beam data
      include 'include/detect.fh'                        ! Detector data
      include 'include/dosval.fh'                  ! Components for dose
      include 'include/matdta.fh'                        ! Material data
      include 'include/miscon.fh'              ! Miscellaneous constants
      include 'include/shield.fh'                          ! Shield data
      include 'include/target.fh'                          ! Target data

      real*8                                           ! Local variables
     + Theta,AMTdeg,cosAMT,SltShl,Rsq,Sorc,
     + SltCON,SltFE,SltPB,SltMIS
      integer IOsw,Itheta,Isorc

!     ----------
!     Open files
```

```
!     ----------
      open(UNIT= 5,FILE='shield11.in5',STATUS='OLD')
      open(UNIT= 6,FILE='shield11.out6',STATUS='UNKNOWN')

!     ================
      call DataIO(IOsw)                          ! Read/print input data
!     ================

!     ================================
!     Start of MAIN calculation (loops)
!     ================================
!     ----------------------------------
!     Loop over each detector angle, Theta
!     ----------------------------------
      do ITheta=1,NTheta
        Theta = Theta0 + (ITheta-1)*dTheta    ! Detector angle (degrees)
        AMTdeg = AngShl - Theta                           ! alpha - theta

!       ----------------------------------------------
!       Check for bad production angle vs. shield angle
!       ----------------------------------------------
        if (ABS(AMTdeg).ge.90.D0) then
          write(6,'(''Program stopped: Bad values for AngShl,Theta = '',
     +      2G15.5)')
     +      AngShl,Theta
          stop
        end if

!       -------------------------------------------------------------
!       Primary shielding: Slant thickness and inverse square distance
!       -------------------------------------------------------------
        CosAMT = cos(DegRad*AMTdeg)                ! Cosine(alpha-theta)
        SltShl = ThkShl*RHOmat(IDshl)/CosAMT ! Slant thickness (g/sq.cm)
        Rsq = ((DisShl + ThkShl)/CosAMT)**2    ! 1/R**2 distance (sq.cm)

!       ------------------------------------
!       Additional shielding: Slant thickness
!       ------------------------------------
        SltCON = AddCON*RHOmat(1)/CosAMT            ! Concrete (g/sq.cm)
        SltFE  = AddFE*RHOmat(2)/CosAMT                 ! Iron (g.sq.cm)
        SltPB  = AddPB*RHOmat(3)/CosAMT                 ! Lead (g.sq.cm)
        SltMIS = AddMIS*RHOmat(4)/CosAMT       ! MISC material (g/sq.cm)

!       ----------------------------------
!       Get dose (rem/e) for each component
!       ----------------------------------
        do Isorc=1,5
          Dose(Isorc) = Sorc                           ! rem/e (at 1 cm)
     +    (Isorc,IDtar,TarLen,TarRad,IattSW,Ebeam,Theta)*
     +      exp(-SltShl/Xmfp(IDshl,Isorc))*             ! Primary shield
     +      exp(-SltCON/Xmfp(1,Isorc))*                ! Added CONCrete
     +      exp(-SltFE/Xmfp(2,Isorc))*                        ! Added FE
     +      exp(-SltPB/Xmfp(3,Isorc))*                        ! Added PB
     +      exp(-SltMIS/Xmfp(4,Isorc))/                     ! Added MISC
     +      Rsq                                ! rem/e (actual distance)
        end do

        if (ITheta.eq.1) then
      write(6,'('' *****************************************************
     +*****************'')')
      write(6,'(''                           RESULTS OF CALCULATION'')')
      write(6,'('' *****************************************************
     +*****************'')')
        end if

!       =================
        call DosOut(Theta)         ! Print out each component and totals
!       =================
      end do                                         ! End of ITheta loop
```

```
!     ----------
!     Close files
!     ----------
      close(UNIT= 5)
      close(UNIT= 6)

      stop
      end
!----------------------last line of MAIN program-----------------------
```

D.2 BLOCK DATA

```
!***********************************************************************
!*******************************   STANFORD LINEAR ACCELERATOR CENTER *
      BLOCK DATA
!*******************************   Version:          1 FEB 2005/0800 *
!***********************************************************************
!-----------------------------------------------------------------------
!                       Material Constants (notes)
!-----------------------------------------------------------------------
!   1) The Xmfp values for GRN (fast neutron) attenuation by high-Z
!      materials are based on the so-called 'lid-tank' experiment.
!      These removal cross sections are given in Table 8.3 (p.231) of
!      Chilton, Shultis and Faw, PRINCIPLES OF RADIATION SHIELDING
!      (Prentice-Hall, 1984).  For example:
!
!         Iron     1.98 b/atom --> 47 g/sq.cm
!         Lead     3.53 b/atom --> 97 g/sq.cm
!
!      which are used in SHIELD11 (see below).  However, use of these
!      Xmfp values implies that an appropriate amount of hydrogeneous
!      material FOLLOWS the high-Z shield.  Typically, this amounts to
!      about 2-ft of concrete or 20-30 cm of polyethylene (e.g., see
!      Figure 8.6 ibid).  If there is NO moderating material between
!      the detector and the source (or source plus high-Z shielding),
!      as in the case when a value of zero is assigned to ThkShl,
!      a series of MORSE calculations and experiments by Jenkins
!      suggest that Xmfp=135 should be used for FE (and PB).
!      Accordingly, this is the default value we have assigned below
!      to Xmfp(4,1) for 'MISC' (i.e., we assume 'MISC' is 'PB' without
!      moderator).
!   2) For earth, one can use CONC directly by changing RHOmat(1) from
!      2.35 to 1.70 g/cu.cm, or one can copy all the 'CONC' data to
!      'MISC' and make RHOmat(4)=1.70, thus allowing the use of both
!      'CONC' and 'MISC', simultaneously.
!***********************************************************************
      implicit none

      include 'include/shield11_h.fh'     ! "Header" file for parameters

!     ----------------
!     SHIELD11 COMMONs
!     ----------------
      include 'include/matdta.fh'                      ! Material data
      include 'include/miscon.fh'            ! Miscellaneous constants
      include 'include/sorcon.fh'            ! FUNCTION Sorc constants

!     ------------------
!     For common/MATDTA/
!     ------------------
      DATA MatID /'CONC',  'FE  ', 'PB  ','MISC'/          ! Material ID
      DATA Zmat  /  13.0,  26.0,   82.0,   82.0 /        ! Atomic Number
      DATA Amat  / 26.98, 55.85, 207.19, 207.19 / ! Atomic Mass (g/mole)
      DATA RHOmat/  2.35,  7.87,  11.35,  11.35 /    ! Density (g/cu.cm)
      DATA RLmat /  26.7, 13.84,   6.37,   6.37 /  ! Rad. Len. (g/sq.cm)
      DATA XMUmat/  11.1,  10.7,   14.2,   14.2 /! Moliere Len.(g/sq.cm)
      DATA Xmfp  /  30.0,  47.0,   97.0,  135.0,  ! MFP (g/sq.cm) - GRNs
     +              55.0, 145.0,  200.0,  200.0,  !               - MIDs
```

```
     +             120.0, 145.0,  200.0,  200.0,  !               - HENs
     +              42.0,  33.6,   24.0,   24.0,  !               - GamD
     +             120.0, 145.0,  200.0,  200.0 / !               - GamI
      DATA SorNam/'GRNs','MIDs','HENs','GamD','GamI'/
!     ------------------------------------------------------------------

!     ------------------
!     For common/SORCON/
!     ------------------
!     ------------------------------------------
!     Thresholds and minimums (for FUNCTION Sorc)
!     ------------------------------------------
      DATA ThrHEN/0.150D0/     ! Threshold energy (GeV) for HEN production
      DATA TarLenG/0.01D0/     ! Minimum target length for photons (r.l.)
      DATA TarLenN/17.332196D0/! Minimum target length for neutrons (r.l.)
      DATA TarRadG/1.189869D0/ ! Minimum target radius for photons
      DATA TarRadN/3.736411D0/ ! Minimum target radius for neutrons (Mol.units)
!     ---------------------------------------------
!     Data fit to HEN cross section by T. M. Jenkins
!     ---------------------------------------------
      DATA E_HEN/
     +         0.15,   0.16,   0.17,   0.18,   0.19,   0.20,   0.21,
     +         0.22,   0.23,   0.24,   0.25,   0.27,   0.30,   0.35,
     +         0.40,   0.45,   0.50,   0.55,   0.60,   0.70,   0.80,
     +         0.90,   1.00/
      DATA CS_HEN/
     +      0.00444,0.00711, 0.0111, 0.0156, 0.0222, 0.0298, 0.0382,
     +       0.0489, 0.0547, 0.0622, 0.0711, 0.0889,  0.116,  0.162,
     +        0.211,  0.276,  0.338,  0.404,  0.502,  0.601,  0.711,
     +        0.813,   1.00/
!     ------------------------------------------------------------------

!     ------------------
!     For common/MISCON/
!     ------------------
      DATA DegRad/1.745329D-2/                ! Pi/180 (radians/degree)

      end
!--------------------last line of BLOCK DATA----------------------------
```

D.3 SUBROUTINE DataIO

```
!***********************************************************************
!******************************   STANFORD LINEAR ACCELERATOR CENTER *
      SUBROUTINE DataIO(IOsw)
!******************************   Version:           1 FEB 2005/0800 *
!***********************************************************************
! Subprogram to read/print input data.
!***********************************************************************
      implicit none

      include 'include/shield11_h.fh'     ! "Header" file for parameters

!     ----------------
!     SHIELD11 COMMONs
!     ----------------
      include 'include/beam.fh'                              ! Beam data
      include 'include/detect.fh'                        ! Detector data
      include 'include/matdta.fh'                        ! Material data
      include 'include/shield.fh'                          ! Shield data
      include 'include/target.fh'                          ! Target data

!      real*8                                          ! Local variables
      integer IOsw,i,j
      character*4 NamTar,NamShl


!     ===================
```

```
      read(5,'(I1)') IOsw                                   ! I/O switch
!     ==================
      if (IOsw.lt.0 .or. IOsw.gt.2) then
        write(6,*) 'Program stopped: BAD IOsw = ',IOsw
        stop
      end if

!     ------------------------------------------
!     Print (echo) the material data in BLOCK DATA
!     ------------------------------------------
      if (IOsw.eq.2) then
        write(6,'('' ****************************************************
     +******************'')')
        write(6,'(''                              MATERIAL DATA'')')
        write(6,'('' ****************************************************
     +******************'')')
        write(6,'('' MatID            '',3X,4(5X,A4),/)') MatID
        write(6,'('' Zmat             '',3X,4(2X,F7.2))') Zmat
        write(6,'('' Amat             '',3X,4(2X,F7.2))') Amat
        write(6,'('' RHOmat (g/cu.cm)'',3X,4(2X,F7.2),/)') RHOmat
        write(6,'('' RLmat  (g/sq.cm)'',3X,4(2X,F7.2))') RLmat
        write(6,'('' XMUmat (g/sq.cm)'',3X,4(2X,F7.2))') XMUmat
        write(6,'(60X,''Isorc'')')
        do j=1,5
          if (j.eq.1) then
            write(6,'('' Xmfp   (g/sq.cm)'',3X,4(2X,F7.2),3X,I1,
     +        '' ('',A4,'')'')')
     +        (Xmfp(i,j),i=1,4),j,SorNam(j)
          else
            write(6,'(20X,4(2X,F7.2),3X,I1,'' ('',A4,'')'')')
     +        (Xmfp(i,j),i=1,4),j,SorNam(j)
          end if
        end do
        write(6,'()')
      end if

!     =======================
      read(5,'(F10.0)') Ebeam                        ! Beam energy (GeV)
!     =======================

!     =====================
      read(5,'(A4)') NamTar                            ! Target material
!     =====================
      IDtar = 0
      do i=1,4
        if (NamTar.eq.MatID(i)) then
          IDtar = i
          go to 1
        end if
      end do
      write(6,*) 'Program stopped: Could not find NamTar = ',NamTar
      stop
 1    continue

!     ================================
      read(5,'(2F10.0)') TarLen,TarRad  ! Target length, radius (inches)
!     ================================  ! (and convert to cm below)

!     =====================
      read(5,'(I1)') IattSW          ! Neutron target-attenuation switch
!     =====================
      if (IattSW.ne.0 .and. IattSW.ne.1) then
        write(6,*) 'Program stopped: BAD IattSW = ',IattSW
        stop
      end if

!     =====================
      read(5,'(A4)') NamShl                     ! Primary shield material
!     =====================
      IDshl = 0
```

```
      do i=1,4
        if (NamShl.eq.MatID(I)) then
          IDshl = i
          go to 2
        end if
      end do
      write(6,*) 'Program stopped: Could not find NamShl = ',NamShl
      stop
 2    continue

!     ================================
      read(5,'(2F10.0)') AngShl,DisShl       ! Shield angle (degree) and
!     ================================         distance (inch)

!     ========================
      read(5,'(F10.0)') ThkShl                  ! Shield thickness (inch)
!     ========================

!     ===========================================
      read(5,'(I10,2F10.0)') NTheta,dTheta,Theta0  ! Detector angle data
!     ===========================================

!     ========================
      read(5,'(F10.0)') AddCON              ! Additional concrete (inch)
      read(5,'(F10.0)') AddFE                   ! Additional iron (inch)
      read(5,'(F10.0)') AddPB                   ! Additional lead (inch)
      read(5,'(F10.0)') AddMIS         ! Additional MISC material (inch)
!     ========================

!     ---------------------------
!     Print (echo) the INPUT data
!     ---------------------------
      if (IOsw.ge.1) then                         ! Print out input data
        write(6,'('' ****************************************************
     +******************'')')
        write(6,'(''                                INPUT DATA'')')
        write(6,'('' ****************************************************
     +******************'')')
        write(6,'(1X,I1,34X,''IOsw (0=none,1=input,2=media/input)'')')
     +    IOsw
        write(6,'(1X,F10.3,25X,''Ebeam (GeV)'')')
     +    Ebeam
        write(6,'(1X,A4,31X,''NamTar'')')
     +    NamTar
        write(6,'(1X,2F10.3,15X,''TarLen (inch),TarRad (inch)'')')
     +    TarLen,TarRad
        write(6,'(1X,I1,34X,''IattSW (1=target n-atten., 0=none)'')')
     +    IattSW
        write(6,'(1X,A4,31X,''NamShl'')')
     +    NamShl
        write(6,'(1X,2F10.3,15X,''AngShl (deg),DisShl (inch)'')')
     +    AngShl,DisShl
        write(6,'(1X,F10.3,25X,''ThkShl (inch)'')')
     +    ThkShl
        write(6,'(1X,I10,2F10.3,5X,''NTheta,dTheta,Theta0 (deg)'')')
     +    NTheta,dTheta,Theta0
        write(6,'(1X,F10.3,25X,''AddCON (inch)'')')
     +    AddCON
        write(6,'(1X,F10.3,25X,''AddFE (inch)'')')
     +    AddFE
        write(6,'(1X,F10.3,25X,''AddPB (inch)'')')
     +    AddPB
        write(6,'(1X,F10.3,25X,''AddMIS (inch)'')')
     +    AddMIS
        write(6,'()')
      end if

!     --------------------
!     Convert inches to cm
!     --------------------
```

```
      TarLen = TarLen*2.54D0
      TarRad = TarRad*2.54D0
      DisShl = DisShl*2.54D0
      ThkShl = ThkShl*2.54D0
      AddCON = AddCON*2.54D0
      AddFE  =  AddFE*2.54D0
      AddPB  =  AddPB*2.54D0
      AddMIS = AddMIS*2.54D0

      return
      end
!--------------------last line of SUBROUTINE DataIO---------------------
```

D.4 SUBROUTINE DosOut

```
!***********************************************************************
!*******************************   STANFORD LINEAR ACCELERATOR CENTER *
      SUBROUTINE DosOut(Theta)
!*******************************   Version:           1 FEB 2005/0800 *
!***********************************************************************
! Subprogram to print out the dose equivalent values.
!***********************************************************************
      implicit none

      include 'include/shield11_h.fh'     ! "Header" file for parameters

!     ----------------
!     SHIELD11 COMMONs
!     ----------------
      include 'include/beam.fh'                                 ! Beam data
      include 'include/dosval.fh'                      ! Components for dose

      real*8                                               ! Local variables
     + Theta,ekWh,DoseN,DoseG,DoseT,GNratio


      ekWh = 2.25E+16/Ebeam   ! Electrons/kWh factor (with Ebeam in GeV)

      DoseN = Dose(1) + Dose(2) + Dose(3)           ! Total neutron dose
      DoseG = Dose(4) + Dose(5)                      ! Total photon dose
      DoseT = DoseN + DoseG                                 ! Total dose
      GNratio = DoseG/DoseN

      write(6,'(T8,''--------------------------------------------------
     +-------'')')
      Write(6,'(T8,''Production angle='',G12.5,'' degrees'',4X,
     +             ''[G/N= '',G10.5,'']'')') Theta,GNratio
      write(6,'(T8,''--------------------------------------------------
     +-------'')')
      write(6,'(T10,'' GRN         MID         HEN         Neutron'')')
      write(6,'(T7,4(2X,G10.5),''  rem/e'')')
     +  Dose(1),Dose(2),Dose(3),DoseN
      write(6,'(T7,4(2X,G10.5),''  rem/h/kW'')')
     +  Dose(1)*ekWh,Dose(2)*ekWh,Dose(3)*ekWh,DoseN*ekWh
      write(6,'(/,T10,'' GamD        GamI       Gamma        TOTAL'')')
      write(6,'(T7,4(2X,G10.5),''  rem/e'')')
     +  Dose(4),Dose(5),DoseG,DoseT
      write(6,'(T7,4(2X,G10.5),''  rem/h/kW'')')
     +  Dose(4)*ekWh,Dose(5)*ekWh,DoseG*ekWh,DoseT*ekWh
      write(6,'(T45,''=========='')')

      return
      end
!--------------------last line of SUBROUTINE DosOut---------------------
```

D.5 FUNCTION Sorc

```
!**********************************************************************
!********************************   STANFORD LINEAR ACCELERATOR CENTER *
!
      FUNCTION Sorc(Isorc,IDtar,TarLen,TarRad,IattSW,Energy,Angle)
!
!********************************   Version:           1 FEB 2005/0800 *
!**********************************************************************
! This subprogram returns the dose equivalent (rem/e) at 1 cm.
!**********************************************************************
!    Isorc    Source Type:  1 = Giant Resonance Neutrons (GRNs)
!                           2 = Mid-Energy Neutrons (MIDs)
!                           3 = High-Energy Neutrons (HENs)
!                           4 = Gamma Direct (EM cascade) (GamD)
!                           5 = Gamma Indirect (hadron cascade) (GamI)
!
!    IDtar    Target ID:    1 = CONC   (concrete)
!                           2 = FE     (iron)
!                           3 = PB     (lead)
!                           4 = MISC   (default is lead w/o moderator)
!    TarLen   Target length (cm).  Restrictions: Should be larger than
!             0.01 r.l. for photons & larger than 17.3 r.l. for neutron
!             attenuation by the target itself (i.e., when IattSW=1).
!    TarRad   Target radius (cm).  Restrictions: Should be larger than
!             2-in for Fe (or an equivalent number of GamD relaxation
!             lengths for other materials) for neutrons.  Also, should
!             be at least 3.74 Moliere Units in radius for neutron
!             attenuation by the target itself (i.e., when IattSW=1).
!    IattSW   Switch for neutron attenuation by the target material
!             itself (0=no attenuation, 1=attenuation).
!             [Note: Target length must be .GE. 17.3 r.l. and target
!                    radius must be .GE. 3.74 Moliere Units].
!    Energy   Energy of electron beam (GeV)
!             [Note: Below 1 GeV, approximation schemes (based on data
!                    fitting, etc.) are applied to the MID and HEN
!                    neutron terms.]
!    Angle    Production angle (degrees)
!**********************************************************************
      implicit none

      include 'include/shield11_h.fh'     ! "Header" file for parameters

!     ----------------
!     SHIELD11 COMMONs
!     ----------------
      include 'include/matdta.fh'                         ! Material data
      include 'include/miscon.fh'              ! Miscellaneous constants
      include 'include/sorcon.fh'              ! FUNCTION Sorc constants

      real*8                                            ! Local variables
     + Sorc,TarLen,TarRad,Energy,Angle,
     + AbsAng,CosThe,SinThe,SltSor,CritTar,SltTar,CritCor,SltCor,
     + TarLenGCM,TarLenRL,TarRadGCM,TarRadMU,TarRadRelax,
     + DelCS,Sorc1,Sorc2
      integer Isorc,IDtar,IattSW,k

      AbsAng = ABS(Angle)
      CosThe = COS(DegRad*AbsAng)
      SinThe = SIN(DegRad*AbsAng)
      TarLenGCM = TarLen*RHOmat(IDtar)         ! Target length (g/sq.cm)
      TarLenRL = TarLenGCM/RLmat(IDtar)           ! Target length (r.l.)
      TarRadGCM = TarRad*RHOmat(IDtar)         ! Target radius (g/sq.cm)
      TarRadMU = TarRadGCM/XMUmat(IDtar) ! Target radius (Moliere units)
      TarRadRelax = TarRadGCM/Xmfp(IDtar,4)           ! Relaxation units

      SltSor = 0.0

!     ---------------------------------------
```

```
!     Check for neutron attenuation by target
!         (GRN, MID, HEN, and GamI only)
!     ---------------------------------------
      if (IattSW.eq.1 .and. Isorc.ne.4) then
        if (TarLenRL.lt.TarLenN) then
          write(6,'(/,''Stopped in FUNCTION Sorc with TarLenRL='',G15.7,
     +      '' r.l. < TarLenN='',G15.7,'' r.l.)'')')
     +      TarLenRL,TarLenN
          stop
        end if

        if (TarRadMU.lt.TarRadN) then
          write(6,'(/,''Stopped in FUNCTION Sorc with TarRadMU '',G15.7,
     +      '' m.u.) < TarRadN ('',G15.7,'' m.u.)'')')
     +      TarRadMU,TarRadN
          stop
        end if

        if (AbsAng.gt.90.D0) then                ! NO target attenuation
          SltSor = 0.0                           ! in backward direction
          go to 1000
        end if

!       ----------------------------------------------------
!       Find critical angle and SltTar for cylindrical target
!       ----------------------------------------------------
        CritTar = atan(TarRad/TarLen)/DegRad                  ! (degrees)
        if (AbsAng.ge.CritTar) then
          SltTar = TarRadGCM/SinThe                           ! (g/sq.cm)
        else
          SltTar = TarLenGCM/CosThe                           ! (g/sq.cm)
        end if

!       --------------------------------------------------
!       Find critical angle and SltCor for cylindrical core
!       --------------------------------------------------
        CritCor = atan(TarRadN*XMUmat(IDtar)/TarLenN/RLmat(IDtar))/
     +            DegRad                                      ! (degrees)
        if (AbsAng.ge.CritCor) then
          SltCor = TarRadN*XMUmat(IDtar)/SinThe               ! (g/sq.cm)
        else
          SltCor = TarLenN*RLmat(IDtar)/CosThe                ! (g/sq.cm)
        end if

        SltSor = SltTar - SltCor                              ! (g/sq.cm)

      end if                  ! End of IattSW.eq.1 .and. Isorc.ne.4 loop

!     =====================================
!     Branch to the appropriate source term
!     =====================================
!             GRN  MID  HEN  GamD  GamI
!            -------------------------
 1000 go to (  1,   2,   3,   4,    3   ) Isorc
!            -------------------------

      write(6,'(/,'' Stopped in FUNCTION Sorc: Isorc='',
     +  I5,'' is bad.'')')
     +  Isorc
      stop

!     ==============================
!     GIANT-RESONANCE NEUTRONS (GRN)
!     ==============================
 1    Sorc = 4.93D0*Zmat(IDtar)**0.662D0
      Sorc=Sorc*Energy*1.D-11                             ! rem/e at 1 cm
      if (IattSW.eq.1) then                    ! Apply target attenuation
        Sorc = Sorc*exp(-SltSor/Xmfp(IDtar,Isorc))
      end if
      return
```

```
!      ========================
!      MID-ENERGY NEUTRONS (MID)
!      ========================
 2    Sorc = 43.9D0/Amat(IDtar)**0.37D0/(1.D0 - 0.75D0*CosThe)
      if (Energy.le.0.5D0) then
        Sorc = Sorc*1.6D0*Energy**1.5D0
      else if (Energy.gt.0.5D0 .and. Energy.lt.1.D0) then
        Sorc = Sorc*(0.566D0 + 0.434D0*(Energy - 0.5D0)/0.5D0)
      end if
      Sorc = Sorc*Energy*1.D-11                          ! rem/e at 1 cm
      if (IattSW.eq.1) then                    ! Apply target attenuation
        Sorc = Sorc*exp(-SltSor/Xmfp(IDtar,Isorc))
      end if
      return

!     =========================
!     HIGH-ENERGY NEUTRONS (HEN)
!     =========================
 3    if (Energy.le.ThrHEN) then                         ! Below threshold
        Sorc = 0.D0
      else
        Sorc = 13.7D0/Amat(IDtar)**0.65D0/(1.D0 - 0.72D0*CosThe)**2D0
      end if

      if (Energy.lt.1.D0) then   ! Loop over the energy bins below 1 GeV
        do k=2,23
          if (Energy.lt.E_HEN(k)) then
            DelCS = (CS_HEN(k) - CS_HEN(k-1))*(Energy - E_HEN(k-1))/
     +              (E_HEN(k) - E_HEN(k-1))
            Sorc = (CS_HEN(k-1) + DelCS)*Sorc
            go to 1100
          end if
        end do
      end if
                          ! =========================================
 1100 if (Isorc.eq.5) then  ! INDIRECT PHOTONS FROM HADRON SHOWER (GamI)
                          ! =========================================
        Sorc = 0.267D0*Sorc          ! Sorc on the right is for the HENs
      end if
      Sorc = Sorc*Energy*1.D-11                          ! rem/e at 1 cm
      if (IattSW.eq.1) then                    ! Apply target attenuation
        Sorc = Sorc*exp(-SltSor/Xmfp(IDtar,Isorc))
      end if
      return

!     ================================================
!     DIRECT PHOTONS FROM ELECTROMAGNETIC SHOWER (GamD)
!     ================================================
 4    if (TarLenRL.le.TarLenG) then        ! TarLenG=0.01=minimum target
                                           !          length for photons

        write(6,'(/,''Stopped in FUNCTION Sorc with TarLenRL'',
     +    G15.7,'' r.l. <= TarLenG ='',G15.7,'' r.l.'')')
     +    TarLenRL,TarLenG
        stop
      end if

      if (TarRadRelax.lt.TarRadG) then      ! TarRadG=1.189869D0=minimum
                                            !  target radius for photons
        write(6,'(/,''Stopped in FUNCTION Sorc with TarRadRelax='',
     +    G15.7,'' < TarRadG='',G15.7)')
     +    TarRadRelax,TarRadG
        stop
      end if

!     -----------------------------------------------------------------
!     The GamD model is based on fitting experimental data (vs. theta)
!     for the standard target (12" long cylinder of Fe (R=2")) using two
!     functional forms:    y=a*exp(b*sqrt(theta)) for 0 thru   5 degrees
```

```
!                       and y=a*exp(b*theta)       for 5 thru 180 degrees
!     After normalization, the two source terms are summed.  However,
!     as shown below, two different attenuation factors are applied to
!     the 5-180 degree source term.  Namely,
!
!       exp(-TarRadRelax) for     0 < theta <  90 degrees
!       exp(-TarRadG)     for    90 < theta < 180 degrees
!     ------------------------------------------------------------------
      Sorc1 = 1.06D6*Energy*exp(-TarLenGCM/Xmfp(IDtar,4))*
     +          exp(-0.959D0*AbsAng**0.5D0)

      if (AbsAng.le.90.D0) then
        Sorc2 = 683.D0*exp(-TarRadRelax)*exp(-AbsAng/72.2D0)
      else
        Sorc2 = 683.D0*exp(-TarRadG)*exp(-AbsAng/72.2D0)
      end if

      Sorc = Sorc1 + Sorc2
      Sorc = Sorc*Energy*1.D-11                          ! rem/e at 1 cm
      return

      end
!--------------------last line of FUNCTION Sorc-------------------------
```

D.6 Required PARAMETER (header) file (in subdirectory include/)

```
!----------------------------shield11_h.fh-----------------------------
! Version: 050117-0200                    COMMON used in shield11.f code
!-----------------------------------------------------------------------
!23456789|123456789|123456789|123456789|123456789|123456789|123456789|12

! --------------------------------------------
! SHIELD11 "header" file containing PARAMETERS
! --------------------------------------------

! Maximum number of materials
      integer MXMAT
      parameter (MXMAT = 4)

! Maximum number of source types (i.e., like GamD)
      integer MXSOR
      parameter (MXSOR = 5)

!-----------------------last line of shield11_h.fh----------------------
```

D.7 Required COMMON files (in subdirectory include/)

```
!--------------------------------beam.fh-------------------------------
! Version: 050117-0200                    COMMON used in shield11.f code
!-----------------------------------------------------------------------
!23456789|123456789|123456789|123456789|123456789|123456789|123456789|12

      common/BEAM/                                          ! Beam data
     * Ebeam                                  ! Energy of beam (GeV)

      real*8 Ebeam

!-------------------------last line of beam.fh--------------------------

!-------------------------------detect.fh------------------------------
! Version: 050117-0200                    COMMON used in shield11.f code
!-----------------------------------------------------------------------
!23456789|123456789|123456789|123456789|123456789|123456789|123456789|12
```

```
      common/DETECT/                                    ! Detector data
     * Theta0,                               ! Starting angle (degrees)
     * dTheta,                           ! Angular increments (degrees)
     * Ntheta                                         ! Number of angles

      real*8 Theta0,dTheta
      integer Ntheta

!-------------------------last line of detect.fh------------------------

!-------------------------------dosval.fh------------------------------
! Version: 050117-0200                    COMMON used in shield11.f code
!----------------------------------------------------------------------
!23456789|123456789|123456789|123456789|123456789|123456789|123456789|12

      common/DOSVAL/                                 ! Dose information
     * Dose(MXSOR)                     ! Dose for each source component

      real*8 Dose

!-------------------------last line of dosval.fh------------------------

!-------------------------------matdta.fh------------------------------
! Version: 050117-0200                    COMMON used in shield11.f code
!----------------------------------------------------------------------
!23456789|123456789|123456789|123456789|123456789|123456789|123456789|12

      common/MATDTA/                                    ! Material data
     * Xmfp(MXMAT,MXSOR),                    ! Mean free path (g/sq.cm)
     * Zmat(MXMAT),                                     ! Atomic number
     * Amat(MXMAT),                              ! Atomic mass (g/mole)
     * RHOmat(MXMAT),                               ! Density (g/cu.cm)
     * RLmat(MXMAT),                       ! Radiation length (g/sq.cm)
     * XMUmat(MXMAT),                        ! Moliere length (g/sq.cm)
     * MatID(MXMAT),                              ! Material identifier
     * SorNam(MXSOR)                                      ! Source name

      real*8 Xmfp,Zmat,Amat,RHOmat,RLmat,XMUmat
      character*4 MatID,SorNam

!-------------------------last line of matdta.fh------------------------

!--------------------------------miscon.fh-----------------------------
! Version: 050117-0200                    COMMON used in shield11.f code
!----------------------------------------------------------------------
!23456789|123456789|123456789|123456789|123456789|123456789|123456789|12

      common/MISCON/                          ! Miscellaneous constants
     * DegRad                                 ! Pi/180 (radians/degree)

      real*8 DegRad

!-------------------------last line of miscon.fh------------------------

!-------------------------------shield.fh------------------------------
! Version: 050117-0200                    COMMON used in shield11.f code
!----------------------------------------------------------------------
!23456789|123456789|123456789|123456789|123456789|123456789|123456789|12

      common/SHIELD/                                      ! Shield data
     * AngShl,                       ! Angle of primary shield (degrees)
     * DisShl,                ! Distance of primary shield (inches-->cm)
     * ThkShl,               ! Thickness of primary shield (inches-->cm)
     * AddCON,               ! Added thickness of concrete (inches-->cm)
     * AddFE,                    ! Added thickness of iron (inches-->cm)
     * AddPB,                    ! Added thickness of lead (inches-->cm)
     * AddMIS,                   ! Added thickness of MISC (inches-->cm)
     * IDshl
```

```
      real*8 AngShl,DisShl,ThkShl,AddCON,AddFE,AddPB,AddMIS
      integer IDshl

!-------------------------last line of shield.fh------------------------

!--------------------------------sorcon.fh------------------------------
! Version: 050117-0200                    COMMON used in shield11.f code
!-----------------------------------------------------------------------
!23456789|123456789|123456789|123456789|123456789|123456789|123456789|12

      common/SORCON/                               ! FUNCTION Sorc constants
     * E_HEN,                                                ! Energy (GeV)
     * CS_HEN,                          ! Cross section multiplying factor
     * ThrHEN,                 ! Threshold energy (GeV) for HEN production
     * TarLenG,                 ! Minimum target length for photons (r.l.)
     * TarLenN,                ! Minimum target length for neutrons (r.l.)
     * TarRadG,                        ! Minimum target radius for photons
     * TarRadN          ! Minimum target radius for neutrons (Mol.units)

      real*8 E_HEN(23),CS_HEN(23),ThrHEN,TarLenG,TarLenN,TarRadG,TarRadN

!-------------------------last line of sorcon.fh------------------------

!-------------------------------target.fh-------------------------------
! Version: 050117-0200                    COMMON used in shield11.f code
!-----------------------------------------------------------------------
!23456789|123456789|123456789|123456789|123456789|123456789|123456789|12

      common/TARGET/                                         ! Target data
     * TarLen,                           ! Length of target (inches-->cm)
     * TarRAD,                           ! Radius of target (inches-->cm)
     * IDtar,                                                  ! Target ID
     * IattSW                ! Switch for neutron attenuation by target

      real*8 TarLen,TarRad
      integer IDtar,IattSW

!-------------------------last line of target.fh------------------------
```