Modeling radioisotope sources with GamBet

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We have added new **GamBet** features to model radioisotope sources for medical applications and power sources for space and defense applications. The main challenge is the generation of large primary-particle distributions to represent spatially distributed sources with complex spectra. The primary function of the current **GenDist** utility (distributed with **GamBet**, **Trak** and **OmniTrak**) is the the generation of *beam* distributions. Here, incident particles move predominantly in one direction with a relatively simple energy spectrum. A major advantage of **GamBet** is flexibility in accepting primary particle specifications. This feature facilitates the development of input utilities like **GenDist** for specific applications. This report describes the new **Sourcerer** program to simulate radioisotope sources of any geometry.

We will consider a test problem proposed by a user to motivate the discussion. A radioisotope source is encased in a tungsten case. The source, a cylinder with radius 1.0 cm and length 2.0 cm, consists of 3000 Ci of Europium 152 and 5000 Ci of Europium 154. The case has radius 1.5 cm and length 3.0 cm. The goal is to determine power flow in the assembly and the external dose distribution. The first step is to find the emission characteristics of the isotopes. The **MIRDSoft** site[1] provides data for commonly used sources. The sheet for Eu-154 lists 40 electron and photon emission products, most of which have low energy or low emission probability. For the present study, nine gamma rays account for almost all the emitted power. Even though the number is limited, typing in the information for each run would be tedious. Therefore, **Sourcerer** reads spectral information from a text file with a format like the following:

```
* Europium 154
*   T(i)        f(i)
*  (MeV)       No./NT
* ====================
1.23071e-01   4.056e-01
2.47930e-01   6.915e-02
5.91762e-01   4.962e-02
7.23305e-01   2.011e-01
7.56804e-01   4.542e-02
8.73190e-01   1.220e-01
9.96262e-01   1.053e-01
1.00472e+00   1.791e-01
1.27444e+00   3.499e-01
ENDFILE
```

The file has the suffix `GSS` (**GamBet**/**Sourcerer** Spectrum). As in all Field Precision data files, an asterisk denotes a comment line. The first column (T_i) is the particle energy in MeV. The second column (f_i) is the average number emitted per nuclear transformation (NT). Note that the sum of the second column (1.53) is larger than unity, reflecting the fact that more than one particle may be emitted in a transformation.

[1]Medical Internal Radiation Dose, https://mirdsoft.org/resources/mirdspecs

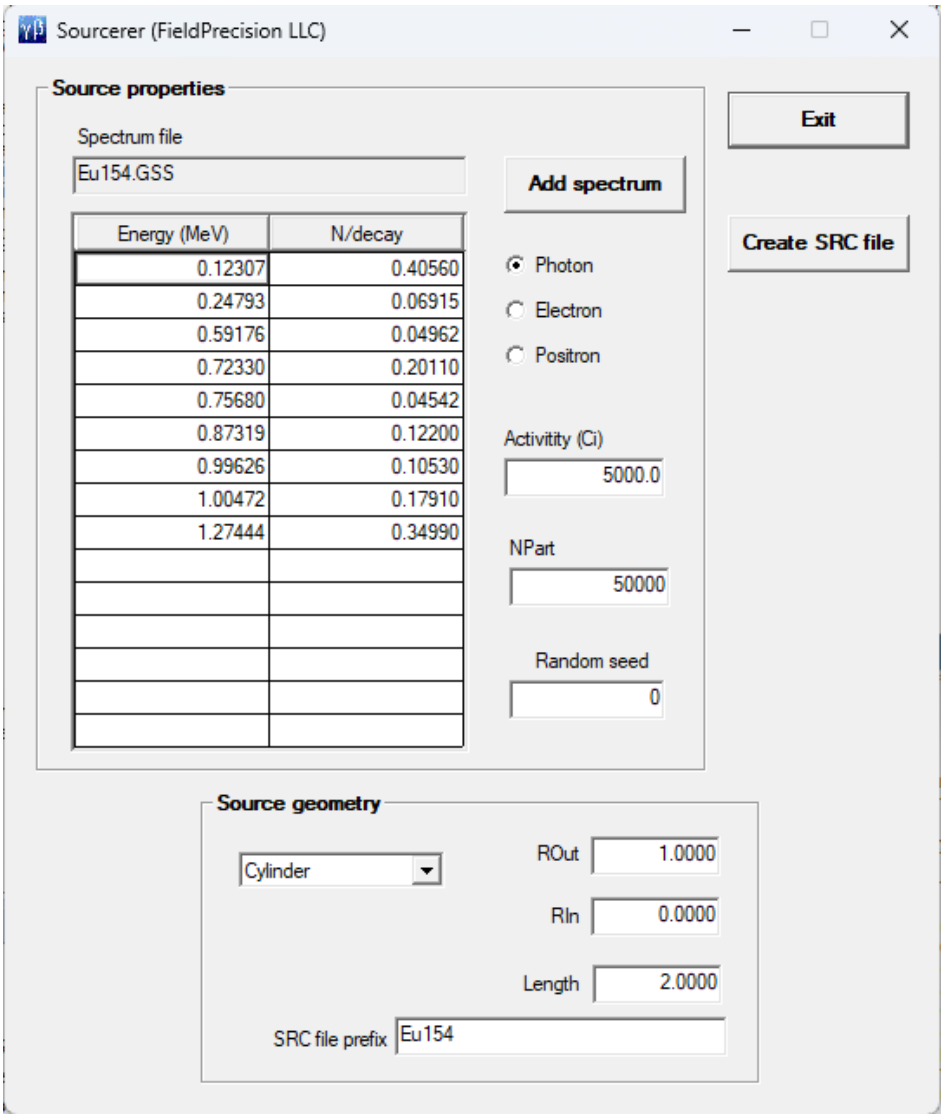

Figure 1: **Sourcerer** interface with parameters for creating a source file for Eu154.

The function of **Sourcerer** is to create one or more standard source files (`SRC`) for **GamBet**. Figure 1 shows the working environment. Operation is straightforward. The first step is load isotope information be clicking the *Add spectrum* button. A load file dialog appears displaying available files with the `GSS` suffix. Making a selection sets the working directory. The program loads and displays data in the list box (maximum number 15). Entries in the box may be edited manually. The radio buttons determine the particle type in the output `SRC` file. If the value in the *Random seed* box is 0, the program sets a seed from the current clock value. Set a non-zero value to repeat a run with the same set of random numbers.

The following source shapes are available:

- **Cylinder or cylindrical shell**. Specify the outer and inner radii and the length. Set the inner radius to 0.0 for a solid cylinder.
- **Block**. Specify the lengths in x, y and z.
- **Sphere or spherical shell**. Specify the outer and inner radii. Set the inner radius to 0.0 for a solid cylinder.

The length units will be specified in the **GamBet** script. Note that more complex source geometries can be represented by creating and loading multiple `SRC` files. Supply values for the source *Activity* in curies and the total number of primary particles to be recorded in the `SRC` file, *NPart*. Finally, enter a prefix for the output source file and click the *Create SRC file* button. The parameters shown in Fig. 1 generate the file `Eu154.SRC` with 50009 data lines and the following content

```
* Radioactive source data prepared with Sourcerer
*   Spectrum file: Eu154.GSS
*   Cylinder  ROut:  1.0000E+00  RIn:  0.0000E+00  Length:  2.0000E+00
*   NPart: 50002
*   Activity:  5.0000E+03
*   Average energy per nuclear event:  1.1136E+00 (MeV)
*   Power generated:  3.3006E+01 (W)
P    1.23071E+05 -2.66135E-01 -8.82456E-01  3.16945E-01  5.11298E-01  3.92067E-01  7.64760E-01  5.65038E+09
P    1.23071E+05 -5.44371E-01 -3.95783E-01  9.69023E-01  3.16596E-01 -9.20795E-01  2.27823E-01  5.65038E+09
P    1.23071E+05  1.75971E-01  8.45992E-01  6.25346E-01 -2.32097E-01 -8.76701E-01 -4.21338E-01  5.65038E+09
  ...
P    1.27444E+06  2.57939E-01 -2.08643E-02  4.82419E-01  4.84127E-01 -6.04442E-01 -6.32670E-01  5.65038E+09
P    1.27444E+06 -7.75984E-01  2.85272E-01  1.80480E-01  2.23528E-01 -7.70427E-01  5.97058E-01  5.65038E+09
P    1.27444E+06  5.63593E-01  3.48923E-01 -7.14629E-01 -7.13678E-01 -1.16966E-01  6.90639E-01  5.65038E+09
ENDFILE
```

A similar set of operations leads to the file `Eu152.SRC` to represent 3000.0 Ci of activity over the same volume. The power inputs determined by **Sourcerer** are 33.006 W for the Eu154 component and 17.890 W for the Eu152 component for a total of 50.896 W.

We will review some of the mathematics underlying **Sourcerer** before discussing the **GamBet** run setup and interpretation. Each line of a **GamBet** `SRC` file includes the following quantities separated by spaces or other delimiters.

- The letters P, E or E+ designating the type of primary model particle.
- The kinetic energy T in eV.
- Three entries to give the model particle position (x, y, z) in units specified in **GamBet**.
- Three entries that represent a unit vector (u_x, u_y, u_z) in the direction of the particle.
- An optional quantity F representing the flux of photons (or the current of electrons or positrons) carried by the model particle.

The presence of the final parameter signals that **GamBet** should perform a rate calculation to determine dose and power levels.

The position values are assigned to create a random-uniform distribution of particles in the volume shape specified in the *Source geometry* section. A box is circumscribed around the shape. Random values of x, y and z are generated along the box sides, discarding any positions that lie outside the shape. Figure 2 illustrates the type of spatial distributions that result. The plot was made in **GenDist** which can load, plot and analyze the `SRC` files created by **Sourcerer**. Particles are emitted isotropically from their generation points. The direction values are generated by calculating random values of u_x, u_y and u_z in a cube with dimensions (-1.0, 1.0). If the radius of the resulting vector exceeds 0.1, the values are normalized to unity radius and assigned to a particle accepted by the spatial assignment.

Next consider assigning values for the photon flux and kinetic energy. If the value in the *Activity* box is A curies, then the rate of nuclear transformations in the source is:

$$R_{NT} = (3.7 \times 10^{10})\ A. \quad \text{(Bq)} \tag{1}$$

The total number of particles produced per nuclear transformation is the sum over the second column in the spectrum file:

$$N_{NT} = \sum_i\ f_i. \tag{2}$$

The total number of particles generated per second is $R_{NT}N_{NT}$. The following value of flux is assigned to each of the N_{part} model particles in the `SRC` file:

$$F = \frac{R_{NT}\ N_{NT}}{N_{part}}. \tag{3}$$

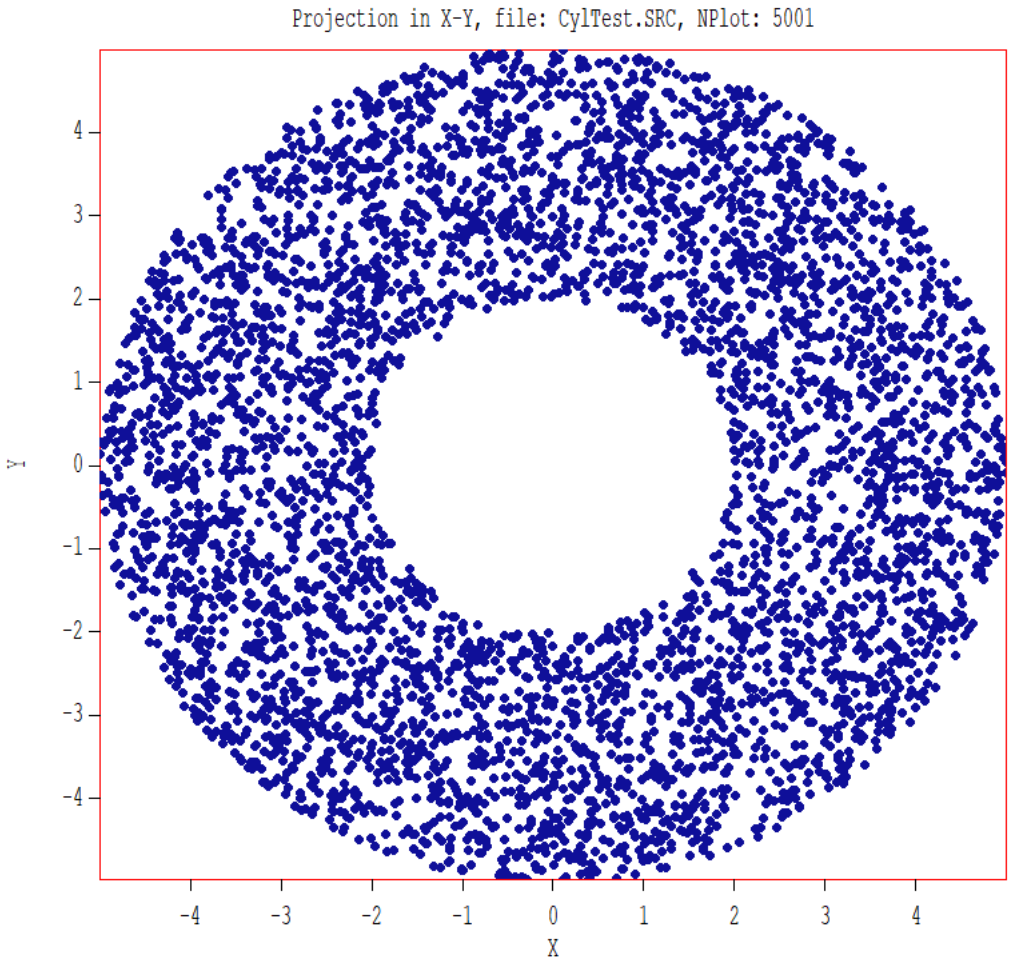

Figure 2: Random-uniform distribution of particles in a cylindrical shell displayed in **GenDist**.

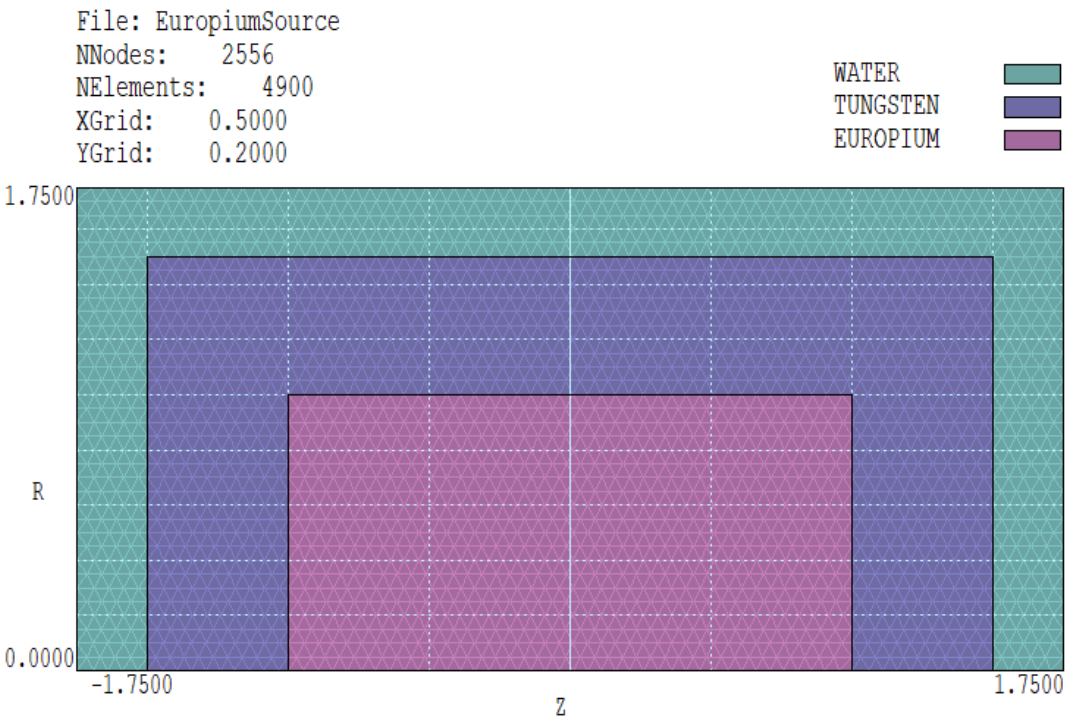

Figure 3: Conformal mesh for the test problem.

The generation process is as follows. First, **Sourcerer** calculates the number of model particles to be generated for each spectral energy:

$$n_i = \frac{N_{part}\ f_i}{N_{NT}}. \tag{4}$$

With kinetic energy values normalized to eV, the program cycles through the spectrum, creating n_i model particles with kinetic energy T_i for a total of N_{part} model particles. We can verify that the process is consistent by showing that the sum over model particle flux equals the total number of source photons per second:

$$\sum_i\ n_i\ F = \sum_i \frac{N_{part}\ f_i}{N_{NT}} \quad \left(\frac{R_{NT}\ N_{NT}}{N_{part}}\right) = R_{NT}\ N_{NT}. \tag{5}$$

We will now proceed to review the setup for and results of the **GamBet** solution of the test problem. Two inputs are required: a conformal mesh defining material shapes and elements for dose scoring and a script to control the **GamBet** run. The geometry is relatively simple, so the mesh and Monte Carlo calculations are performed in two dimensions with cylindrical symmetry. Figure 3 shows the output from the **Mesh** program. The inner europium cylinder dimensions match those used in **Sourcerer**. The source is enclosed in a tungsten case with walls of thickness 0.5 cm. A diagnostic water region of thickness 0.25 cm is included for dose rate calculations outside the case.

Note that relatively large elements are used to minimize statistical variations. Small elements are required in **GamBet** solutions only for close matching of intricate shapes.

The script to control the Monte Carlo solution, prepared interactively using the **GamBet** setup dialog, is listed at the end of this report. The first section controls the geometry:

```
GEOMETRY
  DUnit =   1.0000E+02
  GFile2D = EuropiumSource.MOU  (Cylin)
END
```

The *DUnit* command sets the interpretation of coordinates from **Mesh** and `SRC` files in centimeters. The definition holds throughout the input process unless another *DUnit* command appears. The *GFile2D* command reads the two-dimensional mesh. The *Cylin* parameter designates that element volumes and dose calculations should be weighted in cylindrical coordinates. This section defines the material properties:

```
COMPOSITION
  Material = 278
  Material =  74
  Material =  63
  Region(1) =   1
  Region(2) =   2
  Region(3) =   3
END
```

The material numbers are **Penelope** definitions for water, tungsten and europium. The material properties are assigned to the corresponding region numbers in the **Mesh** file. The source section is the one of greatest interest for the test problem:

```
SOURCE
  SFile = Europium154
  SFile = Europium152
  NPMult =  2
END
```

There are two instances of the *SFile* command to load the two isotope types that comprise the source. There is no limit on the number of *SFile* commands. They could also be used to define different spatial parts of a source. It is not necessary that source parts are contiguous. The value $NPMult = 2$ gives a total of 200,000 shower calculations.

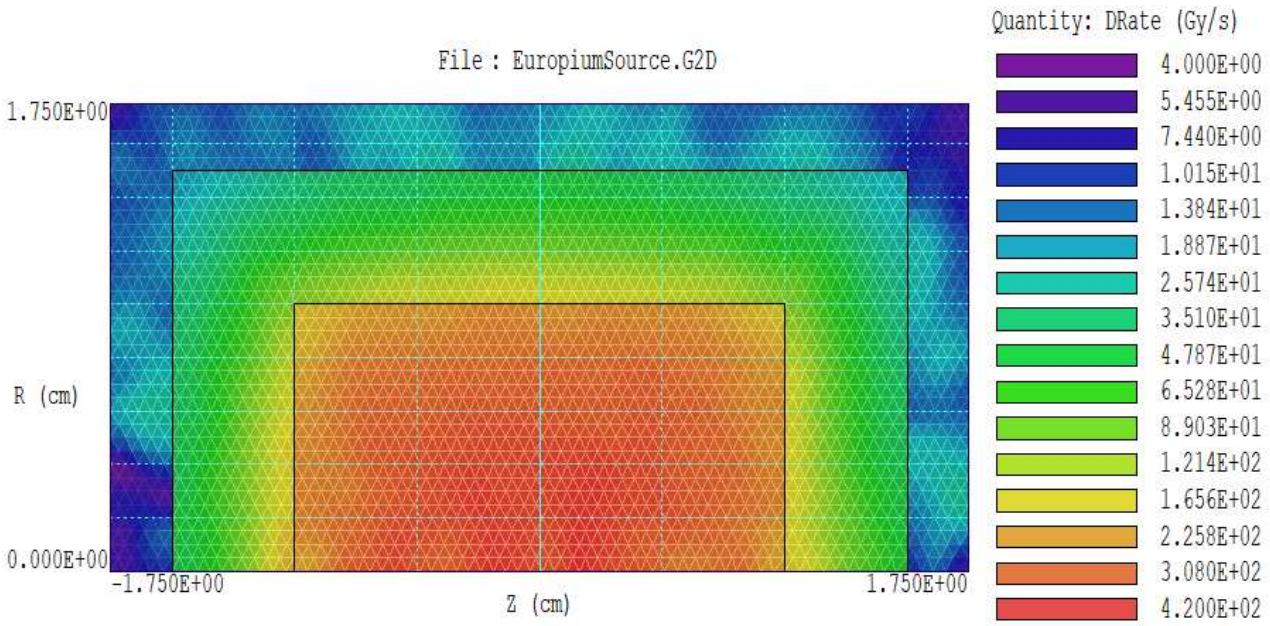

Figure 4: Spatial distribution of the smoothed dose rate for the test example. The smoothing process averages element quantities within a region to reduce statistical variations.

The **GamBet** calculation takes 50 seconds on a computer running Windows 11 Pro with an Intel Core I3 processor at 3.30 GHz. The **GamBet** listing file (`GLS`) contains a wealth of numerical information. For example, the following values of deposited power are listed:

```
Europium: 9.500 W
Tungsten: 19.621 W
Water: 0.202 W
Primary and secondary particle escape from solution volume: 21.594 W
```

Despite a complex series of interactions, the total of 50.917 W is close to the input energy. The **GBView2** solution analysis program can generate plots and numerical results. Figure 4 shows the spatial distribution of the smoothed dose rate plotted on a logarithmic scale. The peak dose rate at the center of the Europium cylinder is about 42 krad/s. With a data file open, the *Dose Analysis/Volume integral* command records the following information:

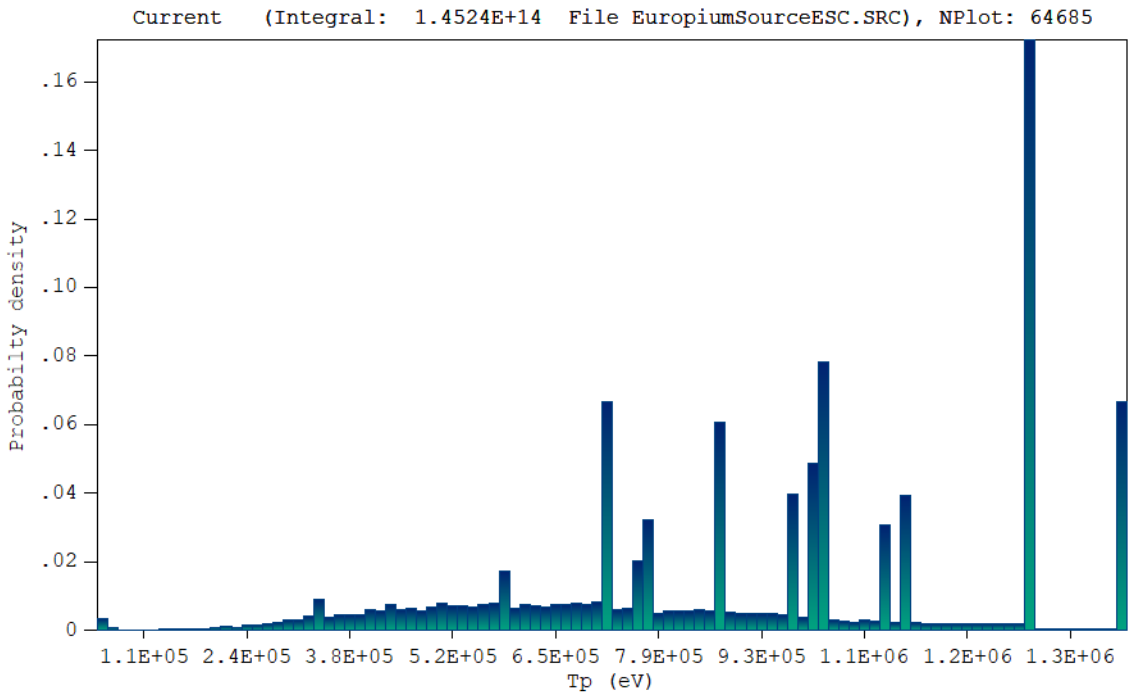

Figure 5: **GenDist** display of the energy spectrum of particles escaping the solution volume.

```
 --- Volume Integrals ---
Global quantities
Volume (m3):   3.367E-05
Mass (kg):   3.334E-01
Energy (J/s):   2.932E+01
Avg dose (Gy/s):   8.795E+01

 RegNo    Volume       Mass       Energy      AvgDose
           (m3)        (kg)       (J/s)       (Gy/s)
=====================================================
    1   1.247E-05   1.247E-02   2.017E-01   1.618E+01
    2   1.492E-05   2.880E-01   1.962E+01   6.813E+01
    3   6.283E-06   3.294E-02   9.500E+00   2.884E+02
```

The table lists the volume-averaged dose rate by region. The dose rate just outside the tungsten case is 1.618 krad/s. The **Mesh** file could be altered to divide the diagnostic regions in multiple parts to find statistically averaged values sections of the tungsten case. Finally, the **GenDist** program can be used to analyze data in the **GamBet** escape file. The escape file lists all particles escaping from the solution in `SRC` format. Figure 5 shows the photon energy spectrum including non-interacting primary particles and a continuous distribution of secondary particles.

GamBet input file for the test calculation

```
* GamBet script (Field Precision)
* File: EuropiumSource.GIN
GEOMETRY
  DUnit =   1.0000E+02
  GFile2D = EuropiumSource.MOU  (Cylin)
END
COMPOSITION
  Material = 278
  Material =  74
  Material =  63
  Region(1) =   1
  Region(2) =   2
  Region(3) =   3
END
SOURCE
  SFile = Europium154
  SFile = Europium152
  NPMult =  2
END
PROCESS
  EMax =   2.0000E+06
  EAbs(Electron) =   5.0000E+04
  EAbs(Photon) =   5.0000E+04
  EAbs(Positron) =   5.0000E+04
  StepMax =  500000
  Time =   86400
END

ENDFILE
```