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Study of Gamma-ray Production from Neutron-induced Activity on Spacecraft for DIORAMA

Tucker C. McClanahan, Daniel T. Wakeford

August 16, 2018

1 Abstract

The Distributed Infrastructure Offering Real-Time Access to Modeling and Analysis (DIORAMA) software provides performance modeling capabilities of the United States Nuclear Detonation Detection System (USNDS) with a focus on the characterization of Space-Based Nuclear Detonation Detection (SNDD) instrument performance [1]. A study was conducted investigating the neutron activation on spacecraft caused by cosmic-ray and trapped proton-induced spallation, and by direct irradiation from hypothetical nuclear detonations as a background component to be incorporated into DIORAMA. The neutron activation background study amasses a database of pre-calculated Monte Carlo data that reflects the delayed gamma-ray production from activated nuclei as a function of incident cosmic or neutron flux, incident energy, material volume, etc. CINDER2008 coupled with MCNPX and the Activation Analysis Tools in the Activation in Accelerator Radiation Environments (AARE) distribution along with a suite of Python scripts are used to calculate and assemble the Monte Carlo database [2–6]. The neutron activation background study improves the fidelity of DIORAMA by providing the neutron-induced activation component to the background of the instruments on-board the spacecraft, and has implications for future instrument design studies.

2 Introduction

The study described in this document includes the generation and example usage of neutron-induced activation delayed gamma data tables of generic spacecraft materials for use as a detector background term in DIORAMA. Neutrons from both proton-induced spallation and hypothetical nuclear detonation events are used as initial neutron flux sources in order to produce the delayed gamma data tables. Currently, DIORAMA does not include neutron-induced activation delayed-gammas in the background component of a spacecraft detector and this study aims at adding fidelity to DIORAMA by contributing to the background term. CINDER2008 coupled with MCNPX and the Activation Analysis Tools in the AARE distribution are used to calculate the delayed gamma data tables. A suite of Python scripts are used to construct the data tables and apply the proper normalization. The AARE distribution has been validated for spacecraft activation and the details are shown in Section 3.1.

CINDER2008 is a transmutation code that is a part of the AARE distribution and it transmutes materials by considering the decay nuclide characteristics and neutron flux, and calculates the decay gamma emission rates as a function of energy, cell, and time. MCNPX is used to calculate the neutron flux because CINDER2008 requires the *hisp* file to be produced if there are reactions above the energy coverage by the cross sections. CINDER2008 cannot read the *hisp* file produced by MCNP6.2.

CINDER2008 was chosen as the transmutation code to calculate the decay gamma emission rates over the built-in activation capability of MCNP6.2 for several reasons. The built-in activation capability in MCNP6.2 is initiated by the use of the *act* card and this feature uses the same CINDERGL.dat ENDF/B-VII.1 cross section file and DELAY_LIBRARY_V5.dat delayed-particle library that CINDER2008 uses [7]. However, the built-in activation feature of MCNP6.2 does not provide the user with the nuclides that are produced as a result of the transmutation of the material, and the delayed gammas that are produced are immediately transported as apart of the MCNP6.2 run. CINDER2008 provides the user with a plethora of information about the transmutation calculation including the details of the nuclides produced as a result of the activation and the delayed gamma emission rate averaged over the volume of material without transporting the photons. The production of the delayed gamma emission rate averaged over the volume of material in time can be used as a source in a secondary MCNPX or MCNP6.2 run or it can be used as a source in a code like DIORAMA.

3 Methods

In order to produce the delayed gamma data tables, single energy neutrons and protons are transported from a sphere just outside of the material sphere and the resulting volume-averaged neutron flux is tallied in the material volume. The neutron flux is then used as input for a CINDER2008 transmutation calculation where both the production and destruction rates for various nuclides are calculated. An overview of the methods used to produce the delayed gamma data tables for incident protons and neutrons is shown in Figures 1 & 2. The resulting decay gamma emission rate (*DioData* in units of $p/\text{MeV}/\text{sec}/\phi(E)/\text{cm}^3$ where p is photons, the $/\text{MeV}$ is dividing by the emitted photon energy bin width, $\phi(E)$ is the incident particle fluence in $\#/\text{cm}^2$ at incident energy E) is written into files for each incident proton or neutron energy, radius, timestep and material. 480 cases were evaluated for incident neutrons and protons for a total of 960 cases evaluated. The 480 neutron cases consisted of combinations of 4 radii, 6 materials, and 20 incident neutron energies ranging from 1E-4 to 21 MeV. Each neutron case was evaluated at 24 timesteps after the initial 1 μs pulse of neutrons. The 480 proton cases consisted of combination of 4 radii, 6 materials, and 20 incident proton energies ranging from 1 MeV to 2 GeV. Each proton case was evaluated at 12 timesteps corresponding to 12 ages of satellites. Details of the MCNPX run, CINDER2008 transmutation calculation, and the post-processing scripts are described in greater detail Sections 3.2, 3.3, and 3.4.

Figure 1: Overview of the production of delayed gamma data tables for incident protons

Figure 2: Overview of the production of delayed gamma data tables for incident neutrons

3.1 CINDER2008/AARE Validation

CINDER2008 and the AARE distribution were validated for calculating neutron-induced activation delayed gammas in materials on spacecraft by successfully replicating the activated HPGe detector on the RHESSI spacecraft. The details of the validation effort are documented in the McClanahan et al report [8]. Figure 3 shows the results from the replication of the activated HPGe detector delayed gamma spectrum. The discrepancies seen in the two spectra could be a result of the HPGe degradation as a result of exposure to years of radiation exposure as seen in the measured RHESSI data whereas the simulated data uses a non-degraded HPGe detector, the real detector geometry is of coaxial design and not a solid block of HPGe, or there is an unknown amount of aluminum referenced in Hajdas' paper located somewhere near the detector that was not included in the simulation [9].

Figure 3: Simulated HPGe detector spectrum (blue) compared with the measured HPGe detector spectrum from Figure 9 in the Hajdas paper (black) [9].

3.2 MCNPX Model

3.2.1 Geometry

Figure 4 shows the geometry used to produce the *DioData* files and the scales are in units of cm. Each neutron or proton case consisted of the geometry shown in Figure 4 with the material

radius set to 0.1, 1.0, 10.0, or 100.0 cm and the material set to either hydrazine, Ti6Al4V, Kapton, SVHoneycomb, Al6061 or Battery. The intent of using the four different material radii is to capture the physics expected for satellite components of varying geometry. For instance, a large plate of Al6061 could be constructed from many 0.1 cm radius *DioData* tables while a large volume of Hydrazine could make use of the 100 cm radius *DioData* table. The details of each material are given in Appendix A.

Figure 4: X-Y cross section of sphere of material (scales in cm)

3.2.2 Source

The source used to produce the delayed gamma emission rates due to incident neutrons was a monoenergetic neutron source distributed around the surface of a sphere with radius 0.001 cm larger than the material radius. 20 energies were used in the neutron cases ranging in energy from 1E-4 to 20 MeV. Each source neutron is emitted inward, toward the material sphere. The **wgt** used for the source neutrons is given in Equation 1 and the resulting source particle **wgt** is given in Equation 2. The cm^2 stems from the source being distributed around the sphere. The **wgt** is set to $1/100\text{E-}8 \text{ sec}^{-1}$ because in the CINDER2008 transmutation, the neutron flux is multiplied by $100\text{E-}8 \text{ sec}$ due to the characteristics of a nuclear detonation.

$$wgt = 1/100E - 8 = 1E6 \text{ sec}^{-1} \quad (1)$$

$$\text{Source Particle} \rightarrow \text{n/sec/cm}^2 \quad (2)$$

The cosmic proton source has the same spatial distribution as the neutron source described above. The proton source is also monoenergetic but the 20 energies selected range in energy from 1 MeV to 2 GeV. There is no time dependence incorporated into the proton source in order to account for the satellite's constant bombardment of cosmic radiation. The **wgt** used for the source protons is given in Equation 3 and the resulting source particle **wgt** is given in Equation 4. Like the neutron source, the cm^2 stems from the spatial distribution of the source.

$$wgt = 1 \text{ sec}^{-1} \quad (3)$$

$$\text{Source Particle} \rightarrow \text{h/sec/cm}^2 \quad (4)$$

3.2.3 Physics

For the incident protons, every avenue for neutron creation was available by the inclusion of neutrons, photons, alpha particles, protons, pions, deuterons, tritons, and helions. The upper energy threshold for each particle species is set to 2 GeV. The neutron transition energy from the cross-section tables to physics models is set to 20 MeV. Physics models were used for all protons.

The physics used in the incident neutrons were the default physics in MCNPX2.7.

3.2.4 Tallies

The tally used for both incident protons and neutrons is was a **F4** tally over the material sphere. The F4 tally was binned in the same 321 group energy structure as the cross sections used in the following CINDER2008 calculation. The resulting units of the flux is shown in Equation 5 where $\phi(E)$ is the proton or neutron fluence in units of ($\#/\text{cm}^2$).

$$\begin{aligned} \text{Tally} &\rightarrow \text{n/cm}^2/\text{sec}/(\#/\text{cm}^3) \\ &\rightarrow \text{n/cm}^2/\text{sec}/\phi(E) \end{aligned} \quad (5)$$

3.3 CINDER2008/AARE Transmutation

The Activation Script (apart of the AARE distribution) is a Perl script that reads in the output file for the material definition and tallied neutron flux, and HISTP file for the production and destruction rates of nuclides produced by high-energy interactions from the MCNPX run described in Section 3.2. CINDER2008 takes the neutron flux and transmutes the material in the MCNPX model for a series of user designated timesteps. *snorm* is a parameter that the user can set that applies a normalization factor to the incoming neutron fluxes and production/destruction rates from the preceding MCNPX run. One of the output files of the CINDER2008 run is the **spectra.h** file that consists of the delayed gammas at the end of each time step grouped into a 25-group energy structure in units of ($snorm \times \text{p/sec/bin}_{E_p}/\text{cm}^3/\phi(E)$) where E_p is the photon energy, $\phi(E)$ is the incident particle fluence, and E is the incident particle energy.

For the production of the delayed gamma emission rates due to incident protons, the *snorm* value is set to 1E12 to avoid non-physical truncation due to machine precision limits. This factor of 1E12 is divided out of the gamma emission rates in the post-processing of the *DioData*. 12 points in time ranging from 0.1 to 40 y are sampled that resemble ages of the satellites, and the “beam is on” during all of the 12 timesteps meaning that the proton flux (and therefore the neutron flux) does not stop as the satellite ages.

In the production of the delayed gamma emission rates for incident neutron, the *snorm* value is set to 1E21 for similar reasons as the incident proton transmutation. This factor is also divided out when post-processing the *DioData*. The neutron flux is incident on the material for 1 μs and then 24 timesteps in the absence of neutron flux are calculated ranging in time from 3 ms to 1E3 sec after the initial 1 μs exposure.

3.4 Post-Processing *DioData*

The **spectra_h** file from each case is read in by the post-processing Python script and the data is converted from $snorm \times \text{p/sec/bin}_{E_p}/\text{cm}^3/\phi(E)$ to $\text{p/sec/MeV/cm}^3/\phi(E)$ by dividing by the $snorm$ factor and the gamma energy bin width of each bin. This data is then written into files for each combination of material, radius, and timestep. For the incident proton data, this results in 288 different files and for incident neutron data, this results in 576 different files. Each file contains a 2-D matrix of data with the gamma energy as the first axis and incident particle energy as the second axis in units of $\text{p/sec/MeV/cm}^3/\phi(E)$ for each timestep, radius, and material. These files are written in a DIORAMA-compatible format. Appendix C includes an example of the *DioData* table file.

4 Results

Figures 5 & 6 show examples of the proton-induced delayed gamma emission rates produced at an age of the satellite, and Figures 7 & 8 show examples of neutron-induced delayed gamma emission rates at a certain amount of time after the $1 \mu\text{s}$ burst of neutrons. Notice the x-axis in each figure is the incident particle energy in discrete steps and the y-axis is the emitted photon energy given in upper energy bin edges. The data in each figure below is the same data that is written into the files for use in DIORAMA. Each file is for a specific material, time, and material radius as it is shown in the titles of the figures below.

Figure 5: Incident Proton *DioData* example for Ti6Al4V at 20 years, $r = 0.1$ cm

Figure 6: Incident Proton *DioData* example for Battery at 40 years, $r = 1$ cm

Figure 7: Incident Neutron *DioData* example for Al6061 at 7.0 sec after burst, $r = 0.1$ cm

Figure 8: Incident Neutron *DioData* example for Kapton at 1.0 sec after burst, $r = 1$ cm

5 Validation of Results

In order to validate the *DioData* produced from incident protons and neutrons, independent MCNP runs were executed in order to validate the *DioData* and demonstrate how the *DioData* is to be used. Figures 9 & 10 show the reproduction of *DioData* for incident neutrons and protons respectively with independent runs using MCNP6.2. The MCNP6.2 runs consisted of the same sphere of material used to create the *DioData* at a radius of 0.1 cm and the same monoenergetic source distributed along the surface of a sphere 0.001 cm greater in radius than the radius of the material sphere. All of the delayed gammas that are produced due to the usage of the **ACT** card are assumed to leak out through the outer surface of the material due to the small radius of material. These photons leaking through the outer surface of the material are tallied with an **F1** (surface crossing) tally. One of the differences between the *DioData* and the MCNP6.2 is that in the MCNP6.2 run, the photons emitted are tallied on the surface of the sphere assuming that all of the photons escape the material. Another potential factor contributing to the discrepancies seen in Figure 10 is the usage of different physics models in switching between MCNPX to produce the *DioData* and MCNP6.2 in order to transport the high-energy incident protons.

Figure 9: Comparison of total photon emission rate induced by 5 MeV neutrons for Al6061

Figure 10: Comparison of total photon emission rate induced by 80 MeV protons for Al6061

To show how the *DioData* can be utilized, a source of $\phi_h(E) = 6.0608E6$ h/cm² 300 MeV protons was applied to the *DioData* by straight multiplication. The MCNPX model consists of the same geometry as the model used to produce the *DioData* with the material radius of 10 cm and almost the same source except with a source resulting in 6.0608E6 h/cm² on the sphere of material. The neutron flux is tallied and CINDER2008 set up and executed in the same manner as in the creation of the *DioData*. The volume of the material sphere has been accounted for in each set of data shown in Figures 11 & 12.

Figure 11: Comparison of DioData and a MCNPX/CINDER2008 delayed gamma emission rates in Hydrazine

Figure 12: Comparison of DioData and a MCNPX/CINDER2008 delayed gamma emission rates in Kapton

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6 Appendix A: Material Cards

c Material Name: hydrazine

c Density (g/cm3): 1.0200E+00

m1

1001 -1.2580E-01

1002 -1.4469E-05

7014 -8.7097E-01

7015 -3.2170E-03

c Material Name: Ti6Al4V

c Density (g/cm3): 4.4700E+00

m2

22048 -6.6348E-01

22049 -4.8690E-02

22050 -4.6620E-02

13027 -6.0000E-02

23050 -1.0000E-04

23051 -3.9900E-02

22046 -7.4250E-02

22047 -6.6960E-02

c Material Name: Kapton

c Density (g/cm3): 1.4200E+00

m3

7014 -7.3000E-02

7015 -2.6963E-04

1001 -2.6359E-02

1002 -3.0316E-06

8016 -2.0916E-01

8017 -7.9673E-05

6012 -6.8374E-01

6013 -7.3951E-03

c Material Name: SVHoneycomb

c Density (g/cm3): 5.6100E-02

m4

29063 -1.9022E-03

29065 -8.4782E-04

22046 -6.1875E-05

22047 -5.5800E-05

22048 -5.5290E-04

22049 -4.0575E-05

22050 -3.8850E-05

30066 -3.4875E-04

24052 -1.6339E-03

30070 -7.7500E-06

26054 -2.0457E-04

26056 -3.2114E-03

26057 -7.4165E-05

26058 -9.8700E-06

14028 -5.5338E-03
 14029 -2.8099E-04
 14030 -1.8523E-04
 25055 -7.5000E-04
 13027 -9.7305E-01
 30064 -6.0787E-04
 24050 -8.4727E-05
 30067 -5.1250E-05
 30068 -2.3437E-04
 24053 -1.8527E-04
 24054 -4.6118E-05
 12024 -7.8990E-03
 12025 -1.0000E-03
 12026 -1.1010E-03
 c Material Name: Al6061
 c Density (g/cm3): 2.7100E+00
 m5
 29063 -1.9022E-03
 29065 -8.4782E-04
 22046 -6.1875E-05
 22047 -5.5800E-05
 22048 -5.5290E-04
 22049 -4.0575E-05
 22050 -3.8850E-05
 30066 -3.4875E-04
 24052 -1.6339E-03
 30070 -7.7500E-06
 26054 -2.0457E-04
 26056 -3.2114E-03
 26057 -7.4165E-05
 26058 -9.8700E-06
 14028 -5.5338E-03
 14029 -2.8099E-04
 14030 -1.8523E-04
 25055 -7.5000E-04
 13027 -9.7305E-01
 30064 -6.0787E-04
 24050 -8.4727E-05
 30067 -5.1250E-05
 30068 -2.3437E-04
 24053 -1.8527E-04
 24054 -4.6118E-05
 12024 -7.8990E-03
 12025 -1.0000E-03
 12026 -1.1010E-03
 c Material Name: Battery
 c Density (g/cm3): 1.0932E+00
 m6

13027 -2.4000E-01
7014 -1.7520E-02
29063 -8.9921E-02
29065 -4.0079E-02
1002 -7.2759E-07
7015 -6.4712E-05
8016 -1.4573E-01
8017 -5.5510E-05
1001 -6.3262E-03
3007 -9.5766E-03
6012 -2.8281E-01
6013 -3.0588E-03
3006 -7.8657E-04
25055 -1.6407E-01

7 Appendix B: Python Post-Processing Script

7.1 Processing Incident Proton Data

```
#####  
### Name: Write Files for Activation Data for DIORAMA  
### Developer: Tucker McClanahan  
### (tcmccclan@lanl.gov or tmcclana@vols.utk.edu)  
### Purpose: This script writes the results of the simulations into discrete files  
### Use: python write_act_dio_data.py  
### Outputs: NONE  
### Dependents:  
### Notes:  
#####  
  
import numpy as np  
import sys, os  
from Spectra_File_Parser import Spectra as spt  
import matplotlib.pyplot as plt  
import datetime  
  
def main():  
    norm_factor = 1E12  
    energies = np.array([1.0000E+00,  
        2.0000E+00, 4.0000E+00, 6.0000E+00, 8.0000E+00, 1.0000E+01,  
        1.5000E+01, 2.0000E+01, 3.0000E+01, 5.0000E+01, 6.0000E+01,  
        8.0000E+01, 1.0000E+02, 1.5000E+02, 2.0000E+02, 3.0000E+02,  
        4.0000E+02, 7.0000E+02, 1.2000E+03, 2.0000E+03])  
  
    material_number = np.array([1, 2, 3, 4, 5, 6])  
    material_density = np.array([1.02, 4.47, 1.42, 5.61E-2, 2.71, 1.0932])  
    material_name = np.array(["Hydrazine", "Ti6Al4V", "Kapton", "SVHoneycomb", "Al6061", "Battery"])  
  
    radius = np.array([0.1, 1.0, 10., 100.])  
  
    n_cases = float(np.size(material_number))* float(np.size(energies))*float(np.size(radius))
```

```

os.system("mkdir Act_Dio_Data_Proton_Files")
c = 1
gamma_data = []
for m in range(np.size(material_number)):
    column_0 = []
    for r in range(np.size(radius)):
        column = []
        for e in range(np.size(energies)):
            data = spt("./case"+str(c).zfill(3)+"cinder-1/spectra_h")
            column.append(data)
            c += 1
        column_0.append(column)
    gamma_data.append(column_0)
    gamma_data = np.asarray(gamma_data)

delta_e = np.ediff1d(gamma_data[0,0,0].energies[1:], to_begin=gamma_data[0,0,0].energies[1])
k = open("./Act_Dio_Data_Proton_Files/key.txt", 'w')
for m in range(np.size(material_number)):
    for r in range(np.size(radius)):
        gamma_mat_data = gamma_data[m,r,:]
        timesteps = gamma_mat_data[0].times
        for t in range(np.size(timesteps)-1):
            t +=1
            f = open("./Act_Dio_Data_Proton_Files/mat_"+str(material_number[m])+
                "_timestep_"+str(t-1).zfill(2)+"_radius_"+str(r+1)+"_act_data.dat", 'w')
            k.write("mat%d: %s timestep %d: %1.4E_Y radius %d: %1.4E\n" % \
                (material_number[m], material_name[m], t-1, timesteps[t]/3600./24./365., r+1, radius[r]))
            f.write("#_VERSION: 0.0\n")
            f.write("#_DATE: %s\n" % str(datetime.datetime.now()))
            f.write("#_MATERIAL: %s\n" % material_name[m])
            f.write("#_Radius(cm): %s\n" % radius[r])
            f.write("#_TIME_Y: %1.4E_Y\n" % (timesteps[t]/3600./24./365.))
            f.write("#_INFO: Material_Density: %1.4E_g/cm3\n" % material_density[m])
            f.write("#_INFO: $Phi_h(E,t) == SA_{mat}\int_{\Delta E} phi_h(E,t)dE\n")
            f.write("#_INFO: $Phi_h(E,t) $is the incident proton flux at energy E at time t \
(age_of_satellite) in units of (h/sec)\n")
            f.write("#_INFO: $Phi_h(E,t) $is the proton flux to which the gamma_data is normalized\n")
            f.write("#_INFO: $SA_{mat} $is the surface area of the material\n")

```

```

f.write("#_INFO: _t$ _is _the _age _of _satellite _(\sec)\n")
f.write("#_INFO: _$\Delta _E$ _is _the _energy _bin _width _of _which _energy _E _resides _in _the _incoming _\
proton _spectrum\n")
f.write("#_INFO: _$\phi _h(E,t)$ _is _the _incoming _proton _flux _in _units _of _(\h/cm2/sec/MeV)\n")
f.write("###_END_OF_HEADER\n")
f.write("2\n")
f.write("\n")
f.write("Photon_upper_energy_bin_edges\n")
f.write("MeV\n")
f.write("%d\n" % (np.size(gamma_mat_data[0].energies[1:])))
f.write("0.0\n")
for erg in gamma_mat_data[0].energies[1:]:
    f.write("%1.4E\n" % erg)
f.write("\n")
f.write("Proton_energy_discrete_values\n")
f.write("MeV\n")
f.write("%d\n" % np.size(energies))
f.write("0.0\n")
for erg in energies:
    f.write("%1.4E\n" % erg)
f.write("\n")
f.write("Data\n")
f.write("MeV-1_s^-1_cm^-3_Phi_h^-1\n")
for he in range(np.size(energies)):
    volume = 4./3.*np.pi*radius[r]**3
    for pe in range(np.size(gamma_mat_data[he].energies[1:])):
        f.write("%d_%d_%1.4E\n" % (pe, he, gamma_mat_data[he].timesteps[t].gamma_data[pe]*gamma_ma
f.write("\n")
f.close()

k.close()

main()

```

7.2 Processing Incident Neutron Data

```
#####
### Name: Write Files for Neutron Activation Data for DIORAMA
### Developer: Tucker McClanahan
### (tmcclan@lanl.gov or tmcclana@vols.utk.edu)
### Purpose: This script writes the results of the simulations into discrete files
### Use: python write-act-dio-data.py
### Outputs: NONE
### Dependents:
### Notes:
#####

import numpy as np
import sys, os
from Spectra_File_Parser import Spectra as spt
import matplotlib.pyplot as plt
import datetime
from scipy.interpolate import interp1d

def main():

    norm_factor = 1E21
    energies= np.array([1E-4, 3E-4, 7E-4, 1E-3, 3E-3, 7E-3, 1E-2, 3E-2, 7E-2, 1E-1, 3E-1, 7E-1, \
    1., 2., 5., 8., 10., 12., 14., 20.])
    material_number = np.array([1, 2, 3, 4, 5, 6])
    material_density = np.array([1.02, 4.47, 1.42, 5.61E-2, 2.71, 1.0932])
    material_name = np.array(["Hydrazine", "Ti6Al4V", "Kapton", "SVHoneycomb", "Al6061", "Battery"])

    radius = np.array([0.1, 1.0, 10., 100.])

    n_cases = float(np.size(material_number))* float(np.size(energies))*float(np.size(radius))

    os.system("mkdir_Neutron_Act_Dio_Data_Files")
    c = 1
    gamma_data = []
    for m in range(np.size(material_number)):
        column_0 = []
        for r in range(np.size(radius)):

```

```

column = []
for e in range(np.size(energies)):
    data = spt("./case"+str(c).zfill(3)+"cinder-1/spectra_h")
    column.append(data)
    c += 1

column_0.append(column)
gamma_data.append(column_0)

gamma_data = np.asarray(gamma_data)
delta_e = np.ediff1d(gamma_data[0,0,0].energies[1:], to_begin=gamma_data[0,0,0].energies[1])
k = open("./Neutron_Act_Dio_Data_Files/key.txt", 'w')
for m in range(np.size(material_number)):
    for r in range(np.size(radius)):
        gamma_mat_data = gamma_data[m,r,:]
        timesteps = gamma_mat_data[0].times
        for t in range(np.size(timesteps)-1):
            t +=1
            f = open("./Neutron_Act_Dio_Data_Files/mat_"+str(material_number[m])+
                "_timestep_"+str(t-1).zfill(2)+"_radius_"+str(r+1)+"_act_data.dat", 'w')
            k.write("mat%d: %s_timestep %d: %1.4EY_radius %d: %1.4E\n" % \
                (material_number[m], material_name[m], t-1, timesteps[t]/3600./24./365., r+1, radius[r]))
            f.write("#_VERSION: 0.0\n")
            f.write("#_DATE: %s\n" % str(datetime.datetime.now()))
            f.write("#_MATERIAL: %s\n" % material_name[m])
            f.write("#_Radius(cm): %s\n" % radius[r])
            f.write("#_TIME(sec): %1.4E\n" % (timesteps[t]))
            f.write("#_INFO: Material_Density: %1.4E_g/cm3\n" % material_density[m])
            f.write("#_INFO: %$\\Phi_n(t) = SA_{mat}\\int_{\\Delta_E}\\phi_n(E,t)dE\\n")
            f.write("#_INFO: %$\\Phi_n(t) $ is the neutron flux in units of n/s\n")
            f.write("#_INFO: %$\\Phi_n(t) $ is the neutron flux to which the gamma_data is normalized\n")
            f.write("#_INFO: %$\\Phi_n(t) $ is assumed to be constant for all us incident on the material\n")
            f.write("#_INFO: %$\\Delta_E $ is the energy bin width of which energy E resides in the incoming
neutron spectrum\n")
            f.write("#_INFO: %$SA_{mat} $ is the surface area of the material\n")
            f.write("#_INFO: %$\\phi_n(E,t) $ is the incoming neutron flux in units of (n/cm2/sec/MeV)\n")
            f.write("###_END_OF_HEADER\n")
            f.write("2\n")
            f.write("\n")
            f.write("Photon_upper_energy_bin_edges\n")
            f.write("MeV\n")

```

```

f.write("%d\n" % (np.size(gamma_mat_data[0].energies[1:])))
f.write("0.0\n")
for erg in gamma_mat_data[0].energies[1:]:
    f.write("%1.4E\n" % erg)
f.write("\n")
f.write("Neutron_energy_discrete_values\n")
f.write("MeV\n")
f.write("%d\n" % np.size(energies))
f.write("0.0\n")
for erg in energies:
    f.write("%1.4E\n" % erg)
f.write("\n")
f.write("Data\n")
f.write("MeV^-1_s^-1_cm^-3_Phi_n_-1\n")
for he in range(np.size(energies)):
    volume = 4./3.*np.pi*radius[r]**3
    for pe in range(np.size(gamma_mat_data[he].energies[1:])):
        f.write("%d_%d_%1.4E\n" % (pe, he, gamma_mat_data[he].timesteps[t].gamma_data[pe]*\
            gamma_mat_data[he].timesteps[t].total_gammas/norm_factor/delta_e[pe]/100E-8))
    f.write("\n")
f.close()

k.close()

main()

```

8 Appendix C: Partial DioData Table

```
# VERSION: 0.0
# DATE: 2018-08-15 15:46:57.567452
# MATERIAL: Al6061
# Radius (cm): 0.1
# TIME (Y): 1.0000E+01 Y
# INFO: Material_Density: 2.7100E+00 g/cm3
# INFO:  $\Phi_h(E,t) = SA_{\text{mat}} \int_{\Delta E} \phi_h(E,t) dE$ 
# INFO:  $\Phi_h(E,t)$  is the incident proton flux at energy E at time t (age of satellite)
# INFO: in units of (h/sec)
# INFO:  $\Phi_h(E,t)$  is the proton flux to which the gamma data is normalized
# INFO:  $SA_{\text{mat}}$  is the surface area of the material
# INFO:  $t$  is the age of satellite (sec)
# INFO:  $\Delta E$  is the energy bin width of which energy E resides in the incoming
# INFO: proton spectrum
# INFO:  $\phi_h(E,t)$  is the incoming proton flux in units of (h/cm2/sec/MeV)
### END OF HEADER
2
```

Photon upper energy bin edges

MeV

25

0.0

1.0000E-02

3.0000E-02

6.0000E-02

1.0000E-01

2.0000E-01

3.0000E-01

5.0000E-01

5.2500E-01

7.5000E-01

1.0000E+00

1.3300E+00

1.6600E+00

2.0000E+00

2.5000E+00

3.0000E+00

4.0000E+00

5.0000E+00

6.0000E+00

7.0000E+00

8.0000E+00

9.0000E+00

1.0000E+01

1.2000E+01

1.7000E+01

3.0000E+01

Proton energy discrete values

MeV

20

0.0

```

1.0000E+00
2.0000E+00
4.0000E+00
6.0000E+00
8.0000E+00
1.0000E+01
1.5000E+01
2.0000E+01
3.0000E+01
5.0000E+01
6.0000E+01
8.0000E+01
1.0000E+02
1.5000E+02
2.0000E+02
3.0000E+02
4.0000E+02
7.0000E+02
1.2000E+03
2.0000E+03

```

Data

MeV⁻¹ s⁻¹ cm⁻³ Phi_h ⁻¹

```

0 0 0.0000E+00
1 0 0.0000E+00
2 0 0.0000E+00
3 0 0.0000E+00
4 0 0.0000E+00
5 0 0.0000E+00
6 0 0.0000E+00
7 0 0.0000E+00
8 0 0.0000E+00
9 0 0.0000E+00
10 0 0.0000E+00

```

...