CHAPTER III

RESEARCH METHODOLOGY

In this research, we created the calibration monitor model with simple geo program which was the initial input file of FLUKA simulation with Monte Carlo method. In this chapter, we describe Monte Carlo principles, how to use FLUKA program including the calibration monitor geometry which was set inside and outside station and the definition of particle beams.

Monte Carlo modeling techniques

1. Monte Carlo method

Monte Carlo method is a numerical technique for physical problem solving that uses random numbers or pseudo-random numbers and probability density distributions to calculate the uniform distribution or Gaussian distribution.

The random numbers of Monte Carlo techniques are generated by using a deterministic algorithm to produce a sequence of numbers from sampling as the accuracy of the simulation result depends on the number of random numbers.

Monte Carlo simulations are often solved by multidimensional integration problems such as statistical mechanics in physics, biophysics and particle transport problems.

From the basics of Monte Carlo methods, f(x) is defined as a function in the range $a \leq x \leq b$ where $f(x) \geq 0$ everywhere

$$\int_a^b f(x)\,dx = (b - a) < f > \qquad (6)$$

where

$< f >$ is the average value of the function,

$(b - a)$ is the interval range of function.

The average function of N values is calculated by setting N random numbers x_i (i = 1…N) from a uniform distribution between a and b, and dividing them by the number of points

$$< f >_N \quad = \quad \frac{1}{N} \sum_{i=1}^{N} f(x_i), \tag{7}$$

so we can define the Monte Carlo estimate of the integral as

$$\int_a^b f(x)\,dx \quad \approx \quad (b - a)\,\frac{1}{N} \sum_{i=1}^{N} f(x_i). \tag{8}$$

In general, the steps of Monte Carlo simulations of integral function in the range of [a , b] are the random point selection in the area.

The integration of d – dimensional function, $f(x_1, \ldots, x_n)$, in a unit hypercube, $[0\,,\,1]^d$ is defined as

$$\int_0^1 dx_1 \ldots \int_0^1 dx_d\, f(x_1,\ldots,x_d). \tag{9}$$

The effective convergence rate in d dimensions for other methods (not Monte Carlo) is multiplied by a factor $1/d$ in the exponent (F. James, 1980)

Since the particle physics simulation has many dimensions, such as 3 dimensions per particles, so the Monte Carlo method is faster than any other method and its statistical error is $1/\sqrt{N}$ as shown in Table 7.

Table 7 Uncertainty as a function of number of points, N

Method	**In one dimension**	**In *d* dimensions**
Monte Carlo	$N^{-1/2}$	$N^{-1/2}$
Trapezoidal rule	N^{-2}	$N^{-2/d}$
Simpson's rule	N^{-4}	$N^{-4/d}$
Gauss rule	N^{-2m+1}	$N^{-(2m-1)/d}$

2. FLUKA (FLUktuierende KAskade)

In order to study the particle transport and interactions in matter for this research, we used FLUKA program for particle transport simulation with the numerical method of Monte Carlo. This program has many applications such as high energy experimental physics, engineering, particle detector, telescope design and cosmic ray studies. The simulation result from this program has high accuracy. The interaction and propagation of the various particles in matter is shown in Table 8.

Table 8 The transport limits of FLUKA

	Secondary particles	Primary particles
charged hadrons	1 keV-20 TeV	100 keV-20 TeV
neutron	Thermal-20 TeV	Thermal – 20 TeV
antineutrons	1 keV-20 TeV	10 MeV – 20 TeV
muons	1 keV – 1000 TeV	100 keV – 1000 TeV
electrons	1 keV – 1000 TeV	70 keV – 1000 TeV(low-Z materials) 150 keV – 1000 TeV (high-Z materials)
photons	1 keV – 1000 TeV	7 keV – 1000 TeV
heavy ions	10 MeV/n-10000 TeV/n	100 MeV/n – 10000 TeV/n

The general characteristics of the FLUKA input file are ASCII. The "standard input" file is *.inp in TEXT file, which consists of the commands called "options". Each option has many lines called "cards". Each card consists of

1. one keyword called CODE
2. six floating point values called WHATs
3. one character string called SDUM

The pattern of "cards" is

```
*...+....1....+....2....+....3....+....4....+....5....+....6....+....7....+....8
 CODE      WHAT-1     WHAT-2     WHAT-3     WHAT-4     WHAT-5     WHAT-6     SDUM
```

The FLUKA program is used for the particle detector creation or neutron monitor by defining the components of geometric models, materials and the sources of particles. Then FLUKA creates a random number sequence to start the simulation. The output file of FLUKA simulation consists of the types of secondary particles, particle energy, interaction and the position vector, etc.

The main structure of the FLUKA input file is defined as

1. The comment titles show the information on objective or identification. This part contains TITLE card and information in text. For example,

```
*...+....1....+....2....+....3....+....4....+....5....+....6....+....7....+....8
TITLE                The calibration neutron monitor (water 25 cm)
```

2. Descriptions of geometry define body or regions. The FLUKA program running will start with GEOBEGIN card with design objective and stop with GEOEND card. In FLUKA program, many types of body can be defined by using codes as:

2.1 RPP (rectangular parallelepiped)

2.2 BOX (general rectangular parallelepiped)

2.3 SPH (sphere)

2.4 RCC (right circular cylinder)

2.5 REC (right elliptical cylinder)

2.6 PLA (generic infinite half-space)

2.7 etc.

The whole geometry must be surrounded by the region of "blackhole", which is limited to a closed body (in this model SPH sphere was used).

Furthermore, the various regions can be defined by using operator, intersection or union with 3 operator symbols as - , + and |, where

– operator means the zone of body wholly outside.

+ operator means the zone of body contained wholly inside

| operator **(OR)** means the union operator which combines sub regions

Example The geometry of some part were used in this simulation in free format

```
GEOBEGIN                                                                  COMBNAME
    0  -10              MC-Cad Test
*...+....1....+....2....+....3....+....4....+....5....+....6....+....7....+....8
* Cyl16
  RCC Cyl16      0.00     -35.00    -152.02       0.00       0.00      70.00
              135.00
* Cyl17
  RCC Cyl17      0.00     -35.00    -151.42       0.00       0.00      69.70
              134.80
  END
*...+....1....+....2....+....3....+....4....+....5....+....6....+....7....+....8
* Reg # the pool
* SWM; assigned material: IRONISOP; mat # (40)
SWM    5   +Cyl16  -Cyl17
  END
GEOEND
```

This example created the body of pool by defining its body as right circular cylinder (RCC) which is called Cyl16 and Cyl17.

Cyl16 is a circular cylinder with 70 cm long and 135 cm radius, which has coordinates of the center point at x = 0, y = -35 and Z = -152.02.

Cyl17 is a circular cylinder with 69.70 cm long and 134.80 cm radius, which has a coordinates of the center point at x = 0, y = -35 and Z = -151.42. The region of the pool is defined as SWM.

A comment line can be defined by using the * in front of line and it can be used anywhere in the input file.

3. The materials in the model are defined as an element of "MATERIAL" card, which consists of atomic number, atomic weight, density, name and a material identification number.

An example using lead as material is shown. The FLUKA material of lead consists of WHAT-1 defines the atomic number, WHAT-2 defines the atomic weight, WHAT-3 defines the density of material and WHAT-4 is a FLUKA number. The SDUM specifies the name of material. The LOW-MAT card assigns the cross sections of material which are in the ENEA 72-group neutron library of the FLUKA data base.

Example:

```
*...+....1....+....2....+....3....+....4....+....5....+....6....+....7....+....8
MATERIAL        82.0      207.2      11.35         17                  LEAD
LOW-MAT           17       82.0       -2.0      296.0                  LEAD
```

The COMPOUND card defines the alloy or mixture of several materials and the percentage by weight of materials for instance polyethylene, which consists of 2 atoms of hydrogen and 1 atom carbon, its density is 0.94 g/cm^3 and the FLUKA number of material is 27 in the name “POLY-CH2” as shown in the example below:

Example:

```
*...+....1....+....2....+....3....+....4....+....5....+....6....+....7....+....8
MATERIAL                                 0.94       27                   POLY-CH2
COMPOUND           2.0  HYDROGEN          1.0    CARBON                  POLY-CH2
```

4. Material assignment is a specification of each region. The materials in each region can be set by ASSIGNMAT card, which consist of WHAT-1, the name of material and WHAT-2, the name of region.

Example:

```
*...+....1....+....2....+....3....+....4....+....5....+....6....+....7....+....8
ASSIGNMAT    HE97CO23       gas
ASSIGNMAT      SSTEEL   counter
ASSIGNMAT    POLY-CH2   Reflect
```

5. Definition of the particle source and running FLUKA program are used to determine particle beam by defining BEAM card. It is composed of the kinetic energy of particle in WHAT-1 and xy-direction of particle in WHAT4-5. The type of particle can be defined in SDUM. The BEAMPOS card defines the position and direction of the beam in x, y and z co-ordinates. The USERDUMP command alerts the user routine MGDRAW. The random number can be set by the RANDOMIZE card. After that the program will start running by the START card with the number of particles and stop running by STOP card.

Example:

```
*...+....1....+....2....+....3....+....4....+....5....+....6....+....7....+....8
BEAM           1.E+00       0.0       0.0     400.0     400.0       1.0NEUTRON
BEAMPOS           0.0     -38.0     500.0                              NEGATIVE
USERDUMP          100        49       7.0       1.0
RANDOMIZE         1.0
START      10000000.0
STOP
```

This case is an example of neutron beam of momentum 1 GeV/c with rectangular beam in xy direction of 400 cm. The starting point of beam is injected at x, y, z co-ordinates as 0, -38, 500 cm, respectively in downward direction. The start number of simulation is 10 million particles.

3. PSNM geometry

In the part of the PSNM station simulations, we designed the geometry of PSNM station which contains a zinc roof, concrete floor, concrete walls, 3 bare counters (bare counter is similar to a neutron monitor but it lacks the reflector and lead producer), 18 tubes neutron monitor and the CALMON which is put in the vacuum box. Figure 16 - 18 show the geometry plot in the different planes in cross sectional views.

The experimental set up of the neutron monitor calibration of the PSNM station at Doi Inthanon detected the neutron count rate of the both inside and outside station. Therefore, in this project we created the model of the CALMON, which was set inside the PSNM station. The position of the CALMON was 50 cm away from the door, which was slightly inclined to the area of the corridor.

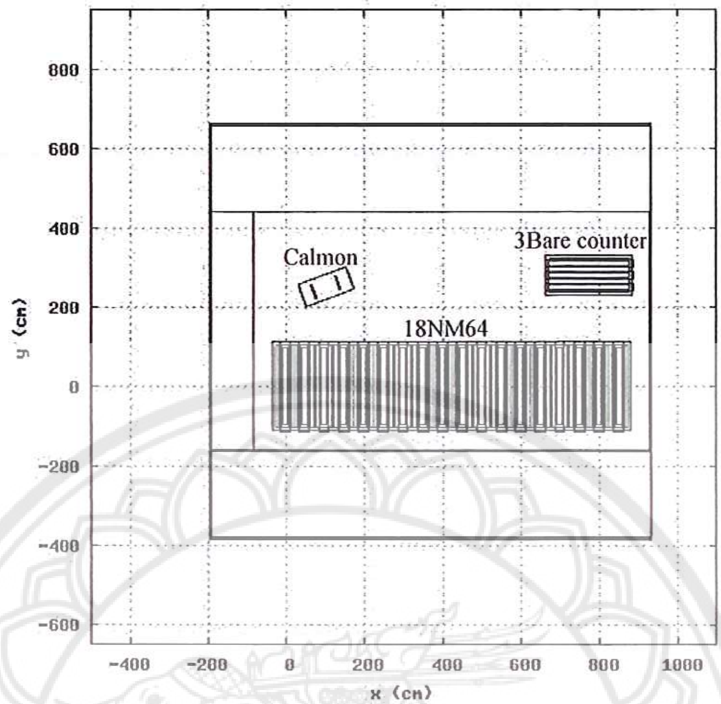

Figure 16 The cross sectional top view (xy plane) geometry plot inside the PSNM station at height of 25 cm from the ground.

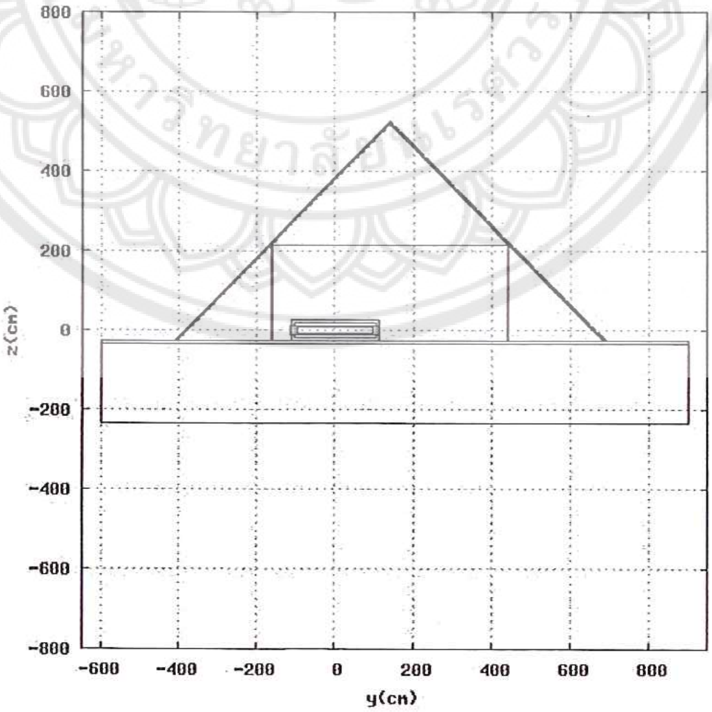

Figure 17 The yz plane geometry plot of the PSNM station.

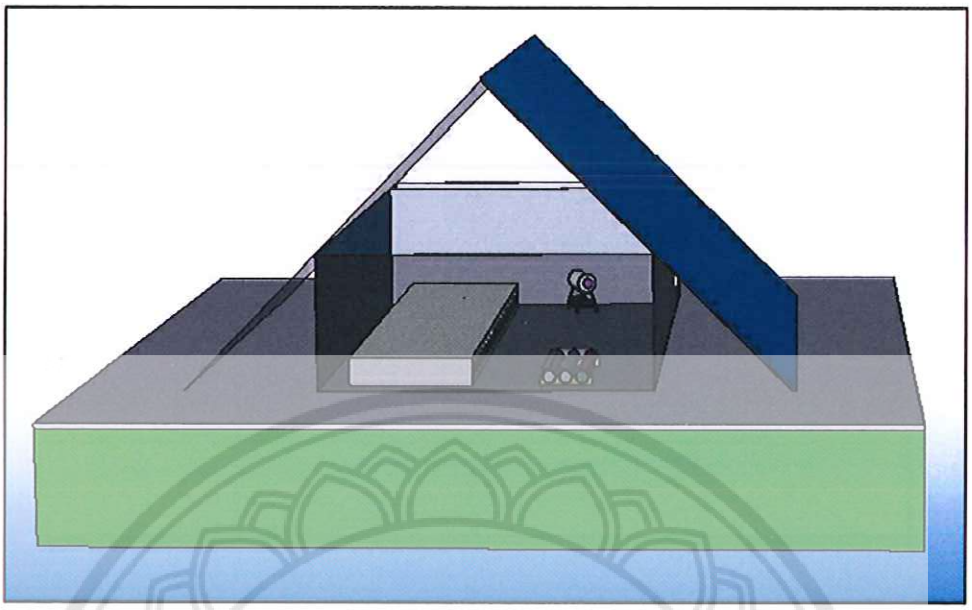

Figure 18 3D sketch of the calibration neutron monitor installation inside the PSNM station.

Monte Carlo model of the calibration neutron monitor

The calibration neutron monitor was created by using FLUKA simulations with Monte Carlo method for studying interaction of neutrons including the effects of the environment on the calibration monitor. The main processes of the calibration monitor modeling are described in following sections.

1. Calibration monitor geometry

In the geometry of calibration monitor, we assigned the structure similar to the calibration of the PSNM station that consists of basalt ground, concrete bunker, wooden roof, pool and calibration monitor.

We set the calibration monitor in the pool with a radius of 135 cm. It was on the top of outside concrete bunker of any building or structure. The concrete bunker had a height 220 cm from the ground with the size of the ground being 645 × 767 cm and a depth of 200 cm as shown in Figure 19 - 22. The height of the calibration monitor was set at 70 and 140 cm above the surface. The heights of water in the pool were at different levels. The heights of water started from 0 to 65 cm.

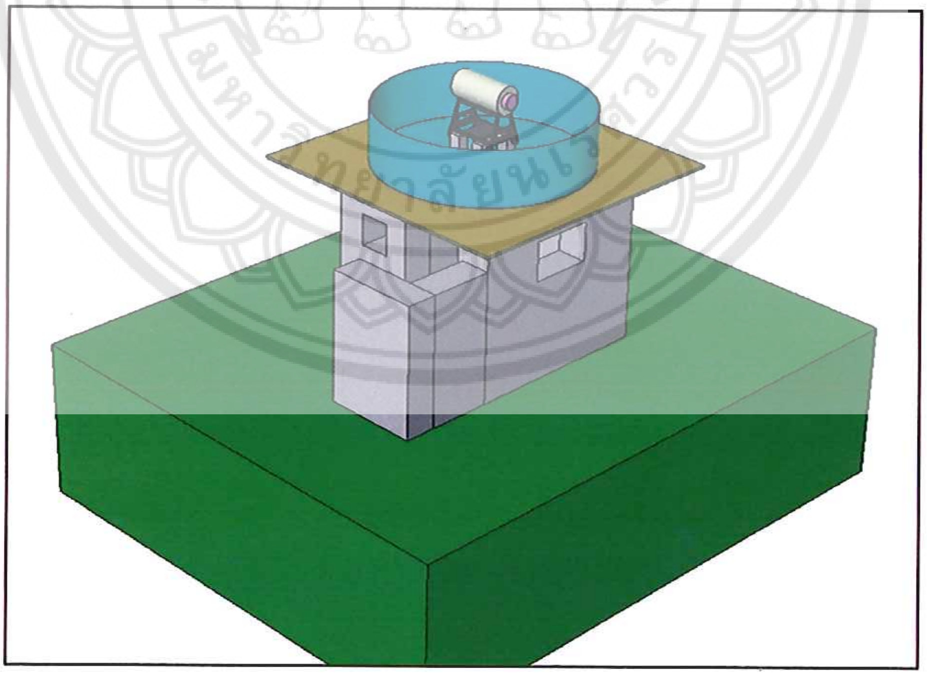

Figure 19 3D sketch of the calibration neutron monitor installation at 70 cm above ground without water.

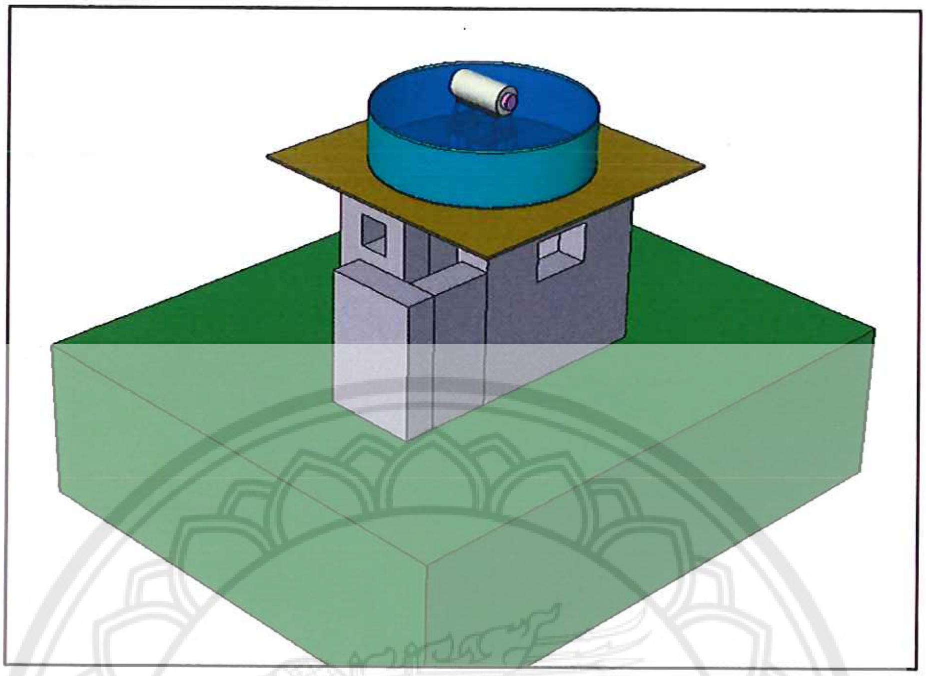

Figure 20 3D sketch of the calibration neutron monitor installation at 70 cm above ground and at the height of 65 cm of water.

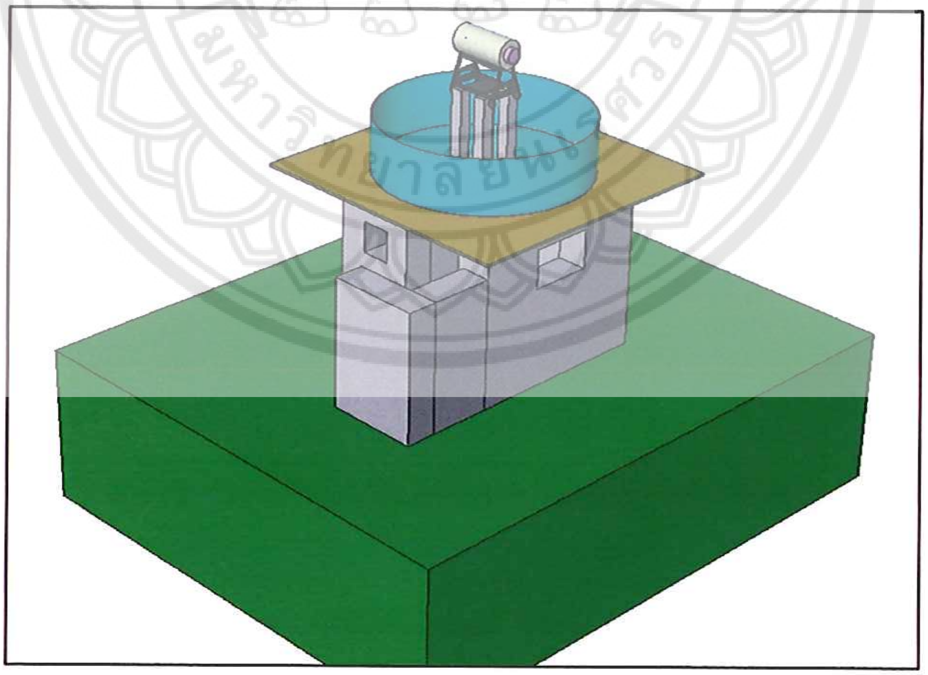

Figure 21 3D sketch of the calibration neutron monitor installation of 140 cm above ground without water.

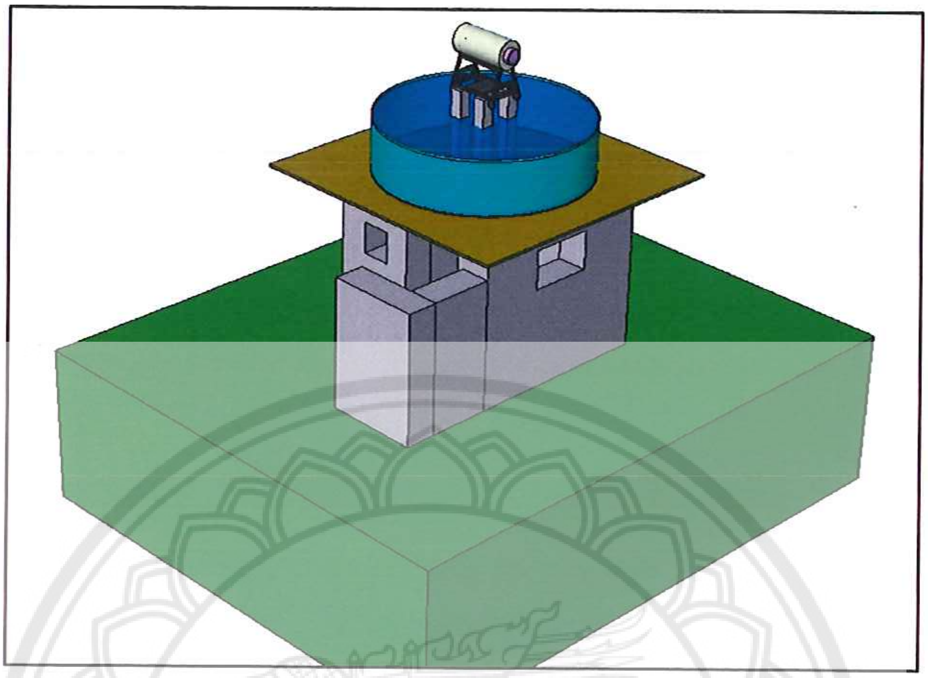

Figure 22 3D sketch of the calibration neutron monitor installation of 140 cm above ground at the height of 65 cm of water.

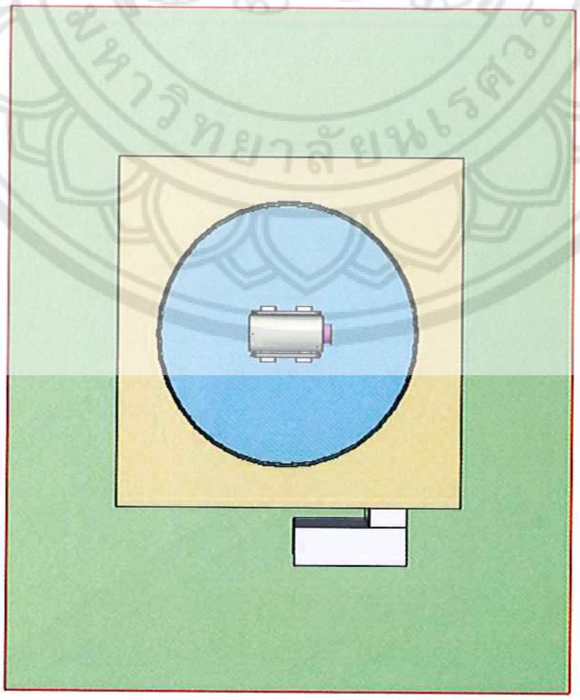

Figure 23 Top view of calibration monitor.

The calibration monitor consists of 4 main parts, which are a polyethylene reflector, a lead producer, a polyethylene moderator and a proportional counter which is filled with ^{3}He 97% and CO_2 3% gas.

Figure 24 shows the various components of the calibration monitor in xy-plane and Figure 26 shows yz plane view of the calibration monitor by using the Simple Geo program.

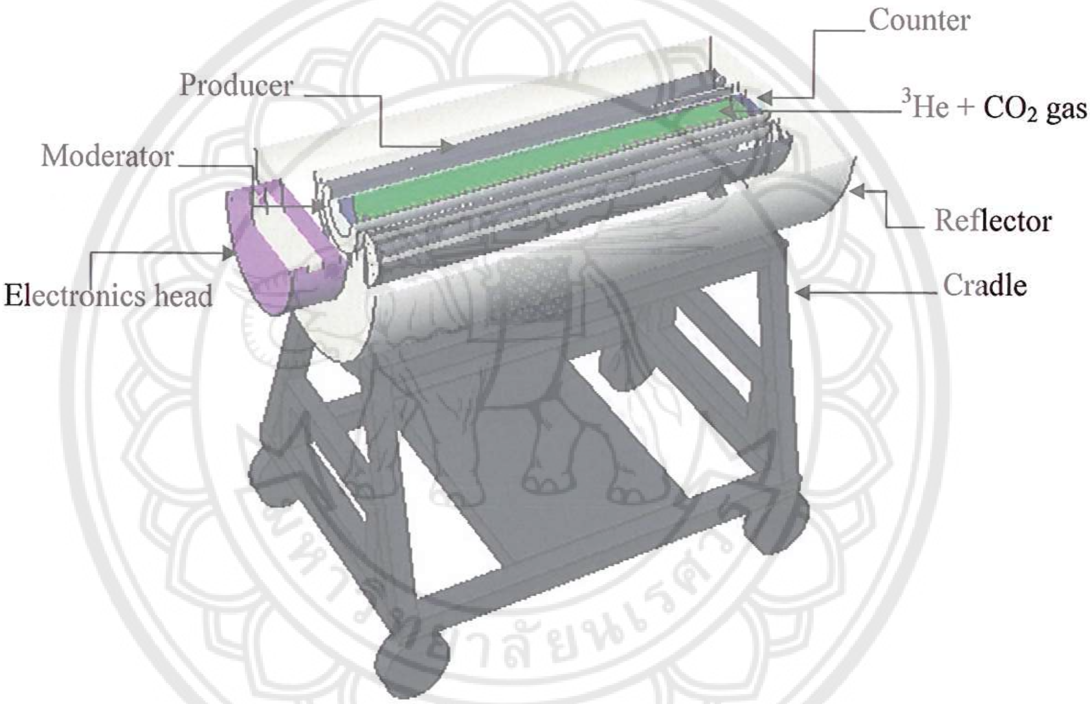

Figure 24 3D xy-plane sketch of the calibration monitor.

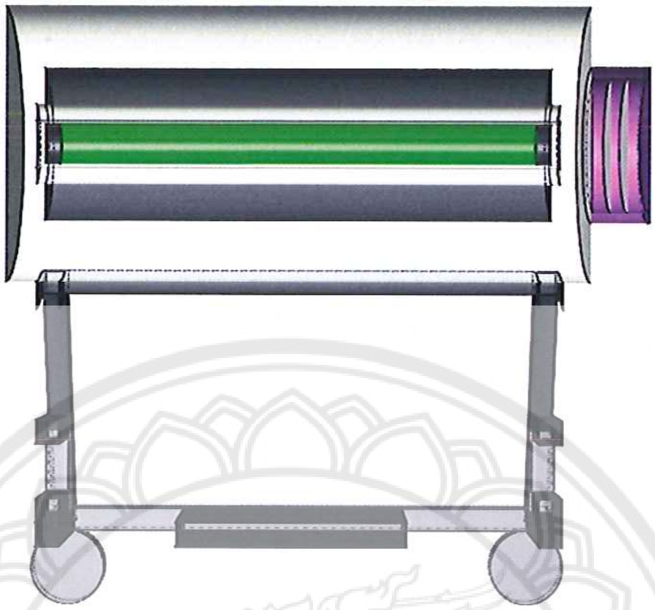

Figure 25 3D yz-plane sketch of the calibration monitor.

The materials of this model are important for FLUKA program in each region. FLUKA requires the value of the volume fractions of the components (atoms, mass or volume fractions). Table 9 shows the chemical composition of materials which were used in this simulation for assigning the material.

Table 9 The chemical composition of materials

Material	Density (g/cm3)	Composition / mass fraction (%)
Polyethylene	0.94	(CH2)n
Lead	11.35	Pb
3He + CO2	0.00075	3He : 97 CO2 : 3
Steel	7.9	Fe : 69 C : 1 Cr : 20 Ni : 10

Table 9 (cont.)

Material	**Density (g/cm^3)**	**Composition / mass fraction (%)**
Concrete	2.35	O : 52.9107
		Si : 33.7021
		Ca : 4.4
		Al : 3.3872
		Na : 1.6
		Fe : 1.4
		K : 1.3
		H : 1
		Mg : 0.2
		C : 0.1
Wood	0.72	$C_6H_{10}O_5$: 50
		$C_5H_{12}O_5$: 25
		$C_9H_{10}O_2$: 25
Pool	4.275	$(C_5H_8)_n$: 50
		Fe : 50
Basalt	3.00	Fe : 9
		Al : 7
		Mg : 6
		Si : 24
		Ca : 7
		O : 47
Air	0.0009415	N : 0.0009256
		O : 0.0002837
		Ar : 0.00001572

2. Beams of atmospheric secondary particles

This research has developed the characteristics of the particle beam in FLUKA simulation. So the simulation results are more accurate. This section will describe the characteristics of the different beams as follows:

2.1 Vertical beam is a determination of the type and energy of particles including positions and directions. For example, the neutron beam has the energy 1 GeV and a height of 300 cm above calibration monitor as shown in Figure 26.

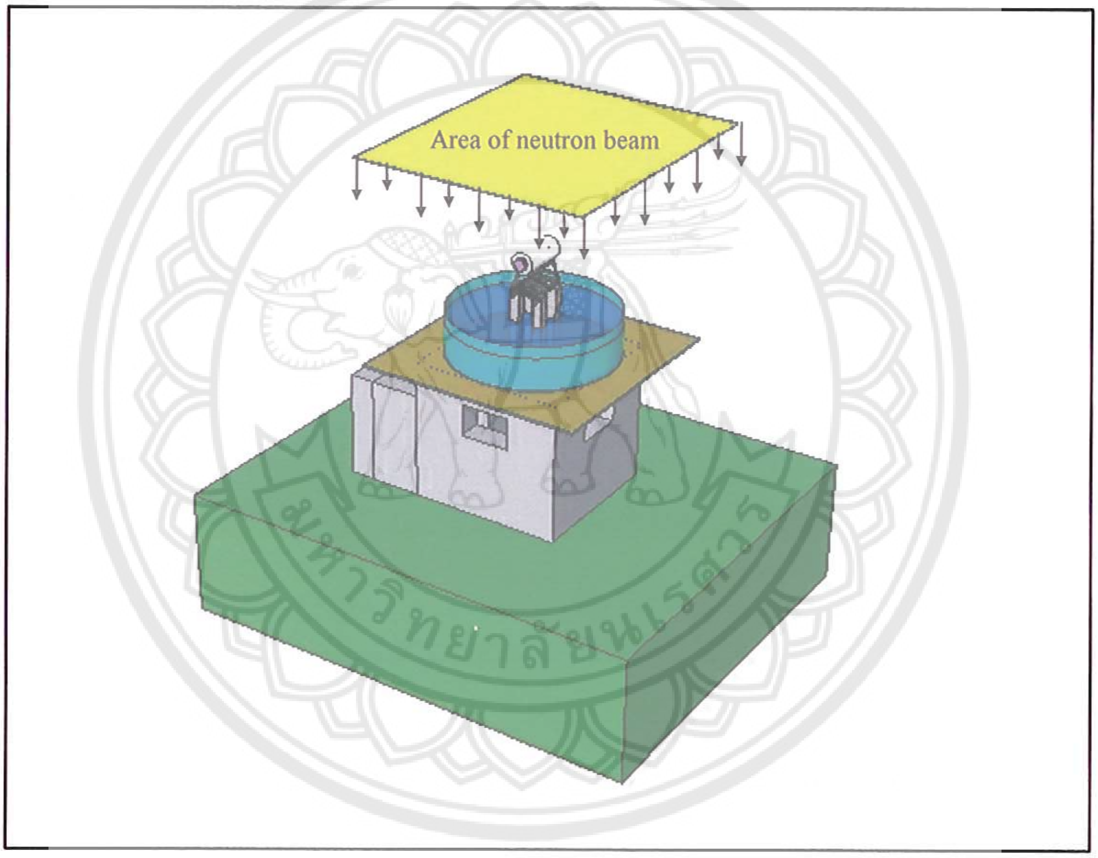

Figure 26 Illustration of the beam area in FLUKA simulation.

The cross section of neutron beam simulation result outside neutron monitor station by FLUKA program is shown in Figure 27

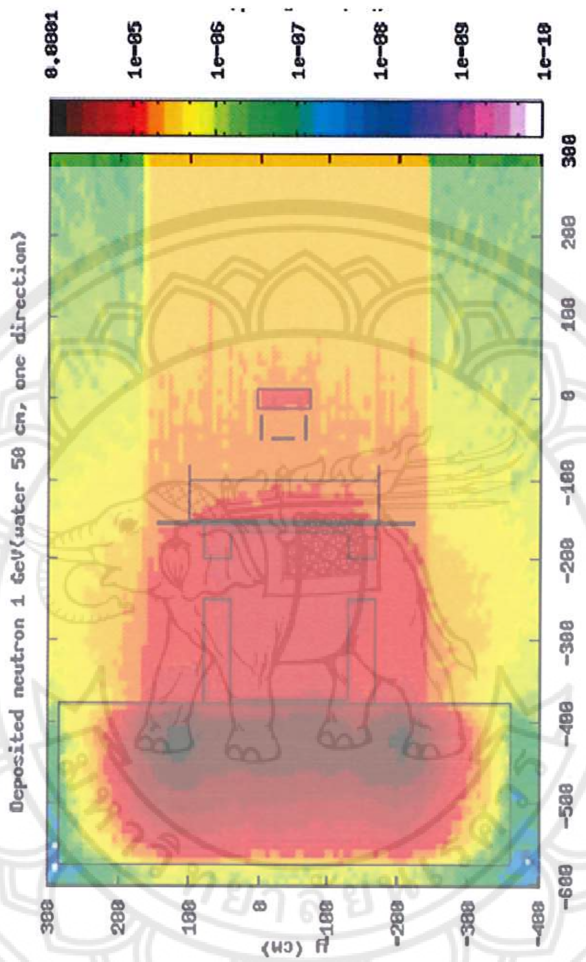

Figure 27 The neutron density plot from the simulation result of neutron beam on yz plane where x, y, z axes are in cm and color scale shows the neutron density.

2.2 The omnidirectional beam

The atmospheric secondary particles have many particles such as electrons, protons, neutrons, positive muons, negative muons, pions or gamma rays. The simulation needs SOURCE.f file for these particles with all energies and directions in FLUKA program. SOURCE.f file can be modified by setting size and coordinates of beam, which depends on the angle of particles. Each beam will have random position within a rectangular beam as shown in Figure 28.

In this research, we used source data of atmospheric secondary particles from the simulation results of John Clem, University of Delaware, which simulated all particles, all energies above the PSNM station of sea level 2,565 m with the cut-off rigidity of 16.8 GV.

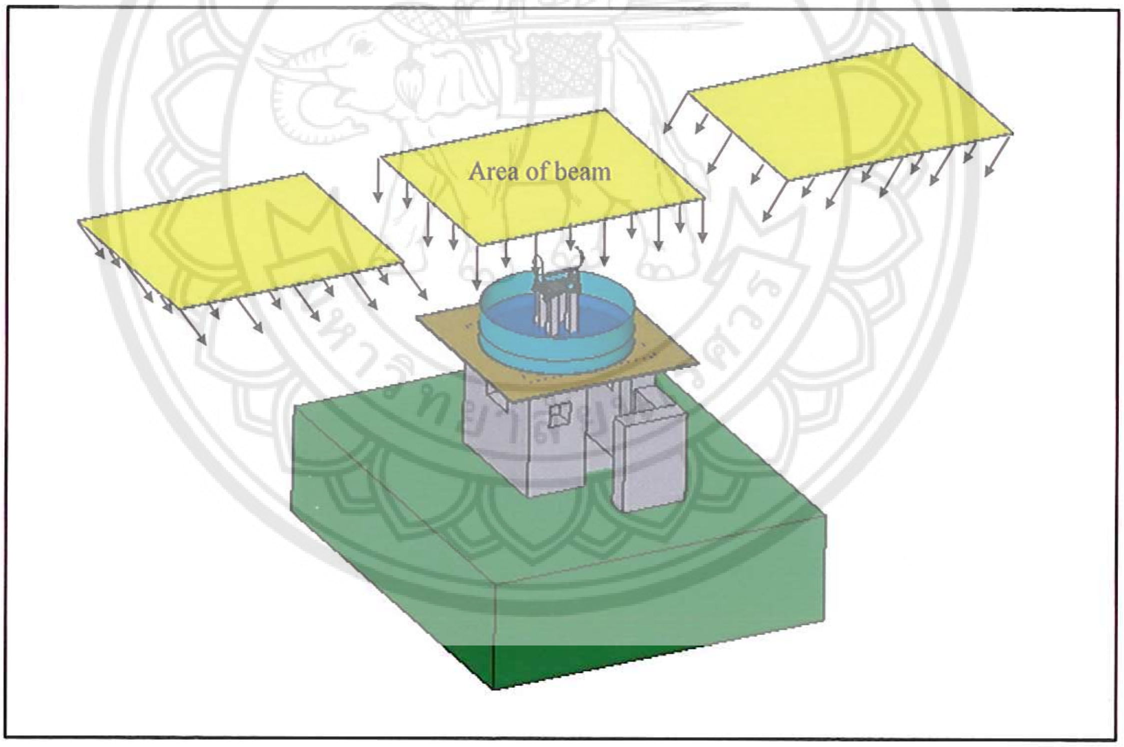

Figure 28 Illustration of the beam area with source routine in FLUKA simulation.

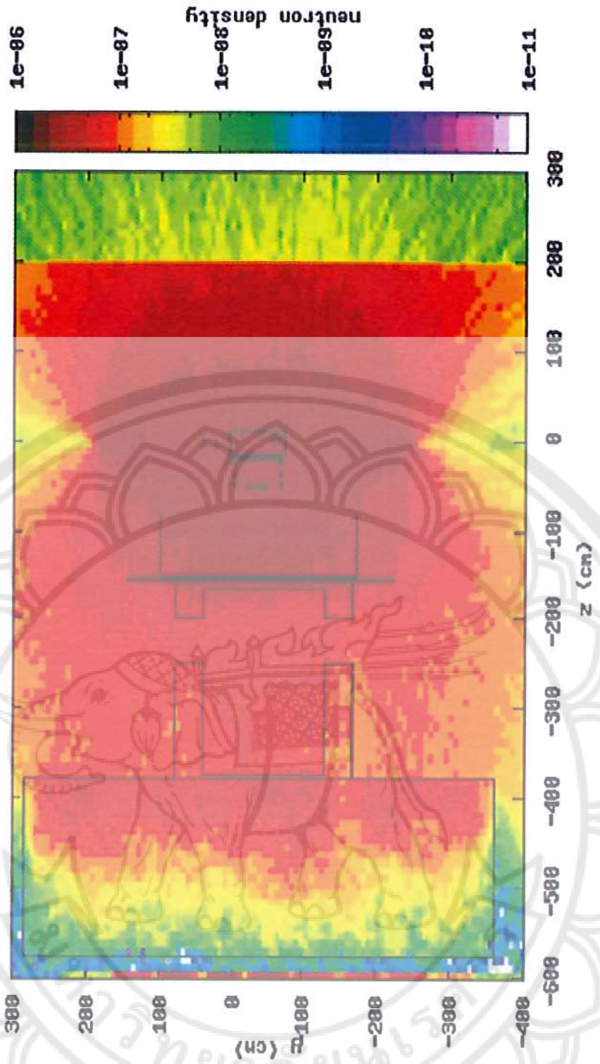

Figure 29 The neutron density plot from the simulation result of beam with source routine on yz plane where x, y, z axes are in cm and color scale shows the neutron density.

Figure 29 shows the example of the rough simulation result by using SOURCE.f with Monte Carlo method. It has the initial position within an area of 380 x 440 cm^2 and 200 cm above the calibration monitor. This figure indicates that the beam simulation of the calibration monitor is not uniform, because the calibrator tube is smaller than neutron monitor therefore it is very sensitive to the effects of walls. Because of the non-uniform beam problem, we developed a new beam as the weight beam.

2.3 The wider beam

This beam is the weight of the particles. It needs SOURCE.f of weights which start on the larger area for larger angle and weight. We modified SOURCE.f file for initial conditions for the resize beam. The far particles have the larger angle, so the area of beam will be resized with weight.

In this work, we set the beam position (zb) at 165 cm above detector and ground position (zg) of z = -375 cm. The weight beam has initial area of 380 × 440 cm^2 as shown in Figure 30. Figure 31 shows the top view of horizontal shift on xy-coordinates including the resized weight beams.

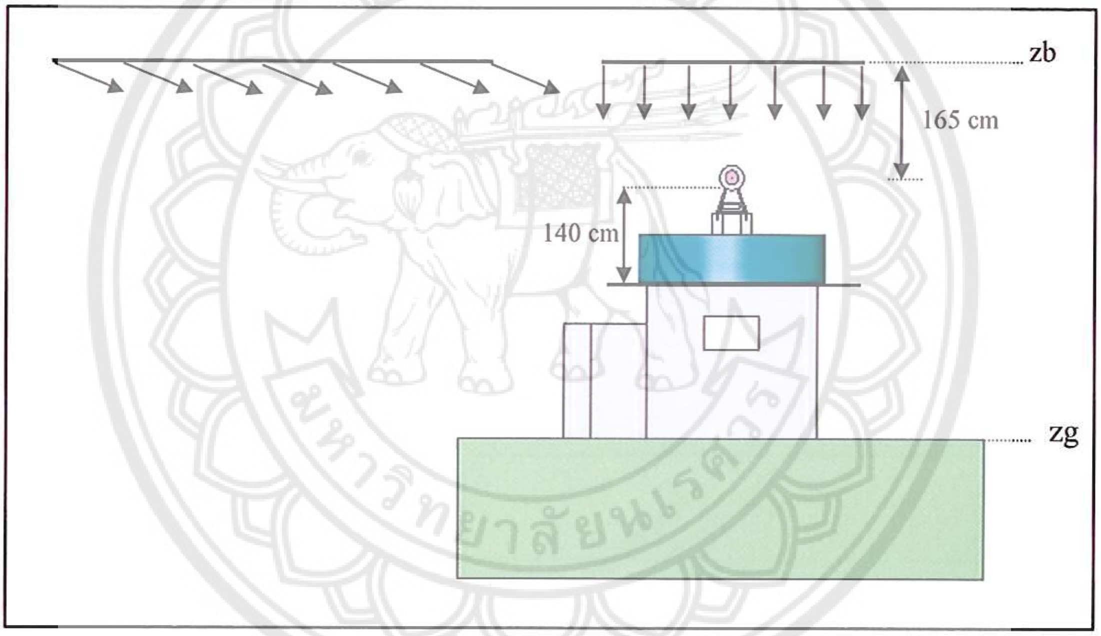

Figure 30 Front view image of the weight beam in the calibration monitor simulation.

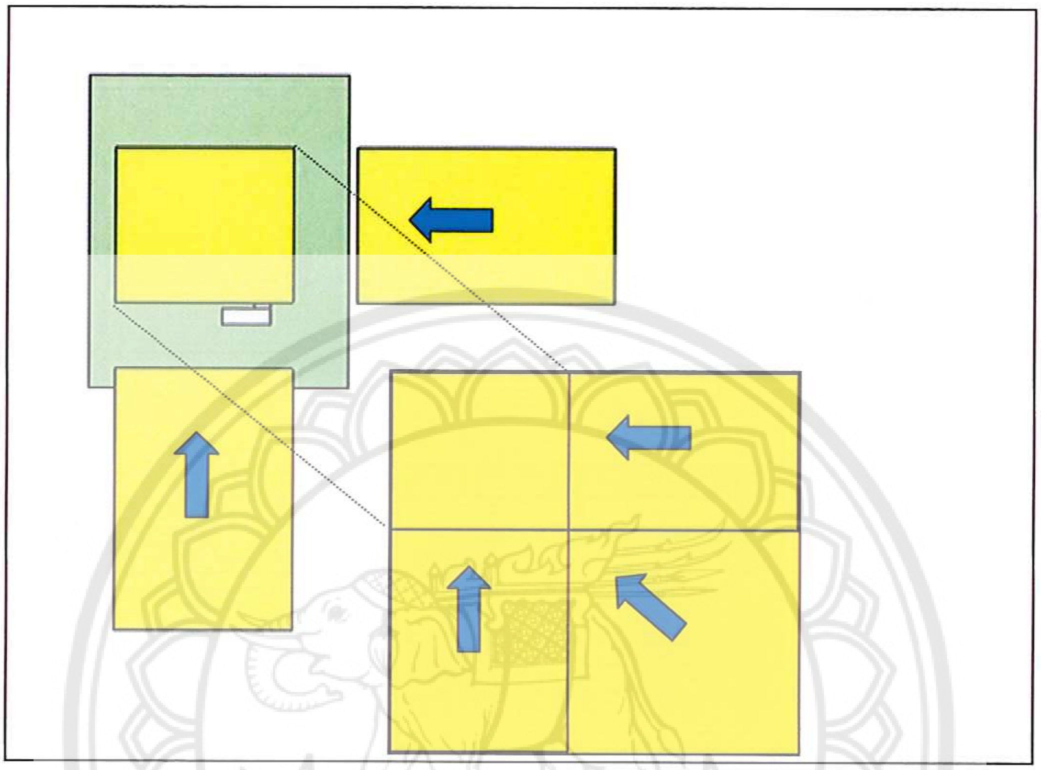

Figure 31 Top view of the weight beam areas and directions as used in the calibration monitor simulation.

Resizing of the weight beam

We adjusted the size of beam area as follows:

x is random position between x_{1b} and x_{2b},

y is random position between y_{1b} and y_{2b}.

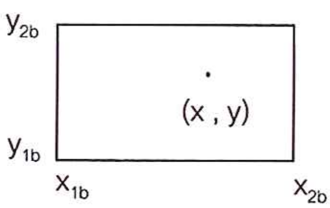

Figure 32 position of (x , y).

For a vertical direction:

$$x_{1b} = x_1 \quad \text{and} \quad y_{1b} = y_1$$

$$x_{2b} = x_2 \quad \text{and} \quad y_{2b} = y_2$$

For other direction:

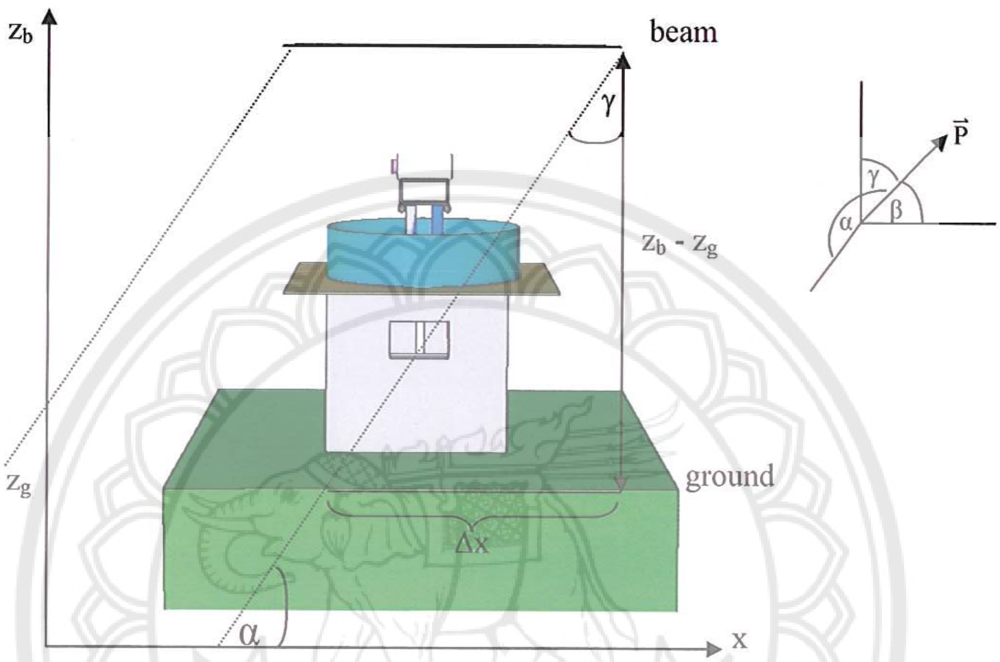

Figure 33 Direction and incident angle of beam.

where $\vec{P}$ is a vector of beam position.

$$\Delta x = \cos\alpha \; \frac{z_b - z_g}{\cos\gamma}$$

$$\Delta y = \cos\beta \; \frac{z_b - z_g}{\cos\gamma}$$

Therefore,

$$x_{1b} = \begin{cases} x_1 & \text{if } \Delta x > 0 \\ x_1 + \Delta x & \text{if } \Delta x < 0 \end{cases}$$

$$x_{2b} = \begin{cases} x_2 + \Delta x & \text{if } \Delta x > 0 \\ x_2 & \text{if } \Delta x < 0 \end{cases}$$

Similarly,

$$y_{1b} = \begin{cases} y_1 & \text{if } \Delta y > 0 \\ y_1 + \Delta y & \text{if } \Delta y < 0 \end{cases}$$

$$y_{2b} = \begin{cases} y_2 + \Delta x & \text{if } \Delta y > 0 \\ y_2 & \text{if } \Delta y < 0 \end{cases}$$

This method can solve the problem of non-uniform beam as shown in Figure 34.

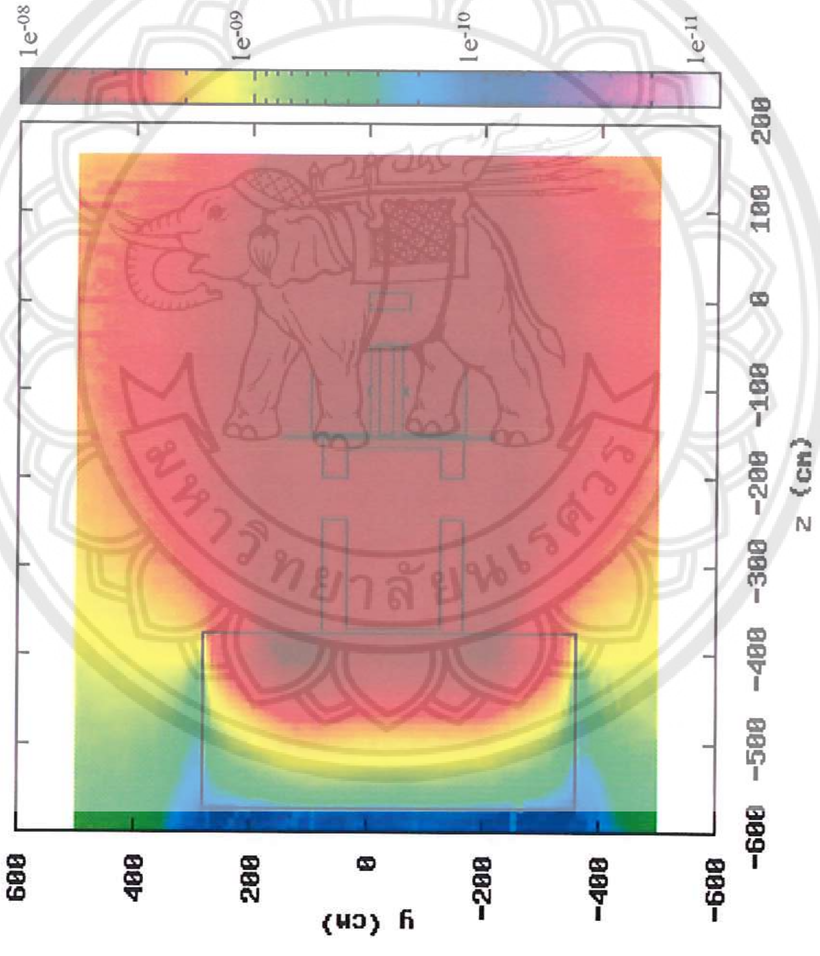

Figure 34 Neutron density plot from the simulation result of weight beam on yz plane where x, y, z axes are in cm and color scale shows the neutron density.

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From the previous descriptions, we explain the simulation process by flow chart as shown in Figure 35.

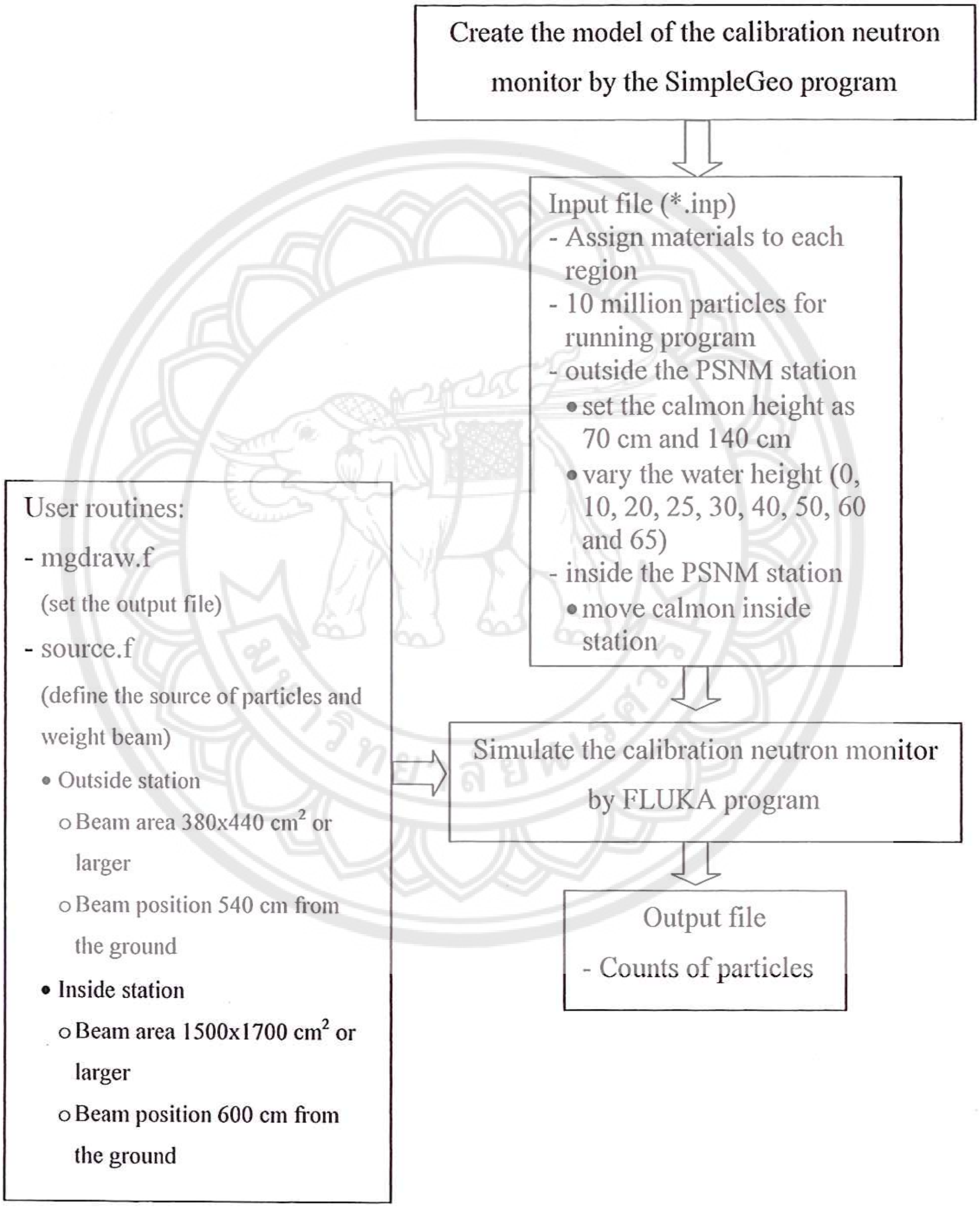

Figure 35 The flow chart of the FLUKA simulation.