CHAPTER II

BACKGROUND KNOWLEDGE

Cosmic rays

Cosmic rays are high energy particles from an explosion on the surface of the Sun or outer space which consist of charged particles such as protons, alpha particles and other atomic nuclei including gamma rays. Most cosmic rays detected on the top of Earth's atmosphere are mainly protons (90%), alpha particles or ions of other elements (9%) and electrons (1%). These cosmic rays are detected on the ground as galactic cosmic rays. The intensity of galactic cosmic rays is related to the solar activity on the Sun as indicated by the 11 year sunspot cycle (Figure 3).

There is an increase in galactic cosmic ray intensity in the range of solar minimum because the detected particles from neutron monitor are the energetic particles from galaxy. Conversely, in the range of solar maximum, which corresponds to increasing of sun spot, the number of detected neutrons from neutron monitor will be decreased because the solar energetic particles come to the earth and push off the energetic particles from galaxy as shown in Figure 3.

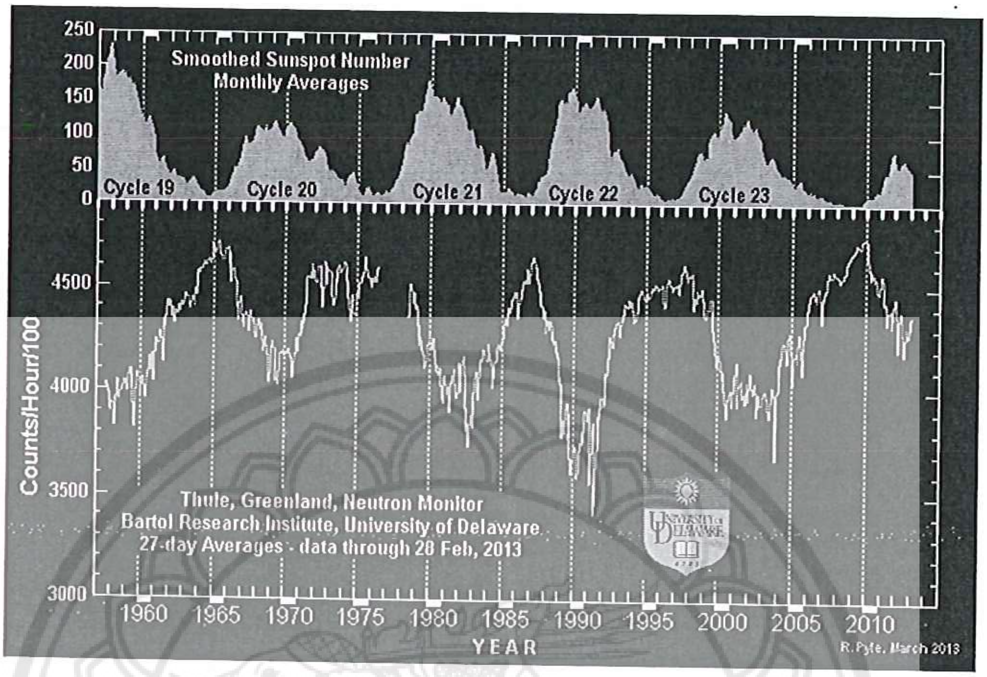

Figure 3 The relation between solar activity and intensity of galactic cosmic rays as indicated by the number of sunspots.

Source: http://neutronm.bartol.udel.edu

1. The energy spectrum of cosmic rays

The spectrum of primary cosmic rays can be described by a power law distribution. Figure 4 shows the energy spectrum of cosmic rays detected at about 10^9 to 10^{20} eV. The energy at $10^7 - 10^9$ includes anomalous cosmic rays. Most particles detected in this energy range are solar cosmic rays. The cosmic ray energy in range of $10^9 - 10^{18.5}$ eV is mostly galactic, while in the energy spectrum of cosmic rays, the range of energy > $10^{18.5}$ eV is extragalactic.

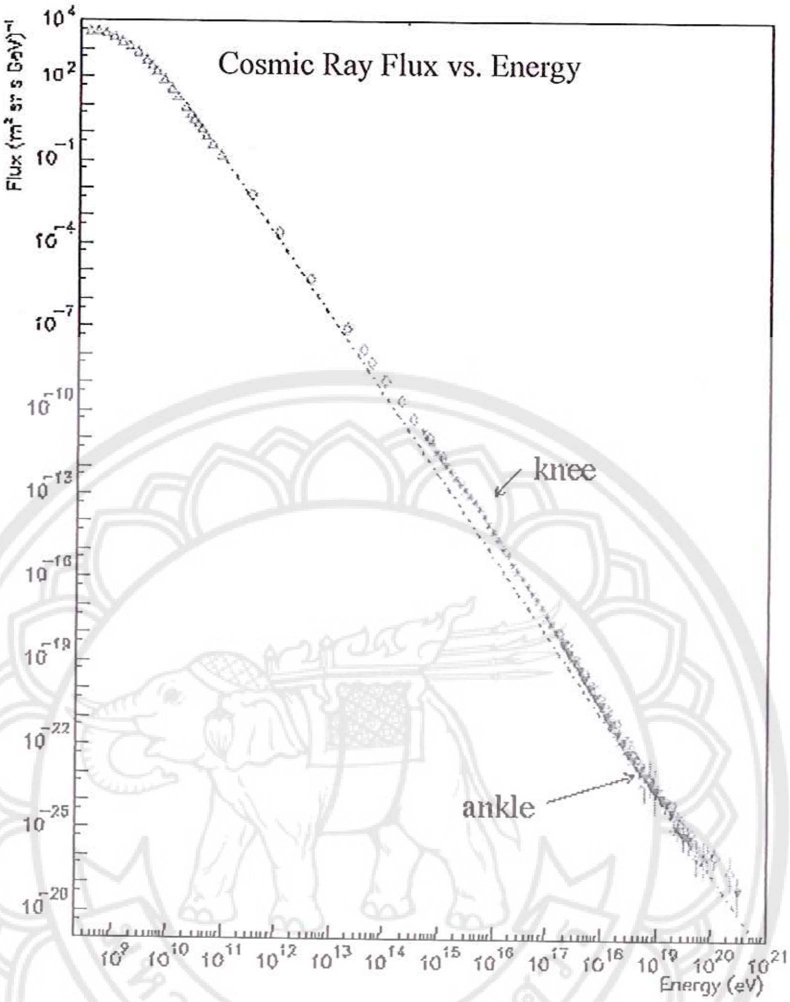

Figure 4 The energy spectrum of cosmic rays measured at Earth

Source: http://hires.physics.utah.edu/reading/uhecr.html

2. Cosmic rays in the atmosphere

The primary cosmic rays are enormously high energy rays in space. When they pass through the Earth's atmosphere, they hit molecules of air, mainly nitrogen and oxygen and produce the secondary cosmic rays with lower energy than the primary cosmic rays as shown in Figure 5.

From Figure 5, the primary charged pion ($\pi^{\pm}$) move to the Earth's atmosphere and will decay to a muon, a muon neutrino, neutral pions or gamma rays. The decayed particle from the primary charge pion is called secondary particle. The group of the secondary cosmic rays can be classified into 3 groups. These are 1) nucleonic component which consists of protons and neutrons, 2) electromagnetic component which consists of electrons, positrons and gamma rays and 3) meson component which is chiefly muons. The secondary particle has less energy than the primary particle.

From a schematic diagram of cosmic ray shower, most of the secondary particles are neutrons so the cosmic ray measurements on the ground are detected by neutron monitors. Because of this neutron monitor stations were setup around the world at different locations, so that the Earth's magnetic field for each station will be different. The horizontal magnetic field of the Earth at various locations are of significant importance for measuring the number of detected neutrons from each neutron monitor. The number of particles that come to the Earth depends on the cut off rigidity of the Earth's magnetic field.

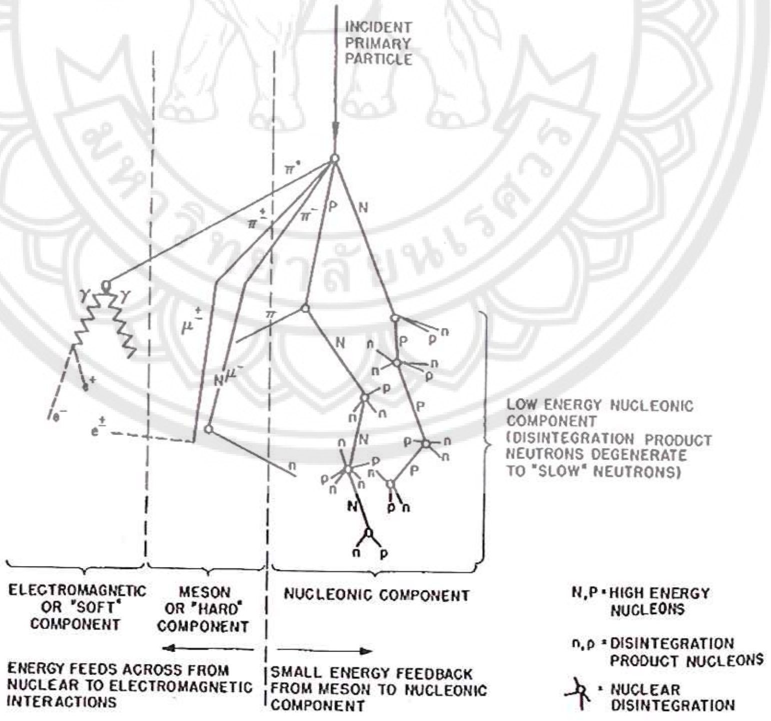

Figure 5 A schematic diagram of cosmic ray shower

Source: Simpson, et al., 1953

Cutoff Rigidities

Because most cosmic rays are charged particles when they arrive on the Earth their motion move along the Earth's magnetic field with a mass, m. The positively charged particle with charge q moves in a circular orbit of radius r with a constant speed $v_\perp$ perpendicular to a uniform magnetic field **B**. The magnetic force on the particle is expressed by the Lorentz equation, so this force acts as a centripetal force, and the particle moves in a circle. Equating these two forces, we get

$$qv_\perp B = \frac{mv_\perp^2}{r},$$

and

$$r = \frac{mv_\perp}{qB},$$

If the particle motion is entirely perpendicular to **B**

$$r = \frac{P}{qB}$$

where P is the momentum of particle (GeV/c).

The definition of rigidity, R, is R = Br = P/q.

From this relation, the motion of charged particle depends on the orbital radius of the moving charged particle (or its rigidity). The number of cosmic rays come to the earth at the various locations are different which depend on the cutoff rigidity.

In cosmic ray physics, the cutoff rigidity (P_c) is the lowest rigidity of a charged particle which can pass and arrive at the Earth's surface. These charged particles move along the magnetic field line, so the Earth's geomagnetic field is a significant parameter of the cutoff rigidity for the neutron monitor location.

In this research, we have the neutron monitor station at the world's highest cutoff rigidity of 16.8 GV, which is the PSNM station. Therefore, the detected data from the PSNM station are special data because we will get the data with the highest energy of particles.

Neutron monitors

A neutron monitor is a ground-based neutron measurement from the outer space cosmic rays. J.A. Simpson improved the method for detecting the secondary neutrons in 1948. He installed the first neutron monitor at Climax station, Colorado of USA in 1951. He found that the Earth's magnetic field act as the energy filter of cosmic rays. Now, there are worldwide network of neutron monitors of about 50 stations as shown in Figure 6. During 1957, International Geophysical Year (IGY), monitors were modified around the world and called IGY monitors. The neutron monitors were continuously developed until 1964. Hatton and Carmichael changed the geometrical arrangements and some materials for increased efficiency of neutron monitor. They called this new type of neutron monitor as NM64. This network of neutron monitors has importance for studying secondary cosmic rays, the characteristics of solar magnetic field, and the interaction between cosmic rays or solar particles with magnetic field. So it is necessary for us to understand the structure of neutron monitor and neutron monitor's interval processes.

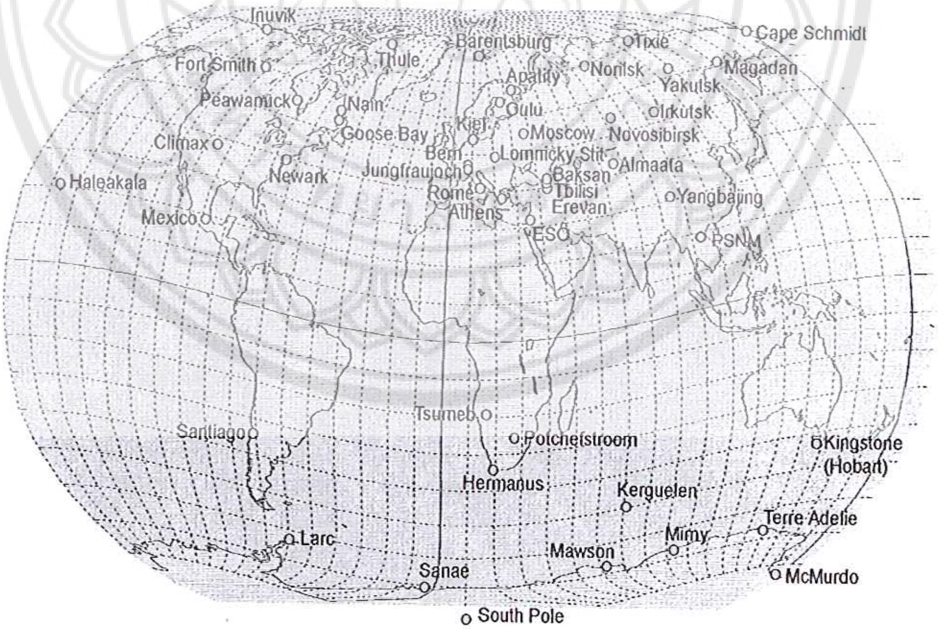

Figure 6 The worldwide neutron monitors of various stations around the world including PSNM in Thailand

Source: http://www.nmdb.eu

Both types of neutron monitors have the same 4 main components, which they are:

1. Reflector, which is the outer tube of proton-rich material such as paraffin and polyethylene. The low energy neutron cannot pass into reflector.

2. Producer, which is lead and is the main component of neutron monitor, because lead has a high atomic mass and nucleus target which are a good source for producing neutron. The fast neutrons move through the reflector and interact with lead and produce lower energy neutrons. This producer part amplifies the electrical signal of neutrons.

3. Moderator, which is a proton-rich material as same as the reflector. The energy and speed of neutrons are reduced by moderator as a function of the neutron energy decreasing with the condition of elastic collisions as in equation (1)

$$\frac{dE}{E} = 4\cos^2\theta \frac{A}{(1+A)^2} \tag{1}$$

where A is the atomic mass (u),
θ is the scattering angle of the recoil nucleus (degree),
E is the energy of neutron (eV).

4. Proportional counter, which is filled gas usually boron trifluoride (BF_3). The incoming neutrons react with nucleus of gas and produce the charged particles.

The 4 main components of neutron monitor are shown in the lower part of Figure 8. The primary particles from space move to the Earth, they interact with the other atoms or molecules in the Earth's atmosphere. They produce secondary particles as shown in the upper part of Figure 7. The most detected secondary particles on the Earth are neutrons. We cannot detect neutrons on the Earth directly, because the neutron particles have no electric charge. Thus, the measurement of neutron flux can be detected by converting the energy released from neutron capture reactions (n , α), (n , p) or (n , γ) to electrical signals.

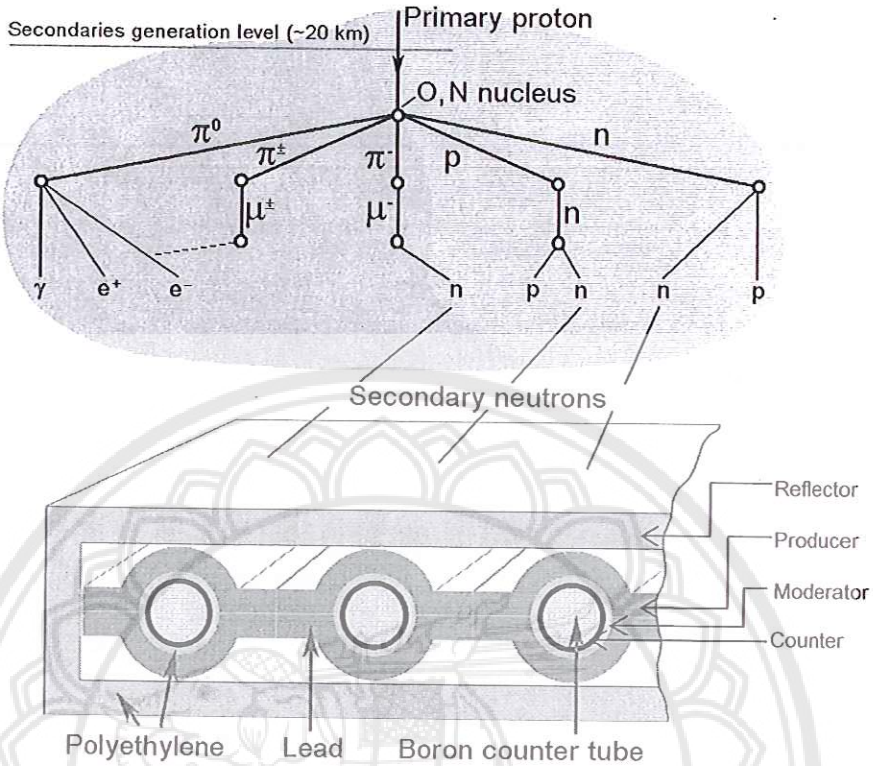

Figure 7 Atmospheric cosmic ray shower, and components of a neutron monitor.

Source: http://physik.uibk.ac.at/hephy/Hess/Yuri_Neutron_Monitor_ Hafelekar.pdf

As described earlier, the neutron monitor was developed with geometry and material for high efficiency detection. The details of the structure and material of two neutron monitors (NM64 and standard IGY) are shown in Table 1.

Two types of counters are chosen for NM64 which are BP28 (with ^{10}B, as used with our neutron monitor) and LND25373 (with 3He, similar to that used in the calibration neutron monitor). The standard IGY has the counter NWG-15-34A.

Table 1 Comparison of the specifications between 6NM64 and a 12-tube IGY monitors.

Type of neutron monitor	**6NM64**		**Standard IGY**
Counter			
Type	BP28	LND25373	NWG-15-34A
Number	6	6	12
Diameter	14.8 cm	4.9 cm	3.8 cm
Spacing	50.0 cm	50.0 cm	15.2 cm
Effective length	191 cm	190.8 cm	86.4 cm
Gas	$^{10}BF_3$	97% ^{3}He + 3%CO_2	$^{10}BF_3$
Pressure	200 mmHg	3040 mmHg	450 mmHg
Operating voltage	2800 V	1300 V	1950 V
Thermal neutron absorption			
Path length	41.0 cm	1.9 cm	18.2 cm
Moderator			
Material	Polyethylene		Paraffin
Average column thickness	1.84 g/cm^2		2.95 g/cm^2
Average thickness	2.0 cm		3.7 cm
Producer			
Material	Lead		Lead
Average column thickness	156 g/cm^2		153 g/cm^2
Length	207 cm		102 cm
Projected top area	6.21 m^2		1.9 m^2
Reflector			
Material	Polyethylene		Paraffin
Average column thickness	7.0 g/cm^2		25.8 g/cm^2
Average thickness	7.5 cm		30.5 cm
Length	222 cm		168 cm

Source: Hatton and Carmichael, 1964; Pyle, et al., 1999; Stoker, et al., 2000; the specifications from the company Lnd, Inc.

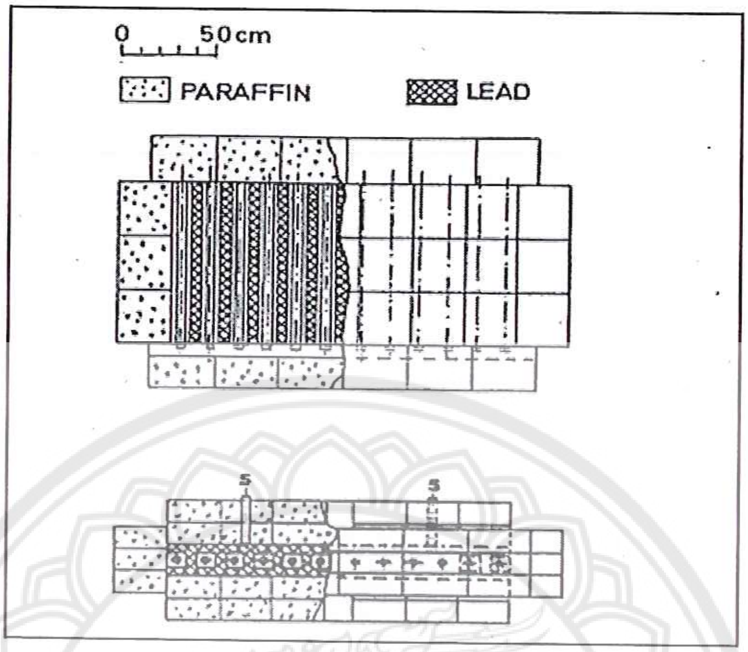

Figure 8 International Geophysical Year (IGY) 12 counters

Source: Simpson, 1957

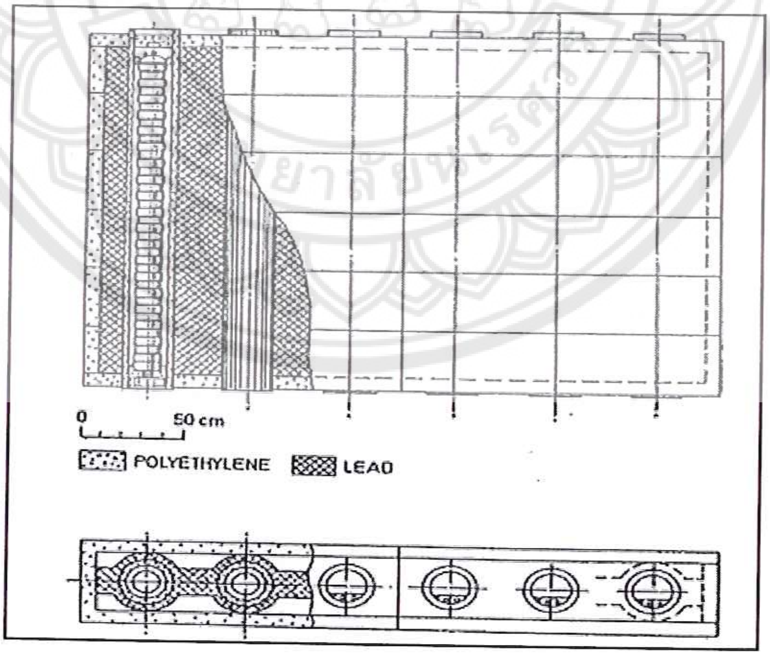

Figure 9 The neutron monitor (6NM64), 6 tubes

Source: Carmichael, 1968

The structure of a neutron monitor shows in Figure 8-9. Figure 8 shows the IGY monitor of 12 counters and Figure 9 shows the NM64 of 6 counters. The structure and the types of materials in each layer can be seen.

Gas used in the counter of a neutron monitor is of 2 types, which are ^{10}B and ^{3}He. Both gas have different specific conditions.

S.A. Korff and W.E. Danforth, in 1939 used boron trifluoride, BF_3 of the isotope ^{10}B in the part of proportional counter because of it is high cross section. The reaction in the counter is

$$^{10}B + n \rightarrow {}^{7}Li^{*} + {}^{4}He + 2.310\ MeV,$$

$$^{10}B + n \rightarrow {}^{7}Li + {}^{4}He + 2.792\ MeV.$$

Pyle et al., in 1999 showed that 3NM64 neutron monitor set up in the last latitude from Hawaii to Seattle used ^{3}He gas instead of $^{10}BF_3$ gas. They determined that the efficiency and the energy response of ^{3}He and $^{10}BF_3$ gas are similar. Nowadays, the $^{10}BF_3$ is not produced with the neutron monitor tubes and replaced with ^{3}He counter. Later, the ^{3}He gas costs higher. The ^{3}He counter is available for using at high pressure area so the measurement efficiency of particles per unit volume is high. ^{3}He gas in the proportional counter reacts with neutrons according to the reaction

$$^{3}He + n \rightarrow {}^{3}H + p + 0.765\ MeV.$$

The Q-value of ^{3}He is smaller than ^{10}B, but the cross-section of ^{3}He is larger as shown in Figure 10. Thus, the high cross section of gas corresponds to the high efficiency for the count rate of neutrons.

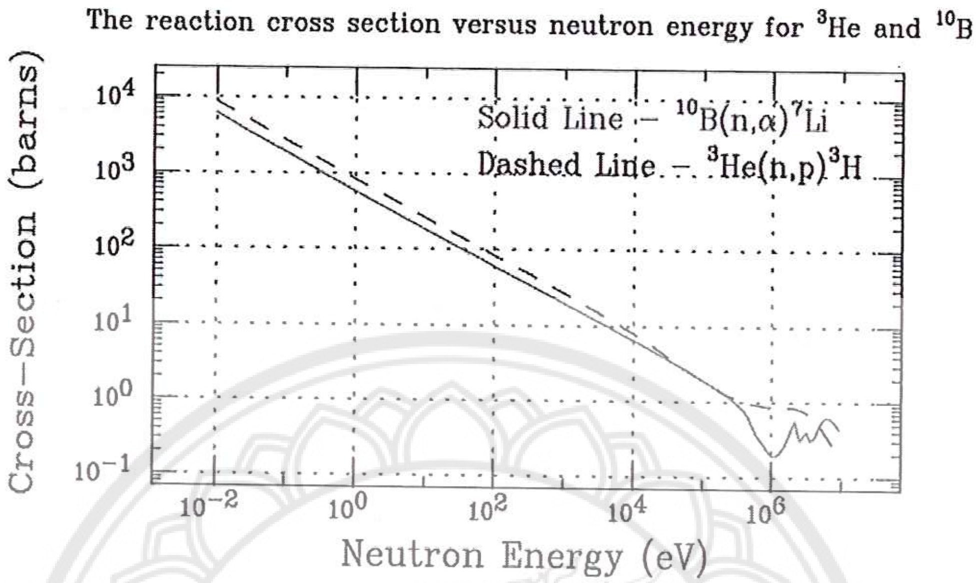

Figure 10 The cross – sections of $^{10}B(n, \alpha)^7Li$ and $^3He(n, p)^3H$

Source: Krane, 1988

The efficiency of the neutron measurement depends on the energy of neutrons as shown in equation (2) (H. Krüger, 2006)

$$\text{Efficiency} = f\,[1 - \exp(-N\,\sigma d)] \tag{2}$$

where Efficiency is the efficiency of the neutron detection of energy E,

d is the thickness of a detector (cm),

N is the number density (atoms per unit volume),

σ is the absorption cross section (barn),

F is the fraction of these interactions.

Differential response functions of neutron monitors

The count rate of a neutron monitor depends on cutoff rigidity and the depth of atmosphere. Accordingly, the differential response functions (dN/dP) are rigidity spectra of secondary cosmic rays in the atmosphere. Thus the relation between the count rate, N, of neutron monitor and intensity, j(P,t) of the primary cosmic rays at the top of the atmosphere, S(P,x) is the neutron monitor yield function of the secondary cosmic rays at atmospheric depth (x) and cutoff rigidity P_c as shown in the equation (3)

$$-\frac{dN}{dP_c} = S(P,x)j(P,t) \qquad (3)$$

and the count rate of neutron monitor is calculated by integrating the response function as

$$N(P>P_c) = \int_{P_c}^{\infty} S(P,x)j(P,t)dP. \qquad (4)$$

In order to derive differential spectra from neutron monitor count rates of the various stationary neutron monitor, the counting rates of individual neutron monitors can be used to find

$$\frac{dN}{dP} \approx \frac{N(P_{c2}) - N(P_{c1})}{P_{c2}-P_{c1}} \qquad (5)$$

where

P_{c1} and P_{c2} are the cutoff rigidity at the different stationary neutron monitors,

$N(P_{c1})$ and $N(P_{c2})$ are the count rates at the different stationary neutron monitors, which must be properly calibrated.

The calibration neutron monitor

The calibration of neutron monitor for each neutron monitor station uses the intercalibration neutron monitor called "CALMON" (Figure 11) for the calibration of neutron monitor at the other locations. This is due to CALMON's small size and ease of transportation. CALMON has a length of about 1/3 of the standard NM64 neutron monitor. Its mass is 201.3 kg, mass of the cradle is 21.5 kg and the total mass is 222.8 kg. Inside the proportional counter, is filled ^3He gas of 97% and CO_2 of 3%, and it is surrounded by a polyethylene moderator, 7 lead rings and a polyethylene reflector. The standard calibration of the world's stationary neutron monitors need to use CALMON for identical standards for each station.

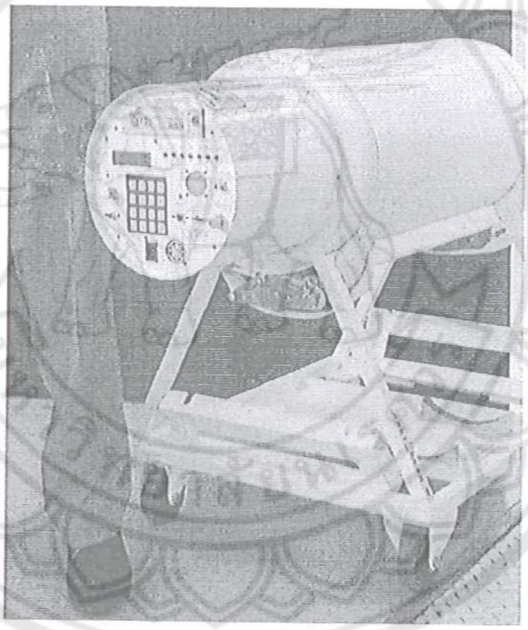

Figure 11 The calibration neutron monitor

Source: H. Krüger, 2006

CALMON consists of the four main components as NM64, which are

1. proportional counter filled with ^3He 97% and CO_2 3% for type LND25382,
2. moderator made of polyethylene,
3. producer with seven lead rings,
4. reflector made of polyethylene.

These components are shown in Figure 12.

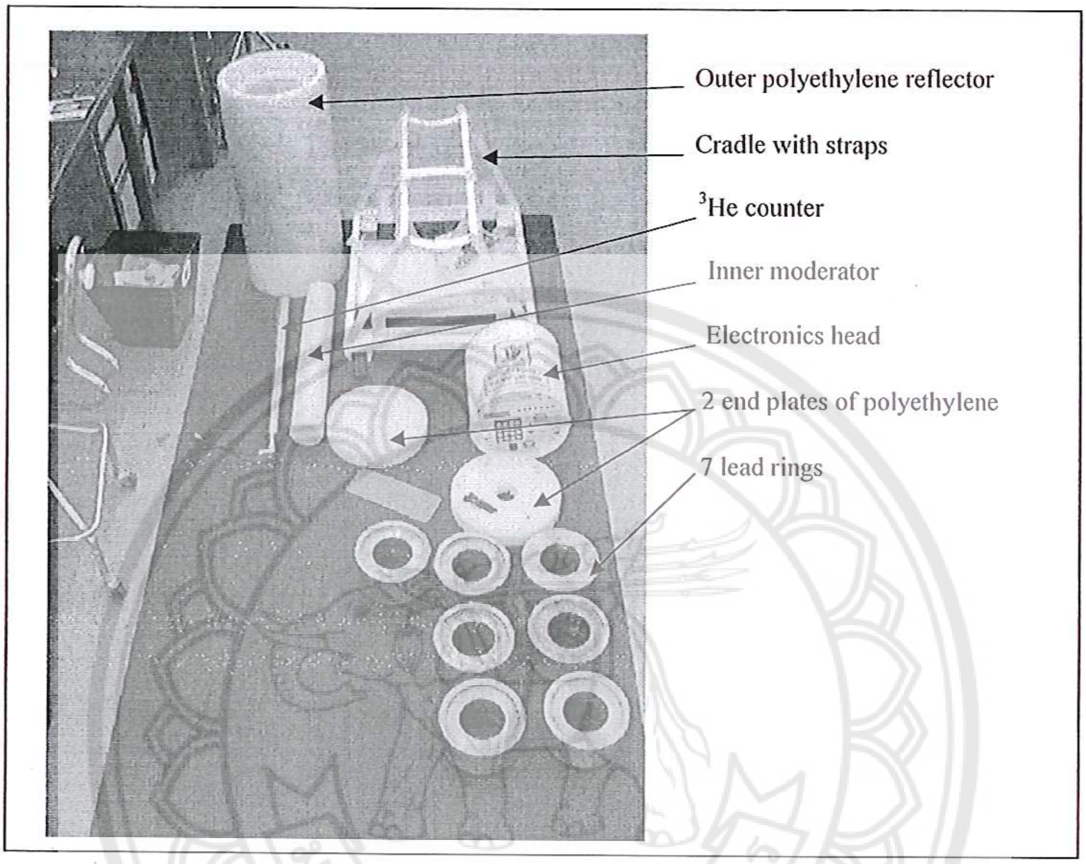

Figure 12 The separate components of a calibration neutron monitor

Source: H. Krüger, 2006

Specification of CALMON

The design of CALMON is described from the manual of the calibration neutron monitor by De Villiers (2003) for each component as:

1. The counter has the pressure 4 atm (3,040 mmHg) which is filled with ^{3}He gas inside the counter of the CALMON. The types of counter are the LND25382 (Figure 13). It has a length of 652 mm, or it is about 1/3 of the LND25373. The details of the LND25382 counter are shown in Table 2. Table 3 shows the electrical specifications of the LND25382 counter.

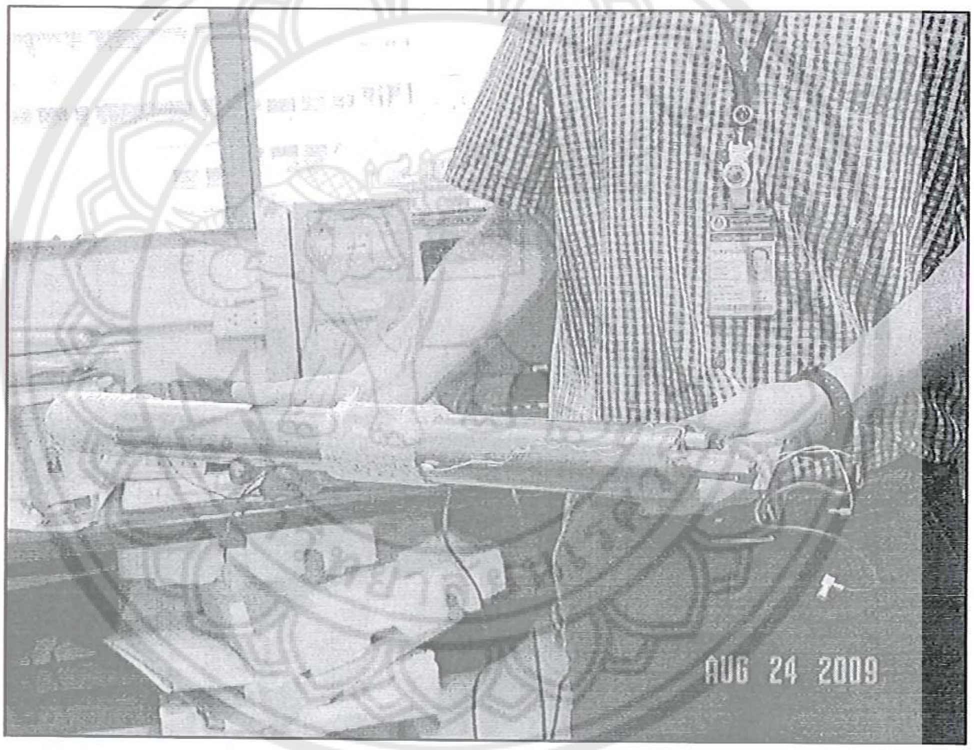

Figure 13 The neutron counter type LND25382 from the calibration monitor

Table 2 The specifications of neutron counter LND25382 type from LND, INC. (private communication)

Cathode material	Stainless Steel
Gas filling	^3He 97% + CO_2 3%
Gas pressure	4 atmospheres
Mass	1.5 kg
Connector type	HN
Pulse height	1 mV
Diameter	50.8 mm
Effective diameter	49.0 mm
Effective volume	1205 cm^3
Operating temperature range	-50 to +100 ^oC

Table 3 The electrical specifications of LND25382

Recommended operating voltage	1300 V
Operating voltage range	1200 – 1450 V
Maximum plateau slope	2% / 100 V
Maximum resolution	10% FWHM
Capacitance	8 pf

2. The Moderator for the calibration neutron monitor uses polyethylene $(CH_2)_n$ as the material, which was provided in Table 4. There is an air gap between the counter and the inner moderator.

Table 4 Moderator

Material	Polyethylene
Inner diameter	60.5 mm
Outer diameter	99.5 mm
Length	675 mm
Mass	3.0 kg
Density	0.95 mg/m^3
Melting point	405 K
Maximum service temperature	370 K
Minimum service temperature	210 K

3. The producers have 7 lead rings in the calibration neutron monitor for producing the number of neutrons. The details of producer is shown in Table 5.

Table 5 Producer

Material	7 lead rings
Inner diameter	101.0 mm
Outer diameter	193.0 mm
Length	653 mm
Mass	145.3 kg

4. The reflector is a polyethylene wrapped layer with specifications shown in Table 6. There are 2 end plates of polyethylene which has mass of 6 kg. The diameter of reflector's plates is 299 mm. The front plate of reflector has a hole for connecting counter and electronics head.

Table 6 Reflector

Material	Polyethylene
Inner diameter	194.0 mm
Outer diameter	350.0 mm
Length	753 mm
Mass	42.5 kg

5. The NWU electronics head can be connected to computer. It has a mass of 3 kg and is movable. The front electronic head is shown in Figure 14

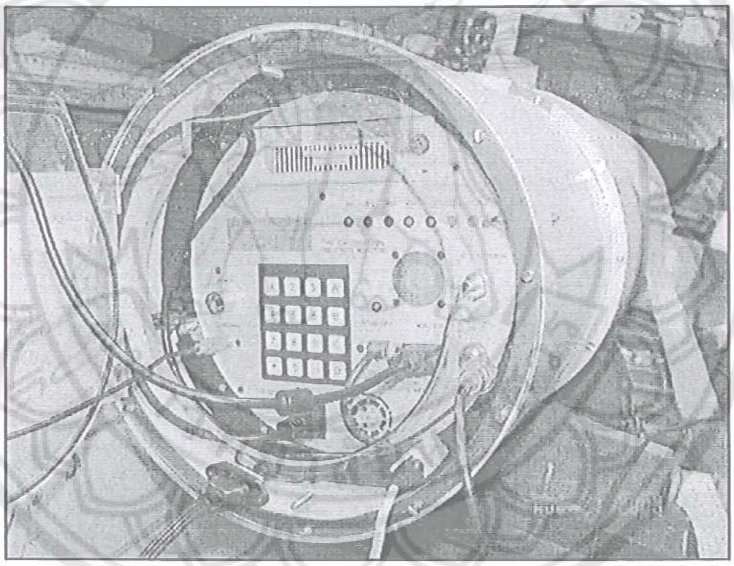

Figure 14 The front electronics head of the calibration neutron monitor

Calibration neutron monitor observations in Thailand

Thailand got the neutron monitor donation from Shinshu University (Japan) and supported by US National Science Foundation. We have kindness from HRH Princess Sirindhorn to construct neutron monitor station which was named "Princess Sirindorn Neutron Monitor Building" at Doi Inthanon, Chiangmai, latitude 18.59°N, longitude 98.49°E. The altitude is 2560 m above sea level and vertical geomagnetic cutoff rigidity is 16.8 GV. The average atmospheric pressure is 563 mmHg and the barometric coefficient is 0.83%/mmHg.

In 2009/2010, the calibration neutron monitor was set up in Thailand for calibration the Princess Sirindhorn of 18NM64 at Doi Inthanon. Because there are many neutron monitor station around the world so the calibration is necessary for analysis and comparison count rate of neutron monitor on the earth.

Krüger et al. described and compared the experiments performed in Potchestroom (South Africa) and the calibration neutron monitor from was installed outside the PSNM station. The calibrator at Doi Inthanon was set at 2 heights, at 140 cm and 70 cm, above surface and varied heights of water in the pool on concrete bunker. The experiment results are compared with the count rates of the Potchefstroom NM as shown in Figure 15.

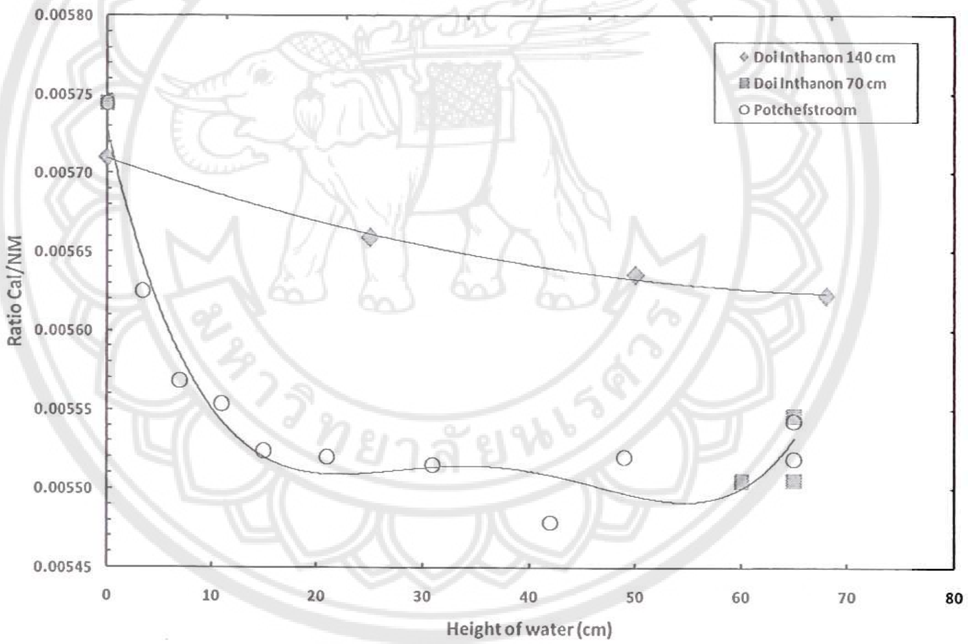

Figure 15 The ratio of calmon/NM at Doi Inthanon and the Potchefstroom as function of varying heights of water beneath the calibration neutron monitor.

Source: Krüger, et al., 2011

From Figure 15, we found that the count rate ratio of Potchefstroom decreases with an increase of water and the count rate leveled off at the water height about 30 cm. The decrease of the count rate as a result of water at 30 cm was about 4.0%.

From the experiment at Doi Inthanon, the count rate leveled off at the height of water about 70 cm for the calibration neutron monitor height of 140 cm. The decrease of the count rate was only 1.56%. When the calibration monitor height was set 70 cm, the count rate decreased 4.2% which correspond to the experiment of Potchefstroom.

The objectives of this research are create the calibration neutron monitor simulation at the Princess Sirindhorn Neutron Monitor station to study the responsed and interaction of cosmic rays in monitor and analyze the effect of environment on the count rate.