NEUTRON MONITOR DESIGN IMPROVEMENTS

PIETER H. STOKER[1], LEV I. DORMAN[2], and JOHN M. CLEM[3]
[1]*Space Research Unit, Potchefstroom University for CHE, Potchefstrom 2520, South Africa*
[2]*IZMIRAN, Moscow, Russia; Technicon, Haifa, Israel*
[3]*Bartol Research Foundation, Newark, USA*

(Received 1 July 1999; accepted 8 June 2000)

Abstract. The original design by J. A. Simpson of the neutron monitor enabled continuous monitoring of the primary cosmic-ray flux by ground-based recordings of the nucleonic component with only a rather simple correction for atmospheric effects. Simpson (1957) extended the original pile to the 12 counter IGY neutron monitor which was deployed in a world wide network during the International Geophysical Year 1957/8. The desirability for monitors with higher counting rates became evident soon afterwards. Subsequently the NM64 super neutron monitor was designed by H. Carmichael for deployment in time for the International Quiet Sun Year 1964. Using unusually large $^{10}BF_3$ proportional counters made at Chalk River, Hatton and Carmichael (1964) studied comprehensively the experimental design of the NM64. Consequently the efficiency of neutron counters to record evaporation neutrons produced in the lead of a monitor increased from 1.9% for the IGY to 5.7% for the NM64, an increase of 3.3 times the counting rate per unit area of lead producer. During the years much attention was given to the neutron multiplicity spectrum in neutron monitors. This spectrum is related to the energy spectrum of the nucleonic component incident on the neutron monitor, but is only weakly dependent on the spectrum of galactic cosmic rays at the top of the atmosphere. Contrary to galactic cosmic rays, solar flare protons and neutrons are observed predominantly as single counts per interaction, in multiplicity 1, because of the softness of solar flare particle energy spectra. Neutron monitors have also been specially designed to record solar neutrons with increased sensitivity. Newly developed ^{3}He counters with a largely reduced thermal neutron absorption mean free path should lead to improved efficiency in recording primary cosmic radiation. Design criteria are discussed.

1. Introduction

After the discovery of cosmic radiation in 1911 by V.F. Hess, variations in the radiation flux were observed in recordings by ionisation chambers. Investigations on these variations led to studies on the nature, origin, acceleration and propagation of cosmic radiation in the universe. The recording of intensity, spectrum, and composition with time, locality and direction proved to be a very suitable and effective means of probing the electromagnetic and plasma conditions of the heliosphere and the universe. More recently, detectors on satellite and spacecraft enabled recordings of cosmic radiation by species and their spectra to much lower energies than is possible within the atmosphere.

The interest of investigators was also in the nature of nuclear interactions induced by primary and secondary cosmic-ray particles in their propagation through

Space Science Reviews **93:** 361–380, 2000.

the atmosphere. This knowledge is important when designing a ground-based detector for monitoring the primary cosmic-ray flux. The ionisation chamber and meson monitor record respectively the ionising and hard components of secondary cosmic rays. These counting rates are to be corrected for variations in atmospheric pressure and production heights in the atmosphere. After the discovery of Simpson (1948) that the latitude variation of the intensity of evaporation neutrons in the atmosphere is several times larger than that of either the ionising or the hard component, the neutron monitor was developed as a continuous recorder of the cosmic-ray primary intensity.

Atmospheric evaporation neutrons may be recorded either by slow neutron detection using a bare $^{10}BF_3$ proportional counter or by fast neutron detection using a $^{10}BF_3$ counter surrounded by a local moderating medium like paraffin wax. Both these detectors are unsuitable for continuous monitoring because of their sensitivities to external climatic conditions and ambient neutron production. Subsequent to a detector, the neutron monitor was developed to record evaporation neutrons produced by interactions in a target or ‘producer’ of high atomic mass inside the monitor (Simpson *et al.*, 1953). The producer-counter assembly has to be shielded by sufficient thickness of moderator against variable neutron production and moderating effects outside the assembly.

The neutron monitor records predominantly energetic nuclear active particles like protons and neutrons, secondary to the primary cosmic-ray particles. Only a small fraction of the counting rate is due to radioactive secondaries like pions and muons (see Hatton, 1971), the intensities of which depend on the production heights in the atmosphere, that is on ambient atmospheric temperatures. Consequently, the counting rate of a neutron monitor proved to be directly related to the primary cosmic-ray flux after a rather simple correction for the local atmospheric pressure. On the other hand, the counting rates of ionisation chambers and muon monitors depend also on the height of atmospheric pressure levels, subjected to atmospheric temperature variations.

Neutron monitors proved to be superior in short and long-term recordings of primary cosmic rays of energies above $\sim$1 GeV because of their long-term stability and their essential insensitivity to atmospheric variations after pressure correction. In this paper improvements to the design of neutron monitors are considered related to efficiency of recordings on both galactic cosmic rays and solar flare protons and neutrons.

2. The Neutron Monitor

The introduction of the neutron monitor (NM) as a continuous recorder of the primary cosmic-ray intensity resulted from the design by Simpson *et al.* (1953) of a neutron monitor pile (Figure 1) for experimental purposes. Their results motivated the design of a 12 tube neutron monitor (Figure 2) (Simpson, 1957) for

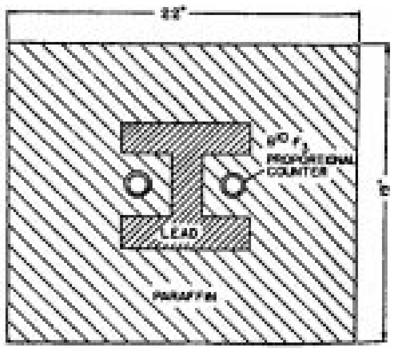

Figure 1. The ‘standard’ neutron monitor pile (Simpson *et al.*, 1953).

world-wide use during the IGY (International Geophysical Year, 1957/8). This IGY neutron monitor quickly became recognized as a superb detector to study primary cosmic-ray variations. World-wide display of the IGY monitor enabled recordings at stations with different cut-off rigidities and asymptotic viewing directions, facilitating studies in primary cosmic-ray spectral variations.

However, it became evident soon that better statistical accuracy was required, in particular for studies of short-term events. Hughes (1961) found for the Leeds IGY neutron monitor that only 1.9% of the neutrons, produced in the lead, were recorded. The efficiency of the neutron monitor to record cosmic radiation will improve if, first of all, the efficiency of the IGY neutron counters to record thermal neutrons is improved. The detector used in the neutron monitor was the boron trifluoride proportional counter, enriched in the 10-boron isotope.

In 1959 the successful construction of large size $^{10}BF_3$ proportional counters at the Chalk River Nuclear Laboratories for the neutron monitor in the Deep River cosmic-ray station led to the design and construction of the super neutron monitor, the NM64 (Figure 3), in time for the International Quiet Sun Year (IQSY) 1965 (Carmichael, 1968). The advantage of the higher counting rate of this super neutron monitor was very striking, as was reported by Steljes and Carmichael (1961) on the solar cosmic-ray events of July, 1961.

Hatton and Carmichael (1964) carried out a long series of measurements in 1960, in order to determine an optimum design for a neutron monitor of very much larger size than the IGY neutron monitor. They used different geometrical arrangements and thicknesses of lead and paraffin wax, and subsequently polyethy-lene instead of paraffin wax, as modera- tors around the big counters and as reflectors and shields encasing a set of three counters. The result was that the counting rate of the NM64 neutron mon- itor per unit area of the lead producer, was nearly 3.3 times that of the IGY NM. This improved efficiency was mainly due to the use of substantially larger counters, whereby the efficiency of the ^{10}B isotope to absorb thermal neutrons in competition with other absorbing materials, principally the ^{1}H in the moderator, was increased on account of the geometrical design.

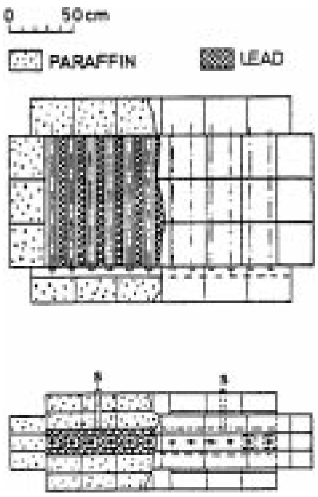

Figure 2. The pile extended to 12 counters, the IGY NM (Simpson, 1957).

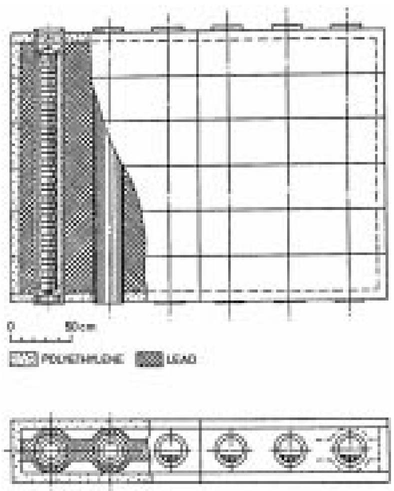

Figure 3. The 6NM64 super neutron monitor (Carmichael, 1968).

An increase in the efficiency of a neutron monitor will in general increase both the number of events recorded and the average number of neutrons detected per event. Hatton and Carmichael (1964) estimated the overall efficiency of the 6-counter NM64 to detect a neutron that is produced in the lead producer, as $(5.7 \pm 0.6)\%$, which was a marked improvement on the $(1.9 \pm 0.3)\%$ efficiency of the IGY neutron monitor (Hughes, 1961). This increase in efficiency is consistent with the above-mentioned value of 3.3 for the ratio of counting rates of the NM64 and IGY neutron monitors per unit area of lead producer.

Although there are significant differences in dimensions between the IGY and NM64 configurations, as shown in Table I, the components used are basically the

TABLE I
Dimensions of 6NM64 and standard IGY neutron monitors.

	6NM64	Standard IGY
Type of counter	BP28	NW G-15-34A
Number of counters	6	12
Spacing of counters (cm)	50.0	15.2
Moderator material	Polyethylene	Paraffin
Average moderator thickness (g/cm^2)	1.84	2.95
Producer material	Lead	Lead
Average producer thickness (g/cm^2)	156	153
Projected top area of producer (cm^2)	6.21×10^4	1.9×10^4
Reflector material	Polyethylene	Paraffin
Average reflector thickness (g/cm^2)	7.0	25.8

same. The average depths of the lead producers around the neutron counters are about the same, *viz.* 153 g cm^{-2} for the IGY and 156 g cm^{-2} for the lead rings of the NM64. This average depth is roughly 80% of a single nuclear interaction pathlength for relativistic nuclei in lead.

Instead of placing the lead rings of the NM64 touching, Hatton and Carmichael (1964) put about 14 cm of lead blocks in between in order that the distance between, the BP28 counters increased from 36 to 50 cm. The event rate increased then by 1.14 per counter, while the mass of the lead increased by 1.46. Hatton and Carmichael (1964:2425) made the remark that ‘at sites where building space and lead are expensive, it might be expedient to install a monitor using lead rings in contact’. The lead blocks in between the rings were given a depth of 16 cm (181 g cm^{-2}) compared to the average depth of the lead rings of 13.7 cm (156 g cm^{-2}). The overall depth of the lead, including the lead blocks in between, is then 14.4 cm (163 g cm^{-2}).

Whereas the IGY monitor uses paraffin as moderator and reflector material, the NM64 uses polyethylene, which is structurally stronger, but has a slightly lower hydrogen content per unit volume. The reflector thickness is 30 cm of paraffin wax (25.8 g cm^{-2}) in the IGY and 7.5 cm polyethylene (7.0 g cm^{-}2) in the NM64.

This small reflector thickness of 7.5 cm makes the NM64 more susceptible to environmentally produced neutrons than the 30 cm reflector thickness of the IGY neutron monitor. The thick curve in Figure 4 shows the percent of counting rate of the 2NM64 without lead, relative to a normal 2NM64 with lead, as a function of reflector thickness (Hatton and Carmichael, 1964). Note that according to the steep curve, about 5% of the normal counting rate is due to neutrons produced locally outside a neutron monitor with a reflector thickness of 7.5 cm.

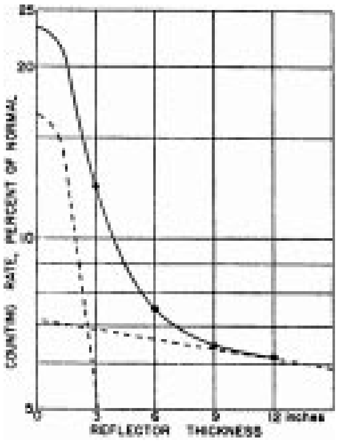

Figure 4. Variation of the counting rate of a 2NM64 with no lead producer inside with change of the thickness of the reflector, relative to the counting rate of the standard 2NM64 (Hatton and Carmichael, 1964). The steeply and slowly declining broken curves depict the contributions from neutrons produced externally and in the moderating material, respectively.

TABLE II

NM response function parameters from Aleksanyan *et al.*, 1985).

	Neutron Monitor Multiplicity					
	Total	m=1	m=2	m=3	m=4	m=5
α_m	8.32	7.16	10.26	13.48	20.30	42.83
κ_m	0.87	0.81	0.95	0.98	1.06	1.29
$R_{\max}$ [GV]	4.76	4.21	5.43	6.96	9.15	11.77

3. The Multiplicity Spectrum

An important characteristic of a neutron monitor is the number of evaporation neutrons generated by each energetic hadron, mostly a neutron or proton, in the neutron producing heavy material of the neutron monitor, which is usually lead. Only a small percentage of these neutrons are recorded (1.9 and 5.7% for IGY and NM64, respectively). Hughes and Marsden (1966) showed experimentally that the number of neutrons recorded per production event, the multiplicity, increases monotonically with incident neutron and proton energy. They expected from their experimental results that time variations in the rates of detected multiplicities would reflect variations in the primary cosmic-ray energy spectra at energies up to the order of 200 GeV.

The interpretation of variations in the multiplicity spectrum observed deep in the atmosphere in terms of primary variations (Dorman, 1974) requires both a knowledge of the response of the monitor as a function of the energy of secondary particles incident upon it and an understanding of the atmospheric cascade processes. Debrunner and Flückiger (1971a, b) calculated multiplicity response functions respectively for the IGY and NM64 neutron monitors at Jungfraujoch and at sea level, both for vertically incident and inclined primary cosmic-ray protons. These theoretical results were found to be in good agreement with multiplicity response functions obtained from latitude surveys with the NM64 monitor.

Aleksanyan *et al.* (1985) determined response functions for different multiplicities as recorded by a 2NM64 neutron monitor during a North Atlantic latitude survey from 6 to 22 April, 1982. They approximated the latitude dependence by the Dorman (1970) response function $N_t = N_0 \left[1 - \exp\left(-\alpha P_c^{-\kappa}\right)\right]$ and found for the coefficients α and κ the values listed in Table II. R_{max} in the bottom row denotes the rigidity P at which the differential response function dN_t/dP obtains a maximum. Note that the maximum of the differential response function shifts to higher rigidities as the multiplicity m increases. Changes in recorded multiplicity spectra of standard neutron monitors are used to interpret variations in the primary cosmic-ray rigidity spectrum, usually during Forbush decreases (see for instance Iucci *et al.*, 1971.)

4. Specially Designed Multiplicity Neutron Monitors

Both Nobles *et al.* (1969a) and Arvela *et al.* (1982) developed special neutron multiplicity monitors having increased efficiencies for multiplicity recording. The geometries were changed considerably from that of the standard monitors. The producer of the Lockheed neutron multiplicity monitor (Nobles *et al.*, 1969a) was bismuth (see Figure 5) with an average thickness of ~450 g cm^2 compared to ~150 g cm^2 of lead in standard monitors. This greater thickness results in a greater probability that the secondary cosmic-ray particle will loose its energy and being totally absorbed. Furthermore, the 26 $^{10}BF_3$ counters surrounding the producer were embedded in a moderator of reactor grade graphite. Bismuth and graphite were chosen instead of the usual lead and paraffin or polyethylene because of their lower thermal neutron capture cross-sections.

The average evaporation neutron detection efficiency of the Lockheed monitor was found to be 16.5%. This is a factor ~3 better than the NM64, but the average observed multiplicity at sea level was only 1.54 compared to 1.42 of the NM64. Assuming the correctness of the average neutron detection efficiency of 16.5%, Hatton (1971) attributed the surprisingly low average multiplicity to a high production rate of neutrons in the graphite moderator. Graphite has a larger cross-section for neutron production than paraffin or polyethylene. The 740 kg graphite in the Lockheed monitor acted as a producer of neutrons in equal area to that of the 810 kg of bismuth producer. Interactions with carbon will give rise to a lower average produced multiplicity than bismuth. Furthermore, the number of stopping and interacting muons per unit area increases almost linearly with producer thick-

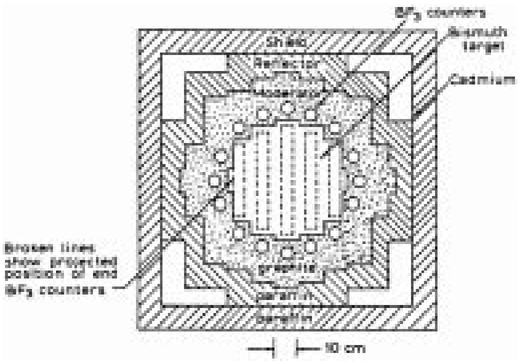

Figure 5. Diagram of the Lockheed neutron multiplicity monitor on White Mountain in vertical cross section (Nobles *et al.*, 1969a).

ness and, thus, muon interactions will be a factor $\sim$3 larger than in standard NMs. On the other hand, neutron production from nucleon interactions increases only by a factor $\sim$2 (Hatton, 1971). Thus the relative muon contribution in the Lockheed monitor was $\sim$1.5 larger than that in the standard NMs.

Differential response functions for multiplicities up to 10 and above were obtained by Nobles *et al.* (1969b) from latitude surveys with the special neutron multiplicity Lockheed monitor. The differential response functions for the altitude of 3,800 meter at White Mountain show that the maxima shift to higher rigidities of the primary cosmic rays with increasing multiplicities. This shift to higher rigidities is also prominent in the differential response functions at sea level, determined by (Lumme *et al.*, 1983a) from Monte Carlo calculations of hadron cascades in the atmosphere and inside the Turku double neutron monitor.

The equatorial cut-off of 15.5 GV prevents full exploitation of the multiplicity latitude distributions at higher rigidities. Nobles *et al.* (1969b) extrapolated the response functions above this cut-off linearly as a function of the logarithm of rigidity.

The Turku double neutron monitor (Arvela *et al.*, 1982) consisted of two neutron monitors, one above the other, with a thick layer of moderating material in between to ensure two independent measurements of multiplicity. The total thickness of lead of each monitor was 271 g cm^{-2} instead of the 156 g cm^{-2} of the standard monitor. With $^{10}BF_3$ counters above and below the lead layer, the average neutron detection efficiency was 12.5%. This double neutron monitor was designed as a sea level hadron energy spectrum recorder from 100 MeV to 1000 MeV.

The recordings of these special multiplicity monitors were used to interpret variations in the primary cosmic-ray rigidity spectrum during Forbush decreases by Nobles *et al.* (1969b) and Lumme *et al.* (1983b).

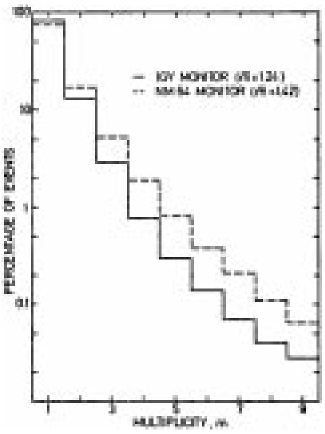

Figure 6. The recorded multiplicity spectrum for high latitude IGY and NM64 monitors at sea level (Hatton, 1971).

5. Response of Neutron Monitors to Solar Flare Protons and Neutrons

Secondary nucleons with a typical energy of 200 MeV produce on the average ~10 evaporation neutrons when they interact inside the monitor (Hatton, 1971). Because of the low efficiency for detecting evaporation neutrons in both the IGY and NM64 monitors (1.9% and 5.7%, respectively), the average detected multiplicities are not much greater than unity, *viz.* 1.24 and 1.42, respectively. In Figure 6 the recorded multiplicity spectra of the IGY and NM64 monitors at sea level and high latitude are shown (Hatton, 1971).

The flatter distribution of the NM64 means that relatively less multiple (*i.e.* >1) neutrons are recorded in multiplicity 1 channel due to the larger neutron detection efficiency of the NM64 than the IGY monitor. This means also that the NM64 counting rate in a multicity 1 channel contains a larger fraction of the low energy events producing mostly only single neutrons relative to events of higher multiplicity than the IGY monitor. Since differential solar flare proton spectra are much softer than the differential galactic cosmic-ray spectrum and have also an upper energy cut-off, the production rate of single neutrons relative to multiple neutrons will be larger for solar protons than for galactic cosmic-rays. This means also that solar protons events will cause a relatively larger enhancement in the total counting rate if the efficiency of the monitor is increased.

Iucci *et al.* (1987) used a 3NM64 with improved efficiency to detect solar neutron events. They put additional Chalk River BP28 neutron counters above and below the shoulders of the lead rings. The efficiency of an experimental 2NM64 to record neutrons produced in the lead was found to increase from 1.4 to 1.8 neutrons per event. The counting rate increased substantially and the recorded multiplicity spectrum was closer to the multiple neutron production spectrum. Furthermore,

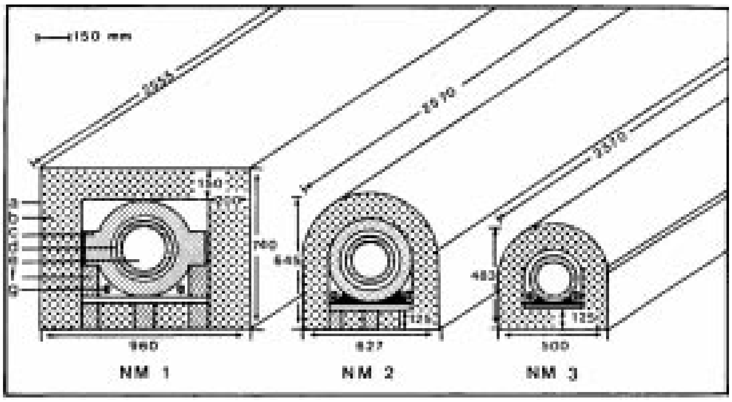

Figure 7. The three detectors with front covers removed, used by Stoker *et al.* (1980) on the sea level surveys in 1976. (a: 5-mm aluminium box; b: paraffin wax; c: lead; d: polyethylene moderator; e: BP28 counter; f: wooden support; and g: heater tube).

the neutron diffusion time was reduced because the air spaces above and below the shoulders of the lead rings were taken up by additional neutron counters.

On the assumption that a solar neutron event will record only in the multiplicity 1 channel, Iucci *et al.* (1987) showed that a threefold increase in efficiency to record neutrons produced in the lead, will result in more than a twofold increase in the fractional enhancement of the total counting rate. They designed also a special neutron monitor with a lead producer surrounded by Chalk River BP28 counters. By choosing the average thicknesses of the lead producer and polyethylene reflector the same as those of a NM64, they envisaged that the response function of the total counting rate to primary cosmic rays will be similar to that of the NM64.

Analyses of neutron monitor observations of solar neutron events require an accurate knowledge of the response of ground-based detectors to the impact of a beam of neutrons upon the Earth's atmosphere. Debrunner *et al.* (1983, 1989) evaluate the sensitivities both of the IGY neutron monitor at Jungfraujoch and of a 6NM64 at sea-level to solar neutrons with kinetic energies 100 MeV$\leq E_n \leq$10 GeV. A Monte Carlo program was used to simulate the development of the nucleonic cascade in the atmosphere for energies $E > \sim$10 MeV.

Muraki *et al.* (1995) constructed a new solar neutron telescope with an area of 64 m^2 on Mt. Norikura with directional sensitivity. The telescope was designed to measure the total track length of protons produced in plastic scintillators by n-p collisions. The detection efficiency of a 1 m^2 prototype telescope was found to be $\sim$25% for neutrons between 50 and 360 MeV, using neutron beams from an accelerator (Matsubara *et al.*, 1995).

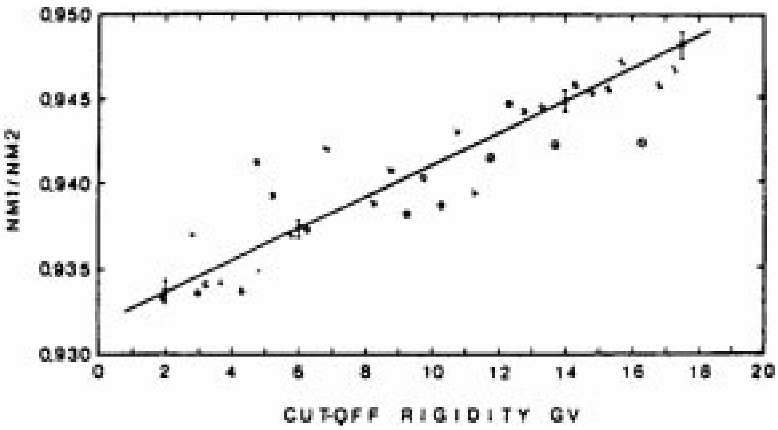

Figure 8. The ratio of counting rates of NM1 and NM2 (Potgieter *et al.*, 1980).

6. NM64 Neutron Monitors With Different Lead Configurations and Without Lead

Figure 7 illustrates the three types of neutron monitors used by Stoker *et al.* (1980) on sea-level latitude surveys during the 1976 solar minimum period. The NM1 is an 1NM64 super neutron monitor, the NM2 is a super neutron monitor with cylindrical lead rings without shoulders, while the NM3 is a BP28 Chalk River counter within the moderating polyethylene cylinder, surrounded by 12.5 cm paraffin wax, but without lead.

The total mass of the shoulderless lead rings of the NM2 was made equal to the total mass of the lead rings with shoulders of the 1NM64 by increasing the outer ring diameter from the standard 35.6 cm to 37.8 cm, with the inner diameter unaltered at 25.4 cm. The average depth of the shoulderless lead rings of the NM2 was 185 g cm^{-2} compared to the 163 g cm^{-2} of the lead rings with shoulders in the 1NM64. The upper half of the paraffin wax reflector of the NM2 was semi-cylindrical, with an overall thickness of 12.5 cm, as indicated in Figure 7.

Figure 8 shows that the NM2 has a higher counting rate at all cut-off rigidities for the same total mass of lead as the 1NM64, and is more sensitive to primary particles in particular at low rigidities $\sim$2 GV (Potgieter *et al.*, 1980). These experimental results and response functions have been simulated by a three-dimensional Monte Carlo Program to calculate the cosmic-ray nucleon spectra at sea-level and the yield function for the fundamental structure of each NM (Raubenheimer *et al.*, 1980).

Bare $^{10}BF_3$ counters, with no lead and no moderating polyethylene cylinders, record thermalized low energy neutrons produced in nearby matter and atmosphere by cosmic rays and from local neutron-emitting radioactive sources. Dorman *et al.* (1999) found on a sea level latitude survey a stronger latitude dependence for the bare counter than the NM64. Simpson and Uretz (1949) and Mischke *et al.* (1973)

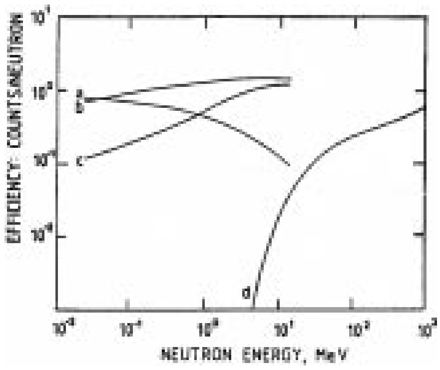

Figure 9. Curves a, b and c depict the sensitivities of neutron counters surrounded by paraffin wax of thicknesses 1.25, 7.5 and 12.5 cm, respectively, as a function of neutron energy (Hess *et al.*, 1959), and curve d of a NM64 neutron monitor (Hatton, 1971).

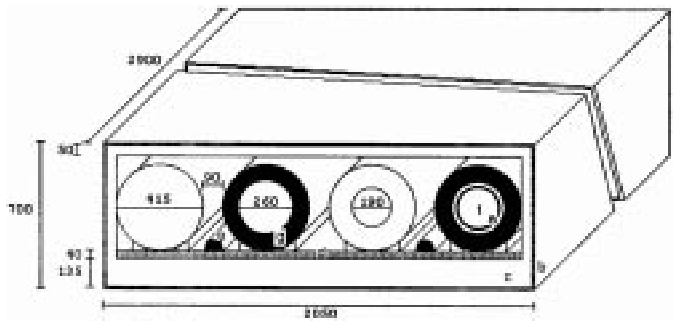

Figure 10. The 4NMD (neutron moderated detector), consisting of 4 NM3's, at Sanae, Antarctica. (a: polyethylene; b: aluminium container; c: paraffin wax; d: wooden support; e: heater; f: BP28 counter; g: wax cylinder)

found during aircraft surveys that bare and paraffin wax enclosed neutron counters have the same latitude and altitude dependencies. This result may have been expected if they all record evaporation neutrons produced in atmospheric nuclei. Figure 9 summarizes experimental results obtained for the sensitivities of neutron counters surrounded by paraffin wax of various thicknesses (Hess *et al.*, 1959) and of the NM64 neutron counter (Hatton, 1971) to neutrons of different energies.

The response function of the NM3 shows a much larger sensitive to low rigidity primary cosmic-rays from ∼2 to ∼8 GV than the 1NM64 (Potgieter *et al.*, 1980). This difference in sensitivities was utilized by operating a 4NMD (Neutron Moderated Detector), consisting of 4 of the NM3 neutron monitors in an aluminium container (see Figure 10), together with a 3NM64 neutron monitor at the South African Antarctic Base, Sanae.

The solid lines in Figure 11 display the specific yield functions for the NM64 and NMD. Stoker (1981) calculated specific yield functions from the response functions of the 1NM64 and NM3 obtained from the 1976 latitude survey and

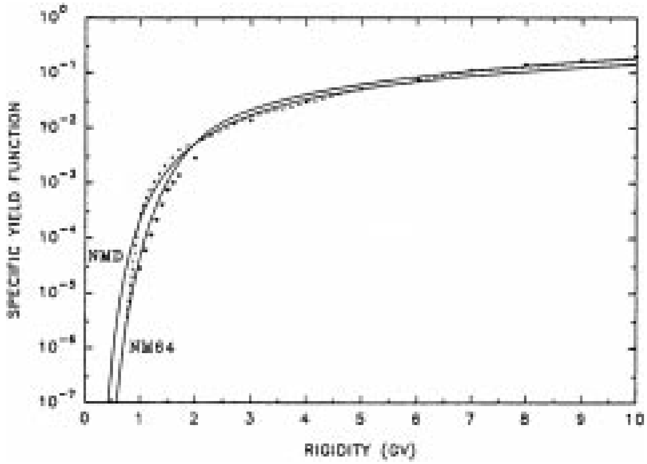

Figure 11. The specific yield functions found for the 3NM64 and 4NMD (Stoker, 1981). The broken line represents the Lockwood *et al.* (1974) and the solid triangles the revised values of Debrunner *et al.* (1982) of specific yield function for a NM64.

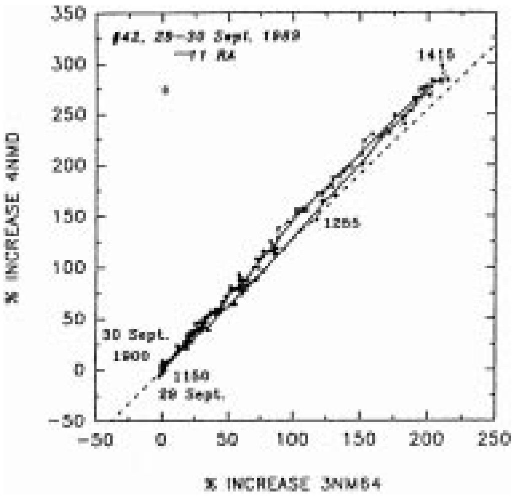

Figure 12. Relative enhancements in 5 minute counting rates of the 4NMD and 3NM64 at Sanae, plotted for the 29 Sept., 1989 ground level event. The gradients of the two straight lines are 1.23 from 1155 to 12:55 UT, and 1.37 from 14:15 UT to the end of the event (Stoker, 1994).

extrapolated the 1NM64 specific yield function to rigidities below 2 GV according to the function of Lockwood *et al.* (1974). The broken line represents Lockwood *et al.*'s specific yield function. The solid triangles are the revised values of Debrunner *et al.* (1982) which have been derived from a Monte Carlo simulation of the nucleonic cascade in the atmosphere. It appears that the NM64 specific yield function follows closely the simulation of Debrunner *et al.* (1982) at low rigidities.

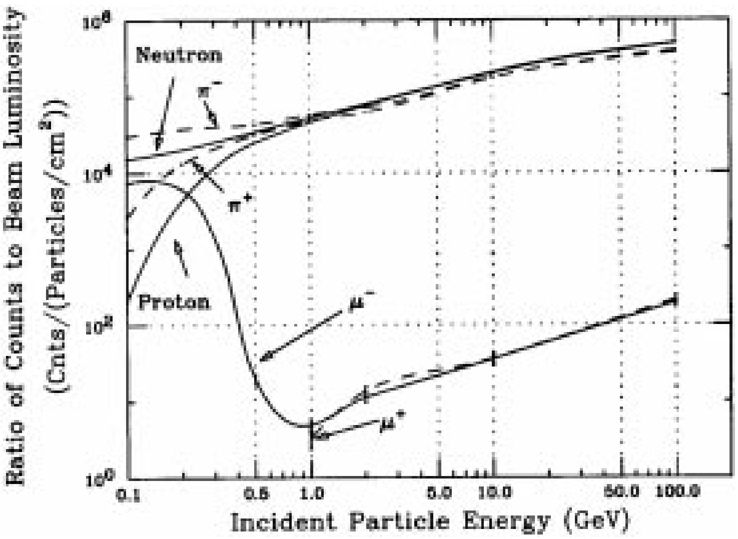

Figure 13. BP28 NM64 calculated (Clem, 1999) detection efficiency of secondary particles arriving in the vertical direction.

From relative enhancements in counting rates of the 4NMD and the 3NM64 during a solar proton flare recorded at Sanae, Antarctica, the spectral index of solar flare protons with rigidity >1 GV was derived (Stoker, 1994), using the specific yield functions of the two detectors displayed in Figure 11. Changes in spectral index during an event follow from changes in gradient of the relative counting rate enhancements. This is illustrated in Figure 12, when there was a change in gradient at 12:55 UT during the solar proton flare event of 29 September 1989.

Also the bare counter has a larger latitude dependence than the NM64 monitor (Dorman *et al.*, 1999). When the counting rates of both the bare counter and the NMD are due to evaporation neutrons produced in the atmosphere, the specific yield functions of the two detectors should be the same.

7. The Helium-3 Counter

A proportional counter tube filled with ^{3}He gas responds to neutrons by the exothermic reaction ^{3}He(n,p)^{3}H, whereas the BP28 responds to neutrons by ^{10}B(n,α)^{7}Li. The Q-values of the ^{3}He and ^{10}B neutron reactions are 765 keV and 2.791 MeV, respectively. In 94% of the ^{10}B(n,α)^{7}Li reactions the ^{7}Li is left in an excited state of 480 keV, with an energy of 2.31 MeV imparted to the recoil particles, the ^{4}He and ^{7}Li nuclei.

Angle dependent neutron monitor detection response to cosmic-ray secondary particles at ground level was calculated by Clem (1999), using a 3-dimensional particle transport package combined with simulations of the ^{3}He and ^{10}BF$_3$ proportional counters and electronics response to energy deposition in the gas. The standard dimensions and composition of materials of a IGY and a NM64 were used as input geometry.

Figure 13 displays the resulting detection efficiency of a NM64 with $^{10}BF_3$ counters for vertically incident particle species. There is practically no difference in the response between neutrons and protons at high energies. At lower energies the ionisation energy loss of protons becomes significant and the probability of a nuclear interaction is greatly reduced. Consequently, the detection efficiency decreases also. It appears that the neutron monitor response for muons above 1 GeV is roughly 3.5 orders of magnitude below that for the hadrons. Below 1 GeV stopping negative muons are captured and absorbed by the lead nucleus. The de-excitation of the lead nucleus occurs with the emission of neutrons which is reflected in the rise in detection efficiency with decreasing muon energy.

In Figure 14 Clem (1999) compared his simulated results with Hatton's (1971) calculations and NM64 accelerator data (Shibata *et al.*, 1997). The calculated detection efficiencies as functions of incident proton and neutron energies show that the IGY has a different response in both magnitude and shape than the NM64. It appears that the thicker reflector of the IGY is much more efficient in preventing low energy neutrons from entering the detector region than the NM64.

Using the general design envelope of commercially available ^{3}He neutron detectors, Clem (1999, see also Clem and Dorman, 2000) did simulations to produce a design that closely simulates the performance of the $^{10}BF_3$ BP28 detector. These units are now commercially available as model LND25373 from LND, Inc, USA.

Pyle *et al.* (1999) replaced one of the 3NM64 counters with this ^{3}He detector on the last part of their 1998/9 latitude survey, from Hawaii to McMurdo and then to Seattle. They concluded that the energy response of this detector is nearly identical to that of the 10BF3 BP28 detector, and that these 3He detectors can be used in a standard NM64. This conclusion is supported when variations in cosmic-rays, recorded by ^{3}He PD631 counters (see Table III) placed above the shoulders of the lead rings in the 18NM64 neutron monitor at Alma Alta, were compared with simultaneous recordings by the BP28 counters (V. G. Yanke, 1999, personal communication). The variations followed each other very narrowly.

Up to recently ^{3}He counters were not used in neutron monitors because of the relatively high cost of the gas. Currently the cost is comparable with that of the $^{10}BF_3$ gas. ^{3}He gas counters can perform at much higher pressures and can attain, therefore, a much larger detection efficiency per unit volume. Because of the lower atomic number, the stopping power for the recoil particles are smaller. Consequently a large pressure is needed and small quantities of heavier gas may be added to ensure that the recoil particles will dissipate most of their energies in the ^{3}He gas.

The reaction cross-sections for both the nuclei ^{3}He and ^{10}B are inversely proportional to the neutron velocity. At thermal energy the cross-sections for these reactions are roughly 5330 and 3840 barns, respectively. With this higher ^{3}He

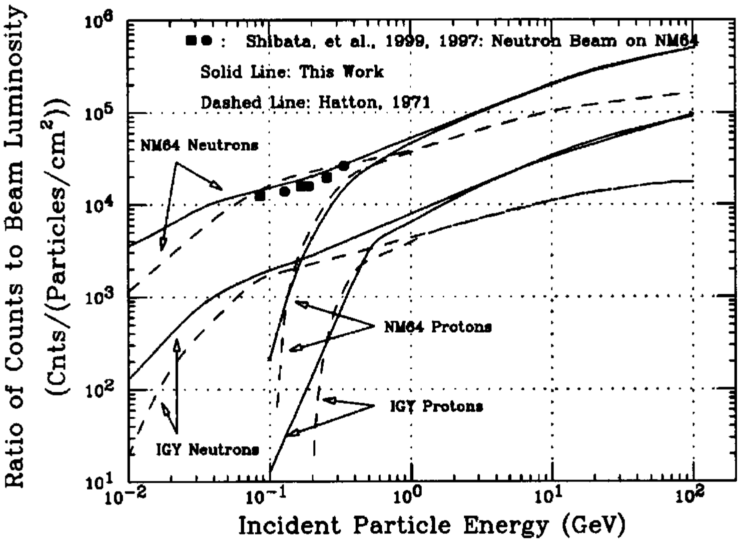

Figure 14. Comparison of the NM64 and IGY neutron monitors detection efficiencies for secondary protons and neutrons with data and calculations by Clem (1999).

TABLE III
Neutron counters used in NM64 and IGY neutron monitors.

	BP28	NW G-15-34A	LND25373	PPD631
Effective diameter (cm)	14.8	3.8	4.8	3.0
Effective length (cm)	191	87	191	102
Gas type	$^{10}BF_3$	$^{10}BF_3$	97% ^3He + 3%CO_2	^3He
Pressure (mm Hg)	200	450	3040	6080
Absorption path length (of thermal neutrons)	41.0	18.2	1.9	0.95 (cm)

cross-section and the much larger gas pressure, the absorption mean free path of a thermal neutron decreases from 41.0 cm in the BP28 to 1.9 cm in the LND25373 and 0.95 cm in the PD631.

When comparing the calculated detection efficiency of a NM64 with BF3 BP28 counters to a NM64 with ^{3}He LND25373 counters for incident protons and neutrons up to 100 GeV (Clem, 1999), there appears to be very little difference between the two monitors down to low incident particle energies. The ^{3}He NM64 response appears to be slightly higher than that of the BP28 NM64.

8. Conclusive Remarks on Design Criteria of Neutron Monitors

The following criteria have to be considered in the design of a neutron monitor in order to study variations in primary cosmic-ray spectra, both of galactic and solar origin:

1. Large counting rate of $\geq 10^6$ per hour for stationary neutron monitors, with a standard deviation of $\sim$0.1% or better. This criterion requires barometric pressure recording accurate to $\sim$0.1 millibar on long term.
2. An accurate total yield function for the full galactic cosmic-ray spectrum to the highest rigidities, that contribute to the counting rate, is required. (The total yield function of a neutron monitor at a particular atmospheric depth is defined as the differential response function $dN/dP(P,t)\ /\ j_g(P,t)$, the galactic differential rigidity spectrum of particles of rigidity P incident on the top of the atmosphere at time t).
3. Because of the small contribution of $\sim$5% of muons to the total counting rate at sea level, effects of changes in atmospheric temperatures to the counting rates may be neglected.
4. In a standard NM64 incident hadrons of energy above 1 GeV produce a count average per incident hadron greater than 1. Hadrons with energy less than 1 GeV would be favoured in the total count rate in particular if a high efficiency of recording evaporation neutrons is attained.
5. Differential solar flare proton and neutron spectra are much steeper (*i.e.* softer, exponent ~ -5) than galactic energy spectra at energies $>\sim$1 GeV and requires, therefore, for analysis of neutron monitor recordings, accurate specific yield functions at rigidities $<\sim$1 GV (whereas 1 GeV $\approx$ 0.35 GV).
6. Solar flare protons produce at sea level mostly single evaporation neutrons in the lead of a neutron monitor because of the steepness (softness) and an upper cut-off in the solar proton flare spectra. Improved neutron monitor detection efficiency will yield a relatively larger enhancement in the total counting rate. However, the increase of the recording efficiency of a neutron monitor will change the standard response function to primary cosmic-rays.
7. Improved efficiency in detecting solar flare neutrons is realized by reducing the path length of solar flare neutrons through the atmosphere. This is obtained by deploying neutron monitors in equatorial regions at high elevations. At these elevations the spectrum of particles incident on a neutron monitor and, hence, the recorded multiplicity spectrum, will be different than at sea level.
8. ^{3}He counters have been developed to perform similarly in a standard neutron monitor than do $^{10}BF_3$ counters. With these currently affordable ^{3}He counters new stations may be constructed to extend the world wide neutron monitor network for better global coverage (Bieber and Evenson, 1995).
9. Advantage may be taken of the short absorption neutron mean free path of ^{3}He counters by increasing the efficiency of a standard neutron monitor for detecting solar flare proton and neutron events.

10. In any new design of a neutron monitor the importance to continue the existing long-time neutron monitor data base must be taken into consideration.
11. When operating a mobile neutron monitor, screening against environmentally produced neutrons are important because of a varying environment. Additional screening on the sides and bottom of a NM64 by about 12.5 cm of paraffin wax or polyethylene, added to the 7.5 cm polyethylene reflector, should be considered seriously. The 7.5 cm polyethylene on the top should be left open. Given that the maximum number of cosmic-ray secondary neutrons is incident at an angle of 30° off zenith at sea level is, it is anticipated that additional screening on the sides and bottom, leaving the top reflector clear, will not affect the differential response of the NM64.

References

Aleksanyan, T. M., Dorman, L. I., Yanke, V. G. and Korotkov, V. K.: 1985, 'Coupling Functions for Lead and Lead-free Neutron Monitors From the Latitude Measurements Performed in 1982 in the Research Station "Academician Kurchatov"', *Proc. 19th Int. Cosmic Ray Conf. (La Jolla)* **5**, 300–303.

Arvela, H., Torsti, J. J., and Valtonen, E.: 1982, 'A Double Neutron Monitor Applied to Cosmic-ray Multiplicity Studies', *Nucl. Instr. Method* **192**, 467–474.

Bieber, J. W. and Evenson, P.: 1995, 'Spaceship Earth - An Optimized Network of Neutron Monitors', *Proc. 24th Int. Cosmic Ray Conf., Rome* **4**, 1316–1319.

Carmichael, H.: 1968, in C. M. Minnis (ed.), *Cosmic Rays (Instruments), Annals of the IQSY* **1**, 178–197.

Clem, J. M.: 1999, 'Atmospheric yield functions and the response to secondary particles of neutron monitors', *Proc. 26th Int. Cosmic Ray Conf., Salt Lake City*, **7**, 317–320.

Clem, J. M. and Dorman, L. I.: 2000, 'Neutron Monitor Response Functions', *Space Sci. Rev.*, this volume.

Debrunner, H. and Flückiger, E. O.: 1971a, 'Calculation of the Multiplicity Yield Function of the IGY Neutron Monitor', *Helv. Phys. Acta* **44**, 241–351.

Debrunner, H. and Flückiger, E. O.: 1971b, 'Calculation of the Multiplicity Yield Function of the NM-64 Neutron Monitor', *Proc. 12th Int. Cosmic Ray Conf., Hobart, Australia* **3**, 911–916.

Debrunner, H., Lockwood, J. A., and Flückiger, E. O.: 1982, 'Specific Yield Function S(P) for a Neutron Monitor at Sea Level', *Proc. 8th Europe Cosmic Ray Symp., Rome*, preprint.

Debrunner, H., Flückiger, E., Chupp, E.L., and Forrest, D. J.: 1983, 'The Solar Cosmic Ray Neutron Event on June 3, 1982', *Proc. 18th Int. Cosmic Ray Conf., Bangalore* **4**, 75–78.

Debrunner, H., Flückiger, E., and Stein, P.: 1989, 'On the Sensitivity of Neutron Monitors to Solar Neutrons', *Nucl. Instr. Methods* **A278**, 573–575.

Dorman, L. I.: 1970, 'Coupling and Barometer Coefficients for Measurements of Cosmic Ray Variations at Altitudes of 260–400 mb', *Acta Phys. Acad. Scient. Hung.* **29**, Suppl. 2, 233–236.

Dorman, L. I.: 1974, *Cosmic Rays, Variations and Space Explorations*, North-Holland, Amsterdam.

Dorman, L. I., Villoresi, G., Iucci, N., Parisi, M., and Ptitsyna, N. G.: 1999, 'Cosmic Ray Survey to Antarctica and Coupling Functions for Neutron Component Near Solar Mininum (1996–1997). 3. Geomagnetic Effects and Coupling Functions', *Proc. 26th Int. Cosmic Ray Conf., Salt Lake City*, **7**, 382–385.

Hatton, C. J.: 1971, 'The Neutron Monitor', in J. ,G. Wilson and S. A. Wouthuysen (eds.), *Progress in Elementary Particle and Cosmic-ray Physics* **X**, North Holland Publishing Co., Amsterdam.

Hatton, C. J. and Carmichael, H.: 1964, 'Experimental Investigation of the NM-64 Neutron Monitor', *Can. J. Phys.* **42**, 2443–2472.

Hess, W. N., Patterson, H. W., and Wallace, R.: 1959, 'Cosmic Ray Neutron Energy Spectrum', *Phys. Rev.* **116**, 445–457.

Hughes, E. B.: 1961, PhD thesis, University of Leeds.

Hughes, E. B. and Marsden, P. L.: 1966, 'Response of a Standard IGY Neutron Monitor', *J. Geophys. Res.* **71**, 1435–1444.

Iucci, N., Storini, M., Villoresi, G., and Griffiths, W. K.: 1971, 'Latitude, Altitude and Primary Modulation Effects on the Multiplicity Distribution in the NM-64 Neutron Monitors', *Nuovo Cimento* **6B**, 111–123.

Iucci, N., Signoretti, F., and Villoresi, G.: 1987, 'A Neutron Monitor for the Detection of Solar Neutron Events', *Proc. Workshop 'The Possibilities of Investigations of Solar Flare Nature by Integrated Studies of Solar Neutrons Using the Net of Neutron Monitors', Irkutsk, June 2–3, 1987, Initiator: G. E. Kocharov*.

Lockwood, J. A., Webber, W. R., and Hsieh, L.: 1974, 'Solar Flare Proton Rigidity Spectra Deduced From Cosmic Ray Neutron Monitor Observations', *J. Geophys. Res.* **79**, 4149–4155.

Lumme, M., Nieminen, M., Peltonen, J., Torsti, J. J., Vainikka, E., and Valtonen, E.: 1983a, 'Multiplicity Response Function of the Double Neutron Monitor at Turku', *Proc. 18th Int. Cosmic Ray Conf., Bangelore* **3**, 538–541.

Lumme, M., Nieminen, M., Peltonen, J., Torsti, J. J., Vainikka, E., and Valtonen, E.: 1983b, 'Energy Dependence of Forbush Decreases Observed by the Turku Hadron Spectrometer', *Proc. 18th Int. Cosmic Ray Conf. (Bangelore)* **3**, 237–240.

Matsubara, Y., *et al.*: 1995, 'Detection Efficiency of the First Solar Neutron Telescope at Norikura', *Proc. 25th Int. Cosmic Ray Conf., Durban* **1**, 57–60.

Mischke, C. F. W., Stoker, P. H., and Duvenage, J.: 1973, 'The Neutron Moderated Detector and the Determination of Rigidity Dependence of Protons From the 1/2 September 1971 Solar Flare', *Proc. 13th Int. Cosmic Ray Conf. (Denver)* **2**, 1570–1575.

Muraki, Y., *et al.*: 1995, 'The 64 m^2 Solar neutron telescope at Norikura', *Proc. 25th Int. Cosmic Ray Conf., Durban* **1**, 53–56.

Nobles, R. A., Alber, R. A., Newkirk, L. L., Walt, M., and Wolfson, C. J.: 1969a, 'White Mountain Cosmic Ray Neutron Multiplicity Monitor', *Nucl. Instr. Method* **70**, 45.

Nobles, R. A., Hughes, E. B., and Wolfson, C. J.: 1969b, 'Emperical Response Functions for a Neutron Multiplicity Monitor', *J. Geophys. Res.* **74**, 6459–6470.

Potgieter, M. S., Raubenheimer, B. C., Stoker, P. H., and van der Walt, A. J.: 'Modulation of Cosmic Rays During Solar Minimum. 2. Cosmic Ray Latitude Distribution at sea Level During 1976', 1980, *S. Afr. J. Phys.* **3**, 77–89.

Pyle, R., Evenson, P., Bieber, J. W., Clem, J. W., Humble, J. E., and Duldig, M. L.: 1999, 'The Use of ^{3}He tubes in a Neutron Monitor Latitude Survey', *Proc. 26th Int. Cosmic Ray Conf., Salt Lake City*, **7**, 386–389.

Raubenheimer, B. C., Flückiger, E., Mischke, C.F.W., and Potgieter, M. S.: 1980, 'Comparison Between the Experimental and Theoretical Responses of Neutron Monitors', *S. Afr. J. Phys.* **3**, 29–35.

Shibata, S., *et al.*: 1997, 'Calibration of Neutron Monitor Using an Accelerator', *Proc. 25th Int. Cosmic Ray Conf. (Durban)* **1**, 45–48.

Shibata, S., *et al.*: 1999, 'Calibration of Neutron Monitor Using Accelerator Neutron Beam', *Proc. 26th Int. Cosmic Ray Conf., Salt Lake City* **7**, 313–316.

Simpson, J. ,A.: 1948, 'The Latitude Dependence of Neutron Densities in the Atmosphere as a Function of Altitude', *Phys. Rev.* **73**, 1389–1391.

Simpson, J. A. and Uretz, R. B.: 1949, 'On the Latitude Dependence of Nuclear Integrations and Neutrons at 30,000 Feet', *Phys. Rev.* **76**, 569–570.

Simpson, J. A., Fonger, W., and Treiman, S. B.: 1953, 'Cosmic Radiation Intensity-time Variation and Their Origin. I. Neutron Intensity Variation Method and Meteorological Factors', *Phys. Rev.* **90**, 934–950.

Simpson, J. A.: 1957, *Ann. Intern. Geophys. Yr.* **4**, 351.

Steljes, J. F. and Carmichael, H.: 1961, Solar Geophysical Data, Part B, CRPL-F 204, 205.

Stoker, P. H.: 1981, 'Primary Spectral Variations of Cosmic Rays Above 1 GV', *Proc. 17th Int. Cosmic Ray Conf., Paris* **3**, 193–196.

Stoker, P. H.: 1994, 'Relativistic Solar Proton Events', *Space Sci. Rev.* **73**, 327–385.

Stoker, P. H., Van der Walt, A. J., and Potgieter, M. S.: 1980, 'Modulation of Cosmic Rays During Solar Minimum. 1. Cosmic Ray Intensity Survey at Sea-level During 1976: Experimental Details', *S. Afr. J. Phys.* **3**, 73–76.

Address for Offprints: Pieter H. Stoker, Space Research Unit, Potchefstroom University for CHE, Potchefstrom 2520, South Africa; fskphs@puknet.puk.ac.za