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The Monitoring of Accelerator-Produced Muons at Fermilab*

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THE MONITORING OF ACCELERATOR-PRODUCED MUONS AT FERMILAB

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ABSTRACT

The fluence of high-energy muons that result from the operation of the TEVATRON accelerator was measured downstream of the experimental area beam lines. Profiles were determined by use of plastic scintillators and associated electronics mounted in a mobile laboratory at various locations on-site and at the site boundary. The experimental method and the properties of the fluence profiles are summarized, and in one case the measurements are compared to Monte Carlo calculations of muon transport. (Fermilab is operated by Universities Research Association under contract with the U.S. Department of Energy.)

1. INTRODUCTION

Muons arise from the decay of pions and kaons, or are produced directly in high-energy proton nucleus interactions. They thus can contribute to radiation problems at high-energy accelerators. It is therefore frequently important for operational health physics concerns to determine dose equivalent in muon fields.

The muon, with a rest mass 205 times that of the electron, has many of the properties of a heavy electron. It interacts only weakly with ordinary matter, losing energy predominantly by ionization and excitation. At higher energies, above ~100 GeV/c, bremsstrahlung, pair production, and nuclear inelastic scattering become more important. But even at these energies muons are at least approximately minimum ionizing particles and exhibit very long ranges in soil (>~500 m).

At Fermilab a mobile laboratory has been instrumented to locate muon radiation fields around the 6800-acre site (1). Plastic scintillators are utilized as flux detectors. This report discusses the measurement techniques, and presents examples of fluence measurements made during the 1987-1988 fixed target running period (2). For health physics purposes measured fluence was converted to dose equivalent by use of the factor 40 fSv-m^2 (25000 muons cm^{-2} per mrem) suggested by Stevenson (3) as appropriate to a wide range of muon energies. In this way estimates of dose equivalent due to muons associated with the various experimental beam lines was obtained both at on-site locations and at the site boundary. Off-site exposures are limited to 10 mrem-yr^{-1} (0.1 mSv-yr^{-1}) by order of the Fermilab Director even though the DOE limits the continuous annual rate to any member of the public to 100 mrem (1 mSv).

2. EXPERIMENTAL

The measurements were performed with the Mobile Environmental Research Lab (MERL). Muons were detected by a pair of 0.64 cm thick plastic scintillator paddles with transverse dimensions of 20.32 cm by 20.32 cm. The paddles were separated by 15 cm with a 2.54 cm thick aluminum plate placed in the gap to remove knock-on electrons. For the measurements discussed here the scintillators were located in the vehicle at a height 1.2 m above the ground.

Figure 1 shows a block diagram of the electronics. Pulses from events within the scintillators passed through the photo-multiplier tube bases into fast discriminators. Standard NIM logic pulses at the output of the discriminators for each paddle were sent into a coincidence unit and into scalers. Both singles and coincidence events were recorded. The scalers were gated on during both beam-on (a 23-sec beam spill time) and beam-off (for background determination) periods in synchronization with the TEVATRON acceleration cycle. Photo-multiplier tube gains and discriminator threshold levels were setup by preliminary measurements in a "known" muon radiation field. Pulses from each scintillator passed into a linear amplifier and then to a multichannel analyzer (MCA) gated by the output from the discriminators. Figure 2 displays typical gain matched threshold gated pulse height spectra for the two paddles S1 and S2, showing the peaks associated with high-energy minimum ionizing muons.

Two scintillator paddles operated in coincidence serve to distinguish muons from other radiation and in weak fields provide a more sensitive measure of their existence

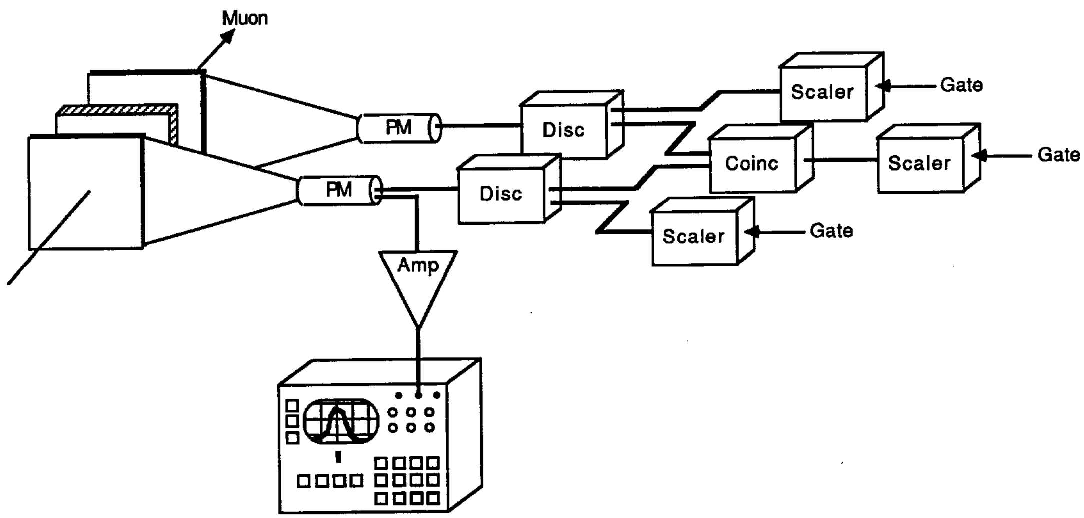


Figure 1. Block diagram of electronics. The Amp and multichannel analyzer are only used to set gains and thresholds.

than do individual singles rates. However, under conditions in which there are no other components of the radiation field for which the plastic scintillator has a finite efficiency, the singles rate provides a better measure of muon flux. This is because the coincidence rate depends upon the direction and divergence of the incident particles. For a broad parallel beam incident normal to the scintillators, the ratio of coincidence-to-singles rates should be close to unity. For a non-parallel beam, or one that is not incident along the normal to the surface, the ratio will be less than one, and can vary dependent on the divergence of the muon trajectories. In the present measurements muon fluence is based on average background-corrected singles rates. Coincidence-to-singles ratios in the peaks of the measured distributions varied from 0.6 to 0.85.

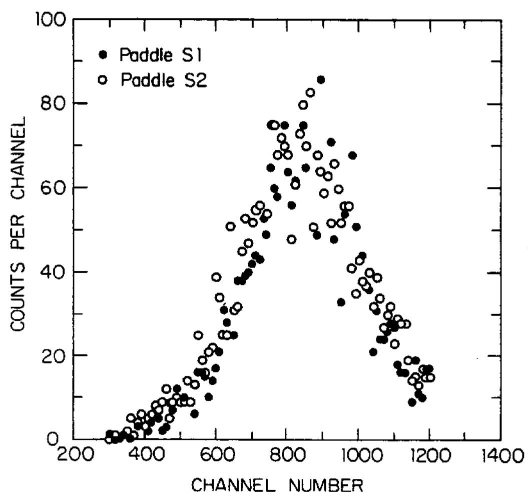


Figure 2. Pulse-height spectrum in MCA after matching the gain and thresholds for the paddles S1 & S2.

3. MEASUREMENTS

Figure 3 displays the 6800-acre Fermilab site showing the 2-km diameter TEVATRON accelerator and beam lines that deliver protons to the three fixed target experimental areas - Meson, Neutrino, and Proton - at distances 2-3 km from extraction. The map also shows that the site boundary - Hwy 38, to the north - is approximately 3-km further away.

Fermilab supports a diverse experimental high-energy physics program. A large number of secondary beams, produced at well shielded target stations, are transported by a variety of beam line components (bending, quadrupole, and toroidal magnets, collimators, etc.) to experimental halls where up to 15 or 16 experiments are setup and run simultaneously. Generally, muons are also produced at the targets and accompany the selected particle of interest in transport down the beam line. The spatial distribution of these muons at locations downstream of the primary target stations depends on the placement of beam line components as well as on the concrete, steel, and earth shielding surrounding the beam lines.

During the 1987-1988 fixed target running period data were collected at a number of locations. Figure 4, an enlargement of part of the Figure 3 map, shows the locations, the distance from the respective target, and the beam lines surveyed. On-site distances varied between 370 and 3350 m, and the site boundary location was up to 3.7 km from muon production targets.

Measurements were performed by scanning

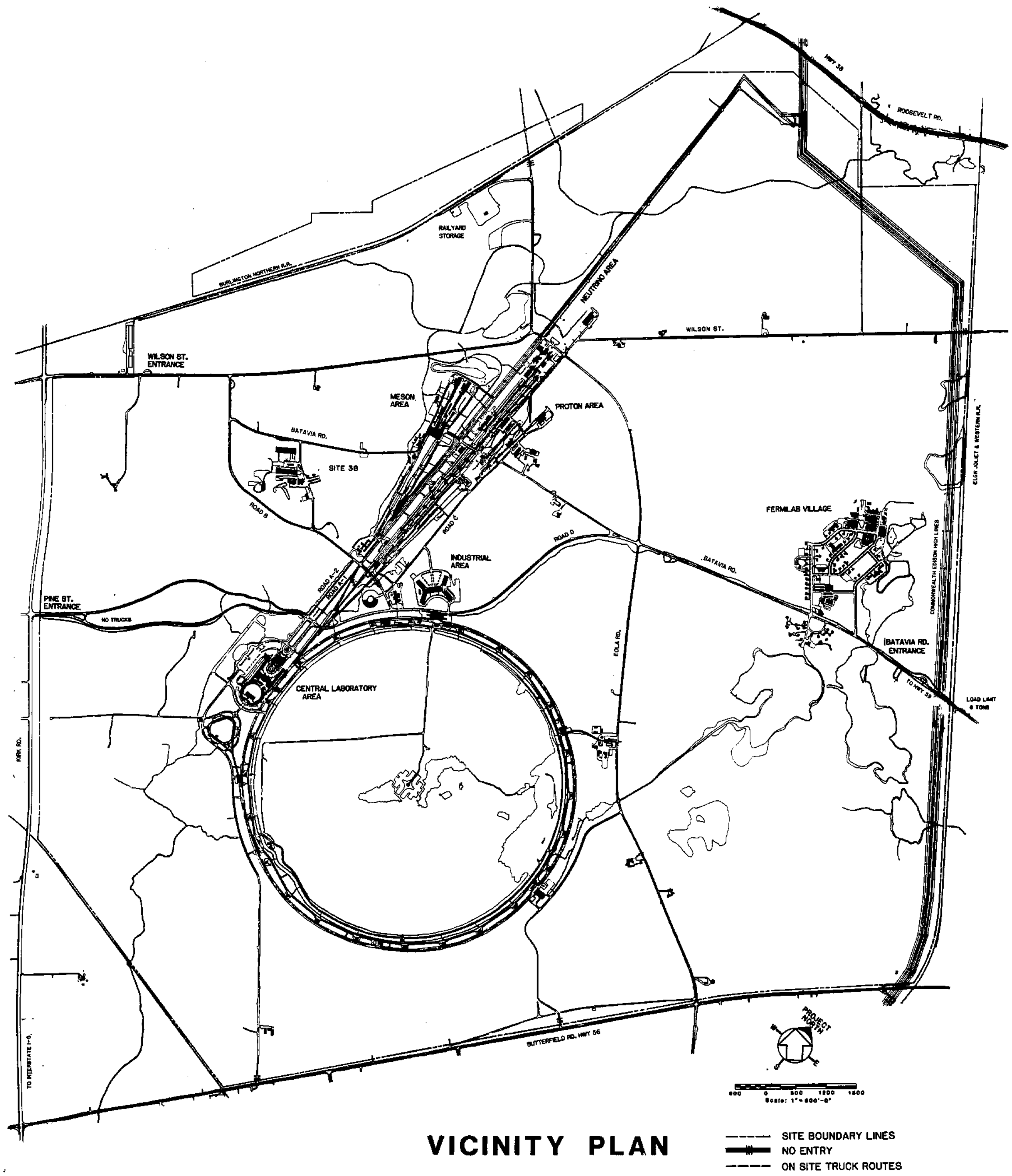
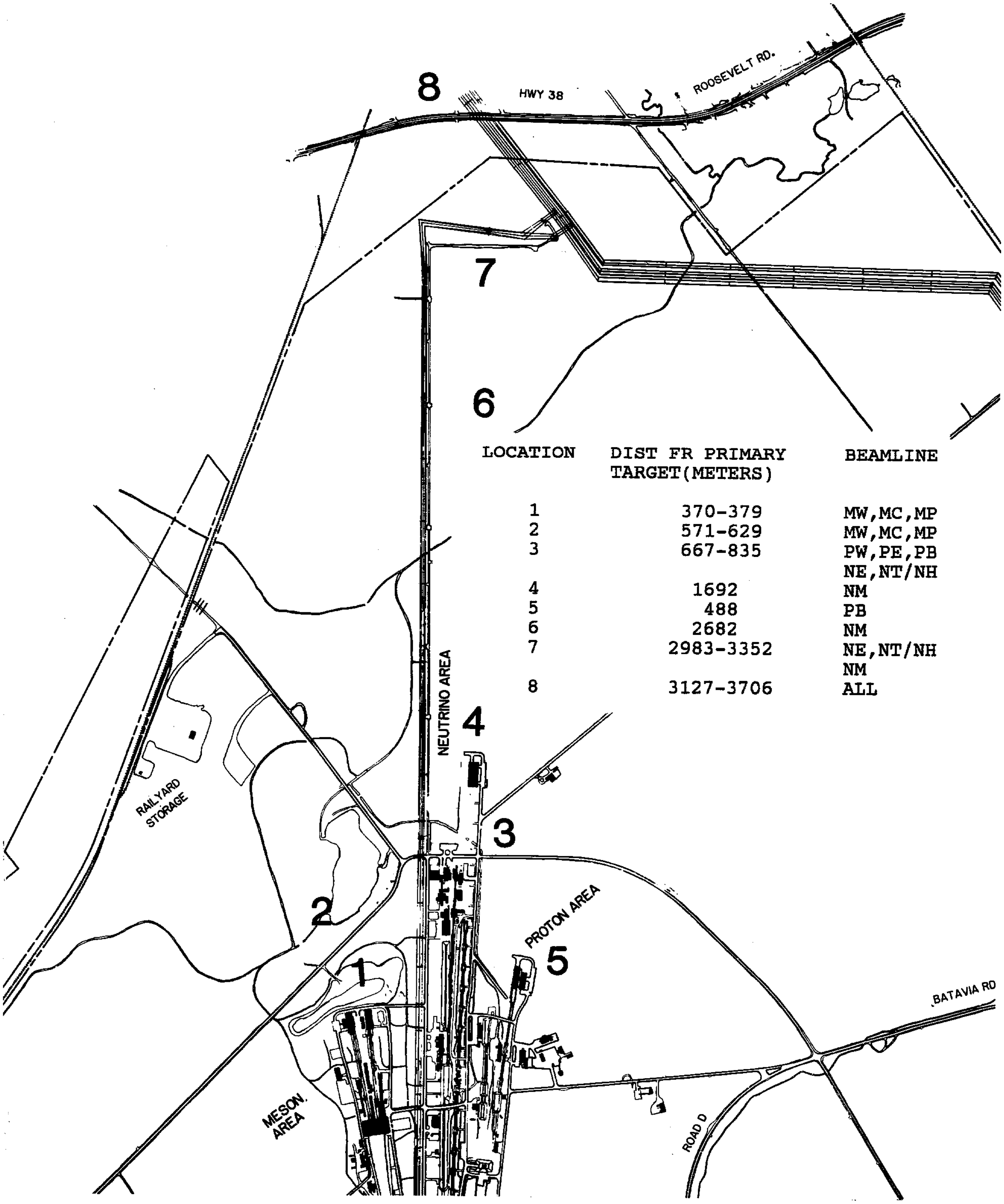


Figure 3. Map of Fermilab site.



LOCATION	DIST FR PRIMARY TARGET(METERS)	BEAMLINE
1	370-379	MW,MC,MP
2	571-629	MW,MC,MP
3	667-835	PW,PE,PB NE,NT/NH
4	1692	NM
5	488	PB
6	2682	NM
7	2983-3352	NE,NT/NH NM
8	3127-3706	ALL

Figure 4. Enlargement of part of Figure 3 showing locations at which measurements were done and the distances from the respective targets for the various beam lines.

across the muon radiation field with the MERL on a line approximately normal to an extension of the beam line. Detector counts were recorded for at least two beam spills at each position along a scan at each location. Primary proton beam intensity information was obtained from secondary emission beam intensity monitors (SEM) upstream of the target stations and relayed to the MERL through a telemetry system. The results reported here were obtained during normal physics running periods, not in runs dedicated to health physics surveys.

4. RESULTS

An elevation profile of the terrain downstream of the Meson Area experimental halls is shown in Figure 5. The locations at which the surveys were done are indicated. Figure 6 shows the fluence

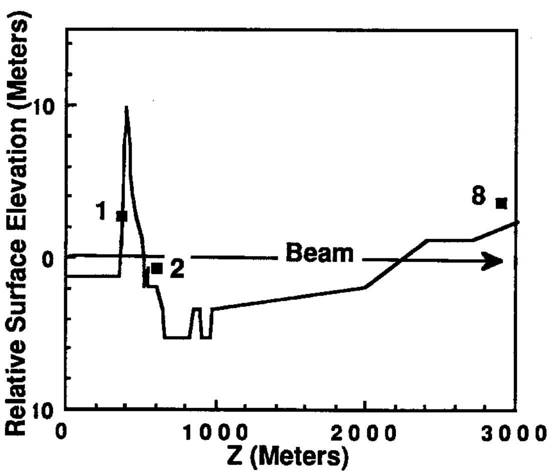


Figure 5. Elevation of surface of earth relative to that of the beam as a function of longitudinal distance from target station. Locations are given in Figure 4.

profiles. At location 1, a road directly in back of the experimental halls, the fluence associated with the MC beam is three times that from either MW or MP, and the distribution is much broader. While the target piles at which most of the muon

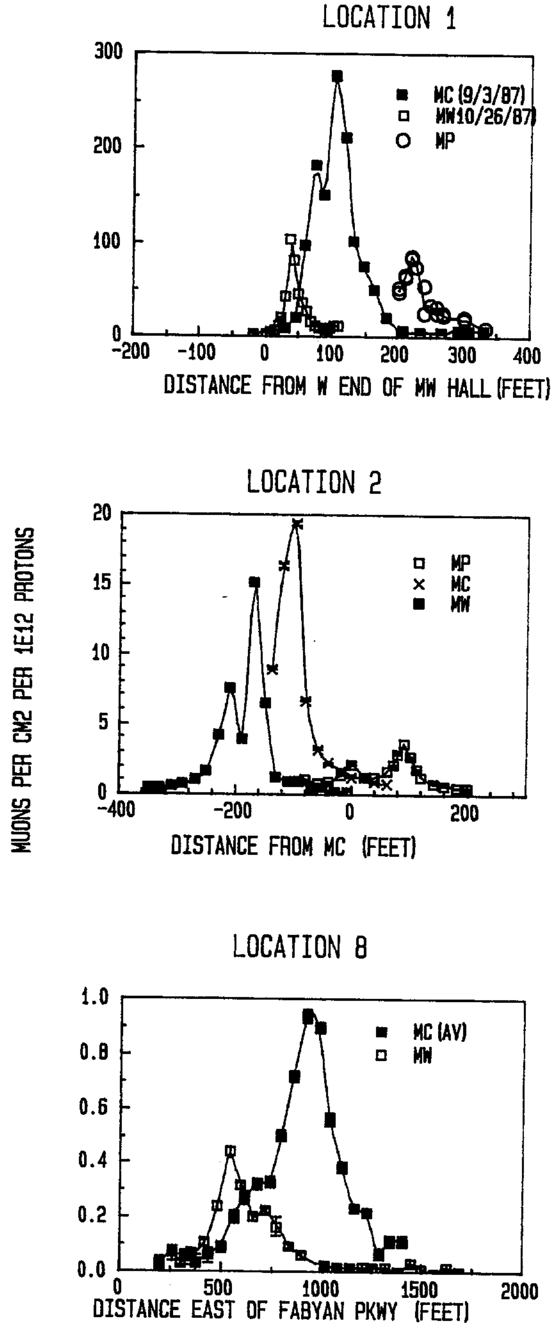


Figure 6. Muon fluence as a function of horizontal distance from a particular landmark. The profiles show relative intensities of the muons from three Meson Area beams at the locations given in Figure 4.

production occurs are similar for all three beams, the MC beam line between the target and the experimental hall is unshielded while both MP and MW beams are shielded by at least a 6 foot thickness of concrete and earth. The muon dose equivalent rate at the road, an accessible but minimally occupied area, was about 0.7 mrem-hr^{-1} during runs.

Location 2 is another road at the foot of a small hill which provides some earth shielding. Maximum fluence is reduced by a factor of 6.5 for MW associated muons, a factor of 14 for MC, and a factor of 25 for MP. Such differences in attenuation through soil shields are probably due to the spectral and directional variation of the muons associated with the three beams.

Downstream of location 2 the muons travel largely in air (see Figure 5) out to the site boundary location 8. To within a factor of two, fluence differences at locations 2 and 8 have, relative to the target station, an inverse distance - squared relationship. Table 1 lists the site boundary values of maximum fluence, coincidence-to-singles ratios, and the annual dose equivalent for the total number of protons delivered to the targets for the beam lines surveyed. Note that the annual dose equivalent for muons associated with MC was about one-third of the Fermilab goal to limit this value to 10 mrem.

Muon fluence at two locations downstream of the Proton area is shown in Figure 7. At the road at location 3 the maximum fluence corresponds to a very small dose equivalent rate of ~0.01 mrem hr^{-1}. Figure 8 illustrates, for the case of the PW beam line at location 3, that muon profiles can change with differences in experimental running conditions from day-to-day. No peaks were observed at the site boundary location (see Figure 7) for proton experimental beams so that the results in Table 1 are upper limits to annual dose equivalent.

The NM beam in the Neutrino Area was newly commissioned during the 1987-1988 run. Because it was designed to deliver a well collimated momentum analyzed pure muon beam to the experimental hall, it differs from the other beam lines for which muons are an undesirable by-product of the interaction between protons and matter. As seen in Figure 9, an elevation profile along the beam line downstream from the

Table 1. Results of Measurements at Route 38, the site boundary location. The fluence is given for 1 x 10^{12} protons incident on the appropriate SEM

Beam Line	Distance from Primary Target (Feet)	Max Muon Fluence (muons-cm^{-2})	Conc. to Singles Ratio	1987 Annual Dose Equivalent (mrem)	1988 Annual Dose Equivalent (mrem)
MW	12069	0.44±0.15	0.60	1.20	1.16
MC	12022	0.94±0.02	0.60	2.90	0.79
PW	10280	0.04[a]		0.07	0.045
PE	10340	0.06[a]		0.17	0.065
PB	10260	0.02[a]		0.05	0.05
NM (No-toroid)	12158	2.77±.02	0.77	12.7	---
NM (Toroid-on)	12158	0.18±.01	0.64	0.44	0.51

[a]No peaks were observed on the muon distributions (see Figure 7). These values are upper limits.

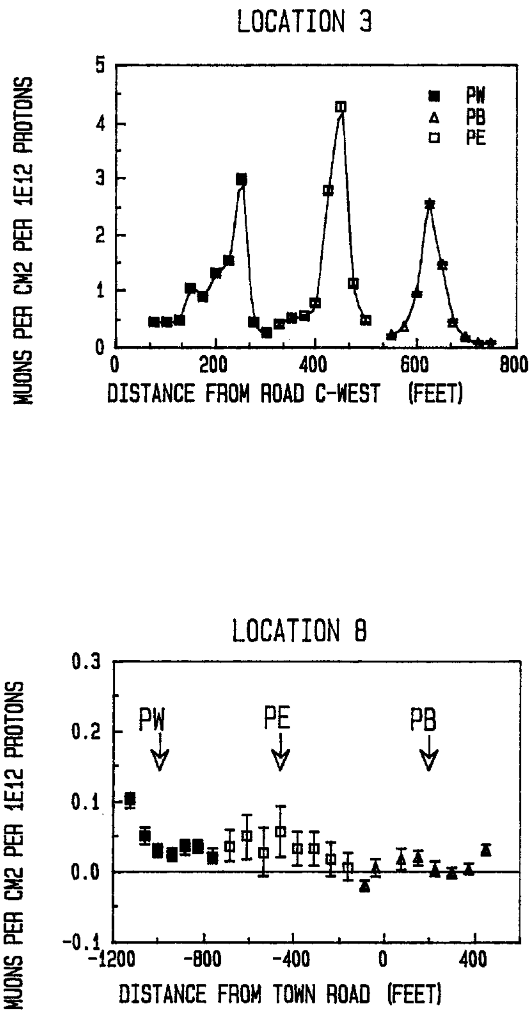


Figure 7. Muon fluence as a function of horizontal distance from a particular landmark. The profiles show relative intensities of the muons from the three Proton Area beams at the locations given in Figure 4.

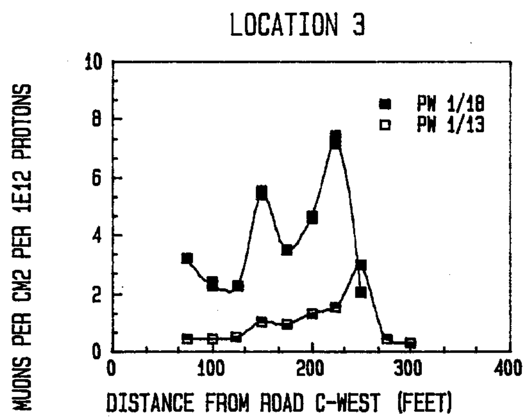


Figure 8. Muon fluence at same location for PW beam for surveys done on different days.

experimental hall, the beam is incident on the earth at a depth of about 3.5 m and remains underground for about 600 m. The results of fluence measurements at the locations indicated are shown in Figure 10. The solid points represent data in which the muons exiting the experiment impinge directly on the earth shield. The fluence at all three locations is large, the distributions are quite narrow (e.g., only 60 feet FWHM at the site boundary), and coincidence-to-singles ratios are over 0.7, all of which suggest that the muons remain in a well collimated beam even after penetrating ~3600 m of soil and air.

In Table 1, the 1987 site boundary dose equivalent due to NM muons was about 13 mrem, 30% higher than the Fermilab Director's goal of 10 mrem. To reduce this off-site fluence two specially built magnets were installed in the beam line downstream of the experiment to deflect muons downward before entering the soil beyond the hall. With the "spoilers" in place the distribution of muon fluence at the same locations is displayed by the open points in Figure 10. As seen, the peak fluence is reduced by a factor of 20 and the peak is broadened, at location 6; the reduction is a factor of ~18 at location 7, and a factor of 15 at the site boundary. At the two most distant locations the observed distributions are so broad as to hardly resemble peaks at all. At such low intensities the muon field may be dominated by contributions from adjacent independently - operated beam lines. The fluence reduction provided by the additional magnets should keep the site boundary dose equivalent below the 10 mrem yr^{-1} goal for any reasonable future total number of incident protons.

Calculations (4) based on the muon

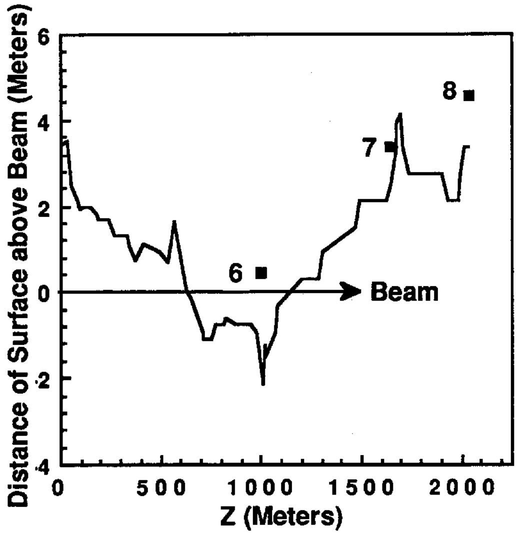


Figure 9. Elevation of surface of earth relative to that of beam as a function of longitudinal distance as measured from the end of the NM experimental hall. Locations are given in Figure 4.

transport portion of the most recent version (5) of the Monte Carlo program CASIM, in which the actual terrain outside of the experimental hall was included in the model, are compared to the measured NM fluence distributions in Figure 11. The agreement in intensity and width is excellent at location 6, about 1000 m away from the experimental hall, and even at the site boundary, over 2000 m from the hall, the calculations and measurements agree to within about 30-40%. Further calculations that include muon production as well as transport mechanisms are in progress (6) to compare with the fluence measurements for the Meson Area beams.

5. CONCLUSION

Plastic scintillators are sensitive detectors of muons. Even with a fairly simple electronic arrangement, fluence rates of $\sim 2\times10^{-3}\,cm^{-2}\,sec^{-1}$ have been measured with two 20.3 cm by 20.3 cm by 0.64 cm thick paddles. Surveys over the large extent of a high-energy accelerator laboratory with detectors setup in a truck can serve to determine the location of sources of muons.

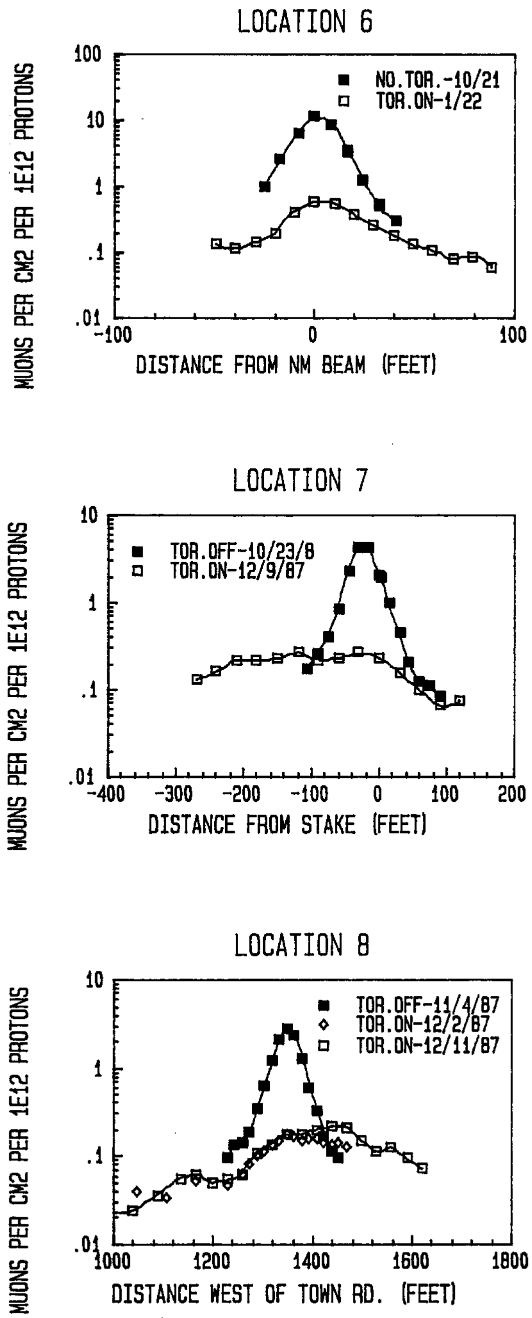


Figure 10. Muon fluence as a function of horizontal distance from a particular landmark at the locations given in Figure 4. Solid and open points are discussed in Text.

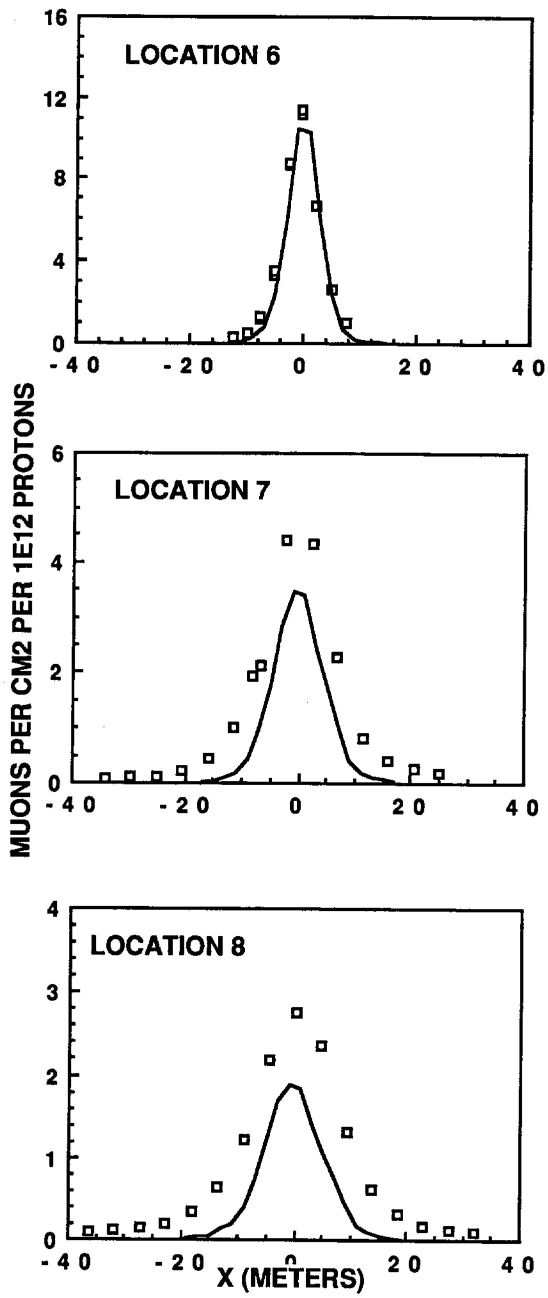


Figure 11. Muon fluence as a function of horizontal distance relative to NM beam at locations of Figure 4 compared to CASIM calculations (solid lines), as discussed in Text.

Systematic measurement of muon fluence can be used not only for operational health physics purposes but also to investigate muon production and transport mechanisms.

6. ACKNOWLEDGEMENT

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