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Abstract

History of radiation studies at Fermilab is overviewed. The general approach and specific philosophy and tools used throughout the Fermilab accelerator complex, in fixed target and collider experiments as well as in new challenging projects such as a muon collider are described. Examples of recent applications at Fermilab are given.

1 Introduction

A comprehensive radiation protection program at Fermilab includes all components to keep the radiological impact on the work place and to the environment As Low As Reasonably Achievable (ALARA): a stringent set of radiation limits and design goals for off and on-site radiation exposure, quantification of radiation source terms, specification of shielding design criteria, radiation instrumentation, provision for access, control of residual activation and proper management. The key role of effective computer simulations of the accelerator radiation environment is described in this paper through a review of radiation studies at Fermilab over last 25 years and most recent applications related to the accelerator complex upgrade, collider and fixed target experiments developments and studies towards new exciting projects such as a muon collider.

2 History at Fermilab

Radiation studies at Fermilab have a long history which matured just prior to the advent of the Tevatron accelerator and has continued to progress toward the present era as new projects are envisioned and their radiation protection issues carefully considered. It was recognized early on by M. Awschalom that effective simulations of the accelerator radiation fields needed to progress in concert with the development of the machine designs themselves. This work continued through the efforts of many physicists and engineers involved with these issues at Fermilab.

The Monte-Carlo program CASIM [1] was used to design the shielding for the Tevatron, its associated colliding beam detector halls, and its associated fixed target experimental areas. It was subjected to several important tests which, through inter-comparisons with the results obtained using other programs, continue to serve as reasonable benchmarks. It is noteworthy that at Fermilab, such benchmarking comparisons have

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always been done in the absolute sense. In no instances have arbitrary factors been used to 'normalize' results of Monte-Carlo calculations when they are compared with data.

The accurate simulation of energy deposition in thin targets continues to be a major concern at particle accelerators. Such measurements were done for 300 GeV protons incident on cylindrical Be, Al, Cu, and W targets of 2.54 cm diameter [2]. These measurements used thermal calorimetry to measure the energy deposited in targets which were several interaction lengths long. Calculations using CASIM which included the primary protons, secondary particles, and electromagnetic showers were in excellent agreement with data. The three processes were tallied separately so that their relative importance was understood. Another benchmark at small radii was reported in measurements of absorbed dose and radioactivation due to 300 GeV protons incident on an aluminum target contained within the bore of a standard Fermilab beam transport magnet [3]. Results of an acceptable quality were obtained for the production of several different radionuclides as well as for a variety of dosimeters. Both of these studies served to verify the accuracy of the modeling for small radial dimensions.

In practical shielding designs it is, of course, necessary to be assured of the accuracy of the simulations for shields of the large dimensions required to provide adequate personnel and environmental protection. Prior to the initial operation of the Tevatron, a series of measurements of absorbed dose external to locations of beam loss and lateral to earth shields as thick as 1608 g/cm^2 (or about 17 absorption lengths) for protons having energies as large as 350 GeV were made [4]. Absorbed dose was chosen as the parameter of interest for these studies because of its nature as a directly measurable physical quantity suitable for comparison with the results of the basic Monte-Carlo calculations without further consideration of complications related to the neutron energy spectra, choice of quality factors, etc. The particular test cases were specifically selected due to their simplicity. 'Simple' was defined as a situation in which both the beam loss and the shielding configuration could be verified by actual measurement in a way that could assure reproducibility. Excluded from these studies were situations in which the beam loss conditions were poorly known (e.g., beam scraping losses) or the shielding configuration could not be verified by direct measurement. This work was later pivotal in leading to an understanding that the energy scaling in the context of the so-called Moyer model is $E^{0.8}$ [5]. Further measurements of this general type were made a few years later for 800 GeV protons [6]. The results of this body of work concluded that the simulations are accurate to within a factor of 2 to 3 for thick shields if beam loss conditions and the shielding configuration are accurately known. Comparisons of measurements with calculations and inter-comparisons of the programs CASIM, MARS and FLUKA were provided in reference [7]. Further successful comparisons for bulk shields of measurements with results calculated using these codes and others have been described in references [8, 9]. In particular, the power law energy scaling parameter has been further confirmed to be approximately 0.8. These results were found to be satisfactory over a large domain of energy.

Given the nature of the equilibrium spectra of neutrons expected to be found external to such shielding, the ability to use such calculations to design the shields was thus established. Throughout the design of the facilities for the Tevatron, calculations of this type were used successfully. New target stations were designed and built based upon these results and were later successfully operated. The simulations considered the external dose equivalent rates, the production of radionuclides in the soil adjacent to these halls, and the radioactivation of the target station components and their cooling water. In general, results obtained with actual operations are in good agreement with the predictions.

Muons are, of course a concern at high energy accelerators. Many improvements in the treatment of muon production have been introduced through the development of an appropriate 'stand-alone' version of CASIM intended to handle these leptons [10]. Operations of the Tevatron for fixed target physics with 800 GeV protons provided opportunities to compare the muon flux densities downstream of complicated target stations with calculations using this program. One set of measurements was able to study the transport of muons through an earth shield without considering their production [11]. In this study, the predicted transport of a beam of muons having a broad spectrum with a FWHM of about 150 GeV and an average energy of about 500 GeV through a soil shield about one km long agreed with measurement to within 5 to 10%. Another study considered the production of muons in three target stations having a reasonable degree of complexity followed by their transport through shielding [12]. In general the agreement of these measurements with the corresponding calculations was typically within a factor of 2, often within 20-30%.

At the same time, many sophisticated studies at Fermilab—targetry, radiation shielding, induced radioactivity, beam collimation system, optimization of backgrounds in collider and fixed target experiments—have been performed with the MARS code [7, 13, 14, 15, 16, 17, 18]. The current version of this program described in [19, 20] and most recently in [21] is available on Web [22] and since February 1998 became the preferred tool in all new projects at Fermilab. The MARS Monte Carlo code system allows fast and reliable inclusive simulation of three-dimensional hadronic and electromagnetic cascades in shielding, accelerator and detector components in the energy range from a fraction of an electron-volt (especially when linked to the MCNP code [23]) up to about 100 TeV. The reliable performance of the code has been demonstrated in numerous applications at Fermilab, CERN, KEK and other centers as well as in special international benchmarking in the framework of SARE/SATIF meetings [24].

3 Ground Water

Ground water activation calculations are of considerable importance at high energy accelerators. Throughout the history of Fermilab, Monte-Carlo calculations have been used to estimate the concentrations of radionuclides that, under worst case conditions, might be found in the aquifers that lie beneath the site. Several years ago, a new methodology was developed [25]. This procedure uses the standard Monte-Carlo codes (e.g., MARS or CASIM) to calculate the concentrations of radionuclides in the media immediately adjacent to a given target station or other source. It is thus called the *Concentration Model*. Standard methods which have been used elsewhere for predicting the migration of other chemical contaminants besides radionuclides [26] are then used to predict the further migration of the radionuclides. It was found that the 'conservative' predictions of migration as a function of depth made by these codes is fit well by simple exponential functions. The result was the development of a 'cookbook' procedure presumably applicable to downward migrations in the glacial till clay that lies between most Fermilab target stations and the underlying dolomite aquifer. This model has now been used for several years. It is presently being modified to incorporate improvements that were identified as being needed based upon the experienced gained in actually using this approach. The modified procedure will clarify several issues. Specifically, the actual planned running time of a given target station will be taken into account. In the initial version of the Concentration Model, the concentrations adjacent to the target station were calculated to saturation. For tritium, for example, the long lifetime renders the former approach unreasonably long compared with plausible lifetimes of facilities. It is also now clear from practical experience that detailed calculations should be performed for each installation, since cookbook approaches can lead to poor results. Finally, both the calculation of initial concentrations and the estimate of migration to the aquifer should be based on the best hydrogeological data that can be obtained. In the strata underneath Fermilab, it is generally cost-effective to perform the necessary sampling rather than to rely on 'cookbook' approaches which can lead to large uncertainties.

4 Fermilab Accelerators

Recent examples of radiation studies and optimization of the radiation environment at Fermilab Booster, Main Injector and Tevatron are given in this section.

Booster. The MARS code has recently been successfully used to study radiation shielding and ground water activation at the 8-GeV Booster. Dose rates at the outer surface (R=5.3 m) of the soil shielding of the Booster tunnel are shown in Fig. 1 for 0.4 and 7.1 GeV proton beam loss in the lattice. MARS results are close to the ionization chamber data even for such a thick shielding.

Comprehensive calculations and measurements have been performed on radionuclide production in the soil underneath a concrete floor of the Booster extraction long straight section [27]. 1% to 2% of the beam was lost in this region from 1973 to 1997. Fig. 2 shows the comparison of the MARS calculated versus measured nuclide production. The agreement in a specific activity over the range of data is impressive. To study the nuclide spatial pattern, a sophisticated model incorporating the irradiation history, a full MARS simulation and differing vertical migration rates was developed [27]. As one can see from Fig. 2(b), the data is most consistent with a rate of 3 cm/yr.

Main Injector. The Main Injector extraction system will be capable of delivering a 120 GeV proton beam to the fixed target experiments at the rate of up to 4×10^{20} protons per year. Up to 2% of the beam is expected to be lost at the extraction septum and the Lambertson magnet. As a result, one expects significant radiation levels in this area. Preliminary MARS studies have shown that [28] both accumulated dose and induced radioactivation in the beam extraction components are high but do not pose extraordinary problem from the point of view of operation. Recently, much more sophisticated MARS studies have been performed in a full 3-D model of all the extraction and NuMI [29] beam line elements in a 160 m long region [30]. Based on these calculations, several ways to improve the radiation environment there have been proposed.

Tevatron. An approach to optimization of the radiation environment at the superconducting (SC) colliders is different of that at the conventional accelerators. A very reliable multi-component beam collimation

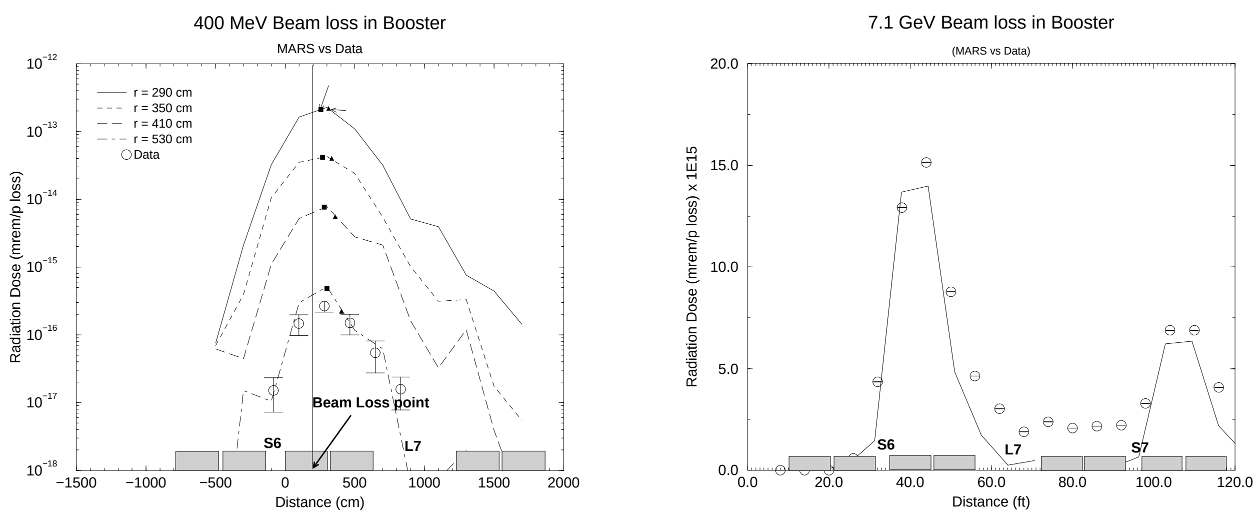
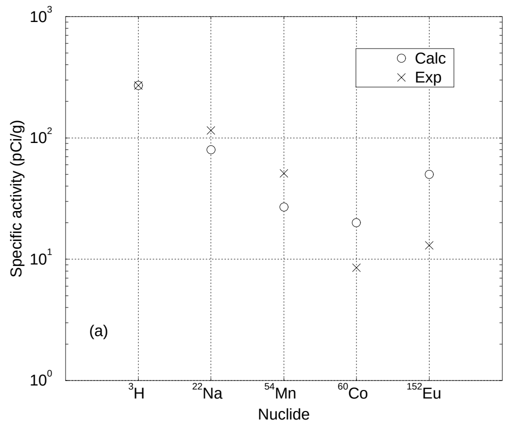


Figure 1: Dose equivalent per proton lost in a soil shielding around a 1.2 m radius Booster tunnel as calculated with MARS and measured with an ionization chamber (Courtesy of C. Bhat): (a) At injection (400 MeV), calculated at four radial distances from the Booster beam line, data taken at R=530 cm; (b) At 7.1 GeV as calculated and measured at R=530 cm.



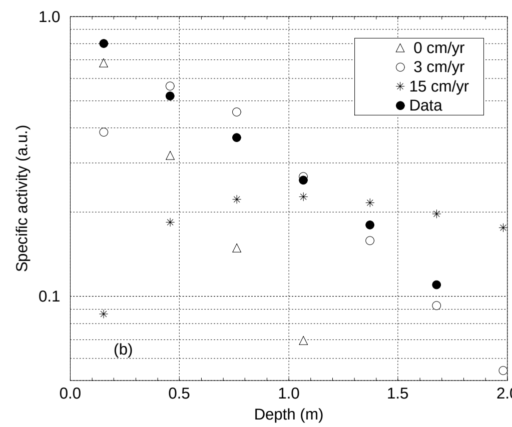


Figure 2: MARS calculated radio-nuclide production in the soil underneath a concrete floor of the Booster in comparison with experimental data [27]: (a) Specific activity of five isotopes at 15-cm depth of soil; (b) Spatial pattern of the tritium activity calculated for the three vertical migration rates and measured.

system is mandatory at any SC accelerator providing [18, 31]: 1) reduction of beam loss in the vicinity of interaction points to sustain favorable experimental conditions; 2) minimization of radiation impact on personnel and environment by localizing beam loss in the predetermined regions and using appropriate shielding in these regions; 3) protection of accelerator components against irradiation caused by operational beam loss and enhancement of reliability of the machine; 4) prevention of quenching of SC magnets and protection of other machine components from unpredictable abort and injection kicker prefires/misfires and unsynchronized abort. At the early Tevatron days the first collimation system was designed [15] on the basis of the full-scale simulations with the MARS and STRUCT [32] codes. The system, consisted of primary and secondary collimators about 1 m long each, was installed in the Tevatron which immediately made it possible to raise by a factor of 5 the efficiency of fast resonant extraction system and intensity of the extracted 800 GeV proton beam. The data on beam loss rates and on their dependence on the collimator jaw positions were in an excellent agreement with the calculational predictions. The new beam collimation system [31] to be installed in the Tevatron by collider Run II will provide further improvement of the radiation environment.

5 Collider Experiments

The collision halls for the CDF and DØ experiments represented unique challenges. Here, the simulations had to be particularly accurate because of the large size of these halls. The large size resulted in structural engineering considerations that specified a maximum thickness for the roof of each of these enclosures. There was no room for significant error in the results as the structures could not support the weight of additional shielding if the results were incorrect. The simulations were performed for each of these two large experimental halls. The radiation levels in these areas have been continually monitored. During many years of their operations, it has never been necessary to turn off the accelerator due to undesirable levels of radiation above the roof of either one of these enclosures.

At superconducting hadron colliders the mutual effect of the radiation environment produced by the accelerator and experiments is one of the key issues in the interaction region and detector development. The

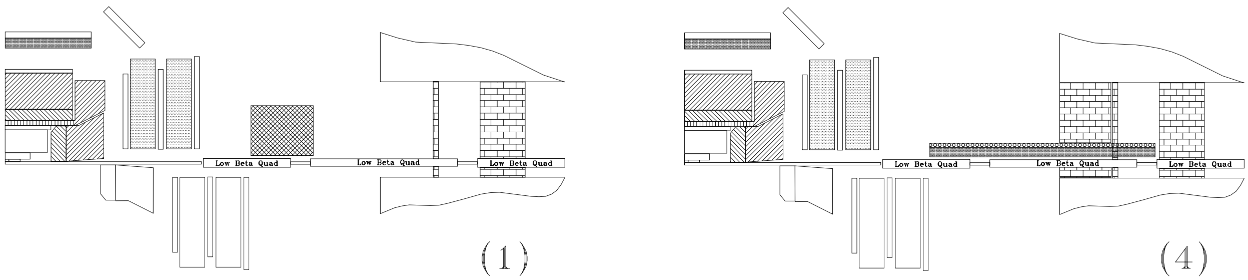


Figure 3: CDF shielding configurations [34]: (1) baseline; (4) most optimal.

overall Tevatron and DØ and CDF collider detector performances are strongly dependent on details of such an interface. Efforts were made at Fermilab to optimize the DØ and BØ regions in the collider Run I and later for the Run II era [33, 34]. Over the last 10 years, the effects of the designed on the MARS basis measures to reduce radiation levels in the DØ experimental hall due to $p\bar{p}$-collisions, beam loss in the Tevatron and Main Ring, and induced radioactivity have been in excellent agreement with the MARS calculations.

Six shielding configurations have been explored [34] to provide minimal radiation levels in the CDF experimental hall for Run II conditions. Fig. 3 shows two of them: a proposed baseline (a recycled hadronic calorimeter at 11 m from interaction point) and the most optimal one with a collar shielding of 40 cm of steel followed by 10 cm of poly with 4 cm of lead radially in the 11 to 17.8 m region and additional 1.8-m thick concrete wall at the hall/tunnel interface with a 30-cm gap filled with polyethylene. Calculations and measurements of hits in Run I in the CDF detector rear plane are presented in Fig. 4(a) [34]. There is a very good agreement between calculations and data. MARS reproduces peaks and dips arising from the configuration asymmetry and effect of magnetic field. It gave us a confidence in our shielding configuration studies. Fig. 4(b) shows azimuthal distributions of radially integrated hits for the six considered shielding configurations. One sees that the configurations 3 to 6 give significant reduction in the number of hits. Remarkably good radiation level suppression of a factor of $\sim$30 is achieved for the fourth configuration, where the new 1.8-m wall (Wall-2) traps nicely the radiation from the tunnel.

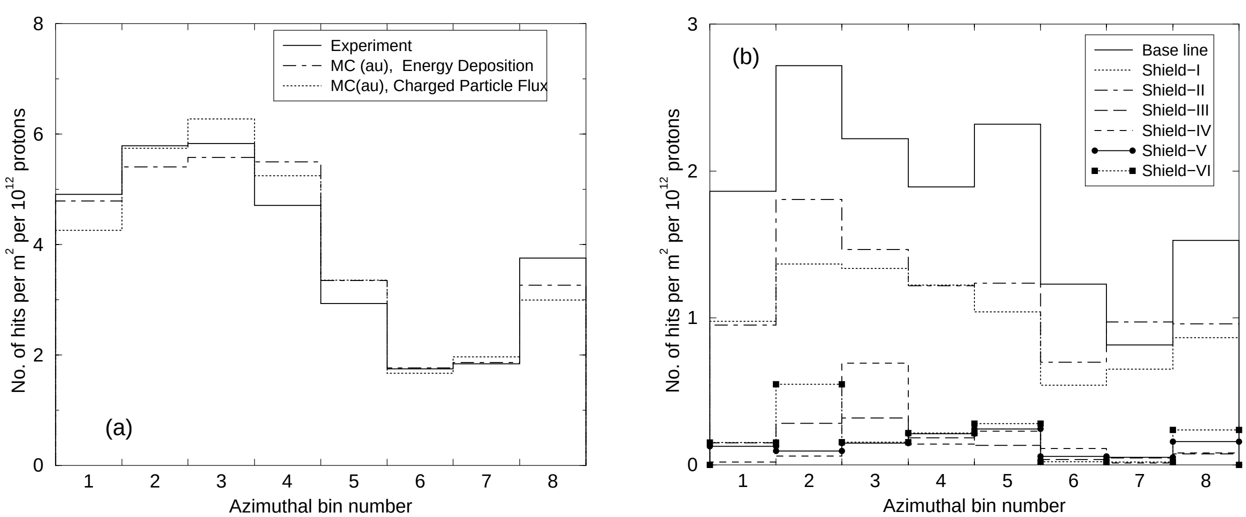


Figure 4: (a) Calculated and measured azimuthal distributions of hits in the CDF rear plane (Run I) radially integrated; (b) Azimuthal distributions of radially averaged hits in the rear plane (Run II).

6 Fixed Target Experiments

A serious study of radiation and background environments has been recently done with the MARS code for the E-872 experiment (DONUT) for the direct observation of ν_τ [35]. A very complex shielding starting from around a 800 GeV tungsten beam dump, through passive and active magnetic elements in the 60 m long channel up to a nuclear emulsion target followed by a spectrometer, was re-optimized to reduce the radiation levels by a factor of 50 to 100. Calculations were verified at several stages with dedicated measurements. A typical example is shown in Fig. 5(a) where calculated and measured hit rates in the veto counters are compared for a few cases.

An exciting new project is the Neutrinos as the Main Injector (NuMI) project [29]. This project will entail the targeting of a beam of 120 GeV proton beam accelerated by the new Fermilab Main Injector. This beam will be of very high intensity, approximately 3.7×10^{20} per year and about 4×10^{13} per spill every two seconds. It will be aimed downward at an angle of 3.3 degrees to direct a beam a secondary pions and kaons toward the Soudan Underground Laboratory in Minnesota some 730 km to the Northwest. The pions and kaons will be afforded an opportunity to decay in an 800 m long decay region before being absorbed. The resultant beam of muon neutrinos will continue onward to the Soudan Underground Laboratory where this beam will be used to study neutrino oscillations. Extensive shielding calculations have been performed at Fermilab to study external shielding, residual activation of components, and soil activation and its effects on ground water. The 800 m decay region is particularly troublesome as massive shielding of the secondary particles is needed since stringent levels of activation must be met due to the fact that the facility is located in an aquifer. Residual activation of components is a serious design issue because of the magnitude of the targeted proton intensity. Muon rates are of concern largely from the point of view of minimizing the backgrounds in a part of the experimental apparatus that is located after the hadron absorption is complete. Initial design studies were undertaken using CASIM. More recent efforts are employing MARS. The complexity of the shielding questions involved is resulting in a serendipitous comparison of the two programs that is most fruitful. In general, the result of these comparisons is that the programs give comparable results. However, the calculations for the NuMI project, because of the long length of the shielding configuration are quite sensitive to details of the calculations that are not present in more standard shielding configurations. Fig. 5(b)

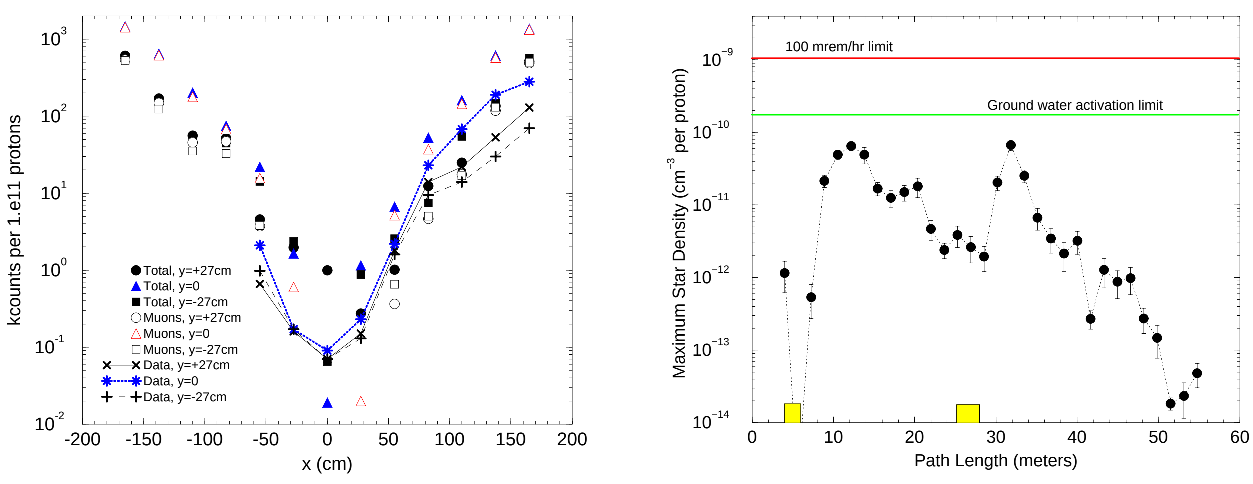


Figure 5: (a) Horizontal scan in the E-872 veto counters as calculated with MARS and measured; (b) MARS calculated star density in the first 10 cm of rock around the NuMI target hall.

shows MARS calculated maximum star density in the first 10 cm of rock around the NuMI target hall for 2-horn medium energy configuration [29]. One sees that the optimized shielding provides the radiation levels to be below both limits: the ground water activation and a 100 mrem/hr residual dose rate on beam line elements.

7 Muon Colliders and Neutrino Induced Hazard

One of the attractive possibilities for high energy physics in general and for Fermilab in particular is a muon collider offering unparalleled new physics opportunities. That is why there is growing activity at Fermilab in all aspects of this exciting project [36]. The spectrum of radiation issues here is wide and challenging [37, 38, 39]. A third of the muon beam power released in the machine components via electromagnetic and hadronic showers results in high heat load to cryogenics, induces radiation levels in the machine and surroundings and creates the enormous background particle fluxes in the detector components. With 2×10^{12} muons in a bunch at 2 TeV one has 2×10^5 $\mu \rightarrow e\nu\tilde{\nu}$ decays per meter in a single pass through an interaction region, or 6×10^9 decays per meter per second. Decay electrons with an energy of about 700 GeV and the huge number of synchrotron photons emitted by these electrons in a strong magnetic field induce electromagnetic showers in the collider and detector components. Detailed calculations [37] have shown that the resulting particle fluxes can exceed those at hadron colliders without significant suppression via appropriate interaction region design, shielding and collimators in the detector vicinity.

All aspects of radiation control at a $\mu^+\mu^-$ collider complex are folded into the design. Considered in detail in [38, 39] are the main collider arcs, the IR and absorption of spent muon beam for operational and accidental cases. Prompt and residual radiation levels have been calculated with the MARS code. In the tunnel, experimental hall and in the first meters of the surrounding soil/rock, the prompt radiation field is composed of low energy photons and neutrons. Farther from the tunnel the only two significant components are secondary muons generated in electromagnetic and hadronic cascades in the magnets and neutrinos from the muon beam decay. Fig. 6(a) shows isodose contours around the collider tunnel. The distributions are asymmetric in the horizontal plane because of lattice and tunnel curvature and effects of the magnetic field. With 10^7 s as a collider operational year, the tolerable on-site limit which is 100 mrem/yr in the soil/rock is reached at about 6 m above the orbit plane, 10 m toward the ring center and ~ 75 m outward in the horizontal plane. In calculations the ^{3}H and ^{22}Na radionuclide production is observed in the first meters of the soil/rock around the tunnel, which would require insulation or drainage of that region. The dolomite stratum at Fermilab may naturally satisfy this condition. Residual dose rates in magnet components immediately after shutdown range from ~ 10 rad/hr (innermost radii) to ~ 0.003 rad/hr at the magnet outer shell.

After about 1000 turns muons are extracted and sent to a beam absorber. For 2 TeV muons the isodose contour coinciding with the tolerable on-site dose limit is 3.55 km long with a maximum width of 18 m at 2.6 km. Deflecting the extracted beam down by 4.5 mrad confines muon fluxes beneath the ground. Estimates show that the absorption of the spent beam can result in annual activity concentration which may exceed the stringent limits for ^{3}H and ^{22}Na radionuclides, 20 pCi/cm^3 and 0.2 pCi/cm^3 respectively, if the beam disposal lines are in aquiferous layers. The problem is solved if the 2 TeV beam is directed into the impervious dolomite layer or to an isolated 2.5 km long 2 m radius rock or concrete plug. For 250 GeV beam this plug is about 550 m long and 1 m in radius. The resolution of these issues requires further study.

The question was raised if neutrino-induced radiation can cause a problem at large distances from the souce at muon colliders, high-intensity neutrino experiments (NuMI and Gran Sasso), as well as extraterrestrial neutrinos [40, 41, 42]. In order to properly address particular concerns about the dose equivalent that might be delivered by neutrinos, it has been necessary to develop a method of calculating the dose equiva-

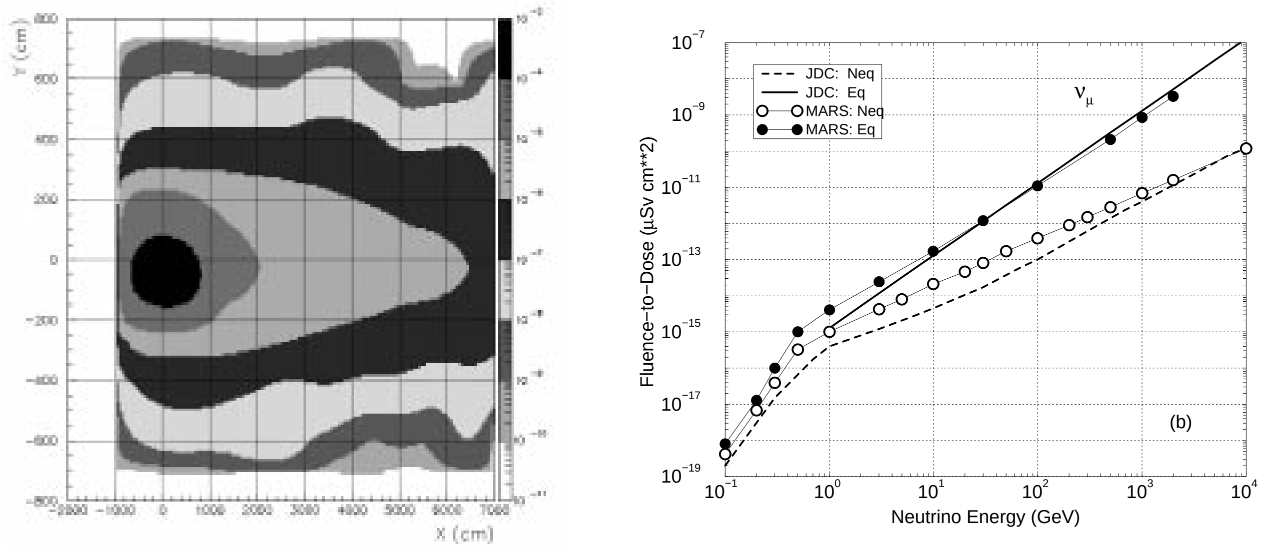


Figure 6: (a) MARS calculated isodose contours in the vertical plane across the collider tunnel and surrounding soil/rock for 2 TeV muon beam decays; y axis is up and x axis points outward along the ring radius; beam axis is at x=y=0; right scale is dose rate in rem/sec; (b) Dose equivalent in a bare (Neq) and embedded into infinite medium (Eq) tissue phantom per unit neutrino fluence as calculated with MARS and in [40].

lent per fluence due to these leptons. This has been done in [40, 42] for neutrinos ranging from 0.1 MeV to 10 TeV. Fig. 6(b) compares the results of these calculations for bare (non-equilibrium) tissue phantom and one embedded into an infinite medium (equilibrium). Based on these results, it is concluded in [40] that the annual dose equivalent associated with the NuMI facility is very small and extraterrestrial neutrinos are not a concern. Detailed MARS calculations have shown that [42] at muon colliders the neutrino-induced radiation is not a problem if muon beam energy is less than 0.5-1 TeV, and rapidly gets the potential of killing the concept of the muon collider without significant suppression if the muon energy is $>$1 TeV.

8 Conclusions

The radiation protection program at Fermilab demonstrates its effectiveness. The computer codes used in the Laboratory provide reliable tools for further progress with the accelerator complex and detector upgrade and work towards the new exciting projects. It is planned to continue code developments, measurements and benchmarking in the framework of the described approach.

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