Fermilab Accelerator Complex Qualitative Beam-On Surveys

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A concern was raised by Fermilab DOE Site Office (FSO) in their conditional approval of the Accelerator Safety Envelope (ASE) Revision 12 (dated August 25, 2020, approved September 29, 2020) pertaining to potential dose to the public due to accelerator operations:

> As the Fermilab site is closed to the general public, the otherwise publicly accessible areas of the site that could exceed public dose restrictions (if not for occupancy adjustment) do not represent a public risk. Prior to Fermilab allowing public access to the site, the areas that would then be publicly accessible, that could exceed public dose restrictions (if not for occupancy adjustment), must be posted as restricted to Fermilab workers unless a subsequent DOE external review proposes alternative expectations that are subsequently accepted by the FSO Manager.

This concern was captured in the iTrack review for the "400 MeV Test Area (MTA) Accelerator Readiness Review (ARR)", item 104538, since the ASE revision was due to changes assessed in the ARR.[1]

In response to this concern, beam-on measurements were performed along the machines making up the main Fermilab accelerator complex as they resumed beam operations following the 2020 Summer Maintenance Shutdown. These surveys were not intended to be quantitative, but rather to identify if there are any areas of concern that warrant further investigation and focus. Approximately ~300 passive area monitor badges are now deployed as part of the routine area monitoring program. Prior to 2021, ~200 passive area monitors were used. Tracking of quarterly area monitor results will take place through the area monitoring program.

These surveys were performed using the following guidelines:

- Beam has been established in each machine and is running stably.
- Survey points should be at a location accessible to the public (i.e., parking lots or roads) nearest to the berm or fencing.
- Survey points should be evenly spaced along the entire length of the beamline.
    - Additional survey locations may be added in points of interest (i.e., MI-30 collimator region)
- Survey should be performed using instrument(s) that measure both gamma and neutron radiation. Background and beam-on surveys should be conducted, using one-minute count times.
    - Bicron analysts were used to survey gamma radiation, with results in counts per minute (cpm), where 10,000 cpm is roughly equivalent to 0.05 mR/hr.
        - Bicron analysts were deemed sufficient for these surveys, over other instruments such as a Log Survey Meter (LSM), because they are more sensitive

and can detect slight increases due to beam or radioactive material stored within buildings. These are not quantitative surveys so a rough equivalency to dose rate is sufficient. The main goal of these surveys is to identify locations with high enough count rate that it could be $\gtrsim$ 0.05 mR/hr, in order to ensure those areas are included in the routine area monitoring program.

- In practice, a "rule of thumb" that has been used for estimating dose rates based on counts per minute is 320-400 cpm ≈ 1 μR/hr. 320 cpm is derived from detector efficiency, and 400 cpm comes from previous field surveys comparing Bicron readings with other dose rate instrument readings. Other previous studies show that 2,000 cpm ≈ 10 μR/hr. [2] To be conservative, for the purpose of this study, 2,000 cpm ≈ 10 μR/hr will be used to convert to dose rates.

$$2{,}000\ cpm \cong 10\ \mu R/hr$$
$$200\ cpm \cong 1\ \mu R/hr$$
$$200{,}000\ cpm\ \cong 1\ mR/hr$$
$$10{,}000\ cpm\ \cong 0.05\ mR/hr$$

  - REM 500s were used to survey neutron radiation, with results in mrem, equating to mrem/min with the one-minute count time.

- Once background and beam-on surveys were completed, results should be compared to identify locations with net results equivalent to:
  - > 0.025 mR/hr with the Bicron
  - > 0.05 mR/hr with the Bicron
  - > 0.001 mrem/hr with the REM 500
- Based on the results of the survey, additional area monitors will be deployed for additional, ongoing monitoring.

Beam began to turn on following the 2020 Summer Shutdown starting in early October 2020, rolling through various machines until mid-January 2021. *(Note: NM and FAST remained off during this time frame due to continued experiment reconfiguration and equipment issues, respectively.)* Background and beam-on surveys were taken at various times, as described in Table 1, based on machine turn on. Table 2 compares beam intensity at the time of the beam-on survey relative to the nominal and Operating Limit intensities. If intensities at the time of the beam-on survey were much lower than the Operating Limit intensities,[3] either repeat surveys will be conducted when intensities increase or area monitors in place as part of the routine area monitoring program will be used to continue monitoring the area as intensities increase.

Table 1. Survey Dates

Machine	Background Survey Date(s)	Beam-On Survey Date(s)
Linac	10/8/2020	12/22/2020
MeV Test Area (MTA)	2/3/2021	2/5/2021
Booster	10/9/2020	12/22/2020
8 GeV	11/17/2020	12/28/2020
Booster Neutrino Beam (BNB)	Included in the 8 GeV survey	Included in the 8 GeV survey
Main Injector (MI) / Recycler (RR)	11/17/2020	12/18/2020 & 12/28/2020
NuMI	Included in the MI/RR survey	Included in the MI/RR survey
F Sector (shared beamlines for SY and Muon Campus)	12/11/2020	12/28/2020
Muon Campus	1/11/2021	12/28/2020
SwitchYard Primary	12/11/2020	1/15/2021
Meson (Primary, Test & Center)	12/11/2020	1/15/2021
FAST	n/a – beam currently not operational due to machine instrumentation issues	n/a – beam currently not operational due to machine instrumentation issues
Neutrino Muon	n/a – beam currently not operational during experiment reconfiguration	n/a – beam currently not operational during experiment reconfiguration
Proton	n/a – machine in “standby” state and not running beam	n/a – machine in “standby” state and not running beam
Tevatron (TeV)	n/a – machine in “standby” state and not running beam	n/a – machine in “standby” state and not running beam

Table 2. Beam Intensity Comparison

Machine	Beam Intensity for Beam-On Survey	Operating Limit Beam Intensity	Operating Limit Beam Energy
Linac	1.2E17 protons/hr	3.54E17 protons/hr	400 MeV
MTA	2.8E14 protons/hr	2.7E15 protons/hr	400 MeV
Booster	1.2E17 protons/hr	2.70E17 protons/hr	8 GeV
8 GeV	1.8E17 protons/hr	2.84E17 protons/hr	8 GeV
Booster Neutrino Beam (BNB)	2.95E16 protons/hr	1.62E17 protons/hr	8 GeV
Main Injector (MI) / Recycler (RR)	--	--	--
- Main Injector	4.1E16 protons/hr	2.93E17 protons/hr	8 GeV
		2.93E17 protons/hr	120 GeV
		2.34E17 protons/hr	150 GeV
- Recycler	2.5E16 protons/hr	2.25E17 protons/hr	8 GeV
NuMI	2.9E16 protons/hr	2.25E17 protons/hr	120 GeV
F Sector (shared beamlines for SY and Muon Campus)	--	--	--
- P1-P2 Line to Muon Campus	1E16 protons/hr	6.5E16 protons/hr	8 GeV
- P1-P2 Line to SwitchYard	1.3E13 protons/hr	3.60E13 protons/hr	120 GeV
Muon Campus	--	--	--
- On Target	1E16 protons/hr	4.32E16 protons/hr	8 GeV
- Off Target	n/a – running On Target	3.60E13 protons/hr	8 GeV
SwitchYard Primary	3.7E13 protons/hr	6.00E14 protons/hr	120 GeV
Meson (Primary, Test & Center)	--	--	--
- Primary	1.4E13 protons/hr	1.68E14 protons/hr	120 GeV
- Test	6.5E12 protons/hr	1.20E13 protons/hr	120 GeV
- Center	2.5E10 protons/hr	1.02E12 protons/hr	120 GeV
FAST	n/a – beam currently not operational due to machine instrumentation issues		
NM	n/a – beam currently not operational during experiment reconfiguration		

Results

Survey location points were approved by the assigned RSO, RPO Department Head, and/or the SRSO prior to conducting any surveys.

RCTs performed all surveys, background and beam-on, at the prescribed locations. Background surveys were performed prior to that machine starting up, or during a down-day if already operational. Beam-on surveys were performed after that machine was operational and running stable beam. After the Linac background survey for both gamma and neutron, it was determined that with the beam off there is no other potential source for neutrons, so no additional neutron background measurements were taken at each survey location. Instead, three sixty-minute background sample measurements were taken, and the average of these measurements was taken to be the background value for all locations.

Gamma Results

Gamma survey results for both background and beam-on measurements were initially reported in cpm. The difference between the two was found to show the net beam-on count rate due to gammas from beam operations of that machine. Locations with net results greater than 1000 cpm were identified, as shown in Table 6. Standard deviation for all results was calculated, $\sigma_{N_S=\sqrt{N_T+N_B}}$, where N_S is the net value, N_T is the gross sample (i.e., beam-on) value, and N_B is the background value.[4]

In order to ensure the bicron surveys did not produce unacceptable false positive or false negative results, critical levels, L_C, and minimum detectable limits, N_D, were calculated, based on the direct cpm measurements. In order to ensure no larger than 5% rate of false positive results, the critical level was found to be $L_C = 2.326\sigma_{N_B}$ or $L_C = 2.326\sqrt{N_B}$,[5] and any net result, N_S, greater than L_C was flagged for confirming counts present above background. In order to ensure appropriate instrumentation was used, a minimum detectable limit (from the sample result), was found to be $N_D = 4.653\sigma_{N_B} + 2.706$ or $N_D = 4.653\sqrt{N_B} + 2.706$.[6]

Results of the gamma radiation surveys, net calculation, and standard deviation calculation were then converted to exposure rate, mR/hr, where 200,000 cpm is roughly equivalent to 1 mR/hr.[2] Results are shown to three decimal places, and rounded to zero for any negative net results. Locations with net exposure rates greater than 0.05 mR/hr, which is the threshold for unlimited occupancy, were identified, as shown in Table 3. Locations with net exposure rates between 0.025-0.05 mR/hr were identified, as shown in Table 4. Table 5 contains a list of machines that do not have any locations with net beam-on exposure rates of greater than 0.025 mR/hr. Table 6 lists locations with net counts > 1,000 cpm but net exposure rates < 0.025 mR/hr. In order to further ensure that appropriate instrumentation was used when considering results converted to dose rates, a minimum detectable limit for dose, D_D, was found by taking the minimum detectable limit for counts and converting units: $D_D = N_D \times \frac{1\ mR/hr}{200{,}000\ cpm}$.

One (1) location was found to have dose rates > 0.05 mR/hr. No locations were found in the 0.025-0.05 mR/hr range. Nine (9) additional locations were found to have count rates > 1000 cpm.

Table 3. Location of Net Beam-On Exposure Rates Greater Than 0.05 mR/hr

Machine	Survey Location #	Geographical Location	Net Beam-On (mR/hr)	Comments
Muon Campus	7	AP0 Service Building parking lot.	0.054	Elevated count rates here expected due to stored activated material and RAW water skid operations. This building is not accessible to the public, roads leading to this building have "Authorized Personnel Only Beyond This Point" signage. This building is posted as a Radiation Area. Area monitors have already been installed in the north and south vestibules and have been added to the routine area monitoring program. Additional area monitor(s) will need to be added in the center of the building, in the parking lot to continue monitoring that location as well. Based on area monitoring results, additional postings to limit occupancy in the area may be needed.

Table 4. Locations of Net Beam-On Exposure Rates Greater Than 0.025 mR/hr

Machine	Survey Location #	Geographical Location	Net Beam-On (mR/hr)	Comments
none				

Table 5. List of Machines with No Locations of Net Beam-On Exposure Rates Greater than 0.025 mR/hr

Linac
MTA
Booster
8 GeV
Booster Neutrino Beam (BNB)
Main Injector (MI) / Recycler (RR)
NuMI
F Sector (shared beamlines for SY and Muon Campus)
SwitchYard Primary
Meson (Primary, Test & Center)

Table 6. Additional Information For Locations with > 1000 cpm Net Beam-On Count Rates (continued onto next page)

Machine	Survey Location #(s)	Geographical Location	Comments
Booster	8	Short 6 (S6) region, near the Booster collimators.	Documented higher dose rates in Long 6 (L6) and S6 region, see previous area monitor readings. This area will continue to be part of the routine area monitoring program.
8 GeV/BNB	16	MI-12 Service Building	May have higher counts due to BNB targeting and the 1,000 cfm fan unit. Monthly dose rate surveys are performed on the fan unit as part of the routine “snoop” survey program, and an area monitor badge has been added to this location and will be added to the routine area monitoring program.
MI/RR	15	MI-30 Parking Lot	This location was only reading a net of 992 cpm, but still included here. This higher reading is due to the LCW DI bottle located in the MI-30 LCW room. This bottle can at times produce a Radiation Area within the LCW room, so this is expected from LCW cooling of the collimator region components. Area monitors have been added in the LCW room, in the parking lot, and across the road near the pond and will be added to the routine area monitoring program.

Machine	Survey Location #(s)	Geographical Location	Comments
MI/RR	43, 44	Kautz Rd, near AP-0 Service Building	Elevated count rates expected here due to Muon Campus targeting operations, RAW system, and stored radioactive material. This building is posted as a Radiation Area. Area monitors have been installed in the north and south vestibules and will be added to the routine area monitoring program.
MI/RR	46	MI-8 Service Building Parking Lot	Elevated count rates due to LCW piping running through the building. LCW water comes from the MI8 collimator region, to a cooling and polishing loop in the MI-8 Service Building. Area monitors have been installed in the LCW room and the adjacent work area and will be added to the routine area monitoring program.
F Sector	6, 7	Main Ring Rd, North of AP-0 Service Building, near F23 Power Supply Building and F2 Service Building (same as positions 5 & 6 for Muon Campus)	Elevated count rates expected here due to Muon Campus targeting operations. The nearby F2 Refrigerator Building already contains an area monitor as part of the routine area monitoring program.
Muon Campus	5, 6	Main Ring Rd, North of AP-0 Service Building, near F23 Power Supply Building and F2 Service Building (same as positions 6 & 7 for F Sector)	Elevated count rates expected here due to Muon Campus targeting operations. The nearby F2 Refrigerator Building already contains an area monitor as part of the routine area monitoring program.
Muon Campus	8	West (downstream) of AP-0 Service Building on the road	Elevated count rates possible from nearby AP-0 Service Building and Muon Campus targeting operations.

Neutron Results

Neutron survey results for beam-on measurements were initially reported in mrem, using one-minute integration time.

Three sixty-minute background sample measurements were taken, and the average of these measurements, $\bar{x}$, was found using: $\bar{x} = \frac{1}{N}\sum_{i=1}^{N} x_i$. A sample standard deviation, s, was then found using: $s = \sqrt{\frac{1}{N-1}\sum_{i=1}^{N}(x_i - \bar{x})^2}$. The average background sample measurement and sample standard deviation were then converted into mrem/min and mrem/hr and applied to all survey locations.

The difference between the average background and gross beam-on measurements, when converted into mrem/min and mrem/hr, was found to show the net beam-on dose rate due to neutrons from beam operations of that machine. Results are shown to three decimal places, and rounded to zero for any negative net results. Locations with any net dose rate due to neutrons were identified, as shown in Table 7. Table 8 contains a list of machines that do not have any locations with any net beam-on dose rates due to neutrons.

In order to ensure neutron readings, converted to mrem/hr, did not produce unacceptable false positive or false negative results, critical levels, L_{C_N}, and minimal detectable dose D_{D_N}, were calculated, based on the direct mrem measurements. Similar to calculating the gamma critical level, L_C, the critical level for neutron, L_{C_N} was found to be $L_{C\_N} = 2.326s$,[5] and any net result greater than this critical level was flagged for confirming readings present above background. All locations were found to be below the critical level, L_{C_N}. In order to ensure appropriate instrumentation was used, a minimum detectable limit for neutron dose, D_{D_N}, was found to be $D_{D\_N} = 4.653s$.[7]

Table 7. Locations of Neutron Dose Rates Found.

Machine	Survey Location #	Geographical Location	Net Beam-On (mrem/hr)	Comments
Muon Campus	10	On Indian Creek Road, above the end of the Transport DS enclosure and start of the Delivery Ring enclosure.	0.115	Above where the M3 line bends to go into the Delivery Ring, but before injection. This location is not accessible to the public, roads leading to this location have "Authorized Personnel Only Beyond This Point" signage. Will need additional follow-up.

Table 8. List of Machines with No Neutron Dose Rates Found.

Linac
MTA
Booster
8 GeV
Booster Neutrino Beam (BNB)
Main Injector (MI) / Recycler (RR)
NuMI
F Sector (shared beamlines for SY and Muon Campus)
SwitchYard Primary
Meson (Primary, Test & Center)

Scaling, Occupancy Time, Public Accessibility & Interlocked Detectors

At the core of the FSO concern about potential dose to the public, we were asked to identify locations that are publicly accessible where public dose restrictions could be exceeded if not for occupancy adjustment. Visitors to Fermilab are limited to 100 mrem in a year.[8] Fermilab radiological design criteria, and therefore dose rate and posting standards, rely on the standard 2,000 hour working-year.[9] For the purpose of this study, potential dose, in mrem, at both the standard 2,000 hour working-year and 24/7/365 occupancies were calculated based on the calculated gamma and/or neutron dose rates.

In order to be conservative in calculating potential dose at both occupancies, the exposure and/or dose rates determined based on beam intensity at the time of the survey was scaled to approved Operating Limit beam intensities.[3] From there, potential dose was calculated for each occupancy, shown in Table 10, with the following assumptions:

- 1 mR/hr is equivalent to 1 mrem/hr
- Occupancy is either the standard 2,000 hr working-year, or 24/7/365. However, since beam is not operational 24/7/365, the dose calculated for this occupancy takes into account annual % beam up-time for the machine (or upstream/limiting machines) noted in the shielding assessment[10][11][12][13], as shown in Table 9.
- Assuming interlocked radiation detectors are not in use
    - *Interlocked radiation detectors are in place and set to trip limits based on the Shielding Assessment for that machine*

Table 9. Annual % Beam Up-Time

	# Weeks Operational	Efficiency	Annual % Beam Up-Time
Linac[10][1]	52	100%	100%
MTA	Use upstream machine - Linac		
Booster[11][2]	52	100%	100%
8 GeV	Use upstream machine - Booster		
BNB	Use upstream machine - Booster		
MI[12]	44	80%	67.7%
RR[13][3]	52	99%	99%
F Sector	Use upstream machine - MI		
Muon Campus	Use upstream machine - MI		
Switchyard	Use upstream machine - MI		
Meson	Use upstream machine - MI		

[1]The Linac Shielding Assessment doesn't specify annual beam up-time. For the purpose of this report it will be taken as 100%.
[2]Booster Shielding Assessment assumed 100% efficiency in order to provide as much beam as possible in order to accommodate for downstream inefficiency, but doesn't specify number of weeks operational. For the purpose of this report it will be taken as 52 weeks.
[3]The Recycler Shielding Assessment specifies that the machine runs at 99% efficiency, but doesn't specify number of weeks operational. For the purpose of this report it will be taken as 52 weeks.

Fourteen (14) locations would exceed 100 mrem in a year at the Operating Limit intensity, assuming 24/7/365 occupancy and annual beam up-time. None of which are publicly accessible.[14] Only seven (7) locations would exceed 100 mrem in a year at the Operating Limit intensity, assuming the standard 2,000 hour working-year. None of which are publicly accessible.[14] Additionally, all locations are in normally not-occupied locations (i.e., roads and parking lots). Figure 1 shows an overlay of these locations on the Fermilab Site Map.

Finally, it is noted that interlocked radiation detectors are utilized to ensure dose rates do not reach certain levels based on that locations posting & occupancy.[8] Table 10 also indicates interlocked radiation detector trip levels that are used for that location.

Table 10. Locations > 100 mrem in a year at Operating Limit Intensities for either 2,000 hr or 24/7/365 Occupancy. (continued on next several pages)

Machine & Survey Location	Geographic Location	At Survey Intensity		Scaled to Op. Limit		Comments	Public Accessibility	Interlocked Radiation Detectors
		2,000 hr working-year (mrem)	24/7/365	2,000 hr working-year (mrem)	24/7/365			
8 GeV/BNB								
16	MI-12 Service Building	20.000	87.600	109.831	481.058	Table 6 > 1,000 cpm	No	3 chipmunks set to trip at 5 mrem/hr and 4 chipmunks set to trip at 1 mrem/hr in and around the MI-12 Service Building
MI/RR								
15	Indian Creed Rd near MI-30 Service Building	10.000	43.800	71.463[1]	211.884[1]	Table 6 > 1,000 cpm	No	MI-30 Service Building LCW room has chipmunk set to trip at 2.5 mrem/hr
				54.878[2]	237.962[2]			
41	Kautz Rd, South of MI-62 Service Building	4.000	17.520	28.585[1]	84.753[1]	Elevated count rates possible here due to close proximity to the MI/RR, NuMI and Muon Campus Beamlines.	No	MI-62 Service Building LCW room has chipmunk set to trip at 2.5 mrem/hr
				36.000[2]	156.103[2]			
42	Kautz Rd, North of MI-62 Service Building	4.000	17.520	28.585[1]	84.753[1]	Elevated count rates possible here due to close proximity to the MI/RR, NuMI and Muon Campus Beamlines.	No	MI-62 Service Building LCW room has chipmunk set to trip at 2.5 mrem/hr
				36.000[2]	156.103[2]			

Machine & Survey Location	Geographic Location	At Survey Intensity		Scaled to Op. Limit		Comments	Public Accessibility	Interlocked Radiation Detectors
		2,000 hr working-year (mrem)	24/7/365	2,000 hr working-year (mrem)	24/7/365			
MI/RR								
43	Kautz Rd, near AP-0 Service Building	38.000	166.440	271.561[1]	805.157[1]	Table 6 > 1,000 cpm	No	AP-0 Service Building has two chipmunks set to trip at 5 mrem/hr and 15 mrem/hr
				342.000[2]	1482.980[2]			
44	Kautz Rd, near AP-0 Service Building	30.000	131.400	214.390[1]	635.651[1]	Table 6 > 1,000 cpm	No	AP-0 Service Building has two chipmunks set to trip at 5 mrem/hr and 15 mrem/hr
				270.000[2]	1170.774[2]			
45	Katuz Rd, just north of the front/North MI-8 Service Building parking lot	4.000	17.520	28.585[1]	84.753[1]	< 1,000 net cpm Bicron survey, but since intensity at the time of the survey was 1 order of magnitude lower than the Op. Limit intensity, any non-zero cpm scales to larger dose rates at the Op. Limit and therefore larger dose values assuming 24/7/365 occupancy.	No	None required – potential dose at standard 2,000 hr working-year less than 100 mrem. Area monitors have been added to the MI-8 Service Building.
				36.000[2]	156.103[2]			

Machine & Survey Location	Geographic Location	At Survey Intensity		Scaled to Op. Limit		Comments	Public Accessibility	Interlocked Radiation Detectors
		2,000 hr working-year (mrem)	24/7/365	2,000 hr working-year (mrem)	24/7/365			
MI/RR								
46	Indian Creek Rd, just past the back/South MI-8 Service Building parking lot	10.000	43.800	71.463[1] 90.000[2]	211.884[1] 390.258[2]	Table 6 > 1,000 cpm	No	None required – potential dose at standard 2,000 hr working-year less than 100 mrem. Area monitors have been added to the MI-8 Service Building.
F Sector								
6*	Main Ring Rd, North of AP-0 Service Building, near F23 Power Supply Building (same as location 5 for Muon Campus)	28	122.640	182.000[3] 77.538[4]	539.616[3] 229.896[4]	Table 6 > 1,000 cpm	No	AP-0 Service Building has two chipmunks set to trip at 5 mrem/hr and 15 mrem/hr
7[†]	Main Ring Rd, North of AP-0 Service Building, near F2 Service Building (same as location 6 for Muon Campus)	20.000	87.600	130.000[3] 55.385[4]	385.440[3] 164.211[4]	Table 6 > 1,000 cpm	No	AP-0 Service Building has two chipmunks set to trip at 5 mrem/hr and 15 mrem/hr

Machine & Survey Location	Geographic Location	At Survey Intensity		Scaled to Op. Limit		Comments	Public Accessibility	Interlocked Radiation Detectors
		2,000 hr working-year (mrem)	24/7/365	2,000 hr working-year (mrem)	24/7/365			
F Sector								
8	Main Ring Rd, near F27 Power Supply Building	6.000	26.280	39.000[3]	115.632[3]	Elevated count rates expected here due to Muon Campus targeting operations. The nearby F2 Refrigerator Building already contains an area monitor as part of the routine area monitoring program.	No	AP-0 Service Building has two chipmunks set to trip at 5 mrem/hr and 15 mrem/hr
				16.615[4]	49.263[4]			
Muon Campus								
5*	Main Ring Rd, North of AP-0 Service Building, near F23 Power Supply Building (same as location 6 for F Sector)	28	122.640	120.960	358.637	Table 6 > 1,000 cpm	No	AP-0 Service Building has two chipmunks set to trip at 5 mrem/hr and 15 mrem/hr

Machine & Survey Location	Geographic Location	At Survey Intensity		Scaled to Op. Limit		Comments	Public Accessibility	Interlocked Radiation Detectors
		2,000 hr working-year (mrem)	24/7/365	2,000 hr working-year (mrem)	24/7/365			
Muon Campus								
6[+]	Main Ring Rd, North of AP-0 Service Building, near F2 Service Building (same as location 7 for F Sector)	24	105.120	103.680	307.403	Table 6 > 1,000 cpm	No	AP-0 Service Building has two chipmunks set to trip at 5 mrem/hr and 15 mrem/hr
7	AP0 Service Building parking lot.	108	473.040	466.560	1383.315	Table 3 > 0.05 mR/hr	No	AP-0 Service Building has two chipmunks set to trip at 5 mrem/hr and 15 mrem/hr
8	Kautz Rd, North of AP-0 Service Building & South of MI-8 Service Building	18.000	78.840	77.760	230.552	Table 6 > 1,000 cpm	No	AP-0 Service Building has two chipmunks set to trip at 5 mrem/hr and 15 mrem/hr

Machine & Survey Location	Geographic Location	At Survey Intensity		Scaled to Op. Limit		Comments	Public Accessibility	Interlocked Radiation Detectors
		2,000 hr working-year (mrem)	24/7/365	2,000 hr working-year (mrem)	24/7/365			
Muon Campus								
10[N]	On Indian Creek Road, above the end of the Transport DS enclosure and start of the Delivery Ring enclosure.	217.34	1,008.364	869.789	2578.857	Table 7 neutron dose	No	Several chipmunks in AP0 Service Building set to trip at either 15 mrem/hr or 5 mrem/hr and AP-10 Service Building set to trip at 2.5 mrem/hr. Also a chipmunk at the Transport DS/Delivery Ring gate in the enclosure set to trip at rate of 5 mrem/hr when Delivery Ring is in access.

[N] due to neutron dose (all others due to gamma dose)

[1] scaled to MI Operating Limit intensity

[2] scaled to RR Operating Limit intensity

[3] scaled to P1-P2 Line to Muon Campus Operating Limit intensity

[4] scaled to P1-P2 Line to Switchyard Operating Limit intensity

* same physical location surveyed in two machine surveys, counted as one location

† same physical location surveyed in two machine surveys, counted as one location

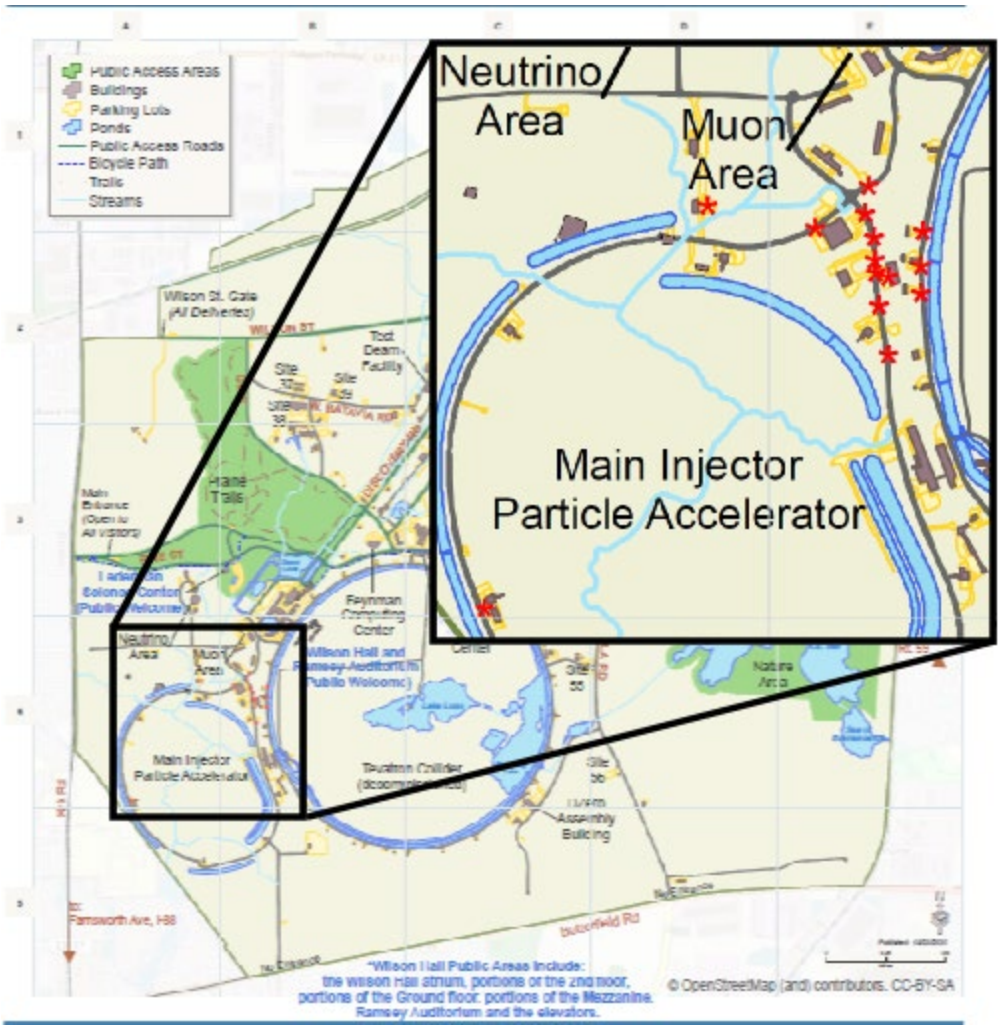

Figure 1. Map of Locations > 100 mrem/year for 24/7/365 Occupancy Overlaid on the Fermilab Public Area Map

Interlocked Radiation Detectors – From Running Conditions

BNB Interlocked Detectors

MUX	Type	Location	QF	R/I Mode	Trip Level	CDC	Device(s) Tripped
1-150	Chipmunk	MI-12 Serv. Bldg Upstairs Stripline Pen.	5	Integrate	5 mrem/hr	E:BNECRD	E:HV860 & BS860
1-148	Chipmunk	MI-12B Shield Blocks	5	Integrate	5 mrem/hr	E:BNECRD	E:HV860 & BS860
1-147	Chipmunk	MI-12 Service Building Downstream	5	Integrate	5 mrem/hr	E:BNECRD	E:HV860 & BS860
1-146	Chipmunk	MiniBooNE Berm US of MI-12	5	Integrate	1 mrem/hr	E:BNECRD	E:HV860 & BS860
1-145	Chipmunk	MiniBooNE Berm Indian Creek Culvert	5	Integrate	1 mrem/hr	E:BNECRD	E:HV860 & BS860
1-144	Chipmunk	MiniBooNE Indian Creek Road	5	Integrate	1 mrem/hr	E:BNECRD	E:HV860 & BS860
1-137	Chipmunk	MI-12A Upstream Berm	5	Integrate	1 mrem/hr	E:BNECRD	E:HV860 & BS860

MI/RR Interlocked Detectors

MUX	Type	Location	QF	R/I Mode	Trip Level	CDC	Device(s) Tripped
1-136	Chipmunk	MI-10 SB LCW	1	Integrate	2.5 mrem/hr	I:MICRD	I:LAM10 & BS10
1-160	Chipmunk	MI-20 SB LCW	1	Integrate	2.5 mrem/hr	I:MICRD	I:LAM10 & BS10
1-169	Chipmunk	MI-30 SB LCW	1	Integrate	2.5 mrem/hr	I:MICRD	I:LAM10 & BS10
1-186	Chipmunk	MI-40 SB LCW	1	Integrate	2.5 mrem/hr	I:MICRD	I:LAM10 & BS10
1-192	Chipmunk	MI-50 SB LCW	1	Integrate	2.5 mrem/hr	I:MICRD	I:LAM10 & BS10
1-200	Chipmunk	MI-52 SB LCW	1	Integrate	2.5 mrem/hr	I:MICRD	I:LAM10 & BS10
1-216	Chipmunk	MI-62 SB LCW	1	Integrate	2.5 mrem/hr	I:MICRD	I:LAM10 & BS10
1-208	Chipmunk	MI-60 S Room 117 Pipe & BUS Pen.	5	Integrate	5 mrem/hr	I:MICRD	I:LAM10 & BS10
1-209	Chipmunk	MI-60 S Room 110 LCW Pens RF Gal	5	Integrate	5 mrem/hr	I:MICRD	I:LAM10 & BS10
1-210	Chipmunk	MI-60 N Room 110 LCW Pens RF Gal	5	Integrate	5 mrem/hr	I:MICRD	I:LAM10 & BS10
1-211	Chipmunk	MI-60 N Room 118 LCW Pen	5	Integrate	5 mrem/hr	I:MICRD	I:LAM10 & BS10
1-212	Chipmunk	MI-60 N Room 118 Pen	5	Integrate	5 mrem/hr	I:MICRD	I:LAM10 & BS10

F-Sector (P1-P2 Line) Interlocked Detectors

MUX	Type	Location	QF	R/I Mode	Trip Level	CDC	Device(s) Tripped
2-244	Chipmunk	F1 Refrigerator Building	5	Integrate	50 mrem/hr	I:P1CRD	R:LAM52, R:V703, I:LAM52, I:V701
2-228	Chipmunk	F0 Service Building Penetration #1	5	Rate	5 mrem/hr	I:P1CRD	R:LAM52, R:V703, I:LAM52, I:V701
2-229	Chipmunk	F0 Service Building Penetration #2	5	Rate	5 mrem/hr	I:P1CRD	R:LAM52, R:V703, I:LAM52, I:V701
2-230	Chipmunk	F0 Service Building Penetration #3	5	Rate	5 mrem/hr	I:P1CRD	R:LAM52, R:V703, I:LAM52, I:V701
2-231	Chipmunk	F0 Service Building Penetration #4	5	Rate	5 mrem/hr	I:P1CRD	R:LAM52, R:V703, I:LAM52, I:V701
2-232	Chipmunk	F0 Service Buildign Penetration #5	5	Rate	5 mrem/hr	I:P1CRD	R:LAM52, R:V703, I:LAM52, I:V701
2-233	Chipmunk	F0 Service Building Penetration #6	5	Rate	5 mrem/hr	I:P1CRD	R:LAM52, R:V703, I:LAM52, I:V701
2-234	Chipmunk	F0 Service Building Penetration #7	5	Rate	5 mrem/hr	I:P1CRD	R:LAM52, R:V703, I:LAM52, I:V701
2-235	Chipmunk	F0 Service Building Penetration #8	5	Rate	5 mrem/hr	I:P1CRD	R:LAM52, R:V703, I:LAM52, I:V701

Muon Campus Interlocked Detectors for both On- and Off-Target Modes

MUX	Type	Location	QF	R/I Mode	Trip Level	CDC	Device(s) Tripped
2-071	TLM	Muon Campus Prevault		Integrate	3000 nC/min	D:M1CDC	I:F17B3 & M:HV100
2-065	Chipmunk	AP-1 Entrance - PreTarget Access Hutch	5	Integrate	5 mrem/hr	D:M1CDC	I:F17B3 & M:HV100
2-069	Chipmunk	AP0 South Vault Wall	5	Integrate	15 mrem/hr	D:M1CDC	I:F17B3 & M:HV100
2-064	Chipmunk	AP0 South Building Wall	5	Integrate	5 mrem/hr	D:M1CDC	I:F17B3 & M:HV100
2-075	Chipmunk	Transport DS/Delivery Ring Gate	5	Rate	5 mrem/hr	D:M1CDC	I:F17B3 & M:HV100
2-080	Chipmunk	AP-10 North Door	5	Integrate	2.5 mrem/hr	D:DELCDC	D:H812 (g-2) or D:H700 (Mu2e) & BS707
2-081	Chipmunk	AP-10 A17R05	5	Integrate	2.5 mrem/hr	D:DELCDC	D:H812 (g-2) or D:H700 (Mu2e) & BS707
2-082	Chipmunk	AP-10 A16R07	5	Integrate	2.5 mrem/hr	D:DELCDC	D:H812 (g-2) or D:H700 (Mu2e) & BS707
2-083	Chipmunk	AP-10 A16R03	5	Integrate	2.5 mrem/hr	D:DELCDC	D:H812 (g-2) or D:H700 (Mu2e) & BS707
2-084	Chipmunk	AP-10 D:QS	5	Integrate	2.5 mrem/hr	D:DELCDC	D:H812 (g-2) or D:H700 (Mu2e) & BS707
2-085	Chipmunk	AP-10 D:QD	5	Integrate	2.5 mrem/hr	D:DELCDC	D:H812 (g-2) or D:H700 (Mu2e) & BS707
2-086	Chipmunk	AP-10 A14R03	5	Integrate	2.5 mrem/hr	D:DELCDC	D:H812 (g-2) or D:H700 (Mu2e) & BS707
2-087	Chipmunk	AP-10 A14R0Y	5	Integrate	2.5 mrem/hr	D:DELCDC	D:H812 (g-2) or D:H700 (Mu2e) & BS707
2-088	Chipmunk	AP-10 MCR SW Door	5	Integrate	2.5 mrem/hr	D:DELCDC	D:H812 (g-2) or D:H700 (Mu2e) & BS707
2-089	Chipmunk	AP-10 Bay A13 South	5	Integrate	2.5 mrem/hr	D:DELCDC	D:H812 (g-2) or D:H700 (Mu2e) & BS707
2-090	Chipmunk	AP-10 Bay A12 North	5	Integrate	2.5 mrem/hr	D:DELCDC	D:H812 (g-2) or D:H700 (Mu2e) & BS707
2-091	Chipmunk	AP-10 A2R01	5	Integrate	2.5 mrem/hr	D:DELCDC	D:H812 (g-2) or D:H700 (Mu2e) & BS707
2-092	Chipmunk	AP-10 SW Rollup Door	5	Integrate	2.5 mrem/hr	D:DELCDC	D:H812 (g-2) or D:H700 (Mu2e) & BS707
2-093	Chipmunk	AP-10 South Door	5	Integrate	2.5 mrem/hr	D:DELCDC	D:H812 (g-2) or D:H700 (Mu2e) & BS707
2-096	Chipmunk	AP-30 South Door	5	Integrate	2.5 mrem/hr	D:DELCDC	D:H812 (g-2) or D:H700 (Mu2e) & BS707
2-097	Chipmunk	AP-30 S Rollup Door	5	Integrate	2.5 mrem/hr	D:DELCDC	D:H812 (g-2) or D:H700 (Mu2e) & BS707
2-098	Chipmunk	AP-30 D:H744	5	Integrate	2.5 mrem/hr	D:DELCDC	D:H812 (g-2) or D:H700 (Mu2e) & BS707
2-099	Chipmunk	AP-30 D:QT303	5	Integrate	2.5 mrem/hr	D:DELCDC	D:H812 (g-2) or D:H700 (Mu2e) & BS707
2-100	Chipmunk	AP-30 A35R07	5	Integrate	2.5 mrem/hr	D:DELCDC	D:H812 (g-2) or D:H700 (Mu2e) & BS707
2-101	Chipmunk	AP-30 A35R01	5	Integrate	2.5 mrem/hr	D:DELCDC	D:H812 (g-2) or D:H700 (Mu2e) & BS707
2-102	Chipmunk	AP-30 D:ISEP	5	Integrate	2.5 mrem/hr	D:DELCDC	D:H812 (g-2) or D:H700 (Mu2e) & BS707
2-103	Chipmunk	AP-30 A34R03	5	Integrate	2.5 mrem/hr	D:DELCDC	D:H812 (g-2) or D:H700 (Mu2e) & BS707
2-104	Chipmunk	AP-30 A33R07	5	Integrate	2.5 mrem/hr	D:DELCDC	D:H812 (g-2) or D:H700 (Mu2e) & BS707
2-105	Chipmunk	AP-30 A33R01	5	Integrate	2.5 mrem/hr	D:DELCDC	D:H812 (g-2) or D:H700 (Mu2e) & BS707
2-106	Chipmunk	AP-30 D:ELAM	5	Integrate	2.5 mrem/hr	D:DELCDC	D:H812 (g-2) or D:H700 (Mu2e) & BS707
2-107	Chipmunk	AP-30 D:V906	5	Integrate	2.5 mrem/hr	D:DELCDC	D:H812 (g-2) or D:H700 (Mu2e) & BS707
2-108	Chipmunk	AP-30 NE Rollup Door	5	Integrate	2.5 mrem/hr	D:DELCDC	D:H812 (g-2) or D:H700 (Mu2e) & BS707
2-109	Chipmunk	AP-30 North Door	5	Integrate	2.5 mrem/hr	D:DELCDC	D:H812 (g-2) or D:H700 (Mu2e) & BS707
2-112	Chipmunk	AP-50 West Door	5	Integrate	2.5 mrem/hr	D:DELCDC	D:H812 (g-2) or D:H700 (Mu2e) & BS707
2-113	Chipmunk	AP-50 A57R07	5	Integrate	2.5 mrem/hr	D:DELCDC	D:H812 (g-2) or D:H700 (Mu2e) & BS707
2-114	Chipmunk	AP-50 A57R01	5	Integrate	2.5 mrem/hr	D:DELCDC	D:H812 (g-2) or D:H700 (Mu2e) & BS707
2-115	Chipmunk	AP-50 A56R04	5	Integrate	2.5 mrem/hr	D:DELCDC	D:H812 (g-2) or D:H700 (Mu2e) & BS707
2-116	Chipmunk	AP-50 A55R08	5	Integrate	2.5 mrem/hr	D:DELCDC	D:H812 (g-2) or D:H700 (Mu2e) & BS707
2-117	Chipmunk	AP-50 A55R02 RFPA	5	Integrate	2.5 mrem/hr	D:DELCDC	D:H812 (g-2) or D:H700 (Mu2e) & BS707
2-118	Chipmunk	AP-50 D:SEXFV	5	Integrate	2.5 mrem/hr	D:DELCDC	D:H812 (g-2) or D:H700 (Mu2e) & BS707
2-119	Chipmunk	AP-50 D:VA03	5	Integrate	2.5 mrem/hr	D:DELCDC	D:H812 (g-2) or D:H700 (Mu2e) & BS707
2-120	Chipmunk	AP-50 A53R07	5	Integrate	2.5 mrem/hr	D:DELCDC	D:H812 (g-2) or D:H700 (Mu2e) & BS707
2-121	Chipmunk	AP-50 A53R01	5	Integrate	2.5 mrem/hr	D:DELCDC	D:H812 (g-2) or D:H700 (Mu2e) & BS707
2-122	Chipmunk	AP-50 Abort Kicker	5	Integrate	2.5 mrem/hr	D:DELCDC	D:H812 (g-2) or D:H700 (Mu2e) & BS707
2-123	Chipmunk	AP-50 D:ASEP	5	Integrate	2.5 mrem/hr	D:DELCDC	D:H812 (g-2) or D:H700 (Mu2e) & BS707
2-124	Chipmunk	AP-50 East Rollup Door	5	Integrate	2.5 mrem/hr	D:DELCDC	D:H812 (g-2) or D:H700 (Mu2e) & BS707
2-125	Chipmunk	AP-50 East Door	5	Integrate	2.5 mrem/hr	D:DELCDC	D:H812 (g-2) or D:H700 (Mu2e) & BS707

Muon Campus Additional Interlocked Detectors when in On-Target Mode

1-001	Chipmunk	MC-1 DS of Q023	5	Integrate	2.5 mrem/hr	D:MC1CDC	D:V003 & D:H005
1-002	Chipmunk	MC-1 g-2 Ring Center	5	Integrate	2.0 mrem/hr	D:MC1CDC	D:V003 & D:H005

Muon Campus Additional Interlocked Detectors when in Off-Target Mode

1-019	Chipmunk	M4 7 foot drop Gate	5	Integrate	1.0 mrem/hr	D:M4CDC	D:H910
1-003	Chipmunk	MC-1 Hall Extraction Stub Gate	5	Rate	2.5 mrem/hr	D:M4CDC	D:H910

Conclusion

The purpose of this initial qualitative survey was to identify areas that warrant further investigation and focus. These surveys identified no locations that are accessible to the public that could exceed the dose limit to members of the public assuming the standard 2,000 hour working-year occupancy, and no locations that are accessible to the public that could exceed the dose limit to members of the public assuming 24/7/365 occupancy and standard beam up-time. Additionally, this survey identified a few locations that warrant additional area monitor dosimeters to be deployed for continuous monitoring through the routine area monitoring program, as well as locations that warrant follow-up survey.

- One (1) location with gamma dose rates > 0.05 mR/hr.
    - This building is not accessible to the public.
    - Area monitors have already been added to the adjacent north & south vestibules and have been added to the routine monitoring program. Additional area monitor(s) will need to be added in the center of the building, in the parking lot to continue monitoring that location as well. (Recommendation 1) Based on area monitoring results, additional postings to limit occupancy in the area may be needed.
    - This location will need to be posted as a Controlled Area, as required by FRCM Chapter 2.[8] (Recommendation 2)
- Nine (9) locations with elevated count rates, but with dose rates < 0.025 mR/hr.
    - These locations are not accessible to the public.
    - These locations will continue to be monitored through the routine area monitoring program. No additional area monitors needed.
- One (1) location with non-zero neutron dose rates.
    - This location is not accessible to the public
    - It is suspected that this reading may have been due to user error (i.e., bumping the instrument during the survey), or within the error bars for background readings. Repeat REM500 surveys should be conducted to determine. (Recommendation 3)
    - Pending results of repeat REM500 surveys, this location may warrant additional investigation, such as repeat neutron measurements, review of previous chipmunk studies, and/or review of the shielding assessment. In particular, special attention should be given to this areas as plans progress to increase beam intensity for Mu2e operations. Based on the results of this additional investigation, postings may need to be applied.

Ongoing monitoring of locations will be handled through the routine area monitoring program, which will capture dose throughout the quarter including if/when intensities increase.

Attached at the end of the report, the following information is provided for each machine survey:

- Background survey including beam intensity plot printout via ACNET
- Beam-on survey including beam intensity plot printout via ACNET
- Gamma & Neutron results table
- Results scaled from survey intensity to Operating Limit intensity and calculations for annual dose, assuming standard beam up-time when looking at 24/7/365 occupancy

Recommendations

1. Additional area monitor dosimeters should be placed at the following locations:
    a. AP-0 Service Building Parking Lot, between the service building and the parking lot (Muon Campus Location 7)
    b. AP-0 Service Building Parking Lot, between the parking lot and the road
    c. Near Indian Creek Road, over Muon Campus beamline (Muon Campus Location 10)
2. Controlled Area postings should be placed around the AP-0 Parking Lot.
3. Repeat REM500 neutron survey measurements should be taken at Muon Campus Location 10 to determine if the original measurement was inaccurate due to user error or is statistically indistinguishable from background.
    - Completed 2/8/2021 – still showing neutron results. Recommend installing area monitors to continue monitoring and evaluation. (Added to Recommendation 1)
4. Confirm that sufficient signage is in place in the field to indicate areas where public is not permitted (i.e., all potential entrances to a side road off of Discovery Rd, potential “non-routine” routes that may be taken, etc.).

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[2] R.P. Note 109 *Radioactivity Release Criteria for Materials, Equipment and Waste.* Rev. 1. May 2013. https://esh-docdb.fnal.gov/cgi-bin/sso/ShowDocument?docid=2202

[3] ADAP-11-0003 *Approved Accelerator Beam Intensity Operating Limits*. Rev. 11. August 25, 2020. https://beamdocs.fnal.gov/AD-private/DocDB/ShowDocument?docid=4977

[4] Knoll, G. F. (2000). *Radiation Detection and Measurement, 3rd Edition.* Equations 3.38, 3.58 & 3.59.

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