TITLE: 1996 DESIGN EFFORT FOR IFMIF HEBT

AUTHOR(S): Barbara Blind AOT-1

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1996 Design Effort for IFMIF HEBT

Barbara Blind

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Introduction

The paper details the 1996 design effort for the IFMIF HEBT. Following a brief overview, it lists the primary requirements for the beam at the target, describes the design approach and design tools used, introduces the beamline modules, gives the results achieved with the design at this stage, points out possible improvements and gives the names and computer locations of the TRACE3-D and PARMILA files that sum up the design work.

The design does not fully meet specifications in regards to the flatness of the distribution at the target. With further work, including if necessary some backup options, the flatness specifications may be realized. It is not proposed that the specifications, namely flatness to $\pm 5\%$ and higher-intensity ridges that are no more than 15% above average, be changed at this time. The design also does not meet the requirement that the modules of all beamlines should operate at the same settings. However, the goal of using identical components and operational procedures has been met and only minor retuning is needed to produce very similar beam distributions from all beamlines.

Significant further work is required in the following areas: TRACE3-D designs and PARMILA runs must be made for the beams coming from accelerators #3 and #4. Transport of 30-MeV and 35-MeV beams to the targets and beam dump must be studied. Comprehensive error studies must be made. These must result in tolerance specifications and may require design iterations. Detailed interfacing with target-spot instrumentation is required. This instrumentation must be able to check all aspects of the specifications.

Overview

The fully implemented IFMIF system will consist of four accelerators, two targets and one beam dump. A schematic layout of this system is shown in Figure 1.

The high-energy-beam-transport system (HEBT) will be capable of taking the beam from each accelerator to either one of the two targets or the beam dump. A goal for the HEBT design was to make the manipulations of the beam by all beamlines as near the same as possible. This results in similar beam dynamics for each line and also minimizes the different kinds of magnetic elements needed. In order to accomplish this goal, periodic lattices with buncher cavities are an important component of the HEBT.

In beamline order, the HEBT consists of a six-dimensional matching section between the accelerator and the first or "upstream" periodic lattice, an upstream periodic lattice, a 90° achromatic bend, a six-dimensional matching section between the bend and the second or "downstream" periodic lattice, a downstream periodic lattice, a four-dimensional (transverse) matching section for the nonlinear expander, a nonlinear expander, an imager, a momentum-compacting cavity, a final bend, and a couple of energy-dispersing cavities.

The accelerators are at different elevations; accelerator #1 is 4.9 m above accelerator #2, and accelerator #3 is 1.2 m below accelerator #4. This causes a slightly different beam transport for the two kinds of lines, those from accelerators #1 and #2 with a final bend consisting of a 10° vertical dipole and those from accelerators #3 and #4 with a final bend consisting of a 2.388° vertical dipole followed by a 10.008° horizontal dipole.

For the HEBT design work, the beamline was assumed to have one upstream periodic lattice and two downstream periodic lattices. This is the nominal beamline for which the HEBT was optimized. It, in fact, represents the line from accelerator #2 to the beam dump. The schematic layout of the nominal beamline is shown in Figure 2 (white boxes). The line from accelerator #1 to the near (from the perspective of accelerators #1 and #2) target is also shown (shaded boxes).

This beamline will be referred to as the shortest beamline. Similarly, the line from accelerator #2 to the far (from the perspective of accelerators #1 and #2) target will be called the longest beamline.

Requirements for Beam at Target

Early specifications detailed the desired beam-intensity distribution at the target. These specifications are repeated here.

The beam should have a 20 cm (horizontal) by 5 cm (vertical) footprint (flat top), with a density uniformity of $\pm 5\%$. To avoid significant heating of adjacent structures, there should be a sharp drop-off in beam intensity beyond the vertical edges. In the consequential higher-intensity ridges near the vertical edges of the beam, the peak current density must not exceed the average density by more than 15%. In each of the two horizontal edges, the beam intensity must be tapered over about 1.0 cm to avoid shocking the flowing lithium target with a sudden increase in deposited power.

A sketch of the desired horizontal beam profile is shown in Figure 3, illustrating the ridges near the vertical edges and the sharp drop-off in beam intensity beyond the vertical edges. A sketch of the desired vertical beam profile is shown in Figure 4, illustrating the more gradual horizontal edges.

For one 125-mA (nominal current) beam, the average current density in the flat top is about 1.04 mA/cm^2 . A maximum current density in the higher-intensity ridges of 1.20 mA/cm^2 follows. No more than $0.5 \text{ } \mu\text{A/cm}^2$ of beam should be beyond the edges, meaning beyond $|x| > 11 \text{ cm}$. With a current density of 2.08 mA/cm^2 from both beams, this means a reduction in beam intensity by a factor of 4160.

The desired energy profile should have a full-width at half-maximum of somewhat over 1 MeV, as shown in Figure 5. For a beam with a nominal energy of 40 MeV, no particle in the distribution is to exceed 41 MeV. The original plan was to achieve this energy profile in a time-average sense using a last cavity with a frequency of about 1 MHz to successively accelerate and decelerate the beam by up to 0.5 MeV. The actual approach taken is to widen the beam-energy profile with the two 175-MHz energy-dispersing cavities downstream of the final bend.

Design Approach

Input Beam Used

All HEBT design work was performed for deuterons of 40.2192 MeV, the synchronous energy of the output beam of the PARMILA deck describing the accelerator, and for a beam current of 134.59 mA, the output-beam current from the accelerator.

In the input-beam card, the PARMILA deck for the HEBT specified a -46 distribution with the same Twiss parameters and rms emittances as the accelerator output beam. This input beam is Gaussian distributed and is truncated at 4 rms. The output beam from a 4000-particle run of the PARMILA accelerator deck was not used for the design work: the input card used made it possible to produce any number of particles desired, typically 1000 to 10000 for the design work and 100000 for final checks. The -46 distribution has transverse profiles that are essentially identical to those of the accelerator output beam. However, while the -46 distribution has a symmetric energy profile, the accelerator output beam has a skewed energy profile of about the same half-width at half-maximum. Figure 6 shows the transverse profiles and Figure 7 shows

the energy profile for 100000 particles with a -46 distribution. Figures 8 and 9 show the same for the 4000-particle accelerator output beam.

Design Tools Used

The 90° bend, a zero-current achromatic bend, was designed using TRANSPORT. Its chromatic aberrations were compared to those of a Karl Brown-type achromatic bend using MARYLIE.

Aside from the 90° achromatic bend, the HEBT to the end of the downstream periodic lattices was designed using TRACE3-D with the nominal Twiss parameters and rms emittances of the accelerator output beam. In all cases, instead of running TRACE3-D with the full current and a beam having an extent of $\sqrt{5}$ rms, the program was run with rms parameters and $1/(5\sqrt{5})$ of the full current.

The design to the end of the downstream periodic lattices was then simulated with a 100000-particle PARMILA run. Subsequently, the HEBT from the end of the downstream periodic lattices through the nonlinear expander was designed using TRACE3-D with the Twiss parameters and rms emittances from this 100000-particle PARMILA run.

The beam imager was designed by iterating between TRANSPORT optimizations and PARMILA runs, to get the right beam size at the target.

The final step in the HEBT design was to use TRACE3-D to adjust the nonlinear-expander matching section for optimum flatness of the beam distribution at the target, with feedback from PARMILA.

Two changes were made to the VAX version of PARMILA in order to be able to execute the design work. The limit on the number of particles allowed was raised from 10000 to 100000 and a vertical bend was incorporated in the code.

Final Product

In the end, the PARMILA deck was scaled from the settings for 40.2192-MeV deuterons to settings for 40.2496-MeV deuterons, because it was discovered that the average energy of the accelerator output beam is 40.2496 MeV, even though the synchronous energy is 40.2192 MeV. When operating an accelerator facility, one would presumably measure the beam energy in the HEBT and set the magnets accordingly. Thus, the final product of the HEBT design work was a PARMILA deck that can be combined with the PARMILA deck for the accelerator to perform end-to-end runs. In addition, PARMILA decks for the shortest beamline and the longest beamline were generated.

Evaluation of Design

To assess the beam distribution at the target, the PARMILA deck for the nominal beamline was used to track 100000 particles of a -46 distribution. The 4000-particle accelerator output beam was also sent through the HEBT, resulting in transverse profiles at the target that are essentially identical to the ones from the -46 input-beam distribution. The longitudinal profile is of course different in the two cases.

Additionally, 100000-particle runs were performed with the PARMILA deck for the shortest beamline (from accelerator #1 to the near target) and with the PARMILA deck for the longest beamline (from accelerator #2 to the far target). These runs illustrate the kinds of variations to be

expected in the beam distribution when the components of all beamlines are running at exactly the same settings.

Description of Beamline Modules

General Remarks

In the actual operation of the facility, the accelerating cavities will be adjusted to achieve a deuteron beam with an average energy of exactly 40 MeV. All magnet settings listed below are those for a beam with an average energy of 40 MeV. They were obtained by multiplying the settings from the HEBT design work by the quotient of the beam rigidity of 40-MeV deuterons and the beam rigidity of 40.2192-MeV deuterons.

The lengths in all tables are effective straight lengths for quadrupoles and effective arc lengths for dipoles, and are given in units of cm. Drift lengths are also given in units of cm. The strengths in all tables are field strengths in T for dipoles, gradients in T/m for quadrupoles, octupole components in T/m³ and duodecapole components in T/m⁵ for nonlinear elements, and effective gap voltages in MV for cavities.

Periodic Lattices

The purpose of the periodic lattices is to achieve the desired geometry for the entire IFMIF system and to build a network of beamlines that all have the same linear beam optics, thus theoretically achieving the same beam on target with all lines. This requires periodic lattices with both transverse and longitudinal focusing.

In order to conform to the desired regular grid of lines from the accelerators and lines to the targets and beam stop, two kinds of periodic lattices were configured, an upstream periodic lattice with a symmetric quadrupole doublet every 2.4 m and with a buncher cavity in the center of every third cell, and a downstream periodic lattice with a symmetric quadrupole doublet every 2.75 m and with a buncher cavity in the center of every other cell. The length of the upstream periodic lattice is consistent with 7.2-m lateral distances between either target and the beam dump. The length of the downstream periodic lattice is consistent with 11.0-m horizontal distances between accelerators #1 and #2, 11.0-m horizontal distances between accelerators #3 and #4, and 5.5-m horizontal distances between accelerators #1 and #3 and accelerators #2 and #4.

In order to minimize the number of components, both periodic lattices have doublets of the same gradients. The upstream and downstream periodic lattices have cavities of such strengths as to provide approximately the same longitudinal focusing along the beamline. The components of the upstream periodic lattice are listed in Table 1, the components of the downstream periodic lattice are listed in Table 2.

Before choosing a gradient for the symmetric quadrupole doublet of the periodic lattices, TRACE3-D was used to study, as a function of quadrupole strength, the transverse matched-beam envelopes for one upstream-periodic-lattice cell without a cavity and with an input beam having the longitudinal properties of the accelerator output beam. For very weak quadrupoles, the matched beam is large in the quadrupoles. With increasing quadrupole strength, the matched-beam size in the quadrupoles first decreases, but remains approximately constant above a certain gradient. At that point, the effect of increasing the quadrupole strength instead is a more narrow waist between doublets. The gradient was chosen such that the beam size is small in the quadrupoles without a narrow waist between doublets.

The strengths of the cavities were chosen so that the full beam covers about $\pm 45^\circ$ in phase.

The matched beams of the periodic lattices were determined using TRACE3-D. The rms beam envelopes for the upstream periodic lattice are shown in Figure 10, and the rms beam envelopes for the downstream periodic lattice are shown in Figure 11.

Table 1. Upstream periodic lattice.
Lengths are in units of cm, quadrupole strengths are in units of T/m
and cavity strengths are effective gap voltages in units of MV.

description of element	length	strength
periodic-lattice F quad	12.0	+21.5803
drift	12.0	
periodic-lattice D quad	12.0	-21.5803
drift	102.0	
upstream-periodic-lattice rf gap	0	0.199448
drift	102.0	
periodic-lattice F quad	12.0	+21.5803
drift	12.0	
periodic-lattice D quad	12.0	-21.5803
drift	204.0	
periodic-lattice F quad	12.0	+21.5803
drift	12.0	
periodic-lattice D quad	12.0	-21.5803
drift	204.0	

Table 2. Downstream periodic lattice.
Lengths are in units of cm, quadrupole strengths are in units of T/m
and cavity strengths are effective gap voltages in units of MV.

description of element	length	strength
periodic-lattice F quad	12.0	+21.5803
drift	12.0	
periodic-lattice D quad	12.0	-21.5803
drift	239.0	
periodic-lattice F quad	12.0	+21.5803
drift	12.0	
periodic-lattice D quad	12.0	-21.5803
drift	119.5	
downstream-periodic-lattice rf gap	0	0.149586
drift	119.5	

Matching Section between Accelerator and Upstream Periodic Lattice

The first module downstream of the accelerator is a six-quadrupole, three-cavity matching section that matches the accelerator output beam in all six dimensions to the matched beam of the upstream periodic lattice.

In designing this matching section, it was discovered that the formation of transverse halo can be minimized with the appropriate settings of a first, symmetric, quadrupole doublet. The next four quadrupoles and the three cavities accomplish the actual match. Only two cavities are needed to match longitudinal phase space, but the second cavity would be too strong and was replaced by two identical cavities in order to stay at reasonable fields. To minimize the cavity voltages, the last two cavities are a fair distance from the first cavity, with two periodic-lattice doublets and a substantial drift between them.

The components of the first matching section are listed in Table 3. The rms beam envelopes through the matching section are shown in Figure 12.

Table 3. Matching section between accelerator and upstream periodic lattice.
Lengths are in units of cm, quadrupole strengths are in units of T/m
and cavity strengths are effective gap voltages in units of MV.

description of element	length	strength
last accelerator quadrupole	8.0105	-60.2534
drift	24.5	
symmetric-doublet quad	12.0	+31.9118
drift	24.5	
symmetric-doublet quad	12.0	-31.9118
drift	24.5	
first matching-section quad	12.0	+29.2291
drift	24.5	
second matching-section quad	12.0	-23.3896
drift	65.0	
third matching-section quad	12.0	+25.5721
drift	12.0	
fourth matching-section quad	12.0	-23.7120
drift	62.3	
first matching-section rf gap	0	+0.196088
drift	62.3	
periodic-lattice F quad	12.0	+21.5803
drift	12.0	
periodic-lattice D quad	12.0	-21.5803
drift	184.0	
periodic-lattice F quad	12.0	+21.5803
drift	12.0	
periodic-lattice D quad	12.0	-21.5803
drift	85.0	
second matching-section rf gap	0	+0.254726
drift	34.0	
third matching-section rf gap	0	+0.254726
drift	85.0	

90° Achromatic Bend

An achromatic bend of a substantial bend angle is needed because the accelerators should not be in line with the targets. Because there are accelerators on both sides of the targets, a bend angle of 90° is the only viable option.

After a thorough investigation of a number of different achromatic bends, it was decided to construct a bend with two 45° dipoles of 85-cm arc length (requiring a field of about 1.2 T to bend 40-MeV deuterons) and with a doublet between dipoles that is centered 2.40 m from the center of the doublet immediately upstream of the bend and 2.40 m from the center of the second doublet in the matching section downstream of the bend. This geometry assures that the longitudinal focusing is preserved, with two cells without buncher cavities following the cell with a buncher cavity just upstream of the bend.

Table 4 shows how the achromatic bend is embedded in the upstream periodic lattice.

TRANSPORT was used to achieve a zero-current achromatic bend, having a transfer matrix with $R_{16} = R_{26} = 0$. The simplest achromatic bend would have a focusing quadrupole centered

between the dipoles to simultaneously satisfy both requirements. However, such a bend would pose a large perturbation to the beam focus. With a doublet between dipoles, there is at least some vertical focusing. The strength of the achromatic-bend defocusing quadrupole was set, and the achromatic-bend focusing quadrupole and the drift downstream of the doublet were adjusted, to achieve achromaticity. For each setting of the achromatic-bend defocusing quadrupole, there is a different solution. The solution proposed here provides a fair amount of vertical focusing while also requiring a drift that is just about as short as reasonably possible, making the bend as compact as possible.

Obviously, the doublet is neither symmetric, nor is it symmetrically placed in the drift between dipoles. The beam envelopes stay reasonable through the bend in this configuration. The rms beam envelopes for the line of Table 4, including the achromatic bend, are shown in Figure 13.

Table 4. 90° achromatic bend embedded in upstream periodic lattice.

Lengths are in units of cm, dipole strengths are in units of T,
quadrupole strengths are in units of T/m,
and cavity strengths are effective gap voltages in units of MV.

description of element	length	strength
periodic-lattice F quad	12.0	+21.5803
drift	12.0	
periodic-lattice D quad	12.0	-21.5803
drift	102.0	
rf gap	0	0.199448
drift	102.0	
periodic-lattice F quad	12.0	+21.5803
drift	12.0	
periodic-lattice D quad	12.0	-21.5803
drift	15.0	
45° dipole	85.0	1.20024
drift	95.0	
achromatic-bend F quad	18.0	+17.55664
drift	18.0	
achromatic-bend D quad	18.0	-13.37287
drift	15.3787	
45° dipole	85.0	1.20024

An early concern with the bend was its possibly large chromatic aberrations. In this regard, a Karl Brown-type achromatic bend is expected to perform much better. Comparing an earlier version of the two-dipole bend to a Karl Brown-type achromatic bend (both designed for 35-MeV deuteron beams) showed that for a beam with an rms momentum deviation of 0.36% the Karl Brown-type achromatic bend performs only marginally better than the two-dipole bend. Thus, for the momentum deviations to be expected in the vicinity of the 90° bend (namely no more than $\pm 0.20\%$, corresponding to an energy spread of ± 0.16 MeV, for the full beam), the chromatic aberrations of the two types of bends should be very similar and use of a two-dipole bend should not pose a problem.

The two-dipole achromatic bend has the advantage that it is compact, has very few components, and allows for easy separation of the straight-ahead beam from the beam being bent.

Matching Section between 90° Achromatic Bend and Downstream Periodic Lattice

The four-quadrupole, two-cavity matching section downstream of the 90° achromatic bend matches the beam exiting the bend to the matched beam for the downstream periodic lattice. In

order to minimize the perturbation on the beam envelopes created by the 90° achromatic bend, the matching section is as close as possible to the bend and is very compact.

The components of the matching section are listed in Table 5. The two matching-section cavities have a combined strength that is about equal to the strength of a downstream-periodic-lattice cavity, a manifestation of the fact that the longitudinal focusing is almost perfectly continuous through the line. The rms beam envelopes for the matching section are shown in Figure 14.

Table 5. Matching section between 90° achromatic bend and downstream periodic lattice. Lengths are in units of cm, quadrupole strengths are in units of T/m and cavity strengths are effective gap voltages in units of MV.

description of element	length	strength
drift	15.0	
first matching-section quad	18.0	+16.2457
drift	15.0	
second matching-section quad	12.0	-16.0834
drift	34.621	
third matching-section quad	12.0	+12.6328
drift	12.0	
fourth matching-section quad	12.0	-12.1234
drift	68.0	
first matching-section rf gap	0	+0.151840
drift	68.0	
second matching-section rf gap	0	+0.022039
drift	68.0	

Matching Section for Nonlinear Expander

The four-quadrupole matching section for the nonlinear expander produces the proper transverse beam parameters into the first nonlinear element to achieve optimum flatness of the beam at the target. TRACE3-D was used to set these parameters. The input-beam parameters of the TRACE3-D deck were those from a 100000-particle run through the nominal beamline to that point.

Table 6 lists the elements of the matching section. The settings are those for the beam from accelerator #2 to the beam dump, provided that the beam distribution at the exit of the accelerator is indeed as assumed. For other distributions, this section needs adjustment. The settings were established after designing the entire line with preliminary settings, observing the profiles of the beam at the target, and adjusting the nonlinear-expander input beam accordingly.

Table 6. Matching section for nonlinear expander. Lengths are in units of cm and quadrupole strengths are in units of T/m.

description of element	length	strength
first matching-section quad	18.0	+9.1558
drift	18.0	
second matching-section quad	18.0	-14.4963
drift	40.0	
third matching-section quad	18.0	+11.2871
drift	18.0	
fourth matching-section quad	18.0	+2.3139
drift	40.0	

Nonlinear Expander

The nonlinear expander serves to initiate the beam redistribution that eventually results in an essentially flat, rectangular beam-intensity distribution at the target from a peaked, elliptical initial distribution. It does so by initiating the folding of transverse phase space that is the reason for the rectangular, near-uniform beam distribution at the target.

The quadrupoles and final drift of the nonlinear expander were adjusted with TRACE3-D to produce the proper horizontal input-beam parameters into the second nonlinear element as well as a vertical linear-beam waist in the center of the second nonlinear element. Here, a linear-beam waist describes the beam with the nonlinear elements turned off.

The elements of the nonlinear expander are listed in Table 7.

Table 7. Nonlinear expander.
Lengths are in units of cm, quadrupole strengths are in units of T/m,
and octupole (first number) and duodecapole (second number) components
of nonlinear elements are in T/m³ and T/m⁵, respectively.

description of element	length	strength
first nonlinear element	50.0	1.72842·10 ⁴ 2.39394·10 ⁷
drift	300.0	
F quad	50.0	+2.37183
drift	75.0	
D quad	50.0	-2.31234
drift	242.1	
second nonlinear element	50.0	1.72842·10 ⁴ 2.79284·10 ⁷

Imager

The six-quadrupole imager serves to produce the correct transverse beam sizes at the target and a horizontal linear-beam waist in the drift upstream of the target, while preserving the beam folding at the target. So far, finding a solution that has a vertical linear-beam waist in the drift upstream of the target as well, and still preserves the folding at the target, has not been successful.

With six quadrupoles, one can in principle adjust both the horizontal and vertical transfer matrix from its respective nonlinear element to the target to set the beam sizes and rms values of the beam edges at the target, as well as force linear-beam waists between the last element and the target. In practice, this approach was not successful. The attempt to set the transfer matrices was made both with TRANSPORT (without space charge) and with TRACE3-D (with space charge). These programs did achieve the desired transfer matrices, but subsequent simulations with PARMILA showed that the beam was not properly folded at the target, usually in the vertical plane. The approach of looking at beam envelopes with TRANSPORT to establish that the desired features had been achieved failed in a similar way. Where TRANSPORT might show a linear waist, PARMILA would not confirm this.

The solution presented here was arrived at after learning which types of TRANSPORT envelopes lead to PARMILA distributions that are indeed folded at the target and, starting from one of them, iterating to achieve the proper beam sizes at the target. Thus, the six-quadrupole imager was designed by establishing initial settings for the quadrupoles using TRANSPORT, running PARMILA and observing the actual beam sizes at the target, and in the next iteration asking for adjusted sizes in TRANSPORT. The elements of the imager are listed in Table 8.

Table 8. Imager.

Lengths are in units of cm, quadrupole strengths are in units of T/m.

description of element	length	strength
drift	300.0	
first imager quad	50.0	-1.46104
drift	100.0	
second imager quad	50.0	+0.96700
drift	100.0	
third imager quad	50.0	-0.82073
drift	100.0	
fourth imager quad	50.0	+0.64691
drift	300.0	
fifth imager quad	50.0	+0.85932
drift	100.0	
sixth imager quad	50.0	-1.00632

Final Bend and Energy-Manipulating Cavities

The final bend is a 10° vertical dipole down for accelerator #1, a 10° vertical dipole up for accelerator #2, a 2.388° vertical dipole up and 10.008° horizontal dipole to the left for accelerator #3, and a 2.388° vertical dipole down and 10.008° horizontal dipole to the right for accelerator #4. Replacing the 2.388° vertical dipole and 10.008° horizontal dipole in the lines of accelerators #3 and #4 by a 10° skew dipole is not an acceptable solution, due to undesirable beam-optics properties: a skew dipole produces a beam spot at the target that has the shape of a tilted parallelogram.

The cavity upstream of the final bend minimizes the momentum spread of the beam, to minimize the yE correlation at the target from the 10° vertical dipole or the xE correlation and yE correlation at the target from the 2.388° vertical dipole and 10.008° horizontal dipole.

The cavities downstream of the final bend achieve the desired beam-energy spread at the target. The beam has been debunching starting from the matching section for the nonlinear expander and covers enough phase at these cavities (approximately $\pm 90^\circ$) to where different phase extents for the different lines do not mean different minimum and maximum energies, only different energy profiles. In other words, with the cavities set at their nominal values, and for a 40-MeV deuteron beam, no particle can have an energy exceeding 41 MeV, one of the criteria specified for the HEBT.

Table 9 shows the line downstream of the last imager quadrupole for accelerators #1 and #2, and Table 10 shows the same for accelerators #3 and #4.

The dipoles were made much longer than necessitated by field limitations. This was done because otherwise the quadrupoles in the imagers of the lines from accelerators #1 and #2 would require very different gradients from those in the imagers of the lines from accelerators #3 and #4, due to the different dipole-edge focusing in the two kinds of lines. Of course, even for a small focusing effect due to the dipole(s), the two types of imagers will have to have slightly different quadrupole settings.

The horizontal dipole in the line for accelerators #3 and #4 has its odd length because it was assumed to physically be the same magnet as the vertical 10° dipole of the line for accelerators #1 and #2.

Table 9. Final bend and energy-manipulating cavities for accelerators #1 and #2.

Lengths are in units of cm, dipole strengths are in units of T and cavity strengths are effective gap voltages in units of MV.

description of element	length	strength
drift	35.0	
momentum-compacting rf gap	0	+0.099724
drift	39.2285	
10° vertical dipole	100.0	0.226711
drift	60.7715	
drift	25.0	
energy-dispersing rf gap	0	-0.365689
drift	50.0	
energy-dispersing rf gap	0	-0.365689
drift	25.0	
drift	1200.0	

Table 10. Final bend and energy-manipulating cavities for accelerators #3 and #4.

Lengths are in units of cm, dipole strengths are in units of T and cavity strengths are effective gap voltages in units of MV.

description of element	length	strength
drift	35.0	
momentum-compacting rf gap	0	+0.099724
drift	24.9978	
2.387899° vertical dipole	30.0	0.180454
drift	14.9402	
10.008° horizontal dipole	100.0002	0.226892
drift	30.89	
drift	25.0	
energy-dispersing rf gap	0	-0.365689
drift	50.0	
energy-dispersing rf gap	0	-0.365689
drift	25.0	
drift	1200.0	

PARMILA Deck

The PARMILA deck for the nominal beamline is shown in Appendix A.

In order to be compatible with the PARMILA deck for the accelerator, the PARMILA decks for the HEBT beamlines have the settings for a 40.2496-MeV deuteron beam.

Summary of HEBT Hardware

There need only be a small number of different magnetic elements in the HEBT, namely 12-cm-long and 18-cm-long quadrupoles with a bore radius of 3.5 cm, 50-cm-long quadrupoles with a bore radius of 10 cm, 45° dipoles with a 7-cm magnet gap, 10° dipoles with a 10-cm magnet gap and 2.388° dipoles with a 10-cm magnet gap, two nonlinear beamline elements with identical octupole strengths and very similar duodecapole strengths, buncher cavities with 2.2-cm aperture radii and buncher cavities with 4.0-cm aperture radii. All apertures are based on 10-rms clearances.

Results and Conclusions

Using PARMILA, 100000 particles of a -4σ distribution were tracked through the nominal beamline, the nominal beamline but with the momentum-compacting cavity turned off, the shortest beamline and the longest beamline. In each case, the horizontal, vertical and energy profile at the target was established. Also plotted were the xy, xE and yE scatter plots of the first 20000 particles.

Figures 15, 16, and 17 show the horizontal, vertical, and energy profile at the target, respectively, for the nominal beamline, that is, the beamline from accelerator #2 to the beam dump. This is the beamline for which the HEBT was optimized. Figures 18, 19, and 20 show the xy, xE and yE scatter plot, respectively. There should be no xE correlation, but there would be a noticeable yE correlation without the momentum-compacting cavity. The profiles do have the general characteristics desired. The horizontal profile does have a sharp edge, with only one out of 100000 particles at $|x| > 11$ cm. The flatness is not quite to specifications ($\pm 7\%$, rather than $\pm 5\%$), and the ridges near the edges are also higher than desired ($+24\%$, rather than $+15\%$). As desired, the vertical profile does have more gradual edges and good flatness. The energy profile does have a width of over 1 MeV, as desired. The width of this profile is easily adjustable with the last two cavities. With the average beam energy at 40.2496 MeV, the highest-energy particles exceed 41 MeV, but with the planned average beam energy of 40 MeV, they will not.

For comparison, the case of the nominal beamline but with the momentum-compacting cavity turned off is shown in Figures 21 through 26. The energy-dispersing cavities were adjusted to recover the nominal energy profile. This meant going from 0.3667-MV settings to 0.3-MV settings. None of the quadrupoles was adjusted. The general characteristics of the transverse profiles remain the same as before, but both profiles are slightly wider than the nominal ones, due to the different transverse focusing by the cavities. The original widths could be recovered by adjusting the imager quadrupoles. Figure 26, to be compared to Figure 20, shows the yE correlation expected for the line without a momentum-compacting cavity.

The same input beam was also sent through a line without the upstream periodic lattice and just one downstream periodic lattice, corresponding to the shortest beamline (from accelerator #1 to the near target), with the results shown in Figures 27 through 32.

The nominal, shortest, and longest beamline theoretically have the same linear focus and ideally should produce identical beam-intensity distributions at the target. Due to the formation of longitudinal halo, the three lines in reality have slightly different space-charge forces and consequently a slightly different beam through the nonlinear expander. In the case of the shortest beamline, the horizontal rms parameters are too large in the second nonlinear element, resulting in excessive ridges of the horizontal profile at the target. On the other hand, the vertical rms parameters are too small in the first nonlinear element, resulting in a peaked center of the vertical profile. It will only take a slight adjustment of the quadrupoles in the matching section for the nonlinear expander of the shortest line to achieve a distribution of the same flatness as from the nominal line.

The input beam was finally sent through a line with two upstream and two downstream periodic lattices, corresponding to the longest beamline (from accelerator #2 to the far target). The resulting distribution is represented by Figures 33 through 38, with a beam-intensity distribution at the target that is close, but not identical, to that from the nominal beamline.

Proposed Future Work

The design evolved in several iterations and there is room for improvement.

For instance, the gradient for the periodic-lattice quadrupoles was decided on at an early stage, using longitudinal properties of the beam as they exist right out of the accelerator instead of those in the periodic lattices. Also, the gradient of the first doublet after the accelerator was optimized for a matching section that matched into an upstream periodic lattice with much stronger buncher cavities, at a time when the scheme was to have the beam cover much less phase, around $\pm 25^\circ$, as opposed to the present $\pm 45^\circ$. Thus, these steps should be repeated for a beam with the correct longitudinal properties.

A more severe shortcoming of the design is that not enough attention has been paid to the formation of longitudinal halo, and that the effect of this longitudinal halo has been underestimated. For all the first matching sections (matching section between the accelerator and the upstream periodic lattice) considered during the HEBT design work, a very similar longitudinal phase space evolves, with halo that initially manifests itself as a large energy spread at the largest phase angles. The transverse and longitudinal phase space at the end of the first matching section are shown in Figure 39.

The fan-shaped tails in energy eventually transform into phase. So, while the beam is linearly matched throughout, the total beam covers more or less phase in the final cavities, depending on how many periodic-lattice cells it has gone through. Figures 40 and 41 show the transverse and longitudinal phase space into the first energy-dispersing cavity and out of the second energy-dispersing cavity, respectively, for the nominal beamline. Figures 42 and 43, and Figures 44 and 45, show the same for the shortest beamline and the longest beamline, respectively.

Consequently, with all magnets set according to the above tables, the beam going through the nominal beamline has a different energy profile from the beam going through the shortest beamline or the longest beamline.

Because of the resulting slightly different space-charge forces, the focus into the nonlinear expander is sufficiently different to where the transverse profiles at the target also look somewhat different for the three lines. To recover identical profiles for the three lines, they need to run with slightly different settings of the quadrupoles of the nonlinear-expander matching section and of the imager.

On the other hand, to produce identical energy profiles with all lines requires different buncher-cavity effective gap voltages in each line, and thus different matching sections for each line. Thus, while having physically identical elements, the lines would have most of these elements running at somewhat different settings, which is probably not desirable. However, to produce energy profiles with the same half-width at half-maximum only requires a slight adjustment of the energy-dispersing cavities.

The preferred approach would be to understand the reason for the formation of the longitudinal halo and to find ways to prevent it.

While the transverse profiles approximate the desired ones, neither the $\pm 5\%$ uniformity nor the $+15\%$ maximum were achieved. We have recently begun to consider nonlinear elements that are tailored to the profiles of the incoming beam and the desired final distribution. The design presented here has octupoles for beam redistribution and duodecapoles for halo control. It should be possible to replace these nonlinear elements with special-function magnets to improve flatness. Other backup alternatives also exist.

In the next iteration, it would also be desirable to resolve why some solutions unfold even though theory does predict they are folded and to see if it is possible to find a solution that has not only a horizontal waist but also a vertical waist in the vicinity of the last bend.

In addition to the above, significant further work is required in the following areas: TRACE3-D designs and PARMILA runs must be made for the beams coming from accelerators #3 and #4. Transport of 30-MeV and 35-MeV beams to the targets and beam dump must be studied. Comprehensive error studies must be made. These must result in tolerance specifications and may require design iterations. Detailed interfacing with target-spot instrumentation is required. This instrumentation must be able to check all aspects of the specifications.

Resources

The TRACE3-D files are located in user_disk:[blind.trace3d]. The file describing the beamline from the accelerator to the downstream end of the downstream periodic lattice is called "hebt1.dat". The input parameters are the Twiss parameters and rms emittances of the 4000-particle accelerator output beam, and $1/(5\sqrt{5})$ of the total current to properly track rms envelopes in the presence of space charge. The file describing the beamline from the downstream end of the downstream periodic lattice to the target is called "hebt2.dat". Its input beam has the Twiss parameters and rms emittances of the 100000-particle PARMILA run through the HEBT to that point. The TRACE3-D files assume 40.2192-MeV deuterons.

The PARMILA files are located in alpha_user:[blind.parmila]. They are called "nominal." for the nominal beamline, "shortest." for the shortest beamline and "longest." for the longest beamline. They show magnetic elements with settings for 40.2496-MeV deuterons. These settings were only introduced after the design work had been completed. In other words, all earlier PARMILA input decks existing in the above-mentioned directory assumed 40.2192-MeV deuterons.

Appendix A

PARMILA deck for nominal beamline.

```

run 001 1
title
40-MeV ESNIT
charge +1
linac 1 40.249609 175. 1.99900754 700.
current 134.58
tank 1 -7.0 -24.7 0.02974 0.00 0.00 5.0
0 3 -3.01 1 1 11 0 2. 2. 0 0. 0 0 0 0 0 0 0 0 1 0
sfdata 0.2032 0.5715 0.0985 0.5722 0.0245 0.2007 79.656 -1
start 0
stop 0
input -46 10000 -0.093 45.403 0.002175 -0.086 158.364 0.002182
-0.985 1476.97 0.005349
optcon 1
scheff 134.58 0.05 0.10 20 40 0 0 1 1 3

transl 1 1 0.000001 0 2.0 0.0 0 1 0 0
transl 2 3 -6044.308 4.00525 2.0 0.0 0 1 0 0
transl 3 1 24.5 5 2.0 0.0 0 1 0 0
transl 4 3 3201.222 12.00 2.0 0.0 0 1 0 0
transl 5 1 24.5 5 2.0 0.0 0 1 0 0
transl 6 3 -3201.222 12.00 2.0 0.0 0 1 0 0
transl 7 1 24.5 5 2.0 0.0 0 1 0 0
transl 8 3 2932.112 12.00 2.0 0.0 0 1 0 0
transl 9 1 24.5 5 2.0 0.0 0 1 0 0
transl 10 3 -2346.320 12.00 2.0 0.0 0 1 0 0
transl 11 1 65.0 13 2.0 0.0 0 1 0 0
transl 12 3 2565.257 12.00 2.0 0.0 0 1 0 0
transl 13 1 12.0 2 2.0 0.0 0 1 0 0
transl 14 3 -2378.661 12.00 2.0 0.0 0 1 0 0

transl 15 1 62.3 12 2.0 0.0 0 1 0 0
transl 16 2 0.196705 -90.00 1 2.0 0 1 0 0
transl 17 1 62.3 12 2.0 0.0 0 1 0 0
transl 18 3 2164.827 12.00 2.0 0.0 0 1 0 0
transl 19 1 12.0 2 2.0 0.0 0 1 0 0
transl 20 3 -2164.827 12.00 2.0 0.0 0 1 0 0
transl 21 1 184.0 38 2.0 0.0 0 1 0 0

transl 22 3 2164.827 12.00 2.0 0.0 0 1 0 0
transl 23 1 12.0 2 2.0 0.0 0 1 0 0
transl 24 3 -2164.827 12.00 2.0 0.0 0 1 0 0
transl 25 1 85.0 17 2.0 0.0 0 1 0 0
transl 26 2 0.255528 -90.00 1 2.0 0 1 0 0
transl 27 1 34.0 7 2.0 0.0 0 1 0 0
transl 28 2 0.255528 -90.00 1 2.0 0 1 0 0
transl 29 1 85.0 17 2.0 0.0 0 1 0 0

transl 30 3 2164.827 12.00 2.0 0.0 0 1 0 0
transl 31 1 12.0 2 2.0 0.0 0 1 0 0
transl 32 3 -2164.827 12.00 2.0 0.0 0 1 0 0

transl 33 1 102.0 20 2.0 0.0 0 1 0 0
transl 34 2 0.200076 -90.00 1 2.0 0 1 0 0
transl 35 1 102.0 20 2.0 0.0 0 1 0 0
transl 36 3 2164.827 12.00 2.0 0.0 0 1 0 0
transl 37 1 12.0 2 2.0 0.0 0 1 0 0
transl 38 3 -2164.827 12.00 2.0 0.0 0 1 0 0
transl 39 1 204.0 40 2.0 0.0 0 1 0 0

transl 40 3 2164.827 12.00 2.0 0.0 0 1 0 0
transl 41 1 12.0 2 2.0 0.0 0 1 0 0

```

```

transl 42 3 -2164.827 12.00 2.0 0.0 0 1 0 0
transl 43 1 204.0 40 2.0 0.0 0 1 0 0

transl 44 3 2164.827 12.00 2.0 0.0 0 1 0 0
transl 45 1 12.0 2 2.0 0.0 0 1 0 0
transl 46 3 -2164.827 12.00 2.0 0.0 0 1 0 0
transl 47 1 102.0 20 2.0 0.0 0 1 0 0
transl 48 2 0.200076 -90.00 1 2.0 0 1 0 0
transl 49 1 102.0 20 2.0 0.0 0 1 0 0
transl 50 3 2164.827 12.00 2.0 0.0 0 1 0 0
transl 51 1 12.0 2 2.0 0.0 0 1 0 0
transl 52 3 -2164.827 12.00 2.0 0.0 0 1 0 0
transl 53 1 15.0 3 2.0 0.0 0 1 0 0
transl 54 13 2.0 0.5 0.0 0.0 0 1 0 0
transl 55 4 45.0 108.22536 22.5 22.5 0 1 0 0
transl 56 13 2.0 0.5 0.0 0.0 0 1 0 0
transl 57 1 95.0 19 2.0 0.0 0 1 0 0
transl 58 3 1761.191 18.00 2.0 0.0 0 1 0 0
transl 59 1 18.0 3 2.0 0.0 0 1 0 0
transl 60 3 -1341.497 18.00 2.0 0.0 0 1 0 0
transl 61 1 15.3787 3 2.0 0.0 0 1 0 0
transl 62 13 2.0 0.5 0.0 0.0 0 1 0 0
transl 63 4 45.0 108.22536 22.5 22.5 0 1 0 0
transl 64 13 2.0 0.5 0.0 0.0 0 1 0 0
transl 65 1 15.0 3 2.0 0.0 0 1 0 0
transl 66 3 1629.683 18.00 2.0 0.0 0 1 0 0
transl 67 1 15.0 3 2.0 0.0 0 1 0 0
transl 68 3 -1613.399 12.00 2.0 0.0 0 1 0 0
transl 69 1 34.621 7 2.0 0.0 0 1 0 0
transl 70 3 1267.259 12.00 2.0 0.0 0 1 0 0
transl 71 1 12.0 2 2.0 0.0 0 1 0 0
transl 72 3 -1216.155 12.00 2.0 0.0 0 1 0 0

transl 73 1 68.0 13 2.0 0.0 0 1 0 0
transl 74 2 0.152318 -90.00 1 2.0 0 1 0 0
transl 75 1 68.0 13 2.0 0.0 0 1 0 0
transl 76 2 0.022108 -90.00 1 2.0 0 1 0 0
transl 77 1 68.0 13 2.0 0.0 0 1 0 0

transl 78 3 2164.827 12.00 2.0 0.0 0 1 0 0
transl 79 1 12.0 2 2.0 0.0 0 1 0 0
transl 80 3 -2164.827 12.00 2.0 0.0 0 1 0 0
transl 81 1 239.0 48 2.0 0.0 0 1 0 0
transl 82 3 2164.827 12.00 2.0 0.0 0 1 0 0
transl 83 1 12.0 2 2.0 0.0 0 1 0 0
transl 84 3 -2164.827 12.00 2.0 0.0 0 1 0 0
transl 85 1 119.5 24 2.0 0.0 0 1 0 0
transl 86 2 0.150057 -90.00 1 2.0 0 1 0 0
transl 87 1 119.5 24 2.0 0.0 0 1 0 0
transl 88 3 2164.827 12.00 2.0 0.0 0 1 0 0
transl 89 1 12.0 2 2.0 0.0 0 1 0 0
transl 90 3 -2164.827 12.00 2.0 0.0 0 1 0 0
transl 91 1 239.0 48 2.0 0.0 0 1 0 0
transl 92 3 2164.827 12.00 2.0 0.0 0 1 0 0
transl 93 1 12.0 2 2.0 0.0 0 1 0 0
transl 94 3 -2164.827 12.00 2.0 0.0 0 1 0 0
transl 95 1 119.5 24 2.0 0.0 0 1 0 0
transl 96 2 0.150057 -90.00 1 2.0 0 1 0 0
transl 97 1 119.5 24 2.0 0.0 0 1 0 0

transl 98 3 918.459 18.00 2.0 0.0 0 1 0 0
transl 99 1 18.0 3 2.0 0.0 0 1 0 0
transl 100 3 -1454.193 18.00 2.0 0.0 0 1 0 0
transl 101 1 40.0 8 2.0 0.0 0 1 0 0
transl 102 3 1132.261 18.00 2.0 0.0 0 1 0 0
transl 103 1 18.0 3 2.0 0.0 0 1 0 0

```



```

transl 104 3 232.114 18.00 2.0 0.0 0 1 0 0

transl 105 1 20.0 4 2.0 0.0 0 1 0 0
transl 106 2 0.0 -90.00 1 2.0 0 1 0 0
transl 107 1 20.0 4 2.0 0.0 0 1 0 0

transl 108 11 1.0 173.386 24.0148 50.0 0 1 0 0
transl 109 1 300.0 60 10.0 0.0 0 1 0 0
transl 110 3 237.930 50.00 10.0 0.0 0 1 0 0
transl 111 1 75.0 15 10.0 0.0 0 1 0 0
transl 112 3 -231.962 50.00 10.0 0.0 0 1 0 0
transl 113 1 232.100 46 10.0 0.0 0 1 0 0
transl 114 1 10.000 2 4.0 0.0 0 1 0 0
transl 115 11 1.0 173.386 -28.0163 50.0 0 1 0 0

transl 116 1 20.0 4 10.0 0.0 0 1 0 0
transl 117 2 0.00 -90.00 1 3.0 0 1 0 0
transl 118 1 280.0 56 10.0 0.0 0 1 0 0

transl 119 3 -146.564 50.00 10.0 0.0 0 1 0 0
transl 120 1 100.0 20 10.0 0.0 0 1 0 0
transl 121 3 97.004 50.00 10.0 0.0 0 1 0 0
transl 122 1 100.0 20 10.0 0.0 0 1 0 0
transl 123 3 -82.331 50.00 10.0 0.0 0 1 0 0
transl 124 1 100.0 20 10.0 0.0 0 1 0 0
transl 125 3 64.895 50.00 10.0 0.0 0 1 0 0

transl 126 1 300.0 60 10.0 0.0 0 1 0 0
transl 127 3 86.203 50.00 10.0 0.0 0 1 0 0
transl 128 1 100.0 20 10.0 0.0 0 1 0 0
transl 129 3 -100.949 50.00 10.0 0.0 0 1 0 0

transl 130 1 35.0000 7 10.0 0.0 0 1 0 0
transl 131 2 0.100038 -90.00 1 10.0 0 1 0 0
transl 132 1 39.2285 7 10.0 0.0 0 1 0 0
transl 133 11 2.0 90. 0.0 0.0 0 1 0 0
transl 134 13 5.0 0.5 0.0 0.0 0 1 0 0
transl 135 4 10.0 572.957795 5.0 5.0 0 1 0 0
transl 136 13 5.0 0.5 0.0 0.0 0 1 0 0
transl 137 11 2.0 90. 0.0 0.0 0 1 0 0
transl 138 1 0.00001 1 10.0 0.0 0 1 0 0

transl 139 1 60.7715 12 10.0 0.0 0 1 0 0
transl 140 1 25.0 5 20.0 0.0 0 1 0 0
transl 141 2 -0.366840 -90.00 1 10.0 0 1 0 0
transl 142 1 50.0 10 10.0 0.0 0 1 0 0
transl 143 2 -0.366840 -90.00 1 10.0 0 1 0 0
transl 144 1 25.0 5 20.0 0.0 0 1 0 0
transl 145 1 1200.0 240 50.0 0.0 1 1 0 0

output 1 0 1 0 0 0 1 1
output 2 0 1 0 0 0 1 100 1
output 2 1 1 0 0 0 1 100 1
output 3 1 1 0 0 0 1
output 4 1 1 0 0 0 1
begin
end

```

Figure 1. Layout of fully implemented IFMIF system.

Figure 2. Schematic layout of nominal beamline (from accelerator #2 to beam dump) and also of beamline from accelerator #1 to near target.

Figure 3. Sketch of desired horizontal beam profile at target.

Figure 4. Sketch of desired vertical beam profile at target.

Figure 5. Sketch of desired beam energy profile at target.

Figure 6. Transverse profiles of HEBT input beam consisting of 100000 particles of a -4σ distribution.

*1.0E-03

Figure 7. Energy profile of HEBT input beam consisting of 100000 particles of a -46 distribution.

Figure 8. Transverse profiles of 4000-particle accelerator output beam.

*1.0E-03

Figure 9. Energy profile of 4000-particle accelerator output beam.

I= 12.0mA
W= 40.2192 40.2192 MeV
FREQ= 175.00MHz WL=1713.10mm
EMITI= 1.345 1.350 286.30
EMITO= 1.392 1.350 287.16
N1= 1 N2=104

PRINTOUT VALUES
PP PE VALUE
MATCHING TYPE = 0

CODE: TRACE3D v44
FILE: ESHEBTFIN.DAT;11
DATE: 20-AUG-96
TIME: 16:58:54

NP1= 77

NP2= 86

Figure 11. Rms envelopes of matched beam for downstream periodic lattice.

I= 12.0mA
W= 40.2192 40.2192 MeV
FREQ= 175.00MHz WL=1713.10mm
EMITI= 1.345 1.350 286.30
EMITO= 1.392 1.350 287.16
N1= 1 N2=104

PRINTOUT VALUES
PP PE VALUE

MATCHING TYPE = 0

CODE: TRACE3D v44
FILE: ESHEBTFIN.DAT;11
DATE: 20-AUG-96
TIME: 16:52:22

NP1= 1

NP2= 28

Figure 12. Rms beam envelopes in matching section between accelerator and upstream periodic lattice.

I= 12.0mA
W= 40.2192 40.2192 MeV
FREQ= 175.00MHz WL=1713.10mm
EMITI= 1.345 1.350 286.30
EMITO= 1.392 1.350 287.16
N1= 1 N2=104

PRINTOUT VALUES
PP PE VALUE

MATCHING TYPE = 0

CODE: TRACE3D v44
FILE: ESHEBTFIN.DAT;11
DATE: 20-AUG-96
TIME: 16:57:27

NP1= 43

NP2= 63

Figure 13. Rms beam envelopes in 90° achromatic bend embedded in upstream periodic lattice.

I= 12.0mA
W= 40.2192 40.2192 MeV
FREQ= 175.00MHz WL=1713.10mm
EMITI= 1.345 1.350 286.30
EMITO= 1.392 1.350 287.16
N1= 1 N2=104

PRINTOUT VALUES
PP PE VALUE

MATCHING TYPE = 0

CODE: TRACE3D v44
FILE: ESHEBTFIN.DAT;11
DATE: 20-AUG-96
TIME: 16:58:19

NP1= 54

NP2= 76

Figure 14. Rms beam envelopes in matching section between 90° achromatic bend and downstream periodic lattice.

Figure 15. Horizontal beam profile at target, for nominal beamline.

Figure 16. Vertical beam profile at target, for nominal beamline.

Figure 17. Beam energy profile at target, for nominal beamline.

Figure 18. Particle xy scatter plot at target, for nominal beamline.

Figure 19. Particle xE scatter plot at target, for nominal beamline.

Figure 20. Particle yE scatter plot at target, for nominal beamline.

Figure 21. Horizontal beam profile at target, for nominal beamline,
but with momentum-compacting cavity off.

Figure 22. Vertical beam profile at target, for nominal beamline, but with momentum-compacting cavity off.

Figure 23. Beam energy profile at target, for nominal beamline, but with momentum-compacting cavity off.

Figure 24. Particle xy scatter plot at target, for nominal beamline, but with momentum-compacting cavity off.

Figure 25. Particle xE scatter plot at target, for nominal beamline, but with momentum-compacting cavity off.

Figure 26. Particle yE scatter plot at target, for nominal beamline, but with momentum-compacting cavity off.

Figure 27. Horizontal beam profile at target, for shortest beamline.

Figure 28. Vertical beam profile at target, for shortest beamline.

Figure 29. Beam energy profile at target, for shortest beamline.

Figure 30. Particle xy scatter plot at target, for shortest beamline.

Figure 31. Particle xE scatter plot at target, for shortest beamline.

Figure 32. Particle yE scatter plot at target, for shortest beamline.

Figure 33. Horizontal beam profile at target, for longest beamline.

Figure 34. Vertical beam profile at target, for longest beamline.

Figure 35. Beam energy profile at target, for longest beamline.

Figure 36. Particle xy scatter plot at target, for longest beamline.

Figure 37. Particle xE scatter plot at target, for longest beamline.

Figure 38. Particle yE scatter plot at target, for longest beamline.

Figure 39. Transverse and longitudinal phase space at end of first matching section.

Figure 40. Transverse and longitudinal phase space into first energy-dispersing cavity of nominal beamline.

Figure 41. Transverse and longitudinal phase space out of second energy-dispersing cavity of nominal beamline.

Figure 42. Transverse and longitudinal phase space into first energy-dispersing cavity of shortest beamline.

Figure 43. Transverse and longitudinal phase space out of second energy-dispersing cavity of shortest beamline.

Figure 44. Transverse and longitudinal phase space into first energy-dispersing cavity of longest beamline.

Figure 45. Transverse and longitudinal phase space out of second energy-dispersing cavity of longest beamline.

*Small Mammal Study of Sandia Canyon,
1994 and 1995*

*Kathryn Bennett
James Biggs*

MASTER

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Small Mammal Study of Sandia Canyon,

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by

Kathryn Bennett and James Biggs

ABSTRACT

A wide range of plant and wildlife species utilize water discharged from facilities at Los Alamos National Laboratory (LANL). The purpose of this study was to gather baseline data of small mammal populations and compare small mammal characteristics (species diversity and composition, small mammal density, biomass, physical characteristics, and lean body mass) within three areas of Sandia Canyon (a canyon that receives outfall effluents from multiple sources). The head of Sandia Canyon is near the University House in Technical Area 3 at LANL. Three small mammal trapping webs were placed in the upper portion of Sandia Canyon, the first two webs were centered within a cattail-dominated marsh with a ponderosa pine overstory and the third web was placed in a transition area with a ponderosa pine overstory. This third area was much drier than the habitat surrounding the first two webs and is more riparian than marsh in nature. Capture-recapture trapping of small mammals took place for 1 to 2 weeks. Webs 1 and 2 had the highest species diversity indices with deer mice the most commonly captured species in all webs. However, at Web 1, voles, shrews, and harvest mice, species more commonly found in moist habitats, made up a much greater overall percentage (65.6%) than did deer mice and brush mice (34.5%). The highest densities and biomass of animals were found in Web 1 with a continual decrease in density estimates in each web downstream. Results from the General Linear Model (GLM) demonstrate that there is no statistical difference between the mean body weights of deer mice and brush mice between sites (GLM [deer mouse], $F = 1.0$, $p = 0.3705$; GLM [brush mouse], $F = 2.49$, $p = 0.10$). Mean body length was also determined not to be statistically different between the webs (GLM [deer mouse], $F = 0.89$, $p = 0.4117$; GLM [brush mouse], $F = 2.49$, $p = 0.0999$). Furthermore, no statistical difference between webs was found for the mean lean body masses of deer and brush mice (GLM [deer mouse], $F = 2.54$, $p = 0.0838$; GLM [brush mouse], $F = 1.60$, $p = 0.2229$). Additional monitoring studies should be conducted in Sandia Canyon so comparisons over time can be made. In addition, rodent tissues should be sampled for contaminants and then compared to background or control populations elsewhere at the Laboratory or at an off-site location.

1.0 INTRODUCTION

A wide range of plant and wildlife species utilize water discharged from facilities at Los Alamos National Laboratory (LANL). Discharges from these outfalls are regulated

by the National Pollutant Discharge Elimination System (NPDES) under the Clean Water Act. The waters of these outfalls are routinely monitored for compliance with the NPDES permit. In addition, as part of the Environmental Surveillance Program at LANL, sediment samples are taken and the data published annually in LANL's Environmental Surveillance Report. Although chemical analyses of sediment and water can tell us the concentration of a chemical substance present, they are not sufficient to assess or describe effects on wildlife populations. The purpose of this study was to gather baseline data of the nocturnal small mammal population and compare characteristics of the small mammal populations found within three areas of Sandia Canyon (a canyon that receives outfall effluents from multiple sources) to each other and, where data were available, to other areas within Los Alamos County. The characteristics evaluated were species diversity and composition, small mammal density, biomass, and physical characteristics (weight, length, and lean body mass). This information can be helpful in determining the general health of the small mammal population. With this study, we hope to provide information that can be used to assess the health of the small mammal population in Sandia Canyon and relate the population conditions to environmental conditions.

2.0 ENVIRONMENTAL SETTING

2.1 General Setting

Sandia Canyon is located within the boundaries of LANL. The Laboratory is located in north-central New Mexico on the Pajarito Plateau, approximately 120 km (80 mi) north of Albuquerque and 40 km (25 mi) west of Santa Fe (Fig. 1). The plateau is an apron of volcanic rock stretching 33–40 km (20–25 mi) in a north-south direction and 8–

Figure 1. Location of Los Alamos National Laboratory.

16 km (5–10 mi) from east to west. The average elevation of the plateau is 2286 m (7500 ft). It slopes gradually eastward from the edge of the Jemez Mountains, a complex pile of volcanic rock situated along the northwest margin of the Rio Grande rift. From an elevation of approximately 1890 meters (6200 ft) at White Rock, the plateau scarp drops to 1646 meters (5400 ft) at the Rio Grande. Intermittent streams flowing southeastward have dissected the plateau into a number of finger-like, narrow mesas separated by deep, narrow canyons. The bedrock consists of Bandelier tuff that erupted from the Jemez Mountains about 1.1 to 1.4 million years ago. The tuff overlaps other volcanics that in turn overlay the Puye Formation conglomerate. This conglomerate intermixes with Chino Mesa basalts along the Rio Grande (LANL 1988).

The LANL area is characterized by a semiarid, temperate mountain climate. In the summer months, temperatures typically range from a daily low of around 10 deg C (50 deg F) to a high of 27 deg C (80 deg F). Winter temperatures generally range from near -10 deg C (14 deg F) to about 10 deg C (50 deg F) during a 24-h period. Annual precipitation varies from 33 to 46 cm (13 to 18 in.), with most of it falling as rain in July and August (Bowen 1990).

2.1.1 Description of Sandia Canyon

The head of Sandia Canyon is near the University House in Technical Area 3 (TA-3) at LANL in Los Alamos, New Mexico, and the canyon extends southeastward to the Rio Grande. The area of the drainage basin is approximately 13.5 km² (5.6 mi²). Industrial and sanitary effluents from LANL activities maintain stream flow in portions of Sandia Canyon year-round.

The National Wetlands Inventory conducted by the US Fish and Wildlife Service shows three types of wetlands, or water systems, in Sandia Canyon. Primarily, our research effort was concentrated in the uppermost wetland area, a "persistent, artificially flooded, palustrine wetland" (Cowardin et al. 1979). Situated below TA-3, this wetland receives or received effluent from a steam power plant, a sewage treatment plant, and an asphalt plant. Additional sources of effluent include treated cooling water and noncontact cooling water. Storm water runoff and snowmelt also contribute to the stream seasonally.

Farther downstream where the stream meets East Jemez Road, the wetland area changes to a "temporarily flooded, palustrine wetland" type, and the lower section is an "intermittent, temporarily flooded, riverine streambed" (Cowardin et al. 1979). The National Wetland Inventory Map of Sandia Canyon is Figure 2.

2.1.2 Description of the Study Site

Three small mammal trapping webs were placed in the upper portion of Sandia Canyon. The first two webs were centered within a cattail-dominated marsh with a ponderosa pine overstory (persistent, artificially flooded, palustrine wetland). The third web was placed in a transition area between the persistent, artificially flooded, palustrine wetland and the temporarily flooded, palustrine wetland with a ponderosa pine overstory. This area was much drier than the habitat surrounding the first two webs and is more riparian than marsh in nature. The three webs were placed in a downstream gradient with Web 1 being closest to the outfall discharges and Web 3 farthest away. A rubble landfill is located to the west of the study area and immediately adjacent to Web 1. A sanitary landfill (for Los Alamos County) is located on the mesa top to the north of the study

PEM1KFX = Palustrine, emergent, persistent, artificially flooded.
PSS1A = Palustrine, shrub-scrub, broadleaf deciduous, temporarily flooded.
R4SBA = Riverine, intermittent, streambed, temporarily flooded.
R4SBKC = Riverine, intermittent, streambed, artificially flooded.
R2UBH = Riverine, lower perennial, unconsolidated bottom, permanently flooded.

Fig. 2. National Wetland Inventory map for Sandia Canyon.

location and Webs 1 and 2 were located below the landfill. Web 3 was located downstream from these landfills (Fig. 3).

3.0 METHODOLOGY

3.1 Field Methods

Capture-recapture trapping of small mammals was performed at three locations within Sandia Canyon. A web method of 148 traps was utilized and data was analyzed (population density) using Buckland et al. (1993) and Laake et al. (1994). Each web consisted of 12 lines of traps spaced at 5- to 10-m intervals with 4 traps placed in the center (Parmenter 1994). Each web was placed at least 200 m apart to prevent overlap of species between webs. Data on small mammals for each web were pooled for analysis. Trapping took place over 4 to 8 consecutive nights. Traps were baited in late afternoon with a molasses-coated horse feed and a dry mixture of peanut butter and checked in early morning to record nocturnal species. Animals were marked with size #FF rodent ear tags. Location of capture, species name, sex, presence of physical aberrations, weight, body length, tail length, ear length, foot length, tag number, and E-value were recorded. An E-value was obtained for each animal using the EM-SCAN Model SA-2. The EM-SCAN is a rapid, nondestructive method for determining lean body mass. Incidental kills were kept for species confirmation/accuracy rates, stomach analysis for habitat information, and chemical analysis for percent body fat. Additionally, on the final day of trapping, all or a portion of the total number of animals captured were sacrificed for species confirmation/accuracy rates, stomach analysis for habitat information, and chemical analysis for percent body fat.

Fig. 3. Locations of webs within Sandia Canyon.

Fat-free mass (FFM), or lean body mass, was also calculated for each animal. A regression equation was developed to calculate FFM from the EM-SCAN, E-value, and the length of the animal. A subset of the Sandia Canyon small mammal population (n = 30) was analyzed for percent body fat. This was converted to the grams of lean body mass for the animals. A regression analysis was conducted to develop the regression equation. The F value generated from the analysis of variance in the regression procedure was 117.115 and the probability was 0.0001. The model equation used was

$$\text{FFM} = -17.43 + (\text{E value} \times 0.021) + (\text{Animal Length in cm} \times 3.01).$$

The R^2 generated from the analysis was 0.9001. Therefore, 90.01% of the measured variation in animal lean body mass was accounted for by the regression model.

Biomass was calculated for each of the three webs. The following equation was used :

$$\text{Biomass (g/ha)} = \text{Density (\#/ha)} \times \text{Mean Body Weight (g)}.$$

3.2 Data Analysis

Data were initially entered into a Lotus spreadsheet and then converted for compatibility with the Statistical Analysis System (SAS). To determine which kind of test was most appropriate for the data, we used the SAS univariate normal procedure to determine if the data collected were normally distributed at each site. If data were normally distributed, a parametric test was conducted. If data were not normal the equivalent nonparametric test was performed. Most of the data were found to be normally distributed, therefore parametric analysis was chosen.

Because most data had unequal sample sizes between the webs, a General Linear Model (GLM) was used to test if there were differences in the mean weight, mean length, or mean lean body mass of small mammals between the three webs, as well as used to test differences in mean daily number of captures and mean daily number of species captured between the three webs. If a difference was detected with the GLM, a Multiple Range Test, Student-Newman-Keuls (SNK), was used to determine where the difference occurred. The number of density and biomass estimates was limited to two per web. Analysis on differences in density, diversity indices, and biomass between webs could not be performed. However, a GLM was used to compare density estimates of Sandia Canyon (pooled Webs 1, 2, and 3 data) with other animal density estimates obtained in other areas within the County.

Qualitative information on physical aberrations such as tissue swelling, cuts, etc. were recorded for each animal, if observed. There were no statistical analyses run on this data as this was a subjective measurement.

4.0 RESULTS

4.1 Species Diversity

Table 1 lists small mammal species captured in the project area of Sandia Canyon and Table 2 lists species captured by web. A mixture of species common to both dry habitats (i.e., deer mice, pinyon mice, brush mice) and moist or riparian habitats (i.e., voles, shrews) were captured in the project area. Webs 1 and 2 had the highest species diversity indices (Table 3). In addition, there was a statistical difference ($\alpha = 0.05$) in the mean daily number of species captured between the three webs (GLM, $F = 18.37$, $p =$

0.0001). Mean daily number of species was the highest in Web 1 and Web 2, and Web 3 had the lowest mean daily number of species captured (SNK, $\alpha = 0.05$, Web 1 = Web 2 > Web 3). Figure 4 shows the mean daily number of species captured for each web for all years combined.

Table 1. Small Mammal Species Captured in Sandia Canyon, 1994–95.	
Common Name	Scientific Name
Long-tailed vole	<i>Microtus longicaudus</i>
Montane vole	<i>Microtus montanus</i>
Brush mouse	<i>Peromyscus boylii</i>
Deer mouse	<i>Peromyscus maniculatus</i>
Pinyon mouse	<i>Peromyscus trueii</i>
Harvest mouse	<i>Reithrodontomys megalotis</i>
Vagrant shrew	<i>Sorex vagrans</i>
Shrew (unid. species)	<i>Sorex</i> sp.

Table 2. Small Mammal Species Captured in Sandia Canyon, by Web, 1994–95.			
Common Name	Web 1	Web 2	Web 3
Long-tailed vole	x	x	
Montane vole	x	x	x
Brush mouse	x	x	x
Deer mouse	x	x	x
Pinyon mouse			x
Harvest mouse	x	x	
Vagrant shrew		x	
Shrew (unid. spp.)	x	x	

Table 3. Species Diversity Indices of Sandia Canyon, by Web for 1994 and 1995 Data Combined.

WEB NUMBER	SPECIES DIVERSITY INDEX
1	1.60
2	1.65
3	0.67

Figure 4. Mean number of species captures per day by web.

Figures 5, 6, and 7 show relative species composition in Sandia Canyon, by web, for 1994-95. As shown in the figures, deer mice were the most commonly captured species in all webs. However, at Web 1, voles, shrews, and harvest mice, species more commonly found in moist habitats, made up a much greater overall percentage (65.6%) than did deer mice and brush mice (34.5%), which are more commonly found in drier habitats. At Web 2, voles, shrews, and harvest mice made up only 37.8% of the overall species composition while deer mice, brush mice, and pinyon mice made up 62.2%. Furthermore, deer mice and brush mice made up 96.7% of the species composition at Web 3 compared to 3.3% for voles.

Figure 5. Relative species composition for Web 1, Sandia Canyon, 1994-95.

Figure 6. Relative species composition for Web 2, Sandia Canyon, 1994-95.

Figure 7. Relative species composition for Web 3, Sandia Canyon, 1994-95.

4.2 Density Estimates

Table 4 gives the estimated density (# animals/ha) of each web by year and for both years of data combined. The highest densities of animals were found in Web 1, the uppermost portion of Sandia Canyon, with a continual decrease in density estimates in each web downstream. Because the study was limited to only two years, statistical analysis on density estimates between the webs within Sandia Canyon could not be conducted because of insufficient sample size. However, the difference in the daily mean number of small mammals captured could be compared between the webs. Web 1 was found to have a statistically significantly higher number of daily captures than Web 2 or Web 3 (GLM, $F = 33.09$, $p = 0.0001$; SNK $\alpha = 0.05$, $\text{Web 1} > \text{Web 2} = \text{Web 3}$). Figure 8 shows the mean daily number of animals captured at each web.

All density estimates calculated for Sandia Canyon were used to compare the density of small mammals in Sandia Canyon to other canyons and mesas within the area. Figure 9 shows the mean density estimate of Sandia Canyon, Ecological Risk (ECO Risk) Study Canyons (Los Alamos and Guaje Canyons), Mortandad Canyon, and Mesita del Buey. The plot indicates that Sandia Canyon has the highest density estimate. However, no statistical difference ($\alpha = 0.05$) was found between the mean density estimate of Sandia Canyon and the density estimates of the ECO Risk study canyons, Mortandad Canyon, and Mesita del Buey (GLM, $F = 3.32$, $p = 0.057$).

Table 4. Small Mammal Density Estimates of Sandia Canyon, Webs 1, 2, and 3.

Density Estimation for All Webs, 1994-95		
YEAR	LOCATION	DENSITY EST.
1994	Web 1	103.7
1994	Web 2	53.9
1994	Web 3	31.8
1995	Web 1	165.8
1995	Web 2	65.7
1995	Web 3	23.9
Average Density (#/ha)		74.1
Standard Deviation (n=6)		53.1

Density Estimation for All Webs, 1994		
YEAR	LOCATION	DENSITY EST.
1994	Web 1	103.7
1994	Web 2	53.9
1994	Web 3	31.8
Average Density (#/ha)		63.1
Standard Deviation (n=3)		36.8

Density Estimation for All Webs, 1995		
YEAR	LOCATION	DENSITY EST.
1995	Web 1	165.8
1995	Web 2	65.7
1995	Web 3	23.9
Average Density (#/ha)		85.1
Standard Deviation (n=3)		72.9

Density Estimation for Web 1, 1994-95		
YEAR	LOCATION	DENSITY EST.
1994	Web 1	103.7
1995	Web 1	165.8
Average Density (#/ha)		134.8
Standard Deviation (n=2)		43.9

Density Estimation for Web 2, 1994-95		
YEAR	LOCATION	DENSITY EST.
1994	Web 2	53.9
1995	Web 2	65.7
Average Density (#/ha)		59.8
Standard Deviation (n=2)		8.3

Density Estimation for Web 3, 1994-95		
YEAR	LOCATION	DENSITY EST.
1994	Web 3	31.8
1995	Web 3	23.9
Average Density (#/ha)		27.9
Standard Deviation (n=2)		5.6

Figure 8. Mean daily number of captures of small mammals by web.

Figure 9. Estimated number of small mammals per hectare by location.

4.3 Biomass Estimates

Average weights for each species by web and year and average weights for all species combined by web and year are given in Table 5. The highest mean weights given are for voles followed by brush mice and deer mice. This data were used to calculate the

small mammal biomass (Table 6). The table indicates that Web 1 has the highest biomass. However, because only two years of biomass estimates are available for each web, statistical differences between webs could not be determined.

4.4 Evaluation of Physical Parameters

4.4.1 Body Weight

Deer mice and brush mice were the only two species captured in sufficient numbers in all three webs to conduct statistical analysis on mean body weight, mean body length, and mean lean body mass. Figure 10 shows the mean body weights of brush mice and deer mice for each web. Results from the GLM demonstrate there is no statistical difference between the mean body weights of deer mice and brush mice between sites (GLM [deer mouse], $F = 1.0$, $p = 0.3705$; GLM [brush mouse], $F = 2.49$, $p = 0.10$).

Table 5. Mean Weights of Small Mammals Sampled in Sandia Canyon, 1994-95.

YEAR	WEB	SPECIES	N	MEAN WEIGHT (grams)	STANDARD ERROR OF MEAN
1994	1	Vagrant Shrew	3	5.23	0.28
	1	Harvest mouse	7	12.36	1.75
	1	Deer mouse	47	17.57	0.56
	1	Brush mouse	2	17.5	3.50
	1	Montane vole	6	16.42	2.68
	1	Long-tailed vole	13	31.38	1.43
1995	1	Shrews (unid. and vagrant)	7	4.57	0.52
	1	Harvest mouse	47	10.33	0.38
	1	Deer mouse	27	16.44	1.00
	1	Brush mouse	8	19.56	1.44
	1	Montane vole	44	27.40	1.37
	1	Long-tailed vole	34	29.56	2.02

Table 5 (cont.)

YEAR	WEB	SPECIES	N	MEAN WEIGHT (grams)	STANDARD ERROR OF MEAN
1994	2	Vagrant shrew	1	4.5	*
	2	Harvest mouse	1	10	*
	2	Pinyon mouse	1	20.5	*
	2	Montane vole	1	22	*
	2	Deer mouse	23	16.63	0.77
	2	Brush mouse	5	22.40	2.15
	2	Long-tailed vole	7	35.36	3.04
1995	2	Shrews (unid. and vagrant)	7	4.79	0.46
	2	Harvest mouse	9	10.94	0.65
	2	Deer mouse	11	15.32	1.98
	2	Brush mouse	9	25.50	2.96
	2	Montane vole	5	39.80	2.83
	2	Long-tailed vole	5	41.8	3.13
1994	3	Montane vole	1	20.5	*
	3	Deer mouse	19	16.14	1.16
	3	Brush mouse	3	26.50	1.26
1995	3	Deer mouse	10	17.35	2.26
	3	Brush mouse	7	20.36	3.00
1994	1	All species	78	18.84	0.85
1995	1	All species	167	19.91	0.88
1994	2	All species	39	20.49	1.44
1995	2	All species	46	20.86	1.90
1994	3	All species	23	17.75	1.24
1995	3	All species	17	19.00	1.86
1994-95	1	All species	245	19.57	0.66
1994-95	2	All species	83	20.69	1.30
1994-95	3	All species	39	18.28	1.05
1994	All webs	All species	140	19.13	0.65
1995	All webs	All species	230	20.03	0.77

4.4.2 Body Length

Mean body length was also determined not to be statistically different between the webs (GLM [deer mouse], $F = 0.89$, $p = 0.4117$; GLM [brush mouse], $F = 2.49$, $p = 0.0999$). Figure 11 shows the mean body lengths of deer and brush mice captured at the three webs.

Table 6. Rodent Biomass Estimates for Sandia Canyon, 1994 and 1995.

YEAR	WEB #	DENSITY EST. (#/ha)	MEAN WEIGHT (grams)	BIOMASS EST. (g/ha)
1994	1	103.7	18.84	1,953.7
	2	53.9	20.49	1,104.4
	3	31.8	17.75	564.5
1995	1	165.8	19.91	3,301.1
	2	65.7	20.86	1,370.5
	3	23.9	19.00	454.1
1994-95	1	134.8	19.57	2,638.4
1994-95	2	59.8	20.69	1,237.3
1994-95	3	27.9	18.28	510.0
1994	1,2,3	63.1	19.13	1,209.0
1995	1,2,3	85.1	20.03	1,704.6

GLM
 Deer mouse $F=1.00$, $n=134$, $p=0.3705$
 Brush mouse $F=2.49$, $n=33$, $p=0.10$

Figure 10. Mean body weights of mice by web.

Figure 11. Mean body length of mice by web.

4.4.3 Lean Body Mass

Lean body mass was calculated from the derived regression equation (See Methods) and the mean lean body masses of deer and brush mice at each web is shown in Figure 12. Again, no statistical difference between webs was found for the mean lean body masses of deer and brush mice (GLM [deer mouse], $F = 2.54$, $p = 0.0838$; GLM [brush mouse], $F = 1.60$, $p = 0.2229$).

4.4.4 Physical Aberrations

Based on a qualitative evaluation of each animal, there did not appear to be a significantly high amount of surface or subdermal abnormalities on the animals. Several individuals contained small lumps that appeared to be infections from physical contact with one another or possibly from insect bites. The amount and degree of physical

abnormalities did not appear to be dissimilar from small mammal studies conducted elsewhere at the Laboratory.

$$\text{Lean Body Mass} = -17.43 + (\text{E Value} \times 0.02) + (\text{Body Length} \times 3.01)$$

Figure 12. Lean body mass of mice by web.

5.0 DISCUSSION

The purpose of this study was to gather baseline nocturnal small mammal data and compare characteristics of the small mammal populations found within three areas within Sandia Canyon (a canyon that receives outfall effluents from multiple sources) to each other and, where data were available, to other areas within Los Alamos County. The characteristics evaluated were species diversity and composition, small mammal density, biomass, and physical characteristics (weight, length, and lean body mass).

This study showed that Web 1 and Web 2 had a greater number of different species captured daily than Web 3. This is mostly due to habitat differences. Web 1 and

Web 2 were centered within a cattail-dominated marsh and the ends of the web lines were in an upland area. These webs captured species indicative of wet environments (shrews and voles) as well as upland environments (deer and brush mice). Web 3, however, was centered over a very narrow riparian stream channel. Therefore, the majority of the species captured were more from upland environments.

Although there was insufficient data to statistically determine if the species diversity index was different between the three webs, Web 1 (1.60) and Web 2 (1.65) had similar calculated species diversity indices and Web 3 had a much lower calculated index (0.67). When these values are compared to other species diversity indices from similar habitats within the area, the values are also very similar (Raymer and Biggs 1994). During the summer of 1993, Raymer and Biggs conducted a series of small mammal studies in various locations within Los Alamos County. They trapped an area within Sandia Canyon within a cattail marsh as well as a cattail marsh in Mortandad Canyon. They calculated species diversity index of 1.79 for Sandia Canyon and an index of 1.46 for Mortandad Canyon. Raymer and Biggs (1994) also trapped an area in Three-Mile Canyon with similar habitat to the Web 3 location. However, the Three-Mile Canyon site was much drier with no standing or flowing water. The species diversity index for the Three-Mile Canyon location was 0.33, somewhat lower than the Web 3 index of 0.67. The differences in species diversity indices appear to be directly related to habitat.

Density estimates were calculated for all three webs. Web 1 had the highest density estimate. Statistical analysis could not be performed on the estimates because of insufficient sample size. However, the mean daily number of rodent captures was

compared between the webs. Web 1 was found to have a statistically higher number of rodents captured. When the density estimates for each web were pooled and compared to other areas within the County, no differences were found. However, the analysis was conducted at the alpha level of 0.05 and the probability generated was 0.057. If the sample size was increased, statistical significance may be determined. The location of Web 1, within the marsh habitat, may be the primary driver for the possible high density estimate and the higher number of rodent captures. Web 1 is located within the widest portion of the marsh. The species composition is comprised of approximately 40% voles (montane and long-tail voles). This habitat is extremely favorable to voles (Raymer and Biggs 1994). Web 2 was located further downstream from Web 1 where the cattail marsh decreases in width and the percent of vole captures also decreases to 20%. The habitat within Web 3 has a low amount of cattails and voles only contributed 3.3% to the species composition.

Statistical analysis was not performed on the biomass estimates due to insufficient sample size. However, it appears that Web 1 (2,638 g/ha) has a higher estimate than Web 2 (1,237 g/ha) and Web 3 (510 g/ha). Considering that voles make up 40% of the species composition of Web 1 and also have the highest body weight of the species captured, it is not surprising that Web 1 has such a high biomass.

Some health conditions can be manifested in decreased body weight, body length, and percent body fat (or an increase in lean body mass). These factors were evaluated for rodents captured within each web. For all of these factors, no statistical differences were found between Web 1 and the two downstream webs (Webs 2 and 3). Furthermore, no

significant degree of physical aberrations were found on individual animals. Food source availability is an important factor influencing body weight, body length, and lean body mass. These data should be compared to data collected at a comparable site in habitat type and size. However, for this study, an appropriate control site was never located. Deer and brush mice captured within the three webs appear to have a mean body weight and body length within the normal range for these species (Whitaker 1980). Data on lean body mass were only available from a site in northwestern New Mexico. The habitat was extremely different from Sandia Canyon, therefore no comparisons were made. Comparisons of lean body mass will be made in the future when additional data are collected within similar habitats within the County.

Further monitoring studies (i.e., repeating study every 3 to 5 years) should be conducted in Sandia Canyon so comparisons over time can be made. In addition, rodent tissues should be sampled for contaminants and then compared to the rodent population characteristics. These data over time may be very useful in assessing impacts to the rodent community in Sandia Canyon.

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