FERMILAB – ACCELERATOR DIVISION

Mu2e Experimental Area Preliminary Shielding Assessment

Including the mu2e service building, production solenoid/transport solenoid/detector solenoid rooms, extinction room, main beam absorber, and remote handling room

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A preliminary shielding assessment is required by the Fermilab Radiological Controls Manual (FRCM) prior to construction of mu2e facilities. The purpose of this document is to fulfill that FRCM requirement. This assessment covers the Production Solenoid Room, Transport Solenoid Room, Detector Solenoid Room, the mu2e service building, main beam absorber, and remote handling room.

Contents

1 Introduction

It is intended that the existing Antiproton Source facilities will be repurposed to deliver an 8 kW, 8 GeV proton beam[1] through a new beam enclosure, the M4 line, to a new mu2e target station where it will strike a tungsten target located within the Production Solenoid (PS) [1]. The un-interacted primary proton beam and secondary beam shower travel through an air gap and finally to a new beam absorber. A secondary muon beam is transported in the direction opposite the primary proton beam through a Transport Solenoid (TS) and finally toward a Detector Solenoid (DS) which are all to be located in new facilities. The layout of the mu2e experiment is shown in Figure 1.

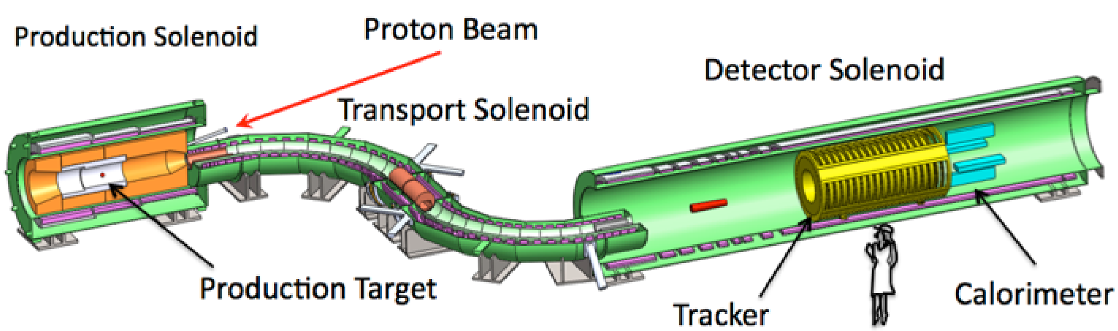

Figure 1 The Mu2e apparatus.

The facilities covered by this preliminary shielding assessment include:

- Production Solenoid enclosure
- Transport Solenoid enclosure
- Detector Solenoid enclosure
- mu2e service building
- main beam absorber
- extinction monitor room
- target replacement robotics staging room

The 8 kW primary proton beam is directed to the tungsten target located in the Production Solenoid. The remaining primary beam and secondary shower cross an air gap between the PS and the main beam absorber. Consequently, the mu2e facility must be designed for this normal condition.

Preliminary construction drawings for the subject facilities have been prepared [10][11].

[1] An 8 GeV, 8 kW proton beam is equivalent to 6.25E12 protons/second with kinetic energy of 8 GeV

2 Radiation Safety Plan Design Approach

2.1 Requirements

Radiation Safety Plan design comes from the consideration of the mu2e project physics goal and the FRCM [2] requirements. The mu2e project physics goal is to deliver an 8 kW proton beam by 1/3 integer, slow resonant extraction to the Production Solenoid [1]. The various FRCM requirements for controlling prompt effective dose rate are introduced in this section.

2.1.1 Prompt Effective Dose Control

The FRCM requirement to control the prompt effective dose rate outside of accelerator and beam lines tunnels fall into two broad categories: the normal condition and the accident condition. Since the normal condition is one in which all beam is stopped within the facility, the normal condition represents worst case condition as well. The permitted effective dose rates for the conditions cover a wide range of values depending upon the controls which can be implemented on a location by location basis. Table 1 and Table 2 containing the range of limits are reproduced from the FRCM for convenience.

Table 1: Control of Accelerator/Beamline Areas for Prompt Radiation Under Normal Operating Conditions (from Table 2-6 of FRCM)

Dose Rate (DR) Under Normal Operating Conditions	**Controls**
DR < 0.05 mrem/hr	No precautions needed.
0.05 ≤ DR < 0.25 mrem/hr	Signs (CAUTION -- Controlled Area). No occupancy limits imposed.
0.25 ≤ DR < 5 mrem/hr	Signs (CAUTION -- Controlled Area) and minimal occupancy (occupancy duration of less than 1 hr).
5 ≤ DR < 100 mrem/hr	Signs (CAUTION -- Radiation Area) and rigid barriers (at least 4' high) with locked gates. For beam-on radiation, access restricted to authorized personnel. Radiological Worker Training required.
100 ≤ DR < 500 mrem/hr	Signs (DANGER -- High Radiation Area) and 8 ft. high rigid barriers with interlocked gates or doors and visible flashing lights warning of the hazard. Rigid barriers with no gates or doors are a permitted alternate. No beam-on access permitted. Radiological Worker Training required.
DR≥ 500 mrem/hr	Prior approval of SRSO required with control measures specified on a case-by-case basis.

Table 2: Control of Accelerator/Beamline Areas for Prompt Radiation Under Accident Conditions When It is Likely that the Maximum Dose Can Be Delivered (From Table 2-7 of FRCM)

Maximum Dose (D) Expected in 1 hour	**Controls**
D < 1 mrem	No precautions needed.
1 < D ≤ 10 mrem	Minimal occupancy only (duration of credible occupancy < 1 hr) no posting
1 ≤ D < 5 mrem	Signs (CAUTION -- Controlled Area). No occupancy limits imposed. Radiological Worker Training required.
5 ≤ D < 100 mrem	Signs (CAUTION -- Radiation Area) and minimal occupancy (duration of occupancy of less than1 hr). The Division/Section/Center RSO has the option of imposing additional controls in accordance with Article 231 to ensure personnel entry control is maintained. Radiological Worker Training required.
100 ≤ D < 500 mrem	Signs (DANGER -- High Radiation Area) and rigid barriers (at least 4' high) with locked gates. For beam-on radiation, access restricted to authorized personnel. Radiological Worker Training required.
500 ≤ D < 1000 mrem	Signs (DANGER -- High Radiation Area) and 8 ft. high rigid barriers with interlocked gates or doors and visible flashing lights warning of the hazard. Rigid barriers with no gates or doors are a permitted alternate. No beam-on access permitted. Radiological Worker Training required.
D ≥ 1000 mrem	Prior approval of SRSO required with control measures specified on a case-by-case basis.

2.2 Technical Design

2.2.1 Primary shielding design

The 8 GeV primary proton beam is delivered via the M4 beam line [8] to the production solenoid room. The beam passes through a collimator before entering the PS. The beam interacts in tungsten target [3] which produces a secondary particle shower. The radial portion of the shower intercepts the heat and radiation shield (HRS) [4] within the PS. The forward portion of the shower, along with the un-interacted primary beam, exits the downstream end of the PS, travels across an air gap, and is absorbed in the main beam absorber [5]. The PS room radiation shielding is nominally 16 feet thick. MARS simulations have been made to predict the effective radiation dose rate over the PS room and main absorber area. The results are shown in Figure 2. A radiation area fence will be required on the berm surface where the normal effective dose rates exceed 5 mrem per hour.

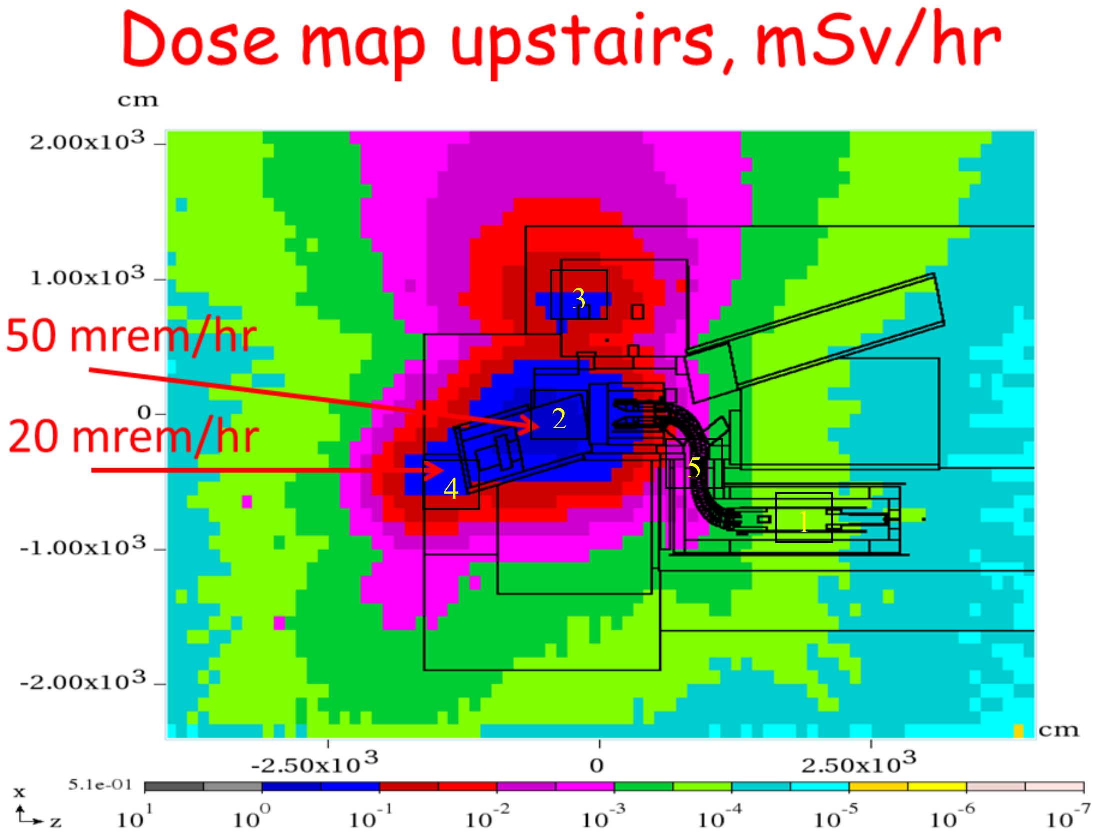

Figure 2: This MARS simulation histogram shows the nominal operating condition for an 8 kW, 8 GeV proton beam directed to the tungsten target. The color legend is in units of mSv/hr. The annotations indicate the effective dose rate in mrem/hr above the shielding berm surface just downstream of the PS and the main beam absorber. Drop hatches are indicated by numbers: 1 - Detector Solenoid; 2 - Production Solenoid; 3 - Remote Handling Room; 4 - Extinction Room; and 5 - Transport solenoid.

There are two major lobes indicated in Figure 2. The upper lobe is due to the presence of the remote handling room which is an underground structure originally intended to station a remote handling system for target changes. At the time of this writing, it is thought that the remote handling room will be removed from the project. In the event this occurs, the upper lobe in the effective dose rate histogram should be suppressed.

2.2.2 Hatches

A number of drop hatches are required for the mu2e facilities. They are:

- Detector Solenoid hatch
- Production Solenoid hatch
- Remote Handling Room hatch
- Extinction Room hatch

- Transport solenoid hatch

In the simulation result shown in Figure 2, the hatches are filled to the contour of the surrounding shield. The effective dose rate in the vicinity of each of the hatches is indicated in Figure 2. The mu2e project will make additional simulations to determine if the number of shield blocks used in the penetrations can be reduced as a cost savings measure.

2.2.3 Exit stairways

There are three exit stairways considered in this assessment. The stairways are located at the Circulation Vestibule, adjacent to the Transport Solenoid, and at the Extinction Monitor Room. Labyrinth attenuation worksheets have been prepared for the Transport Solenoid and Extinction Room exit stairways. The source term for each stairway has been produced from MARS simulations. The location and analysis for each of the stairways is given below.

Circulation Vestibule Exit Stairs

This stairway is indicated as stairway 1 in the drawing set Mu2e Conventional Facilities PDF and Revit files [11], sheets A2, A10, A33, and A35. The stairway is essentially a large vertical shaft or penetration connecting the lower level with the main level of the mu2e facility and containing stairway risers. The lower end of this shaft from elevation 721' to 731' is unshielded between the Detector Solenoid and the vertical shaft. A minimum of 6 feet of shielding is present from elevation 731' to 746.5'. No credit is taken for any structures within the stairway. The source term for this stairway (pen #35), produced from MARS simulations, is 0.001 mrem/hr. No further consideration of the stairway is required.

Transport Solenoid Area Exit Stairs

The features of this stairway, indicated as stairway 2, can be examined on sheets A2, A3, A9, A13, A14, A15, SC-2, SC15, and SC19 of Mu2e Conventional Facilities PDF and Revit files [11]. Stairway 2 has 3 major legs which are further subdivided due to changes in their aspect ratios. The source term for this stairway (pen #14) was produced from MARS simulations and a Labyrinth Attenuation spreadsheet has been prepared. The effective dose rates at the entrance/exit of the stairway are 136 mrem/hr/<0.05 mrem/hr, respectively.

Extinction Monitor Room Exit Stairs

The features of this stairway, indicated as stairway 3, can be examined on sheets A2, A12, SC5, and SC20 of Mu2e Conventional Facilities PDF and Revit files [11]. The stairway has 1 leg, subdivided in three parts due to changes in aspect ratio. The source term for this stairway (pen#12) was produced from MARS simulations and a Labyrinth

Attenuation spreadsheet has been prepared. The effective dose rates at the entrance/exit of the stairway are 130 mrem/hr/0.3 mrem/hr, respectively.

2.2.4 Elevator

A service elevator, located near the Circulation Vestibule exit stairway, is included in this assessment. The elevator is indicated on sheets A2, A10, A27, and A36 of Mu2e Conventional Facilities PDF and Revit files [11]. A labyrinth attenuation worksheet has been prepared for the elevator shaft. The source term for the elevator shaft (pen# 36) was produced from MARS simulations. The elevator shaft has about 1 foot of shielding on the detector Solenoid side from elevation 721' to 731'. The remainder of the shaft from 731' to 746.5' has a minimum of 6 feet of shielding between it and the Detector Solenoid. The effective dose rate at the entrance of the elevator is <0.001 mrem/hr. No further consideration of the elevator is required.

2.2.5 Penetrations

A list of penetrations, organized by the area of the facility from which they originate, are listed in the following Table. The "pen #" refers to an index number used to keep track of MARS histogram surfaces used for source terms for the respective penetrations. For convenience, the labyrinth attenuation spreadsheet [9] associated with each penetration includes the penetration number. The master list of penetrations is included with this document as Attachment A. The drawings referenced are included in [11].

Area	Pen #	Name	terminus	Effective dose rate (mrem/hr)	Drawing numbers & comments
Remote Handling					
	1	Supply air 14" dia	Outdoors, west end of Mechanical Room	<0.05	M2, M4, M5,M7
	2	Supply air 6" dia	Outdoors, west end of Mechanical Room	<0.05	M2, M4, M5,M7
	3	Vacuum exhaust 3" dia	Outdoors, berm above Remote Handling Room	<0.05	M2
Production Solenoid					
	7	ODH supply air 24" dia	Outdoors at fan ODH-MUA-1	<0.05	M5, M7
	37	Absorber cooling air 14" dia	Outdoors, west end of Mechanical Room	<0.05	M3, M7
Extinction Monitor					
	10	Supply air duct 6" dia	Outdoors, west end of Mechanical Room	<0.05	M3, M7
Detector &					

Transport solenoid					
	16	Intermediate level Penetration to Solenoid PS room	Main level floor of Solenoid PS room	1.2	SC9, SC10, SC11, SC15 Included in MARS model
	15	ODH exhaust pipe 24” dia	Exhaust outdoors from ground	<0.05	M3, M10
Mechanical Lower					
	21	Pipe chase	Main level Mechanical room	<0.05	SC-4, SC-6, SC-10
Electrical lower					
	25	Penetration to upper mechanical room	Main level Mechanical room	<0.05	SC-4, SC-6, SC-10
	27	18 Conduits to upper DAQ room	Exit at alcove 009, drawings show 3 legs, only 1 leg employed	<0.05	SC-4, SC-6, SC18
Alcove #1					
	34	Alcove #1 penetrations from intermediate to main level	Main level	<0.05	SC-4, SC-6
Alcove #2					
	34	Alcove #2 penetrations from intermediate to main level	Main level	<0.05	SC-4, SC-6
Alcove #3					
	34	Alcove #3 penetrations from intermediate to main level	Main level	<0.05	SC-4, SC-6

2.2.6 Deuterium-Tritium Generator

The Mu2e experiment requires a gamma source for Detector Solenoid calibration. A Deuterium-Tritium (DT) neutron generator, to be located in the Detector Solenoid room within a shielded pit, will be used to activate a fluid (Fluorinert™) for this purpose. The fluid is pumped around the neutron generator and proceeds immediately through a piping system to the Detector system. A design of the DT generator installation has been produced [12] which meets the requirements of the FRCM [2]. The peak effective dose rate calculated for the surface of the floor shield plug is approximately 2 mrem/hr; thus, the minimum posting level required for the Detector Solenoid room will be “Controlled Area”.

2.2.7 Ground water activation

The major sources of groundwater activation for the Mu2e experiment include losses at the following locations:

- Main beam absorber
- Production Solenoid

Detailed groundwater activation calculations for Mu2e operation were completed for the mu2e experiment during the pre-conceptual design phase for a 25 kW beam power scenario [4]. No ground water issues were identified. Since the final design beam power is now 8 kW, no further consideration is warranted for this preliminary shielding assessment.

2.2.8 Surface water activation

The major sources of surface water activation due to beam operations at the Accumulator/Debuncher facility for the Mu2e experiment are the same sources as those listed for ground water activation. Detailed calculations for surface water activation for Mu2e operation of the Accumulator/Debuncher Rings have been completed [6]. No surface water issues were identified.

2.2.9 Airborne radioactivity

The major source of airborne radioactivity due to beam operations for the Mu2e experiment is from primary/secondary beam passing through the air volume between the Production Target Solenoid and the Main Beam Absorber. Detailed calculations for airborne radioactivity for Mu2e operation have been completed [4]. Engineered ventilation controls will be used to limit the impact of air emissions for the Mu2e project. Absorber cooling air, provided at 800 scfm will exit the reentrant beam dump space and will be exhausted into the M4 beam line enclosure; the air will be drawn to the junction of the Delivery Ring/M4 beam line to allow for radioactive decay. The calculated transit time is 58 minutes and will result in about 55 curies of activity released per year assuming continuous operation [6] [7].

The Production Solenoid Enclosure air system will be continuous with the M4 beam line. The air supply in the Production Solenoid Enclosure will come from a supply duct located adjacent to the Production Solenoid Beam Absorber. This air will pass through the Production Solenoid Enclosure and will be exhausted at an exhaust trunk located near the upstream end of the M4 beam line enclosure. The exhaust flow rate at the normal fan speed will be about 800 cfm. In the event of an ODH alarm in the Production Solenoid Enclosure, a high speed fan will exhaust air at 10,000 cfm from a separate exhaust stack near the PS room.

2.3 References

[1] Mu2e Collaboration, Mu2e Conceptual Design Report, arXiv:1211.7019 [physics.ins-det], (November 2012)
[2] Fermilab Radiological Controls Manual, http://esh.fnal.gov/xms/FRCM
[3] Production Target Requirements, R. Coleman, Mu2e doc 887-v17, December 2013
[4] Requirements for the Mu2e Production Solenoid Heat and Radiation Shield, Mu2e doc 1092-v15

[5] Mu2e Proton Beam Absorber Requirements, Mu2e doc 948-v7, R. Coleman, March 2012
[6] Groundwater and air activation for Mu2e areas, Mu2e Document 1553-v1, Kamran Vaziri, May 1, 2011
[7] Mu2e Proton Absorber Design (TRANSIT TIME DEPENDENCE), mail message from K. Vaziri to E. Huedem, December 4, 2012
[8] Muon Campus Preliminary Shielding Assessment, Beams-doc 4513-v3, A. Leveling, May 2014
[9] Labyrinth and Penetration Spreadsheet, ESH&Q RP NOTE 118
[10] Muon Campus Radiation Shield Drawing Set, FESS, Mu2e Document 4165-v1 May 2014
[11] Mu2e Conventional Facilities PDF and Revit files – current 100% submittal, Mu2e Document 3494-v4, October 2013
[12] Deuterium-Tritium generator for mu2e detector calibration, Mu2e-doc-4142-v2, A. Leveling, May 2014

Attachment A

NN	Name	MARS coordinates from drawings				Tony's notices/comments	Existed MARS model					
		Drawings	X	Y	Z		Element	Hist.	X-range	Y-range	Z-range	Type
REMOUT HANDLING												
1	Suppy air 14'' steel pipe	SC-1	586.6	287.2	-615.0	near ceilling	"room1"	XY	425.0 / 1140.0	-231.2 / 287.2	-359.6 / 802.2	**Hole**
2	Suppy air 6'' steel pipe	SC-1	491.8	287.2	-615.0	near ceilling	"room1"	XY	425.0 / 1140.0	-231.2 / 287.2	-359.6 / 802.2	**Hole**
3	Vacuum exhaust 3'' steel pipe	SC-1	1128.5	287.2	210.2	near ceilling	"room1"	XZ	425.0 / 1140.0	-231.2 / 287.2	-359.6 / 802.2	**Hole**
4	Hatch	SC-3,12	988.8	652.7	-145.2	roof+4.5'=19'	None	XZ	Overlap with "walls1" and "hatch1"			**Hatch**
5												
6												
PRODUCTION SOLENOID												
7	ODH suppy air 24'' steel pipe	M-3,7	-355.0	-94.0	-299.4	centerline 5'	"dumpv2"	YZ		-120 / 226	-730 / -999	**Hole**
8	ODH exhaust 24'' steel pipeto surface fan	M-3,10	-391.1	226.0	2016.1	centerline 15'-1''	None	YZ	Overlap with "wall4", but for x=-417.5 air (inside "Dstube")			**Hole**
9	Hatch	SC-3,13	26.2	972.8	-267.0	roof+3'=20''	None	XZ	Overlap with "hatch3"			**Hatch**
EXTINCTION MONITOR												
10	Suppy air 6'' steel pipe	SC-5,M-3,7	-529.7	-81.3	-1088.9	approx 7'-6''	None	YZ	Overlap with "W_D_-X"			**Hole**
11	HATCH	SC-4,20	-1100.6	850.8	-1434.4	roof+1.5'=10'-6''	"hatchExt"	XZ	-965 / -410		-1450 / -1300	**Hatch**
12	STAIRS	SC-4,20	-	421.9	-		"stairWl2"	XZ	-1140 /		-1300 / -	**Stair**

			1226.2		1434.4				-910		630	
13												
DETECTOR SOLENOID & TS												
14	Supply air duct	M-3,9	- 1151.0	71.1	1051.8	approx 9'-9'' from DS floor	"Dstube"	XY	-1160 / 1060	-230 / 360		???
15	ODH exhaust 24'' steel pipeto surface fan	M-3,10	-391.1	226.0	2016.1	centerline 14'-7''	None	YZ	Overlap with "wall4", but for x=-417.5 air (inside "Dstube"			Hole
16	PENETRATION TO SOLENOID PS ROOM	SC-6,9	- 1398.8	-2.6	778.8	cellling	None	XZ	Overlap with "walls1"			**Hatch**
17	STAIRS TO UPPER LEVEL	SC-4,19	- 1238.8	-231.2	1020.2	start floor level	"Dstube"	YZ	-1160	-230 / 345	650 / 5165	**Stair**
18						start floor level						
19	OPENNING TO UPPER HIGH BAY	SC-6,8	-764.3	911.8	2384.0	ceilling	None	XZ	Overlap with "hatch8"			**Hatch**
20	OPENNING TO UPPER HIGH BAY	SC-6,9	-695.2	911.8	880.3	ceilling	None	XZ	Overlap with "tssl9", "hatch5", "hatxh7"			**Hatch**
MECHANICAL LOWER												
21	Penetration / chase to upper mech room	SC-4,10	- 1884.7	88.8	2853.9	ceilling	None	XZ	Overlap with "hatchz9", "soil"			???
22	SUPLLY DUCT ODH (routed in the penetration/chase)	M-3,7	- 1428.0	1121.3	2787.4	near ceilling	None	YZ	Not represented			???
23	RETURN AIR DUCT#1 (routed in the penetration/chase)	M-3,7	- 1428.0	1121.3	2899.9	ceilling	None	YZ				???

24	VARIOUR WATER PIPPING (routed in the penetration/chase)	M-3,7	-1428.0	1121.3	2959.4	ceilling	None	YZ				
ELECTRICAL LOWER												
25	Penetration to upper mech room	SC-4,10	-1384.7	88.8	2616.2	ceilling	None	XZ	Overlap with "hatchz9"			???
26	RETURN AIR DUCT#2 (routed in the penetration/chase)	M-3,7	-1428.0	1121.3	2632.1	ceilling	None	YZ	Not presented			???
27	CONDUIT TO UPPER DAQ RM	SC-4	-1384.6	88.8	2452.0	ceilling	None	YZ	Not presented			???
ALCOVE #1 (ROOM 005)												
28	Carrier pipe for LCWS (to beam tunnel)	SC-1	-85.6	53.3	4422.3	elev 729'-10''	None	YZ	Overlap with "walls1"			Hole
29	Carrier pipe for chilled water pipe (to beam tunnel)	SC-1	-85.6	53.3	4422.3	elev 729'-10''	None	YZ				Hole
30						ceilling						
31	Ducts elect to High bay	SC-4,12	-119.6	88.8	4693.2	ceilling	None	YZ	Overlap with "walls1"			Hole
32						ceilling						
ALCOVE #2 (ROOM 006)												
33	Ducts elect to High bay	SC-4,12	-119.6	88.8	3901.1	ceilling	None	YZ	Overlap with "walls1"			Hole

ALCOVE #3 (ROOM 007)												
34	Ducts elect to High bay	SC-4,12	-119.6	88.8	3108.7	ceilling	None	YZ	Overlap with "walls1"			Hole
CIRCULATION VESTIBULE												
35	STAIR	SC-4,11	-1906.9	-231.2	3816.3	start floor level	None	YZ	Not presented			Stair
36	ELEVATOR	SC-4,11	-1613.9	-231.2	3629.4	start floor level	None	YZ				Elevator
BEAM TUNNEL												
37	Absorber air cooling duct	SC-1										