Department of Energy
Review Committee Report

on the

Technical, Cost, Schedule, and
Management Review

of the

MUON to ELECTRON CONVERSION EXPERIMENT (Mu2e)

June 2012

EXECUTIVE SUMMARY

A Department of Energy Office of Science (DOE/SC) review of the Muon to Electron Conversion (Mu2e) project was conducted June 5-7, 2012 at Fermi National Accelerator Laboratory (FNAL). The review was conducted by the Office of Project Assessment and chaired by Daniel R. Lehman at the request of Dr. Michael Procario, Director of Facilities, Office of High Energy Physics (HEP). The purpose of the review was to determine whether the project had satisfied the requirements of Critical Decision (CD) 1, Approve Alternative Selection and Cost Range.

The Committee found that the Mu2e project has satisfied the requirements for CD-1. The Mu2e project team demonstrated ownership of the project and is commended for a successful review. The Committee recommended that the program expedite CD-1 approval, expand the CD-1 cost estimate upper range, and schedule a mini-review three months after the CD-1 ESAAB.

Technical

A large amount of work is required for the Accelerator and Muon Beamline due to extensive reuse of existing equipment. The Committee suggested a several percent increase in project contingency for installation activities. The Committee also recommended: a project-wide installation coordinator be appointed before CD-2 (Approve Performance Baseline); a full reevaluation of all installation costs be completed and necessary revisions incorporated into the CD-2 baseline; exploration of the possibility of early procurement of the solenoid superconductor by the next DOE/SC review; and consideration of the possibility of initiating practice Production Solenoid (PS) and Detector Solenoid (DS) coil winding by additional vendors and FNAL before the next review. The Committee also recommended the project refine the calculations of expected rates in the tracker system through complete simulations to evaluate the efficiency for detecting signal electrons and generate detailed and reliable estimates of background radiation (species, energy spectra, and flux) at various points within the detector in order to support the upcoming design decisions. The Committee noted the importance of the INFN Laboratory (in Italy) to the calorimeter system and recommended that the project proceed with all reasonable timeliness to formalize the INFN contribution to Mu2e.

Conventional Facilities

The civil design appears to be adequately mature for CD-1. The schedule and cost estimate for the Detector Hall appears to be appropriately detailed for this level of design. The

Committee recommended that the project consider reducing the duration between preliminary design completion and final design start to support the Architect/Engineer team continuity; consider accelerating the start of civil construction to take advantage of construction market conditions; and coordinate the design of interface elements within the Muon Campus Program Plan projects and Mu2e Detector Hall to ensure scope is not omitted.

Cost and Schedule

The Total Project Cost range is $200-290 million. CD-2 is scheduled for the second quarter of FY 2014. The Committee suggested that the project should consider evaluating activity sequencing and completing a full project-wide resource analysis and leveling exercise to ensure the project schedule is optimized. The Committee felt contingency amounts were low for several Level 2 subprojects. The Committee recommended that the project reevaluate the cost range prior to CD-1 approval; revisit escalation rates to ensure cost estimate is not overly optimistic prior to CD-2; and reevaluate the funding profile and schedule to ensure a smooth manpower ramp-up and ramp-down prior to CD-2.

Management

The project team demonstrated ownership of the project and is commended for a successful review. The Committee was concerned with the interdependencies of the Mu2e, Muon g–2, Accelerator Improvement (AIP) and General Plant (GPP) projects. Any delays to the g–2 project could impact the schedule of the Mu2e project. The Committee noted that the AIP, GPP, and the Recycler Ring upgrade projects are necessary, although they are not part of the Mu2e project. The Committee emphasized that close supervision of these projects is essential. The Committee recommended that the project team re-evaluate and optimize the schedule consistent with the funding profile; expedite the CD-1 approval; and schedule a DOE/SC mini-review in three months.

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1. INTRODUCTION

The discovery of non-zero neutrino masses and flavor mixing established the fact that individual lepton-flavor numbers (electron-number, muon-number, and tau-number) are not conserved. All such flavor-violating effects to-date have been observed in the neutral lepton sector, through the phenomenon of neutrino oscillations. Charged lepton flavor violation (CLFV), on the other hand, has been the subject of intense experimental searching since the discovery of the muon but no evidence for it has ever been uncovered.

The Muon to Electron Conversion Experiment (Mu2e) experiment will search for CLFV in muon-to-electron conversion in the field of a nucleus, probing new physics at mass scales that exceed the reach of the Large Hadron Collider (LHC) by a factor of 1000.

In its report, "U.S. Particle Physics: Scientific Opportunities, A Strategic Plan for the Next Ten Years," the U.S. Particle Physics Project Prioritization Panel (P5) identified this opportunity as a top priority:

> *A muon-to-electron conversion experiment at Fermilab could provide an advance in experimental sensitivity of four orders of magnitude. The experiment could go forward in the next decade with a modest evolution of the Fermilab accelerator complex.*

The Mission Need Statement for the Mu2e experiment was approved in September 2009 by Dr. William F. Brinkman, Director of the Office of Science. This project has been in the conceptual design development stage since then. Critical Decision CD-1 will mark the transition from conceptual design to engineering design.

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2. TECHNICAL SYSTEMS EVALUATIONS

2.1 Accelerator Physics

2.1.1 Findings

This section addresses two Level 2 Work Breakdown Structure (WBS) elements of the Mu2e project: WBS 1.2, Accelerator; and WBS 1.5, Muon Beamline. The Level 3 elements contained within this work scope include:

WBS 1.2

- Recycler RF and Extraction
- Rings and Transport to Rings
- Radiation Safety Improvements
- Resonant Extraction System
- Delivery Ring RF
- External Beamline
- Extinction
- Target Station

WBS 1.5

- Vacuum System
- Collimators
- Muon Beamline Shielding
- Stopping Target
- Stopping Target Monitor
- Proton Absorber
- Muon Beam Stop
- Neutron Absorber
- Detector Support Structure
- Systems Integration, Test and Analysis

These are noted to ensure the reader of the review's thoroughness in that all of these issues were looked at, and also to observe that it was not possible to dig deeply into technical issues associated with each of these complex subsystems. In the following remarks, unless specifically noted, references refer to all subsystems.

The work captured in these WBS elements is extensive. The Total Project Cost (TPC) associated with WBS 1.2 and 1.5 is $45.3 million and $14.1 million, respectively. These numbers do not convey the extent of the work in that a significant amount of the hardware is being repurposed from previous Fermilab facilities, and an additional significant amount of systems are being provided "off project." Estimates of off-project work provided to the Committee are shown in Table 2-1.

2.1.2 Comments

The Committee concurred that this work scope will be done on schedule. Cost estimates of work that the project has evaluated are thorough and reasonable for this stage of the project.

Table 2-1. Estimates of Off-Project and Muon g–2 Project Work ($k)

Off-Project Work	
Ring AIP	9,700
Cryo AIP	8,000
Beam Line GPP Enclosure	9,200
Site Prep GPP	3,200
Total of Required AIP and GPP	**30,100**

Muon g–2 Project	
Recycler RF System	6,900
RR Extraction Kicker and Beam Line Stub	2,600
Connection of M3 Line to Delivery Ring	1,500
Upstream External Beamline	
Magnets	703
PS	918
Mechanical and Installation	240
Total from Muon g–2 project	**12,861**

Risk analysis is thorough for this stage of project, and positions it well for the future.

The above list of subsystems addressed in this work scope conveys something of the quantity of physics requirements and interface issues that impact the design of these systems. The Committee judged that these requirements and interface issues are well defined with substantial documentation; however, there are a number that remain to be finalized, primarily from outside this work scope. This needs to be done soon to proceed to CD-2 design.

Conceptual Design work is well advanced across this work scope.

As in other areas of the project, many staff are shown to leave the project for a year or more between design and fabrication/installation/commissioning. Should this actually be the way the project is executed, it will have detrimental effects on the outcome. Comments in the management section also address this concern.

Alternatives have been considered in most areas; many areas retain alternative approaches. R&D is being done in key areas to identify alternative solutions and reduce risk.

Several particularly challenging areas are noted here, and Committee encouraged the ongoing focused efforts with sufficient resources:

- Resonant extraction: pulse-to-pulse intensity variations in the spilled beam will impact the experiment negatively. Simulations may not be able to address this issue authoritatively. The simulation efforts should certainly continue; additionally the project should be involved in similar work being done elsewhere.

- Extinction requirements remain challenging. The approach appears to work, but additional R&D is needed. The project hopes to demonstrate a solution that is two orders of magnitude better than the requirements. This has yet to be verified in design.

- Throughout these WBS elements there is a significant amount of engineering effort needed. A particular example is the Muon Beamline vacuum system, but this is the case elsewhere. Shortcuts motivated by budget constraints should be avoided.

There was not time in this review to address instrumentation needs. The project is aware of them, but a thorough assessment of instrumentation to support the challenges of low beamloss, resonant extraction, extinction, etc., should be done and presented at the next review.

Some hardware reuse may not be viable in which case new hardware will be needed. Controls are a particular area of concern within Fermilab.

Beam loss issues are a concern. The concern relates to radiation skyshine originating in the existing pbar rings, which were designed and shielded for much lower intensity beams. The Fermilab ES&H group has chosen to place the limit on public exposure 100 times lower than the DOE Order. Since it is expensive to redo the shielding of the existing facility to the level needed, the project is utilizing selected shielding at known loss points within the enclosures, and extensive interlock systems are being developed to enforce this limit. This approach could limit operation of the Mu2e experiment.

High-level software applications are not included in the project.

Installation costs are spread through each Level 3 WBS element. An overall evaluation and roll-up of installation costs before CD-2 is advised.

The Committee was concerned about the dependencies on off-project activities, particularly those associated with another project, Muon g–2 (see Section 5, Management, recommendations).

Technical peer design reviews at each Level 3 WBS element should be done before CD-2.

2.1.3 Recommendation

1. Appoint a project wide installation coordinator before CD-2. Fully reevaluate all installation costs and incorporate into the CD-2 baseline.

2.2 Superconducting Solenoids

The Committee found that the solenoid section of the Director's review was very complete and, as such, did not re-review this information. However, specification, procurement/contracting, and oversight of the fabrication of the solenoid system will be a challenge. The Laboratory is encouraged to begin this process as quickly as possible including a reassessment of the make-buy analysis.

2.2.1 Findings

Considerable detailed paper studies have been completed on the magnet system. The construction methods proposed are similar to those of other large detector systems within the field of high energy physics. The Committee concurred with technical findings from the previous Director's Review.

One model coil is under construction in industry at this time.

There are a number of acquisition proposals. In each of these proposals significant fabrication will be done by outside vendors. Initial procurement specification packages have not been generated.

Schedule contingency has been accounted for by transforming into a risk with attendant cost consequences.

The Transport Solenoid (TS) is on the project critical path and the Detector Solenoid (DS) is not far behind.

Scope contingency was not identified in the presentations. The point estimate includes contingency resulting from estimate uncertainty. The cost range was calculated by considering

the risks. They include “opportunities” and “threats.” A dollar value was assigned to each risk. The low end of the cost range was found by considering possible opportunities and subtracting their cost from the point cost. The high end was found by adding to the point cost the cost associated with the threats.

2.2.2 Comments

Budgetary information has been received from four vendors and was used in setting up the project budget. However, this information is not binding.

The conceptual design owes a debt to the CERN staff member who spent a sabbatical year at Fermilab and who is still listed as a Level 3 manager.

2.2.3 Recommendations

2. Prepare at least one of the initial specification packages by the next mini-review.

3. Prepare an initial plan for contract/procurement oversight of vendors by the next mini-review.

4. Explore the possibility of early procurement of the aluminum stabilized superconductor by the next mini-review.

5. Prepare a detailed make/buy analysis prior to the next mini-review.

6. Consider the possibility of having practice coil winding by additional vendors by the next mini review.

2.3 Detector Systems, Electronics, and Data Acquisition

2.3.1 Detectors

2.3.1.1 Findings

The Mu2e performance requirement of single event sensitivity for muon to electron conversion in Aluminum at the level of $2x10^{-17}$ would represent a major advance over previous searches. The detector systems are required to detect 105 MeV/c electrons emitted from muonic atoms with high resolution in a high rate environment. These systems, which include the tracker, calorimeter, cosmic ray veto and data acquisition (DAQ)/trigger, appear to be well planned,

reasonable solutions to the experimental challenges. The teams associated with these systems have done a good job of scoping the conceptual designs after considering alternatives.

Firmly establishing the Mu2e detector system's ability to reach the performance specifications, maintaining sufficient acceptance while suppressing backgrounds to extremely low levels, represents a major challenge. The collaboration has done studies including detailed simulations to estimate particle rates and backgrounds, and has provided some estimates for the uncertainties associated with the background estimates and the preliminary nature of these estimates. However, this makes a detailed evaluation of their reliability difficult. Procedures have been devised to estimate selection criteria resulting in the overall acceptance of the Mu2e system, which along with the anticipated muon exposure, determines the ultimate sensitivity of the experiment. The actual acceptance achieved will depend on conditions encountered during the experiment. Preliminary studies indicate that the system may be able to meet the performance requirements. In order to fully establish whether the proposed system can meet the very challenging performance specifications, the team should further evaluate and determine the reliability of all factors pertaining to the acceptance to provide a firm estimate of the uncertainty or provide a range of acceptance values, which can be supported with high confidence.

Recent rescoping of the experiment will require considerably longer running time than originally proposed to achieve the performance requirement. Further descoping should be approached with great care in order to maintain the performance requirements.

2.3.1.2 Comments

Since the installation and integration activity is managed in a different WBS element (5.10), careful attention should be paid to maintaining good communications between the detector subsystems and the installation subsystem.

Factors outside of the detector systems have stretched out the CD-3b date and have created a gap in the detector systems schedules between design and construction. This gap is cause for concern over the potential loss of momentum and experienced personnel. Each subsystem is dealing with this problem in their own way, but all would benefit from an overall project solution.

The Committee found that the cost books were very hard to evaluate due to the combination of costed and uncosted labor hours and the inclusion of non-Fermilab labor in M&S.

2.3.1.3 Recommendations

7. Improve background rate simulations for the detector systems to refine requirements and design decisions in support of CD-2.

8. Develop quantified assessments of uncertainties in overall acceptance in support of CD-2.

2.3.2 Tracker (WBS 6.0)

2.3.2.1 Findings

The tracker is a low mass straw chamber system located in the vacuum of the warm bore of the superconducting detector solenoid downstream of the muon stopping target at a radius of 40cm<r<85cm. At this radius the tracker does not see electrons from the muon decay in orbit with momentum P<60 MeV/c. The straws operate at an expected peak rate of 20 kHz/cm^2 during the measurement period but must also deal the 3 MHz/cm^2 "beam flash" prior to the measurement period. The tracker is designed for a very large mean time between failures due to difficult access and the straws must have a sufficiently small leak rate to maintain the vacuum at 10^{-4} torr.

The tracker has 20,000 straws of varying lengths in 18 stations with planes rotated by 60°. The straws are 5mm diameter and made of 18μm Mylar with 500Å Al and 200Å Au. The chamber gas (Ar:CO_2); 10kA of 2V power; 1A of 1.5kV high voltage; fiber optics for signal and 20kW of cooling, all must be brought through vacuum feedthroughs (WBS 5.10) to the straw chamber. The tracker was intended to have double-ended readout of each straw with Analog Digital Converters (ADC) and Time to Digital Converters (TDC) to obtain dE/dx information for particle identification and for timing. End-to-end timing provides position information of hits along the straws to facilitate track pattern recognition. Position resolutions of 100-200 μm (3-9cm) in the drift (longitudinal) direction is anticipated resulting in momentum resolution that exceeds the required performance; overall momentum resolution is dominated by interactions in the muon stopping target.

Some consideration of the effect of various particle rates and performance parameters on the tracker has been made. For example, rates that are twice presently anticipated would result in a 40 percent reduction in reconstruction efficiency (without degrading the momentum resolution). Further efforts to define the expected rates encountered by the tracker, including rates due to

decays and particle emission from the downstream muon absorber, are ongoing. The subsystem cost is $7.0 million with a 33 percent contingency of $1.9 million for a total cost of $8.9 million.

2.3.2.2 Comments

Labor allocated for straws and straw assemblies appears light.

The tracker electronics ASIC development could suffer from extended gaps in the schedule and might benefit from a rethinking of when final prototype work should actually begin.

The ASIC design team has not yet carefully considered packaging options especially as they affect the number of channels per die. A more integrated design approach might result in a different optimum number of channels than presently imagined.

The project appears to be on track to refine the present conceptual design into a preliminary design that fully matches the functional requirements of the experiment.

2.3.2.3 Recommendation

9. Continue to refine calculations of the expected rates in the tracker system through complete simulations to evaluate the efficiency for detecting the signal electrons and detailed requirements for the electronics.

2.3.3 Calorimeter (WBS 7.0)

2.3.3.2 Comments

The calorimeter design consists of 1936 LYSO crystals in four vanes and a length of 1.3m. The crystals are 3cm×3cm×11cm and are read out by two cooled APDs. The crystals are calibrated with a with 6 MeV ^{16}O gammas from a neutron generator/Flourinert system similar to BaBar and a two wavelength laser system. Crystals will be tested with cosmic rays and in an electron beam. The acceptance of the calorimeter is 73 percent.

The calorimeter cost is based on an assumption of shared cost between DOE and INFN. One third of the crystal and photosensor cost is assigned to the DOE project. The DOE cost is $4.3 million with a 30 percent contingency for a total of $5.6 million.

There is an alternative crystal geometry under study. This geometry consists of two disks separated by half of the wavelength of the spiraling electrons. This geometry improves the acceptance by approximately eight percent for the same volume of crystal. However, more background is expected.

2.3.3.2 Comments

The calorimeter is an important element of the experiment that provides a valuable redundant definition of the signal.

The calorimeter requirements “to confirm that a reconstructed track is well measured” are translated into a position resolution of 1cm, energy resolution of two percent and time resolution of less than 1ns. These characteristics must be maintained over the lifetime of the experiment, considering the radiation environment. Additional requirements are providing particle identification and a possibility to trigger the experiment. The Committee judged that these are a reasonable set of requirements.

The critical arguments for justification of the specific requirements of the calorimeter should be sharpened for the next stage of the project with more detailed studies.

The Committee was encouraged by detailed cost model developed for LYSO crystals and the quotes from three vendors, which match the expectations of the cost model. Nevertheless, the Committee urged caution based on previous crystal procurement experience.

Studies of sensitivity and background estimates at the sufficient precision should be available to decide on the final geometry and to confirm the resolution requirements for the detector at high confidence.

For CD-2, the R&D should be sufficiently advanced to assure that the detector will be able to achieve the requirements at high confidence. The necessary studies include, but are not limited to, radiation hardness studies, establishing longitudinal uniformity, minimizing dead material associated with the mechanical support, and test beam studies of prototypes.

2.3.3.3 Recommendation

10. Given the importance of INFN to the Calorimeter system, project management should proceed with all reasonable timeliness to formalize the INFN contribution to Mu2e.

2.3.4 Cosmic Ray Veto (WBS 8.0)

2.3.4.1 Findings

The Cosmic Ray Veto (CRV) consists of 2,088 counters (each with four fibers and two end Silicon Photomultiplier (SiPM) readout and 16,704 photosensors in 58 modules. The CRV covers 330m^2. The three layers of CRV (with 5mm absorbers between layers) are required to have two hits.

The project's requirements are to reduce the background to 0.05 events over the course of the experiment, with an inefficiency of 10^{-4}, while using less than five percent of the DAQ bandwidth and less than one percent dead-time.

The cost is $4.4 million with a 33 percent contingency of $1.4 million for a total cost of $5.8 million.

2.3.4.2 Comments

The proposed extrusion of scintillator by the Northern Illinois Center for Accelerator and Detector Development (NICADD) is well matched to the CRV needs. SiPM readout appears promising. At neutron fluxes greater than 10^8 n/cm^2, alternative detector technologies may be required. The plans to develop module fabrication procedures with mockups or prototypes and a vertical slice test are well thought-out.

2.3.4.3 Recommendation

11. Consider possible experiments to measure the production of 105 MeV delta rays from cosmic muons to validate the simulation used for the background estimate.

2.3.5 Trigger and Data Acquisition (WBS 9.0)

2.3.5.1 Findings and Comments

The data acquisition (DAQ) project presented a plausible and fairly detailed conceptual design. The DAQ project is pursuing a low risk, essentially all commercial hardware, design. The DAQ plan, as presented, retains some obsolete tasks and some apparent duplication and reduplication adding to a large total number of man-hours—two-thirds of which are costed on

the project. The front end to DAQ interface is currently largely undefined. Progress on the front ends and the DAQ would be expedited by a timely agreement on that interface and the underlying protocol(s).

2.3.5.2 Recommendations

12. A new, bottoms-up estimate for the Trigger and DAQ should be generated in time for CD-2.

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3. CONVENTIONAL FACILITIES

3.1 Findings

A conceptual design of the Detector Hall has been prepared by FESS Engineering, including guiding principle sustainability considerations.

The Conventional Facilities (CF) scope required to deliver beam to the Mu2e Detector Hall is captured in two Accelerator Improvement Projects (AIP), and three General Plant Projects (GPP). A detailed Muon Campus Program Plan was developed to coordinate these projects.

A construction estimate for the detector building has been developed resulting in a total $13.5 million with indirect and escalation. An independent estimate validated the cost. The total WBS 3 cost is $18.5 million without contingency. Contingency is currently estimated at 33 percent ($6 million) resulting in a Total Estimated Cost (TEC) for civil cost at $24.5 million.

Civil design requirements have been collected from technical areas and compiled in the Mu2e CF Requirements Specifications document and is in the process of being approved by stakeholders.

A categorical exclusion is anticipated for the detector hall construction. A waiver from the Army Corps of Engineers has been obtained that determined the wetlands that are impacted by this project are not jurisdictional. An abandoned water well will need to be sealed prior to detector hall construction.

MARS calculations have been performed to defend the current civil design radiation shielding. Cooling methods for the absorber will be determined in preliminary design.

Value Engineering efforts in 2011 saved over $16 million in civil construction cost with change from 25kw to 8kw beam.

The detector hall conceptual design has undergone internal and external design reviews.

WBS 3 breakout presentations included, requirements development, sustainability, life safety, risk, cost, schedule, fire protection, mechanical, electrical and staffing.

Two WBS activities were traced from the resource-loaded schedule through the basis of estimate and cobra (indirects and escalation) and found to match the project roll-up WBS 3 values.

The civil schedule includes preliminary design in FY 2013 followed by a six-month gap before starting final design after CD-2 approval in FY 2014. Construction of the detector hall is planned to begin in late FY 2015 and is expected to last 20 months. A total of 146 working days of schedule contingency is currently estimated on the detector hall construction.

3.2 Comments

The Mu2e civil team is very experienced with this size and type of construction.

The conceptual design is adequately mature for CD-1. The conceptual design construction cost estimate appears appropriately detailed and defendable for this stage of design.

Pursue the final National Environmental Policy Act (NEPA) determination early in preliminary design. Consider sealing of the domestic water well soon to avoid the potential for regulatory permit delays during detector hall construction.

Conventional construction risks appear to be appropriately detailed and actively managed.

Managing the program of AIP, GPP and Mu2e-funded civil construction projects will be challenging. Vigilance is needed to ensure that scope at interface points of these smaller projects is not omitted. Consider a periodic scope gap analysis during preliminary and final designs.

The potentially high magnetic fields from the solenoid may have an impact on metallic civil components such as piping and reinforcement bars. Consider these impacts and design solutions early in preliminary design.

The six-month gap between preliminary and final design could be challenging to the Architect Engineer (A/E) and may not be as cost effective as a continual design process.

With the currently aggressive construction market conditions, it may be advantageous to consider starting the civil construction sooner than late FY 2015.

3.3 Recommendations

13. Consider reducing the duration between preliminary design completion and final design start to support A/E team continuity (evaluate within three months after CD-1 approval).

14. Consider accelerating the start of civil construction to take advantage of the recent aggressive construction market conditions (evaluate within three months after CD-1 approval).

15. Coordinate the design of interface elements within the Muon Campus Program Plan projects and Mu2e detector hall to ensure scope is not omitted (complete prior to CD-2).

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4. COST and SCHEDULE

4.1 Findings

The Total Project cost range for the Mu2e project is $200-190 million. CD-1 is planned for the fourth quarter of FY 2012 and CD-4 is planned for the second quarter of FY 2021. The Committee determined that the conceptual design report and supporting documentation adequately justify the stated cost range and project duration. However, the Committee felt contingency amounts were low for several Level 2 subprojects.

Mu2e Project Status (as of June 2012)		
Project Type	Line Item	
CD-1	Planned: 4th Qtr. FY 2012	Actual:
CD-2	Planned: 2nd Qtr. FY 2014	Actual:
CD-3a	Planned: 2nd Qtr. FY 2014	Actual:
CD-3b	Planned: 4th Qtr. FY 2015	Actual:
CD-4	Planned: 2nd Qtr. FY 2021	Actual:
TPC Percent Complete	Planned: N/A	Actual: N/A
TPC Cost to Date	$17.6M	
TPC Committed to Date	$18.2M	
TPC (CD-1 Point Estimate)	$229.3M	CD-1 TPC Range $200M-$290M
TEC	$177.7M	
Contingency Cost (w/Mgmt Reserve)	$51.6M	32% to go
Contingency Schedule on CD-4b	18 months	20%
CPI Cumulative	N/A	
SPI Cumulative	N/A	

The project has developed a preliminary resource loaded schedule using (Primavera) P6 with 4,016 activities and 98 control accounts. A project critical path (solenoids) has been developed; sub-project (Level 2) critical paths and near-critical path activities are understood. Constrained activities within the schedule have been minimized. The project currently has 18 months (20 percent) of schedule contingency to CD-4.

A preliminary, bottoms-up cost estimate has been developed using the COBRA Cost Processor. The CD-1 point estimate is $229.3 million with a cost range of $208.1-$286.8 million. The CD-1 point estimate includes $51.6 million (32 percent) cost contingency. Obligations vs. funding curves have been developed for the project and appear reasonable.

The project developed a qualitative risk register with a total of 137 risks; 25 of these risks are classified as “opportunities.” The risk register has been prepared and a qualitative risk analysis was used to develop the CD-1 cost range. The project plans to implement a quantitative risk process as part of the CD-2 process.

Mu2e project EDIA is approximately 37 percent and the standing army costs are approximately $800K per month.

4.2 Comments

Several Level 2 WBS activities contain internal schedule contingency (calorimeter, tracker); the project should consider evaluating activity sequencing to determine if some activities can start earlier than currently scheduled. Likewise, resource curves with steep ramp-ups and ramp-downs are included in several Level 2 subprojects. The project should consider completing a full project-wide resource analysis and leveling exercise to ensure the project schedule is optimized. The project should consider optimizing the schedule to match the funding profile (Table 4-1).

Table 4-1. Mu2eProject Funding Profile ($M)

	FY 2010	FY 2011	FY 2012	FY 2013	FY 2014	FY 2015	FY 2016	FY 2017	FY 2018	Total
OPC - R&D	0.500	0.5	1	5						7.000
OPC - Design	4.277	7.9	5							17.117
TEC – PED			24	20	5					49.000
TEC - Construction					20	25	42.4	45.5	23.1	156.000
Total Project Cost	**4.777**	**8.4**	**30**	**25**	**25**	**25**	**42.4**	**45.5**	**23.1**	**229.177**

For the percentage of project design complete (approximately 20 percent) the Cost Range (approximately $290 million) appears optimistic. The project may benefit from increasing the upper limit by including additional project contingency as shown in Table 4-2, Committee Contingency Analysis and Recommendations.

The project developed a bottoms-up resource loaded schedule and the initial schedule logic has been established. The Level 2 Project Managers are maintaining separate critical path schedules for each of the subprojects that are subsequently integrated to produce the overall project schedule and critical path. The Level 2 Managers have provided initial input in preparing schedule contingency calculations. The schedule contains 18 months of schedule contingency

from completion of the project Key Performance Parameters (KPP) to the Level 0 CD-4 milestone and 13 months of schedule contingency from CD-4 approval to the Level 0 CD-4 milestone. The Committee judged that 18 months of schedule contingency may be optimistic.

Table 4-2. Mu2e Review Committee Contingency Analysis and Recommendations

WBS	Mu2e Bottoms Up Cost Analysis - FNAL	Project Estimate				DOE Review Estimate					Comment
		Base (BCWS)	Budgeted Contingency		Total	Base (BCWS)	Budgeted Contingency		Total	Delta	
		$k	%	$k	$k	$k	%	$k	$k	$k	
1	Project Management	20,491	0.4%	83	20,574						
2	Accelerator	35,362	33%	9,939	45,301						Recommend a few percent increase in contingency for installation.
3	Conventional Facilities	18,535	33%	5,979	24,514						
4	Solenoids	71,713	39%	26,520	98,233	71713	45	30600	102,313	4,080	
5	Muon Beamline	10,942	33%	3,120	14,062						Recommend a few percent increase in contingency for installation.
6	Tracker	6,971	33%	1,915	8,886						
7	Calorimeter	4,294	30%	1,270	5,564						
8	Cosmic Ray Veto	4,418	33%	1,359	5,777						
9	Trigger and DAQ	4,941	32%	1,461	6,402						The manpower estimate appears high by a factor of two. Recommend reevaluation.
	Sub-Totals (TEC)	177,667	32%	51,646	229,313						
	Alotted Project Contingency	$51,646									
	Un-allocated TEC (contingency)	$0									
	Total Estimated Cost (TEC)	$229,313									
	Escalation	$25,000									
	Other Project Costs (OPC)	$24,177									
	Total Project Cost (TPC)				$229,313						

Project risks appear to be well understood for CD-1 and the risk assessment methodology appears reasonable for CD-1.

It is unlikely the future market conditions will support the current escalation rates. The project should continue updating escalation rates to ensure estimates reflect the latest projected market conditions.

The project has minimal scope contingency.

The project should complete a parametric cost comparison with similar projects to prepare for CD-2.

4.3 Recommendations

16. Reevaluate the cost range prior to CD-1 approval.

17. Revisit escalation rates to ensure cost estimate is not overly optimistic prior to CD-2.

18. Reevaluate the funding profile and schedule to ensure a smooth manpower ramp-up and ramp-down prior to CD-2.

5. PROJECT MANAGEMENT and ENVIRONMENT, SAFETY and HEALTH

5.1 Findings

In discussions with the project team it was determined that the project has minimal scope contingency at this time. The Mu2e project is dependent on other projects including the Muon g–2 project and several AIP and GPP Projects. The Committee noted that drafts of CD-1 documentation have been completed.

A general overview of the solenoid scope indicates that three superconducting solenoids are required for muon production, transportation, and selection. Two of the three solenoids are planned to be procured commercially. The delivery of these solenoids is on the critical path for the Mu2e project.

The muons are stopped within a target, and the resulting electron decays are measured in a straw-tube Tracker. A calorimeter for measuring the electron energy is located behind the Tracker. This calorimeter will be jointly delivered by Italy and the U.S. A large cosmic ray veto surrounds the analysis area.

6.2 Comments

The Committee noted that the project team demonstrated ownership of the project and is commended for this successful review. Also, the project management team should be acknowledged for a good job developing the plans and documentation necessary for building Mu2e. The draft documentation required for CD-1 approval is adequate.

A number of projects for AIP, GPP, and the recycler upgrade are necessary for Mu2e, although they are not part of the Mu2e project. Close supervision of these projects is essential, and the Project Managers have instituted good contacts with these projects.

Concerning overall resources, the Committee suggested that the project team re-evaluate and optimize the schedule consistent with the funding profile. Also, resource leveling of labor should be undertaken by the project team to address the schedule contingency in the detector subsystems. An earlier completion of the Mu2e building and the detector analysis subsystems could allow additional time for commissioning and cosmic ray tests.

6.3 Recommendations

19. Evaluate procuring the solenoids earlier. A draft procurement plan should be presented at a mini-review in three months for early procurement of the superconducting cable.

20. Consider advancing the schedule of detector subsystems (especially the Tracker) in order to build and commission these detectors earlier.

21. Fermilab should reevaluate the dependence of Mu2e on projects outside the control of Mu2e.

22. Ensure a rapid NEPA approval.

23. Expedite the CD-1 approval.

24. Schedule a mini-review in three months.

APPENDIX A

CHARGE MEMORANDUM

Department of Energy
Washington, DC 20585
APR 11 2012

MEMORANDUM FOR DANIEL LEHMAN, DIRECTOR
OFFICE OF PROJECT ASSESSMENT

FROM: MICHAEL PROCARIO
DIRECTOR, FACILITIES DIVISION
OFFICE OF HIGH ENERGY PHYSICS

SUBJECT: REQUEST TO CONDUCT CD-1 REVIEW OF THE MU2E PROJECT AT FERMILAB

I request you conduct an Independent Project Review of the "Mu2e" Project (for construction of the Muon-to-Electron Conversion Experiment) on June 5-7, 2012 at Fermilab, in order to validate readiness of the conceptual design and cost range for Critical Decision CD-1.

In your review, please evaluate whether the Project is prepared to enter the next phase, preliminary design. In performance of a general assessment of progress, current status and the identification of potential issues, the committee should address the following specific items:

1. Does the conceptual design satisfy the performance requirements?
2. Do the conceptual design report and supporting documentation adequately justify the stated cost range and project duration?
3. Does the proposed project team have adequate management experience, design skills, and Laboratory support to produce a credible technical, cost and schedule baseline?
4. Are ES&H aspects being properly addressed and are future plans sufficient given the projects current stage of development?
5. Is the documentation required by DOE, satisfying Order 413.3B, ready for approval of CD-1?

Dr. Theodore Lavine is the program manager for the Mu2e Project in this office and will serve as the OHEP contact person for the review.

We appreciate your assistance in this matter. As you know, these reviews play an important role in our program. I look forward to receiving your Committee's report.

Sincerely,

Michael Procario, Director
Facilities Division
for High Energy Physics

APPENDIX B

REVIEW PARTICIPANTS

Department of Energy/Office of Science (SC-1) Review of the
Muon to Electron Conversion Experiment (Mu2e)
June 5-7, 2012

Daniel R. Lehman, DOE/SC, Chairperson

SC1
Accelerator Physics

* Rod Gerig, ANL

SC2
Superconducting Solenoids

* Peter Wanderer, BNL
Bruce Strauss, DOE/SC

SC3
Detector Systems

* Steve Kettell, BNL
Douglas Bryman, TRIUMF
Rik Yoshida, ANL

SC4
Electronics/DAQ/Control Systems

* Rick Van Berg, U of Penn.

SC5
Civil Construction

* Jeff Sims, ANL

SC6
Cost and Schedule

* Ethan Merrill, DOE/SC
Rick Blaisdell, DOE/OECM
Brian Huizenga, DOE/OECM

SC7
Project Management and ES&H

* Dick Loveless, U. of Wisconsin
Kurt Fisher, DOE/SC

Observers

Mike Procario, DOE/SC
Ted Lavine, DOE/SC
Alan Stone, DOE/SC
Mike Weis, DOE/FSO
Pepin Carolan, DOE/FSO
Paul Philp, DOE/FSO

LEGEND

SC Subcommittee
* Chairperson

COUNT: 14 (excluding observers)

APPENDIX C

REVIEW AGENDA

DOE/SC (CD-1) Review of the
Muon to Electron Conversion (Mu2e) Experiment at Fermilab
June 5-7, 2012

AGENDA

Tuesday, June 5, 2012—Wilson Hall, the Comititum

8:00 am	DOE Executive Session ..... D. Lehman
8:45 am	**Plenary Session—1 West,** Welcome ..... Pier Oddone
9:55 am	Project Overview ..... Ron Ray
10:10 am	**Break—Outside 1 West**
10:25 am	WBS 1.2 Accelerator ..... Steve Werkema
10:50 am	WBS 1.3 Conventional Construction ..... Tom Lackowski
11:15 am	WBS 1.4 Solenoids ..... Mike Lamm
11: 45 am	WBS 1.5 Muon Beamline ..... Sandor Feher
12:05 pm	**Lunch—WH2XO**
1:05 pm	WBS 1.6 Tracker ..... Aseet Mukherjee
1:25 pm	WBS 1.7 Calorimeter ..... Stefano Miscetti
1:45 pm	WBS 1.8 Cosmic Ray Veto ..... Craig Dukes
2:05 pm	WBS 1.9 Trigger and DAQ ..... Mark Bowden
2:25 pm	Common Projects that Support Mu2e ..... Doug Glenzinski
2:50 pm	**Break—Outside 1 West**
3:10 pm	**Subcommittee Breakout Sessions**
4:40 pm	DOE Executive Session—**Comitium** ..... D. Lehman
6:30 pm	Adjourn

Wednesday, June 6, 2012

8:00 am	Subcommittee Breakout Sessions (Continued in same rooms)
9:30 am	Break—**Outside Comitium**
9:45 am	Subcommittee Breakout Sessions
11:30 pm	**Lunch—WH2XO**
1:30 pm	Subcommittee Working Session—**Comitium**
3:00 pm	**Break—Outside Comitium**
3:15 pm	DOE Full Committee Executive Session—**Comitium** ..... D. Lehman

Thursday, June 7, 2012

8:00 am	Subcommittee Working Session—**Comitium**
10:00 am	**Break—Outside Comitium**
10:15 am	DOE Full Committee Executive Session Dry Run—**Comitium** ..... D. Lehman
12:00 pm	**Lunch—Outside Comitium**
2:00 pm	DOE Summary and Closeout—**1 West** ..... D. Lehman
3:00 pm	Adjourn

APPENDIX D

COST TABLE

Mu2e Cost Table

Costs are fully burdened in AY $k

% contingency is calculated for remaining cost.

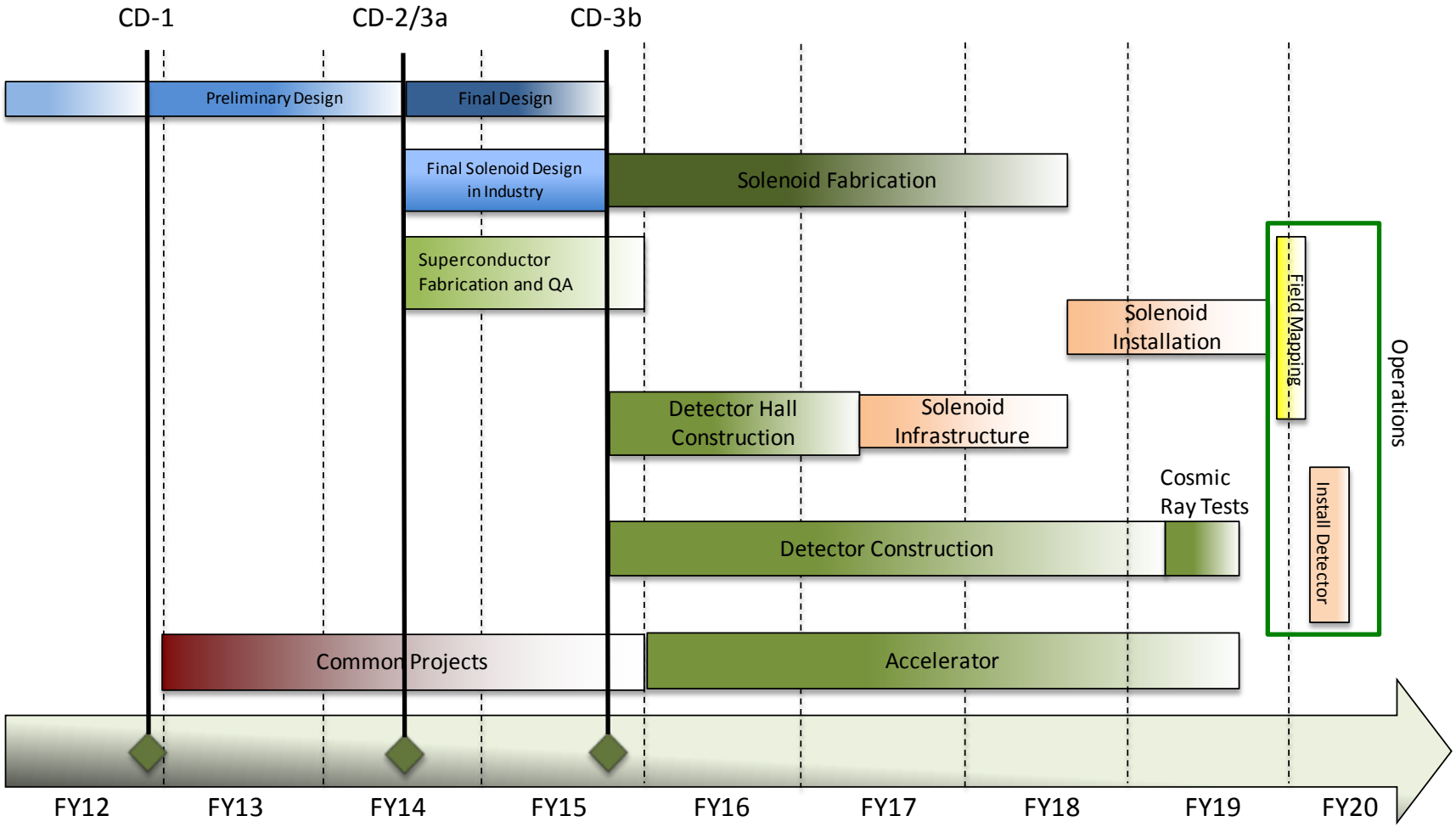
	Base Cost			Estimate Uncertainty			
	Labor	M&S	Total	Labor	M&S	Total	Total Cost
WBS 1 Project Management	$18,660	$1,832	$20,491	0	$83 (14%)	83(0%)	**$20,574**
WBS 2 Accelerator	$21,033	$14,329	$35,362	$5,439 (33%)	$4,500 (33%)	$9,939 (33%)	**$45,301**
WBS 3 Conventional Construction	$2,566	$15,969	$18,535	$799 (33%)	$5,179 (33%)	$5,979 (33%)	**$24,514**
WBS 4 Solenoids	$31,602	$40,111	$71,713	$10,683 (38%)	$15,837 (40%)	$26,520 (39%)	**$98,233**
WBS 5 Muon Beamline	$5,910	$5,033	$10,942	$1,342 (30%)	$1,778 (36%)	$3,120 (33%)	**$14,062**
WBS 6 Tracker	$2,247	$4,725	$6,971	$511 (28%)	$1,404 (35%)	$1,915 (33%)	**$8,886**
WBS 7 Calorimeter	$351	$3,943	$4,294	$109 (34%)	$1,161 (29%)	$1,270(30%)	**$5,564**
WBS 8 Cosmic Ray Veto	$885	$3,533	$4,418	$261 (35%)	$1,098 (32%)	$1,359 (33%)	**$5,777**
WBS 9 Trigger and DAQ	$4,032	$909	$4,941	$1,279 (36%)	$182 (20%)	$1,461 (32%)	**$6,402**
Total	**$87,286**	**$90,384**	**$177,669**	**$20,423 (27%)**	**$31,221 (36%)**	**$51,644 (32%)**	**$229,313**

Estimate uncertainty excluding Project Management is 36%.

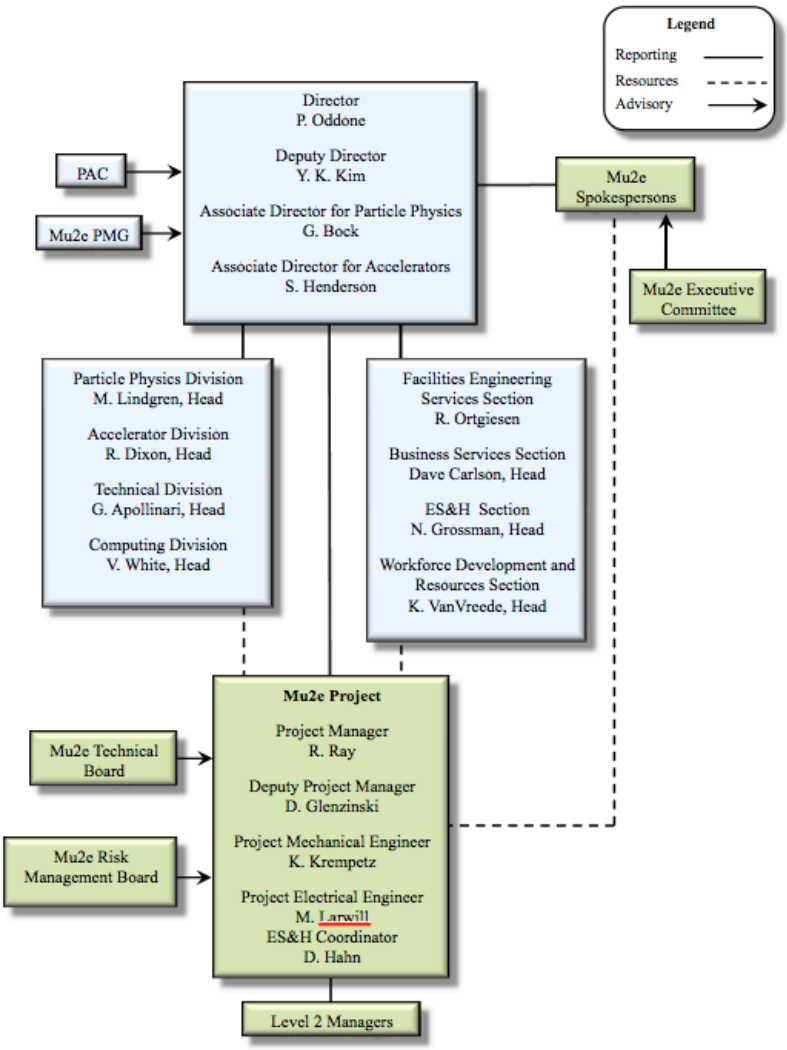
APPENDIX E

SCHEDULE CHART

Mu2e Schedule



APPENDIX F

MANAGEMENT CHART

Mu2e Organization