Office of Project Assessment
Review Committee Report on the

Muon to Electron Conversion Experiment (Mu2e) Project

at Fermi National Accelerator Laboratory

October 2014

EXECUTIVE SUMMARY

A Department of Energy/Office of Science (DOE/SC) review of the Muon to Electron Conversion (Mu2e) project was conducted on October 21-24, 2014 at the Fermi National Accelerator Laboratory (Fermilab).* The review was conducted by the Office of Project Assessment (OPA), and chaired by Kurt W. Fisher, OPA, at the request of Michael Procario, Director of Facilities for High Energy Physics. The purpose of the review was to evaluate the project's readiness for Critical Decision (CD) 2/3b—CD-2 to approve the project baseline and CD-3b to allow the project to utilize up to $24 million to initiate the start of civil construction of the detector hall and allow the project team to start fabrication of Transport Solenoid (TS) Modules (the TS assembly is on the critical path).

Accelerator / Muon Beam

In general, the Committee considered the Mu2e accelerator systems to be well defined and ready for baselining. There are four areas that the Committee judged to have existing challenges and should be carefully monitored: 1) resonant slow extraction, because the efficiency requirements are very stringent; 2) extinction and extinction monitoring, in that this is novel in accelerator science and technology; 3) radiation safety improvements, because the delivery ring is being used for a much higher power beam than it was designed for; and 4) the proton target and its remote handling because this is also somewhat unique. The Committee focused on these four areas because of a greater concern for them.

The Committee expected to see technical design review reports; however, for most of the Mu2e accelerator design, these were not available because reviews were not done. The recent Director's Review was cited by Fermilab as fulfilling the requirement, but the DOE/SC Committee does not consider it to be a "peer-reviewed" technical review. Furthermore, these reviews should include a charge element to evaluate interface/integration issues. A recommendation from the Committee is for the project team to insert milestones into the Primavera schedule for technical design reviews prior to critical actions. In particular, perform technical design reviews prior to the CD-3c review, and have reports available to the Review Committee.

The first threshold Key Performance Parameter (KPP) for accelerator systems is considered by the project and by the Committee to have installation inconsistencies. The Threshold KPP is broad and includes installation/testing of the electrostatic septa. The Objective KPP requires extracted beam on the absorber. The Objective KPP will be satisfied by a single turn kick extraction, which cannot be done with the septa installed. This should be resolved.

In the Muon Beamline scope, all but a few of the Level 3 WBS elements are at or beyond the preliminary design level and some are quite advanced, nearing the final design. None of these WBS elements are scheduled for final design before CD-3c; most are to be at that stage almost two years later. The Committee judged that it would seem desirable and possible for all of these WBS elements to be at the final design at CD-3c.

* The review charge memo (Appendix A) originally requested the dates of August 19–21 which were later revised.

The Committee concurred with the proposed proton extinction scheme of two upstream collimators and one downstream, and encouraged further development adding more upstream collimation.

Superconducting Solenoids

The scope of the solenoid magnets represent a major fraction of the project: three superconducting solenoids, the Production Solenoid (PS), the Detector Solenoid (DS), and the TS (on the critical path). Estimated costs are $112 million including 34% contingency.

The Committee was informed that the Mu2e project team plans to purchase two large superconducting Niobium-Titanium (NbTi) solenoid magnets (PS and DS) from a single vendor. Responses to a Request for Proposals (RFP) have been received from three vendors with capabilities close to those needed by Mu2e. Responses to the RFP are the basis for the $30 million baseline cost estimate including 15% contingency.

The first TS module prototype is in the final stages of assembly. Testing will be at Fermilab; however, a test and acceptance plan was not presented. The Committee strongly recommended that the project team deliver a test and acceptance plan for the prototype TS module by November 7, 2014.

Detector Systems

For the Detector Systems, specifically with regards to the Tracker, the Committee judged that integration of the electronics into the panel rim is also a complex and challenging task. A full prototype at the earliest possible time would be valuable to fully qualify the design. The current plan is to insert the fully assembled tracker into the solenoid to test for mechanical compliance, but not powered until a year after that.

The calorimeter team is to be commended for its rapid pivot from LYSO to BaF_2, as the LYSO cost had increased by a factor of four by the end of 2013. The Committee judged that the choice made by the project team is appropriate. The backup CsI alternative leaves less headroom to meet the experiment's requirements.

The Committee recommended that the project team perform Vertical Slice Tests of each detector subsystem, including advanced prototypes of detector components, subdetector electronics, and data acquisition system before the CD-3c review.

Civil Construction

The Committee noted that the Mu2e civil team is very experienced at this size and type of construction. The project team should be commended for the strategic approach to combining the scope of the Mu2e Detector Hall and the Muon Campus Beamline Enclosure. This delivery method reduces risk of construction scope conflict and reduces cost of general conditions.

The Committee concurred that expeditious completion of the award and notice to proceed of the detector hall and beamline scope is critical to begin excavation before the potentially adverse winter weather.

Environment, Safety and Health

The Committee judged that there is insufficient Environment, Safety, and Health (ES&H), and Quality Assurance (QA) expertise on the project to deliver stated/required responsibilities and recommended that the project team put in place technically experienced ES&H and QA leads.

Cost and Schedule

The Total Project Cost (TPC) presented was $271 million, with in-kind contributions of approximately $4 million from INFN (Istituto Nazionale di Fisica Nucleare, Rome), which are not included in the TPC. Through September 2014, the cost to date was $52.6 million, or roughly 24% of the Budget at Completion (BAC). Contingency of $52.72 million (32% BAC to go) consisted of $46.2 million in estimate uncertainty and $6.5 million in risks. Project baseline basis of estimate (BOE) consisted of 24% actual, 37% quotes and level-of-effort labor, 27% engineering estimate and 12% expert opinion. The project is managing to the early finish date of first quarter 2021 with a CD-4 date of first quarter 2023 (accommodating two years of schedule contingency).

The Committee performed a drill down with six Control Account Managers (CAMs) who in aggregate were responsible for cost and scope representing 36% of the BAC. During the CAM interviews and drill downs, the Committee verified the quality and accuracy of those portions of the cost estimate. In addition, the CAMs interviewed demonstrated ownership and confidence in their scope, cost, and schedule estimates. They also demonstrated knowledge of their schedule contingency, their activities status relative to the critical path, and their risks. The CAMs have received formal training on the Earned Value Management System and most understood the processes. However, it was apparent that the CAMs have no input (or ownership) in determining monthly reported Estimate at Completion (EAC), as EAC is currently computed automatically via the cost processing software. The project should consider holding routine EAC discussions as part of the monthly status meetings.

Management

The Committee judged that the scope contingencies, which were shown, did not appear to be scientifically optimal. The project should consider a set of less draconian scope contingencies. For example, the shielding at full intensity is unlikely to be needed early in the experiment and that option indeed was presented by the project as a more benign alternative.

The Committee suggested that the project team consider executing agreements, such as Statement of Work/agreements with university groups and international partners. It appears there is substantial M&S (approximately $5 million) cost exposure for INFN and Labor cost exposure (approximately 60 FTE) for university groups. These estimated costs would be significant if they would need to be assumed by the project. The project should work to getting formal commitments as soon as possible in order to retire these risks.

The Committee recommended that the project team convene external expert advisory groups for all high-consequence WBS systems, similar to that established for the solenoids, in advance of key decision points (e.g., independent peer review, design, and procurement reviews). (This was a comment in the DOE CD-1 review report.)

CONTENTS

1. INTRODUCTION

With the discovery of non-zero neutrino masses and flavor mixing, the fact that individual lepton-flavor numbers (electron-number, muon-number, and tau-number) are not conserved has been established. All such flavor-violating effects have been observed to-date 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 coherent conversion of muons into electrons in the field of a nucleus, probing new physics at mass scales that exceed the reach of the Large Hadron Collider.

In its 2008 report, "U.S. Particle Physics: Scientific Opportunities, A Strategic Plan for the Next Ten Years," the U.S. High Energy Physics Advisory Panel (HEPAP) and its 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 the Director of the Office of Science (SC), Department of Energy (DOE). This project has been in the design-development stage since then.

Now, in 2014, the Mu2e project has advanced through the preliminary design phase and is proposing a Performance Baseline incorporating scope, cost and schedule, and a plan to commence civil construction and technical fabrication activities. The new HEPAP Strategic Plan for U.S. Particle Physics ("Building for Discovery," 2014) has reiterated the priority of the Mu2e program as an immediate target of opportunity in the drive to search for new physics, with its science case undiminished relative to the earlier prioritization.

2. TECHNICAL SYSTEMS EVALUATIONS

2.1 Accelerator Physics

Accelerator Physics addresses two Level 2 WBS elements—Accelerator (WBS 475.02) and Muon Beamline (WBS 475.05). The issues addressed during this review are noted below, and generally align with Level 3 WBS elements. Talks were presented on each of the following topics and the Committee thoroughly evaluated each topic at the review.

Accelerator (WBS 475.02)

- Delivery Ring RF
- Resonant Extraction System
- Radiation Safety Improvements
- External Beamline
- Extinction and Extinction Monitoring
- Target Station
- Instrumentation and Controls

Muon Beamline (WBS 475.05)

- Vacuum System
- Collimators
- Upstream External Shielding
- Stopping Target
- Stopping Target Monitor
- DS Internal Shielding
- Muon Beam Stop
- Downstream External Shielding
- Detector Support Structure

The work captured in these WBS elements is extensive. The TPC associated with WBS 475.02 is $50.2 million and with WBS 475.05, $25.5 million. 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" from Accelerator Improvement and General Plant Projects (AIP and GPP) projects, and from the Muon g-2 project. In all cases, the Committee assessed the interfaces between these projects and the Mu2e project. These appear to be well managed, but concerns remain due to the complexity of the tasks.

Both the accelerator and muon beamline teams are very experienced and are to be commended for preparing and delivering clear presentations and for enthusiastic help in answering questions raised during the follow-up discussions.

2.1.1 Findings

2.1.1.1 Accelerator Physics and Accelerator Systems

Since CD-1 the accelerator part of the project significantly advanced.

The Committee was presented with a comprehensive, well-documented look at the accelerator costs. The accelerator CD-2 baseline estimate was created using standard methods for Basis of Estimate. Adequate contingency has been appropriately applied to each Level 3 cost line to address uncertainty and risk in these estimates.

The overall schedule for the accelerator systems is driven by the project's funding profile and not technical issues or vendor supply issues. The current activities for installation of the Electrostatic Septa and the Extinction Monitor appear to be on the critical path for achieving the project's CD-4 early finish date in early October 2020 (with approval in early November). The official CD-4 date is first quarter FY 2023, which includes 24 months of programmatic schedule contingency.

Delivery Ring RF

Delivery system radio frequency (RF) is a fairly straightforward copy of what is being done for the Recycler RF. High-level and low-level RF will also be based on existing designs.

Resonant Extraction System

The slow resonant extraction system is one of the challenging aspects of this scope of work. What makes this challenging is the requirement of 98% efficiency. Simulation work is ongoing.

Although there were no presentations about collective effects in the delivery ring, the Committee was told that they were calculated and rather weak as the beam current is much below instability thresholds even with added impedance from the electrostatic septum.

R&D on the resonant extraction electrostatic septa (ESS) is needed. This is due, in part, to a desire to use higher voltages than in the past. There was recently a down-select from wires to foils.

Radiation Safety Improvements

Due to repurposing of the Delivery Ring tunnel, shielding and radiation safety is a challenge. The Delivery Ring tunnel was designed for a program, which ran 13 watts of beam power, and for this project it must operate with 8 kW beam power.

External Beamline

The M4 external beamline, which transports protons from the delivery ring to the proton target, has recently been reworked. The motivation included:

- Location and bearing of Muon g–2 ring were established.
- Optics for the extinction section of the line were refined.
- Magnets were chosen from available inventory of Fermilab spares.
- Minimize vacuum preparation work, reuse vacuum pumps, and parts inventory from Accumulator ring.

Extinction and Extinction Monitoring

The Mu2e experiment has very stringent limits on the amount of beam that appears between pulses. The extinction system provides this with a requirement of 10^{-10} protons between pulses, on average. It is claimed that 10^{-5} will occur naturally out of the Delivery Ring extraction system, and additional factor of 10^{-7} will be produced by the external extinction system provided in the work scope.

Collimators clean-up transverse tails in the beam, and a set of resonant dipoles will kick the beam into a collimation system, such that only in time beam will be transmitted to the production targets, producing the additional factor of 10^{-7}.

Regardless of the extinction level that the beam delivery scheme achieves, the experiment can only base its background estimate on the extinction level it can measure. Therefore, it is absolutely vital to measure extinction with adequate accuracy for the experiment analysis and once the extinction level is established, it must be continuously controlled over the entire life of the experiment. Thus, statistical monitoring using an integral device that measures the extinction over many Mu2e cycles will be employed with the integration time of the order of three hours (at the level of the extinction ratio of 10^{-10}).

Target Station

The production target must: maximize the number of stopped muons (high-Z material), have a small radius, and minimize target support structure material to reduce pion reabsorption. The target lifetime must be greater than one year to minimize interruptions to the experiment and target replacement time should be less than one month. The target-beam alignment should be less than 0.5 mm transverse, and less than 10 mr angle.

A remote handling system is being built for changing the target after activation. This is novel technology at Fermilab, and the final design approach has not been chosen.

If the radiatively cooled target proves unworkable, the fall-back is a water or helium-cooled target.

Instrumentation and Controls

Instrumentation and controls designs are based on existing Fermilab hardware. In some cases existing hardware is being repurposed. There are many instrumentation needs that are being met by Accelerator Improvement Projects (AIP) and the Muon g–2 project.

2.1.1.2 Muon Beamline

Vacuum

Since CD-1, the vacuum system design changed from cryo pumps to diffusion pumps to resolve issues of pumps working in strong magnetic fields. Outgassing rates of materials used in vacuum system were verified and in some cases measured and pump-down times and ultimate vacuum levels calculated. Pump-down times do not meet initial criteria as they are dominated by long manifold conductances necessary for pump radiation shielding. Ultimate vacuum levels are predicted to be better than required.

Collimators

Collimator designs have been refined and materials chosen.

Upstream External Shielding

Shielding has been added to the production solenoid. Engineers have optimized the design of shielding blocks to reduce stacking time and radiation leakage.

Stopping Target

The project modified the wire size supporting target.

Stopping Target Monitor

The design philosophy has changed considerably since CD-1. New design detects delayed gamma rays from target activation product (Mg-27) instead of prompt muonic X-rays. This was done due to inherent problems in the initial design and has entailed a considerable re-design that is still ongoing.

DS Internal Shielding

There are three absorbers in this task; all are new or considerably changed since CD-1. The optimization calculations and material choices are ongoing.

Muon Beam Stop

The shielding design was optimized, lead shielding eliminated, and more polyethylene shielding was added. Shielding support changed to allow for easier installation and alignment.

Downstream External Shielding

The shielding thickness is substantially increased and more high-density concrete is used due to refined shielding calculations. The shielding block design has been modified for easier installation and less radiation leakage. Installation planning is being performed.

Detector Support and Installation System

The design of the Detector Support and Installation System was refined to allow for easier installation and alignment. Heaters were also added to keep equipment at a constant temperature to reduce alignment error due to temperature expansion/contraction.

2.1.2 Comments

The Committee expected to see technical design review reports. In most cases, these were not available because reviews were not done. The recent Director's Review was cited as fulfilling the requirement, but this Committee looked at the Director's Review report and does not consider it to be a "peer reviewed" technical review. Furthermore, these reviews should include a charge element to evaluate interface/integration issues. A recommendation follows.

The first Threshold Key Performance Parameter (KPP) for accelerator systems is considered by the project and by the Committee to have installation inconsistencies. The "Threshold KPP" is broad and includes installation/testing of the electrostatic septa. The "Objective KPP" requires extracted beam on absorber. The Objective KPP will be satisfied by a single turn kick extraction, which cannot be done with the septa installed. This should be resolved.

2.1.2.1 Accelerator Physics and Accelerator Systems

In general, the Committee considered the Mu2e accelerator systems to be well defined and ready for baselining. There are four areas that the Committee judged to have existing challenges and should be carefully monitored. These are: resonant slow extraction, because the efficiency requirements are very stringent; extinction and extinction monitoring, in that this is novel in accelerator science and technology; radiation safety improvements, because the delivery ring is being used for a much higher power beam than it was designed for; and the proton target and its remote handling because this is also somewhat unique. The Committee focused on these four areas because of a greater concern for them.

Cost and Schedule

The current Basis of Estimate (BOE) for the Accelerator appears to be appropriate for CD-2. As of this review, the Committee did not see any high-risk items or activities threatening the costs in the Accelerator areas. Managing the costs over the next year or so, where lower levels of effort and materials and supplies are planned, will be important.

The overall schedule for the Accelerator appears to be driven by the project's funding profile and not technical issues or vendor supply issues. The current activities for installation of the Electrostatic Septa and the Extinction Monitor testing appear to be on the critical path for achieving the project's CD-4 early finish date in early October 2020 (with approval in early November). The official CD-4 date is first quarter FY 2023, which includes 24 months of programmatic schedule contingency.

It would have been clearer to see both early finish and official CD-4 dates and schedule contingency on all schedules.

The project should consider deferring/delaying items in other WBS areas, with respect to the funding profile, that have less effect on meeting the early date finish for CD-4.

Planned effort levels for the combined accelerator activities, from FY 2015 to FY 2020 appear quite frugal.

Delivery Ring RF

The Committee concurred that the Delivery Ring radio frequency (RF) system is low risk.

Resonant Extraction System

The simulation work for the slow resonant extraction system is ongoing and making progress. Two simulation codes are being used, looking at different aspects of the problem (i.e., Synergia for spill simulation and MARS for beam loss calculations).

Extraction at the third- order resonance was selected over the second- order resonance after careful analysis of *pros* and *cons* of both options. The important aspect of using the third- order resonance is the ability of independent fine tuning of the orientation of the resonance separatrix in the phase space using two families of sextupoles that helps to maintain the extraction angle parallel to the foil plane in the electrostatic septum. This explains a need for ramping power supplies for sextupoles. Addition of the rf knockout and dynamic orbit bump also helps to maintain a better control of the extraction efficiency and stability of a spill rate. Leftover primary proton beam in the Delivery Ring will be sent to the existing Delivery Ring abort beamline that will be upgraded to accommodate the faster cycle times.

The Committee judged that the project should now consider increasing the beta at the electrostatic septa (ESS) in order to contribute to the reduction in losses at the ESS.

If space is too tight to consider new installations that will allow added flexibility to the lattice, one can consider a space trade-off between dipole correctors currently used for the dynamic orbit bump and trim quadrupoles that could help to afford lattice modification with a larger beneficial impact for the slow resonance extraction.

The Committee recognized that particle tracking simulations show small sextupole magnet contributions to the betatron tune dependencies from the amplitude of the particle oscillations. Nevertheless, obtaining these numbers numerically will be useful for future considerations and completeness of the analysis.

That Committee judged that a thorough design review of resonant extraction should address and document all lattice and technical issues in the delivery ring needed to make this deliverable successful.

Radiation Safety Improvements

The project is dealing with the radiation issue in the delivery ring through both passive (shielding) and active (interlock) approaches. The Committee judged that this is being dealt with appropriately (i.e., by assigning a Level 3 manager in accelerator systems to this task, and by the requisite inclusion the laboratory safety division), but continued scrutiny is necessary.
The Committee agrees that use of a total loss monitor (TLM) simplifies radiation control.

External Beamline

Based on the presentation, the Committee judged that good progress has been made on the M4 external beamline and that it meets the needs of the project.

Extinction and Extinction Monitoring

The Committee recognized that proof of concept for proton extinction at the level of 10^{-10} is difficult, requiring extensive simulations that are yet to be completed. The Committee judged that the proposed scheme with two upstream collimators and one downstream collimator has a good chance to work and encouraged its further development adding, perhaps, more upstream collimation. This will help to reduce or even eliminate dependencies for accurate prediction of proton population in the tails of the incoming beam and raise the confidence in the extinction design.

Target Station

Several unresolved issues remain in the target system area. The method of cooling the target has not been fully resolved. This incurs some risk, as the back-up plans are more expensive. Also, there are several methods being considered for remote handling of the target. The Committee determined that the choice does not impact civil construction plans now underway, but could involve an add-on building later. These issues should be resolved soon, and must be determined by CD-3c.

The beam size at the target was increased to reduce power density and simplify beam steering on the target. Upper steering boundaries were also redefined and become ±0.8 degree in angle and ±1 cm in coordinate. The Committee asked the project to reconsider if the range and beam steering accuracy are sufficient.

It was understood that vacuum requirements in the target vessel are mainly driven by concerns of target survivability due to corrosion under continuous target oxidation. Thus, recently proposed use of silicon-carbide (SiC) coating for target material is a step in a right direction. Besides, SiC has a better emissivity and this allows to drop the target temperature from about 1700 °C to about 1200 °C. The ongoing research and experimentation in the Rutherford Laboratory that also include testing of target mechanical durability under stress and fatigue, which will aid in informing the final decision.

The project should determine if there are any issues with radiation induced galvanic corrosion with the use of bronze in the target heat shield.

Instrumentation and Controls

Most of the instrumentation needed for operation of the Mu2e Delivery ring already exists, but it should be modified or upgraded to accommodate the faster cycle times. The existing DC current transformer (DCCT) will be used to monitor beam intensity through the slow spill cycle. Beam position monitors (BPMs) and beam loss monitors (BLMs) will be used to monitor the positions and losses in the line. Both systems will need significant hardware and electronics modifications to work under Mu2e operational conditions; however, much of the needed equipment can be repurposed from unused collider equipment. To regulate and optimize the Debuncher resonant extraction process, a delivery ring tune measurement scheme will be required. Schottky detector hardware and electronics will be recycled from the Tevatron to make this system.

2.1.2.2 Muon Beamline

In the Muon Beamline, all but a few of the Level 3 WBS elements are at or beyond the preliminary design level. Some are quite advanced, nearing the final design. None of these WBS elements are scheduled for final design before CD-3c; most are to be at that stage almost two years later. Except for vacuum, which achieves final design within six months of CD-3c, all WBS elements here have a "second iteration design" before CD-3c and have very little engineering resources after this point. It would seem desirable and possible for all of these WBS elements to be at the final design at CD-3c rather than two years later.

The present installation plans call for the solenoid systems to be carefully aligned and then surrounded by approximately 1,000 tons of shielding. It is possible that this shielding will change the alignment due to floor deformation and underlying soil compaction that may take a long time (years) to stabilize. Sufficient planning should take this into consideration.

Vacuum

The use of diffusion pumps resolves the issue of vacuum pump performance in strong magnetic fields as it has no moving parts. Despite having a cold baffle, there is a very real possibility of diffusion pump vapor/oil entering the vacuum system, especially in an accident scenario. This vapor/oil would not be able to be removed. The reviewers have been assured that there is no requirement that the vacuum system be kept oil free. However, in the proton target presentation, it was shown that thin coatings on the surface of the proposed Tungsten target could lower the peak target temperature from 1,700 to 1,200°C by changing the emissivity. Since the emissivity (and peak temperature) of the target is this sensitive, it is possible that oil vapor deposits on the target could be detrimental to emissivity. The system being used to test target performance is presently turbo-pumped. The Committee suggested that diffusion pumps be substituted to model design conditions and further that diffusion pump oil be deliberately introduced to the vacuum system to simulate an accident scenario.

The anti-proton stopping window at the TSu/TSd interface (between the upstream and downstream halves of the TS solenoid magnet) will be made from a beryllium plate whose thickness is 0.2 mm in center line of window and linearly increasing to 1.3mm on outer window border at distance of 150mm. This window forms a vacuum barrier between the upstream and downstream vacuum system and will most certainly rupture if a significant pressure differential develops between the two vacuum systems. Changing this window requires unstacking much shielding and potential exposure to highly activated beryllium shards. At present, there is no system equalize pressure in the two systems, especially in an accident/leak occurrence. The reviewers judged that such a safety system is desirable and should be considered.

Collimators

The collimators appear on the critical path of the project. Their design should be completed before CD-3c.

Upstream and Downstream Shielding

The shielding plans for this WBS propose to use barite (heavy) concrete rather than the usual iron loaded concrete as it is non-magnetic. While this has been used at other nuclear facilities, experience at Fermilab and local concrete casters is very limited. Tests are planned—this is very desirable as this is a significant cost/design element.

Muon Stopping Target

The Muon Stopping Target design appears nearly complete and represents a significant physics and engineering effort. This design could be easily at the final design level soon.

Muon Stopping Target Monitor

This is a fairly complex system and is the least advanced element in this WBS. The designs are beyond the conceptual stage but not yet at the preliminary design level. As this system is both physically large and complex, it may impact the design/installation planning of other systems. Additional resources may be needed here.

DS Internal Shielding

Detector Solenoid (DS) Internal Shielding is fairly far advanced but may not be at the preliminary design level yet. However, the overall task is not very complex or extensive.

Muon Beam Stop

The Muon Beam Stop is well beyond the preliminary design level and can be advanced to the final design level fairly soon.

Detector Support

Detector Support is well detailed and approaching final design level.

During installation the detector assembly is planned to be contained in a temporary plastic sheeting “clean room”, which will supply air conditioning and de-humidification while the outside hatch is open and equipment is being loaded. It may be desirable to have air filtration and a positive pressure system as well, as a great amount of dust and dirt may be present.

2.1.3 Recommendations

1. Modify the first accelerator Threshold KPP to be consistent with the installation plans of the project. Revise by November 30, 2014.

2. At Level 3, insert milestones into the Primavera (P6) schedule for technical design reviews prior to critical actions. In particular, perform technical design reviews prior to the CD-3c review, and have reports available to the DOE/SC Review Committee.

2.2 Superconducting Solenoids

2.2.1 Findings

There are three large superconducting solenoids; the production solenoid (PS), detector solenoid (DS), and the transport solenoid (TS). These three magnets, along with substantial support infrastructure, constitute a major fraction of the Mu2e project. The total cost for this task is $112 million and includes a 34% contingency. The number of FTEs peaks in FY 2015 at 30. At the time of this review, the TS magnet is on the critical path followed closely by the other two solenoids (PS, DS). The task is dominated by large procurements. The bulk of the magnet fabrication will be done through industrial contracts that are based on extensive technical design work performed by the Fermilab team.

All major procurements are reviewed by an Acquisitions Oversight Committee, composed of external and internal experts. This acquisition committee has been in operation for several years. Mu2e plans to purchase the DS and PS solenoid magnets from a single vendor. Responses to a request for proposals (RFP) have been received from three vendors with capabilities close to those needed by Mu2e. Responses to an RFP are the basis for the $30 million baseline cost estimate and 15% contingency. Design is at preliminary design level. The final design will be prepared by the vendor. These magnets are on a near-critical path for the project. The project plans to issue a purchase order (PO) for a final design October 27, 2014 in a phased contract that includes construction. A PO for construction will be issued following CD-3c.

The TS solenoid consists of coil modules that each nominally contain two of a total of 52 coils. The coils and module assemblies will be fabricated in industry along with the cryostat and mechanical supports. Testing and final assembly will be done at Fermilab.

Due to the schedule dependence on completion of the TS magnet, the project has requested CD-3b approval. The TS module design is 90% complete and the drawings are 70% complete. It is estimated that it will take two designers, three months to complete the required drawings.

The Mu2e solenoid team has incorporated “lessons learned” from recent community magnet procurements. This was a CD-3a recommendation.

Top-level requirements for the task are well defined. The TS module procurement requirements have been identified but need to be completed. The project team plans to complete the design and drawings prior to a final design review, followed by a successful test of the TS prototype module before releasing the design contract. Final TS coil module specification is not complete, potential changes depend on prototype test results, which are expected March 2015. A written plan for test and acceptance of the prototype TS coil module was not presented. TS production module testing seems to be the most uncertain activity on the solenoid critical path; it is susceptible to any problem with the single test facility available. There are various options to help this schedule, including a contract to test at CEA, Saclay and discussion of a possibility to duplicate the cryostat dome and/or hanging structure below the dome. These options are still under consideration and not a part of the existing schedule and budget.

There are three responsible parties for TS coil test success: conductor vendor, magnet vendor, and Fermilab for test. The Committee judged there was not a clear set of criteria for assigning responsibility. This responsibility assignment will be defined in a responsibility matrix in the procurement specification. The first TS module prototype is in the final stages of assembly. Testing will be completed at Fermilab.

Significant engineering and design have been completed for System Integration, Installation, and Commissioning as this work must be integrated with the building construction. This is required for CD-3b.

There are four configurations of the superconducting cable: DS1, DS2, PS, and TS. Prototypes of all configurations have been successfully completed in industry. Production orders for the DS1, DS2, and TS conductors have been placed and are in process. The order for the PS cable will be executed shortly.

2.2.2 Comments

The project has put together a strong core technical team that is enhanced through strategic partnership with INFN (Genoa). The proposed technical design and associated implementation approach satisfy the performance requirements. The project team has ensured that the subsystems will be fully integrated through excellent coordination between the task integration Level 3 and Mu2e integration team. A detailed plan was presented by the Level 3 integration manager. The CD-4 goals appear to be reasonable and are well defined.

Oversight at superconductor vendors appears to be going well. A recent lesson learned from another High Energy Physics magnet project is that substantial schedule time and cost are added to a project that includes a magnet that requires significant training through numerous quenches. Consideration did not appear to be given to this lesson learned. Engineering, design, and execution plans for energizing and controlling the magnet system appear to be well-planned and complete. Quench detection plans appear to be complete. Magnet measurements and fixture designs are well planned. The management structure is adequate for the defined scope of work and, at least for FY 2015, resources appear to be adequate to deliver the proposed technical scope within the baseline budget and scheduled as specified in the Project Execution Plan. However, close attention will be required to ensure required levels of support in the future.

The Committee noted that the documentation required by DOE Order 413.3B for CD-2 is complete.

The project responded to the recommendations from the June 2014 DOE/SC (CD-3a) review. In particular, they performed a thorough “lesson-learned” analysis of similar recent projects.

With respect to the request for CD-3b, the Committee found that the detailed design is not yet sufficiently mature to continue with procurement and fabrication at this time. A plan for completing the design and generating the documentation required for CD-3b was discussed with the project and it was agreed that approval of CD-3b will be contingent on the completion of a series of milestones given in the recommendations.

Long-lead procurement approvals under CD-3a are progressing well. All but one of the conductor purchase orders have been released and the last one will be released very soon.

2.2.3 Recommendations

3. Deliver a test and acceptance plan for the prototype TS module by November 7, 2014.

4. Deliver the following, in the order given below, by April 1, 2015 prior to final approval of the TS module procurement:

   a. Successful test of TS prototype,
   b. Complete TS coil module design,
   c. Complete TS coil module drawings, and
   d. Final TS coil module procurement readiness review following TS prototype test

5. Include a key personnel requirement in procurement contracts.

6. Aggressively pursue procurement and testing options that will reduce TS schedule risk.

2.3 Detector Systems

2.3.1 Findings

Tracker

The plan is to use thin walled tubes (or "straws") for the charged particle tracking system of the experiment to determine the momentum of candidate electrons.

The full system of the electronics necessary to process raw signals from the straws through the data acquisition system was reviewed in detail including technical specifications and cost.

Test results for a 96-straw panel (120º arc) will become available in July 2015, but test results for a complete plane (six overlapping arcs for 360º) will not become available until mid-2016. The first cosmic ray test of the fully assembled and powered tracker in the vacuum environment of the DS is scheduled to occur in May 2020.

The Mu2e tracker team is a very experienced group with many years of expertise with the design, construction, and operation of similar wire chambers. The tracker group has members from Fermilab and several U.S. universities and will likely grow.

Calorimeter

The Calorimeter Team presented an update of the system since CD-1. The cost of LYSO had increased by a factor of roughly four by the end of CY 2013. This was deemed to be unaffordable. The radiator choice was re-evaluated. Barium fluoride (BaF_2) and cesium iodide (CsI) were considered as cheaper alternatives. BaF_2 has been chosen as the baseline. Development has focused here. There is also continuing investigation and development of CsI as a backup solution. Selection of crystals was driven by the need for a detector with fast response. BaF_2 has one component of its scintillation light, which has the shortest decay time of any inorganic scintillator. This 0.9 ns component at 220 nm leads to timing precision of less than .5ns. BaF_2 will provide energy resolution better than 5% and about 1 cm spatial resolution, satisfying the requirements of the experiment.

The fast component of the scintillation light produced is the smaller component of light output. In order to reduce the effects of the dominant scintillation component (650 ns decay time at 300 nm), it is advantageous to reduce the light sensor efficiency for wavelengths above 250 nm and/or decrease the emission of the long-lived component by appropriate doping of the BaF_2 crystal.

A consortium of Caltech, the Jet Propulsion Laboratory, and the commercial vendor RMD (Radiation Monitoring Devices, Inc., Watertown, MA) has engaged in production of a 'solar-blind', large area APD. The APD is a delta-doped super-lattice APD with high quantum efficiency that incorporates an Atomic Layer Deposition antireflection filter to reduce the longer wavelength component.

Designs for front-end electronics, which had been produced for the LYSO investigations, are now being adapted to use with the BaF_2 crystals. The design of the final digitizer is in process.

The calibration system consists of a source calibration to establish the absolute energy response of each crystal as well as a laser driven light pulser for overall integrity verification. Cosmic rays and decay-in-orbit muons will also be used to set the final E/p calibration.

The status of simulations was presented. Mechanical design concepts were presented where the hexagonal crystals are stacked in two monolithic disks (a change since CD-1 where vanes of crystals were the baseline). Electronics readout crate locations on the disks were shown.
The CsI back-up solution uses the ultra-violet-enhanced sensitivity SPL MPPC (multi-pixel photon counter) to match the light emission of the CsI crystal. For BaF_2, if the consortium development of the UV sensitive and 'solar blind' APDs fails, a Hamamatsu photodiode is available as a backup, though it is not 'solar blind'; it can be used with electronic filtering to decrease the contributions of the long lived component.
The technology choice will be made in May 2015. The choice will be reviewed by a committee that includes members external to the collaboration.

Bases of estimate and schedule were reviewed with Calorimeter management, as well as the monthly process of updating the status of the subsystem.

The Italian contributions to the detector were presented. The status of the proposal for future contributions for the detector was discussed. Items already proposed as contributions include: design, procurement, and assembly of the mechanical support; front-end electronics; the waveform digitizer; and the laser calibration system. Additional items include 50% of the photo-sensors and about a third of the crystals.

Cosmic Ray Veto

The Cosmic Ray Veto (CRV) subsystem is a large array of scintillation counters surrounding the detector and downstream part of the TS. It is required to provide a veto of signals derived from cosmic ray muons to a precision of one part in 10^4.

The CRV is a fairly conventional scintillator system and the planned design closely follows recent successful system designs. It entails co-extruded plastic scintillator, wavelength shifting (WLS) plastic optical fibers for light collection, commercial-of-the-shelf (COTS) silicon photomultiplier (SiPM) photo-detectors for readout, and COTS components for the three types of custom electronics boards.

A strong group has developed an advanced design for which all components, except the ultrasound front-end boards (FEBs), have been tested in early prototypes.

Evidence that the 10^{-4} rejection can be achieved comes from analysis of photoelectron yields, coupled with detailed simulations.

Simulation supporting the rejection performance so far comprises: a) a sample equivalent to 2% of the full data sample for the whole veto array; and b) a 100% simulation of potential vulnerable areas, including the TS hole, edges, and gaps. A preliminary simulation without the full optical model has been used.

A series of prototypes is planned to test and demonstrate important aspects of the construction and performance of the CRV.

Data Acquisition

The Data Acquisition (DAQ) system receives essentially un-triggered (but time period selected) data from Read Out Cards (ROCs) that are part of each sub-detector (Tracker, Calorimeter, and Cosmic Ray Veto) and provides a 590 kHz master clock, derived from the accelerator clock, to all those detector elements. The DAQ system then assembles that data into time blocks or "events". For the Tracker and Calorimeter, the detector data is always "streaming" into the DAQ but for the CRV the data may either be streaming or can be acquired from the CRV ROCs via request—a delayed trigger mode.

Once all the data for a given time slice (or event) is moved into a DAQ processor, the DAQ system data processing algorithms either accept or reject events based on Tracker and Calorimeter data and then may request data for accepted time slices from the CRV unless the CRV is also operated in a streaming mode.

Full events that satisfy the DAQ trigger algorithms are then passed to On Line tasks via standard switched network connections.

The design is based entirely on commercial hardware (commercial high speed communication cards, commercial servers, and switches) with custom firmware and software.

2.3.2 Comments

The Detector's proposed technical design and the implementation approach satisfy the performance requirements. Detector subsystems are working with other project systems and the civil engineering team. The CD-4 goals are reasonable.

The management structure and resources of the detector subsystems are adequate to deliver the proposed technical scope within the baseline budget and schedule. An extensive Technical Design Report (TDR) has been prepared. The project responded satisfactorily to the recommendations from the previous independent project review.

Tracker

Reviewers were impressed with the quality of R&D performed on single straw-tube prototypes. The proposed plan of using straws for the charged particle tracking system of the Mu2e experiment appears sound and adequate to meet the Objective KPP.

The complex logistics of straw-tube fabrication, involving several institutions and transfers, was found to be plausible, based on previous good experience in other projects.

The mechanics of assembling the tubes into planes appears to be complex due to tight space constraints and individually varying tube lengths. The validity of a design change from a machined structure to a printed plastic structure remains to be fully verified.

The location of a particle track along the wire (z coordinate) requires precise timing from both ends of the wire. To achieve the desired z-resolution in a large-scale system such as the proposed tracker, a sophisticated calibration system will be necessary.

The full system of the electronics necessary to process raw signals from the straws through the DAQ system was reviewed in detail including technical specifications and cost and found to be appropriate and of relatively low risk.

The integration of the electronics into the panel rim is also a complex and challenging task. The collaboration has a detailed 3D model (including structural and thermal finite element analysis (FEA) calculations) that lends plausibility to the design. A full prototype at the earliest possible time would be valuable to fully qualify the design.

The panel is comprised of 96 straw tubes of varying length, so the range of acoustic resonance modes will be wide, and will exist in both mylar tubes and tungsten wires. As some modes may be excited by ambient vibration, increased fatigue and early failure may become more likely.

The processing power and data bandwidth requirements are based upon detailed physics simulations.

Slow Controls and Monitoring are also part of the DAQ WBS and are planned to be implemented using commercial hardware combined with custom firmware and code. This slow controls scope is not yet fully defined, but is clearly finite and relatively modest.

The fully assembled tracker will be inserted into the solenoid to test for mechanical compliance, but not operated under power until a year after that.

The milestone schedule, as presented, shows test results available for the straw-tube panel, plane, and fully assembled tracker relatively late and thus presents a risk that rework needed to address unforeseen problems encountered only through these tests could place the tracker near or on the project critical path.

An 18-station tracker may compromise physics reach and/or reliability. Cost/benefit considerations may indicate that twenty or twenty-two stations may be a better choice.

For electronics ensconced in the solenoid, it is important to strive for high reliability, long before failure. The extra cost of using known reliable parts, IPC3 levels of design and assembly and extended burn-ins is tiny compared with the cost of opening the solenoid and so serious efforts should be expended to ensure high quality components and assemblies.

Calorimeter

The Calorimeter Team is to be commended for its rapid pivot from LYSO to BaF_2. The Committee judged that the choice made by the team is appropriate. The CsI alternative leaves less headroom to meet the experiment's requirements.

The radiator technology choice will occur in May 2015. A reasonable research plan is progressing toward that down-select. The selection will be reviewed by a team that includes members external to the collaboration.

The photo-sensor development is going well. The path chosen, to develop a solar blind APD, is reasonable. Risks and alternatives have been adequately considered. The R&D process may not converge in time for the May 2015 technology choice.

The development of the electronics and the mechanical systems is proceeding well, and is at an appropriate level of maturity for this stage of the project.

Plans for a full-chain test (vertical slice test) of the detector components (crystals with photon readout and electronics and DAQ) are vague. Development and execution of such a test, on the time scale of the CD-3c review, is desirable.

Locating the DT neutron generator and the source calibration system fluid lines illustrates the positive functioning of the project's integration team; civil construction as well as detector subsystem and muon beamline.

Simulation development is mature and is able to rapidly turn around changes in the calorimeter design; this has contributed to the successful change of baseline radiator.

The project has proposed the second calorimeter disk as scope contingency. The Committee judged that the loss of physics reach that this choice entails is a serious compromise and needs more careful evaluation.

Management is functioning well, has full understanding of the BOEs, and has begun reporting status of effort for the Earned Value Management System (EVMS).

The Calorimeter Team is working together very effectively, as evidenced by the test beam series performed to develop the LYSO option. The Calorimeter benefits from very strong participation by the INFN collaborators. Their efforts, as well as the proposed in-kind contributions, are crucial to the future success of the project.

Cosmic Ray Veto

Given the near-surface location of the experiment, an efficient CRV system becomes critical for the success of the experiment. The required veto inefficiency of 10^{-4}, while stringent, is not pushing the technology. The project team is capable of this assembly project and the costs and labor are robustly based.

The partial simulation and use of the preliminary simulation system leave the important demonstration that the CRV will achieve the required cosmic ray rejection plausible but significantly incomplete. The collaboration has plans to move to a full version of the Monte Carlo, to simulate the full veto system with a 100% sample, and to simulate the potential vulnerable areas with a sample equivalent to ten times the full data sample. Completion of these improved simulations is an important goal.

Full-sized, pre-production prototype modules will not be built and tested until late FY 2016. This comes after the CD-3c review and, in any case, comes later than would be desirable for timely understanding of the construction process and detailed performance measurements. The Committee noted that the prototype program could be accelerated so that pre-production modules are built and tested before the CD-3c review.

The assembly labor BOE is based on detailed time-motion estimates from defined tasks and stations. The project team practiced them on a small scale without the final fixturing and tools. The basis and contingency are reasonable for CD-2. An extensive Quality Assurance (QA) program is documented for this activity.

The Level 3 manager for Silicon Photomultipliers is being promoted to Deputy Level 1 Project Manager. It will be important to find a strong replacement with broad knowledge of SiPMs. The veto coverage at the downstream end of the detector should be completed. The current simulations show one-third of all muon background entering through this hole.

Data Acquisition

The design relies on modular and extensible individual components so that changes in bandwidth or processing requirements can be handled incrementally and efficiently. The design, as presented, does not include a great deal of margin in bandwidth or processing power but, as the final implementation can be expanded in either dimension, that should not present a problem.

The design relies upon CANBUS to recover from accidental loss of configuration information in inaccessible Field Programmable Gate Arrays (FPGAs)—a somewhat unusual technique motivated by the difficulty of operating an Ethernet connection in a magnetic field. This deserves more analysis and testing.

The Controls part of the DAQ system as presented is largely monitoring of detector parameters with very little actual “control” functionality—this may change as the design of the detectors is finalized.

The data processing group identified and implemented speed-ups for the off-line code that nearly satisfy the expected requirements if scaled to the latest announced processor benchmarks.

The timing system requirements are relatively modest in today’s technology and the planned system seems fully adequate to the task. The planned timing distribution; however, may not be optimal in terms of single point failure modes. Reducing the number of active fanouts or multidrop elements inside the relatively inaccessible solenoid volume may be a useful strategy.

In terms of MTBF, trading off reliability versus penetrations of the vacuum system should be analyzed.

2.3.3 Recommendations

7. Evaluate, before the CD-3c review, the benefits versus difficulties of conducting, before mapping the field in the DS, a short cosmic ray test run with the fully assembled tracker and calorimeter inside the vacuum vessel (at modest vacuum, if possible), with the DS powered.

8. Perform Vertical Slice tests of each detector subsystem, including advanced prototypes of detector components, subdetector electronics, and DAQ system before the CD-3c review is held.

9. Complete improved simulations of the CRV system, including use of the full Framework simulation, and, at least a large fraction of the goals of 100% simulation of the full veto system and 10x simulation of the hole, gap, and edge regions, before the CD-3c review.

3. CIVIL CONSTRUCTION

3.1 Findings

The project team presented a comprehensive set of plenary and breakout talks that discussed the scope, cost, and schedule for the conventional construction of Mu2e.

Eight proposals have been received and initially evaluated. The best value selection criteria for the Mu2e detector hall was based 40% on price and 60% technical. The apparent successful vendors proposed cost is 4% below the independently verified cost estimate. The construction of the General Purpose Project (GPP) funded Muon Campus (MC) beamline enclosure will be included in the awarded scope of this contract resulting in one general contractor for all of the MC construction.

The Conventional Construction WBS includes a Budget at Completion (BAC) of approximately $21 million. A total of $2.8 million has been spent to date on design and construction document scope.

A detailed logically linked schedule containing nearly 300 lines and 73 milestones is in Primavera (P6). Durations of construction activities are based on input from consulting firms and Facility Engineering Services Section (FESS) recent experience.

The Project Manager presented a proposed 15% to go contingency as a result of the favorable bids.

The FESS personnel resources are in place and poised to deliver the construction scope once awarded.

A detailed value engineering effort was completed after preliminary design identifying 62 opportunities that resulted in nearly a $1 million cost savings. This cost savings allowed the project team to expand the facility to include additional capabilities.

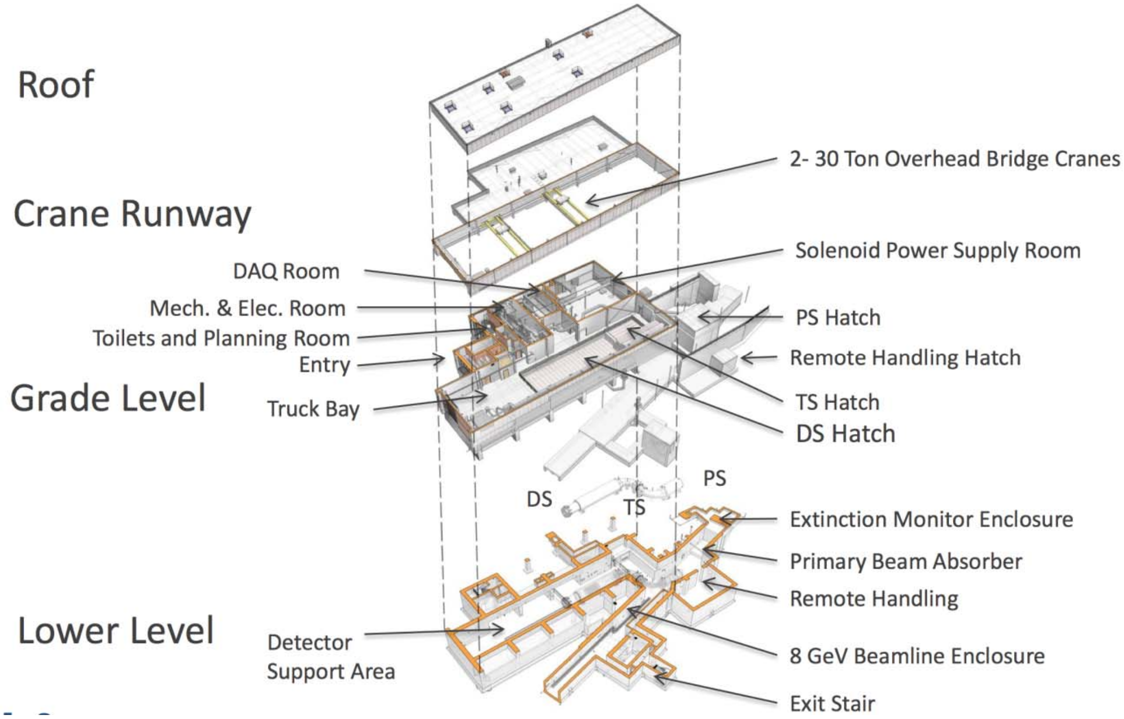
The project risk register includes two construction risks; one threat and one opportunity. An additional 35 risks are included in the subproject risk register.

A laboratory-wide comment and compliance review, by Fermilab staff both internal and external to the project, was conducted on the 90% final design of the Mu2e detector hall that is out for bid. Aon, Inc. (a consultant) did an independent review of the final design of fire and life safety aspects of the project.

A Project Execution Plan (PEP) including input from Conventional Construction has been produced for the project.

The project has produced a TDR, which incorporates overview write-ups and sample drawings from conventional construction. The schematic below depicts the conventional scope.

Table 3-1. Conventional Scope



The Architect/Engineer (A/E) produced a cost estimate for the final design. An Independent Cost Estimate (ICE) was completed and ended up within .4% of the A/E estimate.

A National Environmental Protection Act (NEPA) Categorical Exclusion was obtained and confirmed by the Fermi Site Office.

A muon campus Storm Water Pollution Prevention Plan (SWPPP) permit was obtained to cover MC-1, Mu2e, and the MC Beamline. A soil erosion control plan has been developed.

A Domestic Water Permit to Construct has been obtained. An Illinois Environmental Protection Agency (IEPA) Sanitary Sewer Permit is not required.

Utility requirements are well documented and have been communicated and coordinated between the scientific technical teams via the doc db system.

A Site Specific Safety Construction Safety Plan has been developed including topics related to excavation hazards, personal protection equipment (PPE), Arc Flash, Lock-out Tag-out (LOTO), etc. This information is included in the subcontract documents to ensure General Contractor expectations are set on implementation. FESS will deliver the construction utilizing the in place construction oversight team following existing policy and procedure.

All recommendations from prior reviews have been closed.

3.2 Comments

The Mu2e civil team is very experienced at this size and type of construction. The organization and number of full-time equivalents (FTE) appear reasonable to manage the proposed construction scope. The project team should be commended for the strategic approach to combining the scope of the Mu2e detector hall and the MC beamline enclosure. This delivery method reduces risk of claims at handoff points and reduces cost of general conditions.

Expeditious completion of the award and notice to proceed of the detector hall and beamline scope is critical to begin excavation before the potentially adverse winter weather.

The value engineering exercise is a best practice that resulted in substantial improvement in the function and capability of the detector hall.

The anticipated remaining conventional construction contingency of 15% is likely sufficient due the results of the solicitation.

The development of a site specific safety plan including relaying those requirements to the general contractor is a best practice and will likely reduce the risk of claims related to work planning and control.

3.3 Recommendations

10. Complete the evaluation, and award the civil construction contract as soon as practical.

11. Complete a transition to operations plan at least six months prior to beneficial occupancy turnover to the Fermilab Particle Physics Division (PPD).

4. ENVIRONMENT, SAFETY and HEALTH

4.1 Findings

Relevant documents required for CD-2 are complete and signed-off; Hazard Analysis Report (HAR), QA Plan, Security Vulnerability Plan, and Integrated Safety Management System (ISMS) Plan.

The project has designated ES&H staff embedded into the project and access to central ES&H staff support as needed. Independent to the project, review committees are in place to analyze and approve all aspects of radiation shielding design and the Total Loss Monitoring (TLM) system design and implementation.

Fermilab institutional ES&H staff are engaged with the project, roles have been identified, and they have built flexibility into their programs to address project needs as they appear. ES&H staff are involved in program reviews and Performance Oversight Group (POG) meetings through the Directors Office.

The Project Management Plan (PMP) defines the roles, responsibilities, authorities, and accountabilities for staff on the project team.

Plenary sessions devoted time to ES&H in a consistent manner.

4.2 Comments

The project team, including support personnel, are working well together and understand the project needs. Central ES&H is supportive of the project though it is not apparent that the project team is taking full advantage of central resources (e.g. QA expertise).

The PMP states that "activities conducted at Universities will adhere to the ESH&Q policies and procedures of those specific institutions. The annual Statements of Work (SOW) signed between the institution and the Mu2e project will identify a responsible safety person for Mu2e activities at each institution". The one SOW reviewed (between U of V and Fermilab) clarified ES&H expectations, defined roles and is consistent with the PMP.

Several ES&H risks are identified in the risk registry, but attributed to either Project Management or Accelerator Division; others have been transferred to Operations. The project should clearly identify risks transferred to Operations and verify and document that they are understood and accepted by Operations. There is also a risk with the development and operational function of the robot for target handling. While this may not be a new technology, we were advised that Fermilab has no operational experience with robots used for this purpose.

There is a comprehensive design review and approval process for the Total Loss Monitor system and Passive Shielding design that is outlined in the Fermilab Radiation Control Manual, Chapter 10. This chapter defines roles, authorities etc., and provides the path forward for technical analysis, independent review (external to the project), and approval by ESH&Q Director. The process for approval of these systems has been initiated and appears to be thorough, with conditional approval being granted by the lab ESH&Q Director for designs to move along. Beyond the high level QA Plan, the Committee could not identify how rigorous internal engineering peer reviews or Project Design and Milestones reviews are being organized or how ESH&Q was integrated into these or other reviews such as the target handling system.

The Committee reviewed pertinent documents that support CD-2, such as: the Hazard Analysis Report (HAR), QA Plan, Security Vulnerability Plan, and Integrated Safety Management System (ISMS) Plan. Other documents were provided upon request, including the Static Magnetic Fields program that establishes controls for posting and use of ferrous tools in residual magnetic fields.

The Project Management Plan (PMP) states that "ES&H risk is anticipated to be very low on this project" and that "The Mu2e Project ES&H Coordinator has overall ES&H oversight responsibility for the project". In the course of the review, project leadership acknowledged that the ES&H risk is moderate. The PMP should reflect the level of risk documented in the HAR, which appears to have a more reasonable assessment of risk. The PMP also identifies an ES&H Coordinator role in section 3.17 (not including quality) and separate, as yet unfilled, QA Manager in section 3.20. Further, as described in section 3.20 of the PMP, the Quality Assurance Manager (QAM) reports to the Project Manager. The QAM promotes quality achievement and performance improvement throughout the project. The Project Manager is currently assuming the role of QAM as that position remains unfilled. This approach does not lend itself to the expected and necessary independence of quality assurance and oversight. Both the ES&H Coordinator and QA Manager roles need to be clarified, documented in the PMP, and filled with qualified persons.

A HAR has been developed based on requirements stemming from the institutional ES&H Manual (Doc 2060). Hazards were identified in an iterative process with Level 2 and 3 managers, following a prescribed hazards checklist. The checklist, however, is not all encompassing. As an example, there is no mention of robot operations, which present their own unique hazards. The probability table lacks any time definition and consequently can be misinterpreted when assessing overall risk. The HAR should be revisited to ensure all ES&H risks are evaluated, including proposed activities and installations (e.g., Remote Target Handling, Robot operations).

It is clear from presentations, discussions etc., that everyone understands the project has ES&H risks, but these were consistently presented as not unique to the project and standard at Fermilab. When discussing ES&H risk, the project should widen its view and understanding and ensure that the complexity and nature of hazards they may encounter or introduce and the consequences are well understood. The Committee cautioned against complacency or drifting from good conduct of operations. Risks may not be unique, but they may pose significant challenges as the project matures and construction, installations, and testing activities take place.

The present schedule is not resource loaded to reflect ES&H requirements through the life of the project, including those required from central ES&H support. As the project gathers momentum and operational needs pull on institutional ES&H support, there is a need to document and clarify work load, expectations and priorities.

The lack of a dedicated QAM has left the program vulnerable. A strong QA role will help the project establish the QA foundation, define the methodologies, set the acceptable quality tone, create acceptance and rejection criteria, ensure project reviews at all levels are scheduled, and provide support for improving the level of quality in the organization. Coupled to this was the lack of defined procedures that establish Project Design and Milestone Review requirements and the basis for Engineering Peer Reviews, both of which will ensure quality is driven through design into fabrication, and ultimately into commissioning and operations.

4.3 Recommendations

12. Put in place well-qualified ES&H and QA leads, immediately.

13. Clearly identify those risks transferred to Operations and verify and document they are understood and accepted by Operations, prior to CD-2 approval.

14. Resource load the schedule to reflect ES&H requirements through the life of the project, including required central ES&H support, prior to CD-2 approval.

15. Revisit the HAR to ensure ES&H risks are evaluated, including proposed activities and installations (e.g., Remote Target Handling, Robot operations), by third quarter FY 2015.

16. Update the PMP and PEP to reflect actual project execution and ESH&Q roles and responsibilities, prior to CD-2 approval.

17. Close the remaining Director's Review finding on QA documentation, prior to CD-2 approval.

18. Document and track QA risks in the Project Risk Registry or in a separate QA document.

5. COST and SCHEDULE

5.1 Findings

PROJECT STATUS as of September 2014 Pre-CD-2 Baseline		
Project Type	Line Item	
CD-1	Planned: 4QFY12	Actual: 7/2/2012
CD-2	Planned: 1QFY15	Actual: TBD
CD-3a	Planned: 4QFY12	Actual: 7/10/14
CD-3b	Planned: 1QFY15	Actual: TBD
CD-3c	Planned: 2QFY16	Actual: TBD
CD-4	Planned: 1QFY23	Actual: TBD
TPC Percent Complete	Planned: ~24%	Actual: ~24%
TPC Cost to Date	$52.6M	
TPC Committed to Date	$58.3M	
TPC	$271M	
TEC	$247.3M	
Contingency Cost (w/ Mgmt. Reserve)	$52.72M	32% to go
Contingency Schedule on CD-4	24 months	33% to go
CPI Cumulative	N/A	
SPI Cumulative	N/A	

The project proposed a baseline with a Total Project Cost (TPC) of $271 million with in-kind contributions from INFN (approximately $4 million), which are not included in the TPC. Through September 2014, the cost to date was $52.6 million, or roughly 24% of BAC. The proposed contingency of $52.72 million (32% of BAC to go) consisted of $46.2 million in estimate uncertainty and $6.5 million to cover risks. The project baseline BOE consisted of 24% actuals, 37% quotes, and level of effort (LOE) labor, 27% engineering estimate, and 12% expert opinion. In addition, bids have been received for the primary conventional construction contract and are within the estimate.

The project is managing to the early finish date of first quarter 2021 with a CD-4 date of first quarter 2023 (two years of schedule contingency). A schedule risk analysis was completed and the project considers the schedule contingency to be adequate. The P6 schedule has 7,116 activities, 1,100 milestones, 327 constraints, 74 control accounts, and 30 control account managers (CAMs). The critical path currently runs through the transport solenoids; the production and detection solenoids are near critical path with little schedule contingency. Each

Level 2 WBS has its own schedule, which all roll-up to the master schedule. There are three FY 2016 Level 2 milestones, and eight in FY 2017.

The project has begun implementation of EVMS and has been practicing performance measurement since April 2014. Formal EVMS training has been provided to the CAMs, and the primary tools (P6 and Cobra) are in place. However, significant cost variances were found in the monthly EVMS data, which were due to inaccurate EVMS reporting. The Committee found several instances where costs were incurred without any association of work being performed, which resulted in erroneous negative cost variances. Inconsistencies were found in the September monthly report between the Level 2 stop-light report and the cost summary. In addition, the change control process is not being properly implemented. Several procurement change requests (PCRs) approved during the previous several months were not reflected in the BAC nor in the monthly status reports. In addition, the Committee learned that while there had been a revision to one of the change requests (CR#2), the relevant documentation was not made available to the Committee.

The risk register was updated in October 2014 and reflects both bottom-up and top-down analyses. The Project Manager reported that the Technical Board meets weekly and has discussed risks, as well as other issues. However, the formal Risk Management Board has not met since before the Director's Review.

The draft PMP lists the members of Fermilab's project management team and details their roles and responsibilities. The description of the Project Manager's role appears ninth in the list of personnel. None of the six CAMs interviewed appeared cognizant of the importance of the Contractor Project Manager/Federal Project Director (CPM/FPD) line management relationship.

5.2 Comments

The project presented detailed cost estimates and schedules that appear to be well defined and reasonable. Project risks appear appropriately identified and cost/schedule contingency appears adequate. The schedule contains a significant number of external dependencies, which are shown as milestones. Only three Level 2 milestones have been identified for FY 2016, yet there are eight for FY 2017. There are also too many constraints and open ends in the P6 schedule. As was noted in the Director's review, the use of LOE as a performance measurement method is too high (currently at 20.6% of BAC). Best practice for LOE is closer to15%. The near critical path report threshold (less than one week) appears to be too tight. The project should consider changing the threshold to more than two months in order to more efficiently track activities near the critical path.

The Committee performed a drill down with six CAMs who in aggregate were responsible for cost and scope representing 36% of the BAC. During the CAM interviews and drill downs, the Committee verified the quality and accuracy of those portions of the cost estimate. In addition, the CAMs interviewed demonstrated ownership and confidence in their scope, cost and schedule estimates. They also demonstrated knowledge of their schedule contingency, their activities status relative to the critical path, and their risks. The CAMs have received formal training on EVMS and most understood the processes. However, it was apparent that CAMs have no input (or ownership) in determining monthly reported EAC as EAC is currently computed automatically via the cost processing software. The project should consider holding routine EAC discussions as part of the monthly status meetings.

EVMS is a critical management system and the project should embrace it and fully incorporate it into its culture. The project controls staff appears strong and competent, and ready to implement EVMS. However, the Committee found several instances of poor quality EVMS data input, as well as improper implementation of the change control process. The project also needs to improve internal variance reporting and should include appropriate variance explanations in the monthly status reports. In the spirit of continuous improvement, CAMs should receive periodic EVMS training updates. In addition, the project should strongly encourage Fermilab to quickly finish the development and roll-out of the project monitoring tool called the eCAM notebook.

While the Committee recognized the value of holding risk discussions at the Project's Technical Review Board's weekly meetings, the Risk Management Plan commits to having separate and regular (but with unspecified periodicity) Risk Management Board (RMB) meetings. The RMB has not met since Spring 2014 and it is important that it meet again soon and then with appropriate regularity in the future.

The Committee heard concern from many project staff about whether sufficient staff with critical skills will be available in the years FY 2016 and beyond. The project should continue to work with the Laboratory to develop the tools and appropriate staffing plans in order to address this issue moving forward.

The Committee was also concerned about a lack of clarity as to the project's primary line management chain. As noted above, the PMP is deficient in that it does not clarify the primacy of the CPM/FPD reporting relationship. Further, interviews with the CAMs revealed little knowledge and no appreciation of the project's primary management chain.

5.3 Recommendations

The Committee recommended that the following be completed before CD-2:

19. Restart Risk Management Board meetings, commit to their periodicity, and update the Risk Management Plan.

20. Initiate monthly in-person CAM/project controls status meetings.

21. Clarify the project's line management chain, update the PMP and PEP, and have signed.

22. Generate additional FY 2016 Level 2 milestones.

23. Revisit accelerator-related threshold and objective KPPs.

24. Complete cleanup of baseline schedule; perform monthly cleanup during status process.

25. Demonstrate EVMS and change control proficiency for two months prior to CD-2 approval.

26. Ensure periodic CAM refresher training, at least annually.

27. Review LOE usage project-wide to reduce to closer to 15%.

6. PROJECT MANAGEMENT

6.1 Findings

The new senior management at Fermilab implemented organizational changes in October 2014 with the intention of creating "one laboratory." This arrangement is expected to strengthen support to the Mu2e project. The new organization streamlines reporting to the Laboratory Director, and includes a Chief Project Officer accountable for the successful execution of projects in concert with successful science program operation. Projects are located in various technical divisions. For example, the Mu2e, Muon g-2, CMS projects reside in the Particle Physics Division, while Muon Campus General Plant Projects (GPPs) and Accelerator Improvement Projects (AIPs) reside in the Accelerator Division.

Mu2e is one of many projects underway at Fermilab, and when CD-2/3b is approved, it will be the largest project at the Laboratory. An experienced, cohesive management team is in place, matrixed from several Fermilab divisions. Good project management systems are in place. The project funding profile is consistent with DOE guidance. A recent independent cost estimate review convened by DOE validated the proposed baseline project costs.

The project presented a resource-loaded schedule with a fully sufficient granularity. As presented, the schedule was both functional and complete. The project has made significant progress in adding collaborators and attracting new resources to the project. Scope contingency was identified. A significant amount of work to date was presented. $52 million was spent on project management, conceptual and preliminary design (including value engineering), CD-2 documentation, final design of the detector hall, risk reducing R&D, infrastructure refurbishment, and prototypes.

The project presented the current status of the Interface Control Documents (ICDs). In discussion, several Level 2 managers reported that their ICDs were not yet fully functional. There are many interconnections within the project between Level 2 managers and outside the project with AIP, GPP Projects (Muon Campus) that are crucial to the success of Mu2e. In addition, there are many Fermilab divisions (Particle Physics, Technical, Accelerator, and Computing) that contribute both labor and materials.

Procurement support for project is centrally managed by the Fermilab Procurement Department (PD), which assigned two staff to be their focal points for the project. Currently, less than 20% of their time is required to support Mu2e. The delegated authority of the two PD staff is at a level that would require review two to four levels above their authority.

A recent Laboratory Director's review recommended several actions that are currently in progress. They include documenting and tracking the quality assurance risks in the Project Risk Registry or in a separate QA document.

A plan to specify and achieve CD-4 was presented by the project. It is made more complex because of schedule issues and dependencies. The CD-4 project completion plan, which was shown leaves many parts of the experiment not fully installed and commissioned. However, the connections to beamline schedules and to experimental needs were the driver for this definition of CD-4. A phased approach for transition to operations is being pursued.

6.2 Comments

The overall project is in good shape at this early stage. The project manager provided the Committee a set of thoughtful lessons learned from the work to date. These lessons will prove valuable guidance as the project goes forward. The project team and senior Fermilab management must remain vigilant.

There has been a good start in putting useful ICDs in place. The coordination among all the parties responsible for the success of Mu2e requires that all the parties be fully aware of their cost, schedule, and performance responsibilities. It is crucial that all ICDs be real tools and specify who the responsible parties are, what is the specific handoff (keyed to project requirements documents), and when does it occur (ICD milestone in the resource-loaded schedule). In addition, because of the impact on requirements, should there be changes, the ICD specifications should be controlled documents linked to baseline change requests.

It is early in the procurement phase of the project and there are significant amounts of procurements for the current and upcoming fiscal years. Procurement and project management should remain aware of the demands of the two assigned procurement staff as they split their responsibilities between Mu2e and other demanding projects. A procurement training program for technical staff that details the acquisition process and their roles and responsibilities is a best practice implemented at other DOE laboratories. The Fermilab Procurement Department has evaluated the Thomas Jefferson National Accelerator Facility training program. The Committee encouraged them to implement that program for Mu2e. In future DOE independent project reviews, a procurement breakout session would be beneficial to identify progress on significant, major, and critical procurements as they relate to project cost and schedule.

QA recommendations from the Director's Review should be implemented and closed out prior to CD-2.

The scope contingencies, which were shown, did not appear to be scientifically well informed. The project should consider a set of less draconian scope contingencies. For example, the shielding at full intensity is unlikely to be needed early in the experiment and that option indeed was presented by the project as a more benign alternative.

There are in-kind contributions assumed to be made by university groups (especially in DAQ) and foreign contributors (Detectors from INFN). The project should consider inserting the estimated U.S. metric based costs into the WBS as an assumed contribution so that they can be tracked for percent complete status and so that the financial risk is fully transparent. The project should also consider executing agreements such as statements of work with university groups and international partners. It appears there is substantial M&S (approximately $5 million) cost exposure for INFN and labor cost exposure (approximately 60 FTE) for university groups. These estimated costs would be significant if they were assumed by the project. The project should work to get formal commitments as soon as possible in order to retire these risks.

The transition to operations occurs in three phases and begins well before CD-4. The first phase, scheduled for February 2016, is the beneficial occupancy of the Detector Hall. At that point the Particle Physics Division takes responsibility for operations for the hall. An overall transition plan for this phase should be put in place in a timely manner. After the installation KPPs are satisfied for the solenoids, the field mapping exercise is off project. In fact, the project designs and procures the field mapper, so that only the actual measurements and possible field shimming are off project, as they were judged to be fully the responsibility of the Experiment. The tasks, which occur after the field map cover the testing of the remaining upstream beam line devices, and are scheduled for January 2020. The upstream elements of the beamline will be commissioned by the Accelerator Division (AD), which makes efficient use of calendar time. The "extinction" function will be tested in the upstream beamline in the Objective KPP.

The AD Muon Department is responsible for Mu2e operations. The final element for CD-4 is scheduled to occur in September 2020 when detector elements are completely installed. The three phases of CD-4 are called out and factored in order to make operations tasks occur as soon as possible. The last phase covers cosmic ray data taking, which will test the complete detector system for the Mu2e experiment. Given the scheduling uncertainties, the project should plan for flexibility to define project completion between Threshold and Objective KPP depending on experience. The project should also keep flexibility between Operations and Project in order to smooth out the complexities of the CD-4 end game.

A notional estimate of the time frame for operations (overlapping with the project near CD-4) and the annual costs should be provided for CD-2. The final Experimental Operations Plan should be in place well before CD-4. Because the time needed to measure the solenoid fields with sufficient accuracy to meet the requirements of the experiment is long, operations must start in a timely way after the project delivers solenoids, which meet the KPP requirements.

6.3 Recommendations

28. Demonstrate proficiency with management systems (EVMS, change control, risk management, QA, staffing plans, ICD, lessons learned) across the project as soon as possible, but prior to CD-2 to inculcate a project management culture.

29. Identify a dedicated, experienced QAM for the project as soon as possible, and deploy that person at no later than CD-2.

30. Prior to CD-2, clarify roles, responsibilities, authorities, and accountability in the PMP for the Project Manager and key project personnel, and insure consistency with the PEP.

31. Convene external expert advisory groups for all high-consequence WBS systems, similar to that established for the solenoids, in advance of key decision points—e.g., at engineering design and procurement reviews, and before DOE independent project reviews. (This was a comment in the DOE CD-1 review report.)

32. Prepare a plan to address mitigating delays in review and award of procurements not addressed on major procurement advanced procurement plans that are above the approval threshold of the assigned procurement staff. Present the plan at the next DOE review.

33. Provide procurement breakout sessions at future DOE reviews that address progress and issues on significant, major, and critical procurements.

34. Update the Transition to Operations sections in the PMP and summarize that information in the PEP. Specifics associated with the handoff of the Detector Building to Particle Physics Division should be documented in the PMP no later than six-months before beneficial occupancy.

35. Proceed to CD-2 and CD-3b after updating all required documentation, and incorporating all recommendations from this review associated with these Critical Decisions.

Appendix A Charge Memo

Department of Energy
Office of Science
Washington, DC 20585

JUN - 2 2014

MEMORANDUM FOR STEPHEN MEADOR, ACTING DIRECTOR
OFFICE OF PROJECT ASESSMENT

FROM: MICHAEL PROCARIO
DIRECTOR OF FACILITIES
FOR HIGH ENERGY PHYSICS

SUBJECT: REQUEST TO CONDUCT AN INDEPENDENT PROJECT REVIEW OF THE Mu2e PROJECT

I request that you conduct an Independent Project Review of the Muon-to-Electron Conversion (Mu2e) Project on August 19–21, 2014 at Fermilab. The purpose of this review is to evaluate the project's readiness for Critical Decision CD-2 which will approve of the proposed Performance Management Baseline for technical scope, cost and schedule, as well as the project's readiness for Critical Decision CD-3b which will approve the continuation of procurement and fabrication. Critical Decision CD-3a permitted the initial procurement of conductor for the project.

Your review committee is requested to perform a general assessment of the project's progress, current status, and the identification of potential issues, as well as addressing the following specific questions for CD-2:

1. Do the proposed technical design and associated implementation approach satisfy the performance requirements? How has the project team ensured that the subsystems will be fully integrated? Are the CD-4 goals reasonable and well defined?
2. Is the cost estimate and schedule consistent with the plan to deliver the technical scope? Is the contingency adequate for the risk?
3. Are the management structure and resources adequate to deliver the proposed technical scope within the baseline budget and schedule as specified in the PEP?
4. Is the documentation required by DOE Order 413.3B for CD-2 complete?
5. Are ES&H aspects being properly addressed given the project's current stage of development?
6. Has the project responded satisfactorily to the recommendations from the previous independent project review?

The committee is also asked to address the following questions specifically for CD-3b:

7. Is the detailed design sufficiently mature so that the project can continue with procurement and fabrication? Has there been adequate progress on the long-lead procurement activities approved under CD-3a?
8. Is the documentation required by DOE Order 413.3B for CD-3b complete?

Dr. Theodore Lavine is the program manager for the Mu2e Project in this office and will serve as the DOE Office of HEP 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.

cc:

M. Weis, FSO
P. Carolan, FSO
P. Philp, FSO

P. Dehmer, SC-2
J. Siegrist, SC-25
M. Procario, SC-25
T. Lavine, SC-25
J. Kogut, SC-25
K. Fisher, SC-28

Nigel Lockyer, FNAL
Greg Bock, FNAL
Dean Hoffer, FNAL
Ron Ray, FNAL

Appendix B Review Committee

Department of Energy/Office of Science (CD-2/3b) Review of the
Muon to Electron Conversion Experiment (Mu2e) at Fermilab
October 21-24, 2014

Kurt Fisher, DOE/SC, Chairperson

SC1
Accelerator Physics

* Rod Gerig
Roy Cutler, ORNL
Geoff Pile, ANL
Sasha Zholents, ANL

SC2
Superconducting Solenoids

* Stephen Gourlay, LBNL
Ken Marken, DOE/SC
Bruce Strauss, DOE/SC
Peter Wanderer, BNL

SC3
Detector Systems

* William Wisniewski, SLAC
Howard Gordon, BNL
Richard Kass, Ohio State
Jeff Nelson, W&M
David Nygren, U of Texas, Arlington
Larry Price, DOE/SC
Rick Van Berg, U. of Penn

SC4
Civil Construction

* Jeff Sims, SLAC

SC5
Environment, Safety and Health

* Ian Evans, SLAC
Craig Ferguson, SLAC

SC6
Cost and Schedule

* Jim Krupnick, LBNL
Jerry Kao, DOE/CH
Tony Mennona, BNL

SC7
Project Management

* Don Rej, LANL
Dan Green, FNAL emeritus
Lynn McKnight, TJNAF
Steve Meador, DOE/SC

Observers

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

LEGEND

SC Subcommittee
* Chairperson

COUNT: 26 (excluding observers)

Appendix C Review Agenda

Department of Energy/Office of Science (CD-2/3b) Review of the
Muon to Electron Conversion Experiment (Mu2e) at Fermilab
October 21-24, 2014

AGENDA

<u>Tuesday, October 21, 2014—One East (WH1NE)</u>

8:00 am	Executive Session	K. Fisher
8:50 am	Welcome and Fermilab Context—**Curia II (WH2SW)**	J. Lykken
9:10 am	Motivation, Requirements and Sensitivity	D. Glenzinski
9:25 am	Project Overview	R. Ray
10:10 am	WBS 2 Accelerator	S. Werkema
10:40 am	**Break—Outside Curia II**	
11:00 am	WBS 3 Conventional Construction	T. Lackowski
11:20 am	WBS 4 Solenoids	M. Lamm
11:50 am	WBS 5 Muon Beamline	G. Ginther
12:20 pm	**Lunch—WH2XO**	
1:00 pm	**Photo for DOE Reviewers—Atrium**	
1:20 pm	WBS 6 Tracker—**Curia II (WH2SW)**	A. Mukherjee
1:40 pm	WBS 7 Calorimeter	S. Miscetti
2:00 pm	WBS 8 Cosmic Ray Veto	C. Dukes
2:20 pm	WBS 9 Trigger and DAQ	M. Bowden
2:40 pm	Integration	K. Krempetz
2:55 pm	**Break—Outside Curia II**	
3:10 pm	**<u>Subcommittee Breakout Sessions</u>** • Session 1 Management—One East (WH1NE) • Session 2 Accelerator/Muon Beamline—Black Hole (WH2NW) • Session 3 Conventional Construction—Snake Pit (WH2NE) • Session 4 Solenoids—Racetrack (WH7XO) • Session 5 Calorimeter/Cosmic Ray Veto—Theory (WH3NW) • Session 6 Tracker/DAQ—Comitium (WH2SE)	
5:00 pm	Full Committee Executive Session—**One East (WH1NE)**	
6:30 pm	Adjourn	

<u>Wednesday, October 22, 2014</u>

8:00 am	Subcommittee Breakout Sessions—Continued in same rooms
11:30 am	**Lunch—WH2XO**
12:30 pm	Subcommittee Breakout Sessions—Continued in same rooms
2:00 pm	Response to Reviewer Questions—**One East (WH1NE)**
3:00 pm	**Break—Inside One East (WH1NE)**
3:15 pm	Subcommittee Executive Session/Report Writing
4:30 pm	Full Committee Executive Session—**One East (WH1NE)**

<u>Thursday, October 23, 2014</u>

8:00 am	Subcommittee Breakout Sessions—Continued in same rooms
11:30 am	**Lunch—WH2XO**
12:30 pm	Subcommittee Breakout Sessions—Continued in same rooms
2:00 pm	Response to Reviewer Questions—**Comitium (WH2SE)**
3:00 pm	**Break—Inside One East (WH1NE)**
3:15 pm	Subcommittee Executive Session/Report Writing
4:30 pm	Full Committee Executive Session—**One East (WH1NE)**

<u>Friday, October 24, 2014</u>

8:00 am	Subcommittee Working Session—**One East (WH1NE)**
9:30 am	Full Committee Executive Session Dry Run/Working Lunch—**One East (WH1NE)**
11:00 am	Closeout Presentation—**Auditorium (WHGround)**
12:00 pm	Adjourn

Appendix D Mu2e Funding and Cost Tables

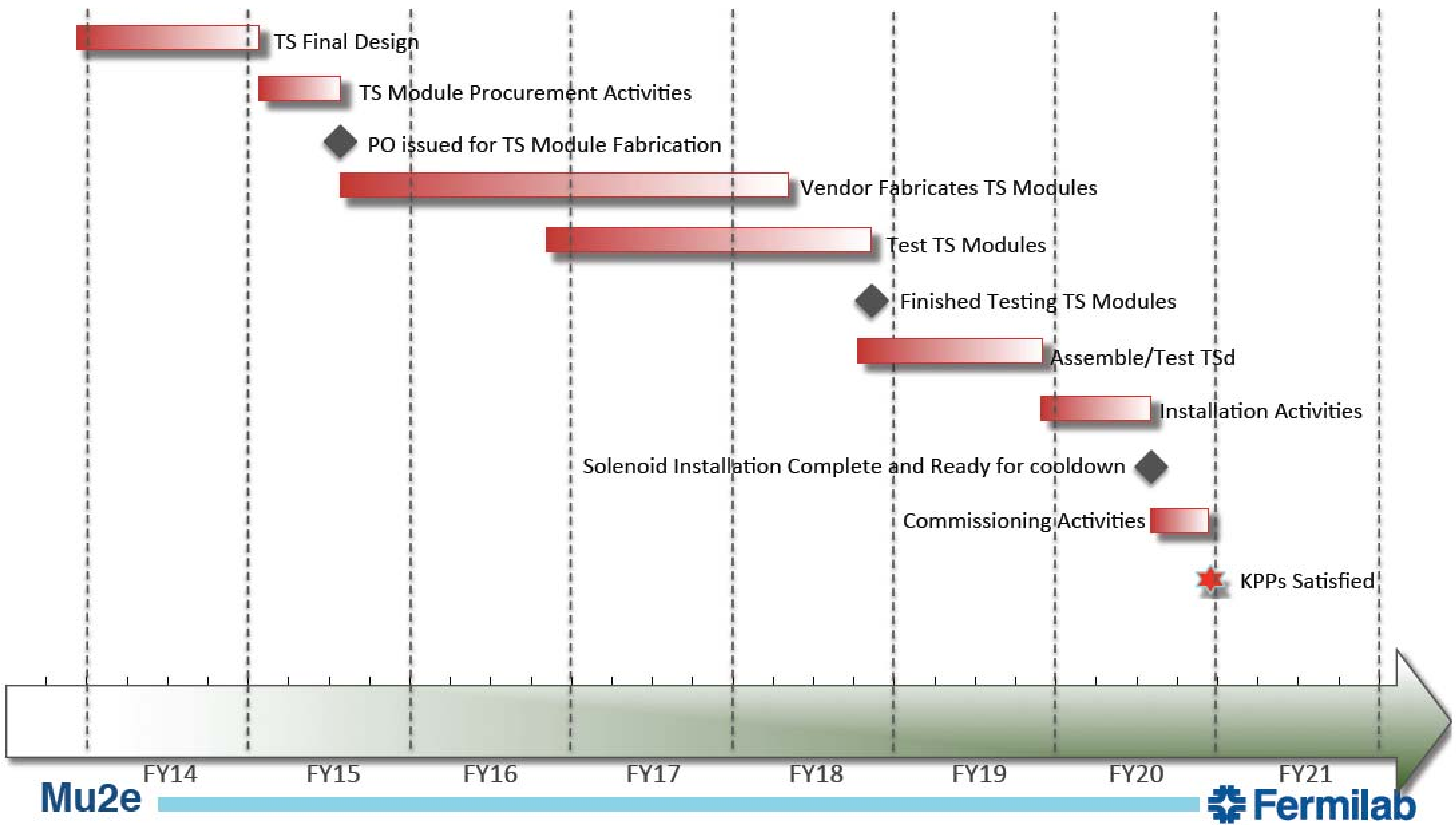
Proposed Funding Profile by Fiscal Year ($M)

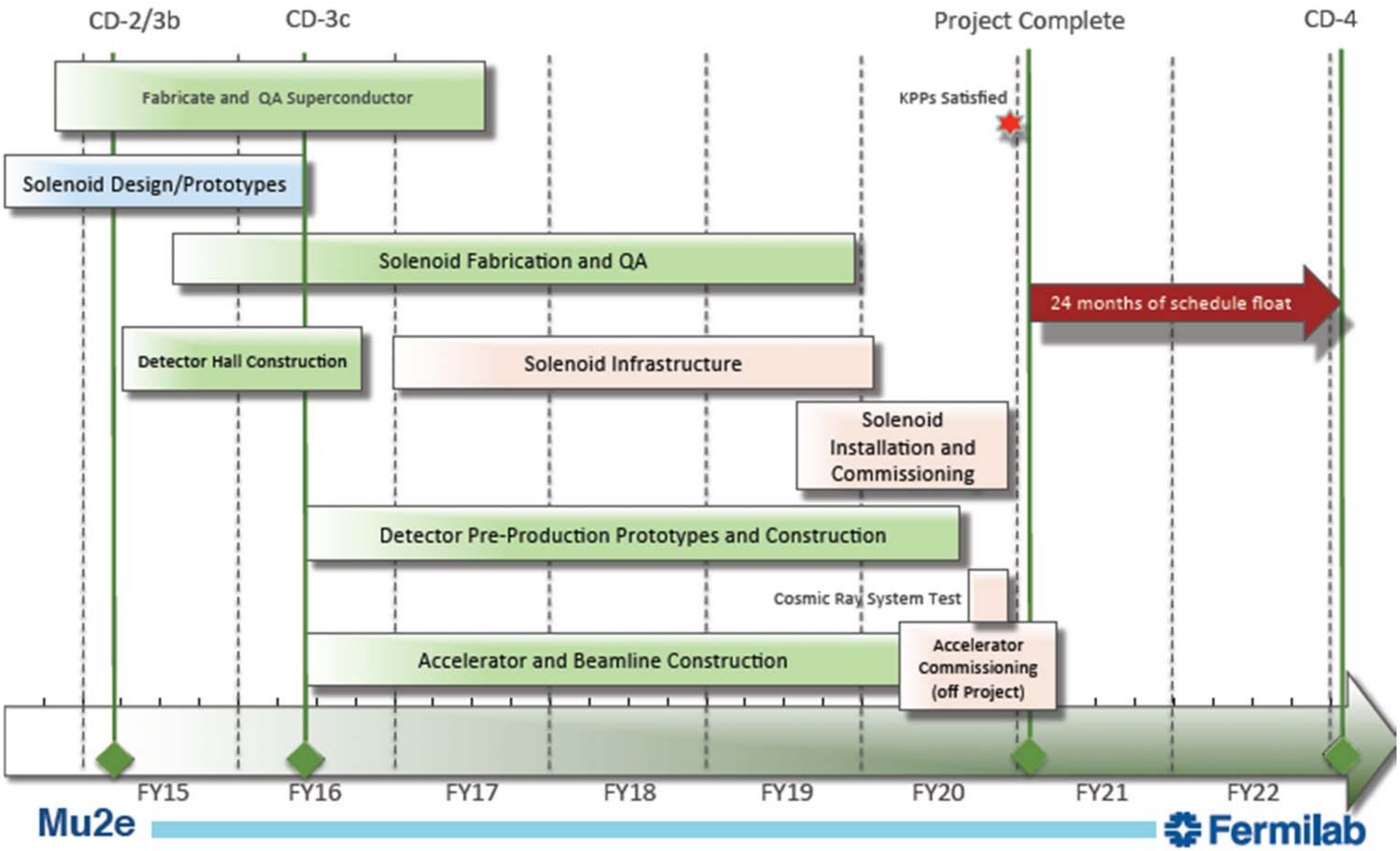
Prior	FY-13	FY-14	FY-15	FY-16	FY-17	FY-18	FY-19	Total
45.177	10.5	35.0	25.0	35.1	45.6	46.0	28.623	271.0

Cost Breakdown

(Values in AY $k)	Performed	ETC	Contingency EU + Risk	% Cont on ETC	Total
Project Management	9,565	11,104	2,125	19%	**22,794**
Accelerator	11,790	29,016	9,433	33%	**50,239**
Conventional Construction	2,642	18,603	2,825	15%	**24,070**
Solenoids	16,743	71,225	24,322	34%	**112,290**
Muon Beamline	4,406	15,161	5,922	39%	**25,490**
Tracker	2,941	8,582	3,760	44%	**15,283**
Calorimeter	522	4,406	1,164	26%	**6,092**
Cosmic Ray Veto	1,543	5,229	1,963	38%	**8,735**
Trigger & DAQ	1,829	2,971	1,207	41%	**6,007**
Total	**51,982**	**166,296**	**52,722**	32%	**271,000**

Appendix E Mu2e Schedule Charts




CD-2/3b
CD-3c
Project Complete
CD-4
Fabricate and QA Superconductor
KPPs Satisfied
Solenoid Design/Prototypes
Solenoid Fabrication and QA
24 months of schedule float
Detector Hall Construction
Solenoid Infrastructure
Solenoid Installation and Commissioning
Detector Pre-Production Prototypes and Construction
Cosmic Ray System Test
Accelerator and Beamline Construction
Accelerator Commissioning (off Project)
FY15
FY16
FY17
FY18
FY19
FY20
FY21
FY22
Mu2e
Fermilab

Appendix F Mu2e Management Chart