U.S. DEPARTMENT OF ENERGY

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Closeout Report on the DOE/SC Review of the

Muon to Electron Conversion Experiment (Mu2e) Project

Fermi National Accelerator Facility

October 21-24, 2014

Kurt Fisher

Committee Chair

Office of Science, U.S. Department of Energy

http://www.science.doe.gov/opa/

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COUNT: 26 (excluding observers)

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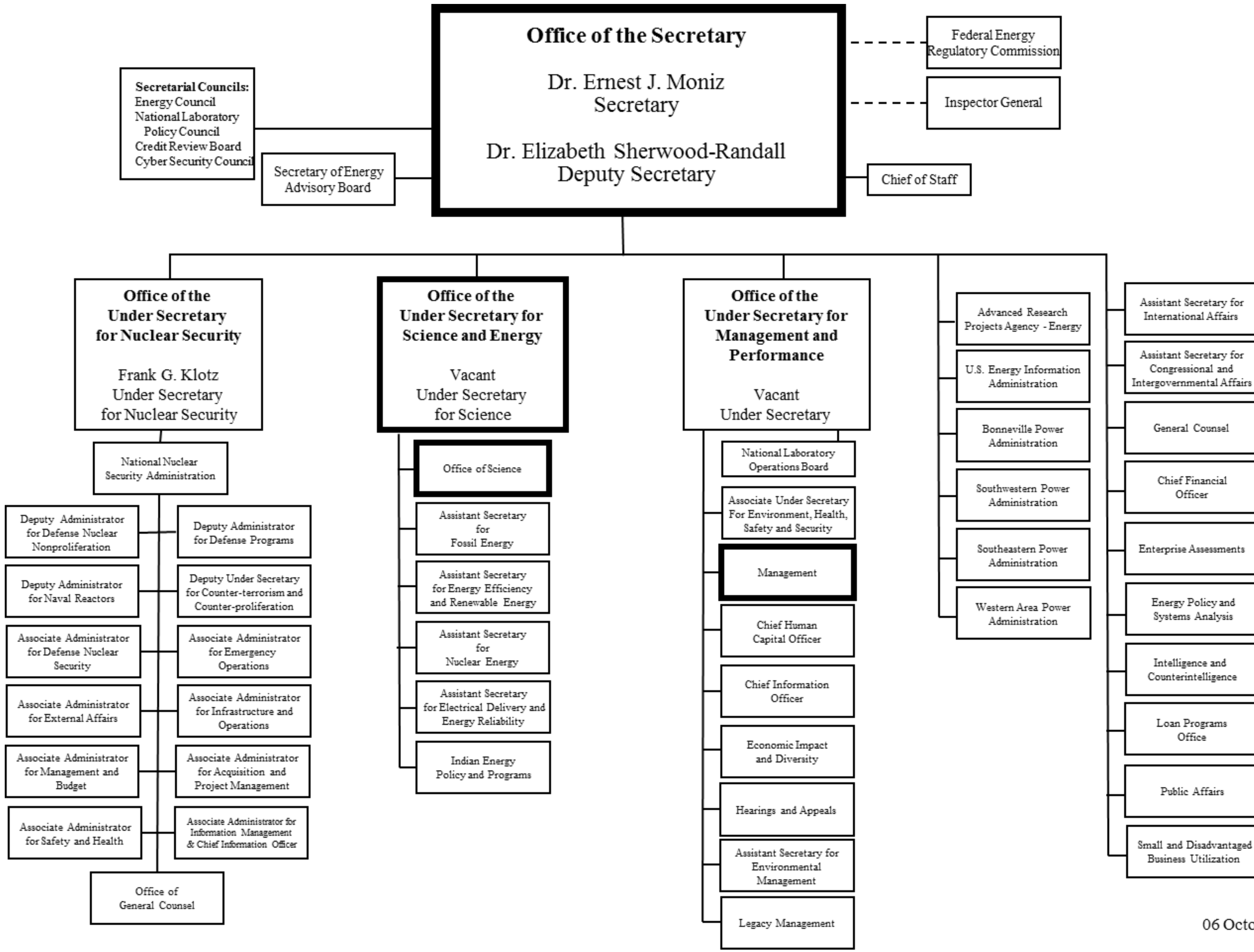

06 October 2014

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Charge Questions

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?

Charge Questions

Specific Questions 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?

1. Do the proposed technical design and associated implementation approach satisfy the performance requirements? Yes. Has the project team ensured that the subsystems will be fully integrated? Yes Are the CD-4 goals reasonable and well defined? No, recommendation made below.

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? Yes

4. Is the documentation required by DOE Order 413.3B for CD-2 complete? Yes

6. Has the project responded satisfactorily to the recommendations from the previous independent project review? Yes.

Findings:

- Considerable progress has been made since the CD1 IPR.
- The base of accelerator systems is $40.8M, with a total cost (including contingency) of $50.2M. The base cost of the muon beamline systems is $19.6M; total cost of $25.5M
- Technical design reviews have not been done for most areas of this portion of the project
- The challenging aspects of the accelerator portion of the project are: slow resonant extraction with 98% efficiency and beam extinction between microbunches at a level of 1e-10.
- Due to repurposing of the delivery ring tunnel, shielding and radiation safety is a challenge. The tunnel was designed for a program which ran with 13 watts beam power, and for this project it must operate with 8 kW beam power.

Findings:

- The Anti-proton stopping window at the TSu/TSd interface 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.

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 review team looked at that 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. Recommendation follows.

- The first threshold 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.

Comments:

- Increasing the beta function in the vicinity of the electrostatic separator region will simplify design and improve slow resonant extraction efficiency. We strongly encourage the project to consider this change at this stage of design.

- Committee recognizes that proof of concept for proton extinction at the level of 10^{-10} is difficult requiring extensive simulations that are yet to be completed. We think that the proposed scheme with two upstream collimators and one downstream collimator has a good chance to work and encourage 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.

Comments:

- The project is dealing with the radiation issue in the delivery ring through both passive (shielding) and active (interlock) approaches. The committee feels that this is being dealt with appropriately (i.e., by assigning an L3 manager in accelerator systems to this task, and by including the laboratory safety division), but continued scrutiny is necessary.
- The remote target handling system is novel at Fermilab. Design issues remain open. This issue should be resolved soon, and must be determined by CD-3c.

Comments:

- In 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 2 years later. Except for vacuum, which achieves final design within 6 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.

- The present installation plans call for the solenoid systems to be carefully aligned and then surrounded by ~1000 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.

Comments:

- Changing the beryllium window requires unstacking much shielding, and potential exposure to activated beryllium shards during actual window change out. At present, there is no system to equalize pressure, especially in an accident/leak occurrence. We believe that such a safety system is desirable and should be considered.

Recommendations:

1. Modify the first accelerator threshold KPP to be consistent with the installation plans of the project. Revise by Nov 30, 2014.
2. At the L3 level, insert milestones into the 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 IPR review team.

- **Charge Questions**

1. Do the proposed technical design and associated implementation approach satisfy the performance requirements? **YES** How has the project team ensured that the subsystems will be fully integrated? **Communication between all elements of the project appear to be adequate. A detailed plan was presented by the L3 integration manager.** Are the CD-4 goals reasonable and well defined? **YES**

2. Superconducting Solenoids

S. Gourlay (LBNL), K. Marken (DOE/SC), B. Strauss (DOE/SC), P. Wanderer (BNL)

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? **Presently YES, but close attention will be required to ensure required levels of support in the future.**

4. Is the documentation required by DOE Order 413.3B for CD-2 complete? **YES**

6. Has the project responded satisfactorily to the recommendations from the previous independent project review? **YES**

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? **NO, but a plan was presented to complete it.** Has there been adequate progress on the long-lead procurement activities approved under CD-3a? **YES, all but one purchase order has been released.**

8. Is the documentation required by DOE Order 413.3B for CD-3b complete? **NO, but a plan was discussed with the project.**

2. Superconducting Solenoids

S. Gourlay (LBNL), K. Marken (DOE/SC), B. Strauss (DOE/SC), P. Wanderer (BNL)

- **2.2.1 Findings**
  - Solenoid magnets represent a major fraction of the project:
    - Scope – Three superconducting solenoids
      - Production Solenoid (PS)
      - Transport Solenoid (TS) – Critical path
      - Detector Solenoid (DS)
      - Support infrastructure
  - $112M including 34% contingency
  - 30 FTEs in FY15 (peak)
  - Large procurements based on extensive technical design
  - Requesting CD-3b approval for TS procurement to maintain schedule
    - TS module design 90% complete, drawings 70% complete

2. Superconducting Solenoids

S. Gourlay (LBNL), K. Marken (DOE/SC), B. Strauss (DOE/SC), P. Wanderer (BNL)

- **2.2.1 Findings continued**
  - "Lessons learned" have been appropriately incorporated from recent community magnet procurements (CD-3a recommendation)
  - Top level requirements are well-defined
  - TS Module procurement requirements are defined and need to be delivered
    - Complete design
    - Complete drawings
    - Successful test of TS prototype
    - Final design review
  - Significant engineering and design have been completed for System Integration, Installation and Commissioning as this work must be integrated with the building construction. (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.

- **2.2.1 Findings continued**
  - 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.
  - Design contract for the PS and DS is about to be signed.
  - 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

- **2.2.1 Findings continued**

  - 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 Saclay and a duplicate top hat and/or hanging structure below top plate. These are uncertain 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 FNAL for test. There was not a clear set of criteria for assigning responsibility. This was discussed during the review. This responsibility assignment will be spelled out in a responsibility matrix in the procurement specification.

  – The first TS module prototype is in the final stages of assembly. Testing will be at FNAL.

- **2.2.1 Findings PS/DS Solenoids (CD2)**

  – Major procurements are reviewed by an internal/external committee, the Acquisitions Oversight Committee. This committee has been in operation for several years.

- **2.2.1 Findings PS/DS Solenoids (CD2)**
  - Mu2e plans to purchase two large superconducting NbTi solenoid magnets from a single vendor. Responses to an RFP have been received from three vendors with capabilities close to those needed by Mu2e.
  - Responses to RFP are the basis for the $30M baseline cost estimate and 15% contingency.
  - Design is at Preliminary design level. Final design will be prepared by vendor.
  - These magnets are on a near-critical path for the Project.
  - Project plans to issue PO for a final design 27 Oct 2014 in a phased contract that includes construction. PO for construction will be issued following CD-3c.

- **2.2.2 Comments**
  - Strong core technical team enhanced through strategic partnership.
  - Excellent coordination between task integration L3 and Mu2e integration team.
  - In process oversight at superconductor vendors appears to be going well.
  - A recent lesson learned from another HEP magnet project is that substantial schedule time and cost are added to a project that includes a magnet which 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 thought out and complete. Quench detection plans appear to be complete.
  - Magnet measurements and fixture designs are well planned.

- **2.2.3 Recommendations**
  - Deliver a test and acceptance plan for the prototype TS module by November 7, 2014
  - Deliver the following by April 15, 2015 prior to final approval of TS module procurement. In order:
    1. Successful test of TS prototype
    2. Complete TS coil module design
    3. Complete TS coil module drawings
    4. Final TS coil module procurement readiness review <u>following test of TS prototype</u>
  - Include a key personnel requirement in procurement contracts
  - Aggressively pursue procurement and testing options that will reduce TS schedule risk

2.3 Detector Systems

H.Gordon (BNL), R.Kass(OSU), J.Nelson(W&M), D.Nygren(UTA), L.Price(DOE-SC), R.van Berg(UPenn), W.Wisniewski(SLAC) - Subcommittee 3

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?

   The 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.

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?

   Yes.

4. Is the documentation required by DOE Order 413.3B for CD-2 complete?

   An extensive Technical Design Report has been prepared.

6. Has the project responded satisfactorily to the recommendations from the previous independent project review?

   Yes.

2.3 Detector Systems

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- **Findings**
  - **Tracker**
  - The proposed plan of using thin walled tubes (or "straws") for the charged particle tracking system of the Mu2e experiment, to determine the momentum of candidate electrons, appears sound and adequate to meet the objective KPP.
  - 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 and found to be appropriate and of relatively low risk.
  - 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 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.

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- **Findings**
  - Test results for a 96-straw panel (120degree arc) will become available in July 2015, but test results for a complete plane (six overlapping arcs for 360 degrees) 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 Detector Solenoid is scheduled to occur in May 2020.

2.3 Detector Systems

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- **Findings**
  - **Calorimeter**
  - The Calorimeter Team presented an update of the system since CD-1
  - The cost of LYSO had increased by a factor of ~4 by the end of CY2013. This is unaffordable. The radiator choice was re-evaluated. Barium fluoride and cesium iodide were considered as cheaper alternatives. Barium fluoride was 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, as one component of its scintillation light which has the shortest decay time of any inorganic scintillator. That 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 output 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.

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- **Findings**
  - A consortium of Caltech, JPL and the commercial vendor RMD 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, setting the final E/p calibration.
  - The status of simulations was presented.
  - Mechanical design concepts were presented. The hexagonal crystals are stacked in two monolithic disks. Electronics readout crate locations were shown.
  - Bases of Estimate and schedule were reviewed with Calorimeter management, as well as the process of updating the status of the subsystem monthly.

2.3 Detector Systems

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- **Findings**
  - 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 photosensors and about a third of the crystals.
  - The CsI back-up solution uses the UV-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 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 include members external to the collaboration.

2.3 Detector Systems

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- **Findings**
  - **Cosmic Ray Veto**
  - The Cosmic Ray Veto subsystem is a large array of scintillation counters surrounding the detector and downstream part of the Transport Solenoid. 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, COTS SiPM photodetectors 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 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.

2.3 Detector Systems

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- **Findings**
  - 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.

2.3 Detector Systems

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- **Findings**
  - **DAQ**
  - The DAQ system receives data from Read Out Cards (ROCs) that are part of each subdetector (Tracker, Calorimeter and Cosmic Ray Veto)
  - The DAQ provides a 590 kHz master clock, derived from the accelerator clock, to all detector elements
  - The DAQ system assembles data into time blocks or “events”
  - The DAQ system supports either streaming or triggered mode
  - The DAQ system data processing algorithms accept or reject “events” based on Tracker and Calorimeter data and then request data for accepted time slices from the CRV
  - Full “events” are then passed to On Line tasks
  - The design is based entirely on commercial hardware with custom firmware and software
  - The processing power and data bandwidth requirements are based upon physics simulations
  - Slow Controls and Monitoring are also part of the DAQ WBS and are also planned to be implemented using commercial hardware combined with custom firmware and code

- **Comments**
  - **Tracker**
  - Reviewers were impressed with the quality of R&D performed on single straw-tube prototypes.
  - 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 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 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.

2.3 Detector Systems

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- **Comments**
  - 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 time 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.

2.3 Detector Systems

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- **Comments**
  - **Calorimeter**
  - The Calorimeter Team is to be commended for its rapid pivot from LYSO to BaF_2. The Committee feels 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. 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. The R&D process may not converge in time for the May technology choice. Risks and alternative have been adequately considered.
  - 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 are vague for a the full-chain test (vertical slice test) of the detector components (crystals with photon readout and electronics and DAQ). Development and execution of this test on the time scale of the CD-3c review is desirable.
  - Locating the DT 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.

- **Comments**
  - Simulation development is mature and is able to turn around rapidly changes in the calorimeter design, contributing to the successful change of baseline radiator.
  - The Project has proposed the second calorimeter disk as scope contingency. The Committee feels that the loss of physics reach of this choice 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 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.

- **Comments**
  - **Cosmic Ray Veto**
  - Given the near-surface location of the experiment, an efficient cosmic ray veto (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 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 10 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 notes that the prototype program could be accelerated so that pre-production modules have been built and tested before the CD-3c review.

2.3 Detector Systems

H.Gordon (BNL), R.Kass(OSU), J.Nelson(W&M), D.Nygren(UTA), L.Price(DOE-SC), R.van Berg(UPenn), W.Wisniewski(SLAC) - Subcommittee 3

- **Comments**
  - The assembly labor BOE is based on detailed time-motion estimates from defined tasks and stations. They have practiced them on small scale without the final fixturing and tools. The basis and contingency are reasonable for CD2. An extensive QA program is documented for this activity.
  - The L3 manager for Silicon Photomultipliers is being promoted to Deputy L1 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 1/3 of all muon background entering through this hole.

H.Gordon (BNL), R.Kass(OSU), J.Nelson(W&M), D.Nygren(UTA), L.Price(DOE-SC), R.van Berg(UPenn), W.Wisniewski(SLAC) - Subcommittee 3

- **Comments**
  - **DAQ**
  - 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 lot 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 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 has already identified and implemented speed ups for the off-line code that nearly satisfy the expected requirements if scaled to the latest announced processor benchmarks.

- **Comments**
  - 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 vs penetrations of the vacuum system should be analyzed.

2.3 Detector Systems

H.Gordon (BNL), R.Kass(OSU), J.Nelson(W&M), D.Nygren(UTA), L.Price(DOE-SC), R.van Berg(UPenn), W.Wisniewski(SLAC) - Subcommittee 3

- **Recommendations**

1. Evaluate, before the CD-3c review, the benefits *vs* 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.

2. 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.

3. Complete improved simulations of the Cosmic Ray Veto 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

J. Sims, SLAC / Subcommittee 4

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? **Yes, it appears that requirements and interfaces of subsystems were captured appropriately and integrated into the design through multiple stakeholder meetings and reviews. These efforts are documented in the interface documents and review and comment spreadsheets.**

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? **Yes**

4. Is the documentation required by DOE Order 413.3B for CD-2 complete? **Yes**

6. Has the project responded satisfactorily to the recommendations from the previous independent project review? **Yes**

7. Is the detailed design sufficiently mature so that the project can continue with procurement and fabrication? **Yes**

8. Is the documentation required by DOE Order 413.3B for CD-3b complete? **Yes**

3. Civil Construction

J. Sims, SLAC / Subcommittee 4

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 GPP funded MC Beamline Enclosure will be included in the awarded scope of this contract resulting in one general contractor for this portion of the Muon Campus construction.

Conventional Construction WBS includes budget at complete of approximately $21M. $2.8M 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 P6. Durations of construction activities are based on input from consulting firms and FESS recent experience.

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

The Facility Engineering Services Section (FESS) personnel resources are in place and poised to deliver the construction scope once awarded.

3. Civil Construction

J. Sims, SLAC / Subcommittee 4

Findings

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

The project risk register includes 2 construction risks; one threat and one opportunity both related to the value of construction bids to be received on July 23, 2014. An additional 35 risks are included in the sub project 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 & life safety aspects of the project.

A Project Execution Plan including input from Conventional Construction has been produced for the Project.

The project has produced a Technical Design Report (TDR) which incorporates overview write-ups and sample drawings from conventional construction.

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

Findings

A NEPA Categorical Exclusion was obtained and confirmed by the Fermi Site Office.

A Muon Campus SWPPP permit was obtained to cover MC-1, Mu2e, and MC Beamline. A soil erosion control plan has been developed.

A Domestic Water Permit to Construct has been obtained. 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 out.

3. Civil Construction

J. Sims, SLAC / Subcommittee 4

Comments

The Mu2e civil team is very experienced at this size and type of construction. The organization and number of FTE appear reasonable to manage the proposed construction scope.

The 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 construction scope conflict 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 to 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. Civil Construction

J. Sims, SLAC / Subcommittee 4

Recommendations

1. Complete the evaluation and award the civil construction contract as soon as practical.
2. Complete a transition to operations plan at least 6 months prior to beneficial occupancy turnover to PPD.

4. Environment, Safety and Health

I. Evans & C. Ferguson, SLAC

Subcommittee 5

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? No, need to augment team with technically experienced ESH&Q support

4. Is the documentation required by DOE Order 413.3B for CD-2 complete? Yes

5. Are ES&H aspects being properly addressed given the project's current stage of development? Mostly

6. Has the project responded satisfactorily to the recommendations from the previous independent project review? Yes

8. Is the documentation required by DOE Order 413.3B for CD-3b complete? Yes

4. Environment, Safety and Health

I. Evans & C. Ferguson, SLAC

Subcommittee 5

Findings

- Documentation supporting CD-2/3b is complete and signed-off
- Project team is well established and working well together, ESH staff are embedded in the Project organization and Project has access to capable institutional ESH resources.
- The Project Management Plan (PMP) defines the ESH&Q roles, responsibilities, authorities and accountabilities for staff on the project team
- ESH&Q for the civil construction of detector hall is adequately addressed and is ready for CD-3b

4. Environment, Safety and Health

I. Evans & C. Ferguson, SLAC
Subcommittee 5

Comments

- A comprehensive design review and approval process for the Total Loss Monitor system and Passive Shielding is in place, reviews are in their early stages.
- The process used to identify hazards in the HAR has not captured them all, leading to unmitigated ESH risks.
- Several ESH risks are identified in the risk registry, but attributed to either Project Management or Accelerator Division; others have been transferred to Operations.
- Some project and support personnel stated that there are not unique hazards with this project and that ESH risk is very low. We would caution against complacency or drifting from good conduct of operations. Effort should be applied to ensure hazards and mitigations remain visible and well understood
- The PMP reflects that ESH risks are anticipated to be very low, however this is in contrast to the hazard analysis sheets in the HAR.
- There is insufficient ESH and Quality expertise on the project to deliver stated/required responsibilities.
- Overhead target remote handling option should have an integrated risk-based evaluation with a decision to the PM prior to CD-3c.

4. Environment, Safety and Health

I. Evans & C. Ferguson, SLAC
Subcommittee 5

Recommendations

- Put in place technically experienced ESH and QA leads. (Immediately)
- Clearly identify those risks transferred to Operations and verify and document they are understood and accepted by Operations. (Prior to CD-2 Approval)
- Resource load the schedule to reflect ESH requirements through the life of the project, including required central ESH support. (Prior to CD-2 Approval)
- Revisit the HAR to ensure ESH risks are evaluated, including proposed activities and installations (e.g. Remote Target Handling, Robot operations). (by FY15 Q3)
- Update PMP and PEP to reflect actual project execution and ESH&Q roles and responsibilities. (Prior to CD-2 Approval)
- Close the remaining Director's Review finding on QA documentation (Prior to CD-2 Approval)

  "Document and track the Quality assurance risks in the Project Risk Registry or in a separate QA document"

5. Cost and Schedule

J. Krupnick, T. Mennona, J. Kao

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? **Yes, but one Accelerator KPP needs to be revised.**

2. Is the cost estimate and schedule consistent with the plan to deliver the technical scope? Is the contingency adequate for the risk? **Yes**

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? **Not yet. The project should demonstrate EVMS and change control proficiency. Project management structure should be better defined.**

4. Is the documentation required by DOE Order 413.3B for CD-2 complete? **Not yet. The PMP and PEP need to be updated and finalized/signed.**

6. Has the project responded satisfactorily to the recommendations from the previous independent project review? **Yes**

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? **Yes**

8. Is the documentation required by DOE Order 413.3B for CD-3b complete? **Not yet, see question 4.**

FINDINGS

- Total Project Cost (TPC) of $271 million, with in-kind contributions of approximately $4M from INFN which are not included in the TPC.
- Through September 2014, the cost to date is $52.6M, or roughly 24% of BAC.
- Contingency of $52.72M (32% BAC to go) consisting of $46.2M in estimate uncertainty and $6.5M in risks.
- Project baseline basis of estimate (BOE) consists of 24% Actual, 37% Quotes and LOE labor, 27% Engineering Estimate, 12% Expert Opinion.
- Project is managing to the early finish date of 1st QTR 2021 with a CD-4 date of 1st QTR 2023 (2 years of schedule contingency).
- A schedule risk analysis was completed and the project considers the schedule contingency to be adequate.
- Bids have been received for the primary conventional construction contract and are within the estimate.

FINDINGS

- The P6 schedule has 7,116 activities, 1,100 milestones, 327 constraints, 74 control accounts, and 30 CAMs.
- The critical path currently runs through the transport solenoids. The production and detection solenoids are near critical path with little float.
- Each level 2 WBS has its own schedule which all roll up to the master schedule.
- There are only 3 FY16 L2 milestones.
- Project has begun implementation of EVMS and has been practicing performance measurement since April 2014. Primary tools are in place.
- Significant cost variances found in the monthly EVMS data were due to inaccurate EVMS reporting.
- The near critical path report is set at a threshold < 1 week.
- Inconsistencies were found in the September monthly report between the level 2 stop light report and the cost summary.

FINDINGS

- Project has provided formal EVMS training to CAMs.
- During CAM interviews, some L2 and L3 managers were not fully cognizant of the importance of the CPM/FPD relationship.
- Change control process is not being properly implemented.
- The risk register was updated in October 2014 and reflects both bottom up and top down analyses.
- The Risk Management Board is not meeting regularly.

COMMENTS

- Project Cost and Schedule are well defined and appear 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 3 L2 milestones have been identified for FY16, yet there are 8 for FY17.
- There are too many constraints and open ends in the P6 schedule.
- As was noted in the Director's review the use of LOE performance measurement (20.6% of BAC) is too high.
- The near critical path report threshold (<1 week) appears to be too tight. Consider changing threshold >2 months.

COMMENTS

- The CAM interviews demonstrated ownership and confidence in their scope, cost, schedule, and risk estimates, and most understand EVMS processes.
- Appears that CAMs have no input or ownership in determining monthly reported EAC. Consider routine EAC discussions as part of the monthly status meetings.
- The project controls staff appears strong and competent.
- The committee found several instances of poor quality EVMS data input as well as improper implementation of the change control process.
- Project needs to improve internal variance reporting and should include appropriate variance explanations in the monthly status reports.
- CAMs should receive periodic EVMS training. Develop and roll out as quickly as possible project monitoring tools such as eCAM notebook.

COMMENTS

- EVMS is a critical management system and the project should embrace it and fully incorporate it into its culture.
- The projects technical review board meets regularly and has been discussing risks. However the project's Risk Management Plan commits to having separate regular Risk Management Board meetings.
- There are potential future labor resource allocation issues and the project should continue to work with the laboratory to develop tools in order to evaluate these issues in FY16 and beyond.
- The Committee is concerned about a lack of clarity as to the project's primary line management chain.

RECOMMENDATIONS

- By CD-2 approval:
  - Restart Risk Management Board meetings, commit to their periodicity, and update the Risk Management Plan
  - Initiate monthly in-person CAM/project controls status meetings
  - Clarify the project's line management chain, update the PMP and PEP, and have signed
  - Generate additional FY16 L2 milestones
  - Revisit accelerator-related objective and threshold KPPs
  - Complete cleanup of baseline schedule; perform monthly cleanup during status process.
  - Project should demonstrate EVMS and change control proficiency for 2 months prior to CD-2 approval
- Ensure periodic CAM refresher training, at least annually
- Review LOE usage project-wide to reduce to closer to 15%

5. Cost and Schedule

J. Krupnick, T. Mennona, J. Kao

PROJECT STATUS		
Project Type	Line Item	
CD-1	Planned: 4th Qtr FY2012	Actual: July 2, 2012
CD-2	Planned: Nov. 2014	Actual:
CD-3a	Planned: 4th Qtr FY2012	Actual: July 10, 2014
CD-3b	Planned: Nov. 2014	Actual:
CD-3c	Planned: Mar. 2016	Actual:
CD-4	Planned: Nov. 2022	Actual:
TPC Percent Complete	Planned: __24_%	Actual: __24_%
TPC Cost to Date	$52.6 M	
TPC Committed to Date	$58.3 M	
TPC	$271 M	
TEC	$247.3 M	
Contingency Cost (w/Mgmt Reserve)	$52.72 M	_32_% to go
Contingency Schedule on CD-4	__24__months	_33_% to go
CPI Cumulative	n/a	
SPI Cumulative	n/a	

6. Project Management

Rej, Green, McKnight, Meador / SC7

1. Do the proposed technical design and associated implementation approach satisfy the performance requirements?

   Yes.

   How has the project team ensured that the subsystems will be fully integrated?

   Project has made a good start in putting useful Interface Control Documents (ICD) in place. It is crucial that ICDs be real tools and specify who are the 2 responsible parties, what is the specific handoff (keyed to requirements documents) and when does it occur (ICD Milestone).

   Are the CD-4 goals reasonable and well defined?

   Yes.

6. Project Management

Rej, Green, McKnight, Meador / SC7

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?

   Yes for FY15. Sustained resource commitments will be needed in future years.

4. Is the documentation required by DOE O413.3B for CD-2 complete?

   Yes, but all documents need to be updated as part of exercising Mu2e management systems and implementing the recommendations by this committee.

6. Has the project responded satisfactorily from the previous independent project review?

   Yes. There have been rigorous external reviews for solenoid and detector hall; this rigor provides an excellent precedent for the other subsytems.

7. Is the detailed design sufficiently mature so that the project can continue with procurement and fabrication?

   Yes, for the detector hall.

   Has there been adequate progress on the long-lead procurement activities approved under CD-3a?

   Yes.

8. Is the documentation required for DOE O413.3B for CD-3b complete?

   Yes, but all documents need to be updated. The detector hall is ready; however, the TS solenoid module design and prototype need to be completed first.

Findings

- Fermilab organizational changes implemented in Oct 2014 with intention of creating "one laboratory." This arrangement is expected to strengthen support to the Mu2e project.

- New organization streamlines reporting to the Lab Director, and includes a Chief Project Officer accountable for the successful execution projects in concert with successful science program operation.

- Projects are located in various technical divisions. (Mu2e, Muon g-2, CMS in the Particle Physics Division, Muon Campus General Plant and Accelerator Improvement projects in the Accelerator Division.

- Mu2e is one of many projects underway at Fermilab, and if CD-2/3b is approved, will be the largest project at the Laboratory.

Findings

- An experienced, cohesive management team is in place, matrixed from several Fermilab organizations.
- Good project management systems are in place.
- The funding profile is consistent with DOE guidance.
- A recent independent cost estimate review convened by DOE Review validated the proposed baseline project costs.
- Procurement support of the Mu2e project is centrally managed by the Procurement Department (PD) which has assigned two staff as the focal points for the project. Currently less than 20% of their time is required to support Mu2e. The delegated authority of the two PD members is at a level that would require review 2 to 4 levels above their authority.

6. Project Management

Rej, Green, McKnight, Meador / SC7

Findings

- 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 phased approach for transition to operations is being pursued.

- A significant amount of work to date was presented at this review. $52M 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 present status of the Interface Control Documents. In discussion several L2 managers reported that they were not yet fully functional. The Project has many interconnections within the Project between L2 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 that contribute both labor and materials; PPD, Technical, Accelerator, and Computing.

Findings

- The Project presented a Resource Loaded Schedule (RLS) with a fully sufficient granularity. As presented and 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 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 beam line schedules and to experimental needs were the driver for this definition of CD-4.

Comments

- So far, so good! Overall project is in good shape in this early stage. The project team and senior Fermilab management must stay vigilant.

- The Project has made a good start on putting useful Interface Control Documents (ICD) 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 the ICD be a real tool and specify who are the 2 responsible parties, what is the specific handoff (keyed to requirements documents) and when does it occur (ICD Milestone). In addition, because of the impact on requirements, should there be changes, the ICD specifications should be controlled documents linked to BCR.

Comments

- It is early in the procurement phase of the project and there are a significant amounts of procurements for the current and preceding FY's. Procurement and Project management should remain aware of the demands of the two Mu2e assigned procurement staff as they split their responsibilities for Mu2e with other demanding project.

- 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 labs. FNAL Procurement Department has evaluated the JLAB program. We encourage implementing of that program for Mu2e.

- A procurement breakout session would be beneficial to identify progress on significant, major and critical procurements as they relate to project cost & schedule.

Comments

- 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 un-costed contributions assumed to be made by university groups (especially in DAQ) and foreign contributors (Detectors). Consider inserting the estimated US 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.
- Consider executing agreements such as SOW/agreements with university groups and international partners. It appears there is substantial M&S (~ 5 M$) cost exposure for INFN and Labor cost exposure(~ 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.

Comments

- The transition to Operations goes in three phases. The beneficial occupancy of the hall is scheduled for Feb. 2016. At that point the Particle Physics Division takes responsibility for Operations for the hall. An overall plan for this phase should be put in place in a timely manner.

- After the installation KPP 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 scheduled for Jan. 2020. The upstream elements of the beam line will be commissioned by the Accelerator Dept. which makes efficient use of calendar time. The "extinction" function will be tested in the upstream beam line in the Objective KPP. The AD Muon Dept. is responsible for Mu2e operations in AD.

Comments

- The project manager provided the review committee a set of thoughtful lessons learned from the work to date. These lessons will prove valuable guidance as the project goes forward.

- The final element for CD-4 is scheduled to occur in Sept. 2020 when detector elements are completely installed. The 3 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.

Comments

- 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.

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

Recommendations

- 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.

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

- 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.

- 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., IPR, design and procurement reviews). (This was a comment in the DOE CD-1 Review report.)

Recommendations

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

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

- 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 6-months before beneficial occupancy.

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