Quality Assurance Plan for the U.S. CMS HL-LHC Project

Revision 5

November 21, 2018

CMS-doc-13093

Contents

REVISION HISTORY

Revision	Date	Author	Summary of changes
New	2017-10-06	J. Dolph	Initial Release before NSF PDR
1	2018-04-02	J. Dolph	Incorporation of international CMS QA practices and the role of U.S. CMS with respect to said practices.
2	2018-05-18	J. Dolph/C. Wilkinson	Incorporate DOE subproject QA activities tables into the appendices. Re-write intro to clarify CMS practices and purpose. Re-organize body of document to emphasize and clarify USCMS practices for design and production QA. Clarified section on training.
3	2018-10-31	C. Wilkinson/TJ Sarlina/Chris Hill/Jeff Spalding	Clarify CMS QA approval process; remove incorrect flow charts. Reorganize Section 6 with Fermilab QA. Add section 7 on participating institutions. Extend QAP to cover both DOE and NSF scope. Create separate appendix for subproject QA descriptions that follow a template.
4	2018-11-06	V. O'Dell	Replaced iCMS with CMS. The CMS collaboration is the full international collaboration, of which U.S. CMS is a part. Did some general cleanup. Added signature page.
5	2018-11-21	C. Wilkinson	Changed "institutional QA plans" in section 7 to "institutional QA plans/procedures" to prevent confusion with this QAP.

Approvals

Vivian O'Dell date

HL-LHC CMS Project Manager

Anders Ryd date

HL-LHC CMS Deputy Project Manager

Robert Tschirhart date

Fermilab Chief Project Officer

T.J. Sarlina date

HL-LHC CMS Project ESH&Q Manager

ABBREVIATIONS AND DEFINITIONS

Abbreviations

Abbreviation	Definition
CMP	Configuration Management Plan
CMS	Compact Muon Solenoid, the international collaboration and the associated detector at CERN
HL-LHC	High Luminosity - Large Hadron Collider
LHC	Large Hadron Collider
LHCC	LHC Committee (endorses Technical Proposals and Technical Design Reports)
L2 Manager	Person responsible for activities at Level 2 of the Work Breakdown Structure
L3 Manager	Person responsible for activities at Level 3 of the Work Breakdown Structure
PEP	Project Execution Plan
PM	Project Manager
PPMP	Preliminary Project Management Plan
QAP	This document, the Quality Assurance Plan for U.S. CMS
QA plans/procedures	Specific, detailed QA plans and procedures for individual efforts within the U.S. CMS Project, that conform to the QAP.
SEMP	Systems Engineering Management Plan
TDR	Technical Design Report, a CMS document that defines the technical specifications, physical characteristics, and functional operating parameters of each CMS subdetector.
TP	Technical Proposal, a CMS document that establishes the physics case for a detector or upgrade (similar to a Conceptual Design Report in the U.S.)

Definitions

Terminology	Definition
Acceptance Method	A science simulation, engineering analysis, specification selection, drawing detail, quality control test or inspection, or R&D analysis or test that provides all or a portion of documentation required to validate a requirement.
Baseline	The point at which Technical Requirements are "frozen" and after which all changes must be tracked and approved.
Configuration Management	The systematic control and evaluation of all baseline documentation and changes to baseline documentation that has reached a baseline point.
Interface Control Document	A document that identifies all technical boundaries, inputs and outputs of a system.
Programmatic	Activities of or relating to the administrative management of the Project such as cost, schedule, personnel, etc. The Project is wholly comprised of two components, Programmatic and Technical.
Requirement	A statement of precise technical parameters that the specific system, subsystem or component feature must conform to. Each requirement must have prescribed acceptance methodology that, when accomplished, validates the requirement is met.
CMS Detector	The complete experimental apparatus used to carry out research the CMS research program
CMS Subdetector	Physically (and functionally) distinct pieces of experimental apparatus that together form the CMS Detector
Project	The U.S. CMS HL-LHC project that is responsible for carrying out each of the subprojects in the DOE and NSF scopes.
Subproject	The U.S. CMS L2 organization that is responsible for delivering a piece of a CMS subdetector.
System	The piece of the CMS subdetector that is a U.S. CMS subproject deliverable.
Subsystem	An aggregation of components that forms a subordinate system within a U.S. CMS subproject deliverable.
Components	The U.S. CMS L3/L4 deliverables such as hardware (including electronics), firmware and/or software, and all associated CM documentation, that satisfy an end use function in the system being delivered by the U.S. CMS subproject.

1 Introduction and Purpose

Quality Assurance is an integral part of the design, fabrication, construction and installation of the HL-LHC U.S. CMS Upgrade Project. The primary goal of Quality Assurance for U.S. CMS deliverables is to ensure that the CMS experiment achieves the science requirements and goals listed in the document *Science Goals and Requirements for U.S. CMS HL-LHC* [Ref-1]. Thus, all components and subproject deliverables must meet approved Science and Engineering Technical Requirements that flow down from the science goals and requirements. These Science and Engineering Requirements are the basis for all QA activities during design and production. U.S. CMS Technical Requirements are described and listed in individual documents for each Work Breakdown Structure (WBS) Level 2 subproject.

QA requirements set forth in this Plan will be implemented by the development of system and component-specific quality plans, procedures, and guides that accommodate the specific quality requirements. The Plan unifies the U.S. CMS QA activities spread across multiple U.S. institutions, with special attention paid to items that are most critical to the schedule and performance requirements of the Project.

All work performed on the Project by U.S. CMS will draw on the guidelines and criteria set out in the Fermilab *Quality Assurance Manual* [Ref-2]. These include:

- Management criteria
  - Quality Assurance Program
  - Documentation and records
- Performance Criteria
- Work Processes
- Procurement
- Assessment

CERN has a formal review and approval process for all LHC experiments, including the International CMS (CMS) collaboration. The U.S Quality Assurance Plan will follow the review and approval process described in the CERN document LHCC-G-164, *Large Hadron Collider Committee: LHC Experiments Phase II Upgrades Approval Process* [Ref-3] and in the *Review Process in International CMS for Detector Upgrade Projects* [Ref-4] . This multi-step approval and verification process is compatible with internationally recognized large project management methods (e.g. ISO 21500(2012)), with phases, reviews, and decision points detailed in the document.

Throughout this process, the LHC Committee (LHCC) is responsible for reviewing the technical aspects of the projects and the Upgrade Cost Group (UCG) for reviewing and approving the programmatic aspects (cost, schedule, resources, risks and QA). These committees recommend approval at each stage of the process to the CERN Research Board (RB).

2 Scope and Applicability

This plan describes a common Quality Assurance (QA) program for both DOE and NSF funded subprojects in the U.S. CMS HL-LHC Upgrade Project, covering all relevant aspects related to the QA effort. It provides Quality Assurance requirements applicable to all U.S. Project participating institutions, encompassing all activities performed by or for the Project, from research and development (R&D) through systems acceptance and check-out. It serves as a guide for project management at all levels. It is authored by the Project Management team, reviewed by the assigned U.S. CMS QA Coordinator for the project, and approved by the Project Manager and Deputy Project Managers. The Plan is reviewed on a yearly basis and updated as necessary to improve clarity and incorporate changes.

3 CMS Project QA Organization

There are two areas of responsibility for ensuring that the upgraded CMS detector meets the stated scientific goals and engineering requirements. The first area is integrated oversight for QA of the entire CMS collaboration that is managed through the formal CERN review and approval process. The second is individual responsibility for CMS subdetector work performed by the collaborative institutions in charge of designing, producing, and testing upgraded CMS detector components.

3.1 Integrated International QA Oversight Organization

Overall responsibility and approval for integrated CMS QA is held by CERN and the CMS collaboration. The CMS Technical Coordinator (TC), appointed by CERN, holds overall responsibility for QA for all CMS activities. The TC has unique responsibility for the final installation and integration of the upgrades at CERN and works with the CMS Upgrade Coordinator (UC) to fulfill QA responsibilities in the design and fabrication of the upgrade projects. The Upgrade Coordination Group (UCG) includes the international leaders for each of the upgrade subdetector projects, each with oversight of the QA functions within their project. Within each US subproject under a subdetector project, the US L2 Manager maintains close coordination with the corresponding CMS subdetector project leader. Both the TC and UC report to the CMS Spokesperson and the CMS Management Board. (See the *Preliminary Project Management Plan* (PPMP) [Ref-9] for the organization chart for the Upgrade Coordination Group and the International CMS Management Board.)

3.2 U.S. CMS QA Organization

Each CMS collaborator or participating institution is responsible for day-to-day QA practices and performance that meet QA processes developed by each of the subdetectors. These QA processes are approved at Step 2 of the CERN approval process and reviewed at the Step 3 stage (EDR/ESR reviews). The QA process within each subdetector is typically carried out across several contributing institutions and countries. The U.S. CMS HL-LHC Upgrade Project, as an essential collaborator in CMS, is integrated into the organization and follows CMS QA methodology and standards. In most cases, the CMS processes are compatible with the Fermilab QAM. If there is a discrepancy between CMS and Fermilab, the CMS process will supersede that of Fermilab.

The PPMP [Ref-9] describes the Project Management structure, responsibilities, systems, and processes used for managing the U.S. HL-LHC CMS Upgrade Project. The PPMP includes the management and oversight to achieve the scientific, technical, cost and schedule objectives for the HL-LHC CMS Upgrade Project, including quality assurance for U.S. deliverables.

4 International CMS Integrated QA Review and Approval Process

4.1 CMS QA Process Overview

For the HL-LHC Upgrade Project, CMS follows long established practices that rely on typical QA methodology, backed by standardized stage gate reviews and approval processes.

These CMS collaboration QA practices are embedded in the formal review and approval process described in the *LHC Experiments Phase II Upgrades Approval Process* [Ref-3]. This multi-step approval and verification process follows recognized large project management methods (e.g. ISO 21500(2012)), with phases, reviews, and decision points detailed in the document.

CMS uses a formal review process to monitor progress and ensure overall technical specifications and interfaces are well understood. Reviews are called by the CMS TC in conjunction with the UC and include non-CMS technical experts. The process involves collaboration and interactions between Subject Matter Experts (SMEs) from individual subdetector management levels up through CMS. All levels participate in the proposal, review, and decision-making to meet the integrated upgrade project goals and requirements.

The types of technical review are spelled out in the CMS Constitution [Ref-6]. Examples include, but are not limited to, the following:

- Electronics Systems Review (ESR) – Review the soundness and documentation of the electronics design, including interfaces of electronics to other systems (trigger to the DAQ, for example) prior to the start of construction
- Engineering Design Review (EDR) - review and document final design prior to the start of construction
- Procurement Readiness Review (PRR) – determine/approve readiness prior to committing funds to major purchases (a PRR may precede the EDR in certain circumstances)
- Manufacturing Progress Review (MPR) – evaluate/monitor fabrication and delivery from a vendor or institution during construction
- Installation Readiness Review (IRR) – determine readiness prior to approving installation of the new detector or system
- Engineering Change Review (ECR) – review and document any design changes needed after the EDR
- Operations Readiness Review (ORR) – determine readiness prior to transferring the new detector to operations

The exact details of the CMS review and approval process depends upon the phase or stage of the project as project planning matures from initial and final design, through construction, installation and commissioning, to acceptance and readiness for operation. CMS reviews are held for each of the four major project steps, which are summarized below:

Step 1: Initial Design – review overall scope and cost for the entire upgrade program for each experiment, retaining the possibility for different options which may depend on technical issues and/or on funding availability. Approve readiness to proceed to Step 2. Step 1 is documented in the CMS Upgrade Technical Proposal [Ref-7] and Scope Documents [Ref-8].

Step 2: Baseline Design – review and approve Technical Design Reports and QA plans for each subdetector. This documents the baseline scope, cost and schedule for the subsequent change control process.

Step 3: Final Design / Start of Construction – review and approve the final design and the production of the major detector components, verifying that they meet the requirements and are compatible with the installation plan. Establish follow-up reviews/approvals for installation readiness.

Step 4: Installation and Commissioning – review and approve the installation and commissioning of the major detector components. Evaluate the capability of the integrated detectors to provide the expected performance. Review and approve readiness for operations.

Each of these steps includes review/approval at the CMS level, followed by review/approval by CERN LHCC/UCG and RB.

4.2 Initial Design – Technical Proposal and Scoping (Step1)

The Technical Proposal (TP) [Ref-16] includes description of the overall upgrade program, including all subdetectors and systems. It covers the physics performance goals, detector specifications, technical choices, R&D program leading to demonstration of technology choices and an initial set of project milestones and cost estimate for M&S (Material and Services) for the final installed components. The Scope Document [Ref-8] describes options to adjust the scope of work for each subdetector, the cost implications, and the impact on physics performance. These documents are reviewed by the CERN LHCC/UCG that report to the CERN Review Board (RB) for approval. At this early stage, an initial R&D and assembly plan for each project is included, but without specifics on QA.

4.3 Baseline Design Review and Approval (Step 2)

During the design phase, individual subdetector Level 2 leads and SMEs from the different contributing nations work collectively with each other and the CMS subdetector leads and systems engineers to propose research and development plans that incorporate QA activities as well as preliminary production QA plans. These activities are reported to the CMS Upgrade Coordination Group via regularly scheduled meetings. The exact details of the coordination, integration, and execution of these QA activities and practices can vary from subdetector to subdetector, based on the specific needs of each detector component/deliverable.

The resultant plans must ensure that the initial science and engineering requirements will be demonstrably met. The QA activities in the design phase usually include simulations, prototyping, material testing, and engineering mockups. Various internal reviews may be called by the individual subproject Level 2 leads or by the CMS UC during this interactive process. Updates to the initial requirements will be proposed as necessary.

The CMS UC calls for the preparation and review of a Technical Design Report (TDR) when he or she judges the subdetector project to be ready for a baseline design review and for transition to final design. Appointing a subdetector QA Manager is a UCG requirement at the Step 2 review. The CMS QA Manager is responsible for defining common test procedures, data-base and tracking tools and coordinating these activities throughout the project. When the subdetector has satisfied the findings of the CMS review, the TDR is reviewed by the Large Hadron Collider Committee (LHCC). The report from the LHCC goes to the CERN Review Board (RB) for approval to proceed to final design.

The inputs to the baseline design process are the Science Goals, Science Requirements, and Engineering Requirements.

The outputs from the baseline design review process for QA purposes include updated Science and Engineering Requirements, an approved R&D QA plan for final design, and an approved Preliminary Production QA plan. QA activities for production can include vendor qualification, manufacturability tests, pilot production runs, assembly process testing, and integrated subcomponent performance tests. Quality Control metrics and processes may also be incorporated into the plans. These outputs are presented/reviewed in talks to the UCG but are not yet formally documented. The formal documentation is created/reviewed as part of the EDR/ESR in the following step.

4.4 Final Design Review and Construction (Step 3)

The review and approval process for final design (Figure 1) is similar to the baseline design process. Individual subdetector Level 2 leads and SMEs from the different contributing nations carry out approved prototype and design activities. In collaboration with other contributing national leads, the CMS subdetector leads and systems engineers, and the CMS UCG, they evaluate and verify the success of those activities, propose production plans that incorporate QA activities, and present preliminary installation and

commissioning QA plans. The exact details for the execution of these QA activities and practices may vary from subdetector to subdetector. Updates to the requirements can be proposed as necessary.

In addition to the formal multi-step reviews, the individual subdetector Level 2 leads or by the CMS UC may call for interim reviews during the interactive processes leading to readiness for a step review.

The CMS TC is responsible for calling for an Engineering Design Review (EDR) or a Production Readiness Review of the production plan when he or she judges the subdetector project to be ready for transition to production or construction. The EDR explicitly includes review of the QA process for the construction phase of the project. The formal documentation (test procedures, travelers, database, etc.) is created/reviewed as part of the EDR/ESR.

The subsequent final report is reviewed by the LHCC/UCG, which passes its report and recommendations to RB for approval to proceed to production.

The outputs from the final design review process for QA purposes include any updates to the Science and Engineering Requirements, an approved Production QA plan, and an approved Preliminary Installation and Commissioning (I&C) QA plan. Although I&C is outside the U.S. CMS project scope, project members participate in planning, providing input from their expert knowledge of the systems they will deliver. QA activities for installation and commissioning can include fit and function tests, in situ component checkout, integrated subcomponent tests, and integrated performance tests with beams.

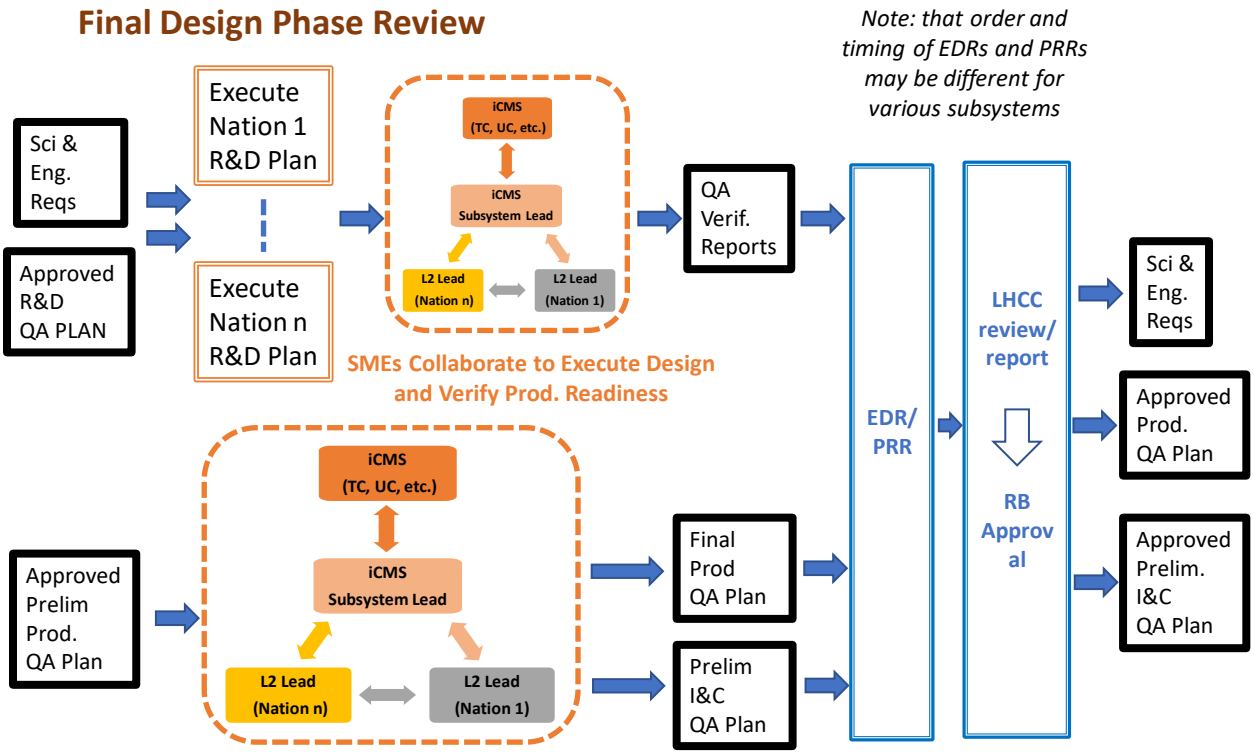

Figure 1. CMS Step 3 review and approval process with respect to QA plans, at the end of the final design phase, showing approval to proceed to the production/construction phase

During construction, the contributing subdetector Level 2 leads and SMEs carry out approved production and construction activities. The collaboration, composed of all contributing national leads, CMS subdetector leads and systems engineers, and CMS UC/TC, evaluates and verifies the success of those activities. Final installation and commissioning plans incorporate input from other relevant CMS subdetectors and the LHC infrastructure organizations. Interim reviews may be held during the review and verification process.

The outputs from the construction review process for QA purposes include any updates to the Science and Engineering Requirements, an approved Installation and Commissioning QA plan, and Preliminary Operations Manuals.

4.5 Installation and Commissioning Review and Approval (Step 4)

The CMS TC calls for an Installation Readiness Review (IRR) at an appropriate time. Following successful passage of the IRR, the TC manages installation and checkout, and then hands over to CMS Run Coordination (RC) for commissioning for physics (with cosmic rays or beam). Operating procedures/manuals are then reviewed and accepted by RC.

5 QA Roles and Responsibilities

Roles and responsibilities for Project Quality Assurance throughout the CMS collaboration are described in the following subsections. These descriptions are generic and typically apply to all CMS subdetectors for the review and approval process. For U.S CMS personnel, roles and responsibilities are detailed here and included in summary form in the full descriptions in the Preliminary Project Management Plan (PPMP) [Ref-9] for DOE scope and in the Project Execution Plan (PEP) [Ref-10] for NSF scope. Some details of the coordination, integration, and execution of QA activities and practices may vary from subdetector to subdetector, based on the specific needs of each detector component/deliverable. The details of QA practices for each U.S. CMS subproject will be explained in the separate *Appendix to the Quality Assurance Plan for the U.S. CMS HL-LHC Project*, under the same reference as this document.

5.1 Roles and Responsibilities for CMS QA Oversight

CERN LHCC/UCG: The LHCC/UCG are responsible for approving plans for QA as part of Step 2 baseline design approval and at Step 3 for detailed implementation approval.

CMS Upgrade Coordination Lead: The CMS Upgrade Coordinator is responsible for calling for and conducting the CMS internal reviews leading to Step 2 and working with the CMS TC for reviews leading to Step 3.

CMS Technical Coordination (TC) and Electronics Coordination (EC) Leads: The CMS TC and EC are responsible for providing technical oversight and coordination of all parts of the detector. They are responsible for:

- Keeping up-to-date drawings and ensuring overall inter-compatibility between CMS subcomponents and LHC infrastructure.
- Participating in planning of QA activities and metrics.
- Calling for reviews of all subprojects during design, after final designs, before production, before installation, and before operations (EDR, PRR, IRR, ORR).
- Coordinating CMS subprojects points of contact to CMS Technical and Electronics Coordination
- Maintaining technical documentation in the CMS EDMS document system, including specifications and QA procedures.

CMS Subdetector Leads: Subdetector leads are responsible for oversight and management of their integrated detector subsystems, which include efforts from all participating contributors.

CMS Subdetector QA Manager: For Step 2 approval, the members of each CMS subdetector identify a QA Manager who is responsible for coordinating QA processes across all participating institutions for that subdetector. The QA Manager is responsible for defining or approving test procedures for each component or subassembly and the use of a common data-base and tracking tools to ensure selection/matching of components in the final assembly and to allow correlation between operational performance and the history of components in the construction process.

5.2 Roles and Responsibilities for U.S. CMS QA Oversight

Overall roles and responsibilities for these individuals and entities are described in the PEP [Ref-10] and the PPMP [Ref-9]. The Project is managed by members of the Project Office from both the Department of Energy and the National Science Foundation. U.S. Subprojects, based on CMS subproject detector systems, are organized under WBS Level 2 (L2) and Level 3(L3).

U.S. CMS Project Manager/Deputy Project Managers: The Project Manager and Deputy Project Managers are responsible for:

- Overseeing and coordinating QA activities for U.S. CMS DOE and NSF funded scope to ensure that they meet both CMS and Fermilab QA requirements;
- Supporting CMS Project Quality Assurance activities;
- Promptly notifying CMS oversight entities of issues related to QA activities and the ability of U.S. CMS to meet CMS technical and scientific requirements.

U.S. CMS QA Coordinator: The QA Coordinator is responsible for:

- Developing the U.S. CMS Quality Assurance Plan (this document). Reviewing the QAP and updating the Plan as necessary or at least once a year;
- With the Project Scientist, coordinating the Quality Assurance planning of WBS Level 2, 3, and 4 Systems Engineers/Managers to ensure that the work meets science objectives and Technical Requirements;
- Providing planning support, review, and approval of the participating institutions' QA plans/procedures developed with the WBS Level 2, 3, and 4 Systems Engineers/Managers, including site visits as necessary;
- Participating in surveillance reviews of work execution to ensure that the QA plans/procedures are followed;
- Providing training and coaching in QA practice for Project Office and WBS Level managers, as needed;
- Tracking the U.S. Quality Assurance efforts, ensure proper documentation, and facilitate integration with overall CMS.

U.S. CMS Project Scientist: The Project Scientist is responsible for:

- Developing Technical Requirements using the Science Flow Downs, working with the L2 and L3 managers;
- Supporting planning and providing review of the Quality Tests and Inspections developed by the WBS Level 2, 3, and 4 Systems/Managers, as identified in the CMS reviewed and approved Technical Requirements;

- With the QA Coordinator, coordinating the Quality Assurance planning of WBS Level 2, 3, and 4 Systems Engineers/Managers to ensure that the work at all participating institutions meets the Science and Technical Requirements.

U.S. CMS Subproject Level 2 Managers: In Quality Assurance, Level 2 Managers are responsible for:

- Working with CMS subproject leads, the Upgrade Coordination, Technical Coordination, and Electronics Coordination Leads to provide integrated QA for the U.S. scope.
- Developing their Level 2 System's Quality Assurance programs per the graded approach in this Plan, working with the U.S. QA Coordinator and participating U.S. institutions as appropriate;
- Overseeing Level 3 and 4 QA planning and execution to ensure that it follows their QA plans/procedures and meets science objectives and Technical Requirements;
- With the QA Coordinator, providing review and approval of the Quality Assurance planning and execution of work at all participating institutions, including site visits, to ensure that it meets science objectives and Technical Requirements;
- Promptly notifying Project Managers, Project Scientist and Project Engineer of proposed or potential changes to Technical Requirements Acceptance Methods.

U.S. CMS Subproject Level 3 and 4 Managers: In Quality Assurance, Level 3 and 4 Managers are responsible for:

- Developing their System's Quality Assurance programs per the graded approach in this Plan, working with the Level 2 Managers and the participating institutions and QA Coordinator as appropriate;
- Overseeing execution of work at all participating institutions to ensure that it follows the QA plans/procedures and meets science objectives and Technical Requirements;
- Promptly notifying Level 2 Managers of proposed or potential changes to Technical Requirements Acceptance Methods.

6 U.S. CMS QA Program

6.1 U.S. CMS QA Program Overview

The U.S. CMS QA Program deals with implementation of QA and QC processes for the activities and deliverables under the U.S. areas of responsibility. This program follows the outline of the Fermilab Quality Assurance Manual [Ref-2], with detailed processes specifically applicable to U.S. CMS[1]. The U.S. CMS Project Manager is responsible for overseeing QA for all U.S. activities. The guidelines and practices in this QAP apply to all work performed at Fermilab and to all QA plans/procedures for work at collaborating or participating institutions. The specifics of each U.S. CMS L2 subproject QA activities are given in the Appendix to this document.

Fermilab uses a graded approach to ensure that only the controls appropriate to the activity are applied. For the CMS upgrade project, controls range from Subject Matter Expert reviews to more formal peer review and other formats appropriate for design and construction.

Highlights of the U.S. CMS QAP are the following:

- All components must be fabricated to pre-determined design specifications that will allow them to operate properly when integrated into the total system.

[1] Where the Fermilab QAM is in conflict with CMS QA requirements, the CMS requirements take precedence.

- Agreements will be in place with each vendor that explicitly state the operating parameters of the piece or pieces they construct. These agreements will also assign the responsibilities for testing and verification of the final product.
- Agreements will be in place with each participating or collaborating institution that explicitly state the operating parameters of the piece or pieces they construct. These agreements will also include institutional QA plans/procedures and will assign the responsibilities for testing and verification of the final product.
- Procured items must meet established requirements and perform as specified. In some cases, testing of a certain percentage of components will be performed and documented.
- Vendor qualifications are reviewed as part of the bid process and are taken into consideration prior to bids being awarded. Vendor site visits may be conducted periodically throughout the duration of the fabrication contracts to ensure quality requirements are understood and being adhered to properly.
- Every electronic system must have a fully documented testing and troubleshooting procedure with clearly assigned responsibilities to be carried out by the vendor and/or U.S. CMS.
- Within the HL-LHC CMS Upgrade production facilities, a Traveler will accompany each component through the assembly process. These information packets are used to identify, report, correct, and trend non-conformance situations adverse to quality detector performance. The Travelers will contain whatever historical information accompanies the equipment, list the specified operating parameters, and provide a place for testing results to be entered. The test results and certifications will then be compared to the required specifications to determine the item's final use or disposition of those items.
- Once components are assembled and integrated for a given subproject, system tests will be performed. These tests will involve the activation, debugging and tune-up of the completed deliverable. Though such tests pertain to the system under study alone, they may require other subprojects' systems to be operational to enable the tests.
- Check-out consists of the process of integrating working systems into an operational piece of the CMS subdetector and is the final stage of preparation for commissioning. At this stage, unanticipated interactions and potential conflicts between distinct subdetectors may occur. The checkout process will evolve gradually as subdetectors are assembled and tests on the complete CMS detector are performed.
- All test results and Traveler information will be maintained in a data-base that allows the history and performance of the finally installed components to be traced.

Note: Testing and verification for performance within proper operating parameters will occur multiple times throughout the construction process. This multi-tiered testing approach ensures that improperly installed, faulty, or failed components are detected at the earliest possible opportunity and allow immediate remedial action to be taken without jeopardizing or negatively impacting operations. If non-conforming items are discovered, they will be documented and controlled to preclude inappropriate use until compliance with the applicable technical requirements is demonstrated.

6.2 Graded Approach

A key element of the U.S. CMS QA Program is the concept of Graded Approach; that is, applying an appropriate level of analysis, controls, and documentation commensurate with the potential to have an environmental, safety, health, radiological, cost and schedule, or quality impact. Four graded ESH&Q Risk levels are defined:

- ESH&Q Level 1 – Critical potential impacts, requiring a disciplined set of actions.
- ESH&Q Level 2 – Major potential impacts, justifying a balanced set of actions.
- ESH&Q Level 3 – Minor potential impacts, justifying a flexible approach.
- ESH&Q Level 4 – Negligible potential impacts, justifying a minimal approach.

Table 6.1 below provides examples of appropriate actions for each risk level. Consultation with the Quality Assurance Coordinator is expected whenever QA Risk levels are being determined,

Table 6.1 Appropriate QA actions for the four Risk Levels in the U.S. CMS Graded Approach.

	Grade			
	Level 1 - Disciplined	**Level 2 – Balanced**	**Level 3 – Flexible**	**Level 4 - Minimal**
Actions	Design reviews, independent verification, and validation	Design reviews, verification, and validation	Little or no design reviews, verification, or validations	No design review, verification, or validations
	Thorough documentation	Adequate and appropriate documentation	Minimal documentation	Minimal documentation
	Established inspection criteria	Established inspection criteria	Established inspection criteria as needed	Count, condition, and identity
	Vendor qualification and surveillance	Vendor qualification or evaluation	Little or no vendor qualification	No vendor qualification
	Formal procedures	Formal procedures	Formal procedures as needed	No formal procedures
	Complete oversight and assessment	Oversight covered under general management assessments	Oversight provided by line management	Oversight provided by line management
	Controlled measuring and test equipment	Controlled measuring and test equipment	Measuring and test equipment generally not used	Measuring and test equipment not used
	Document worker qualifications	Document worker qualifications	Document worker qualifications as needed	Knowledgeable personnel employed
	Formal inspection and testing	Formal inspection and testing	Normal receipt with inspection only	Normal receipt with inspection only
	Requires QA representative approval	Requires QA representative approval	QA consultation as needed	No QA consultation needed

6.3 Personnel Qualifications and Training

The selection of personnel to perform Project work requires a process for screening personnel that assures proper qualifications for performing assigned work. The U.S. CMS Project Managers and subproject Leads are responsible for identifying the resources to ensure that their team members are adequately trained and qualified to perform their assigned work. Before allowing personnel to work independently, they are responsible to ensure that their team members have the necessary experience, knowledge, skills, and abilities. Personnel qualifications are based on the following factors:

- previous experience, education, and training
- performance demonstrations or tests to verify previously acquired skills
- completion of training or qualification programs

- on-the-job training

For work conducted at other U.S. institutions or by non-Fermilab personnel, the appropriate manager (PM or subproject L2 lead) has the responsibility to ensure that personnel are properly qualified.

6.4 Technical Requirements and Quality Activity Validation

The primary goal of Quality Assurance for the US CMS project is to ensure that the CMS experiment achieves the science requirements and goals listed in the *Science Goals and Requirements for US CMS HL-LHC* [Ref-1]. Thus, all components and systems must meet approved Science and Engineering Technical Requirements that flow down from the science goals and requirements. These Science and Engineering Requirements are the basis for all QA activities during design and production. US CMS Technical Requirements are described and listed in in individual documents for each L2 subproject[2].

Validation of the Technical Requirements and related Quality Activities ensures that any given component, subsystem or system meets the Technical Requirements, that acceptance criteria are defined, and that all characteristics crucial to the safe and proper use of the component, subsystem or system and its associated interfaces have been identified.

Technical Requirement validation and acceptance methods include, but are not limited to, any one or combination of the following quality activities:

- Design review
- Engineering analysis
- Engineering demonstration (prototyping)
- Qualification testing
- Inspection
- Trial construction
- Comparison of the design with a similar proven design, if available

In any review, validation of conformity to requirements follows verification that the engineering design or computer code meets all criteria. Overall responsibility for approval of the Technical Requirements and related Quality Activities rests with CMS and follows the review process summarized in Section 4 of this document. Technical Requirements validation shall be completed and approved before production of the component, subsystem and/or system begins.

6.5 Design Work Processes and Controls

Design Quality Assurance requires continuous technical coordination and periodic technical reviews of design and engineering demonstrations (prototypes, material testing, simulations, etc.) to determine the Technical Requirements and Interfaces and to define the Quality Assurance and Control activities that will demonstrate satisfactory compliance.

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[2] 402.2 Outer Tracker -- Requirements and Interfaces [Ref-11]
402.3 Barrel Calorimeter -- Requirements and Interfaces [Ref-12]
402.4 Endcap Calorimeter -- Requirements and Interfaces [Ref-13]
402.5 Endcap Muons -- Requirements and Interfaces [Ref-14]
402.6 Trigger and DAQ-- Requirements and Interfaces [Ref-15]
402.7 Forward Pixels -- Requirements and Interfaces [Ref-16]
402.8 MIP Timing Detector – Requirements and Interfaces, [Ref-17]

The Project design processes are enhanced using systems engineering principles. The primary design inputs are the Project's programmatic data (cost, schedule, management reports, etc.), technical requirements (science requirements, engineering requirements, specifications, drawings, engineering reports, etc.) and Configuration Management documentation. *The US CMS HL-LHC Systems Engineering Management Plan* [Ref-18] defines the scope of design work for any given scientific/engineering work group. Work groups begin preliminary design by breaking their work down into sets of engineering drawings, specifications and reports. This is the design output that must meet with CMS approval before moving into the next phase.

Throughout the design process, engineers and designers work with Level 2 Managers, who work within CMS, to determine QA/QC verification and inspection criteria of fabricated products and installations. Close coordination must be made with Project scientists to assure the engineering satisfies the Technical Requirements of the experiment. Configuration Management, as documented in *the US CMS HL-LHC Configuration Management Plan* [Ref-19], will be implemented in Preliminary Design. Final Design work sets the final Quality Assurance parameters for the system and its components. Design efforts during the Final Design phase and production are confined to Change-Controlled changes, as above; and, minor changes necessary to facilitate production, drawing error correction, material substitutions and similar functional areas.

6.6 Production Work Processes and Controls

Production Quality Assurance includes activities (tests, inspections, analyses, etc.), defined during the design phase, which will demonstrate actual compliance. Fabrication work on the Project shall be performed to established technical standards and administrative controls using approved instructions and procedures. Work shall be performed safely, in a manner that ensures adequate protection for employees, the public, and the environment. Team members, Project Management and participating institutions shall exercise a degree of care commensurate with the work and the associated hazards.

Within the U.S. HL-LHC CMS Upgrade Project production facilities, a graded approach will be used to determine what information (travelers) will accompany each component through the assembly process. These information packets are used to identify, report, correct, and trend non-conformance situations adverse to quality detector performance. Travelers may contain historical information, list the specified operating parameters, and provide a place for testing results to be entered. Test results and certifications can be compared to the required specifications to determine the item's final use or disposition.

6.7 Software Quality Assurance

The Fermilab QAM [Ref-2] outlines the software quality assurance requirements in Chapter 12003 – *Fermilab Software Quality Assurance Program* and Chapter 12090 - *Software Quality Assurance Grading & Inventory Procedure*. These chapters provide the program elements to guide application owners on the design, development, verification, validation testing, and documentation that will ensure the software performs the intended functions correctly. As with all project components, software designed in support of the project must meet with the approval of CMS prior to moving from the design phase into development.

Wherever the design method involves the use of computer software to make engineering calculations or static dynamic models of the structure, system, or component's functionality, the software must have been demonstrated to produce valid results. However, exemptions may be made for commercially available software that is widely used and for codes with an extensive history of refinement and use by multiple institutions. Exemptions affecting systems or components shall be identified to the Project Systems Engineering team.

Critical software and firmware computer codes, especially those codes that are involved in controlling Data Acquisitions systems (DAQ), shall also be subjected to reviews for acceptance and validation. Some items to be considered during computer code review are:

- Adequacy of code testing scheme
- Code release control and configuration management
- Output data acceptance against code configuration
- Acceptance that code meets applicable standards
- Acceptance of code compatibility to other systems that use the data
- Acceptance that code meets applicable hardware requirements
- Adequacy of code maintenance plans
- Adequacy of code and data backup systems

6.8 Procurement

Procurement actions follow the specific guidance outlined in the *Fermilab Procurement Manual* [Ref-20] and are described in the Procurement Management Plan for the HL-LHC CMS Detector Upgrade Project [Ref-5]. Procured items must be fabricated to pre-determined design specifications that will allow them to operate properly when integrated into the total system. Agreements will be in place with each vendor that explicitly state the operating parameters of the components they construct. These agreements will also assign responsibilities for testing and verification of the final product.

The L2 Project requesting procurement of items and services are responsible for providing all documentation that adequately describes the item or service being procured so that the Supplier can understand what is required for the Projects' acceptance. Development of this documentation may be achieved through the involvement of Subproject Managers and established review and approval systems. The following factors will be considered for review and approval of this documentation:

- Technical requirements for vendor qualifications and certifications
- Inclusion of technical performance requirements
- Identification of required codes and standards, laws and regulations
- Inclusion of acceptance criteria, including requirements for receiving inspection and/or source inspection
- Assignment of responsibility for testing and verification of the final product.
- Every electronic system must have as an essential part of its deliverable, a fully documented testing and troubleshooting procedure.
- Project intention to perform acceptance sampling in lieu of full inspection and test item acceptance

Unacceptable Supplier items or services shall be documented. Records of Supplier performance, Inspection Test Records (ITR) and contract-required submittals, are kept for future procurement consideration.

Inspections shall be conducted to detect counterfeit, defective, and/or suspect parts so they can be managed per Section 6.14 below.

6.9 Inspection and Acceptance Testing

The Project will follow the specific guidance of the U.S. CMS QAP requirements and, as appropriate, the Fermilab QAM [Ref-2] including Chapter 12002 – *Fermilab Quality Assurance Program*, Section 5.8 and subsections with respect to inspection and acceptance testing of components.

U.S. CMS Upgrade Project acceptance tests will include fit and function checks as well as some performance testing of subcomponents or integrated subsets of system components. Each inspection, test or review will

feed the QA evaluation process, which is a comparison of results with acceptance criteria to determine acceptance or rejection. QA reporting formality escalates as the significance of any identified nonconformance increases. Higher levels of management must be aware of and participate in the correction of the most significant non-conformances. Section 6.14 Suspect/Counterfeit/Defective Items Management identifies the required course of action when non-conformances are encountered.

The Projects will define a system of controls to ensure that items are handled, stored, shipped, cleaned, and preserved to prevent them from deteriorating, being damaged, or becoming lost. Equipment used for process monitoring or data collection shall be calibrated and maintained.

Integrating working subsystems into an operational system is the final stage of preparation for installation and commissioning. Once components are assembled and integrated into subsystems, system tests will be performed to the extent possible. Such tests will involve the activation, debugging and tune-up of the assembled system. Though such tests pertain to the system under study alone, they may require other subsystems to be operational to enable the tests. Additional tests will be performed during the installation and commissioning phase of the delivered subsystems into the full detector under the management of CMS TC, RC, and the CMS subsystem project leaders.

6.10 Issue Tracking and Quality Improvement

All Project personnel participate in quality improvement activities that identify opportunities for improvement. They will have the ability to respond to the discovery of quality-related issues and follow up on any required actions. This quality-improvement process requires that any failures and non-conformances be identified and reported to the appropriate L2 Manager; and, that root causes be identified and corrected. All Project personnel, participating institution staff, and subcontractors are encouraged to identify problems or potential quality improvements and may do so without fear of reprisal or recrimination.

6.11 Documents and Records

Engineering and scientific documents (including drawings) are prepared by Project personnel to define the design, manufacture and construction. The U.S. CMS Project manages all documents under its scope, regardless of the originating institution, under a central system to control document preparation, approval, issuance to users, and revision that is described in the *Configuration Management Plan* [Ref-19]. Project Management, the Project Engineer and L2 Managers are responsible for identifying the information to be preserved. The CMS Technical Coordinator, along with the CMS project lead, is responsible for maintaining final approved engineering and scientific documents in the CMS EDMS document system.

6.12 Management Assessments

Management assessments are performed by an organization to evaluate management processes and their implementation to identify noteworthy practices, uncover issues, identify corrective actions, and ensure that the work being performed is satisfactory and according to requirements. The Project Office Team and Level 2 Managers determine the extent and adequacy of this process.

WBS Level 2 subprojects are discussed and reviewed during regularly scheduled project meetings. Additional reviews and workshops may be organized on an ad hoc basis for selected systems and components as the need arises. The Project Manager has the authority to form an ad hoc review team.

6.13 Project Technical Assessments

Project Management may plan reviews as independent assessments to assist line managers in identifying opportunities for quality/performance-based improvement and to ensure compliance with specified requirements. Independent assessments typically take the form of design reviews, engineering note reviews,

or readiness reviews (e.g. procurement readiness reviews, production readiness reviews, operational readiness reviews, etc.) Personnel conducting independent assessments shall be technically qualified and knowledgeable in the areas assessed. A lead auditor who is an SME in the technical area of assessment, is required. The team may include other SMEs to evaluate the adequacy and effectiveness of activities only if they are not responsible for the work being assessed.

The Project uses a formal process for assigning responsibility in response to recommendations from independent assessments and these recommendations are tracked to closure.

6.14 Suspect/Counterfeit/Defective Items Management

For work funded by DOE, counterfeit/suspect/defective parts must be identified, segregated, and disposed of in accordance with Department of Energy requirements. For issues identified at Fermilab, the requirements outlined in *Quality Assurance Manual* [Ref-2] *Chapter 12020*, *Suspect/Counterfeit Items (S/CI) Program*, will be followed.

Inspection and test reports or similar tools will be used to implement this requirement. Items, services, and processes that do not conform to specified requirements shall be identified, documented and controlled as appropriate to prevent their unintended use. Controls will be established according to instructions, specifications, drawings, and technical manuals for items that are sensitive, have a high cost, or have been identified as having a significant impact on the environment or schedule. Each L2 Manager is responsible to report non-conformances to the Project Manager and the QA Coordinator. Non-conformances are also reported via the regular CMS UCG meetings and in the UC Annual Review cycle for each project. Ad-hoc reviews are then called by UC/TC, including lessons learned. The outcome of these reviews is reported at the Management Board. Depending on the severity of the non-conformance, incidences may be reported via the Fermilab Project Lessons Learned database in order to document the occurrence and educate CMS workers and others performing similar work.

Procured items that do not meet Project specifications must not be used. It is the responsibility of the participating institution that receives the items to properly segregate and isolate the material from use and decide on its final disposition.

7 U.S. CMS Participating Institution QA Plans/Procedures

Participating U.S. CMS institutions that perform work on DOE or NSF funded scope for the U. S. CMS HL-LHC Project CMS Upgrade Project must follow QA plans/procedures that satisfy CMS Subdetector requirements and this QAP. Specific details of the plans and procedures addressing institutional work will depend on the technical requirements and/or the nature of the international collaboration. For example, a single procedure may cover assembly at all module production centers while separate QA procedures may be needed for each institution participating in DAQ development.

The U.S. L2, L3, and L4 subproject leads are responsible for collecting and reviewing the QA plans/procedures for universities and other participating institutions performing work for the U.S. CMS Upgrade Project. They will work with representatives from participating institutions and the US CMS QA Coordinator to create QA plans/procedures that conform to the graded approach in this QAP and with CMS requirements. In many cases, the institutional plan will simply be to follow CMS approved assembly and testing procedures required of all collaborators, including the U.S., within a subdetector Project. The institutional QA plan/procedures will be reviewed and approved by the subproject L2 lead and the U.S. QA Coordinator and be included in the

document control system for the subproject QA activities. The institutional QA plans/procedures form part of the overall CMS QA Plan for each Subdetector, and as such, are included in the CMS review and approval process. As the project planning matures and project work commences, the institutional QA plans/procedures will be updated as needed.

A designated contact responsible for QA from each institution will be identified as part of a capability analysis. The U.S. subproject leads are responsible for the evaluation and verification an institution's ability to perform work to CMS specifications. Per the graded approach, site visits by the subproject L2 lead and QA Coordinator to evaluate QA may be made prior to commencement of specific activities, including prototyping, pre-production pilot fabrication, production, assembly, shipping, and/or testing. The *CMS Quality Assurance Audit Field Checklist and Report Template* [Ref-21] will be used to document the findings of site visits for participating institutions and/or vendors, adjusted as needed for the graded QA approach.

The institutional QA plans/procedures should cover all U.S. CMS work managed by the institution, including subawards to vendors or other participating institutions. The designated contact and the staff of the participating institution are responsible for ensuring that work performed by their sub-awardees will meet the requirements of their approved U. S. CMS QA plan/procedure. They are also responsible for ensuring that the U.S. CMS related QA plans/procedures conform to any QA Program requirements of the participating institution.

References

[Ref-1] US HL-LHC CMS Science Goals and Requirements, CMS Document 13337

[Ref-2] Fermilab Quality Assurance Manual, http://eshq.fnal.gov/manuals/qam/

[Ref-3] LHC Experiments Phase II Upgrades Approval Process, CERN-LHCC-2015-007

[Ref-4] Review Process in International CMS for Detector Upgrade Projects, CMS Document 13392

[Ref-5] Procurement Management Plan for the HL LHC CMS Detector Upgrade Project CMS Document 13267

[Ref-6] CMS Constitution, CMS-doc-3035

[Ref-7] CMS HL-LHC Upgrade Technical Proposal, CDS-2020886

[Ref-8] CMS Phase II Upgrade Scope Document, CDS-20155167

[Ref-9] Preliminary Project Management Plan for the HL-LHC CMS Detector Upgrade Project, CMS Document 13104

[Ref-10] Project Execution Plan for the HL-LHC CMS Detector Upgrade Project, CMS Document 13279

[Ref-11] 402.2 Outer Tracker Requirements and Interfaces, CMS Document 13388

[Ref-12] 402.3 Barrel Calorimeter Requirements and Interfaces, CMS Document 13317

[Ref-13] 402.4 Calorimeter Endcap Requirements and Interfaces, CMS Document 13447

[Ref-14] 402.5 Endcap Muons Requirements and Interfaces, CMS Document 13281

[Ref-15] 402.6 Trigger and DAQ Requirements and Interfaces, CMS Document 13318

[Ref-16] 402.7 Forward Pixels Requirements and Interfaces, CMS Document 13304

[Ref-17] 402.8 MIP Timing Detector – Requirements and Interfaces, CMS-doc-13536

[Ref-18] Systems Engineering Management Plan for the USCMS HL-LHC Upgrade Project, CMS Document 13194

[Ref-19] Configuration Management Plan for the HL-LHC CMS Detector Upgrade Project, CMS Document 12907

[Ref-20] Fermilab Procurement Manual, Fermilab Procurement Policy

[Ref-21] CMS Quality Assurance Audit Field Checklist and Report Template, CMS Document 13668