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QUALITY ASSURANCE ASPECTS OF THE MAJOR PROCUREMENTS FOR THE LARGE COIL TEST FACILITY*

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Abstract: The Large Coil Test Facility (LCTF) project is comprised of the test stand, supporting cyrogenic systems, instrumentation, data acquisition, and utilities necessary for testing the large superconducting coils of the Large Coil Program (LCP). A significant portion of the facility hardware has been obtained through procurement actions with industrial suppliers. This paper addresses the project's experience in formulation and execution of quality assurance (QA) actions relative to several of the major items procured.

Project quality assurance planning and specific features related to procurement activities for several of the more specialized test facility components are described. These component procurements include: (1) the coil test stand's major structural item (the bucking post) purchased from foreign industry, (2) fabrication and testing of high-current power supplies, (3) industrial fabrication of specialized instrumentation (voltage-tap signal conditioning modules), and (4) fabrication, installation, and testing of the liquid helium piping system.

Each of the items selected has unique characteristics requiring careful consideration to ensure visibility and control of critical quality-related aspects of each particular procurement. Quality planning; experience with each supplier; results from the fabrication, installation, and testing conducted; and recommendations related to how well the original plans matched actual events are covered. A summary with a discussion of areas that should receive different attention in future, similar procurements is also included.

General Quality Assurance Planning

Initial planning for LCTF procurement activity included conducting a Quality Assurance Assessment (QAA) to analyze the risk involved in the design, fabrication, and installation of all project subsystems. All facility subsystem components were identified, an attempt was made to assess any conceivable mode of failure for each component, and the consequences of and probability of occurrence of each conceivable failure were evaluated. The participants in this assessment were the Responsible Engineering Designers, Procurement Engineer, Project Engineers, and representatives of the Fusion Energy Division (FED) of Oak Ridge National Laboratory (ORNL), including the Division QA Coordinator.

Items with both a significant mode of failure and a high probability of failure were termed an unacceptable risk and were included in the project Quality Assurance Plan (QAP). The QAP identified the tasks to be undertaken by the project to preclude the failure modes identified in the QAA. Included in the QAP was a description of the QA concern, the special action to be taken to reduce the risk of failure, the responsible individual or group, and the scheduled date of completion for the activity. The data from the QAP were then entered in a computerized data base that was used to remind the Project Engineer of upcoming QA actions.

Many components listed in the QAA were determined to have significant modes of failure with low probabilities of occurrence. The low probabilities of occurrence were typically based on use of standard engineering practices, development of prototypes, or use of established reliable designs. Although the probabilities of occurrence were low, the tremendous possible impact to expensive experimental equipment led to adoption of special QA actions as a matter of practice. Some of those QA activities include:

1. specifying special inspections and tests, including hold points and acceptance criteria during procurement;
2. requiring traceability of material and/or hardware;
3. identifying requirements for controlling special processes such as welding, heat treating, cleaning, and nondestructive testing;
4. identifying requirements for protecting items against deterioration and damage during handling, shipping, and storage;
5. reviewing procurement documents by the QA coordinator for specification of QA requirements;
6. conducting source surveillance and inspection;
7. reviewing the vendor's QA program;
8. reviewing the vendor's bid proposal by appropriate project participants;
9. conducting pre- and post-award meetings with vendors;
10. performing receiving inspections based upon defined acceptance testing; and
11. using a formal document to ensure proper review.

As a matter of procedure, all specifications have sections addressing QA. The QA section describes the treatment of deviations and nonconformances. Deviations are defined as changes from drawings or specifications prior to the start of manufacture as recommended by the manufacturer. Nonconformances are defined as changes from drawings or specifications detected after the start or completion of manufacture, typically during inspections. Deviations and nonconformances are documented by reports in standard formats provided as part of the contract documents.

Deviation or nonconformance reports received from vendors are sent through Purchasing to the assigned Procurement Engineer. The Procurement Engineer has the responsibility to resolve the issue with input from design, project, and QA coordination personnel. Resolution of deviation reports means to accept or reject the deviation. Resolution of nonconformances means to accept, accept with rework, or to reject (with the component in question being remanufactured). The QA Coordinator acknowledges that the respective reports receive proper approval.

The Procurement Engineer is also responsible for including appropriate QA documentation in the contract requirements and ensuring that all documentation is received before release of final payment. In addition, the Procurement Engineer works closely with Purchasing and the Responsible Engineering Designers to see that qualified people are available to witness tests at vendor plants.

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Specific examples of specialized procurements on the LCTF project, with emphasis on the QA requirements and how these were met or how difficulties were resolved, are given in the following sections.

Bucking Post

The bucking post is a 28-ton stainless steel forging that is the central structural component of the coil test stand. Along with the upper and lower collars, shims, and the torque rings, the bucking post supports the superconducting coils. During a single coil test, the bucking post must react to a maximum bending moment of 1.2×10^8 in.-lb. The maximum load during a six-coil test is 4560 tons in compression. In addition, the bucking post must be cooled to liquid helium temperatures to minimize the amount of heat transferred to the coils.

The primary QA concerns for the manufacture of the bucking post were the quality of the alloy to be forged; a requirement for uniform grain size, free from inclusions or other internal flaws; dimensional tolerances of the final machined piece; and the final surface finish of the forging.

To ensure uniformity of allowable properties and grain size, the procurement specification required:

1. two ultrasonic examinations of the forging, first after rough machining and then after final machining;
2. microscopic examination of samples taken from the rough forging; and
3. testing two sets of 36 specimens taken from the forging — one set tested at room temperature and the other tested at liquid helium temperatures.

The specification also required submittal of manufacturing plans, as well as plans for testing and cleaning. Hold points were specified to perform the above test, along with dimensional inspections.

Few domestic manufacturers were interested in fabricating the bucking post, so foreign vendors were included as prospective fabricators. It was decided that the only special requirements for foreign vendors would be that all drawings must be labeled in English and that all dimensions must be in English units. All specified hold points were to be the same for domestic or foreign fabricators.

The source selection resulted in a vendor in Japan being awarded the contract to fabricate the bucking post. The vendor sent representatives from Japan to ORNL at the onset of the job to be absolutely sure that the job was completely understood. All required documentation was received from the vendor with no difficulties, and all manufacturing plans and other submittals were approved with only minor modifications. During fabrication, visits were made to the vendor at two different points to inspect the condition of the forging.

The first visit was made to perform ultrasonic tests on the rough-machined forging to check for included flaws and to examine the grain size of metal samples taken from the forging. All tests ran smoothly with no difficulties.

An additional visit was made after completion of final machining. Ultrasonic tests were once again performed to check for included flaws in the grain structure. Dimensional inspections were made, and all dimensions were within tolerance. A lot of 36 specimens had been taken from the forging. The specimens were inspected along with test results which examined grain size and alloy composition. The other 36 samples, which were to have been sent to ORNL for cryogenic testing, were lost during shipment.

The bucking post went through final polishing and then was shipped to the Y-12 Plant. It was received on schedule and inspected once again for dimensions. All measured dimensions were well within tolerance.

In summary, this particular vendor's reputation was based on delivery of a high quality product. The vendor went to great lengths to understand the job before the onset of fabrication. They had a thorough knowledge of the problems that could be encountered during fabrication and took all of the necessary precautions to preclude difficulties. Each increment of fabrication was conducted with such care to ensure the quality of the bucking post that there were no problems to speak of during the manufacture of the piece. In this instance, no additional tests were necessary, and some of the tests performed were perhaps not necessary.

High-Current Power Supplies

Six high-current power supplies were procured for the LCTF. Four of the supplies are designed to supply a peak current of 16,000 A at 12 V; the two others are designed to supply 25,000 A at 12 V. The procurement package included a performance specification describing all operational parameters, required tests and documentation, and interface drawings defining the spatial envelope.

The control circuitry of the power supplies was specified to require the capability to vary both current and voltage with a close tolerance setpoint control during system operation. In addition, the circuitry must be capable of inverting the voltage to allow an operating mode that acts to discharge the stored energy of the superconducting coil back into the ac power lines. During the design and procurement phases, there was a QA concern that the control circuitry would not perform adequately — resulting in possible damage to the test coil, adjacent test coils, the test stand, and the superconducting power leads.

An additional concern existed with respect to power supply electromagnetic interference with the test coil diagnostics. This resulted in a carefully defined voltage ripple specification of less than 250 mV at 0 to 300 Hz and less than 500 mV at 300 Hz to 1 MHz. Such a low level of ripple is difficult to achieve in power supplies with these high levels of current. For this reason, there was a QA concern that the power supplies would not meet the ripple specification.

The procurement specification addressed these QA concerns by requiring the vendor to:

1. supply an overall system schematic, detailed control diagrams, and transformer assembly drawings, including plans for review and approval;
2. supply a detailed test plan for the testing of power supply transformers prior to installation and for complete operational testing of the assembled power supplies at the vendor's site; and
3. provide an advance notice of two weeks before the performance of any tests to allow for observation.

Particularly significant areas in which difficulties occurred, the interactive efforts undertaken to resolve these problems, and some indication of possible actions that could have been taken to mitigate these circumstances are summarized below.

Initial testing of the power supplies, after completion of fabrication, revealed the anticipated problems with ripple exceeding the specified limits over a broad range of frequencies, drift from set point, overheating of the secondary bus system in the power supply cabinet, and a decrease in output voltage resulting from an associated transformer regulation and drop in line voltage at full power output.

Once these difficulties had been identified, the vendor and representatives from ORNL worked closely together to come up with solutions and corrective actions. Suggestions were made on how to rearrange components within the power supply cabinets to shorten path lengths and thus reduce the ripple. New printed circuit boards were fabricated with slight modifications to the circuitry to eliminate the drift from the setpoint. ORNL supplied equipment to locate the hot spots within the secondary bus system, allowing the vendor to redesign bus connections and modify air-cooling apparatus. Last, it was decided that the voltage drop on the output side due to a line voltage drop was the result of a design error affecting operation of the transformer. Because the voltage drop problem only occurred at full power (140% of standard operating current) and transformer replacement was the only solution, this condition was accepted as a nonconformance.

After completion of these modifications, the power supplies were retested and accepted; the only remaining problem was a 300-mV ripple at 60 Hz. Meeting the ripple specification was expected to be the most difficult technical achievement. Careful review and analysis with the vendor resulted in a decision to accept this condition since it was agreed that there was no certainty that redesign of power supply subsystems would eliminate the out-of-specification ripple.

To summarize, the original QA concerns defined by tight, but necessary, specifications proved to be valid. Reaction to difficulties encountered was rapid; expert advice and participation were brought into this activity; and vendor response was positive and cooperative. Key problem areas and suggestions on how to avoid recurrences are listed in the following paragraphs.

Design reviews were held to try to avoid difficulties with the control circuitry and with the ripple. However, actual layout of circuit components in the control circuitry and layout of components within the power supply cabinets turned out to be the most significant causes of problems discovered in testing. It was not possible to identify these problems in advance, because only schematics of the circuitry were required prior to fabrication. In retrospect, a final design review and plant visits during fabrication would have eliminated or certainly reduced some of the difficulties by identifying problem areas and initiating earlier reaction to design details.

A design review of the bus design by both electrical and mechanical engineering may have eliminated the difficulties encountered with overheating of the secondary bus system by bringing heat-transfer expertise to this job. The problem with voltage drop on output resulting from a drop in line voltage was caused by an inadequate transformer design. Detailed review of the transformer design and testing of transformers before installation should have identified the problem. However, the design calculations were not checked closely enough to turn up the problem, nor was testing extensive enough.

In several instances, the vendor did not have sufficient equipment to perform tests required by the test procedures. ORNL personnel responded by supplying much of the special equipment for testing. This lack of on-site capability resulted in testing delay. A valuable action to consider in future procurements requiring special testing would be to include this subject for discussion as part of a pre-award conference.

Voltage-Tap Signal Conditioning Instrumentation

The voltage-tap instrumentation and control system for the LCTF consists of a set of modular electronic units which assemble into an integrated array. The components of the system are the Isolation Amplifier, the Compensation Module, the Buffer/Gain Decoder, and the Quench Detector. Assembled, this system is intended to perform three functions: (1) provide voltage isolation to protect personnel and equipment from possible high voltage during superconducting coil, stored energy discharges, (2) provide input signals for initiating coil discharges based on voltages due to normal zones in the superconductor, and (3) provide coil diagnostics voltage signals related to layer-to-layer and heated zone voltages within the coils.

The Isolation Amplifier provides voltage isolation for the rest of the system. The detection of normal zones and the monitoring of voltages within the coils are accomplished by amplifying the signal coming from a voltage tap internal to the coil, compensating for voltages induced by adjacent experimental coils, comparing the voltage signal with a preset reference, and processing the signal within the data acquisition system.

During system definition, there was a QA concern that the method of compensating for induced voltages would not be able to accurately detect normal zones or provide meaningful data on voltages within the coils. To overcome this concern, a development program was set up. The strategy for providing a working system was to: design and build prototype units, perform detailed bench tests to simulate system operation, assemble detailed manufacturing drawings, perform a system peer review by engineering and ORNL Magnetics personnel, issue a procurement contract for the required number of production modules as a build-to-print package, obtain first-article modules from the vendor for additional bench testing and modification, and conduct a receiving inspection of all components of the system.

Upon completion of manufacture, the vendor performed an input/output comparison under power. Upon receipt from the vendor, all of the units were inspected using a piece of test apparatus known as the General Radio Test Station (GENRAD). GENRAD is a computer-assisted piece of test equipment programmed to test electronic components. A schematic of the test article's circuit is programmed into GENRAD along with expected output signals for given inputs. GENRAD is then used in a complete circuit test by simulating operating conditions and pointing out defective components in the circuitry.

Most of the units tested turned out to have no problems. For those with problems, minor repairs were performed. As an additional measure to ensure the integrity of the system, a component test circuit was set up using a small superconducting magnet as the test coil. Testing pointed out some deficiencies in the circuitry that had been overlooked during design and bench testing.

The input side of the isolation amplifier was designed to provide circuit protection during a coil energy discharge, but it was not designed to process voltage data from within the coil during this transient time. Only after all units had been fabricated was it decided that it was desirable to take data during this transient. Testing with the small magnet showed that the amplifier saturated once the input voltage reached 200 V, making it impossible to take data during the transient.

Testing with the magnet also pointed out that momentary shorts across the output buffers created severe reliability problems. During bench testing, shorts across the output buffers were never observed because units were either hardwired or installed in chassis with great care. The final production units were fabricated without key pins to align the modules upon installation, resulting in pins being misaligned on the rear of the modules. This misalignment caused shorting across the rear of the amplifiers and, in many cases, failure of the units. This problem was corrected by performing slight modifications to the modules.

In summary, most of the problems incurred with the units were the result of insufficient time spent prototyping during design. Additional problems with the system were the result of an incomplete understanding of the experimental application of the system at the time of design of the units. Sufficient time and resources for prototyping developmental components must be allowed for up-front project planning to address these types of difficulties. One of the risks of this type of effort is that the system will not be able to handle all of the desired experimental applications conceived at a later date.

The quality of manufacture of the various components was good. There were virtually no difficulties with the vendor, and there was full cooperation at each stage of manufacture. In future procurements, it would be beneficial to perform additional tests, under power, at the vendor's site to ensure proper function of circuit components. Testing components in the exact environment in which they will normally be operated is extremely beneficial in discovering possible difficulties. A key recommendation is to test similar types of equipment in such a manner in future procurements.

Liquid Helium Piping System

The liquid helium piping system for the LCTF is designed to distribute liquid, gaseous, and supercritical helium from the liquid helium refrigeration system to the test coils, the test stand, the helium vapor-cooled lead dewars, and the superconducting power bus.

Procurement of these system elements was complicated both by the complexity of the flow network and by the interfacing of components (within the flow system) supplied by several different manufacturers.

Of the QA concerns assessed, the primary ones were that components of the system would fail to meet interface conditions, spool pieces would exceed the maximum specified heat leak, and poor manufacturing techniques would result in a line rupture — spilling or leaking cryogens during operation. The design requirements called out in the procurement specification to address these concerns included: review and approval of vendor-supplied drawings for interfaces, angles, and dimensions; review and approval of vendor-supplied heat leak calculations; testing of three randomly selected spool pieces to see that heat leak specifications were achieved; and review and approval of vendor-supplied manufacturing plans, as well as procedures for welding, cleaning, and leak testing.

A summary of the significant events during fabrication and installation of the piping system and corrective actions taken to alleviate some of the problems are listed below.

The vendor supplied all of the documentation required by the specification. All documentation was reviewed and approved by the design team.

At various stages of fabrication, representatives from Engineering and the ORNL Quality Assurance and Inspection (QA&I) Department visited the vendor's shop. These visits turned up several problems regarding welding and cleanliness. Inspection of welds on several completed lines indicated that weld porosity was greater than radiograph reports had indicated. A review of procedures between personnel from the vendor and representatives of QA&I corrected the weld problem.

While using a boroscope to inspect welds, QA&I recognized that a good deal of contamination remained in the lines after completion of manufacture and after the lines had supposedly been cleaned. Cleaning procedures were once again reviewed with the vendor, and the importance of cleanliness with respect to other components in the helium stream was once again stressed.

Additional visits to the vendor were made to perform heat leak tests. In all instances, the spool pieces tested fulfilled the requirements of the specification. Upon completion of individual heat leak tests, partial shipments were authorized.

During the early stages of installation, it was recognized that the problem of contamination in the lines had not been corrected. Rather than return the spool pieces to the vendor's plant, procedures were developed to allow the installation contractor to clean the spool pieces with high-pressure air and/or freon before installation.

Several fit-up problems were incurred, such as poor fit-up of a few spool pieces because of incorrect angular or length dimensions or incompatible end bayonets. Also, some of the jumper pieces for the nitrogen trace lines and for the vacuum gauge fittings were rotated 90° or 180° away from their correct orientation, and some of the temperature sensors did not fit.

The lead engineer communicated with the vendor on a daily basis during the peak period of spool piece installation to work out these problems. Recommendations were made by both parties about how to best handle ongoing difficulties. To meet an upcoming test date of the liquid helium refrigerator, it was imperative that installation of all spool pieces be completed. Because of this restriction, there was no time to return lines to the vendor's shop. The vendor worked closely with ORNL by sending representatives to supervise modifications of individual lines by the on-site installation contractor.

As a result of the cooperation between ORNL representatives and the vendor, all equipment was installed and operational in time to perform critical test sequences on the refrigerator.

In conclusion, all equipment furnished by the vendor functioned as required by the specification. Tests on the installed system showed no leaks in the system, and heat leak for the system is less than that required to support the helium refrigerator.

The QA concerns turned out to be valid. Review of vendor drawings corrected several interface dimension problems. Problems discovered by on-site weld inspection avoided possible difficulties with overstressed weld joints at a later date. However, additional dimensional inspection and assembly of components to check fit-ups and cleanliness at the vendor's plant before shipment would have saved considerable construction time during installation. Close cooperation between ORNL and the vendor overcame all of the difficulties without severely delaying other facility activities.

Summary

Aside from the fabrication of the bucking post, with virtually no difficulties, the procurements discussed above incurred significant problems during the precurement process. QA provisions and planning resulted in timely recognition of possible difficulties which enabled corrective measures to be planned and implemented, preserving the critical operating features; provided technology input to industrial fabricators; and identified areas in which additional interactions would be beneficial in future similar procurements.

Resolution of these problems required expenditure of tremendous amounts of engineering and construction resources before they were corrected. Although the problems which arose were unique to each type of equipment, some of the activities undertaken to solve these problems are not unique. The comments listed below indicate specific areas derived from these procurements which can be applied in a generic sense to all high technology or special item procurements.

1. Design reviews should be held at defined critical design points involving all pertinent disciplines as an effective tool to minimize later difficulties. A matrix check of design requirements and the method of verification for those requirements before release for fabrication is especially useful. This approach could point out a need for additional or different tests to verify the key design parameters of a component.

2. A pre-award conference with the vendor to ensure complete understanding of the specified requirements and clear identification of personnel and physical resources necessary to carry out the procurements would also be extremely important elements to consider.

3. In the case of procurement to performance specifications, in which vendors provide designs for fabrication, a final design review at the vendor's site would be extremely beneficial. Key design points can be reviewed along with manufacturing plans, test plans, and other key procedures. Depending upon the vendor's organizational structure, it is important to make sure that key fabrication personnel are included, in addition to the key design personnel.

4. In instances in which prototypes are involved, every effort must be made to allow sufficient time for thorough testing of these units prior to authorization to proceed with production unit fabrication. Modifications made at this point have much less impact on project cost and schedule.

5. Probably the most important point of all, though, is that time and materials must be included in up-front project planning to allow for more extensive on-site vendor inspection. Not only must the funds be identified for this effort, but more importantly, key qualified people must be identified who will be available to the project team for vendor inspections. Additional on-site inspections would have done more to accelerate the successful project completion of LCTF than any other activity.

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