Fermilab

Fermi National Accelerator Laboratory
Technical Division / SRF Department
P.O. Box 500
Mail Stop 316
Batavia, IL 60510
Phone: 630.840.3441 Fax: 630.840.8036

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LBNF Project Manager's Final Design Review – Final Report

Type of review: Final Design Review
Title of review: Cryostat #1 Steel Support Structure (Warm Structure)
Date(s) of review: August 21-22, 2017
Location of review: Sanford Underground Research Facility (SURF), Lead, SD
Report distribution: Project management, Review committee

Reviewers:

T. Nicol (Fermilab) – chair
K. Fahey (Fermilab)
M. Andrews (Fermilab)
J. Niehoff (Fermilab)
R. Rucinski (Fermilab)
T. Hart (LBNL)
D. Taylor (SURF)

Presentations by:

M. Nessi (CERN)
D. Mladenov (CERN)
O. Beltramello (CERN)
A. Catinaccio (CERN)
C. Bault (CERN)
D. Fieto (CERN)
J-C. Lopes (CERN)
L. D'Angelo (CERN)
D. Montanari (Fermilab)

Agenda:

- Cryostat project introduction, scope, milestones, strategy – Marzio Nessi
- ProtoDUNE lessons learned – Dimitar Mladenov
- Agreed design rules, testing requirements – Olga Beltramello
- Design engineering, design details – Andrea Catinaccio
- CAD models, drawings, components list – Christophe Bault
- Components logistics, manipulations, lowering – Dimitar Mladenov
- Structural analysis strategy – Andrea Catinaccio

- Structural analysis 1 – Diego Alvarez Feito
- Structural analysis 2 – Joao Carlos Batista Lopes
- Steel plates strategy and structural analysis – Luca D'Angelo
- Structural tests – Dimitar Mladenov, Joao Carlos Batista Lopes
- Access requirement during all phases – Olga Beltramello
- Answer to referees received questions – Marzio Nessi
- Cavern Initial Requirements Prior Installation – Marzio Nessi
- Installation sequence – Christophe Bault, Dimitar Mladenov
- Installation tools – Dimitar Mladenov
- Cryo mezzanine design and requirements – David Montanari, Dimitar Mladenov
- Engineering remaining activities – Andrea Catinaccio
- Open issues detector vs. cryostat – M. Nessi

Executive Summary:

A final design review of the warm structure for the first liquid argon cryostat to house the Deep Underground Neutrino Experiment (DUNE) detector was held at the Sanford Underground Research Facility (SURF) in Lead, SD on August 21-22, 2017. Although presentation material covered other parts of the cryostat and detector assemblies, the focus of this review was the warm structure, i.e. the framework inside of which all the remaining components of the detector reside. It was clear from the outset of the review that a significant design effort has been undertaken by many engineering professionals at CERN in arriving at a design well-suited to the requirements of the detector and the collaboration. The presentations and material presented show that the design complies with the design rules and will meet its function as the structural support for the membrane cryostat and the load of the DUNE detector. The committee was impressed not just by the presence of so many from CERN actively involved in the design, but by the thorough way each piece of the design was addressed, the candor in explaining the design and answering questions, and in conveying how important this project is to the ultimate success of DUNE. We were especially impressed by the explanation and verification of analysis results, most of the time by at least two independent schemes, and sometimes three. We would like to extend our thanks to all those who came together to make the review a success. As detailed in the responses to the charge questions below, we feel that, for the most part, the design is ready to enter the procurement process. Ongoing work needs to be completed to resolve some access and egress issues and an agreement needs to be struck between all interested parties on how to resolve the pressure test issue.

What follows are the detailed charge and its responses, a list of findings and recommendations in no particular order, and finally, recommendations from the review.

Charge:

The Long Baseline Neutrino Facility (LBNF) Cryostat for Detector #1 will provide the cryostat for the first of four Deep Underground Neutrino Experiment (DUNE) liquid argon time-projection chamber (TPC) modules. The cryostat is composed of two major elements: the membrane cryostat interior (cold vessel) that contains the liquid argon, and the steel support structure (warm structure) external to the membrane.

The cold primary membrane vessel is made of a stainless-steel liner that contains the cryogenic liquid and gas. This liner maintains leak tightness and is corrugated to provide strain relief due to temperature-related expansion and contraction. The insulation is composed of two layers of polyurethane foam, providing a thermal barrier between the membrane at the liquid cryogen temperature and the steel support structure at ambient temperature; a secondary barrier located between the layers of insulation is a physical protection that contains the liquid argon in case of a failure of the first membrane. The surrounding cryostat warm steel structure support consists of large vertical beams alternating with a framework of smaller structural members and a steel plate liner, also acting as vapor barrier to prevent the moisture from entering the insulation space.

The steel support structure provides support for all internal and external loads acting on the cryostat, including hydrostatic pressure, gas pressure, thermal, weight, and seismic loads. The loads from the liquid head and the gas pressure are transferred from the cold vessel stainless steel membrane vessel to the steel support structure through the insulation. The top steel frames will serve also as a support structure for the detector and the internal cryogenics.

This external, independent review is of the final design of the Cryostat #1 steel support structure, which is 18.9m wide x 17.8m high x 65.8m deep, and will be installed a mile underground at the Sanford Underground Research Facility in Lead, SD, in a to-be-excavated chamber. The design has been optimized to reduce weight and connection complexities and facilitate modular fabrication and installation. It includes the feedback from the construction of several smaller prototypes built at CERN in the last couple of years. The design has been done by CERN and documentation is provided by the engineering team for this review.

Ancillary steel structures are associated with the cryostat and are also part of this design review. Access/egress stairways and platforms are integral to the four sides of the steel support structure. An independent mezzanine, supported from the chamber roof and side walls, supports cryogenic equipment and covers part of the area above the cryostat. Platforms supported from the top cryostat steel support structure members support detector equipment and provide walkways to access that equipment as well as the mezzanine.

The review will look at the analysis and design of the steel support structure to answer these charge questions:

1. Does the design meet the functional and performance requirements?
    - ***Yes.***
2. Does the design conform to interface agreements?
    - ***Yes, transportation of components in and around the work area, the ability to handle mechanical loads, and dimensional requirements of installation in the***

cavern appear to be well understood, but some agreements on logistics for storage, above ground transportation, etc. are still works in progress. The project has plans to hire a full-time logistics professional to assist in these issues. This will be crucial to meet the November goal of defining penetrations in the warm structure roof.

3. Does the layout of the stairways, walkways, and platforms meet life safety requirements?
    - ***Not yet. Partial plans exist in the mechanical design of the steel structure, e.g. manholes, access holes, etc., but the system of ladders and walkways is incomplete.***
4. Are design, fabrication, and assembly drawings and specifications complete, or if not yet, is there a plan to complete them prior to the production readiness review (currently scheduled for Sep 2018)?
    - ***The committee was presented with examples of specifications, models, and drawings and there is a plan leading to completion by the production readiness review schedule for next year.***
5. Has the installation process been considered in the design and is it accommodated satisfactorily?
    - ***Yes, we were presented with a credible plan for assembly. This will likely be modified over time, but the potential problems and other issues seem to be well understood. There are plans for a future installation review.***
6. Will the planned destructive testing validate the finite element analysis model and structure mechanical behavior?
    - ***Yes.***
7. Are the design and the testing plan adequate to satisfy the required codes and standards?
    - ***Yes, for the steel structure, the design is adequate to satisfy the required codes. Plans for weld testing also satisfies the required codes. Testing proposed for all the various mechanical joints ensures an adequate design, but is not required by the code.***
    - ***For pressure testing, no. A membrane cryostat pressure test is required by the existing MOU and FESHM. The steel structure is part of the membrane cryostat so FESHM chapter 5031.7 "Membrane Cryostats" applies as does the Memorandum of Understanding "Design, Fabrication, Installation and Testing of LBNF/DUNE and SBND Cryostats", EDMS 1554082 v1. Both documents require a pressure test prior to filling with liquid argon. CERN takes exception to the pressure testing requirement. LBNF management and the authority having jurisdiction will need to resolve this exception or accept responsibility for pressure testing.***

Findings:

1. Main structural steel wide flange beams are made of alloy S460 M. That material has comparable mechanical characteristics to USA alloy A572 Grade 65. The steel has been

tested for ductility down to -50 C. Temperature of the warm liner will be ambient during operation.

2. Based on ProtoDUNE experience, over 4,000 crates are anticipated per LBNF cryostat.
3. ProtoDUNE had a peak of 50 workers assembling cryostats in parallel activities.
4. To accommodate the concrete floor of the chamber being slightly out-of-level, leveling pads are used to level the steel structure under the cryostat floor. Then non-shrinking grout is installed under the floor beams to distribute the load.
5. Loading of the steel structure due to gravitational forces on the liquid argon mass causes the steel beams under the floor to slightly deflect.
6. The warm structure incorporates a warm membrane that is analyzed as if it can move relative to large structure of belts. The team presented that the warm membrane panels will be attached to the I-beams with permanent clamps.
7. Design calculations of the steel structure according to EN993 – EUROCODE 3 were performed by a team of structural engineers at CERN.
8. Fermilab prepared a white paper providing evidence that structures designed per Eurocode standards EN 1990, EN 1991, EN 1993, EN 1999, and EN 14620 have a "generally equivalent level of safety" to structures designed per U.S. building codes.
9. The design calculations will be independently checked by a South Dakota licensed engineer or a subcontracted engineering firm.
10. Interface documentation was not presented. Dune docdb 464 was found by doing a search of interfaces. Dune docdb 464 contains a drawing outlining an interface agreement between the cryostat and excavated cavern on overall envelope size.
11. Construction of the warm structure utilizes two 15 ton hoists on each outer trolley rail and a center 15 ton hoist on a centered trolley rail and a bridge crane that spans between the outer trolley rails. The bridge crane covers almost the entire pit.
12. A Memorandum of Understanding "Design, Fabrication, Installation and Testing of LBNF/DUNE and SBND Cryostats", EDMS 1554082 v. 1 and FESHM chapter 5037.1 "Membrane Cryostats" require that membrane cryostats be pressure tested prior to filling.
13. Another concern is that SURF business interruption during the pressure test may not be feasible. The potential solution is to have CERN submit a variance to the Chief Safety Officer of Fermilab and have the Cryo and Mechanical Safety Subcommittees provide a recommendation to the Directorate.
14. An Interface agreement between the LBNF cryostat and DUNE detector should be developed to cover the interface of the opening and location through which the detector components will be installed.
15. An interface agreement between the LBNF cryostat and DUNE detector should be developed to cover the location of ports and support points and loading. It is noted that the 200 ton uniform load from the detector appears to be conservative and not a driver of the design.
16. Design Engineering Design Details talk slide 28 shows internal cavern to be 19800 wide x 69400 long. Interface agreement drawing in DUNE docdb 964 shows internal cavern to be 19800 wide x 18101 tall x 69641 long. There is a discrepancy in length of 241 mm.

17. The bridge crane that is supported by the outer trolley rails is unique. Most bridge cranes run on top of the rails, not under I-beams. The trolley that runs across the bridge crane might need to be supported by two bridge rails which would reduce the longitudinal coverage. The bridge crane design needs to be further developed.
18. CERN has performed a risk assessment for the pressure test of the membrane cryostats and disagrees that a pressure test should be done because the risk of a failure during the pressure test could be catastrophic. The panel asserts that the risk of a failure during a pressure test should be extremely small. The panel asserts that should a failure during the pressure test occur, that is when you want to have it, under controlled conditions prior to operation.
19. GTT is not involved in the actual design of the warm structure, but is consulted.
20. 200 metric tons is assumed for detector wet-weight. Actual thought to be a little over 150.
21. The mezzanine only connects to the wall and ceiling.
22. The cryostat sits on the floor, but isn't anchored.
23. The mezzanine is ~2.3 m above top of cryostat. No load on cryostat.
24. All components are lowered through existing shafts and drifts.
25. The structure must be accessible through all phases of the project.
26. GTT engineering will start in 2018.
27. Verification of the design will be through a SD consulting engineer on contract engineering firm.
28. Assembly will be ready to start in 2021 – underground.
29. Documentation will be given to the SD engineer by the end of this year or beginning of next.
30. As much as possible, all material is "off-the-shelf".
31. Assembly of first cryostat will take about 5 months. The second will be about half that.
32. Destructive testing will be done on the weakest parts of the structure
33. Pneumatic test to 1.15 MAWP or 1.15 x 350 mbar.
34. Filling will take place in incremental steps.
35. Pressure testing for ProtoDUNE is the same procedure as is planned here.
36. The outer structure will be instrumented with strain gauges during the incremental filling with feedback to the filling process.
37. The internal pressure during filling can go to 350 mbar.
38. The approximate cage dimensions are 3.77 m x 1.42 m x 2.13 m (LxWxH).
39. Even though there are design differences between the final design and ProtoDUNE, the design philosophy is thought to be essentially the same.
40. Need to do weld samples of the outer membrane to see if there's a problem with their being welded to the beam member behind the joint.
41. Welding is MIG.
42. Need to lower 1800 components underground.
43. Gas pressure above liquid will range from 130 mbar to 350 mbar (relief pressure).
44. Actual seismic loading will be less that that assumed due to the fact that the detector is underground.

45. CERN performed a response spectrum seismic analysis of the structure using a spectrum developed from USGS data. A time history analysis was considered but was deemed unnecessary given the magnitude of the seismic loading.
46. Sway is basically a measure of the non-verticality of the structure due mostly to imperfections in the built-up sections.
47. The maximum sidewall displacement is something like 40 mm.
48. The structure itself is basically symmetric, but due to things like sway, it becomes not perfectly symmetric.
49. CERN does not anticipate that there will be any differential thermal expansion between the steel structure and the warm membrane. The warm membrane's insulation was designed to thermally isolate the two systems.
50. EPDM is an elastomer similar to that used under the ProtoDUNE cryostat.
51. There will be welds subjected to plastic deformation, especially at the warm membrane to rib connections. Thus, the weld electrodes will need to be able to achieve ductility without premature fracture.
52. CERN is working with their steel fabricator on welding procedure specifications. The current plan is to use Bohler Ti 52 T-FD weld electrodes, which is equivalent to E71-T1 electrodes that have the necessary properties to achieve ductile behavior.
53. The beams that form the belts around the steel structure have fixed connections at select locations and pinned connections everywhere else. Pinned connections are to be used where possible to ease manufacturing and erection. The location of the transition from fixed to pinned connections was determined to optimize deflections.
54. Testing of joints will be done to 125% of the ULS load.
55. Yield strength of stiffener material is 440 MPa.
56. Spacing of horizontal stiffeners is 400 mm at the bottom, but it increases at several places from bottom to top – increases as you go up.
57. The contract for testing and buying the material are issued.
58. The University of Coimbra is expert is this kind of testing.
59. The M48 bolts are all special.
60. There are 22000 bolts per cryostat.
61. Not all the access holes required for access are included in the mechanical models. Mechanical models will need to be updated as the access models develop.
62. The entire beam structure – side walls, end walls, floor and ceiling are completed (except for the access hole) before the warm membrane is installed.
63. A series of two side monorails, one central rail, and one bridge crane with hoists are used to install the warm membrane and other inner parts.
64. Concrete is poured after the floor is completed and leveled with the leveling bolts.
65. The entire skeleton is completed using only bolted joints, i.e. no welding.
66. Helium is introduced between the insulation and primary membrane at a slightly positive pressure for leak checking the primary membrane.
67. Holes are provided in pieces like the warm membrane to accommodate lifting fixtures.
68. All tools will be provided by CERN, including lifting fixtures.
69. Some pieces may need rollers on the ends to prevent banging against the walls. This will be determined on a case-by-case basis.

70. All items will be transportable down the Ross shaft.
71. The detailed installation sequence being worked out.
72. Anchor bolts in the roof support the mezzanine.
73. Live loads and construction loads are not currently being included in the design of the mezzanine. CERN does not believe these loads are significant compared to the weight of the equipment.
74. Requirements for pipes and valves from the mezzanine to the cryostat are defined.
75. The mezzanine is connected by eight vertical bars to the roof and eight connections to the wall.
76. Total weight of the platform is about 50 tons.
77. The total weight with all the equipment on the mezzanine is 183 tons.
78. The bridge crane is used for all cryostats so it is removed prior to installation of the mezzanine.
79. The lifting fixtures to be used for the crane will be tested at CERN to 1.5 times their rated capacity.
80. The headroom between the cryostat and mezzanine is 2.3 m.
81. Complete 3D models with further details on member fixation brackets, floor jacks, penetrations on the roof and rib local modifications are being developed.
82. Verification (with GTT) of the assumptions concerning the interaction between the insulation and the warm membrane, in terms uniformly distributed load and load transfer is being performed.
83. Stability analysis of intermediate installation steps (from installation company procedure) is being performed.
84. Interpretation of tests and FEA correlation of full scale testing of connections with the Coimbra Civil Engineering Test Lab will be performed.
85. Analysis of prototype testing of the membrane panels reinforced with ribs (including welding of panels together) will be completed.
86. Analysis of prototype testing of support brackets for reinforced membrane will be completed.
87. CAD models, loading details, and specifications will be provided to the South Dakota firm for independent cross check and final validation.
88. Support from the CERN-NP team will be needed for providing specifications to the construction company, for required manufacturing tolerances, and for surface preparation (friction locking connection).
89. Support the CERN-NP team will be needed in the validation of design and calculations to be supplied by the construction company and of quality control plans.
90. Detector feed-throughs and electronics are not fully defined, even for the first single phase detector.
91. The support system and electronics will evolve over time.
92. Waiting for the collaboration to converge on a final concept makes planning cryostat penetrations difficult.
93. The installation procedure of the detector might also influence the cryostat layout, especially the four LAr pumps.
94. The plan is to keep 200 tons of weight on the roof of the cryostat.

95. 216 detector penetrations and 43 cryogenics penetrations for a total of 259 penetrations.
96. It is not clear the where the limit of responsibilities between the cryostat, CF, and DUNE are for all resources related to the penetrations.
97. They need to have baseline interfaces in November to complete engineering on the cold vessel.
98. The hydrostatic head is 14 m x 1400 kg/m2 = 196 kN/m2 = 28.5 psi
99. 350 mbar is 5.1 psi so the total pressure at the bottom is 33.6 psi.

Comments:

1. Contractor incentives should be discussed and arranged such that fire loads related to shipping crates is minimized underground.
2. Personnel plans for assembly should continue to be developed and communicated to SURF for planning maximum underground headcounts.
3. Loading of the concrete floor due to steel beam deflection under load should be reviewed with Conventional Facilities.
4. Other means of procuring the M48 fasteners should be exhausted before special ordering custom bolts. Alternatively, the design of the bolts can be reviewed, factoring in the fabrication tolerances for standard M48 fasteners, to see if standard M48 bolts would still be adequate.

Recommendations:

1. Resolve the penetration issues between the top of the cryostat, detector, and cryogenic equipment before November.
2. LBNF management and the authority having jurisdiction will need to resolve the disagreement that CERN has to performing a pressure test prior to operations.
3. Prior to procuring and manufacturing the warm vessel, the egress ports, ladders, handrails, guardrails, and toe boards to and from the bottom of floor of the cavern should be finalized. This includes appropriate trap door access, ladder access, railings, signage, lighting, and additional handrails, guardrails, and toe boards at intermediate levels of the warm vessel. This design also includes a means to extract an injured worker. This design should be reviewed and approved by the LBNF ES&H Manager.
4. Verify that the base of the structure can adequately support the structure's weight, including the leveling legs, the concrete floor, and the grout placed below the steel beams.
5. Verify that the welding specifications call for weld electrodes that have ductility properties, for example low hydrogen content and Charpy V-notch toughness.