

Cost Benefits of Centrifugally Cast 316L SS Used in the Continuous Electron Beam Accelerator at Thomas Jefferson National Laboratory Newport News, VA, USA



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1. Abstract:

In mid-2007, Spunecast, Inc. was contacted by the **Thomas Jefferson National Accelerator Facility** (TJNAF), Newport News, Virginia, USA to participate in a cost-reduction effort specific to the C100 Helium Vessels. The helium vessels are part of the electron path of the accelerator. The original design of the vessels used titanium as the primary material of construction. Additionally, there were welded joints between the niobium sections and titanium portions of the assembly. If some of the titanium sections could be replaced with ASME SA351 Grade CF3M (cast 316L stainless steel), significant cost savings could be realized.

The part chosen was a section of the C100 cryomodule's **Helium Vessel Head**. To prove out the feasibility of this conversion, numerous criteria needed to be met. First, the part was required to be

completely leak-tight with liquid helium on one side and a vacuum of 10^{-9} torr on the other. In the presence of liquid He (temperature of 2°K) the material needed to exhibit sufficient strength and ductility to support 5 atm of internal pressure and 2 atm of external pressure. Fabricability had to allow for a niobium to SS transition.

The testing was done at the Jefferson test facility on their HTB (**Horizontal Test Bed** – a facility for testing up to two cavities with cryomodule boundary conditions). Validation was determined by thermal shock, thermal cycling, pressure testing and actual function testing. In all cases, the centrifugally cast member passed with ease.

While Spuncast continues to supply this part for TJNAF, it is interesting to surmise what could be possible utilizing the economy of the centrifugal casting process in stringent soundness applications, most notably, a wide variety of vacuum applications.

2. Background

Thomas Jefferson National Accelerator Facility, commonly known as Jefferson Lab (or JLAB), was founded in 1984. Its missions are stated “To provide forefront scientific facilities, opportunities and leadership essential for discovering the fundamental structure of nuclear matter; to partner in industry to apply its advanced technology; and to serve the nation and its communities through education and public outreach.”^[1] Since its inception, it has been one of the premier U.S. research facilities through the **Continuous Electron Beam Accelerator Facility**. (It was known as CEBAF until 1996. The acronym was officially discontinued at that time due to expansion of the facility into other areas. It is still commonly used in reference to the main accelerator.)

The CEBAF is used virtually daily by international universities and scientific organizations to conduct basic research into the sub-atomic world of nuclear physics. In the simplest of terms, the accelerator fires an electron beam into the track of the accelerator which in turn, increases its energy from an initial 500KeV to 6GeV.^[2] These high energy electrons are directed at a wide variety of targets. Targets range from pure metals and alloys to organic solids and to pure elements, such as liquid hydrogen. The particles that are emitted from the collision of the electrons and the target are collected, magnified and analyzed. As such, the accelerator acts as a sub-atomic microscope.^[3] The basic purpose is to study the building blocks of protons and neutrons and the “stuff” that holds matter together, respectively quarks and gluons.

The CEBAF configuration is similar to the racetrack of CERN in Switzerland or Fermilab in Illinois, USA in that the beam is accelerated about a round or oval track. It consists of a pair of **linear accelerators** that utilize **superconducting RF (SCRF)** technology that was designed at JLAB specifically for the CEBAF. The race track is 1400 meters in length.^[4] The beam travels around the track, being turned by powerful magnets and being accelerated in each of the straightaways, passing through the two LINACs (Linear Accelerators). After five passes around the track, the beam is now at 99.9999% of the speed of light and an energy of 6GeV.^[5]

The SCRF technology uses pure niobium cells cooled to 2°K using liquid He to achieve superconductivity. These cells are coupled together to comprise a cavity. (Fig.1)^[6] Internal to the cavity, a vacuum of 10^{-9} torr is required for beam travel. The cavity is then enclosed in a pressure-tight fabrication as shown in Fig. 2.^[7] This pressure-tight structure, or helium vessel, contains liquid helium

around the cavity. Both the cavity and helium vessel are housed inside another vessel which provides an insulating vacuum of 10^{-7} torr. The purpose of the liquid helium is to make the niobium superconducting and much of the design of the entire structure is to minimize the heat load on the helium bath.

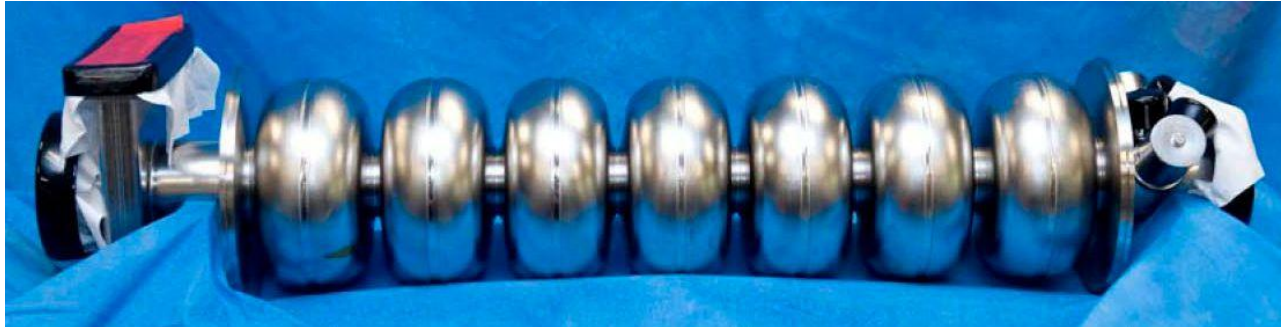


Fig. 1 A 7-cell cavity for He Vessel.

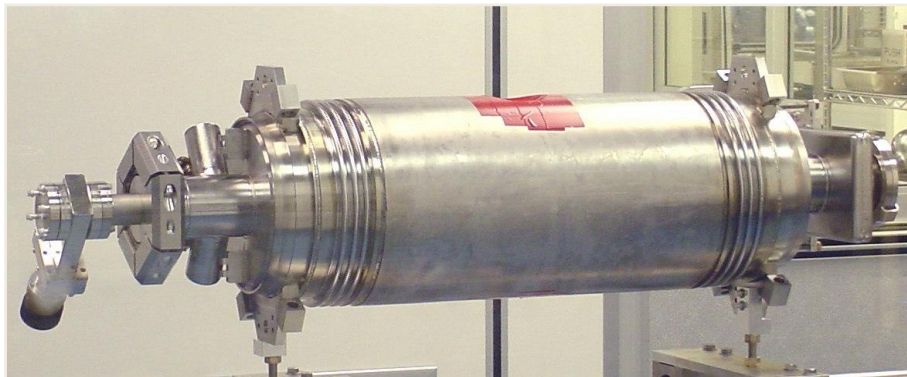


Fig. 2 He vessel fabrication used to contain the cavity and the surrounding liquid.

The current CEBAF configuration has two LINACs comprised of twenty cryomodules each. This configuration can generate an electron beam exit energy of 6GeV. The new upgrade will add five cryomodules per side, which will boost the exit energy to 12GeV. The new configuration is shown in Fig. 3. [8]

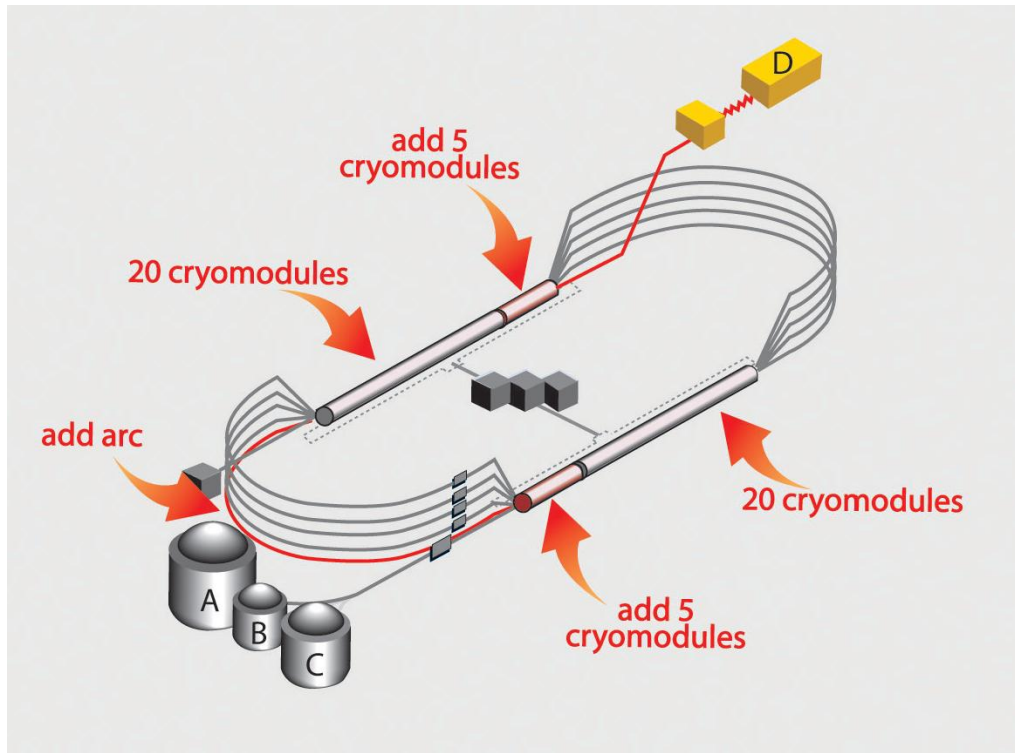


Fig. 3 Schematic of the CEBAF at JLAB showing the 12GeV upgrade currently under construction.
Note the new addition of Hall D designed for 12GeV experiments.

3. The 12GeV Upgrade Design Improvements

As JLAB began to look at design options for the 12GeV upgrade, they started to look at a wide variety of processes that would allow for cost reductions without any sacrifice in quality or functionality.

In the original upgrade design, the helium vessel heads were constructed from titanium metal spinnings. In the initial design phase, it was believed that the strength and thermal properties of Ti were necessary for the application and that wrought material was necessary for vacuum soundness. This original design has, in fact, worked extremely well without any service issues.

Some of the Project Design Engineers at JLAB were familiar with the centrifugal casting process from prior government and US defense projects. It was the belief of these engineers that centrifugals could afford the essential properties and more importantly the essential soundness for the helium vessel heads. In July 2007, Spuncast, Inc. was contacted by JLAB engineers to submit a proposal to produce the vessel heads out of cast 316L. Spuncast initially quoted to ASTM A351 Grade CF3M. Samples were provided for JLAB for testing.

4. Requirements for Vessel Head

The original titanium vessel heads were designed with a number of criteria that needed to be met by the new stainless steel heads:

- They are required to maintain a cavity alignment such that fabrication/assembly dimensional stability would not violate a maximum of $\pm 0.020''$ tolerance stack-up.
- They must provide a suitable metallurgical platform for a brazed transition from the Niobium beam-line cells to the stainless steel Helium circuit.
- They must allow the transmission of up to 820 lbf tuning force.
- Support an internal pressure of 5 atm (@ 2 °K)
- Support an external pressure of 2 atm (@ 2°K)
- Maintain consistent cavity processing techniques so that established processing could continue as previously proven.

To prove out the properties of the stainless steel heads, design verification parameters were set up. A Horizontal Test Bed (HTB), as shown in Fig. 4_[9], was designed and built so that the above criteria could be measured and tests could be accurately repeated. Fixturing was also designed so that alignment could be determined and distortion could be measured.

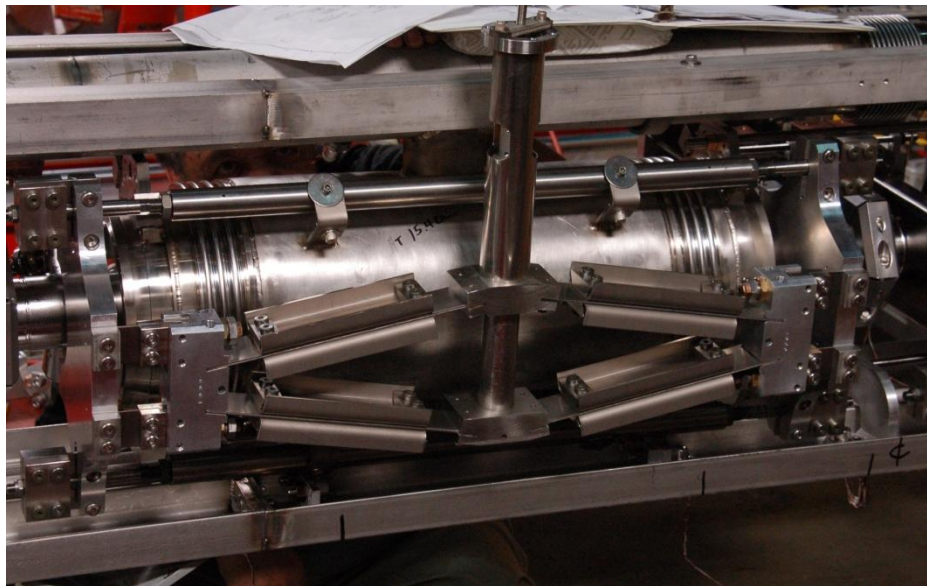


Fig. 4 HTB showing the apparatus for tuning and measuring tuning force.

5. CF3M (316L Stainless Steel) Sample Validation[10]

- 5.1 The revised helium vessel design was validated by thermal shocking a sample fabrication and He-leak testing the SST/Nb braze joints. The thermal shock was done in liquid N₂. Each braze joint was cycled and tested three times. The result was that the joints were considered sound with no detectable leakage.
- 5.2 The revised helium vessel was then tested in the Vertical Test Area (VTA) at Jefferson Lab where both long term testing and rapid-turn testing can be accomplished (Fig. 5). During cold testing, the vessel was filled with and surrounded by liquid helium at a temperature of 2°K. The interior cavity was at 10⁻⁹ torr. This was cycled two times, again to check for helium leaks through the CF3M vessel head or in the transition areas. The test was successful with no leakage detected.

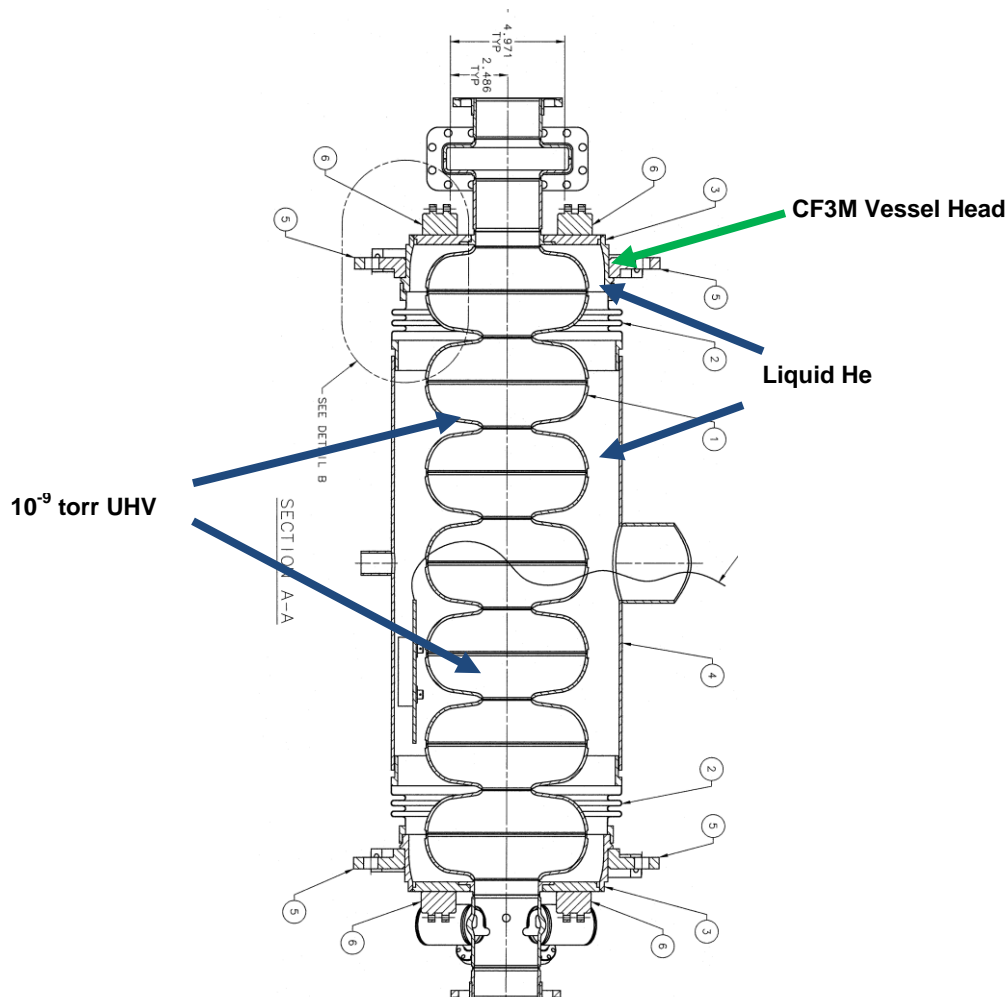


Fig. 5 Test He Vessel in the VTA

- 5.3 Tests were then run to full functionality in the Horizontal Test Bed. These were run with full vacuum in the internal cavity (10^{-9} torr) and insulating vacuum external to the cavity and helium vessel (10^{-7} torr).
- 5.4 Finally, a test fixture, Fig 6, was constructed to take the stainless steel vessel head to 110% of design pressure (82.5 psi). Again, no distortion or leakage was found.



Fig. 6 Specially designed pressure test fixture for SS vessel heads.

6. Move to Prototype Production

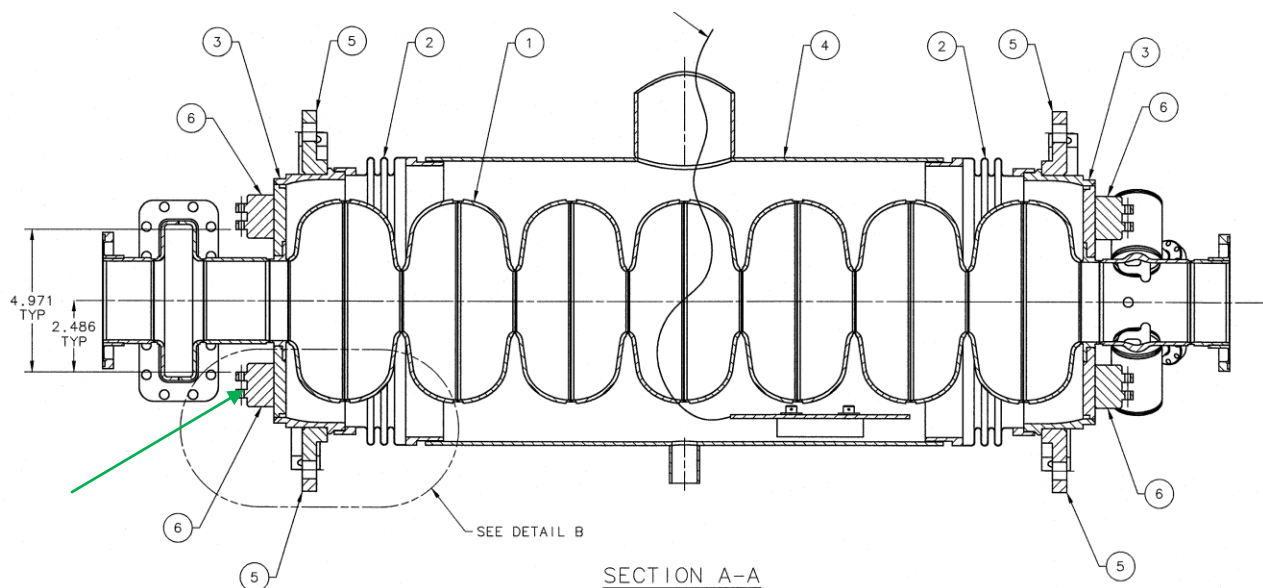


Fig. 7 Cross section of a completed C100 He Vessel with Stainless Steel Vessel Head

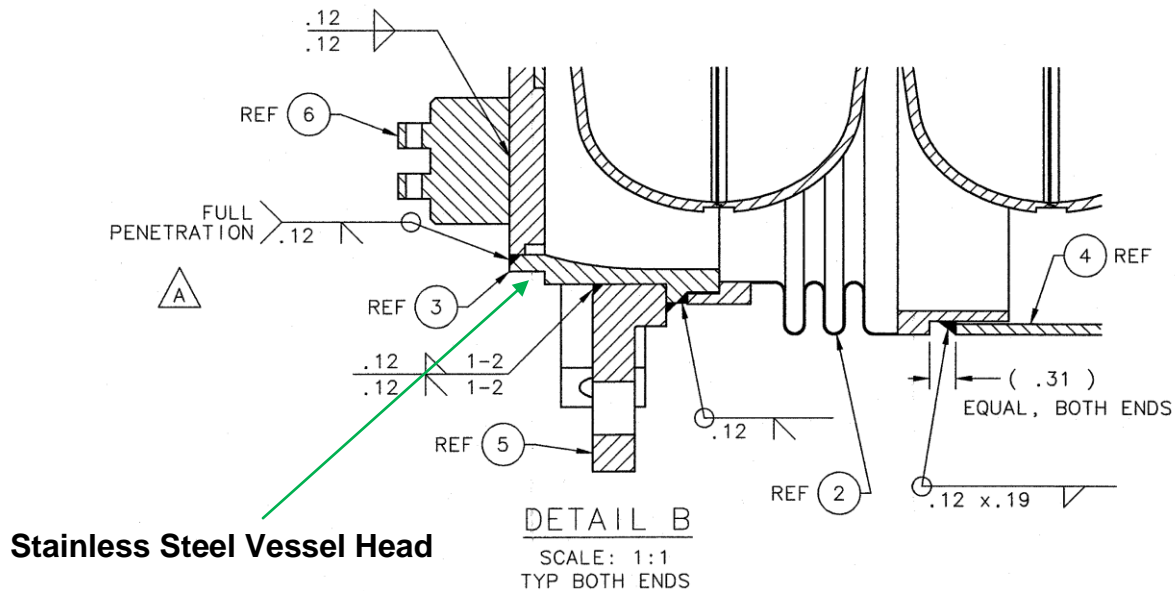


Fig. 8 Detail of vessel head in He vessel assembly

After the initial test runs, prototype parts were delivered. Inadvertently, during the first set-up, it was noted that a magnetic level was attracted to the stainless vessel head. It is not uncommon for cast austenitic stainless to have residual ferrite content such that there is some level of magnetism in the material. As there had never been a question regarding the non-magnetic or magnetic nature of the cast material, the material was cast to a standard ASME SA351 Grade CF3M. The resulting in-spec chemistry yielded a ferrite content of approximately 8 vol %. The allowance for any magnetization of the part in this specific application would be extremely detrimental to the operation, in that it could cause the niobium cavities to disipate more energy into the helium bath thus increasing the operational costs of the accelerator. Higher ferrite content can allow for this magnetization. Once this was known by the foundry, it was actually quite simple to adjust the chemistry to tailor a ferrite level to achieve the desired maximum magnetic permeability (a simple measure of ferrite content). The specification, as agreed upon, was 1.2 μ maximum as measured by a Severin gage. A revised internal specification was derived and maintained throughout the remaining production.

Parts were delivered that entirely met the desired specification. JLAB is now in the process of fabricating C100 Cryomodule #5 for the 12GeV upgrade. Thus far, all process testing has continued on successfully.

7. Cost Savings Realization

Based on the 2007 cost model used for justification, the cost differential between the Titanium forging (US\$49.50/kg) and the cast stainless steel (US\$8.87/kg) was significant. The cost savings was calculated

to be US\$2,050 per vessel head. As 80 vessels are required for the 12GeV upgrade, a total cost savings for the head conversion alone of US\$164,000 was realized.^[11]

The final view of this project from JLAB's perspective was "The potential advantages of moving to a stainless steel helium vessel are significant both for the 12GeV upgrade and future machines. This effort is to be commended and should be continued."

8. Summary

The 12GeV upgrade project holds a wealth of new opportunities for the nuclear physics community. The doubling of the electron beam's energy will allow a whole new set of experimental parameters to be utilized in the continuing search for the origins of matter. As Jefferson Lab embarked on their massive upgrade project, they needed to find new ways to construct the cryomodules that afforded cost reductions without any sacrifice in quality or functionality. The use of centrifugal castings for the helium vessel heads, while a relatively small savings in the overall project, shows the open-mindedness of the designers of the new equipment.

The success of this project brings to mind additional applications. The JLAB application is quite severe in terms of not only atmosphere, where temperature and vacuum are extreme, but also regarding the medium's molecular size. With a vacuum of 10^{-7} torr actually surrounding the outside of the CF3M vessel head and the very small molecules of the liquid helium on the inside, many engineers would worry about the use of castings. Centrifugal castings have proven exceptionally capable of functioning very well. It is very possible to surmise that centrifugal castings can be used in a wide variety of other vacuum applications where pressure tightness is critical to successful operation of the finished product.

9. References

- [1] Jefferson Laboratory Website, About page, <http://www.jlab.org/about.html>
- [2] Personal conversation with JLAB personnel; Chen, G.; Henry, J.; Matalevich, J.; Philips, L.; Wiseman, M. at JLAB, Newport News, VA, September 22, 2011
- [3] Brochure, "Exploring the Nature of Matter", Jefferson Lab, Newport News, VA, 2010
- [4] Ibid.
- [5] Personal conversation, September 22, 2011, Ibid.
- [6] Daly, Ed, "C100 Helium Vessel", Powerpoint presentation, Jefferson Lab, February 2009
- [7] Ibid.

- [8] Hesla, Leah, "The 12-GeV upgrade of Jefferson Lab's CEBAAF accelerator", ILC Newslines, June 9, 2011
- [9] Daly, Ed, Ibid.
- [10] Ibid.
- [11] Ibid.