A GUIDELINE FOR DESIGN, ANALYSIS, AND FABRICATION OF VACUUM VESSELS FOR CRYOGENIC ACCELERATORS*

Robert C. Gentzlinger
Grumman Corporation, Space Systems Division
Bethpage, NY 11714

Kirk E. Christensen
University of California, Los Alamos National Laboratory
P.O. Box 1663, MS H821, Los Alamos, NM 87545

Abstract

This paper describes a methodology for designing, analyzing, and fabricating vacuum vessels that fulfill the unique requirements of cryogenic accelerators. Included is a design approach that allows the vessel to meet the intent of the American Society of Mechanical Engineers Boiler and Pressure Vessel Code, Section VIII, Division 1, both for negative atmospheric pressure and for positive internal pressures that could result from a cryogenic system failure. In addition to ensuring that vessels meet Code requirements for safety, this approach addresses traditional high-vacuum-technology criteria. The design procedure minimizes analysis time by using standard Code guidelines, where applicable, for shell thicknesses, joint details, and penetrations.

I. INTRODUCTION

Recent advances in accelerator technology have allowed the design of much smaller accelerators than those of the previous generation. One such advance is in the area of cryogenic operation. When an accelerator operates at cryogenic temperatures, the amount of radio-frequency (rf) power that is dissipated on the surface of the rf cavity is greatly reduced. In addition, the coefficient of thermal expansion for metals of interest decreases dramatically at these temperatures, providing a significantly more stable structure from the point of view of thermal distortion. When an accelerator is to be operated cryogenically, it must be enclosed in a vacuum envelope, which provides the environment necessary for beam operations. Typically, such vacuum vessels are relatively large (on the order of four times the diameter of the accelerator) to provide space for physical access to the accelerator and for associated equipment, such as diagnostics and cryogenic manifolding. Vacuum vessels for state-of-the-art accelerators usually require numerous penetrations and openings; these are used for assembly, testing, and attaching peripheral equipment. Attempting to meet this diverse set of requirements can be very challenging. We have developed an approach that can reduce the time required to design, analyze, and fabricate vacuum vessels for cryogenic accelerators.

II. STRUCTURAL ANALYSIS

Past experience has shown that in designing a vacuum vessel, the analysis required to assure the safety and proper function of the vessel can be very time consuming. Numerical methods, such as finite element analysis, are usually used because the complexity of the design typically precludes the application of closed-form analytic approaches. These analyses can be very time consuming because of the large physical size of the vessels and because their many smaller features can be accurately simulated only be large numerical models. In addition, the application of external pressure to the vessel requires consideration of the non-linear buckling phenomenon, which is the predominant kind of failure caused by external pressure.

Our systematic approach is described below. In addition to greatly reducing the analysis time needed in the design phase, this approach has also made it easier to obtain approvals from the Laboratory's Pressure Vessel Review Committee for installing and using our vacuum vessels.

III. DESIGN METHODOLOGY

The basic design approach uses the ASME Boiler and Pressure Vessel Code, Section VIII, Division 1 (Code) as a guideline. Because vessels that function at atmospheric pressure do not technically fit within the scope of the Code, and because the Laboratory is not required by any jurisdictional authority to design according to the Code, we attempt to make our design meet the intent of the Code.

*Work support and funded by the US Department of Defense, Army Strategic Defense Command, under the auspices of the US Department of Energy.

0-7803-0135-8/91$01.00 ©IEEE

The first step is to choose a nominal wall thickness using the procedure outlined in Paragraph UG-29 of the Code. This is a good starting point, because it can be shown that if the thickness of the vessel wall is made to be 1.5 times the required thickness, then all openings in the vessel (that fall within the limits of the Code as to size, shape, and spacing) will be integrally reinforced without the addition of reinforcement rings.

The next step is to add nozzles to the main vessel. Their wall thickness can be determined in the same way as for the vessel walls. As a matter of practice, it usually turns out that the thickness of the nozzles will be governed by welding requirements instead of by external pressure requirements. This is because the nozzles are by definition smaller in diameter than the main vessel and therefore need significantly less wall thickness. For this reason, the wall thickness chosen is usually the one that will provide the best match for welding the nozzle to the vessel wall.

Next, the vessel wall must be checked for penetration reinforcement according to the "area replacement rule" described in Paragraph UG-37. As mentioned above, most of the penetrations should already be adequately reinforced if the main vessel wall thickness is made to be 1.5 times the Code-required thickness. But those falling outside the bounds of the Code guidelines need to be examined and have external reinforcement added. For some vessels, such as that used for the Ground Test Accelerator (GTA) Drift-Tube Linear Accelerator (DTL) shown in Figure 1, a very large opening is required for installation of the accelerator modules in the vessel. This rectangular opening runs essentially the entire length of the vessel. This opening is far outside the limits set by the Code and must be handled differently. In this case, we added removable compression struts (Fig. 2) at the opening, which complete the load path around the skin of the vessel.

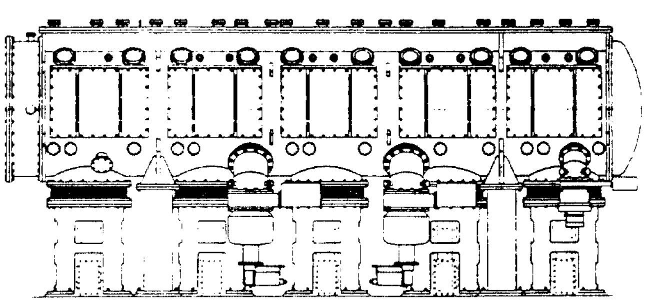

Fig. 1 - GTA DTL Vacuum Vessel

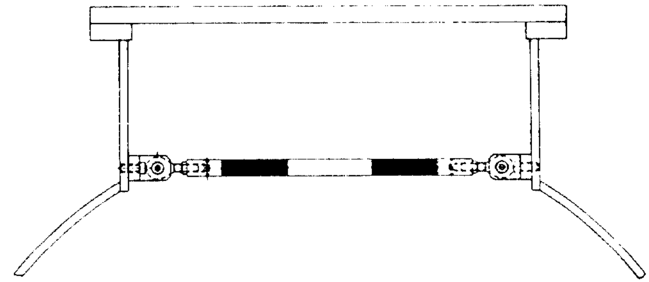

Fig. 2 - Rectangular Opening With Removeable Compression Struts

Flanges must then be added to the vessel and the nozzles. The typical flanges used for vacuum vessels are flat-faced, with metal-to-metal contact outside the bolt circle, (because self-energizing elastomeric O-rings are used for sealing as opposed to the compression type used for raised-face flanges). The size specifications for these flanges can be based on Appendix Y of the Code. Appendix Y flanges are usually much thinner than Appendix 2 (raised-face) flanges for the same pressure, because the large moments caused by raised-face flanges are eliminated. The calculations in Appendix Y can be tedious to perform, but can be simplified by the use of a spreadsheet-type program on a personal computer. Again, it usually turns out that the final thickness will be driven by manufacturing considerations.

Welds must now be designed for attaching the flanges to the vessel and to the nozzles, and for attaching the nozzles to the vessel wall. The Code (Appendix Y and Paragraph UW-13) provides detailed guidance on weld size, taking into account the interaction between shells, nozzles, and flanges. We have found it much quicker to use these guidelines than try to perform a detailed stress analysis of these complex regions. But some sound engineering judgment must also be applied. The Code bases weld sizes on the wall thickness actually being used, which can produce welds much larger than typically used for vacuum vessels. We usually base the size instead on the required wall thickness.

One weld of particular interest is shown in Figure 3. This is the weld used to attach the end flange to the vessel wall. Here we use a full penetration weld, welded from both inside and out. It is often pointed out that this appears to violate the standard high-vacuum practice of skip-welding on the outside. We have found though, that our method, which satisfies Code requirements, produces a satisfactory weld, free from virtual leaks. But care must be taken to assure full penetration at the root pass of the weld to eliminate any trapped gas pockets.

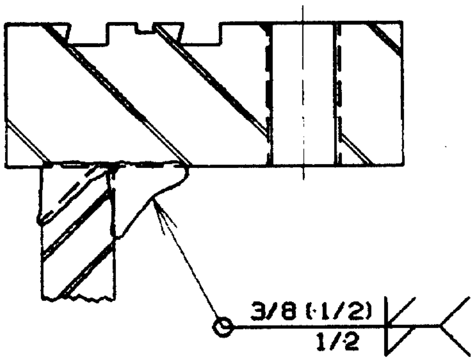

Fig. 3 - Typical Flange-to-Nozzle Configuration Weld

Finally, pressure-relief devices are added to protect against accidental internal pressurization, which could be caused by the rupture of the internal manifolding carrying the cryogenic coolant. The set point should be set low enough to ensure that satisfaction of external pressure requirements still governs the vessel design. Also, there should be redundant relief devices, each with sufficient capacity to vent the largest conceivable coolant leak.

IV. CONCLUSION

The design approach described in this paper has recently been used on three large vacuum vessels. It has proven to be quite successful in meeting the objectives of reducing analysis time, streamlining the approval process, and producing a design that is practical to fabricate.