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HFIR COLD NEUTRON SOURCE MODERATOR VESSEL DESIGN ANALYSIS

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DISCLAIMER

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ABSTRACT

A cold neutron source capsule made of aluminum alloy is to be installed and located at the tip of one of the neutron beam tubes of the High Flux Isotope Reactor. Cold hydrogen liquid of temperature approximately 20 degree Kelvin and 15 bars pressure is designed to flow through the aluminum capsule that serves to chill and to moderate the incoming neutrons produced from the reactor core. The cold and low energy neutrons thus produced will be used as cold neutron sources for the diffraction experiments. The structural design calculation for the aluminum capsule is reported in this paper.

1. INTRODUCTION

A cold neutron source aluminum capsule is to be installed and located at the tip of one of the neutron beam tubes of the High Flux Isotope Reactor. Cold hydrogen liquid of temperature approximately 20 degree Kelvin is designed to flow through the aluminum capsule that serves to chill and to moderate the incoming neutrons produced from the reactor core. The cold and low energy neutrons thus produced may be used as sources for the neutron diffraction experiments. The moderator capsule is designed by the computer-aided design code I-DEAS and the stress distribution of the model is obtained by the finite element code ABAQUS. The moderator capsule is made of 6061-T6 aluminum alloy and is approximately modeled by linear shell elements. The design pressure is 19 bars that corresponds to the rupture disk pressure of the moderator structure. The design follows the ASME BPV Code Section 3, Division 1 guide line that permits the use of design by analysis. The allowable primary stress is 13.5 ksi as recommended by Code Case N-519 with low temperature provision down to as low as 4 degrees Kelvin. More elaborate description on the application of the ASME Code is stated in the following section.

2. ACCEPTANCE CRITERIA ADOPTED IN MODERATOR VESSEL DESIGN CALCULATIONS

As stated in Chapter 2 of this report, the intention is to follow ASME Boiler and Pressure Vessel Code guidelines for the moderator vessel. After some intensive sessions of discussion with ASME Code experts, it was agreed that the design allowable stresses, stress interpretation (using maximum shear criterion), and analysis procedure through finite element analysis will essentially follow Boiler and Pressure Vessel Code Section III, Division I, Class I, Code Case N-519 for aluminum 6061-T6 guidelines. The only exception is that the Code Case N-519 item (k) requires an in-service surveillance program which, for practical reasons, will not be performed.

A list of ASME Boiler and Pressure Vessel Code guidelines that are relevant to this design analysis is shown in the following, including the one that will not be satisfied by this design:

1. Moderator capsule has been classified in HFIR Technical Specifications as Safety Class 3 component (SC-3).

2. According to ASME Code, the design for SC-3 components have to follow Section III, Subsection ND. If so, then the maximum normal stress have to be used in analysis.

3. Section III, NCA-2134 (d), however, allows the analysis of SC-3 components by following higher QA class (e.g., SC-1 or SC-2) rules if needed.

4. The analysis of the moderator capsule essentially follows SC-1 design and analysis rules. SC-1 components may apply the Code Case N-519 for providing allowable aluminum tensile stresses, may use the maximum

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calculated shear stress in comparison with the allowable shear stress, and may apply NC-3200 for the method of design by analysis.

5. According to Code Case N-519, the allowable primary stress (membrane stress) for 6061-T6 aluminum alloy is 13.5 ksi and the secondary stress (bending stress) is $13.5 \times 1.5 = 20.25$ ksi. Provisions on low temperature conditions have been outlined in this code case and these values are good down to about 4K.

6. In Section III, there is no minimum thickness requirements for the structural components.

7. In Section III, for structures of dimensions less than certain specified length or size, the Code does not require the design to follow the Code requirement. The moderator capsule is a structure of small enough dimension that this would allow the vessel to be exempt from the Code. Nevertheless, the project has taken the position that the vessel will follow the Code guidelines, and the design satisfies all of the above items.

8. Code Case N-519 item (k) requires an in-service surveillance program in accordance with ASTM E 185-82. This is the only item that our present design of the moderator capsule will not meet. The in-service surveillance program will not be conducted because there is no access area where specimens could be put in the appropriate radiation field and be kept at the low 20–40K temperature. In addition, in order to get meaningful data, specimens would have to be kept cold through the removal and testing process which is also not practical.

3. SHAPE, THICKNESS, AND DIMENSION OF THE MODERATOR CAPSULE

As shown in Fig. 1, the outer surface of the model consists of a hemisphere that is continued by a circular cylindrical surface. Their dimensions are designed to fit the inner surface of a vacuum tube that is dimensioned and enclosed within the HFIR beam tube HB-4 in order to isolate the moderator unit. The inner surface of the moderator consists of a half ellipsoidal shell surface that is continued by a cylindrical surface of elliptical cross section. The outer circular cylindrical surface and the inner cylindrical surface are then cut with a slant angle at top part and at the lower part. The two cylindrical surfaces are joined and welded together. The moderator shape is shown in the stress distribution figure obtained in a later section

Hydrogen under supercritical condition is designed to flow through the moderator volume where it is used to lower the energy level of neutrons entering the moderator. Hydrogen under supercritical condition requires approximately 15 bars pressure at 20°K. Therefore, the static pressure for the moderator needs to be designed at least to sustain 15 bars. The actual design pressure is 19 bars corresponding to the rupture disk pressure. Stress distribution as a result of transient pressure surge and uneven temperature distribution should also be considered when setting the maximum design stress of the moderator.

The thicknesses of the moderator at different parts of the surface are different. It is determined iteratively by the finite element solutions so that the maximum membrane and secondary stresses follow approximately the ASME Code allowable stresses.

The preliminary thickness distribution is tabulated in the following table:

Surface	Thickness (in.)
Outer spherical cap	0.03937 (1 mm)
Outer cylindrical body	0.07874 (2 mm)
Inner elliptical cap	0.03937 (1 mm)
Inner cylindrical body	0.11811 (3 mm)
Edges	0.11811 (3 mm)
Patch thickness	0.07874 (2 mm)

The thickness of the outer cap is 1 mm and that of the outer cylinder is 2 mm. The thickness ratio is ½. As a result of the basic principles of the shell theory, this thickness ratio will

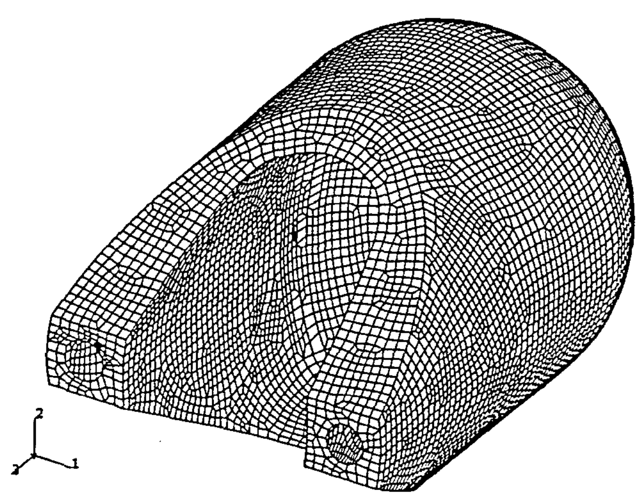

Fig. 1. Cold neutron source moderator capsule located at the tip of one of the neutron beam tubes of the High Flux Isotope Reactor. Moderator internal pressure is 19 bars. The maximum bending stress at patch area is 22.6 ksi. The maximum membrane stress at the lower part of the outer body is 9.1 ksi.

not produce the incompatible deformation across the junction of these two surfaces.

The thickness distribution in the actual fabricated model is a slight modification of the values that are listed in the above table. In order to gain more stiffness for both the inner and the outer cap of only 1 mm thick, the actual fabrication of the moderator allows both caps to be joined smoothly to attach the cylindrical surfaces that are 3 mm and 2 mm thick, respectively.

The thickness variations for the two caps follow the following analytical expressions:

1. The inner cap thickness t in mm follows:

$$t = 3 - 2\left(\frac{z-a}{b_2}\right)^2$$

$$b_2 = 1.051\ in.$$

$$a = 1.171\ in.$$

2. The outer cap thickness t in mm follows:

$$t = 2 - 1\left(\frac{z}{b_1}\right)^2$$

$$b_1 = 1.899\ in.$$

The variable z is expressed in inches and is the distance measured from the center of the outer hemispherical cap along the longitudinal direction of the moderator.

Based on the above formulas, the finite element model for either of the two caps is approximately designed as a series of circular stirps. Each strip is assumed to have constant thickness. The thickness for these strips are shown in the following table:

Strip	Inner cap thickness (in.)	Outer cap thickness (in.)
1	0.1178	0.07858
2	0.1156	0.07720
3	0.1111	0.07449
4	0.1044	0.07039
5	0.0955	0.06492
6	0.0844	0.05811
7	0.0709	0.03937
8	0.0472	N/A

The above numerical values are the realization of the analytical expressions shown earlier.

The material used for the moderator capsule is 6061-T6 aluminum alloy. The material constants used are:

- Young's modulus = 10×10^6 psi
- Poisons ratio = 0.33
- Coefficient of thermal expansion = 13.1×10^{-6}/°F.

The total mass for the moderator is approximately 378 grams and the approximate total heating is 1550 watts.

4. PRESSURE INDUCED STRESS AND THERMAL STRESS

The ABAQUS finite element is used to model the actually fabricated moderator shape. The model has a total of 10,999 nodes and 10,984 elements. Shell element is used in the model. There are three stress output points on each cross section plane of the shell element. The three ABAQUS output points for the shell structure are top shell surface, middle shell surface, and bottom shell surface. All three stress distributions were obtained. With respect to the moderator structure, section point 1 represents the outer surface, section point 2 middle surface, and section point 3 inner surface. The operating internal pressure is 15 bars but the rupture disk pressure of 19 bars is used as the design pressure. ABAQUS output of Tresca stresses for section points 1, 2, and 3 are obtained. The maximum stress at section point 1 is 22.6 ksi at the patch area and the maximum stress at section point 2 is 9.1 ksi at the lower part of the outer surface.

The stress along the middle surface of the shell is the membrane stress that is classified as the "primary stress" in the ASME Code. The code requires the allowable to be 13.5 ksi. For the moderator subjected to internal pressure, this primary stress produces the sustained loading to the structure. The output of the ABAQUS calculation shows that the maximum primary stress is approximately 9 ksi under internal pressure of 19 bars, less than the allowable of 13.5 ksi.

Both the top surface stress and the bottom surface stress are generated partly by bending deformation of the shell. These stresses according to ASME Code are classified as the secondary stress. The allowable secondary stress requirement is 1.5 s_m where s_m is the primary stress of 13.5 ksi. Therefore, the secondary stress has the allowable value of 20 ksi.

Two circular patches of 2 mm thick and 2 inches in diameter each are attached to the inner cylindrical surface at the high bending stress region. These patches produces stiffenning effect that not only lowers the local bending stress but also reduces bending stress away from the patches. The bending stress at the patch is 22 ksi. It is slightly over the ASME Code requirement for the allowable secondary stress of 20 ksi.

Owing to our CAD analysis, the stress calculation is believed to be fairly accurate. Also, it is located at the interior of the inner cylindrical surface and not located within the weldment. Furthermore, the handbook value of the yield stress is approximately 32 ksi. Therefore, the higher secondary stress is believed to still have sufficient margin of safety.

The maximum bending stress along the edge weldment much higher than the allowable secondary stress of 20 ksi. This junction, however, will be designed and fabricated by weldment. Since the weldment will be designed differently from what the finite element model can represents, the edge stress will be reduced substantially lower than the calculated value.

The maximum temperature calculated is approximately 40°K versus the average temperature of 20°K. The corresponding thermal stress calculated from ABAQUS is approximately 3 ksi. Therefore, the thermal stress is small, although this value has to be added to the pressure-induced stress. The thermal stress, according to ASME Code, is also classified as secondary stress.

5. CONCLUSION

Primary membrane stress (maximum) generated by the internal pressure of 19 bars is less than the allowable stress of 13.5 ksi .required by ASME Code. The secondary stress at locations other than the weld region is slightly greater than that required by ASME Code. However, it is considered acceptable as compared with the yield stress of 32 ksi. The thermal stress, that is also classified as secondary stress, is approximately 3 ksi. Along the edge of the weldment, the secondary stress is high and the primary membrane stress is low. Since the weldment is to be designed separately, its allowable stress will be evaluated separately.

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