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APPLICATION OF ASME BPVC SECTION VIII, DIVISION-2, DESIGN BY ANALYSIS REQUIREMENT TO FRIB STATIC BEAM DUMP*

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Abstract

The Facility for Rare Isotope Beams (FRIB) at Michigan State University is a high-power heavy-ion accelerator, and began operation in 2022. Its driver linac is designed to accelerate all stable ions to energies exceeding 200 MeV/u, with a maximum beam power of 400 kW. Currently, FRIB operates at beam powers between 10 and 20 kW, delivering multiple primary beam species. Approximately 75% of the primary beam power is absorbed by the beam dump. The existing mini-channel beam dump (MCBD) absorber is designed to handle up to 20 kW, with plans for an optimized beam dump capable of supporting 30 kW and beyond. This paper presents the design-by-analysis procedures outlined in ASME Boiler and Pressure Vessel Code [1] that have been applied to the MCBD design.

INTRODUCTION

The Facility for Rare Isotope Beams (FRIB), a major nuclear physics facility for research with fast, stopped, and reaccelerated rare isotope beams, has adopted an incremental approach toward the ultimate design beam power of 400 kW prioritizing safe operation and avoiding any possible damage to the machine. Currently, FRIB routinely delivers 10-20 kW primary beams on target and beam dump, producing rare isotopes that are separated and analyzed in the Advanced Rare Isotope Separator (ARIS) [2].

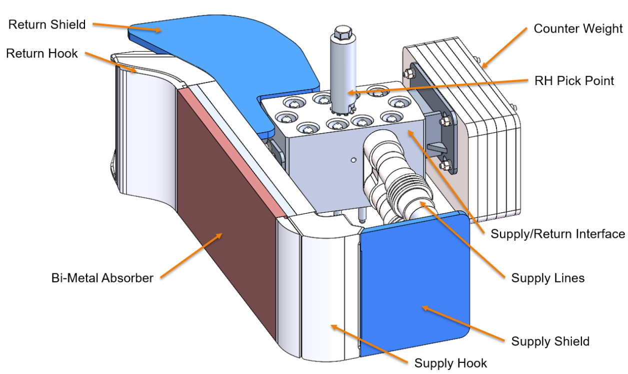

Figure 1: Details of the MCBD with key components as labelled.

The FRIB beam dump system (20kW operations) is shown in Fig 1. The primary components of the Mini-Channel Beam Dump (MCBD) consist of a C18150 copper alloy absorber plate explosion bonded to aluminum 2219 which has cooling channels. The higher thermal conductivity of the copper alloy will help to reduce the temperature increase due to beam heating. However, precautions are needed to ensure that the beam dump cooling water does not encounter the copper alloy, as copper is vulnerable to oxidation that is enhanced by chemical reactions with oxygen produced by secondary particles interacting with the water (oxidation may result in pitting of the material). Hence the cooling channels are made from aluminum alloy. The design is shown in Fig 2. This bi-metal absorber plate is welded to return and supply hooks (3D printed AlSi10Mg) that connect to the cooling water lines. An optimized version of this MCBD for 30 kW beam operation is currently being manufactured and will be installed in summer of 2025 [3]. This paper describes in brief the application of ASME BPVC Sec VIII, Div2 to the 20 kW beam dump. More detailed analysis with results can be found in the FRIB reports [4, 5]

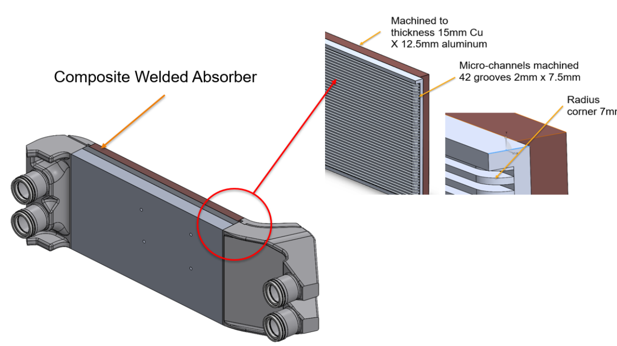

Figure 2: FRIB MCDB showing the mini channels used for cooling.

MATERIALS AND WELDS

Temperature dependent material properties are used as the input for the non-linear analysis. Material properties used for this analysis have been gathered from a mixture of in-house testing, material properties database (MPDB software) [6] and literature [7, 8]. Plasticity is modelled using a *Bilinear Isotropic Hardening* material model.

Welds are produced by the electron beam process (Al-2219 back plate to Al-2219 on the absorber plate with mini channels), and the TIG (GTAW) process for the Al-2219 to the 3D printed AlSi10Mg hooks. The welds are not modelled in the finite element model. All the weld joints are assumed bonded for the contact conditions. Our e-beam welding development and testing for AL-2219 T851 shows about 50% reduction in room temperature yield properties in the weld zone. So, the weld strength of Al 2219 has been derated by 50% in the analysis

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LOAD CASES

To explain the various load cases and the pressure zone, a cut section is shown in Fig 3. There are three volumes which encounter pressurized water:

1. The 3-D printed water supply hook
2. The Al-2219 mini-channel
3. The 3-D printed water return hook

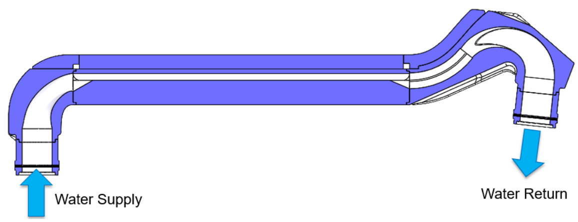

Figure 3: Cross section of the MCBD showing the water pressure volume.

The pressures in these volumes are denoted as P (65 psia). The MCBD is subjected to three basic loads. Gravity, thermal load and pressure. Gravity load is not considered in this stress analysis because the effect is negligible.

For 20 kW operations, U238 beam with σ_1 = 9.77 mm and σ_2 = 2.32 mm was identified as one of the worst-case beam loads for the C18150 absorber plate. This beam will deposit 15 kW of power in the dump. From here on this beam case loading will be referred to as the thermal load, T.

The MCBD Load cases analyzed are:

1. Beam is at the center of the absorber plate during normal operation
2. 30% decrease in thermal conductivity assumed only in a top thin layer of 0.85 mm
3. 3 water channels (in the middle) are considered as blocked
4. X direction beam offset: Max offset 72 mm
5. Y direction beam offset: Max offset 30 mm

DESIGN BY ANALYSIS

Design by analysis section of the BPVC Section VIII, Div.2: Part 5 lays down certain requirements and rules which have been followed for the numerical (FEA) analysis presented here. The analysis types are further elaborated in sections ahead.

Protection against Plastic Collapse

Section 5.2 of the code provides three alternative analysis methods for evaluating protection against plastic collapse. *Limit Load Analysis Method* (Section 5.2.3) has been used here for the analysis and results presented. Limit-load analysis addresses the failure modes of ductile rupture and the onset of gross plastic deformation (plastic collapse) of a structure.

The load case combinations and load factors are as per Table 5.4 of the code. The assessment procedure is followed as outlined in section 5.2.3.5. Elastic perfectly plastic material models have been used in ANSYS with tangent modulus set to zero. Large displacements have been turned off in ANSYS as per the code. Since this is a pass/fail criteria, the actual results like displacements and strains indicated by the solution have no physical meaning

Table 1 shows the analysis results for all the load case combinations analyzed. The FEA model solutions for all cases converged, hence meeting the criteria.

Table 1: Limit load analysis. Load case, design loads combinations and model convergence results.

Load Case	Design Load Combination	Convergence
LC1	1.3(P + T)	Yes
LC2	1.3(P + T)	Yes
LC5	1.3(P + T)	Yes
LC4	1.3(P + T)	Yes
LC5	1.3(P + T)	Yes

Protection against Local Failure

In addition to the stress-based failure criteria, ASME BPVC also considers criteria based on local strain limits, particularly those related to the triaxial state of stress. These criteria are important for assessing the ductile behavior of materials, especially in regions where stress states are complex and may lead to localized plastic deformation.

As per section 5.3.3 of The Code, the requirements are met when the combination of the limiting triaxial strain, ϵ_L, and forming strain, ϵ_{cf}, are less than the strain that occurs because of an elastic-plastic simulation at the required load factors as per table 5.5 of Code. The limiting triaxial strain is given by the equation:

$$\varepsilon_L = \varepsilon_{Lu} \,.\exp\left[-\left(\frac{\alpha_{sl}}{1+m_2}\right)\left(\frac{\sigma_1+\sigma_2+\sigma_3}{3\sigma_e} - \frac{1}{3}\right)\right]$$

σ_1, σ_2, and σ_3 are the principal stresses
σ_e is the equivalent (von Mises) stress
εLu, m_2, and αsl are material constants defined as per Table 5.7 of the code

The limiting triaxial strain is used to calculate the Strain Limit Damage Ratio (SLDR). The local failure requirements are considered met if the SLDR is less than 1. The SLDR is given by:

$$SLDR = \frac{\varepsilon_{peq}}{\varepsilon_L}$$

ε_{peq} is the plastic strain.

Table 2: Protection Against Local Failure Results

Load Case	Design Load Combination	SLDR<1
LC1	1.7(P + T)	Yes
LC2	1.7(P + T)	Yes
LC5	1.7(P + T)	Yes
LC4	1.7(P + T)	Yes
LC5	1.7(P + T)	Yes

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This ratio is calculated in ANSYS using a user defined expression in results. The SLDR calculated from ANSYS models was found to be lower than 1 for each node on the MCBD model. Results are shown in Table 2. The SLDR was calculated for all materials: C18150, Al2219, and AlSi10Mg.

Protection against Collapse from Buckling

Buckling was not identified as concern for the MCBD setup.

Protection against Collapse from Cyclic Load

To show protection against failure from cyclic loading, a fatigue screening analysis and a ratcheting assessment is needed.

Fatigue Assessment The fatigue screening analysis is performed to check if additional fatigue analysis is needed. Two methods are provided in section 5.5.2 of the code, Method A and Method B. Method A has been used here for this case. The number of cycles in Method A are limited based on the criteria provided in Table 5.9 of the code.

$$N_{\Delta FP} + N_{\Delta PO} + N_{\Delta TE} + N_{\Delta Ta} \le 1000$$

Total number of beam trips as estimated from FRIB data is around 1500-2000. Majority of the beam trips are very short duration and the change in power level and hence ΔT for beam dump absorber face would be very small. This would not count as a complete cycle as per the code but to be conservative all beam trips are assumed as complete cycle. Since the total cycles 1500>1000, per Method A, a fatigue analysis is required.

As seen from Fig 4, a total strain of 1% would cause fatigue failure at around 1500 cycles (Violet line with T = 250 °C). For the current uranium beam case presented here (normal operations) the total strain is of the order of 0.29%. with max surface temperature around 250 °C. This is lower than the 1% limit for 1500 cycles. Note that this does not include the effects of radiation damage on the material.

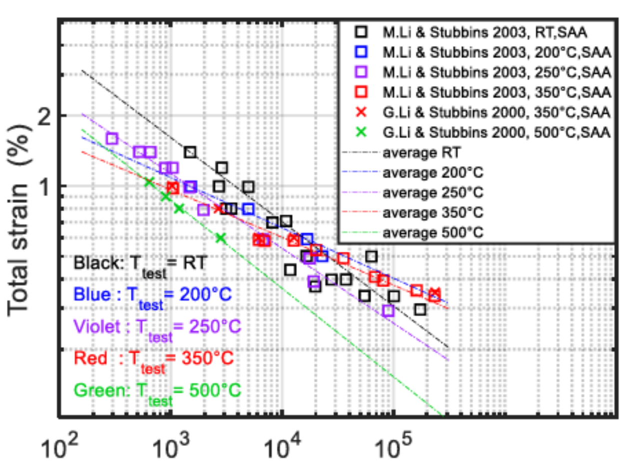

Figure 4: Total strain versus number of cycles to failure [7].

Ratcheting Assessment For MCBD, an elastic-plastic stress analysis (Part 5.5.7) was used since a model for the analysis that accurately represents the component geometry, boundary conditions, applied loads, and material properties was already developed for previous analyses.

The analysis for protection against ratcheting is performed by application, removal and re- application of the applied loadings to show that the structure eventually shakes down to elastic action, i.e., that the incremental increases in plastic deformations from each cycle are small and diminishing as the number of cycles increases. The finite element model was subjected to 7 beam load cycles as shown in Fig 5. Water pressure remains constant for the life of the beam dump. According to the code, if any one of the following conditions is met, the ratcheting criteria are satisfied

- Structure should have an elastic core
- Repeated cycles result in no change in geometry
- There is no plastic action

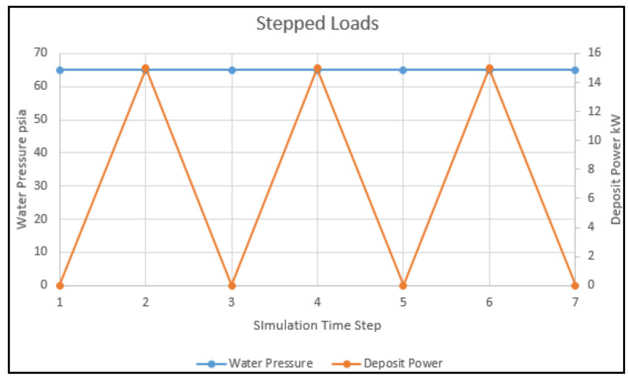

Figure 5: Load case showing constant pressure and beam power cycling.

Analysis shows that there is no change in dimension between the last and next to last cycles (load cycle 5 and 7), demonstrating convergence. This indicates that the structure passes the ratcheting assessment.

CONCLUSION

Structural analysis of the MCBD for 20kW operations shows that it meets the ASME BPVC, Section VIII, Div. 2, Part 5 by satisfying the following requirements:

Protection against plastic collapse, local failure, buckling, and cyclic loading are as follows:

1. Plastic collapse – satisfied by a limit load analysis according to 5.2.3.
2. Local failure – satisfied by an elastic plastic stress analysis performed according to 5.3.2.
3. Buckling – NA
4. Fatigue assessment – the need for a fatigue analysis is assessed according to 5.5.2.3.
5. Ratcheting assessment – satisfied by elastic plastic stress analysis as per 5.5.7

The effect of thermal creep has not been studied in detail. Ref [7] has some creep data for C18150 but concludes that additional testing is required. As we ramp up our beam power more creep related data would be valuable. E-beam testing of this beam dump has been done and more ongoing to validate our thermal analysis and assumptions [9].

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