Thermal and Structural Analysis of Water Cherenkov Detectors under Quintay Weather Conditions

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Abstract

This research investigates the thermomechanical behavior of water tanks employed in Cherenkov effect detectors, which must withstand severe environmental conditions, including thermal gradients and hydrostatic pressures. Using finite element analysis (FEA), the study evaluates the mechanical stresses and thermal deformations that affect the tanks structural integrity under various loads. The work also shows the simulation results from two different software tools, FreeCAD and Autodesk Inventor, to assess their suitability for analyzing these complex conditions and optimizing tank design. To increase the observatory's sensitivity, two different water tank sizes (radius and height) were considered, motivated on the HAWC configuration.

Fig1: HAWC collaboration Water Cherenkov Detectors (Up) & One of the secondary WCD (left)

Introduction

Cherenkov detectors utilize water tanks to observe high-energy particles via the Cherenkov effect. The structural integrity of these tanks is critical, as they are exposed to hydrostatic pressure, thermal gradients, and stresses induced by thermal expansion. This study employs finite element analysis (FEA) to evaluate the mechanical and thermal performance of both primary and auxiliary tanks. Using tools such as FreeCAD and Autodesk Inventor, detailed simulations were conducted to analyze stress distribution and temperature effects, providing a comprehensive understanding of tank behavior. These findings aim to optimize tank designs, ensuring durability and reliability in extreme operational conditions.

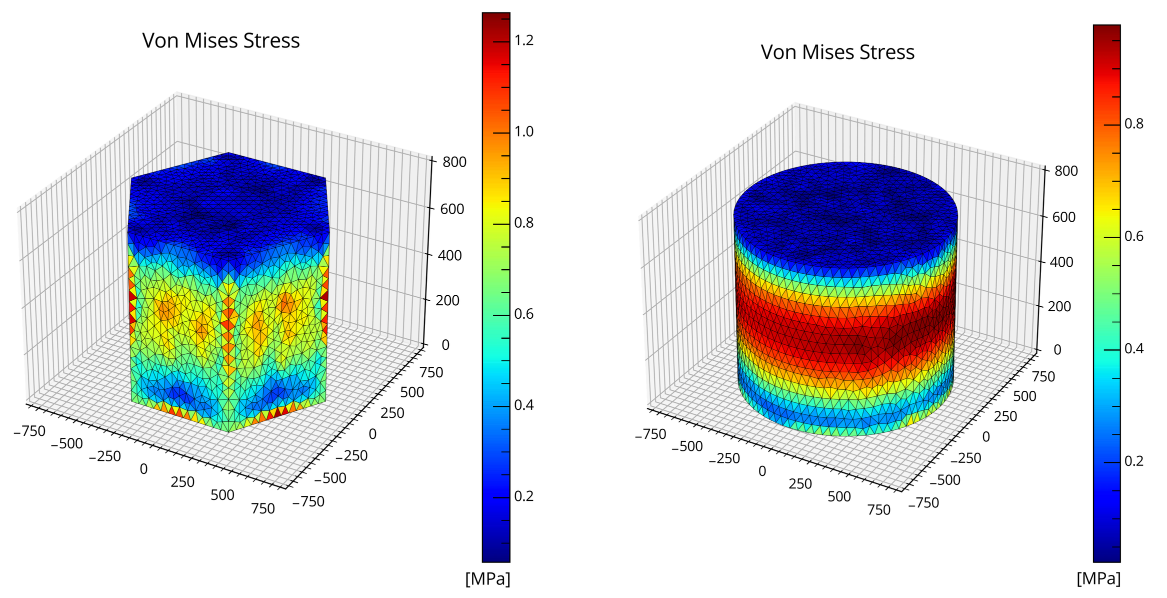
$$\sigma_{\mathrm{vM}} = \sqrt{\frac{1}{2}\left[(\sigma_x-\sigma_y)^2+(\sigma_y-\sigma_z)^2+(\sigma_z-\sigma_x)^2\right]+3(\tau_{xy}^2+\tau_{yz}^2+\tau_{zx}^2)}$$

Methodology

This study investigates the thermal and structural performance of circular and hexagonal base detector geometries, including both main and auxiliary tanks. The main tanks, made from stainless steel 304 for its cost-effectiveness, corrosion resistance, and durability, were modeled in 3D using Python for FreeCAD and analyzed under hydrostatic pressures, self-weight, and solar radiation. GMSH was used to create finite element meshes that balance precision with computational efficiency. For the auxiliary tanks, a commercially available cold-rolled steel barrel was employed, and detailed thermal and structural simulations were conducted using Nastran and Fusion. The thermal analysis examined temperature distribution and heat diffusion, while the structural simulations assessed stress distribution and material performance under internal and external pressures. This comprehensive evaluation of both main and auxiliary tanks provides critical insights into the system's ability to withstand operational stresses and temperature fluctuations, ensuring long-term reliability and efficiency in real-world conditions.

Results of the FEA (FreeCAD)

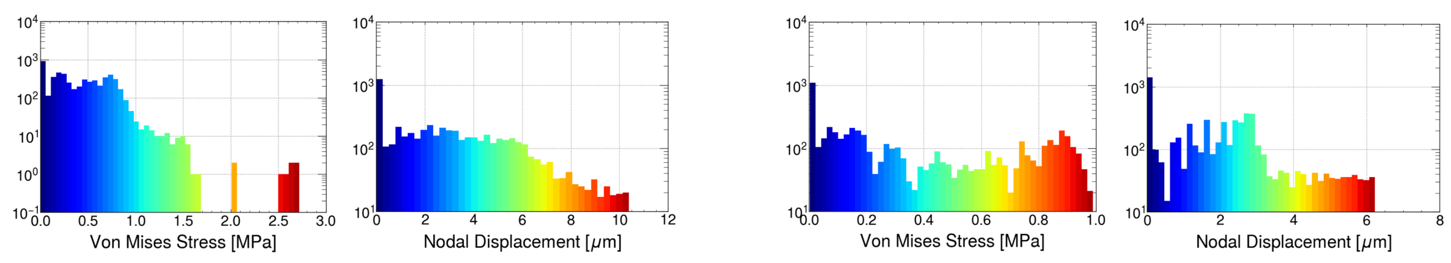
Static Results:



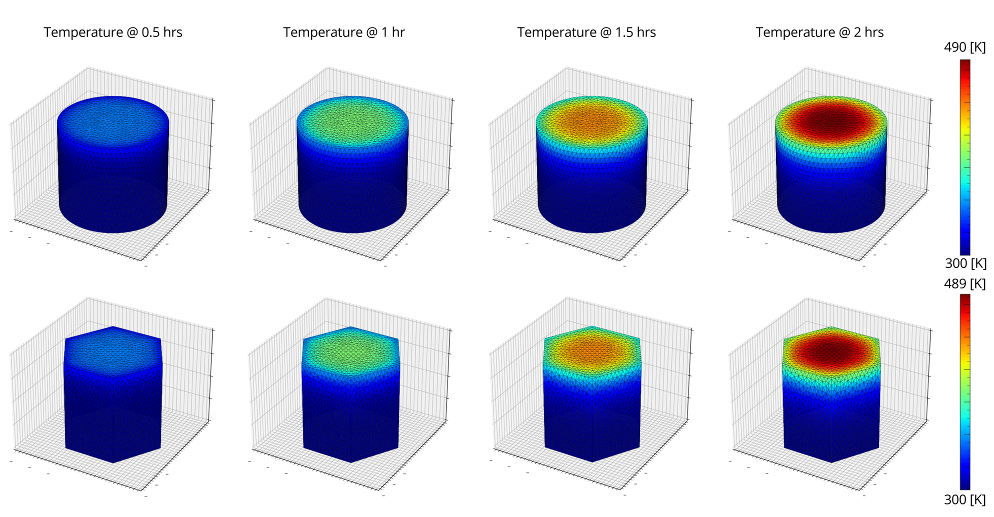
Tanks Properties:

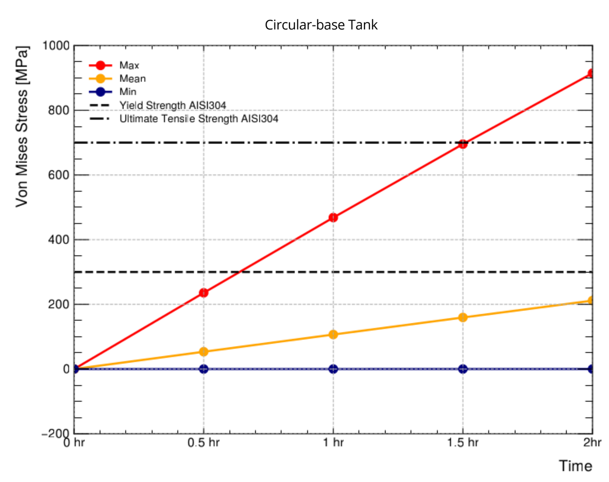
- **Width (Inner):** 1250 [mm]
- **Height (Inner):** 713.93 [mm]
- **Wall Thickness:** 5 [mm]
- **Mesh Min Element:** 10 [mm]
- **Mesh Max Element:** 50 [mm]
- **Material:** AISI304 Stainless Steel

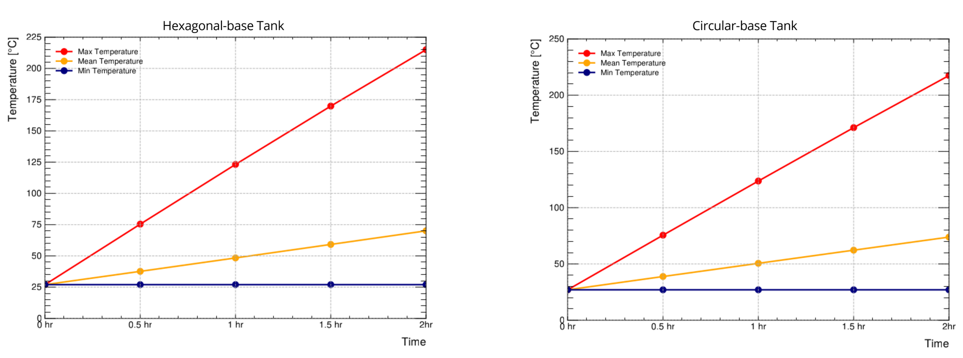
Note: The width in the hexagonal-base WCD, correspond to its maximal diameter.

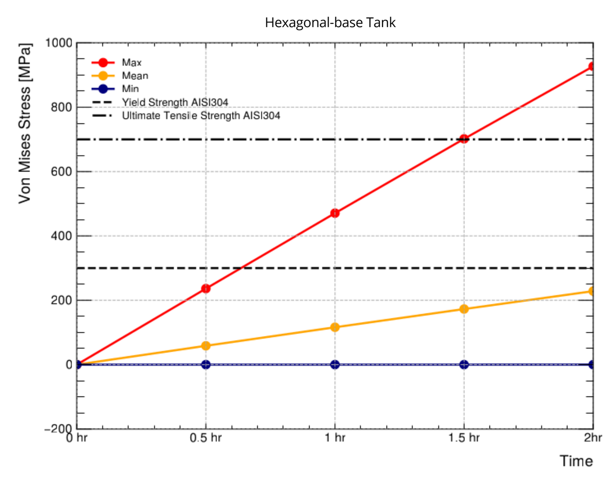


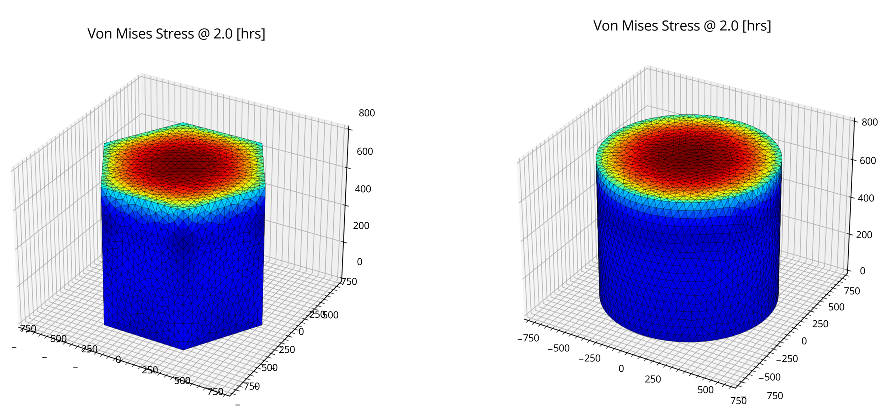
Thermomechanical Results:











Von Mises nodal distributions after 2 hours of solar radiation at the outer top face.

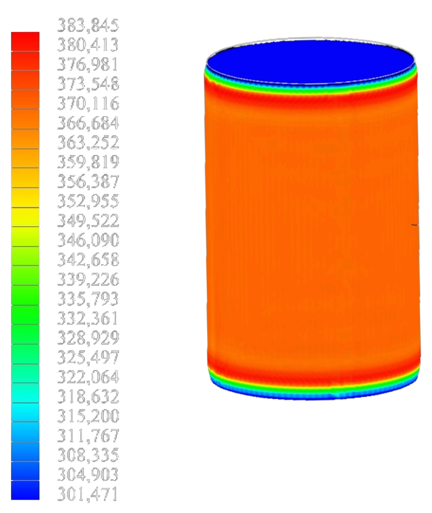
Note: This simulation only considers stresses product of thermal properties of the material, not included water pressure or self-weight constraints

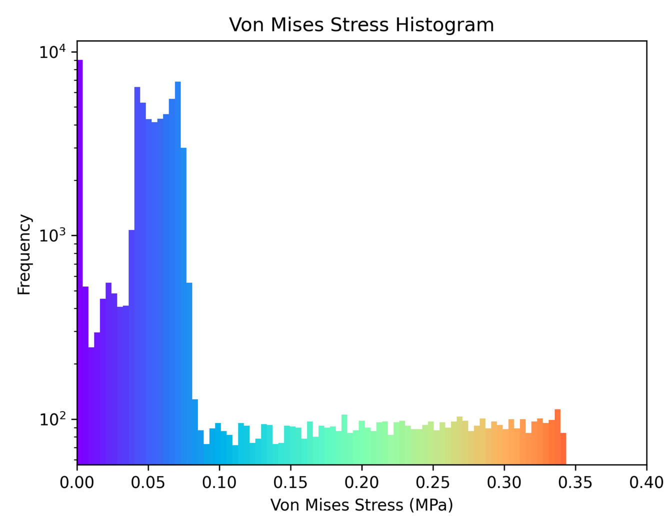
Results of the FEA (Inventor)

Static Results:

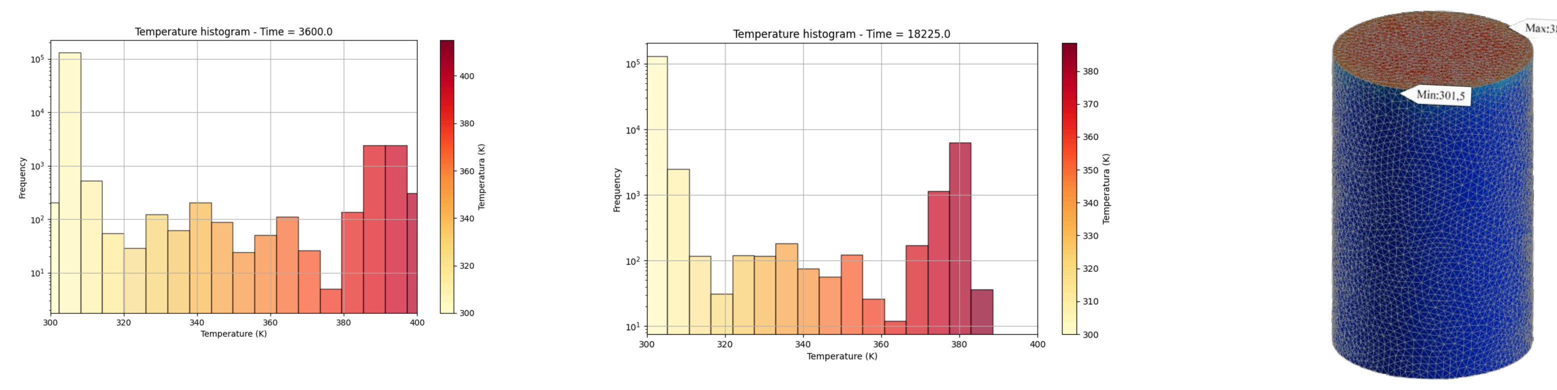
Tank Properties:

- **Width:** 571[mm]
- **Height:** 890[mm]
- **Thickness:** 1.2[mm]
- **Mesh element size:** 0,02[m]
- **Material:** Cold-Rolled Steel



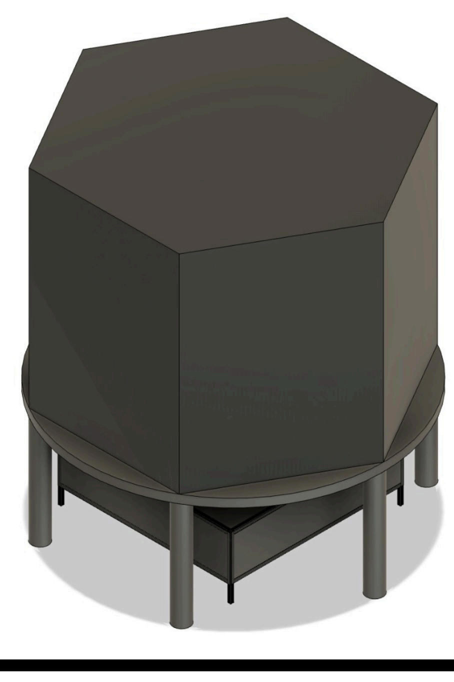


Thermomechanical Results:



Brief conclusions and Perpectives

The cold-rolled steel auxiliary tanks performed well under thermal loads, reaching a maximum temperature of 383 K, well within the material's limits. In contrast, the AISI 304 steel main tanks experienced thermal stresses that exceeded their yield strength within an hour, compromising their integrity. This underscores the need for heat-resistant materials, insulating coatings, and more detailed transient simulations to optimize performance. The final water cherenkov detector aims to be integrated with an hodocope in the bottom, that will improve angle resolution and reduce the energy threshold.



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