

High power mercury target design exploration using Isight

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Abstract: The stainless-steel target vessel directs the flow of mercury at the Spallation Neutron Source (SNS) facility in Oak Ridge National Laboratory, Tennessee, and is struck by cyclic (60hz) proton beam pulses to release neutrons for scientific experiments. The target works under various severe conditions: temperature, radiation, mercury flow, and proton beam pulse pressures. Insufficient strength and durability of the target stainless steel vessel from beam pulse and thermal cyclic loads can lead to mercury leaks and premature target life termination. Neutron production and the scientific user programs at SNS has been disrupted on several occasions due to such incidents. The longevity and reliability of target steel vessel are the key parameters to be improved in creating the new target design for a planned beam power increase by 40%, up to 2 MW.

The one of the most challenging exploration application development tasks was the creation of sophisticated FE model in Abaqus/CAE with many geometric features modifiable by Isight. Design of Experiment (DOE) was performed to create the response surfaces for mercury steel vessel structure on a basis of Abaqus/Explicit dynamic analysis results. Obtained results enable the consideration of possible trade-offs for the most feasible design and for the next design concept enhancements.

The conclusions about applicability of SIMULIA technology for target design development together with the most characteristic results will be presented.

Keywords: Mercury Target, Pulse Loading, Fatigue life, Design Optimization, Design Exploration, Scripting, Response Surface, Abaqus, Isight.

1. Spallation Neutron Source (SNS) Facility

The Spallation Neutron Source (SNS) is a megawatt-class accelerator-based research facility that was constructed by the US Department of Energy (DOE) at the Oak Ridge National Laboratory (ORNL). It produces neutrons by injection of a high-energy proton beam into a mercury target. The mercury target is a flow-through circulation system composed of an inner mercury vessel, an interstitial helium space, and an outer water-cooled shroud. It is comprised of a target module which is mounted on a target carriage that moves on and is propelled by the carriage transport system; and process loops for supplying mercury, water, nitrogen, helium, and vacuum pumping to the target module. Figure 1 shows the overall configuration of SNS facility complex. Red line shows the proton beam path through accelerator, accumulation ring, and the target. After the proper proton charge has been accumulated in the ring the beam is directed into the target where neutrons are produced and moderated.

1.1 Mercury Target Module

During SNS operation, neutrons are produced via high-energy spallation reactions induced by injecting 1 GeV protons into the mercury filled target module at a frequency of 60 Hz. It provides intense neutron bursts to a suite of science instruments. The novel choice of liquid mercury of the target material allows heat removal by circulation through a process system without the loss of neutron intensity. The target module with surrounding core vessel components is shown in Figure 2.

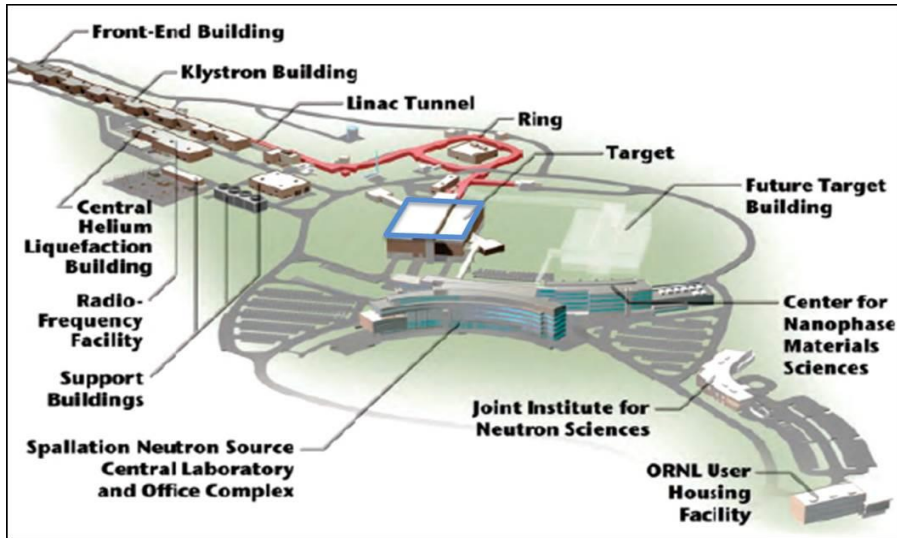


Figure 1. SNS facility complex.

Due to the service environment and elevated level of radiation, the materials used to construct the target module experience radiation and high-cycle fatigue damage. Consequently, the target module has a limited service life and must be periodically removed and replaced. The target module is replaceable exclusively by remote handling equipment. Over 10-year operational history there had been 15 target modules in service. Of these, 7 targets had been replaced prematurely due to occurrence of mercury leaks. Four cases of leak were resulting from fatigue damage of stainless steel vessel containing mercury. The target inner wall damage from fatigue in conjunction with erosion from mercury cavitation is shown in Figure 3.

The length of proton beam pulse is $0.7 \mu\text{s}$ with frequency of 60 Hz. A volumetric pressure field in mercury is initiated with each pulse, with a peak of 18 MPa reached for 1 MW pulses. Propagation of this pressure throughout the mercury subsequent to the pulse and its interaction with the steel vessel leads to vessel fatigue stress. The internal target structure showing the steel vessel and mercury is presented in Figure 4.

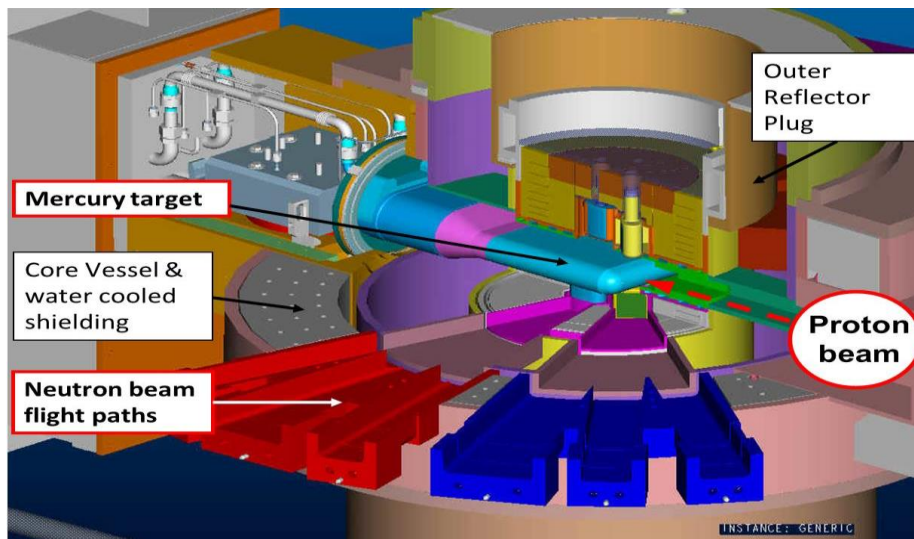


Figure 2. Mercury target module and surrounding components.

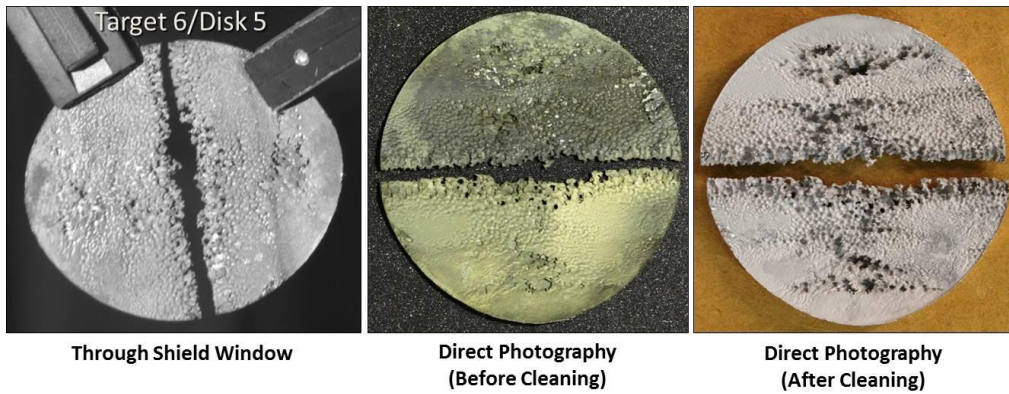


Figure 3. Target inner wall damage due to mercury cavitation and fatigue.

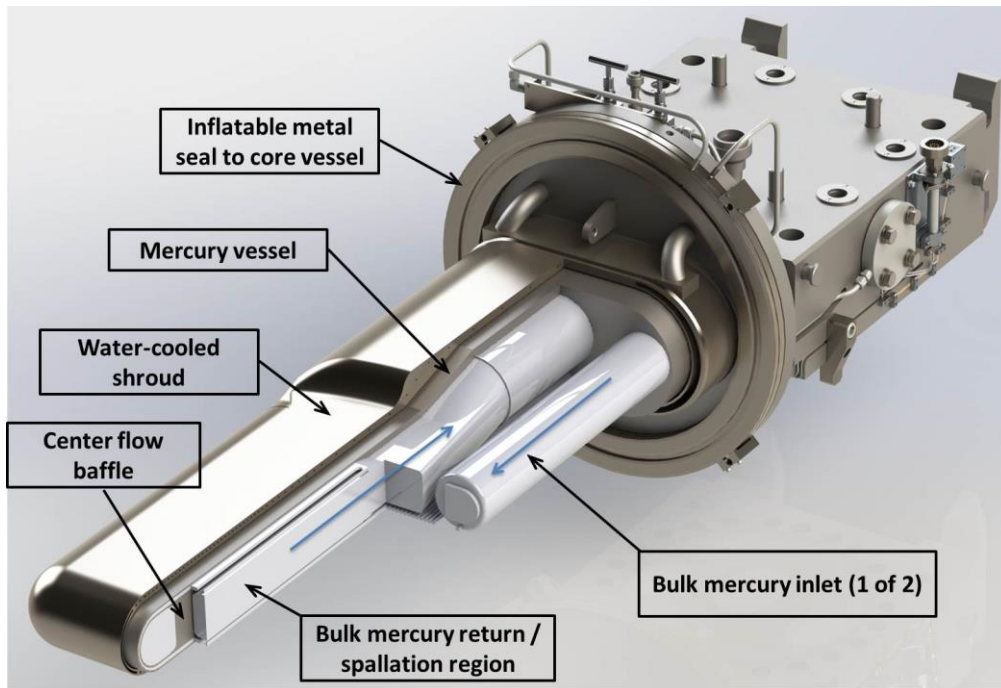


Figure 4. Target internal structure.

1.2 Target Structural Response Simulation

The typical finite element model for target structural simulation is shown in Figure 5. Operating stresses in the mercury vessel result from weight, mercury pressure, steady-state thermal stress, and pulsed pressure from the proton beam. All steady-state loadings are simulated with Abaqus/Standard and pulsed pressure with Abaqus/Explicit. The typical length of time simulated for the SNS target pulse has been 1 ms which has been adequate for capturing maximum vessel strain response. Dynamics of stress changes during pulse simulation are presented in Figure 6.

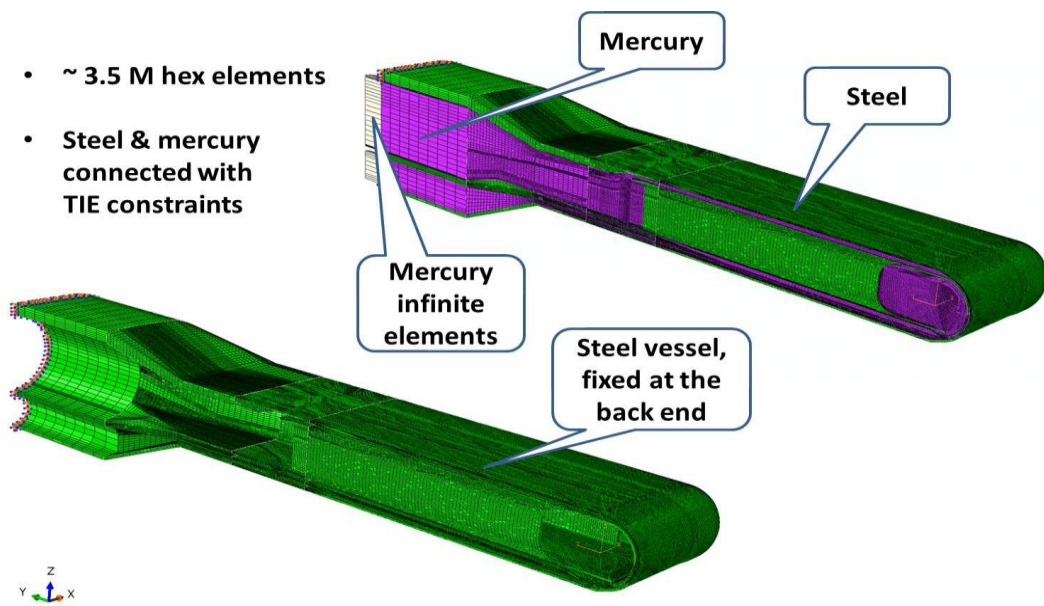


Figure 5. Typical FE model for target analysis.

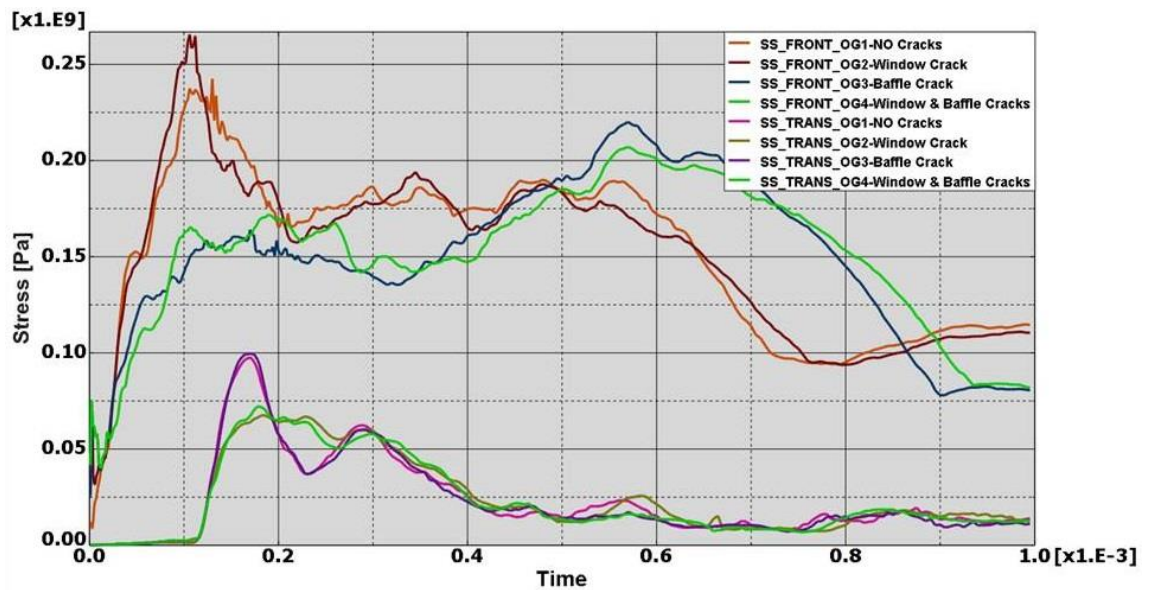


Figure 6. Target pulse max stress histories at different locations.

1.3 Target Steel Vessel Continued Design Development

SNS staff is currently working on the new – second target station project. In relation to it, the maximum power on the targets is planned to increase from 1.4 MW to 2.0 MW. The steel vessel high cycle fatigue with higher power was analysed using fe-safe and is presented in the form of lifetime curves for different locations in Figure 7. The total number of pulse cycles

through the entire regular target service time is expected to be at least 600 million or higher. Curves in Figure 7 indicate the fatigue life reduction above 1.0 MW and significant reduction above 1.4 MW power in comparison with required target service time. That leads to the necessity of developing the optimal vessel design to address the demands of reliable operation.

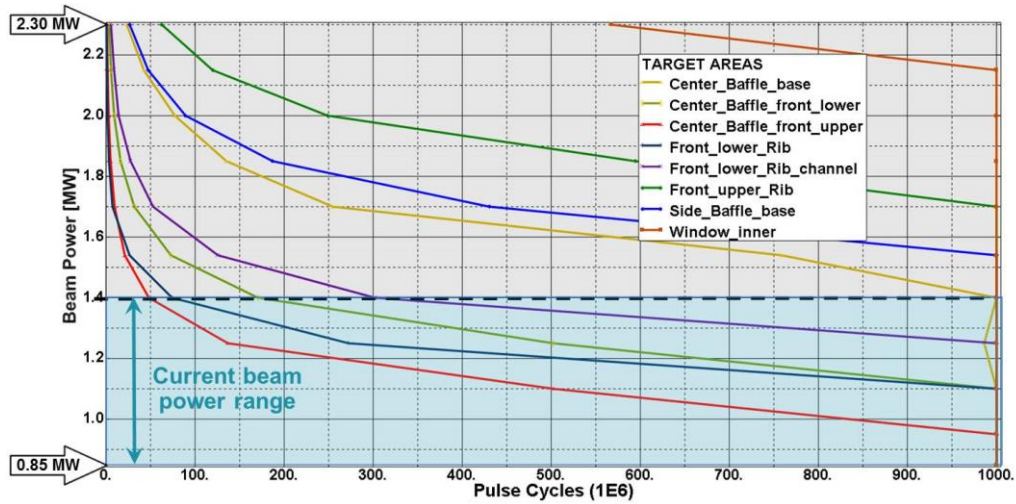


Figure 7. Target pulse fatigue life vs power at different locations.

2. Steel Vessel Design Exploration

2.1 Isight application development

It is obvious from Figure 7 that proton beam pulse cyclic load at higher power levels drastically affects the steel vessel fatigue life and consequently the long-term reliability of target module. The current purpose of design exploration is to identify the best set of design features providing the lowest stress concentrations for the longest fatigue life of steel vessel. The baseline geometry of steel vessel is shown in Figure 8. The three critical geometric design features to vary are presented in Figure 9.

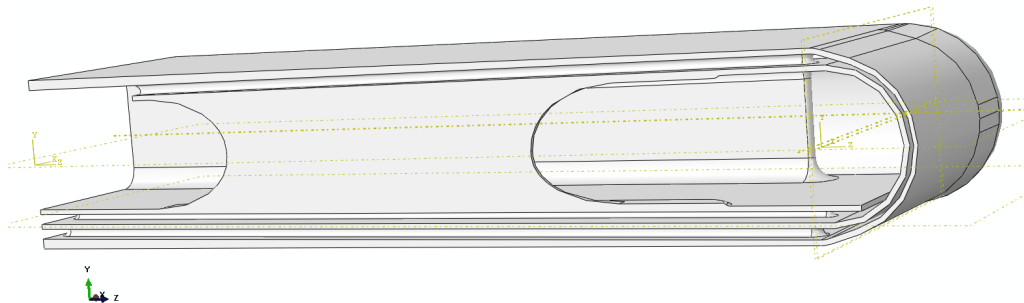


Figure 8. Target steel vessel design

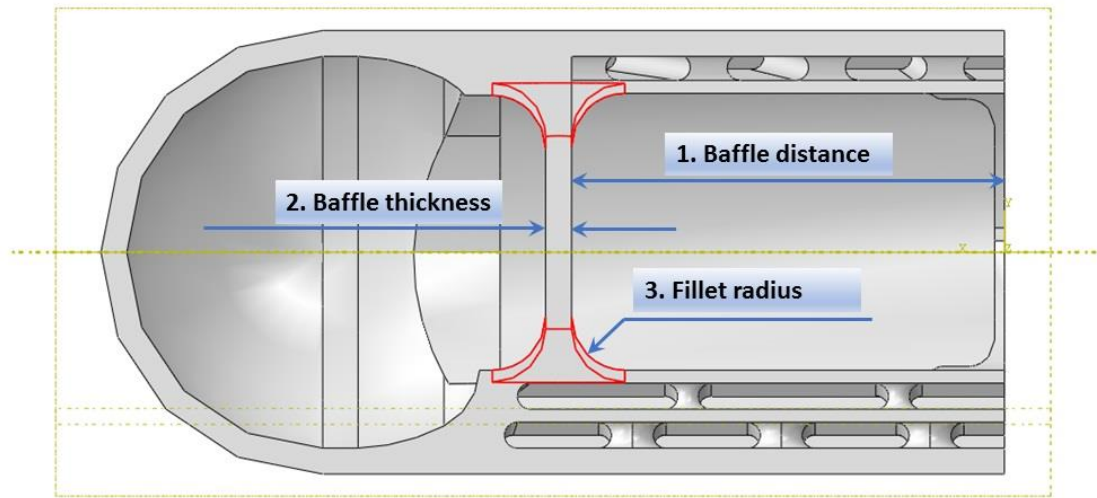


Figure 9. Target steel vessel explored features

The basic Isight workflow schema is presented in Figure 10. To organize the DOE process both steel and mercury parts must be rebuilt, and pulse pressure load recreated for analysis with Abaqus/Explicit at each evaluated point in design space. At first the steel part is being modified following data from design matrix by first Abaqus component in the workflow. Next Abaqus component is responsible for creation the mercury part what fills all empty space inside the steel part. For that purpose, it uses the “chunk” of mercury shown in Figure 11 and runs the separately created Abaqus Python script to merge both parts. Resulting mercury part geometry is shown in Figure 12.

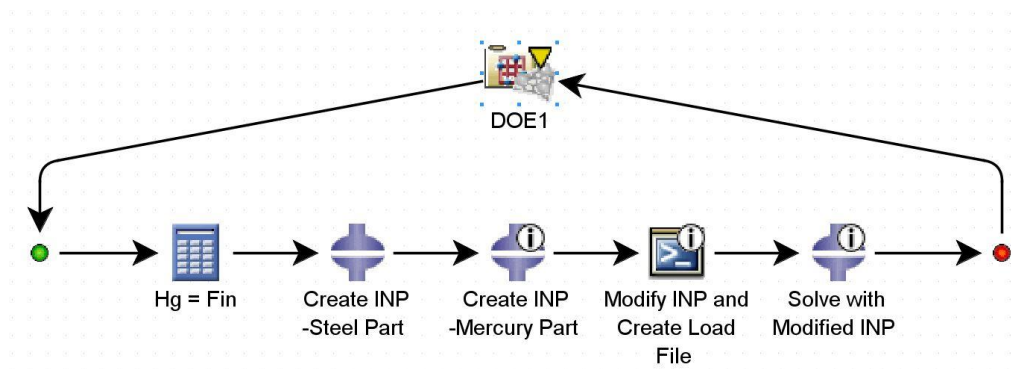


Figure 10. Isight components workflow

The “OS Command” component maps the beam pulse power data imported from separate neutronics calculations onto the modified FE mesh in the form of volumetric pressure. The typical pressure distribution contours are shown in the Figures 13, 14. Mapping and necessary corrections to final Abaqus input file are performed by running separately developed Fortran program.

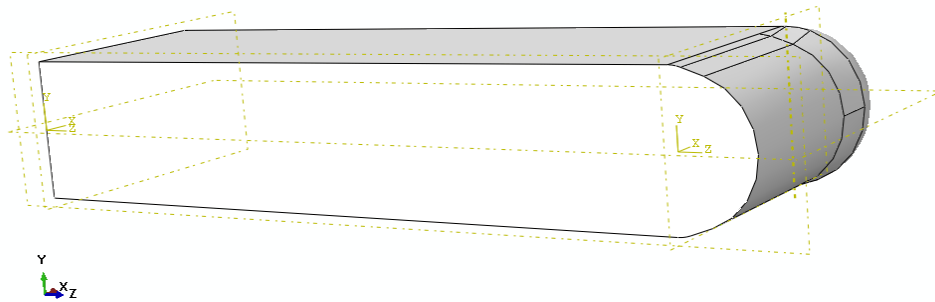


Figure 11. Target mercury part initial geometry

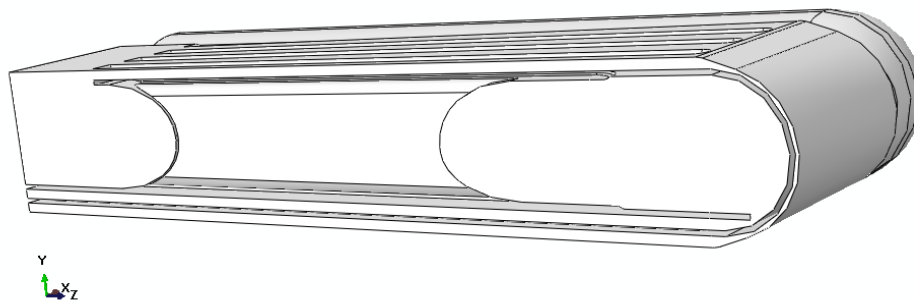


Figure 12. Target mercury part resulting geometry

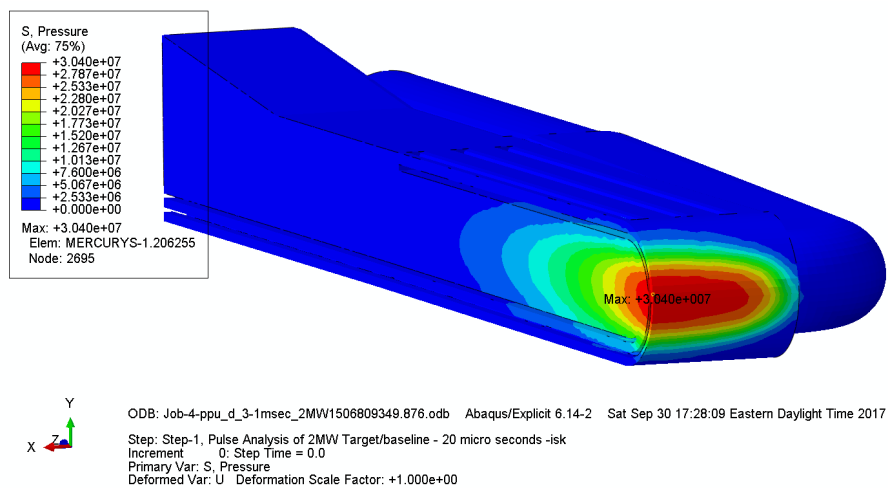


Figure 13. Proton beam pulse pressure contour at target mercury part

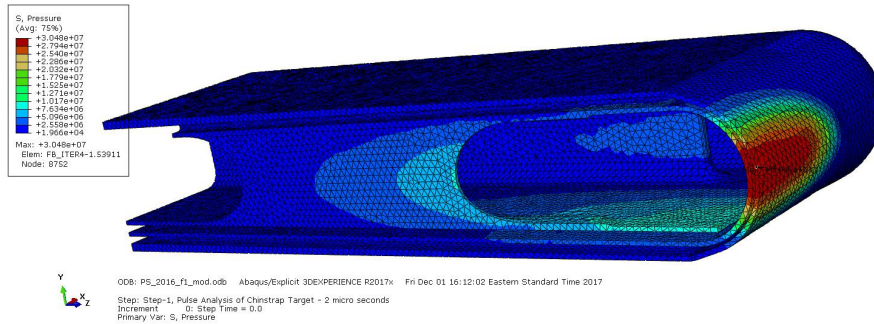


Figure 13. Proton beam pulse pressure contour at target steel part

2.2 Design exploration results

Optimal Latin Hypercube sampling for 48 points was used to run DOE. Each Abaqus simulation with 32 HCP processors took approximately 2 hours. The total DOE run was completed within acceptable timeframe of 96 hours. The response surfaces for max Mises stresses vs each pair of design variables using RSM approximation are presented in Figure 14. The stress response 2D plots for each design variable are presented in Figure 15. The main effects plots are shown in Figure 16.

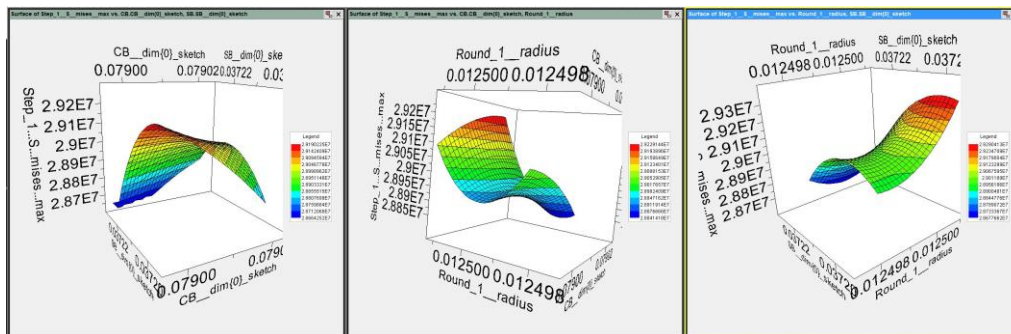


Figure 14. Design exploration response surfaces

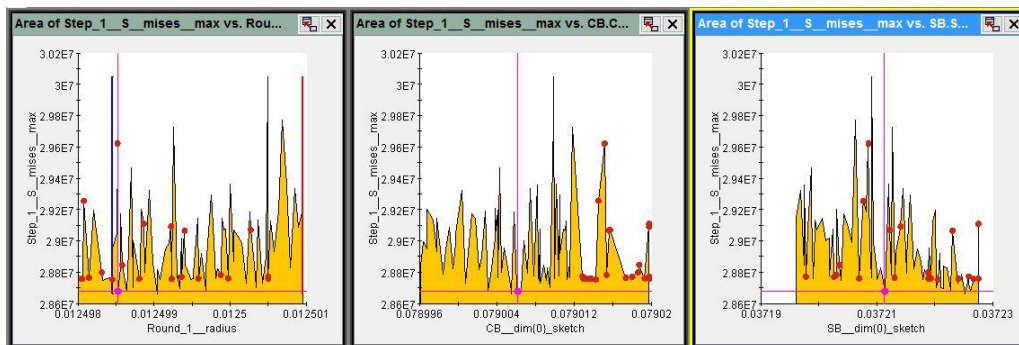


Figure 15. Design exploration responses 2D plots

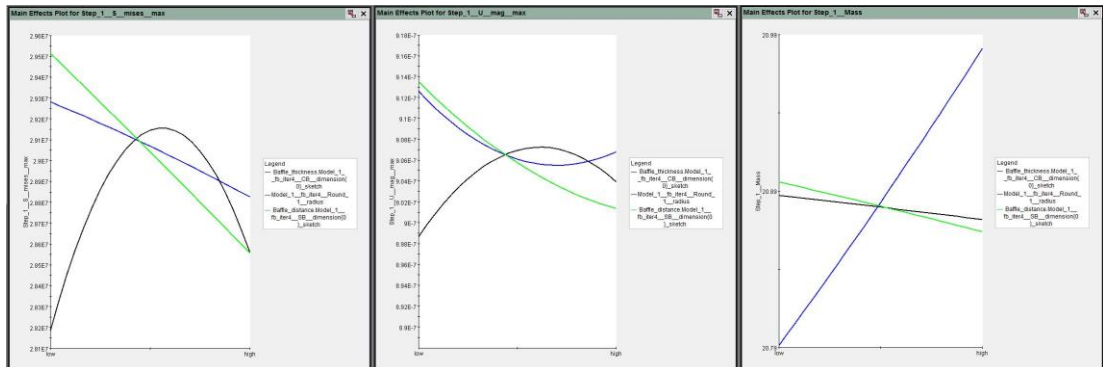


Figure 16. Design exploration main effects plots

The Isight 2D variable graphs shown in Figure 17 allow to search for additional possible trade-offs having in account other factors, such as thermal cycles, mercury induced cavitation erosion, etc.

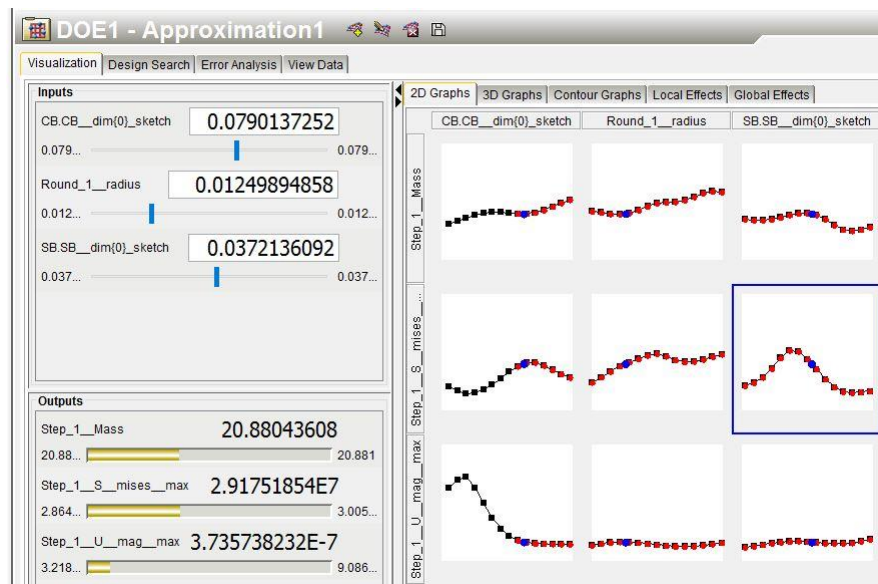


Figure 17. Design exploration 2D variable graphs

3. Conclusions

Harsh operating conditions of SNS mercury target and increasing levels of power require to achieve the high robustness and reliability of the mercury steel vessel.

Traditional “Design-Analysis-Evaluation” path is not sufficient to achieve the required design characteristics.

Isight capabilities of Design Exploration are sufficient to provide the best possible design choices and address the increasing demands.

4. References

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