Predicting Solution Reactor Operational Behavior in Support for Mo-99 Production for SHINE Technologies

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SUPO Reactor Multi-Phase Heat Transfer Study

SUPO, or "Super-Power" was a 45 kW "water boiler" reactor that consisted of a uranyl-nitrate solution within a 30-cm diameter spherical vessel. Supo was operated from 1951 to 1974 at what is currently called Los Alamos National Laboratory. The vessel contained water-cooled spiral coils distributed throughout the solution to maintain desired operating temperatures, re-entrant thimbles containing boron control rods, and a "glory hole" allowing for irradiation of materials. Supo was mainly used for neutron research, and proved to be a versatile and reliable research tool.

Fig. 1 - SUPO solution vessel internal components

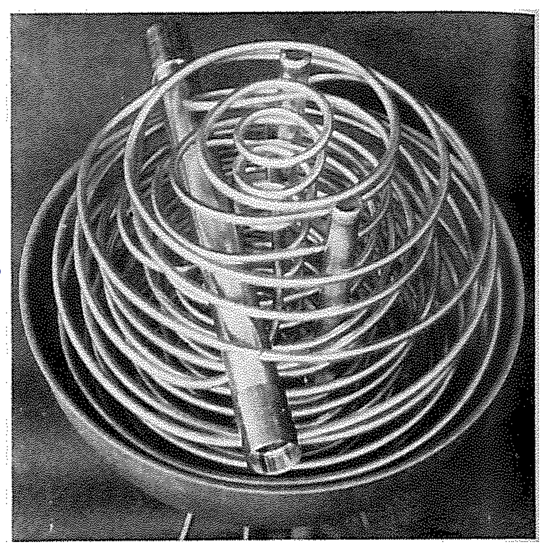
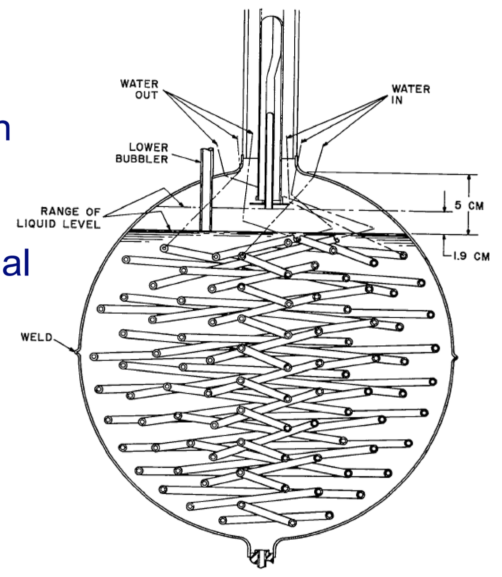


Fig. 2 - Supo solution vessel cross sectional sketch



Solution temperature, gas bubble volume fraction, and heat transfer coefficient (HTC), were determined using a laminar multiphase CFD model at power levels between 0.29-3.05 kW/L (3.8-40 kW). The radiolytic gas bubble generation profile was defined to be proportional to the power profile (2.8E-6 g/s/W), based on hydrogen production measurements. Heat transfer enhancements due to bubble generation were found to begin at a power density of 0.9 kW/L when local volumetric gas generation rates exceeded 3 g/s/m3.

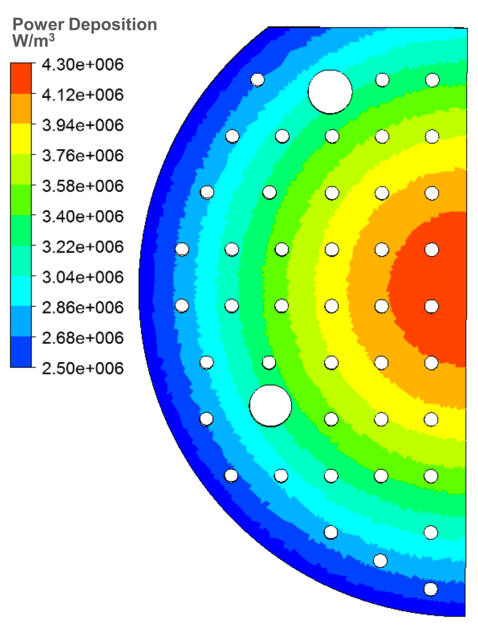


Fig. 3 - Axisymmetric Gaussian power distribution for the highest power (40 kW)

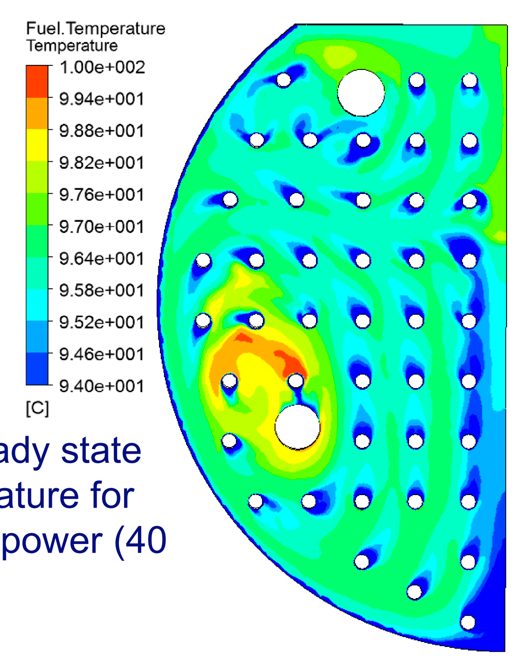


Fig. 4 - Steady state fuel temperature for the highest power (40 kW)

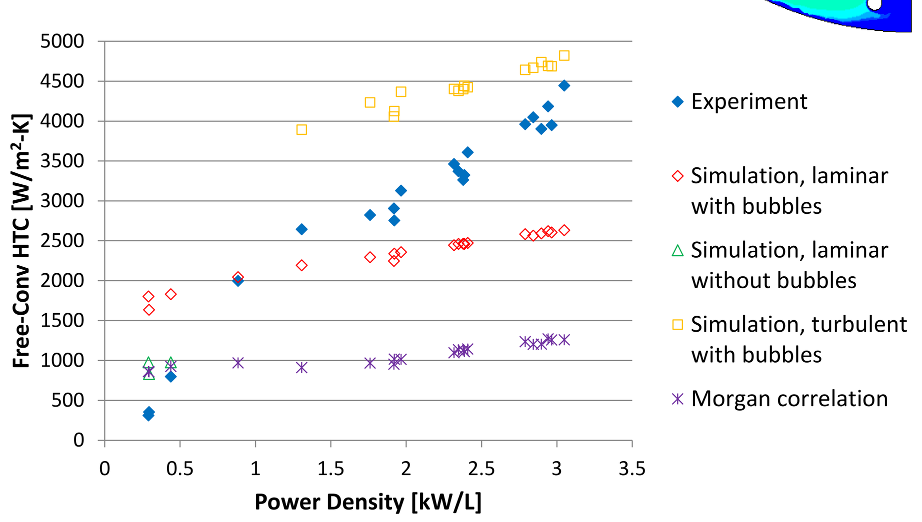


Fig. 5 - Average natural convection heat transfer coefficient of uranyl-nitrate solution at various power densities. It is suspected that no bubble generation occurs below ~0.9 kW/L.

Electron Irradiation of a Uranyl-Sulfate Solution

A rastered 35 MeV electron beam deposited power in a solution of uranyl sulfate at Argonne National Laboratory (ANL) generating heat and radiolytic gas bubbles. Irradiations were performed at beam power levels of 12 and 15 kW. Average bubble diameter was measured to be 267 μm at 12 kW. This measurement agrees with the linear relationship established between bubble diameter and power density, based on SUPO measurements: $\mathit{diameter}[\mathrm{mm}]=0.652*\mathit{power\ density}[\mathrm{kW/L}]+0.11$. Temperatures were calculated using a turbulent multiphase CFD model with estimates for the gas generation rate of 1.4- 4.4E-8 g/s/W based on recorded bubble images.

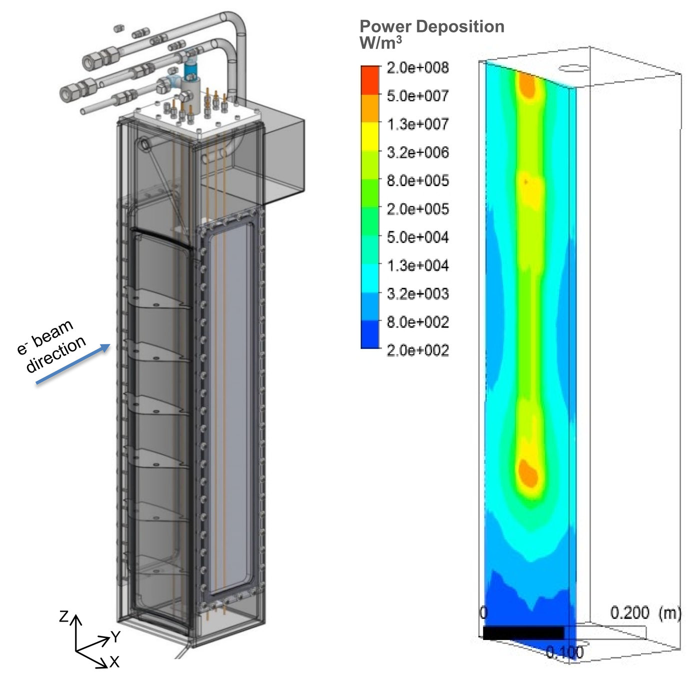


Fig. 6 - Solution vessel and 12 kW power profile

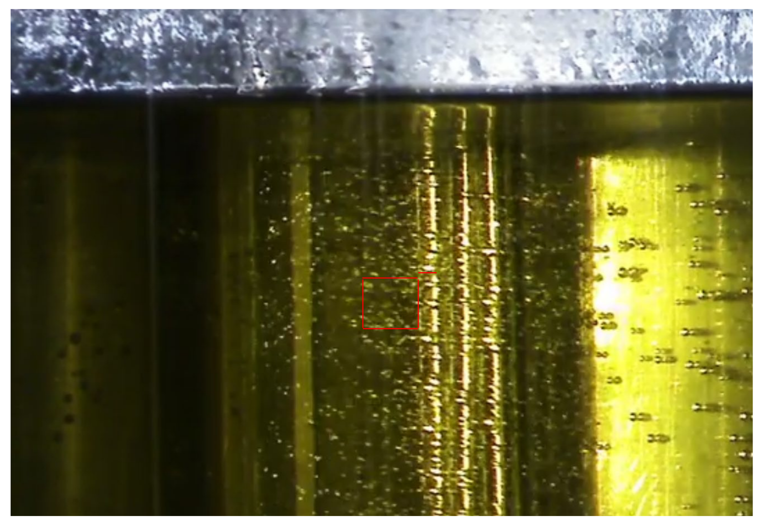


Fig. 7 - Radiolytic gas bubbles during 12 kW test

A transition point was found below which the heat transfer characteristics are indistinguishable from a single phase system, and above which the heat transfer is significantly enhanced by radiolytic gas bubbles. For the SUPO experiment, the local volumetric gas generation rate at which heat transfer enhancement occurs is around 3 g/s/m3. For the ANL bubble experiment, the transition value is about 1 g/s/m3 for both the 12 and 15 kW tests.

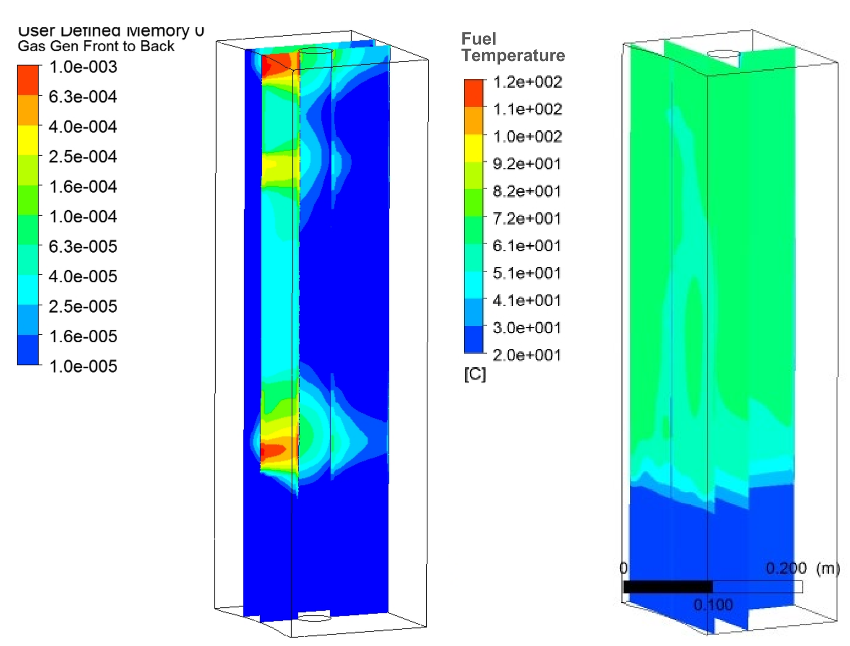


Fig. 8 - Gas generation (4.4E-8 g/s/W), temp, 12 kW

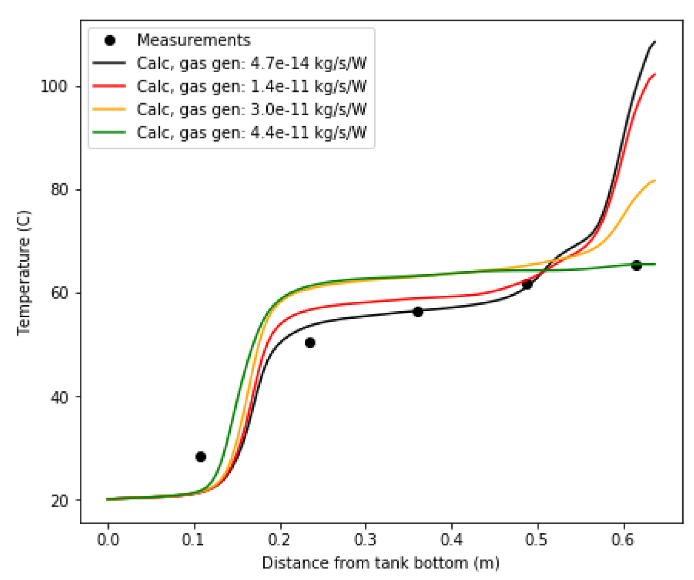
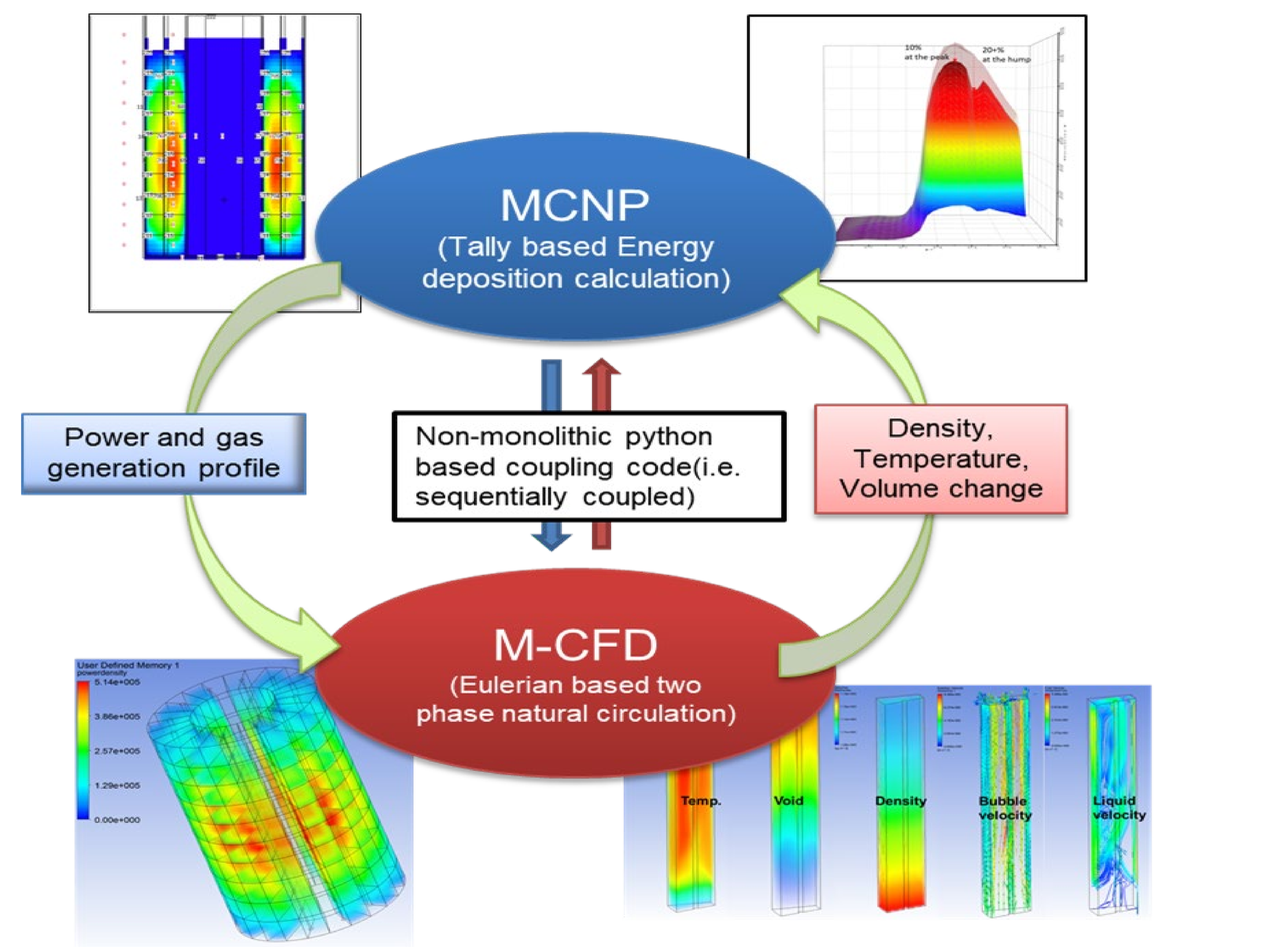


Fig. 9 - Measured, calculated temps, 12 kW

Multiphase CFD and MCNP Calculations

A multi-physics (neutronic + thermal hydraulic) methodology is demonstrated for an accelerator-driven fissile solution vessel application for Mo-99 production technology. A prediction of steady state fissile solution power depends on the thermal hydraulic characteristics and the corresponding neutronic behavior. A vessel configuration study indicated that a higher power and lower fuel temperature are achievable with a slender-shape vessel (Fig.10).



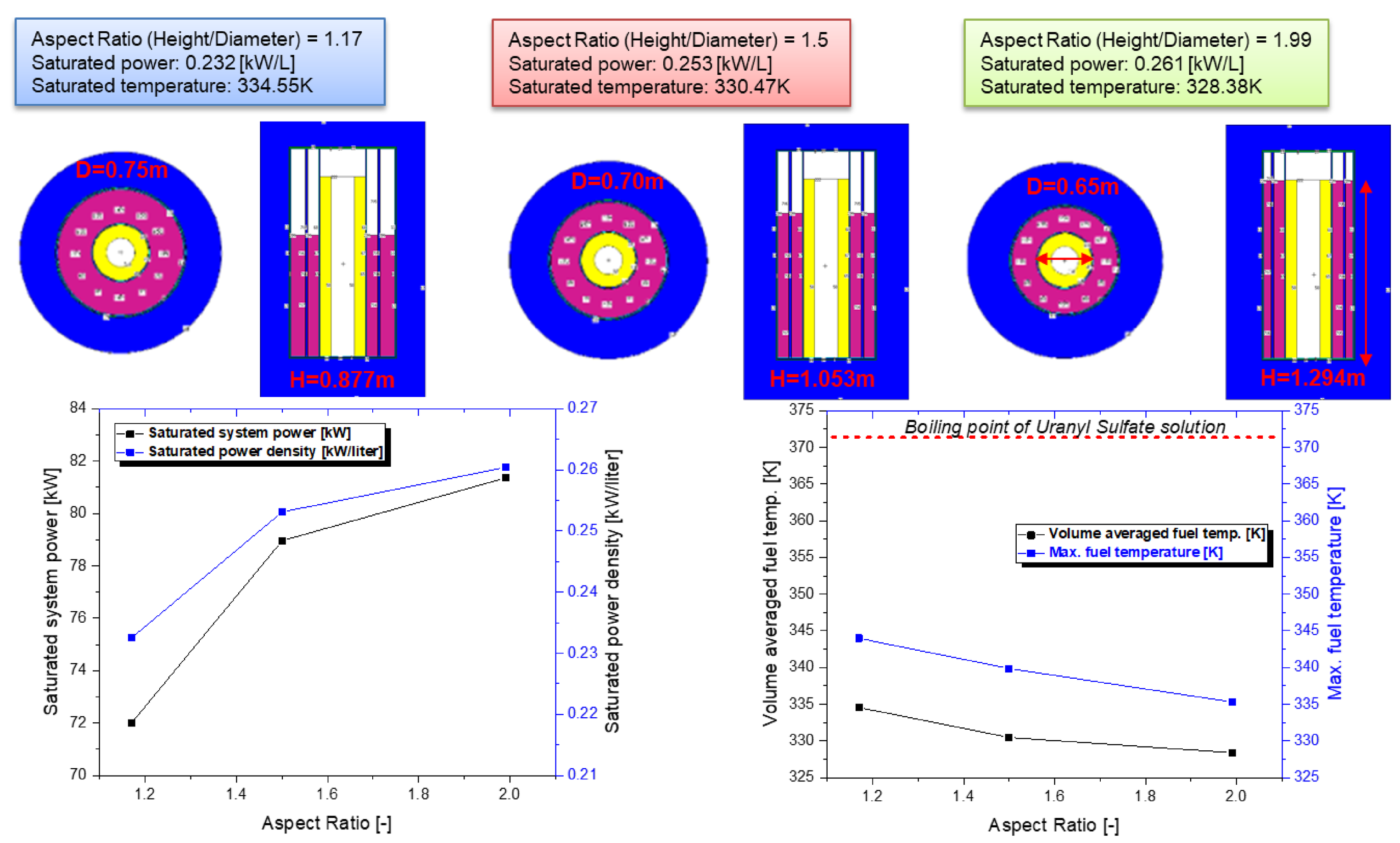


Fig. 10 - Vessel design optimization by comparing Aspect ratio vs system parameter (power, temp)

At the most optimal vessel design, the maximum achievable power density is predicted to be 0.84 kW/L with a target neutron source of 5.83E14 neutrons/s.