An Unsteady State Gas Transport Model in Matrix Laboratory (MATLAB) for PWR Gas Management

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INTRODUCTION

Reactor Coolant System (RCS) hydrogen gas management can be a challenge at Pressurized Water Reactors (PWRs) during shutdown, startup, and steady state operation. Poor hydrogen control can result in higher general corrosion rates for RCS components and increases in critical path time for shutdown or startup. Also, performance indicator penalties may be accrued by entry into Electric Power Research Institute (EPRI) Action Level conditions or by accrual of Chemistry Effectiveness Index (CEI) penalties established by the Institute of Nuclear Power Operations (INPO). Furthermore, poor hydrogen control may increase industrial safety risk due to the creation of an explosive environment. Part of the hydrogen management difficulty arises from the interaction of several phenomena that require complex simulations to fully understand. While hydrogen gas transport models have been developed, the application of these models is limited by the computational intensity required to accurately model the dynamism inherent in plant shutdown or startup. Subsequently, a gas transport model is developed in a suitable computational program to meet these needs and provide input to an optimized RCS hydrogen management strategy for all operational modes.

The gas transport model is used to model RCS hydrogen behavior for an example PWR during an End of Cycle (EOC) Forced Outage (FO) startup, a refueling outage (RFO) shutdown, and during nominal steady state operation. The computational software selected is Matrix Laboratory (MATLAB®).

THEORY AND COMPUTING REQUIREMENTS

The gas model uses three distinct nodes to create an overall mass balance for the active PWR primary system. The nodes include the bulk RCS, the pressurizer, and the Volume Control Tank (VCT). The RCS hydrogen mass balance is summarized in Equation 1 and Figure 1. Figure 2 illustrates a basic mass and energy balance of the pressurizer. The mass streams going into and out of the pressurizer are the same as the RCS mass balance. The diagram also shows pressurizer heater input (q_T) and heat loss (q_0) as well as the gas streams going into the vapor space and condensation (C_v and C_d, respectively).

Due to the dynamic nature of plant parameters, numerical solutions to the DAE system are required. Furthermore, instantaneous changes in plant parameters, such as those followed by valve manipulations lead to 'stiff' DAE systems, where numerical solutions are unstable. Specialized solvers suited to 'stiff' DAE systems are required for such systems. The computational software Matrix Laboratory (MATLAB®) provides solvers suited to solving stiff differential equations and an appropriate solver was identified.

$$M \cdot \frac{d(C_1)_{H_2}}{dt} \cong$$

$$Q_{CL}C^*_{H_2} + Q_2(C_2)_{H_2} - \delta \cdot M(C_1)_{H_2} - [Q_{LD} + Q_{SW}](C_1)_{H_2} -$$

$$Q_1(C_1)_{H_2} - 2Q_{CL}C^*_{O_2} - 3k_2Q_{CL}C^*_{N_2} \qquad (1)$$

Where:

M = mass of water in reactor coolant, excluding the pressurizer (kg)

$(C_1)_{H_2}$= hydrogen concentration in reactor coolant at standard temperature and pressure (cc/kg)

t = Time (minutes)

$(C_2)_{H_2}$ = hydrogen concentration in pressurizer surge line (cc/kg)

Q_{CL} = charging line flow rate (kg/min)

Q_{SW} = reactor coolant pump seal water return flow rate (kg/min)

Q_1 = pressurizer spray flow rate (kg/min)

Q_2 = pressurizer surge line flow rate (kg/min)

Q_3 = pressurizer vent flow rate (kg/min)

δ = hydrogen diffusion constant for steam generator tubes (min^{-1})

$C^*_{H_2}$ = hydrogen charging line concentration (cc/kg)

$C^*_{O_2}$ = oxygen charging line concentration (cc/kg)

$C^*_{N_2}$ = nitrogen charging line concentration (cc/kg)

k_2 = fraction of nitrogen reacting with hydrogen reaction

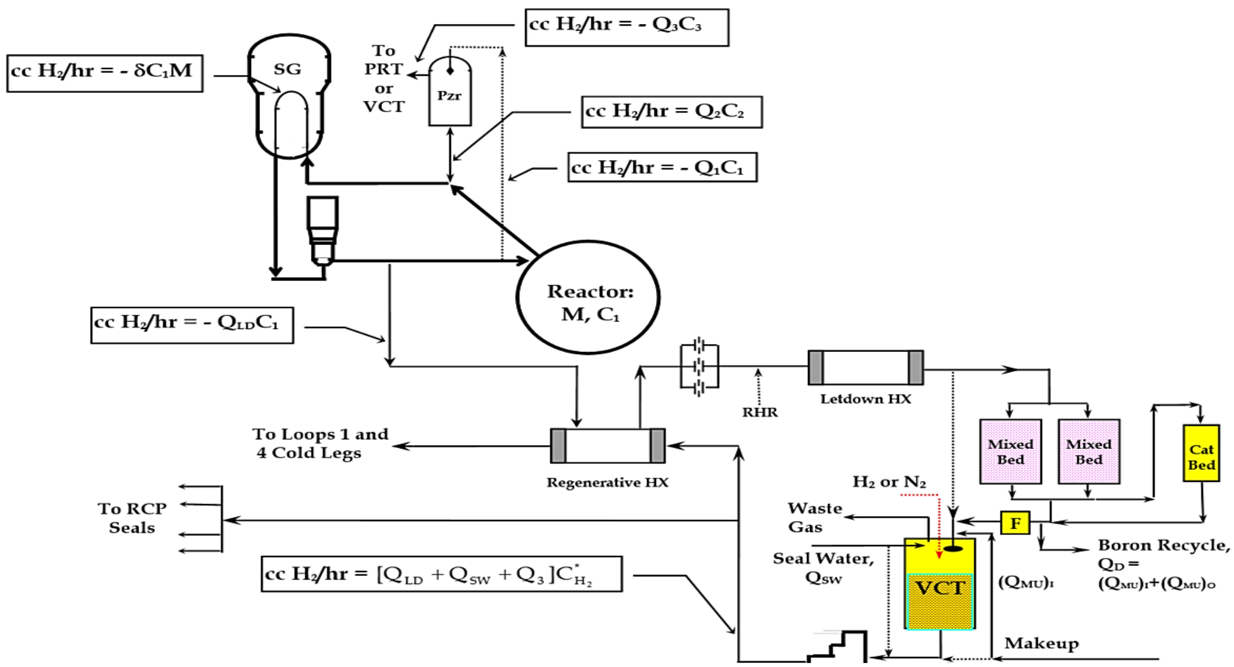

Fig. 1. Hydrogen Mass Balance for the RCS

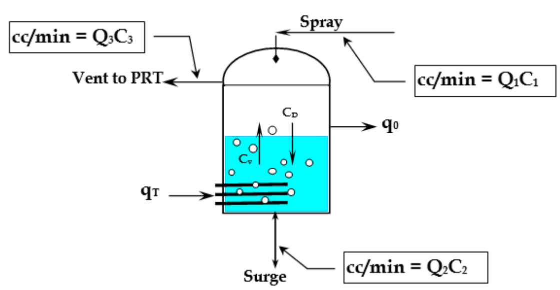

Fig. 2. Pressurizer Mass and Energy Balance

EOC FORCED OUTAGE STARTUP MODEL RESULTS

EOC forced outages at PWRs can require large and rapid dilutions to reduce RCS boron concentration and raise reactor power if no deborating resin beds are available in the Chemical Volume and Control System (CVCS) demineralizers. If dilution rates are high enough and makeup is aligned to charging pump suction during the dilutions for an extended timeframe during startup, RCS hydrogen can be diluted to unacceptable concentrations, resulting in EPRI Action Level entry and/or CEI point accrual.

The gas model is used to determine optimal startup dilution strategies that will prevent RCS hydrogen from decreasing below 30 cc/kg while limiting impacts on unit power ramping rate. Plant data are used to establish a baseline hydrogen model for the plant. After model and data agreement has been established, different cases that vary makeup location (VCT vs. charging pump suction) and makeup timing. Figures 3 and 4 illustrate the baseline model outputs for RCS gas and makeup flow rates. Figures 5 and 6 illustrate the model outputs for an optimized makeup strategy that precludes CEI hits for hydrogen and may potentially minimize impacts on power ramping rate.

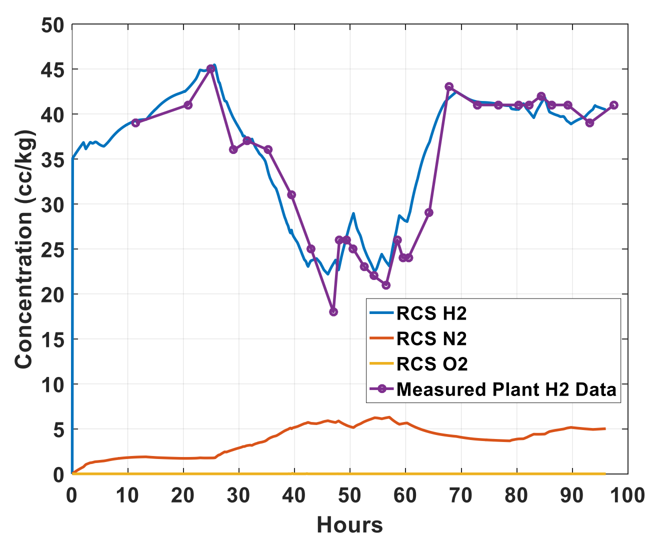

Fig. 3. Startup Model Generated RCS Hydrogen, Nitrogen, and Oxygen and Plant Measured Hydrogen Data

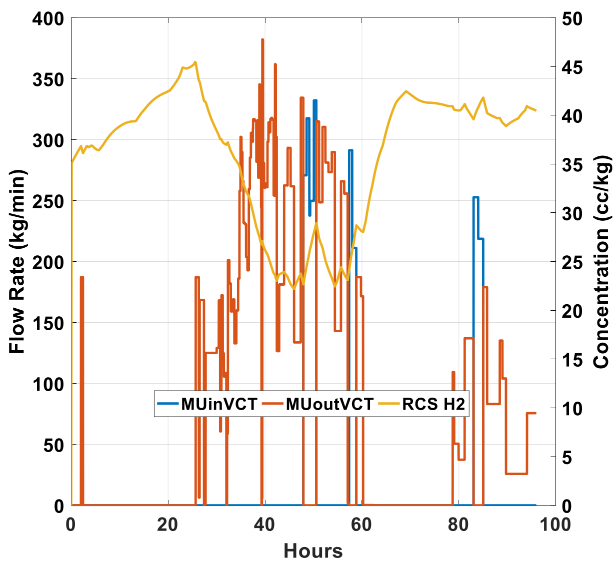

Fig. 4. Makeup to (MUin) and Makeup bypassing (MUout) the VCT for Baseline Case

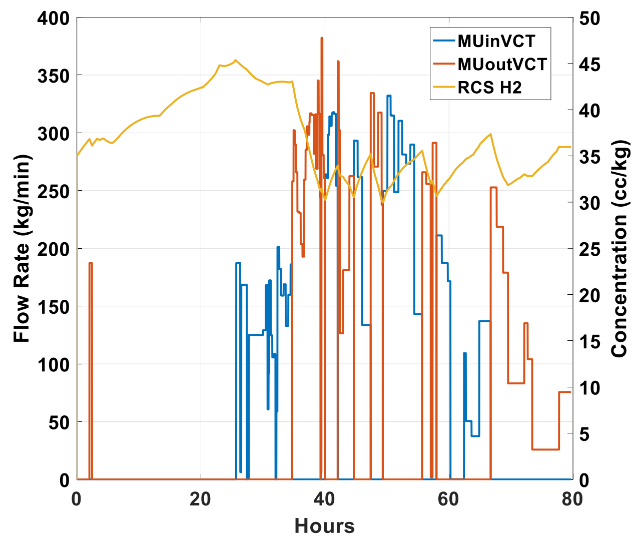

Fig. 6. Makeup to (MUin) and Makeup bypassing (MUout) the VCT for Optimized Startup Case

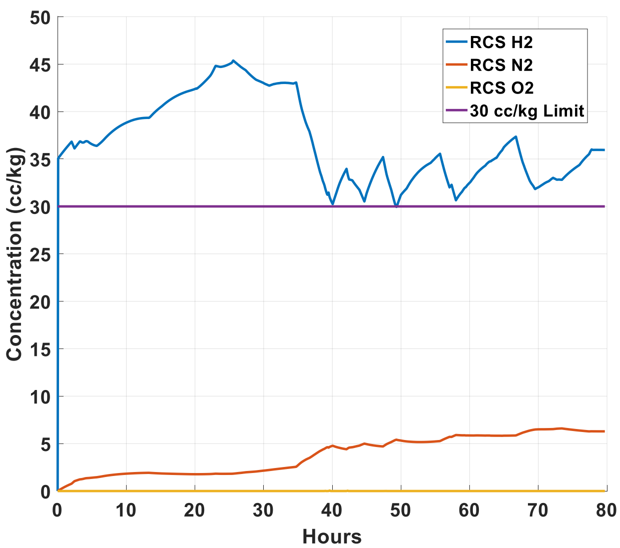

Fig. 5. RCS Hydrogen, Nitrogen and Oxygen for Optimized Startup Case

RFO SHUTDOWN DEGAS MODEL RESULTS

The shutdown degas form of the model can be used to optimize PWR degas strategies to ensure EPRI and industrial safety limits for hydrogen are adhered to, while ensuring degas does not impact critical path or nuclear safety.

In this case, the model is used to determine the optimal time to align nitrogen to the VCT to help expedite the degas process. Figure 7 illustrates the baseline model results, and Figure 8 illustrates the various effects of aligning nitrogen to the VCT at different times prior to shutdown. Based on the model outputs, aligning nitrogen to the VCT 3 hours prior to shutdown was the most optimal approach.

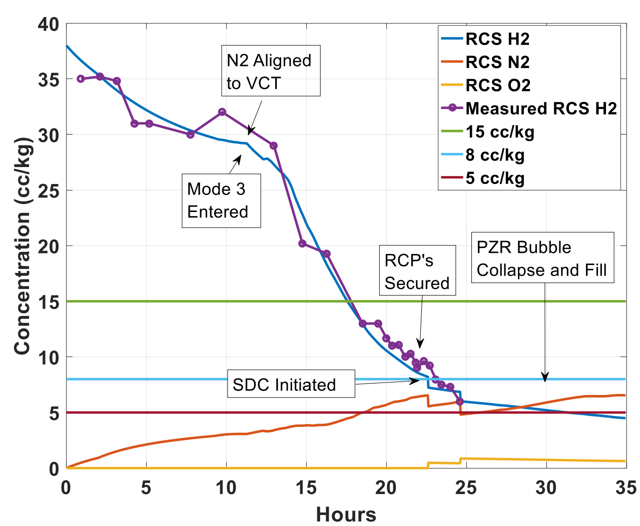

Fig. 7. Shutdown Model Generated RCS Hydrogen, Nitrogen, and Oxygen and Plant Measured Hydrogen Data

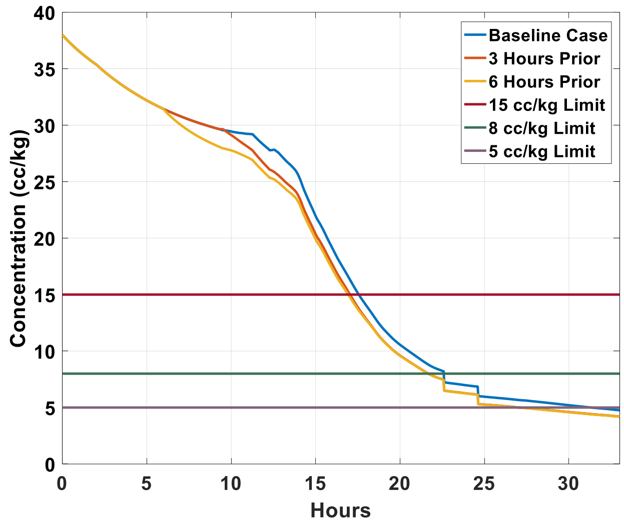

Fig. 8. RCS Hydrogen, Nitrogen and Oxygen for Optimized Shutdown Case

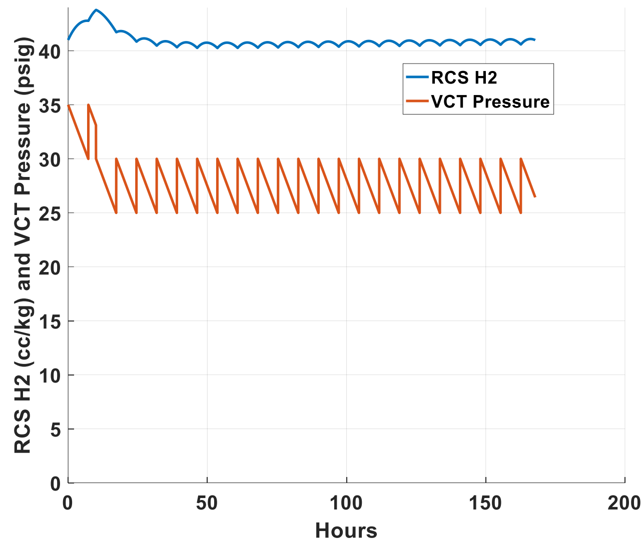

Fig. 9. Model Generated Steady State Behavior Following Adjustments in VCT Pressure

STEADY STATE RCS HYDROGEN MODEL RESULTS

PWRs may periodically change VCT pressure ranges during online operation to adjust RCS hydrogen concentration. Various operational parameters can impact how quickly the plant reaches a new RCS hydrogen concentration equilibrium. This can also impact the appropriate timing of samples to quantify the effects of changing VCT pressure.

The model is used in this instance to determine the time it takes for RCS hydrogen to reach a new equilibrium after changing the VCT pressure range during normal online operations. Figure 9 shows the model output for RCS hydrogen response to VCT pressure adjustments, from 30-35 psig band to a 25-30 psig band (at T=10 hours). Plant parameters, including letdown flow rate are constant. This shows that it takes approximately 15 hours to reach a new RCS hydrogen equilibrium, assuming no other system perturbations occur.

CONCLUSIONS

The application of a numerically robust software to solve complex gas transport problems in Pressurized Water Reactors is an opportunity for plant personnel to improve hydrogen management during operating, startup and shutdown conditions and better manage critical path impact. Furthermore, this enables plant personnel to predict hydrogen trends and take mitigating actions prior to exceeding CEI or EPRI limits, while maintaining nuclear safety standards.

REFERENCES

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