MODELING OF PICKERING NGS B HEAT TRANSPORT SYSTEM SEISMIC BOUNDARY LEAK TIGHTNESS TEST

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Abstract

In case of a seismic event in Pickering NGS B, Class IV and Class III power supplies may become unavailable. In an operating unit, such an event would results in reactor trip with the Heat Transport System (HTS) remaining at hot and pressurized conditions, while decay power is being removed by single-phase thermosyphoning. Under these circumstances, HTS pressure and inventory must be maintained within the seismically qualified portion of the system to prevent the breakdown of thermosyphoning. This paper presents the model employed to simulate the HTS pressure following the seismic event and the comparison between numerical results and actual data obtained with the recently developed P-079 test for HTS at cold and pressurized conditions.

1. Introduction

The Safe Operating Envelope (SOE) Project for Priority 1 systems was completed towards the end of 2004 in PNGS B. The Compliance Table developed for each system identified a number of gaps in the station operating documentation to ensure full compliance with requirements stipulated in the Operational Safety Requirements (OSR) and Instrument Uncertainty Calculation (IUC) reports. For the Heat Transport System (HTS), a new section of the Abnormal Incident Manual (AIM) was created, modifications were made to its Operating Manual, and new tests were developed. In particular, the test P-079 [1] was developed to test the seismic boundary leak rate of the HTS.

In case of a seismic event, all equipment powered by Class IV and Class III power supplies is postulated to become unavailable. Thus, with no Main HTS Pumps (33120-P1 to -P12) or Pressurizing pumps (33310-P1, -P2) in service, the HTS coolant pressure and inventory must be maintained to ensure that single-phase thermosyphoning is the primary mechanism of decay power removal. In PNGS B, the coolant in the HTS is contained within the seismic boundary: the check valves in the Feedlines (33310-NV1 and -NV2) and the Bleed Condenser Level Control Valves (33320-CV122 and -CV123) at the entrance of the Purification system, as shown in Figures 1 and 2.

During the development of the P-079 test, consideration was given to the following two possible pathways where HTS coolant could leak:

1. Leakages caused by breaks in the Pressure Boundary. It was postulated that a single or multiple breaks totaling an area of 1.0 in^2 would form as a result of the seismic event.
2. Leakages through pathways already open. The Gland Return flowpaths become a non-isolatable path between the HTS and the Purification system once the Pressurizing pump is unavailable (see Figure 3). In normal operating conditions, Motorized Valve 33340-MV308 is open to allow the return of approximately 1.0 kg/s of Gland flows. MV308 fails open in a seismic event [2].

This paper presents the development of a numerical model to simulate the pressure transient in the HTS following a seismic event. The model addresses the HTS when in a pressurized and cold conditions —the only testable state—. Modifications to the model will be required to simulate the HTS pressure transient at hot and pressurized conditions, which is the topic of another future publication.

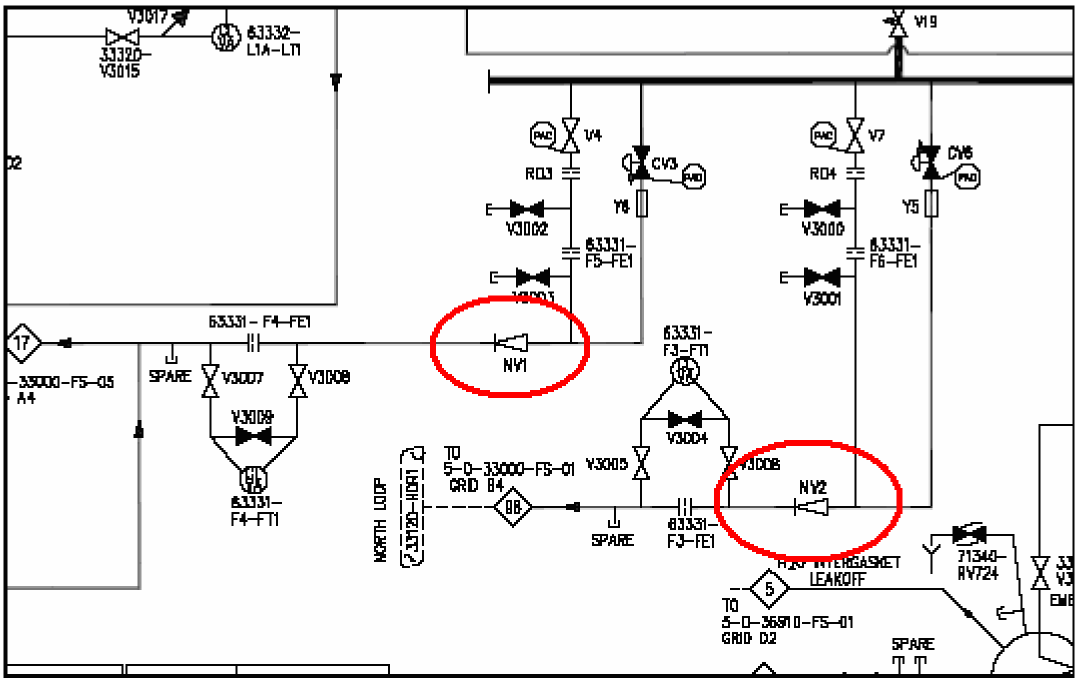

Figure 1. Seismic boundary in the Feedlines.

2. Numerical Model

2.1 Formulation of Model.

The numerical model was developed under the following assumption:

- HTS coolant temperature and volume remains constant throughout the transient.
- The rate of change of density against pressure can be approximated by a linear relationship.

- Hydraulic resistances (K) are derived from initial conditions and remain constant throughout the transient.

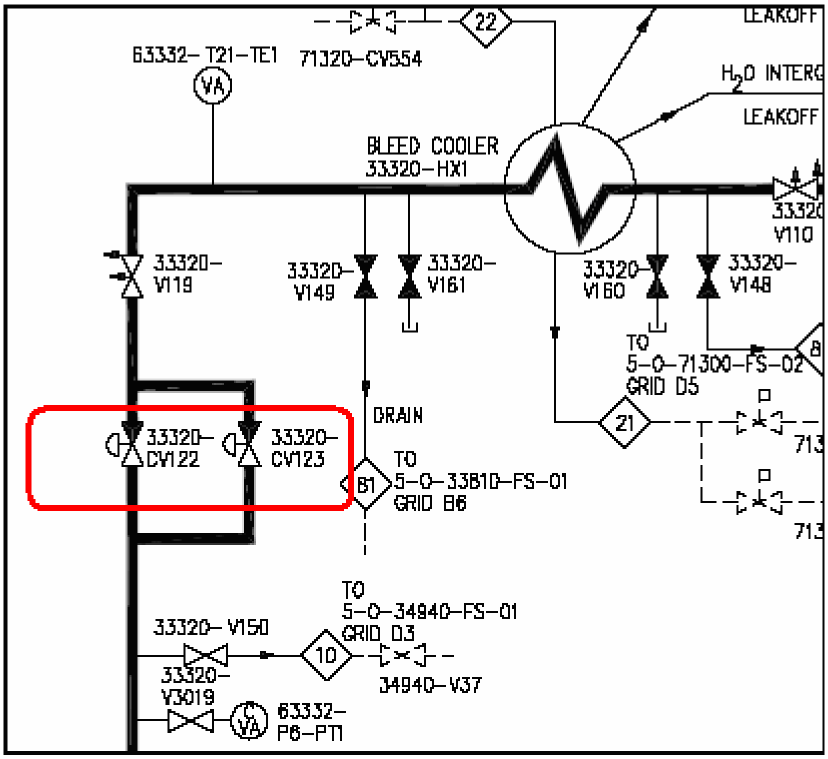

Figure 2. Seismic boundary at the Bleed Condenser Level Control Valves.

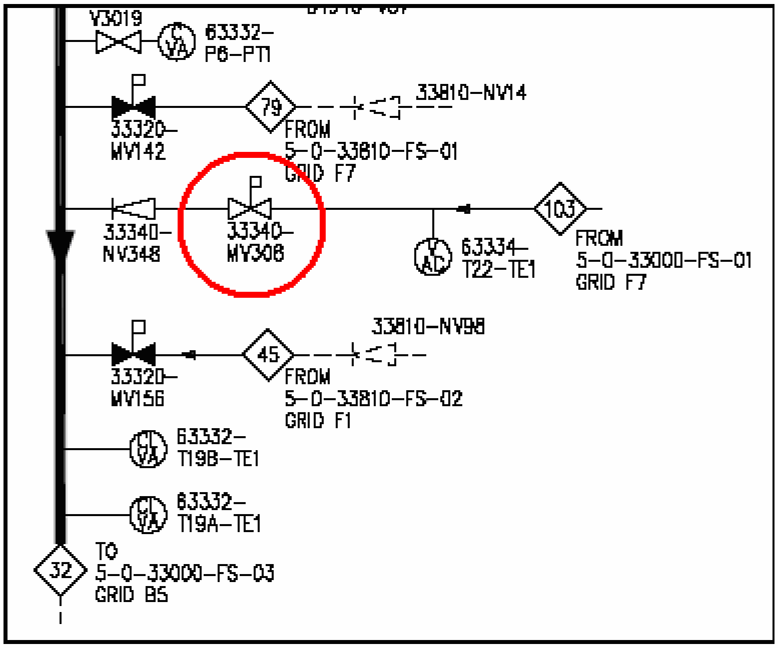

Figure 3. Open pathway through 33340-MV308.

The modeling of the HTS pressure was developed using the Equation of Conservation of Mass:

$$\frac{dM}{dt} = w_{in} - w_{out} \tag{1}$$

where

M: total mass of the system [kg],

w_{in}: mass flow injected into the system [kg/s],

w_{out}: mass flow ejected from the system [kg/s].

The above equation can be written on terms of density (ρ) and volume (V) as

$$\frac{dM}{dt} = \frac{d(\rho V)}{dt} = \rho\frac{dV}{dt} + V\frac{d\rho}{dt} = w_{in} - w_{out} \tag{2}$$

Since the volume is assumed constant, and lack of power supplies prevent mass flow injection, the equation is simplified to

$$V\frac{d\rho}{dt} = -w_{out} \tag{3}$$

The density of the subcooled HTS coolant is a function of the internal energy (u) and pressure (p). Thus, the rate of change of the density can be expressed as

$$\frac{d\rho}{dt} = \frac{d\rho(u,p)}{dt} = \left(\frac{\partial\rho}{du}\right)_p \left(\frac{\partial u}{\partial t}\right) + \left(\frac{\partial\rho}{dp}\right)_u \left(\frac{\partial p}{\partial t}\right) \tag{4}$$

However,

$$\left(\frac{\partial u}{\partial t}\right) = 0 \tag{5}$$

since the internal energy (or temperature) is assumed to remain constant. Therefore, the final form of the equation of Conservation of Mass is

$$V\left[\left(\frac{\partial\rho}{dp}\right)_u \left(\frac{\partial p}{\partial t}\right)\right] = -w_{out} \tag{6}$$

or

$$\left(\frac{\partial p}{\partial t}\right) = -\frac{w_{out}}{V\left(\frac{\partial\rho}{dp}\right)} \tag{7}$$

Leakages.
To simulate the HTS pressure transient at cold and pressurized conditions of the P-079 test, leakages caused by the seismic event with a total break area of 1.0 in^2 are not considered in this version of the model. Their inclusion would be rather simple by means of modeling them as an orifice with the same break area.

Thus, in Equation (7), w_{out} is the Gland Return flow through the failed open Motorized Valve MV308, which is not of a constant magnitude since it depends on the system pressure. The magnitude of w_{out} is obtained from

$$w_{out} = \sqrt{\frac{p - p_{atm}}{K}} \tag{8}$$

where
p_{atm}: atmospheric pressure [kPa(a)],
K: constant hydraulic resistance.

The value of the hydraulic resistance K in Eq. (8) was obtained assuming a flow of 1.0 kg/s between the pressurized HTS and the Purification system at atmospheric pressure.

2.2 Numerical Solution.

To obtain the numerical solution, Equation (7) is then integrated between two consecutive time steps, t_{n+1} and t_n, to obtain p_{n+1} and p_n, respectively.

$$\int_{p_n}^{p_{n+1}} dp = -\int_{t_n}^{t_{n+1}} \frac{w_{out}}{V\left(\frac{\partial \rho}{dp}\right)} dt \tag{9}$$

Finally,

$$p_{n+1} = p_n - \frac{w_{out}}{V\left(\frac{\partial \rho}{dp}\right)}\left(t_{n+1} - t_n\right) \tag{10}$$

which shows that for the case under study, p_{n+1} will always be smaller in magnitude than p_n, i.e., the HTS pressure will always decline as anticipated.

Initial Conditions.

The following set of initial conditions was used:

HTS Pressure:	8875 kPa(g)
HTS Temperature:	40^oC
HTS Coolant Volume:	139 m^3
Leakage flow:	1.0, 2.0, 3.0, 4.0 and 5.0 kg/s.
Hydraulic resistance:	8648.7 kPa(d)/$(kg/s)^2$
Atmospheric pressure:	101.325 kPa(a)

The rate of change of coolant density as a function of pressure for a constant coolant temperature of 40 ^oC is shown in Figure 1 [3]. To simplify the calculation, a straight line was fitted through the data points, which yielded the average slope of $5.0x10^{-4}$ [kg/(m^3/kPa)] used in this model.

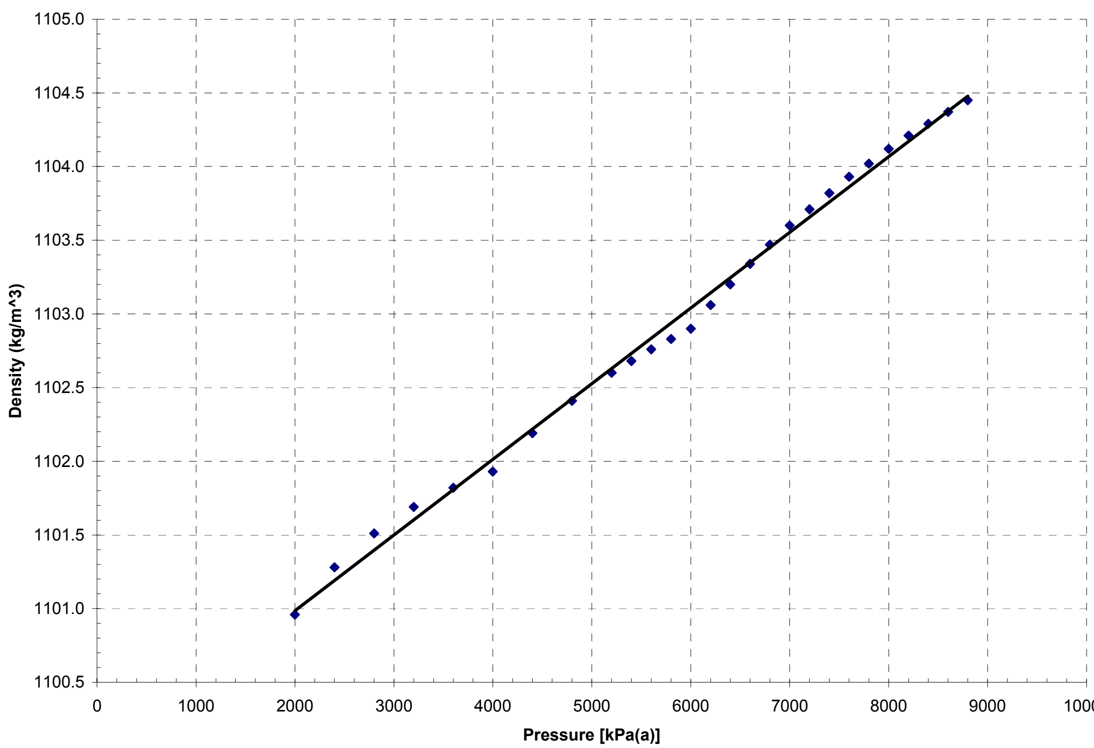

Figure 4. Coolant density as a function of pressure for heavy water at 40^oC.

Solution Process.

Equation (10) was implemented in an Excel spreadsheet and integrated with a time step of 1.0 second, for a total of 120 seconds. It should be pointed out that the evaluation of w_{out} in Equation (8) is carried out with the value of p_n; this was considered acceptable considering the small time step involved.

The first 10 seconds of the calculation for an initial w_{out} of 1.0 kg/s are shown below in Table 1.

Time	HTS Pressure	w_{out}	dP/dt
[s]	[kPa(g)]	[kg/s]	[Pa/s]
0.0	8750.0	1.00	-14388.5
1.0	8735.6	1.00	-14376.5
2.0	8721.0	1.00	-14364.5
3.0	8706.8	1.00	-14352.6
4.0	8692.5	1.00	-14340.6
5.0	8678.1	1.00	-14328.6
6.0	8663.8	1.00	-14316.6
7.0	8649.5	0.99	-14304.7
8.0	8635.2	0.99	-14292.7
9.0	8620.9	0.99	-14280.7
10.0	8606.6	0.99	-14268.8

Table 1. Example of a typical simulation.

The HTS pressure transient was simulated for the specified 5 different flows of w_{out} during 120 seconds.

3.0 Results and Discussion

The P-079 test is usually performed at the beginning of an outage. Once the cooldown evolution is completed, the test instructs the ANO to pressurize the HTS and turn off the Pressurizing pump in service (the Main HTS pumps have already been turned off). The decline of the HTS pressure is then carefully monitored for the next few minutes.

The success criteria indicated in the test is that HTS pressure should be greater than or equal to 4.0 MPa(g) after 90 seconds to demonstrate that the seismic boundary is performing as per design.

Figure 5 shows the results of the parametric study with numerical model for 5 different leakage flows. As anticipated, the HTS pressure will always decline since Feed flow is not available; also, the higher the leakage rate, the faster the decline in pressure. Data collected during the execution of the test are also shown in Figure 5 for both the North and South HTS loops. As shown, the experimental data points match very well with the numerical data for the case where a total leakage is equivalent to 2.0 kg/s, i.e., twice as much as the Gland Return flow.

The comparison of numerical and experimental data suggests that another contributor besides the non-isolatable Gland Return flow through 33340-MV308 dominates the HTS pressure transient. After careful consideration of the options, it was concluded that the most likely contributor was the total leakage passing through the four valves comprising the seismic boundary (NV1 and NV2, and CV122 and CV123).

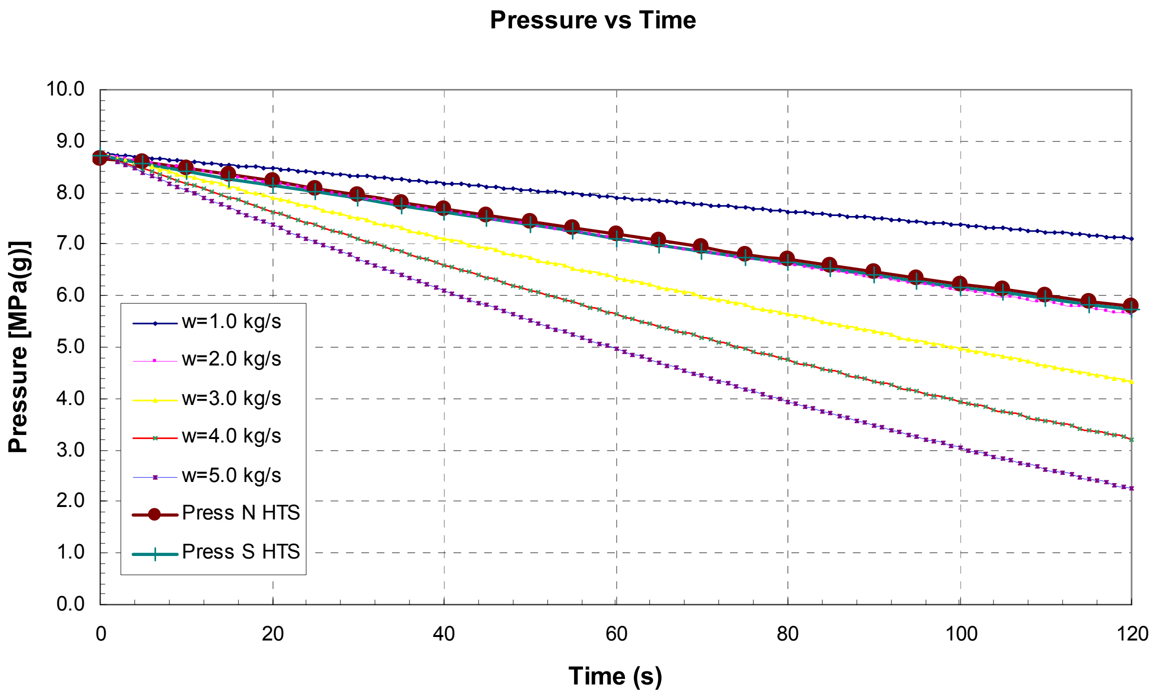

Figure 5. HTS Pressure transient during the P-079 seismic boundary leak tightness test.

Conclusions

A first-principles model was formulated to determine acceptability of the seismic boundary of the HTS based on a leak rate test. The numerical results were compared with experimental data obtained via the test P-079, and show excellent agreement —in both rate and magnitude— with the HTS pressure during the transient. The present version is only limited to cold and pressurized HTS conditions.

References

1. HT Seismic Boundary Leak rate Test, NK30-SRS-P-079.
2. HTS Operating Manual, NK30-OM-5-33000.
3. Nguyen, C., Cheng, S.C., Leung, L.K.H., and D.C. Groeneveld. (1987). 'Tables of Thermodynamic and Transport Properties of Heavy Water,' ARD-TD-243.