ASSESSMENT OF SURVEILLANCE TESTS USED TO ESTIMATE BACKUP INSTRUMENT AIR CAPACITY

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Abstract

In Nuclear Power Plants, Backup Instrument Air (BUIA) is credited as the safety support system powering the mitigating devices used during a design basis accident to ensure that the barriers against radiological releases are maintained. The BUIA normally stored in cylinders or vessels are designed to have adequate capacity to meet minimum mission time requirements, which is confirmed using a Safety Related Surveillance Test (SRST). Normally simple extrapolation of the SRST is performed to determine the available BUIA capacity. This extrapolation is valid dependent upon the conditions and procedure of the test. The available BUIA capacity can be over or under predicted if the thermodynamic changes occurring during the transient, choked flow conditions at the break, and heat transfer from the environment are not rigorously considered. This paper conducts an assessment of the SRST and the typical processes that should be considered for estimating BUIA capacity.

1. Introduction

Airlocks are a key component in a Nuclear Power Plant's path to success for maintaining containment. When the airlock seals are sufficiently pressurized, the airlocks will isolate the atmosphere in the reactor building. Typically, the normal instrument air will supply the seals with an adequate pressure, maintained at a constant set point by a pressure regulating valve. As long as the pressure is maintained, the integrity of the seals will be upheld and can prevent releases from containment. In the event that the normal instrument air is rendered unavailable, BUIA can then be credited as the emergency air supply. A schematic of the normal configuration when the BUIA is in service can be seen in Figure 1. This is the configuration used for simulations within GOTHIC v7.2b [1]. Subsequent inspection and testing is required to ensure the BUIA is replaced as needed and will be able to maintain the pressure in the airlocks for the desired mission time. Since the mission time cannot be measured directly, the pressure drop is measured and extrapolated to determine the mission time. Measuring the pressure drop in the BUIA supply would be ideal, but is difficult due to the required precision and accuracy to detect the small relative changes in a practical time period. The alternative is to perform the test at the airlock seals downstream of the BUIA. A simplified version of the SRST procedure is to isolate the seals from the supply, and observe the pressure decay over a period of time. A schematic for this configuration is shown in Figure 2. Assessment of this SRST for the airlock seals is used as an example and is interchangeable with a general system that has a similar configuration and requires a SRST for BUIA. The importance of incorporating heat transfer and choked flow processes during the BUIA service to the airlocks, and extrapolating the test results for the use of estimating BUIA capacity will be highlighted.

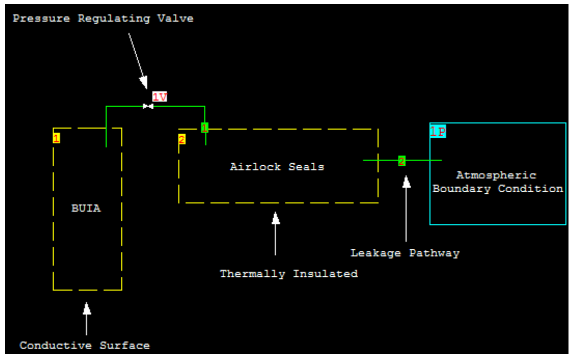

Figure 1: Simplified Normal BUIA and Airlock Configuration with Leak to Atmosphere

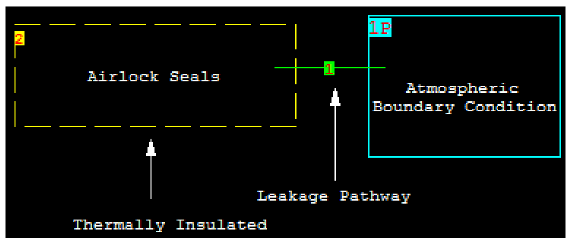

Figure 2: Simplified Testing Configuration with Leak to Atmosphere

2. Assumptions

To simplify the test to be applied generally for a SRST the following assumptions of the system, which is represented by the airlock seals, were made:

- Rigid volumes (the volume of cylinder for BUIA, and volume of the system do not change)
- Pressure in the system is of sufficient pressure relative to that of the surrounding atmosphere such that choked flow occurs at the exit point (for air, the ratio of pressure in the surrounding atmosphere to the system should be less than 0.528)
- Leaks in the system are represented by a small hole or crack to atmosphere, all leaks present in the system are within the isolated volumes tested
- No leaks across isolation valves
- Heat transfer to the gas through the system is not significant and acts as if thermally insulated, furthermore the compression and expansion of air is isentropic
- Energy transfer to the BUIA cylinder from the surroundings in combination with mission time requirements of the system are of sufficient length and capable of keeping the BUIA near ambient temperatures
- Air is dry and assumed to behave as an ideal gas

3. Formulation

3.1 General Formulation

The SRST measures the pressure change in the system (schematic in Figure 2), but in order to properly estimate the BUIA capacity for the configuration as in Figure 1 from the SRST, the underlying processes and how each attributes to the pressure change must be understood. The behaviour of the air can be derived by looking at the transient process of an ideal gas in a rigid volume as shown in Eq (1) or Eq (2).

$$\left(\frac{dP}{dt}\right)V = \frac{\dot{m}RT}{M_{air}} + \frac{mR}{M_{air}}\left(\frac{dT}{dt}\right) \tag{1}$$

$$\left(\frac{dP}{dt}\right)V = \frac{\dot{m}RT}{M_{air}} + \frac{PV}{T}\left(\frac{dT}{dt}\right) \tag{2}$$

Table 1: Description and Units of terms in Equations 1 and 2

Term	Description	Typical Units
dP/dt	Pressure change in the vessel	kPa/h
dT/dt	Temperature change in the vessel	K/h
V	Volume of the rigid vessel	m^3
m	Mass of air in the vessel	kg
$\dot{m}$	Mass flow rate of the gas from or to the vessel	kg/h
R	Ideal gas law constant	kpa.m^3/mol.K
T	Temperature of the vessel	K
M_{air}	Molecular weight of air	kg/mol
P	Pressure in the vessel	kPa

On the boundary between the system and the surrounding atmosphere at the choked point depicted in Figure 3, pressure and temperature will reach critical values as stated in Eq (3).

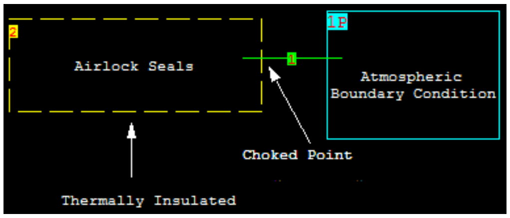

Figure 3: Choked Point between Airlock Seals and Atmosphere

Pressure will drop to the critical pressure which is 52.8% of the system pressure. Temperature as well will drop to the critical temperature which is 5/6th of the system temperature [2].

$$\frac{P_{critical}}{P_{system}} = 0.528 \quad \frac{T_{critical}}{T_{system}} = \frac{5}{6} \tag{3}$$

Knowing the pressure and temperature in the seals allows for calculation of the density and speed of the air escaping at the choked point which can be used to determine the discharge of air dependent on the area of the hole or crack as in Eq (4) [2].

$$\dot{m} = \rho A v = \left(\frac{P}{RT} * M_{air}\right) A \sqrt{kRT} \tag{4}$$

Looking back at Eq (2) the rate of pressure drop in a controlled volume will depend on the rate of the temperature changes, the rate of the mass of air entering/leaving, along with the instantaneous pressure, temperature, and volume of the vessel. Since the volumes of the BUIA and seals are constant, and as shown in Eq (3) and Eq (4) for choked flow, the discharge rate will only depend on upstream (airlock seals) temperature and pressure. The most important variables to consider when measuring pressure decay are the temperature and pressure of the system which is upstream of the break.

3.1.1 Effects of Pressure and Temperature

Pressure having an effect of the pressure decay is intuitive and is evident in the second term in Eq (2). There is a direct relation between pressure and temperature changes; a higher pressure will amplify the effects of a temperature change. The effect of pressure is also present in the first term due to the relation with mass flow. Higher pressures directly upstream of the break will increase the mass flow of air escaping and increase the pressure decay.

The effects of temperature on the rate of pressure drop are more complex. The transient behaviour as well as the instantaneous value of temperature will affect the rate of pressure drop. The instantaneous value of temperature influences the density and speed of the air escaping, and will thus affect mass flow rate. It should be clarified that even though a temperature increase will decrease mass flow, the overall effect of mass flow on the pressure decay will be greater. The temperature also impacts the magnitude of the effect of temperature changes. A higher temperature would result in a smaller effect on the pressure decay, the opposite as seen previously for pressure. The transient behaviour of temperature accounts for the changing density of the vessel on the pressure. If measuring temperature is impractical for the SRST, estimates for temperature changes can be made based on the pressure change. Estimates for the temperature change from the compression or expansion of air is based on an isentropic process shown in Eq (5) [2].

$$\frac{dT}{dt} = \frac{T_1\left(\left(\frac{P_2}{P_1}\right)^{\frac{\gamma-1}{\gamma}} - 1\right)}{dt} \quad \text{where } \gamma\text{=1.4 for dry air} \tag{5}$$

4. Application to BUIA Service and SRST

When the BUIA is connected to the airlock seals such as in Figure 1, pressure is maintained at a constant value in the seals. Since the temperature in the BUIA is roughly constant as well, the seals also experience a roughly constant temperature. Mass flow will be constant since the dependence is on the upstream pressure and temperature. In the configuration for the SRST as in Figure 2 pressure decreases due to the escaping air, and temperature decreases due to the depressurization. This implies the mass flow rate of air escaping during the SRST will change as the test proceeds. The differences in dynamic pressure and temperature between these two scenarios can have large impacts.

The BUIA in service does not experience significant temperature changes like those in the SRST. The impact of the temperature difference can be seen if heat transfer to the BUIA was not considered. Simulations of the airlock seal which has a leak and is supplied air from a BUIA cylinder with the configuration as in Figure 1 were performed. The general system conditions are the same as the example described later in section 5. Shown in Figure 4 the green curve represents the pressure transient when there is no heat transfer between the BUIA cylinder and the surroundings. For the blue curve there is heat transfer to the BUIA, so the temperature is near ambient and does not change significantly as opposed to the green curve where the temperature drops as governed by an isentropic expansion. When there is heat transfer to the BUIA with all other conditions the same the supply lasts ~5000 seconds longer as a result of the temperature being maintained at approximately a constant value.

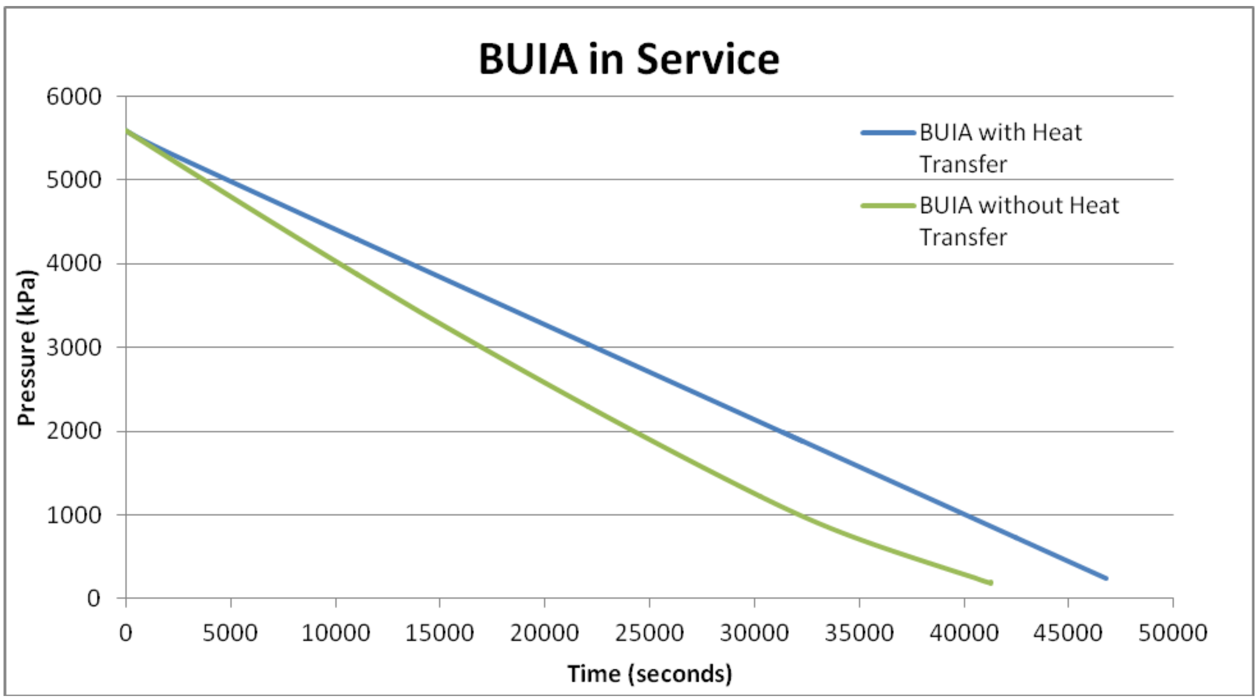

Figure 4: Comparison of the Performance of BUIA With and Without Heat Transfer

4.1 Application to SRST

In the testing procedure (as in Figure 2) the pressure in the airlock seals decreases as it is isolated from its supply. Since the flow is choked and dependent on upstream pressure, this causes the mass flow rate to decrease from that seen at the normal pressure usually maintained by the pressure regulating valve. The rate of pressure decay will decrease alongside mass flow rate. If the test is performed for an extended period of time or too far away from the initial pressure of the system, the pressure decay will not be representative of that which would actually be experienced when the BUIA is in service. The measured pressure decay would be lower and thus overestimate the BUIA capacity. Additionally the seals are thermally insulated, so without the BUIA connection the temperature will decrease due to the depressurization. This will affect the pressure decay through the mass flow rate but more significantly in the second term of Eq (2). All terms in Eq (2) are shown to be applicable since there are temperature and pressure changes during the test. Eq (2.1) can be used to describe the SRST and is specific to the system described.

$$\left(\frac{dP}{dt}\right)V_{sys} = \frac{\dot{m}RT_{sys}}{M_{air}} + \frac{P_{sys}V_{sys}}{T_{sys}}\left(\frac{dT}{dt}\right) \tag{2.1}$$

4.2 Application to BUIA Service

While outside of the testing procedure (as in Figure 1) the BUIA is supplying air to the airlock seals, but since there is natural convection to the BUIA the temperature of the BUIA is kept near ambient temperature. The magnitude of the second term in Eq (2) is insignificant since the temperature change of the process is practically zero. This implies that the mass flow rate out from the seals is the only source for pressure decay. Mass flow rate is also constant as a consequence of the pressure regulating valve and heat transfer. This is shown in Eq (2.2) as the second term in Eq (2) is no longer present. Eq (2.2) is specific to this configuration described.

$$\left(\frac{dP}{dt}\right)V_{BUIA} = \frac{\dot{m}RT_{BUIA}}{M_{air}} \tag{2.2}$$

4.3 Application of SRST to Predict Capacity of BUIA

Since the test is used to predict capacity for BUIA the temperature effects seen in the test procedure must be corrected for to remove the pressure drop caused from the decrease in temperature. The correction should isolate the pressure decay only caused from the mass flow rate of the system. The correction is shown in Eq (2.3) by subtracting the second term in Eq (2.1)

$$\left(\left(\frac{dP}{dt}\right)V_{sys}\right)_{Corrected} = \left(\frac{dP}{dt}\right)V_{sys} - \frac{P_{sys}V_{sys}}{T_{sys}}\left(\frac{dT}{dt}\right) \tag{2.3}$$

This represents the pressure decay solely from the mass flow experienced in the test procedure and should be the identical to that experienced by the BUIA, meaning Eq(2.2) and Eq(2.3) are equivalent. This pressure decay must then have a criteria/limit to compare to for desired mission times. The pass/fail criteria should be based on: the pressures of the system for its function, and the BUIA initial pressure, as well as the mission time required of the system's function. The criteria should define the lowest pressure decay that would cause the BUIA to be unable to maintain the airlock seals at an adequate pressure for the duration of the mission time. To be most conservative the use of the lowest acceptable pressure of the BUIA before it is replaced, and the pressure at which the system is still able to perform its function is recommended. The criteria can be formed through the left hand side of Eq (2), as shown in Eq (6).

$$Pass/fail\ Criteria = \left(\frac{P_{BUIA} - P_{Airlock}}{Mission\ Time}\right)V_{BUIA} \tag{6}$$

The pass/fail criteria represents the maximum pressure decay allowable, as long as the pressure decay for the BUIA from the test found through Eq (2.3) does not exceed that in Eq (6) the seals will last the desired mission time at a minimum. To estimate the remaining time the BUIA can supply the system the pressure decay can be found as in Eq (7) and then extrapolated to find the remaining time the BUIA can supply using the current BUIA pressure and decay rate through Eq (8).

$$\left(\frac{dP}{dt}\right)_{BUIA} = \frac{\left(\left(\frac{dP}{dt}\right)V_{sys}\right)_{Corrected}}{V_{BUIA}} \tag{7}$$

$$Remaining\ Time = \frac{P_{BUIA} - P_{BUIA\ min}}{\left(\frac{dP}{dt}\right)_{BUIA}} \tag{8}$$

5. Example

Considering a BUIA tank with a volume of 54.2 Litres (0.0542 m^3) initially at a pressure of 5.5 MPag (5500kPag) supplying air to airlock seals with a total volume of 5L, maintained at 138 kPag that is to last for 13 hours at an ambient temperature of 20^{o}C (293K).

Figure 4 shows the pressure of the airlock seals while isolated from the BUIA supply until it reaches atmospheric pressure. The temperature decrease is shown in Figure 5, and is large in magnitude occurring in a short period of time. This has a large effect on the pressure through the second term in Eq (2.1). Equations for the Pass/Fail criterion, the pressure decay, and the estimation for BUIA capacity were used to produce results from numerical calculations and software simulations (GOTHIC v7.2b) at t=0 of the SRST and are summarized in Table 2.

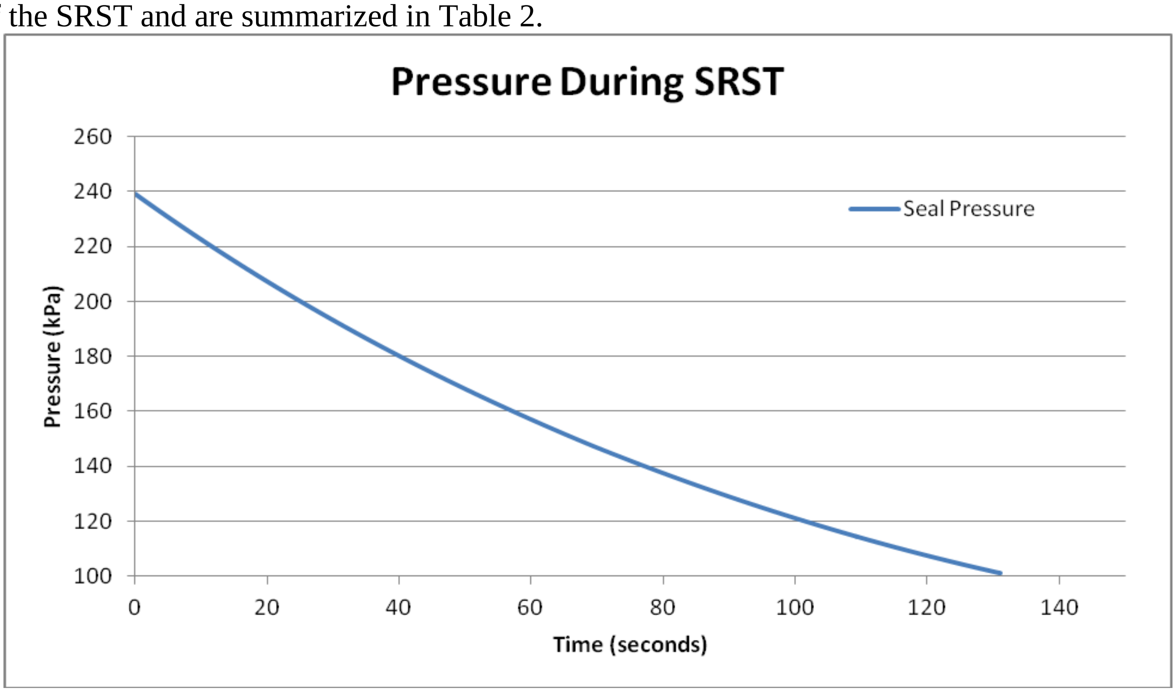

Figure 4: Pressure Transient of Airlock Seals during SRST

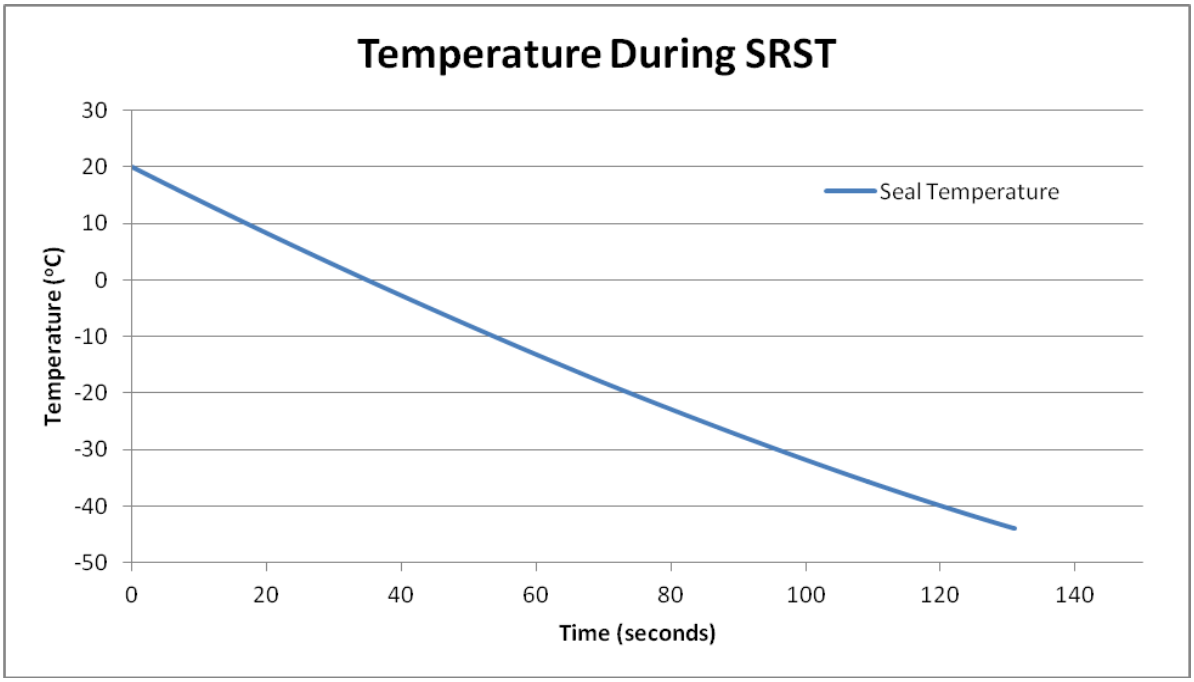

Figure 5: Temperature Transient of Airlock Seals during SRST

Table 2: Numerical and Software Evaluation of SRST

	Numerical	GOTHIC
Pass/Fail criterion Eq (6)	22.355 kPa.m^3/h	22.355 kPa.m^3/h
Measured Pressure Decay Eq (2)	31.255 kPa.m^3/h	30.96 kPa.m^3/h
Corrected Pressure Decay Eq (2.3)	22.302 kPa.m^3/h	22.15 kPa.m^3/h
Pressure Decay Rate Eq (7)	411.48 kPa/h	408.12 kPa/h
Estimated BUIA capacity Eq (8)	13.03 hours	13.12 hours

The results show that the numerical calculations are validated with similar results from GOTHIC. With the correction for temperature the numerical calculation is accurate and only ~0.05 kPa.m^3/h lower than the specified pass/fail criteria.

From the numerical calculations the capacity of the BUIA was predicted with the uncorrected and corrected pressure decay, the values are shown in Table 3. It is seen that applying the correction for the temperature is vital due to the consequential effect on the pressure. Without the correction, the measured pressure decay (31.255 kPa.m^3/h) would have underestimated the capacity to last only 72% of the mission time. The corrections using either numerical or GOTHIC results for the predicted capacity have less than 1% error.

Table 3: Corrected and Uncorrected Predicted BUIA Capacity from Numerical Calculations

	SRST Uncorrected	SRST Corrected
Estimated BUIA capacity	9.30 hours	13.03 hours

6. Conclusion

To properly evaluate the BUIA capacity from the SRST the differences in the applicable processes that occur in the SRST and actual configuration must be considered and accounted for. If not rigorously considered, errors can result. This can be seen in tests when the pressure deviates away from the nominally maintained pressure or occurs over too long of a time period. The observed pressure decay will then be much smaller because choked flow is dependent upon the system pressure, as pressure decreases so will the mass flow and consequently pressure decay. This will lead to an overestimation of the BUIA capacity. Errors can also be observed if temperature effects are not taken into account. Tests of the airlock seals which are considered to be thermally insulated experience large temperature drops which then significantly decrease the pressure. Uncorrected measurements of the pressure drop then underestimate the capacity because this temperature and pressure drop is not seen in the BUIA. With the proper identification of the processes and criteria presented in this paper, the capacity of BUIA can be more accurately predicted in crediting mitigating devices relying on BUIA.

References

[1] Electric Power Research Institute (EPRI), *GOTHIC Version 7.2b (QA)*, Mar, 2009.
[2] R. M. Olson, “Essentials of engineering fluid mechanics”, Fourth Edition, 1980, pp. 16 and 345-346