Containment Isolation for the ARC-100 Sodium Fast Reactor

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Abstract

Containment isolation requirements stated in CSA nuclear standards and CNSC regulatory documents were originally intended for water cooled reactor technology. The requirements can also be applied to advanced reactor technologies such as sodium fast reactors. The functional requirements found in regulatory documents and CSA standards, paired with the abundant international design literature and experience, can be applied to design safe pressure boundary containment penetrations and containment isolation in aSMR technology. Existing design experience and technology within the water cooled reactor industry can also be combined with sodium equipment design expertise to create safe reliable containment isolation for sodium pressure boundary systems.

Butterfly valves are used for containment isolation in CANDU nuclear power plants because of their lightweight and fast actuation. Butterfly valves are a good candidate for containment isolation in sodium pressure boundary systems. Stem sealing in sodium systems is currently achieved by use of bellows seals or sodium freeze plugs, butterfly valves allow for a shorter stem seal reducing the overall size and weight of the containment isolation valve.

1. Introduction

The ARC-100 is a 100 MWe pool type sodium fast reactor (SFR) being designed by ARC Clean Technology. This commercial demonstration unit will be constructed at the Point Lepreau Nuclear Generating Station in New Brunswick Canada and is planned to be operational by 2030. The ARC-100 will provide a stable form of non-emitting electrical power for the New Brunswick grid. This will also make it the first Generation IV reactor in Canada.

Although it may be a Canadian first it is far from the first of its kind; there have been many operational sodium fast reactors across multiple countries with thermal powers up to 3000 MWt [1]. SFR technology has existed since the start of the nuclear industry, but development largely ceased following the sudden drop in new nuclear construction in the late seventies and eighties. Some of the advantages of an advanced sodium fast reactor are a longer fuel life and reduction of the amount of transuranic waste produced. Sodium is used as a coolant in fast neutron reactors due to its nuclear and thermophysical properties: sodium is a weak neutron moderator and has a small neutron capture cross section. Neutron capture by Na-23, the only stable form of sodium, results in the formation of Na-24 which has a half-life of 15 hours and decays to stable Mg-24. Notable thermophysical properties of sodium are a melting temperature of 98°C, a high boiling temperature of 877°C, a high rate of thermal conductivity of 47.7 W/m°C to 86.9 W/m°C, and a specific heat ranging from 1.26 to 1.42 KJ/kg K, the last two varying with the temperature of the sodium [2]. These characteristics make sodium an excellent coolant for fast neutron reactors being a poor neutron moderator, an excellent heat transfer medium, and having a high margin to boil of several hundred degrees Celsius.

Sodium is used in the Primary Heat Transport System and the Intermediate Heat Transport System of the ARC-100. The Primary Heat Transport system is wholly contained within the reactor vessel and is separated into a hot and a cold pool by an internal non pressure bearing divider called the redan, as shown in Figure 1. Primary sodium is pumped from the cold pool and discharged into the core inlet plenum found below the reactor core. From the inlet plenum sodium flows up through the core gaining heat, after which it enters the hot pool, which is contained inside the redan. From the hot pool the sodium flows through heat exchangers and discharges back into the cold pool. The heat exchangers are shell and tube design with primary sodium on the shell side and intermediate sodium on the tube side. Intermediate sodium is used as the heat source for the steam generator. Unlike CANDU technology, the Intermediate Heat Transport System and steam generator are not credited with a core cooling function during an accident scenario. The Primary Heat Transport System in conjunction with the two decay heat removal/shutdown cooling systems are fully responsible for core heat removal of the ARC-100.

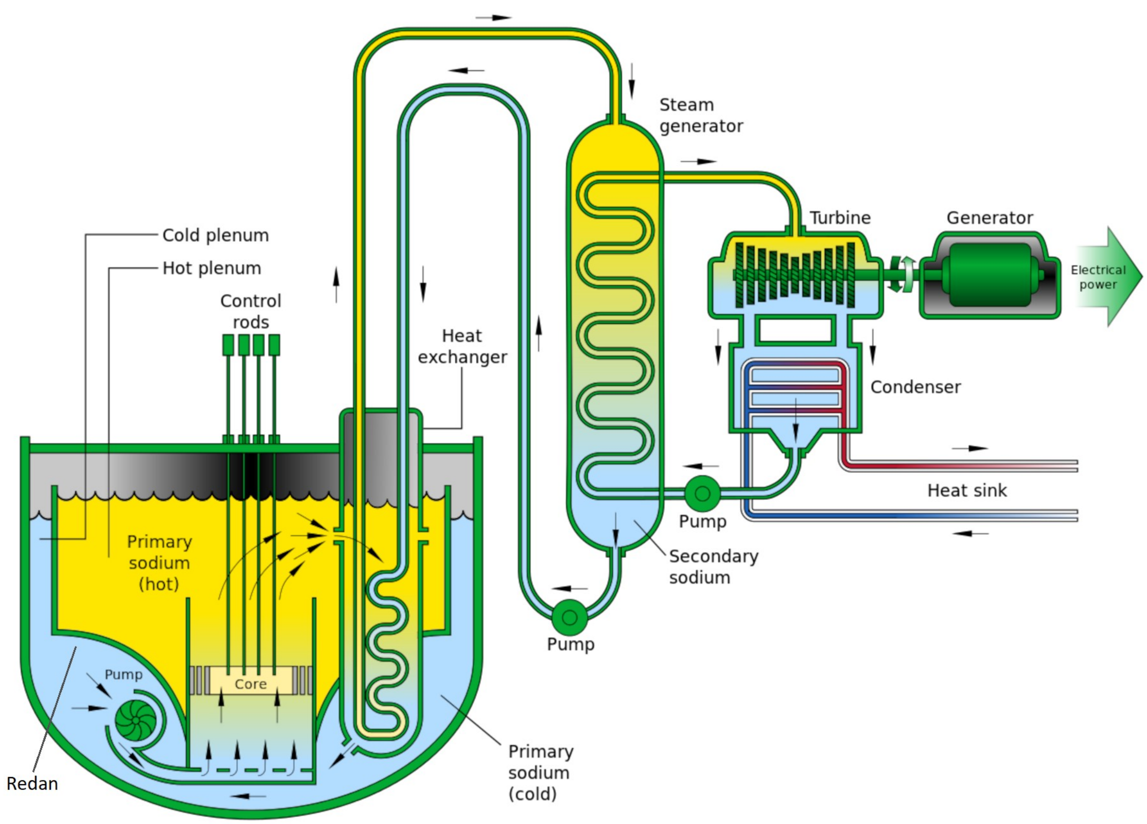


Figure 1 An example diagram of a pool type sodium fast reactor.

The Intermediate Heat Transport System will require four large diameter containment penetrations in the reactor building, making the regulatory requirements of containment isolation applicable to this system.

2. Regulatory Documents and Standards

Requirements for containment isolation stem from regulatory documents, codes and standards, and local jurisdiction requirements. Regulator documents and standards in Canada are generally written for water cooled nuclear technology. However, the governing act with respect to nuclear facilities in Canada is the Nuclear Safety and Control Act, which itself does not specify any specific nuclear technology but rather states that the act applies to nuclear facilities in general and grants the CNSC authority to regulate the industry.

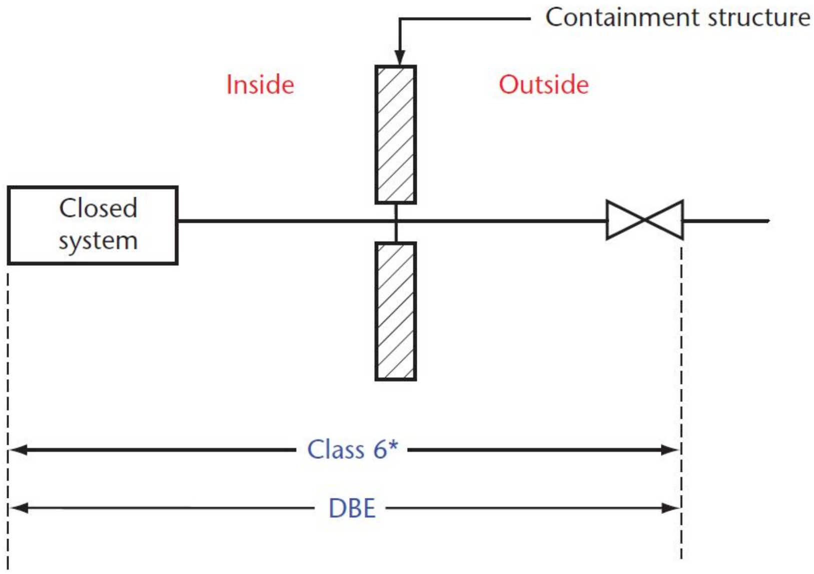
Containment isolation design requirements for reactor facilities are found in CNSC regulatory document Reg Doc 2.5.2. Technologies other than water cooled reactors, like the ARC-100, must meet the safety objectives, high-level safety concepts, and safety management requirements found in Reg Doc 2.5.2 [3]. CNSC regulatory documents can point to CSA standard for additional guidance and information. Also, operating licenses can require utilities to follow CSA standards. Although these standards were written for CANDU technology, the functional requirements found in the standards, like containment isolation, can be applied to non-water cooled reactors to fulfill the safety objectives of the regulatory documents.

Containment safety objectives and high-level safety concepts of Reg Doc 2.5.2 are summarized in section 8.6 “Each nuclear power reactor shall be installed within a containment structure, so as to minimize the release of radioactive materials to the environment during operational states and DBAs” [3]. The purpose of containment is therefore to protect the public, the environment, and the workers from exposure to radioactive substances to the maximum extent practical, whether water based or otherwise.

Section 8.6.6 of Reg Doc 2.5.2 focuses on specific requirements of containment isolation and the arrangement of components responsible for isolation. The concern is implementing isolation quickly enough, with a high degree of reliability, and to ensure that once isolation is in place that any leakage will be within the allowable margins. The Intermediate Heat Transport System of the ARC-100 contains two loops and four total containment penetrations and would be considered a closed system as they are not open to the reactor building atmosphere. The following requirement from section 8.6.6 would apply: “All closed piping service systems shall have at least one single isolation valve on each line penetrating the containment, with the valve being located outside of, but as close as practicable to, the containment structure” [3].

Additional information on containment can be found in CSA N290.3-11 on requirements for the containment systems of nuclear power plants [3]. Design requirements for containment subsystems are found in section 9 with acceptable isolation device arrangements for closed piping systems on new builds covered in Annex B.4 [4]. Figure 2 shows the approximate isolation device arrangement applicable to the ARC-100 Intermediate Heat Transport System piping penetrations of the reactor building, with the exception that rather than Class 6 as show it will be Class 2. This arrangement satisfies the safety requirements and functional requirements of Reg Doc 2.5.2 and CSA N290.3-11.

(a)



*The design pressure of the closed system is greater than the design pressure of the containment boundary. The closed system is either
(a) pressure tested regularly; or
(b) operated at a pressure greater than the containment design pressure and monitored for leaks.

Figure 2 From CSA N290.3-11 Figure B.3 (a) is similar to the containment isolation on the Intermediate Heat Transport System of the ARC-100 with the exception that it will be Class 2 instead of Class 6 [4].

Other relevant CSA standards regarding containment isolation are CSA N285.0-12. The purpose of this CSA standard is to provide requirements on pressure-retaining systems of CANDU nuclear power plants. Although it specifies CANDU technology this standard provides a class designation for pressure retaining systems generally based on system function. CSA N285.0-12 Class 2 designation is for pressure boundary systems that form part of the containment boundary [5]. The specific fluid of the pressure boundary system is not relevant for a Class 2 designation. As mentioned above, sections of the Intermediate Heat Transport System will be CSA N285 Class 2. Based on classification, CSA N285.0-12 provided specific requirements that typically direct the user to relevant sections of the American Society of Mechanical Engineers (ASME) Boiler Pressure Vessel Code (BPVC) [5].

3. Experience with Sodium Valves

The physical and chemical properties of sodium are well understood. In the nuclear industry as a coolant there is a great deal of operating experience as the United States, the United Kingdom, France, Japan, India, Russia, and China all have operational experience with sodium fast reactors and the accompanying systems and components such as valves [1]. Although there are some key differences between valves designed for sodium operation and those used in water operation, they are generally quite similar. In terms of valve types, gate, globe, butterfly, non-lubricated plug, check, venturi-type ball, torque-tube, and freeze seat valves have all been used in sodium systems. Isolation valves that work best for liquid sodium service are gate, globe, and butterfly valves [6]. Velan Inc. has developed sodium valves and manufactures all three of these types of isolation valves, see Figure 3.

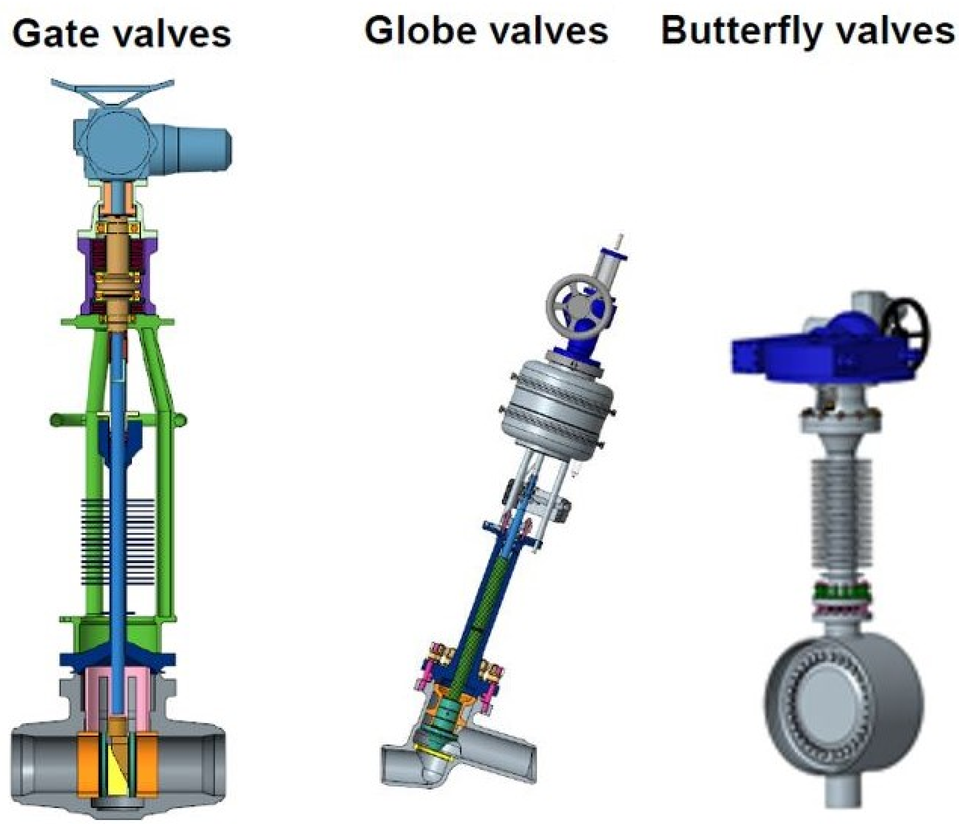


Figure 3 A gate, globe, and butterfly valve for sodium service designed and manufactured by Velan Inc. image curtesy of Velan Inc.

There are certain valve characteristics that make for better performance in liquid sodium service. For example, the disc types used for gate valves in sodium service are typically flexible wedge disc or split wedge disc as they provide better sealing; they also tend to prevent seizing when a valve is closed hot and then opened cold [6]. Similarly globe valves with free standing seat geometry have been found to have excellent internal leak tightness [6]. Another important consideration is the physical size of the valve. Gate valve bonnets can become restrictively large for larger diameter valves due to the requirements for translational travel of the stem, and the need to remove the gate completely from the flow path. Freeze stem sealing also requires large bonnets for heat removal [6]. Globe valves by comparison can have reduced stem travel compared to gate valves as the disc does not have to move as far to fully open the valve [6]. Finally butterfly valves utilize rotational motion of the stem and therefore can have the shortest stem.

Austenitic stainless steels are typically used for the pressure retaining components of valves in sodium service [6]. Furthermore, the material performance in this role has been highly satisfactory [7]. In terms of manufacturing methods forgings are preferred over castings for valve components due to concerns of porosity and sodium leakage [7]. One of the key advantages of austenitic stainless steels such as 304 and 316 is their corrosion resistance. These grades of austenitic stainless steel have been used in sodium service with no mass transfer under 1000°F (538°C) and moderate mass transfer up to

1600°F (871°C) [9]. However, if the concentration of oxygen or carbon is too high the rate of corrosion can become appreciable [8]. Another material consideration for valves in high temperature sodium service is surface hardness of valve internals. Hardness prevents galling and unintended fusing of components [6]. With respect to galling, the use of many conventional lubricants or greases, to reduce wear of components is not possible in sodium systems as sodium will react with carbonaceous material and corrode stainless steel [9].

Another key characteristic of sodium valves is the sealing requirements. Liquid sodium is a difficult substance to seal due to its low viscosity, excellent "wetting" properties, and penetration characteristics at elevated temperatures [6]. The consequences of sodium leakage and possible fire results in the need to maintain absolute external leak tightness [10]. It should also be noted that the need for sealing is also to minimize air ingress into the system. The combination of a liquid that is difficult to seal against and the need for very low leakage rates results in many conventional sealing techniques being insufficient. The two leading techniques for sealing valve components are bellows stem seals and frozen sodium stem seals.

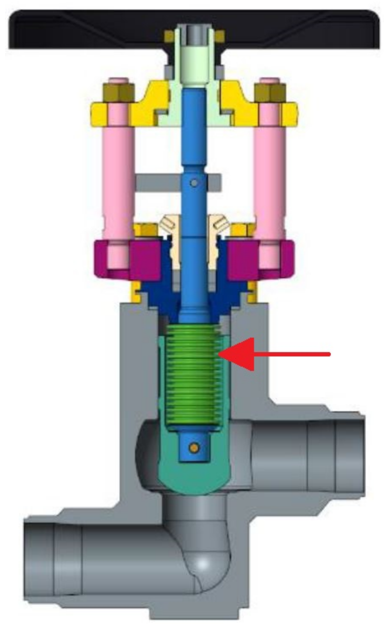


Figure 4 Globe valve with location of bellows indicated, image curtesy of Velan Inc.

A bellows stem seal provides a physical barrier inside the valve between the valve body and the bonnet that is sealed to the stem shaft; this prevents any leakage as long as the bellows seal remains intact [6]. An example of a bellows sealed valve can be seen in Figure 4. The failure of bellows resulting in sodium leakage has been an issue; the thin metal of bellows seals leaves them susceptible to flow induced vibration and fatigue. Also, bellows lack the excess wall thickness that a pipe, or other pressure retaining component, might have to account for corrosion allowance. The thin wall of a bellows makes corrosive damage more of an issue should chemistry control not be maintained, or if the bellows become sensitized [6]. Bellows seals are also subject to failure in sodium systems that are allowed to freeze. If a valve is actuated while containing solid/frozen sodium it will likely rupture [6]. Similarly thawing of a frozen system can damage the bellows seals if not done properly. The expansion of sodium, if trapped in the valve body, can crush the bellows [6]. In practice allowing sodium to freeze in a piping system is avoided where possible. For this reason, sodium piping systems typically incorporate trace heating. Despite these issues overall international operating experience has found the performance of bellows seals to be satisfactory [7]. Bellows seals are used for smaller sized valves with translational movement of the valve stem. Bellows are not well suited for rotational applications, or the large stem travel required in larger sized valves [7].

The other primary form of sealing is valve stem freeze seals. The seal is created by sodium rising in the annulus between the stem shaft and bonnet and freezing to form a seal [6]. Sodium's high conductive rate of heat transfer and melting point of 98°C allow for this type of sealing to be possible, see Figure 5 for a temperature profile of a stem freeze seal. Free convection has been found to be sufficient for cooling sodium below its freezing temperature. Fins are often added to the valve bonnet to aid in heat removal and reduce the large size of the bonnet required for freeze stem sealing [6].

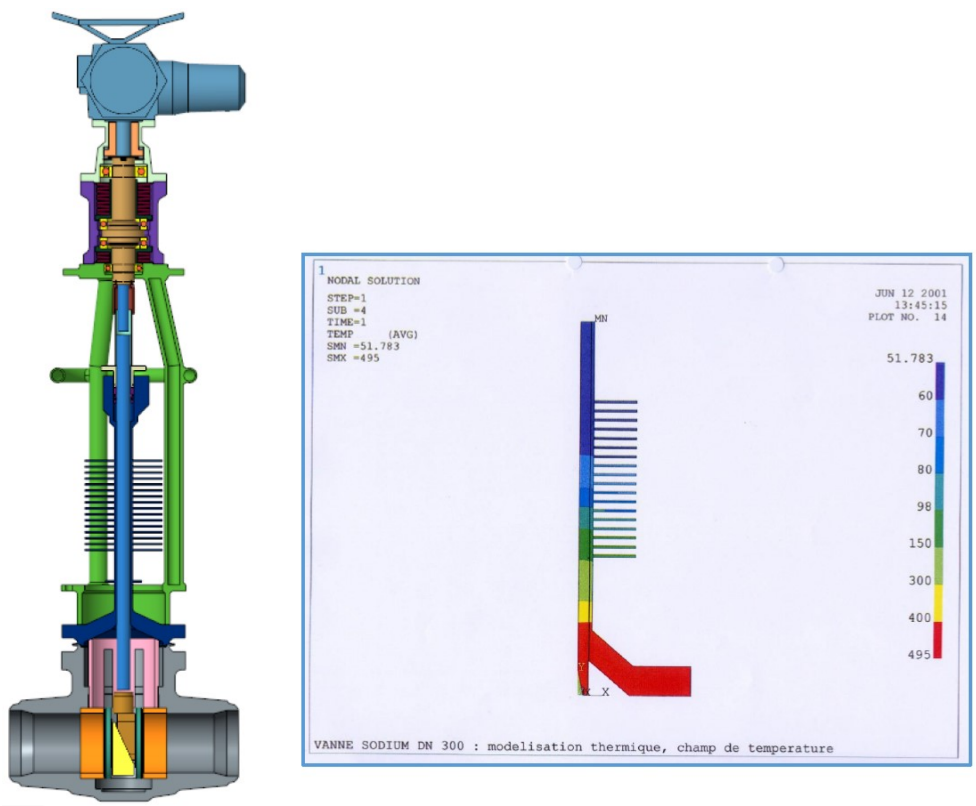


Figure 5 Stem freeze sealing modelled on a gate valve. The image shows how the temperature quickly drops off as the distance up the annulus increases reaching solidification temperatures after about 1/4 of the finned section. Image curtesy of Velan Inc.

Although corrosion of austenitic stainless steels is minimal if impurities in the sodium are controlled, stem seal freezing can act as a cold trap and result in oxide formation.[6]. This is due to the diffusion of oxygen into the frozen sodium seal from the open space in the valve bonnet above the frozen sodium seal [6]. The accumulation of oxides can cause issues with operation of the valve, requiring more force for actuation and can increase the local rate of corrosion; for this reason, the annulus in stem freeze sealed valves should be routinely thawed and purged with inert gas [6]. The frequency of this process will depend on the sodium purity and the valve but for reference, in an average system this procedure can be done less frequently than once a year [6]. This issue of oxide accumulation also leads to a preference for freeze seals in valves where the stems relative motion to the seal will be rotational as opposed to translational [7]. This is due to concerns that translational operation can draw more oxygen into the seal and increase the rate of oxide formation, as part of the stem exits and reenters the frozen sodium seal [6]. There are also concerns about the possibility of extruding the sodium beyond the seal during actuation of a translational stem [7].

Along with these two methods of sealing valve stems, there is often a secondary seal normally in the form of a packing seal with sodium resistant material [6]. In addition, some valves will go even further and incorporate all three types of sealing [6]. The use of redundant sealing works well in conjunction with leak detectors that are often installed between the freeze seal or bellows seal and the secondary seal, allowing the detection of a failure while one seal is still functional [6].

Sealing end connections in liquid metal service should be made by welding to ensure minimal leakage. Mechanical joints are used only when absolutely necessary due to their tendency to leak [6]. Furthermore, it should be mentioned that any mechanical connections present in the system are typically seal welded. Lip sealing a bolted attachment of valve bonnet to body is an example of a seal welded joint to ensure leak tightness.

Another design characteristic that must be considered in sodium valves is the geometry of the valve body. Due to the high operating temperatures, such as with the ARC-100s Intermediate Heat Transport System (325 to 475°C), the thermal growth will be appreciable in the valves and the piping systems. Austenitic stainless steels such as 304 and 316 have high thermal expansion coefficients, which can result in high thermal stresses and distortions. Measures such as consistent thicknesses and gradual transitions between thicknesses to avoid stress concentrations are therefore required. An example of this practice can be seen in Figure 3: the design of the valve is intended to keep thickness constant and use simplified geometries. Simple geometry is also advantageous for sodium valves to resist thermal stress cycling from the high temperatures and cycling that can result in creep-fatigue failures [7]. The high operating temperatures and thermal expansion can also cause issues with internal leakage. Thermal gradients through the thickness of the body can result in uneven thermal expansion and distortion of the seating surface leading to internal leakage [7]. Similarly, thermal expansion in the piping system can result in distortion or bending moments being placed on the valve which can result in distortion of the valve seat that can also lead to internal leakage [6].

4. Comparison of valves for sodium and water service

From the above description of elements important to sodium valves it is apparent that although there are some differences, they are largely like valves used in CANDU service. There are many common features shared between the technologies such as: the use of hard facing of valve internals (primarily for wear in CANDU units), ductile material use for pressure retaining parts, and control of fluid chemistry to minimize impurity concentrations for the reduction of corrosion.

Significant differences between sodium valves and CANDU isolation valves are operating temperatures and pressures, and stem sealing. The higher operating temperatures of sodium service leads to materials that are stronger, more creep resistant, and offer more corrosion protection. This leads to the use of austenitic stainless steels. The high temperatures and increased rate of thermal expansion leads to greater thermal stresses and distortions. This results in the need for simple designs with consistent thickness to minimize thermal stresses and prevent jamming or internal leakage. High temperature issues are not specific to sodium. Refining, process, and non-nuclear power generation sectors experience high temperature issues and are resolved regularly. However, high temperature operation may be novel to the CANDU nuclear industry.

Lower pressures are also a significant difference in the use of sodium valves, the operating pressure in the Intermediate Heat Transport System of the ARC-100 is under 400 kPa(g). Lower operating pressure in sodium systems is the leading cause in the reduction of failure rates of valves in sodium service when compared to water service [11]. This results in a decreased emphasis on pressure as the mode of failure in the face of issues with high temperature operation.

Sealing is important in CANDU valves as well, small leaks can pose safety hazards, radiological problems, and loss of condensate or D2O. The difference between the two is that small leaks are to be minimized as much as possible in water systems, in sodium systems they must be eliminated. For this reason, sodium sealing options are more limited and stringent, this results in the focus on bellows and stem freeze sealing, while packing and other more conventional seals are viewed as secondary. Bellows seals are used in both water and sodium service for their ability to create a positive seal. Stem freeze sealing can be likened to the ice plugs used for online repairs in the CANDU water systems except used for sealing at all times not just repairs.

5. Comparison of containment isolation valves

Before the Astrid project was cancelled in 2019, the CEA, Velan, and Areva, had performed an analysis to determine the best type of valve for isolation of a sodium piping loop [7]. They compared gate, globe, and butterfly valves [7]. Their conclusion was that butterfly valves in particular had distinct advantages [7]. The first being the valve body can easily be designed to match the piping and thus avoid any complex geometry or sudden changes in thickness [7]. This provides an advantage with respect to thermal stresses discussed previously. Butterfly valves also showed advantages in their seismic characteristics: the lighter weight and shorter bonnet creates an advantage in this respect [7].

The seismic response and simplicity of design are not exclusive to sodium, these are desirable attributes in all containment isolation valves, like those found in CANDU plants. Additionally, the fast actuation of butterfly valves fulfills containment isolation requirements. For the CANDU-6 at the Point Lepreau Nuclear Generating Station, each containment isolation, including the time it takes for detection and transmittal of signal, is required to close within seconds [12]. These quick closing times are required as the rising internal pressure inside the reactor building will push radiation outside of containment. The ARC-100 has a distinct advantage over pressurized designs, in the event of an accident the pressure rise inside containment is low making containment requirements less severe than water cooled reactors.

6. Conclusion

For the ARC-100 the containment isolation valves for sodium systems can utilize the existing CNSC regulatory documents and CSA nuclear standards in their current form, by meeting the safety objectives, high-level safety concepts and safety management requirements associated with Reg Doc 2.5.2. Although there are some key differences between valves used in sodium and water service, development of sodium valve technology, by industry leaders, paired with existing CANDU experience on containment isolation valves will create a safe and reliable containment isolation valve for the ARC-100.

7. References

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