Study of isolation valve for Sodium Fast Reactor

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Abstract. In the context of the ASTRID (Advanced Sodium Technological Reactor for Industrial Demonstration) project, the VELAN Company is involved in proposing an isolation valve concept to guaranty the confinement of the reactor block in the event of a severe accident scenario. An innovative and compact design for the isolation sodium valve was developed. Following the basic design phase studies on the sodium secondary loops, a dedicated valve concept was studied to evaluate the technical parameters. The large size of the valve ND 700 mm requires an optimization of the mass and dimensions for cost control purposes and for improvement of seismic behaviour. After a description of the service conditions, the paper presents the mains outcomes of the technical parameters (mechanical behaviour, sealing performance, hydraulic performance) which led on several valve designs. Maintenance aspects are also considered and a proposal of a butterfly valve design is made for detailed studies.

Key Words: Valve, Sodium, Isolation

1. Introduction

The ASTRID (Advanced Sodium Technological Reactor for Industrial Demonstration) project is a technological integration prototype intended for the industrial-scale safety and operation demonstration of 4th generation sodium-cooled reactors. This integrated design reactor includes an intermediate sodium circuit composed of 4 secondary loops. Each ND 700 diameter loop consists of an intermediate exchanger built into the reactor tank, a sodium/gas exchanger and an electromagnetic pump. To reinforce containment, an isolation valve is placed on each of these secondary loops, on each hot and cold leg. The nature of the selected coolant, the operating conditions and associated dimensions, along with the operating requirements, imply an in-depth study of the selection of technology and materials used and, in more general terms, of the overall operation of this specific valve.

At this stage of the project, the functional analysis process serves to structure and break down the main functions of the instrument into technological solutions. We shall initially limit ourselves to mention the various solutions considered. We shall then give a brief description of each solution and will then analyse the advantages and disadvantages of each of the technologies relative to those functions that we consider to be critical and decisive for the final choice of solution.

2. Service conditions

Origin of the need: In the event of severe accident (core meltdown) and of concomitant loss of the 2nd containment barrier at the level of the primary/secondary intermediate exchanger (internal leak), the secondary circuit must be capable of containing any radioactive substances by acting as a 3rd barrier and as an extension of the containment realized by the reactor building.

In order to limit the impact on the secondary circuit, at this stage of the ASTRID project, we propose to implement this containment function by means of two isolation valves fitted onto the circuit's main ND 700 lines, as close as possible to the containment penetrations of the reactor building (see diagram below).

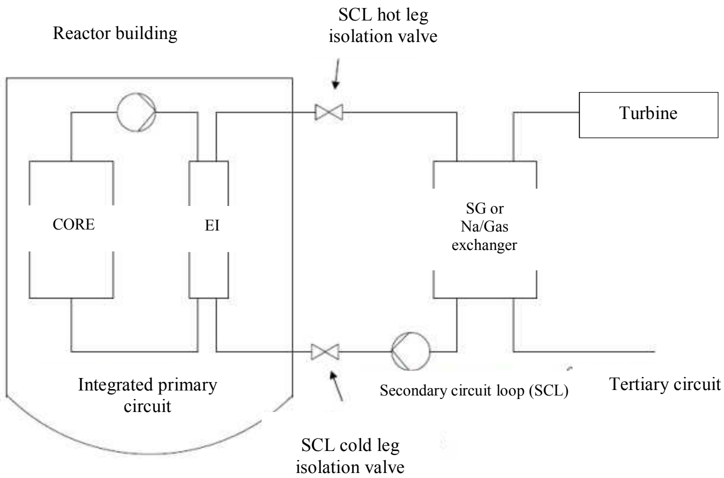

FIG. 1. ASTRID circuit drawing

The main function of the secondary circuit loop (SCL) isolation valves is thus to re-establish the containment as rapidly as possible after the severe accident, while limiting mechanical stresses on the circuit (no rapid shut-off required). Once the valves are closed, they shall guarantee a level of upstream/downstream and external tightness ensuring compliance with the release limits stipulated by the safety studies. This function must be provided under operating conditions corresponding to the severe accident (sodium or argon at 650 °C, possible seismic aftershock, etc.), the valve having previously suffered from the most penalising initiating event identified in the accident studies (Raised Earthquake (RE) = 1.5 Design Basis Earthquake (DBE)).

Beyond this primary containment function, we consider at this stage of the ASTRID project that the presence of isolation valves on the SCLs can be relevant to other lower category accidents leading to internal intermediate exchanger (IE) leaks. The aim in these cases is to close the valves to limit the consequences of this leak in terms of coolant transfer between primary and secondary circuits. Here again, the function must be fulfilled under operating conditions corresponding to the accident in question, previously taking into consideration the most penalising initiating event.

Finally, the presence of valves on the SCLs intrinsically implies the following functions:

- Prevention of chemical risk associated with the presence of sodium, reflecting the need to ensure external tightness anyway.

- Optimization of pressure loss generated by the valves.

Valve operability relative to the aforementioned functions shall be guaranteed any time and thus maintained during the entire service life (60 years) under all the operating situations encountered: normal, upset and accidental (excluding accidental situations not leading to Sever Accident). Function availability is maintained by the implementation, during unit shutdowns, of a periodic in-service inspection and testing programme, followed by a maintenance programme, both of which being adapted to the operating constraints and do not compromising the general reactor availability objectives.

The main valve operating conditions can be summarized as follows:

Normal conditions (open valve):

- Reactor at nominal power: 540 °C, 11 bar, 1600 kg/s (Qn).
- Reactor stopped: 200 °C, 6 bar, 400 kg/s.
- Approximately 1200 start-up transients.

Upset conditions (open valve): thermal cycling (approximately 800 shutdown transients and 6500 frequency adjustment transients).

Accidental conditions:

- Secondary/tertiary exchanger leak (open valve) resulting in overpressure in the valves (maximum 20 bar).
- Primary/secondary intermediate exchanger leak leading to valve closure (at 540 °C, 10% Qn and a 3 bar differential pressure).
- Sudden valve closure (at 540 °C, 10% Qn) leading to a differential pressure of 15 bar (by boiler effect of the isolated volume on the Intermediate Exchanger side).

Severe accident: valve closure at 650 °C, 10% Qn and a 3 bar differential pressure. These operating conditions may change according to the studies conducted and changes in the design of the ASTRID reactor during this development phase.

3. Valve concepts

The functional analysis process is used to structure and break down the main functions of the instrument into technological solutions. Originally, the Functional Analysis was linked to the Value Analysis; it has now become a process in and of itself and is used in many disciplines. The expression of solutions arising from the functional analysis conducted in this article does not intend to provide an exhaustive overview of possible solutions to realize a given function, but rather to apply and to formalize the design process.

The functional analysis presented below is limited to the expression of need by the engineering service in charge of designing the nuclear island. This functional analysis, referred to as the "needs analysis", is part of the equipment technical specification. It is broken down into subunits by the equipment designer in order to demonstrate product compliance with the need (qualification plan). This is referred to as the "product" functional analysis.

At this stage, we shall limit ourselves to describe those functions that we have deemed critical in the context of this study:

- Internal seal
- Manoeuvrability
- Pressure loss
- External seal

The functional analysis thus expresses, without function ranking, the three following main valve technologies:

- Gate valve,
- Butterfly valve,
- Globe valve.

A TRL (Technology Readiness Level) analysis of each of the aforementioned instrument technologies was conducted to determine their maturity for use in the ASTRID reactor. These three technologies are already in use in sodium-cooled reactors such as Phenix and Superphenix. Their applications, however, are governed by reactor circuit function.

In sodium-cooled facilities, Gate valves (see FIG. 2) are generally used for isolation purposes. As such, these devices are governed by current nuclear safety rules. The Gate valve technology presents numerous technical advantages, in particular the possibility of full internal passage, guaranteeing its privileged position in the isolation valve studies conducted on the ASTRID reactor secondary sodium loops. Some of the disadvantages of this technology include the equipment's significant weight and size.

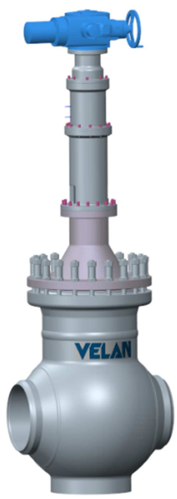

FIG.2. ND 700 mm locking gate valve

The butterfly valve *(see FIG. 3)* is used on RNR (Superphenix SCL) to shunt the sodium to the sodium/air heat exchangers in parallel to the steam generators, in order to dissipate the residual power. These ND 700 devices are able to direct almost all the sodium to this circuit, but are not designed to realize an isolation compatible with the requirements of the ASTRID SCL valve.

The Butterfly valve technology has a proven track record in the field of cryogenics, particularly in the transport of liquid natural gas. This valve concept can also be applied to high temperatures, specifically in gas, oil and nuclear processes. Used in particular as a steam circuit sectional valve on the US nuclear market, this technology can operate continuously at temperatures of more than 550 °C. An optimized version of this concept could reach the performance level required for a sodium environment.

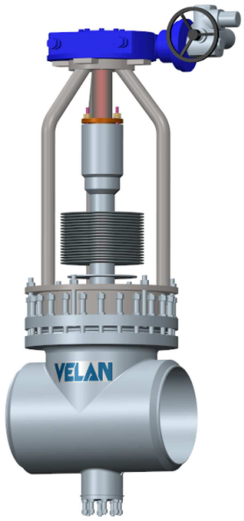

FIG.3. ND 700 mm Butterfly valve

Finally, it should be noted that the Butterfly valve technology offers some major technical benefits, with in particular its significantly smaller weight and size, while its main disadvantage consists in maintaining the seal in the valve flow path in the open position (additional line pressure loss).

Globe valves *(see FIG. 4)* are used for flow or pressure control, in particular on circuits of a diameter of less than 150 mm. Some of these devices, however, can also be used for isolation purposes. This robust technology presents the advantage of having no frictional internal parts throughout the manoeuvre phase. Under some conditions, however, an occluder guide system may be considered. In this case, some precautions must be taken to avoid jamming in the event of a possible thermal shock. It should also be noted that the bodies geometry (Y, Z or angular) can impact the system's hydrodynamic performance and has a major influence on system layout.

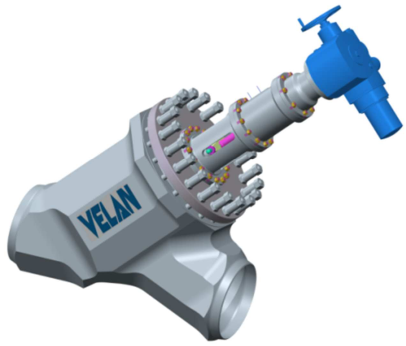

FIG.4. ND 700 mm Globe valve

4. Performance

4.1 Materials

The main material-related issues are tribology, fatigue/creep behaviour and the behaviour of interposed sealing surfaces.

The feedback from Phenix and Superphenix has shown that the use of austenitic steel for sodium valve and fitting shells is highly satisfactory. The sodium/oxygen reaction requires an high external seal between the room environment and the inside of the sodium circuit. For this reason, the casting of pressure retaining parts, with the potentially resulting porosity, shall be prohibited in sodium circuit applications [1].

The materials used for the shell and occlusion system of valves in contact with sodium or hot argon are thus given by code RCC MRx. Generally made from low-carbon austenitic steel, the Z2 CND 18-12 controlled-nitrogen grade is considered for use as the enclosure material due to its good mechanical properties at 540 °C. The fatigue/creep behaviour of this grade, also used for the reactor tank and intermediate circuits, is perfectly well-controlled during manufacture and use.

The recent tribological studies conducted in a sodium environment to replace the stellite, in addition to the progress made in terms of control of depositing processes, show that the nickel-based alloys currently appear to be interesting candidate for this alternative [2]. As the SCL isolation valve is not exposed to neutron flux, the replacement of the stellite is hence not essential.

The sodium environment behaviour of interposed metal seal seating faces remains poorly understood. The 2017-2019 work programme shall thus focus on the characterization of these components.

4.2 Internal tightness

As stated in the previous paragraph, the choice of materials for the seating areas is not the only decisive parameter in the design of a sectional valve for ASTRID. In the field of nuclear valves and fittings, several types of internal tightness surfaces are used. For this function, all solutions with a metal/metal or interposed seal type contact are considered. The topology of internal tightness surfaces is a key aspect of overall valve behaviour. A tightness function is governed by numerous parameters. The most important of these parameters are : type of fluid, operating temperature, pressure and mechanical loading on the seat .

Indeed, when characterising a leak, some parameters such as surface defects, functional gaps, flatness and many more may be decisive for valve performance. For this reason, in this study, we have paid close attention to the classification of solutions proposed for the sectioning function.

We can note two main tightness principles: so-called "direct" metal contact, or "indirect" seal contact (gasket). Direct contact is generally preferred for its ease of use and robustness. Indirect contact, however, generally offers improved valve tightness performance.

In the case of the butterfly valve on the ASTRID SCL line, the thermal gradients through the thickness of the body tend to cause deformation of the seating face. As we need to guarantee internal tightness over this type of temperature range, we thus need to develop several solutions:

- To design a sufficiently flexible seal to compensate for such a difference.
- To guarantee that the temperature difference between the body and internal parts of the valve remains limited in closed position.
- To ensure maximum material homogeneity in terms of their thermal expansion coefficient.

A combination of these three proposals seems possible.

4.3 Kinematics and Motorization

This analysis tends generally to want to limit the number of parts in contact with the sodium. In this respect the Globe valve solution appears interesting. As mentioned above, close attention shall be paid to the choice of materials and to the friction behaviour of the guide areas in a sodium environment. These issues apply to all proposed solutions.

The choice of kinematics remains intrinsically linked to valve technology. Combined or mixed kinematics may, however, be more appropriate depending on the application. In our case, in a sodium environment, permanent contact of parts with the fluid may be problematic. Consequently, we have focused on design robustness in order to limit the risk of leakage from the stem.

In light of the operating conditions defined in the ASTRID specifications and for reasons of actuator size and permissible stress, we have directed our choice of device motorization towards an electric actuator. Indeed, a pneumatic actuator would take much more space than an electric actuator and its earthquake resistance would be questionable. Moreover, there are no rapid closing requirements for these valves. The chosen actuator is thus of the type multi-turn servomotor with reduction gear.

4.4 Body mechanical strength at high temperature and pressure

There are numerous possible solutions for improving a valve body's strength at high pressure and temperature. Some geometries, however, are not particularly well-suited to the treatment applied to sodium valves. Due to the body's behaviour under fatigue caused by internal pressure and repeated thermal transients, this criterion is a major factor in the choice of technology. Moreover, good geometry creep behaviour will guarantee the maintenance of performance over time. We must therefore opt for a solution combining performance and durability.

A butterfly valve type body is generally very similar to a cylinder or tube, the absence of geometric accidents limits the impact of fatigue and creep at high temperatures. Body design thus becomes a compromise between pressure resistance and resistance to thermal stress.

4.5 Pressure loss

Similarly, the absence of geometric accident of a butterfly valve body limits pressure loss.

Boundary pressure loss values are given in the following table. The current design does not take into consideration any possible optimizations to the valve's mechanical and hydrodynamic design, but it provides an initial classification and serves to ensure compatibility with the requirements of the ASTRID secondary sodium loops.

TABLE I: Flow coefficient

Technology	Hot Valve	Cold Valve
Butterfly valve	$\xi = 2.3$	$\xi = 1.5$
Globe valve	$\xi = 2.2$	$\xi = 2.8$
Gate valve	$\xi < 0.5$	$\xi < 0.5$

The isolation valves on the SCLs are assembled in opposite position due to the increasing pressure from the primary/secondary intermediate exchanger in case of severe accident.

4.6 External tightness

The major innovation concerns the primary external tightness. It should be noted that the frozen sodium seal concept, with rising stem, has been eliminated from the list of solutions proposed by this study. In light of feedback, this type of seal is deemed too risky for reasons of sodium-induced internal oxidation and of risk of sodium extrusion beyond the seal.

To date, our knowledge is based on the use of frozen sodium seal and metal bellows. Feedback from Phenix and Superphenix has highlighted the difficulties encountered in the requirement of this first barrier (bellows or frozen sodium seal) to provide total tightness.

The globe and gate valve, with linear kinematics, historically used with a frozen sodium seal or bellows primary tightness system, is unlikely to be used in this field. Despite the globally positive operating feedback for small metal bellows, the use of these components on a ND 700 mm device remains to date a major problem for isolation valve durability.

In this case, the butterfly valve offers new innovation prospects for the primary tightness system around the stem. Indeed, the ¼ valves historically used with a frozen sodium seal primary tightness system now pave the way for new technologies in this field. Following an initial analysis of the market and of current solutions, we considered testing the following technological solutions:

- Mechanical seals
- Elastic metal lip seal
- Backup solution: frozen sodium seal

According to current engineering practice primary body/stem tightness remains, to date, the most critical function of this device, thanks to its dynamic or quasi-static aptitude. It is important to note that, according to our current knowledge, the primary tightness is insufficient, alone, to ensure enclosure tightness under all conditions of use, particularly under accidental conditions.

In all cases, a safety barrier seal is planned. This second barrier, referred to as "secondary tightness", plays various roles depending on the nature of the primary tightness. Its main function is to provide safety by guaranteeing enclosure integrity in the event of loss of primary tightness during the time required to drain the sodium circuit. The integrity of this safety barrier over time has not as yet been clearly defined, though it is widely agreed that one hour would be sufficient to ensure facility safety and to preserve enclosure integrity. It should be noted that a tertiary tightness system is generally required to provide an argon barrier and thus to prevent sodium or seal oxidation during operation at high temperature. Our choice thus tends towards a primary tightness resistant to sodium at high temperatures. Consequently, the metal joint would seem interesting. This latter solution, however, remains to be studied, particularly in terms of its pressure/temperature behaviour with sodium. A number of lines of work have been identified and are being studied in depth.

Body/bonnet connection tightness is dependent upon the type of technology chosen. Many solutions can be considered for this type of static tightness. In our case, however, the main risk identified to date is compensation for the thermal expansion occurring in this type of assembly. Due to industrial growth in the energy sectors, many manufacturers propose nowadays many innovative seal solutions. The metal gasket would appear to be a good candidate for this function. A solution based on held welding tightness could be considered as long as the maintenance programme does not identify any operations involving the systematic removal of this connection.

5. Conclusion

The study of the isolation valves for the ASTRID secondary circuit loops is based on a need functional analysis, derived from the nuclear island studies, which has identified the most appropriate technological concepts in terms of performance and maturity.

In technological terms, no insurmountable obstacle was identified during the Preliminary Design of these ND 700 sodium isolation valves.

Several valve concepts were assessed and compared (Butterfly valve, Globe valve and Gate valve). As the levels of maturity of these three concepts are similar, this criterion was insufficient to make a final decision. The decisive point for the choice of the best concept was based on the assessment of the valve placed in its environment: in particular its connection with the SCL, its weight, its size, and its handling.

Having considered all of these points, the Butterfly valve was shown to present distinct advantages in terms of weight (impact on earthquake resistance calculations) and body simplicity (thus facilitating design, manufacture and operational monitoring). A decision remains to be made concerning the choice of model within the butterfly valve family. In the context of our study, the adaptation of a rotating frozen sodium seal remains a possibility. This choice will be made during the detailed design phase.

Consequently, we have decided to include butterfly valves on each of the legs (hot and cold) of the four SCLs, in lay-out and civil work mock-up at the end of the conceptual design phase of the ASTRID project.

Subsequent studies (in the context of ASTRID basic design) shall consist of continuing the analysis of the critical butterfly valve subunits suffering from lack of maturity, in order to define the most appropriate technological solutions and associated qualification programme.

Analysis of the level of technological solution maturity will enable us to identify design ways to develop in order to limit the risks of project failure. Amongst these high-risk functions, we have already identified stem tightness.

Appendix 1: References

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