



A Thermomechanical Leak Valve for Ion Source

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Our study aims to design and manufacture a robust, low-cost, reliable leak valve and, study the working characteristics to deliver a stable flow of gas. As a result, a simple thermomechanical leak valve has been developed at the Particle Accelerator Laboratory, Department of Physics, Mizoram University. The leak valve uses a mechanically actuated, stainless steel ball that provides seals against a polished stainless steel seat. Our study shows that the methodology employed in previous studies results in a varying leak rate over time, which is undesirable. Therefore, a new method is introduced for controlling the leak valve. The new methodology helps us maintain a stable leak rate/gas flow as long as we maintain the operating parameters. The amount/leak rate of molecular gas required to produce an efficient yet stable high ion beam current has also been optimized.

Keywords: Thermomechanical leak valve, coefficient of thermal expansion, particle accelerator, plasma, ion source.

1 Introduction

Leak valves or gas leak valves are required to regulate the gaseous material for the formation of a plasma in an ion source. A carefully designed leak valve allows a stable flow of high-purity gas for the required operation time. The plasma density in a radio frequency (RF) ion source depends on parameters such as RF power, gas pressure, magnetic field, *etc.*^{1,2,3}. As inhomogeneity in the gas pressure affects the net electron energy in a plasma, different flow rates produce different luminosity of plasma^{1,4}. This inhomogeneity causes fluctuations in ion currents, which are unwanted in an ion source. This holds for other plasma generators where the controlled gas flow plays a crucial role in the generation of high energy electrons⁵. Of all types of gas available for use with an RF ion source, deuterium (D²) gas is chosen. Among the three types of deuterium leak valves commonly used⁶: palladium leak valve, thermomechanical leak valve, and a needle leak valve; the thermomechanical leak valve has been chosen.

Palladium leak valves encased in glass allow permeation of hydrogen isotopes through a palladium tube. The rate of permeation for deuterium gas diminishes after a long operation and therefore requires regular maintenance. Needle leak valves normally consist of a movable piston or valve needle forced against a valve seat. Fine adjustment of the

movement and position of the needle allows precise regulation of gas. Needle leak valves consist of several small parts and are therefore compact. However, they require high precision machining, therefore, the manufacturing cost is considerably high. This makes it difficult to manufacture them at local enterprises. A thermomechanical leak valve takes advantage of the difference in the coefficient of thermal expansion (CTE) of different materials to create a reproducible and robust sealing surface. A material having lower CTE is encased inside a material having higher CTE. As they are heated, the difference in expansion creates a gap allowing gas to pass through to the plasma chamber. This type of leak valve was first developed by Gale⁷ in 1961. Since then, its design has been modified and the current design manufactured and employed in our study is a modified version of the design put forward by Jayantha Kumar *et al.*³ in 1984.

Gale⁷ employs a tungsten wafer, pyroceram (quartz) rod, and stainless steel ball of ball type socket fitted against a valve seat. An Inconel tube with stainless steel flange serves as an expansion tube. Upon heating, a 200 Psi gas pressure is operated at approximately 200°F (~93°C). Naylor⁸ uses a simple hairpin-shaped heater made from nichrome wire and stainless steel alloy. This simple leak valve allows fast response to a change in gas pressure to occur within minutes of changing heater current. Using these

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settings, hydrogen gas at 14 Atm (~205 Psi) allows effective control to about 2×10^{-4} torr liter per second with a normal working range of 15 to 35° C. Jayantha Kumar *et al.*³ uses non-magnetic stainless steel for the expansion tube while Invar and stainless steel ball provide seals at room temperature. A power supply of 0–30 V DC provides the required heating to maintain the gas at 5 μ deuterium pressure. IAEA-TECDOC⁶ also reports a simple thermomechanical leak valve where the leak rate is controlled by an electric current used for heating the leak valve. So, previous studies use constant heater current directly or indirectly to control the thermomechanical leak valve for stable gas flow.

Thermomechanical leak valves are robust, have a high operating lifetime, and at the same time easy to be controlled while being fairly precise. Moreover, thermomechanical leak valves can be easily manufactured at a mechanical workshop at a lower price and are suitable for operation with all types of gases. The various reasons provided led to the study and design of the thermomechanical leak valve.

2 Thermomechanical Leak Valve

2.1 Materials and Methods

The thermomechanical leak valve is manufactured using Austenitic chromium-nickel stainless steel grade 316 (SS 316) and Invar 36 (FeNi36). Both materials have high tensile strength with one having higher CTE ($17.3 \times 10^{-6} K^{-1}$) and the latter having lower CTE ($1.2 \times 10^{-6} K^{-1}$) (Ref. 9). The leak valve consists of ten components as shown in Fig. 1; seven components (Part No.1-6 and 9) manufactured from SS 316, two Viton O-rings, and an Invar rod.

The surface roughness for the conical countersink section of the inlet flange *i.e.*, stainless steel seat is designed in accordance with ISO/FDIS 3601-2:2015(E).

O-ring grooves are also designed and manufactured in accordance with ISO/FDIS 3601-2:2015(E). O-rings are designed and then used in accordance with ISO 3601–1. All screw threads, nuts, and bolts are designed using the design principles of ISO general purpose metric screw threads ("M" series threads) defined in international standard ISO 68-1:1998. The major, minor, and pitch diameters of the external (bolt) and internal (nut) metric threads are calculated according to ISO 724:1993, and tolerance calculated and applied in accordance with ISO 965-1:1998.

2.2 Design

A 2-Dimensional schematic diagram of the thermomechanical leak valve designed using Autodesk AutoCAD 2018 is shown in Fig. 1. The inlet flange (Part No. 1) has a conical countersink with very low surface roughness. This conical countersink acts as a seat for the stainless steel ball as shown in Fig. 2(a). The countersink is compatible with round balls ranging from 2.5 – 5 mm in diameter. An Invar rod is positioned horizontally inside the full nipple flange (Part No. 2). High-temperature vacuum O-rings situated axially on both sides of the full nipple flange prevents any gas leak.

As shown in Fig. 2 (b) & (c), the set screw (Part No. 3) has a hexagonal head screw with a cylindrical-shaped groove tail. The closing flange (Part No. 4) provides ample space in case full threading of the set screw is not required. The outlet flange (Part No. 5) is a small rectangular SS flange that provides a connection to the plasma chamber.

2.3 Working Principle

A thermomechanical leak valve works on the principle of differential thermal expansion coefficients of different materials.

As gas enters the leak valve (Fig. 1), a high-grade stainless steel ball is held by an Invar rod against a

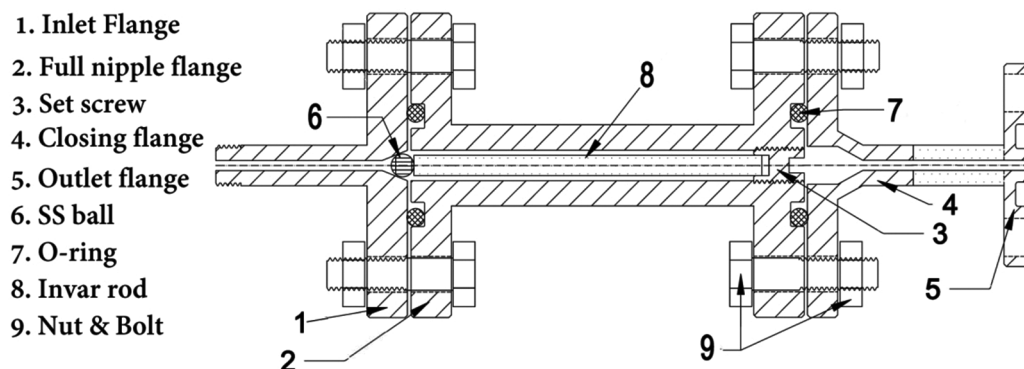


Fig 1 – A schematic diagram of the thermomechanical leak valve.

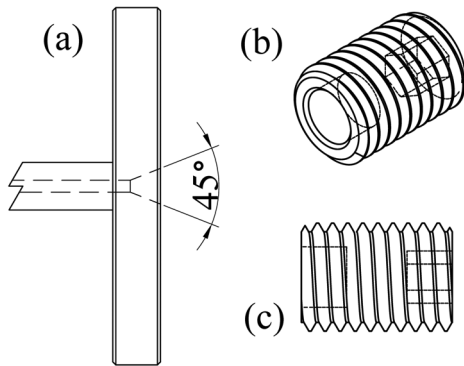


Fig 2 – (a) A schematic drawing of the inlet flange, (b) & (c) A schematic drawing of the set screw.

precision polished seat. This action provides robust seals at room temperature. The force necessary to block the gas flow is provided by the set screw. As the set screw is fastened, a rotational force of the set screw translates into a compression force on the Invar, which results in a linear axial force being applied on the stainless steel ball. This way, the thermomechanical leak valve blocks gas flow at room temperature. The amount of force exerted on the Invar 36 is controlled by suitable adjustment of the number of threads screwed on the full nipple flange.

Earlier, studies²⁻⁵ generally utilize constant heater current for controlling the leak valve. A heater coil is wound around the cylinder portion of the inlet and full nipple flange. During operation, the heater current is turned on, which heats the leak valve. Over time, the difference in the coefficient of thermal expansion (CTE) of the inner Invar 36 and outer SS 316 leak valve wall creates a small gap, and gas flows through the small gap created. As the heater current increases, the leak/flow rate increase due to the increased temperature. In this fashion, the heater current controls the gas flow of the leak valve. And, the thermomechanical leak valve provides continuous gas flow to the plasma chamber. The stainless steel ball returns to its seat in case of current switch-off or insufficient heating, thereby closing the valve.

3 Experimental Details

Figure. 3 shows the experimental setup for the thermomechanical leak valve. All studies are conducted using 99.99% high-purity D² gas. The D² gas cylinder is connected to the leak valve using a high-pressure flexible pipe. The flexible pipe allows easy maneuvering of the leak valve as required. A stainless steel ball of 2.5mm diameter is used for the present study. A heater coil placed inside ceramic

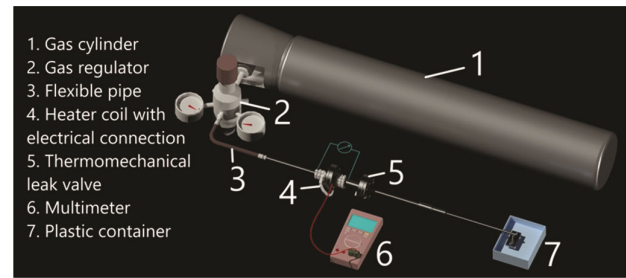


Fig 3 – Experimental setup for the thermomechanical leak valve.

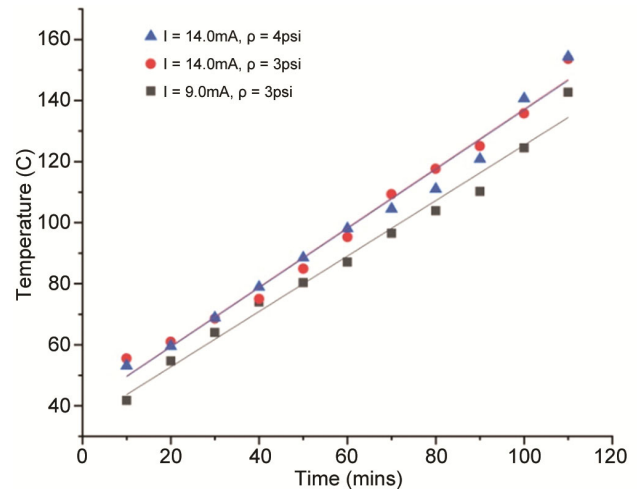


Fig 4 – Temperature vs time at constant current.

beads connected to a power supply provides electrical heating. The temperature of the leak valve wall is measured using a Fluke 17B+ digital multimeter having a temperature sensor thermocouple with an accuracy of 0.1 °C. The leak valve outlet is then dipped into a small plastic container filled with water at a shallow depth (~ 20mm) to minimize the force exerted on the gas bubbles by water molecules.

The size and number of bubbles formed over time determine the amount of gas flow. The gas is maintained at a fixed pressure (1-4 Psi) using a gas regulator. As an electric current is applied to the heater coil, 10 mins are approximately required before any leak is observed. Here, leak rate is defined as the number of bubbles formed over time.

4 Results and Discussion

A constant heater current must heat the leak valve slowly and linearly over time.

Figure. 4 shows the variation of temperature with time at a constant heater current. The temperature of the leak valve rises with a constant heater current even after hours. For the heater currents with similar gas pressure (3Psi), the higher heater current

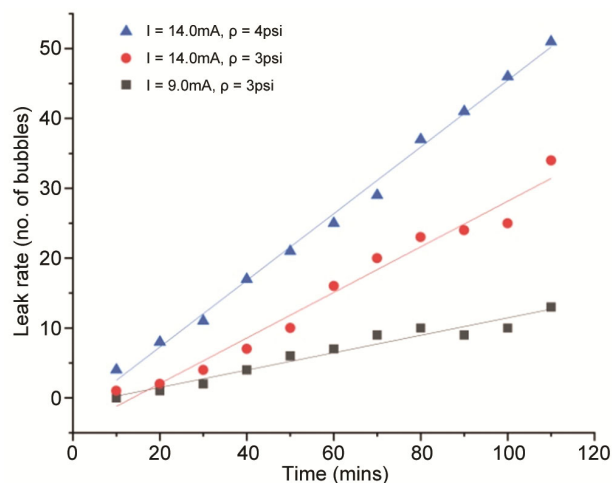


Fig 5 – Leak rate of bubbles vs heating time.

($I = 14$ mA) achieves a higher temperature as expected. For gas pressures with a similar heater current ($I = 14$ mA), the leak valve attains a similar temperature. This similarity shows that the temperature attained depends on the heater current and is independent of the gas pressure.

Figure. 5 shows the variation of leak rate with time at constant heater current and gas pressure. For $I = 9.5$ mA, $\rho = 3$ Psi, no leak i.e., no bubble was observed in 10 mins. The leak rate increases slowly with time and lie within the range of 0-10 bubbles. For $I = 14.0$ mA, $\rho = 3$ Psi, the leak rate remains almost similar to the former for 10-20 minutes. The leak rate increases with an increase in time. So, the leak rate lies in the range of 0-35 bubbles per minute. At $I = 14.0$ mA, $\rho = 4$ Psi, leak rate increases even more rapidly with time. The leak rate lies in the range of 3 - 50 bubbles per minute. For the studies, the leak rate does not show saturation with time. The slope of the fitting lines increases with an increase in the heater current and gas pressure. For similar gas pressure, a higher heater current produces a higher leak rate as expected. Also, for a similar heater current, higher gas pressure produces a higher leak rate.

From Fig. 4 and Fig. 5, we observe that temperature and leak rate increase with time as a result of supplying a constant current to the leak valve. This increase shows that a constant leak rate can not be achieved with this methodology, which is not desirable. In the present work, we, therefore, develop a new methodology for the heating procedure to achieve constant temperature and constant gas flow.

Steadily heating the leak valve with a constant heater current results in a lengthy procedure. A

Table 1 – Set of heater voltage for the leak valve

Gas pressure (Psi)	Heating Voltage (Volts)		
	Initial	Stable	
1	60	37	38
2	45	28	29
3	43	25	26
4	41	23	24

technique is required in such a manner that the required temperature is attained within a short time.

For this purpose, the leak valve is initially heated with a higher voltage for rapidly acquiring the operational temperature given in Table 1. Then, a transition is made to a lower voltage for stable heating at a specific time. As the required temperatures differ, each gas pressure requires a different set of heating voltages. The required operation time for our recent applications is around ~ 60 minutes. So, a stable leak must be maintained for at least 60 minutes. Table 1 shows the set of voltages used to heat the leak valve for different gas pressures.

Figure. 6 shows the heating curve for the gas pressures with their respective heating voltage given in Table 1. All the gas pressures follow a similar characteristic. The operational temperature range is attained after $t = 10$ mins using an initial heating voltage, then the input voltage is immediately shifted to stable heating voltage, as shown in Table 1. The lower heating voltage continues to heat the leak valve. The rate of increase in temperature is very slow as compared to Fig. 4. And so, the operating temperatures are maintained for a much longer time.

Figure. 7 shows the time required for bubble formation, or, leak time of one bubble with a heating temperature of the leak valve. At constant pressure, the leak time of one bubble decreases with an increase in temperature. At 1 Psi, the first bubble occurs at 80°C with leak time decreasing rapidly with increasing temperature. The required leak time is achieved at $\sim 150^\circ\text{C}$ and above and is stable. For 2, 3, and 4 Psi, the rapidly decreasing leak time slows down and a stable required leak time is achieved at a lower temperature of around 105°C . At higher temperatures, the leak time characteristic almost becomes similar. From Fig. 6, the leak curves for the gas pressures achieve saturation at different temperatures. This saturation shows that the leak rate becomes stable at these temperatures. The operational temperature range for different gas pressures is shown in Table 2.

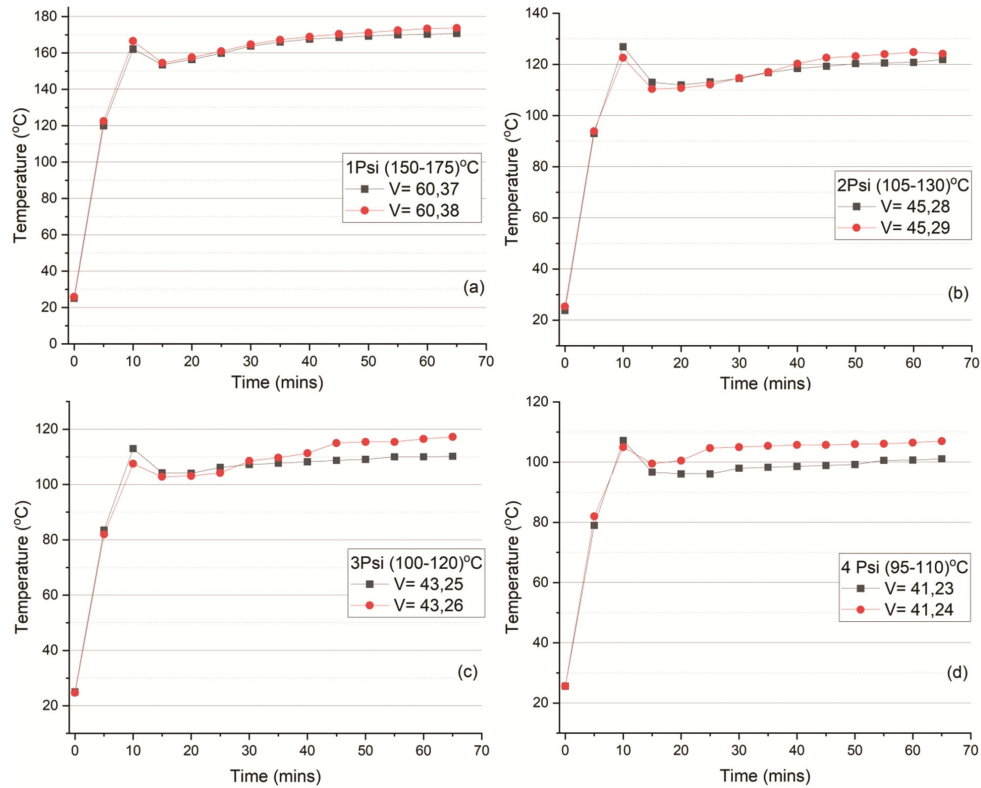


Fig 6 – Temperature vs time plot for (a)1 Psi (b) 2 Psi (c) 3 Psi (d) 4 Psi at their respective heater voltage.

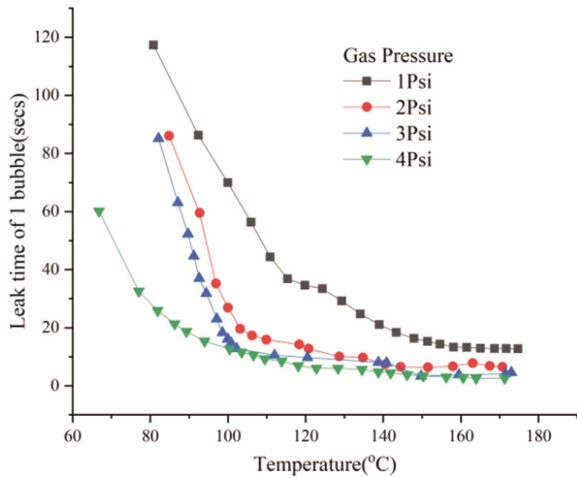


Fig 7 – A plot of leak time of one bubble against heating temperature at different gas pressure.

The study is performed at 1 - 4 Psi inlet gas pressure as our system works well with these parameters for the required bubbles. If only higher inlet pressure of the order of ~200 Psi works for the system, consumption of all the gas stored in the cylinder is not feasible. Operating at lower pressure allows full consumption of the gas.

From our preliminary studies, based on the luminosity of plasma, the number of gas bubbles

Table 2 – Operational temperature range for the leak valve

Gas pressure (Psi)	Temperature range (°C)		Temperature difference (°C)
1	150	175	25
2	105	130	25
3	100	120	20
4	95	110	15

required per minute is 4 - 6 bubbles. Based on this requirement, a bubble is required every 10 - 15 seconds. The amount of time required for the formation of a bubble, i.e, leak time of 1 bubble is measured to enable a more precise measurement of the gas flow.

Measurement of the size of D^2 gas bubbles is required to determine the amount of gas required/ consumed. Even the same type of gas can have different bubble sizes depending on the outlet of a system, its surrounding temperature, and pressure at which the experiment is done, and the depths of water from which bubble measurements are made.

Figure 8 shows a deuterium (D^2) gas bubble with a metal scale. Several photographs of the gas bubble are taken at random and their diameter is measured/ determined using the scale. Several measurements are made even for a single bubble at different gas pressure. The bubble size remains similar for different



Fig 8 – Photograph of a D^2 gas bubble.

gas pressures. The volume of the gas bubble is calculated using the measured mean diameter. The average amount of gas required is $3.5\text{ml} \pm 0.7\text{ml}$ per minute, or, $210 \pm 42\text{ml}$ per hr.

Measured radius of a gas bubble = 5.5 mm

Therefore, the volume of the bubble (sphere)

$$= \frac{4}{3}\pi r^3 \quad \dots(1)$$

$$= 696.9 \text{ mm}^3 \text{ or, } 0.7 \text{ ml}$$

Bubble required per minute (5 ± 1 bubble) = $3.5\text{ml} \pm 0.7 \text{ ml}$ per minute

5 Conclusions

A thermomechanical leak valve is designed using AutoCAD and manufactured accordingly. Our design encompasses a simple and reliable system for controlling the gas flow. SS 316 is used for the higher expansion outer tube while Invar 36 serves as a lower expansion inner material. Their difference in CTE makes them applicable to our required applications.

A leak valve must supply a constant gas flow to the plasma chamber. To achieve this stability, a thermomechanical leak valve is controlled by a constant heater current. It is found that a constant heater current supply causes the leak rate to rise over time (Fig. 4). A higher heater current produces a higher temperature for the same amount of time. Therefore, utilizing only constant heater current for controlling the leak rate is undesirable for a thermomechanical leak valve. Our study shows that gas pressure plays an important role in the leak rate (Fig. 5). Higher pressure corresponds to a higher leak rate at the same temperature. This confirms that the leak rate of a thermomechanical leak valve depends not only on the heater current but also on the gas pressure.

The amount of gas required for producing a stable ion current is determined by the number of bubbles obtained per minute. Our preliminary studies on the luminosity of plasma show that 4-6 bubbles are

required per minute. To obtain the desired number of bubbles at a specific range of temperatures, the leak time of a bubble at different input pressure with varying temperatures has been plotted (Fig. 7). The operating temperatures for the gas pressures are given in Table 2. The low gas pressure coupled with higher temperature allows a wider temperature range, while higher gas pressure allows operation of the leak valve at a lower temperature. This combination provides the operator with a different choice of operational parameters. The working parameters allow full usage of gas and make it more cost-effective. The size of the gas bubble measured determines the amount of gas required for producing stable ion current ($210 \text{ ml} \pm 42 \text{ ml}$ per hr).

To bypass the lengthy heating required for stable gas flow, a technique is developed in such a way that the required temperature is attained within a short time. To achieve this, the leak valve is heated with a set of voltages, one for rapidly acquiring the operational temperatures and the other for stable heating after the desired temperature/parameter has been attained (Fig. 6). A different set of heater voltage is required for different gas pressures (Table 2). Using this methodology, the rate of increase in temperature is very slow (as compared to Fig. 4). So, operating temperatures can be maintained for a much longer time which corresponds to a stable gas flow. The temperature acquired at a particular time can sometimes be different ($\sim 2^\circ\text{C}$). This occurs due to fluctuations ($\sim 1\text{Volts}$) in the heating voltage. Yet, the heating voltage maintains the leak valve within their respective temperature range.

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References

- 1 Ganguly A K & Bakhru H, *Nucl Instrum Methods*, 21 (1963) 56.
- 2 Eubank H P, Peck J R A & Truell R, *Rev Sci Instrum*, 25 (1954) 989.
- 3 Jayantha K S S, Chindhade V K & Bhoraskar V N, *Pramana*, 22 (1984) 453.
- 4 Gupta D N, Suk H & Ryu C M, *Phys Plasmas*, 12 (2005) 093110.
- 5 Gupta D N & Suk H, *J Appl Phys*, 101 (2007) 114908.
- 6 IAEA, Manual for troubleshooting and upgrading of neutron generators, (IAEA, Vienna), IAEA-TECDOC-913, (1996) 63.
- 7 Gale A J, US Pat 3,010,690, 1961.
- 8 Naylor H, *Nucl Instrum Methods*, 76 (1969) 357.
- 9 Bernd D, Henriette M & Gross H, *Handbook of Optical Systems* (John Wiley & Sons, Germany), 5 (2012) 154.