

Article

Sealing Performance of Sn58Bi Low-Melting-Point Alloy for B-Annulus Plugging Under Cyclic Loading

Chunqing Zha ¹, Jiajun Sun ¹, Wei Wang ^{1,*}, Gonghui Liu ¹, Wei Liu ² and Jun Li ³

¹ College of Mechanical and Energy Engineering, Beijing University of Technology, Beijing 100124, China; chachunqing@bjut.edu.cn (C.Z.); jiajun130613@emails.bjut.edu.cn (J.S.); lgh_1029@163.com (G.L.)

² CNPC Engineering Technology R&D Company Limited, Beijing 102206, China; liuweidri@cnpc.com.cn

³ School of Engineering, China University of Petroleum (Beijing) at Karamay, Karamay 834000, China; lijun446@vip.163.com

* Correspondence: wangwei53@bjut.edu.cn; Tel.: +86-13946897245

Abstract

In geological carbon storage, cyclic casing loading can induce micro-annuli in the B-annulus cement sheath, risking CO₂ leakage. Compared with conventional cement, the Sn58Bi low-melting-point alloy boasts excellent flowability and favorable elastoplastic behavior, emerging as a promising sealing alternative. This study focuses on enhancing wellbore integrity by using Sn58Bi alloy to seal the B-annulus cement sheath. An experimental system was established to simulate micro-annulus evolution, with gas migration tests conducted under cyclic internal pressure to systematically evaluate the effects of temperature and cyclic loading on the alloy's sealing performance. Additionally, a three-layer casing-annulus-formation coupling model was constructed to investigate the radial displacement of the Sn58Bi alloy sheath and cement sheath at 30 °C and 20 MPa casing pressure, clarifying their distinct mechanical responses. Results show that the alloy's sealing performance improves with temperature (30–90 °C), while elevated cyclic internal pressure accelerates gas breakthrough and reduces sustainable cycles. Under identical conditions (30 °C, 20 MPa), Sn58Bi alloy exhibits significantly superior CO₂ sealing capacity to conventional cement. This study confirms the alloy's potential for enhancing wellbore integrity and provides theoretical support for its application in B-annulus plugging during subsurface carbon storage.

Keywords: CCUS; Sn58Bi alloy; B-annulus; micro-annulus; gas migration

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1. Introduction

In response to the escalating challenges of global climate change, Carbon Capture, Utilization and Storage (CCUS) has been widely recognized as an essential pathway for reducing greenhouse gas emissions and achieving carbon neutrality targets [1]. As the terminal stage of the CCUS chain, geological CO₂ sequestration aims to inject captured CO₂ in a supercritical or liquid state into deep geological formations, ensuring long-term and stable containment and preventing its release into the atmosphere. Nevertheless, any CO₂ leakage may not only offset the expected emission-reduction benefits but also lead to groundwater contamination, ecological risks, and wellbore integrity failures [2].

Therefore, maintaining the integrity and safety of the sequestration process is of critical importance.

In CO₂ storage wells, the B-annulus refers to the annular region between the intermediate casing and the surface casing. The cement sheath, acting as the primary sealing barrier in this region, plays a decisive role in ensuring zonal isolation. Owing to the high permeability and chemical reactivity of CO₂, together with cyclic internal pressures generated during long-term injection operations, radial microcracks and micro-annuli are prone to develop within the cement sheath [3]. This degradation is primarily attributed to the brittle and strongly alkaline nature of cement, a multiphase material that is susceptible to microcrack propagation under cyclic loading. Furthermore, the mismatch in elastic modulus between the cement and steel casing promotes interfacial crack growth, eventually forming leakage pathways [4]. Consequently, the cyclic loads associated with CO₂ injection and shut-in, combined with the intrinsic brittleness of cement, constitute the two major causes of sealing failure and subsequent gas leakage.

Several strategies have been proposed to enhance the sealing performance of cement systems. Zhou et al. reported that cement systems with lower elastic modulus and higher Poisson's ratio can effectively reduce residual stresses after unloading [5]. Tao et al. indicated that conventional Grade G cement is more susceptible to damage and integrity failure under cyclic fracturing loads compared with shale-gas dedicated cement systems [6].

Although these enhanced cement systems show improvements in mechanical performance, their construction procedures are relatively complex, and their long-term stability remains uncertain.

In recent years, low-melting-point Sn58Bi alloy has attracted increasing attention as an alternative sealing material to conventional cement. This alloy undergoes volumetric expansion during cooling and solidification, forming a highly conformal interface with favorable environmental compatibility and chemical stability. Abdelal et al. investigated the long-term creep behavior of BiSn alloy plugs through experimental and numerical approaches, confirming their durability under downhole conditions [7]. Manataki et al. examined the sealing performance of the alloy at various temperatures, providing theoretical support for its application in abandoned and CO₂ storage wells [8]. A series of studies by Zha et al. evaluated the sealing capability of Sn58Bi alloy at multiple system scales—including casing–alloy annuli, alloy–cement composite plugs, and rock perforation sealing—demonstrating significant improvements in long-term wellbore integrity and offering a multi-level design framework for CCUS and well abandonment operations [9–11]. Chen et al. further reported that the mechanical properties of Sn58Bi alloy are strongly dependent on temperature and strain rate [12]. Despite these promising findings, pressure fluctuations commonly encountered during CCUS operations—such as the alternating internal pressures during CO₂ injection and shut-in—may jeopardize interface integrity and long-term sealing performance. These effects may eventually induce B-annulus sealing failure (Figure 1). Existing studies on Sn58Bi low-melting-point alloys have mainly focused on their mechanical properties, corrosion resistance, and static sealing performance. However, during CCUS operations, wells are frequently subjected to cyclic injection and production pressures, which may induce progressive degradation of annular sealing integrity. The sealing behavior and failure mechanism of Sn58Bi alloy under cyclic loading remain poorly understood. Therefore, a systematic investigation of the sealing performance evolution of Sn58Bi alloy under cyclic loading is still lacking. Therefore, the evolution of sealing performance of Sn58Bi alloy under cyclic loading at different temperatures requires further investigation and verification.

In this study, Sn58Bi alloy is employed as the sealing material for the B-annulus in CO₂ sequestration wells. An experimental apparatus capable of characterizing micro-annulus formation under cyclic internal pressure is designed, and gas-migration tests are

conducted to evaluate the influence of temperature-dependent elastic–plastic deformation of the alloy–casing system on micro-annulus development and subsequent gas leakage. In addition, a three-layer coupled model comprising casing, annulus material, and surrounding formation is established to compare the sealing performance of Sn58Bi alloy sheaths with that of conventional cement sheaths under cyclic loading conditions.

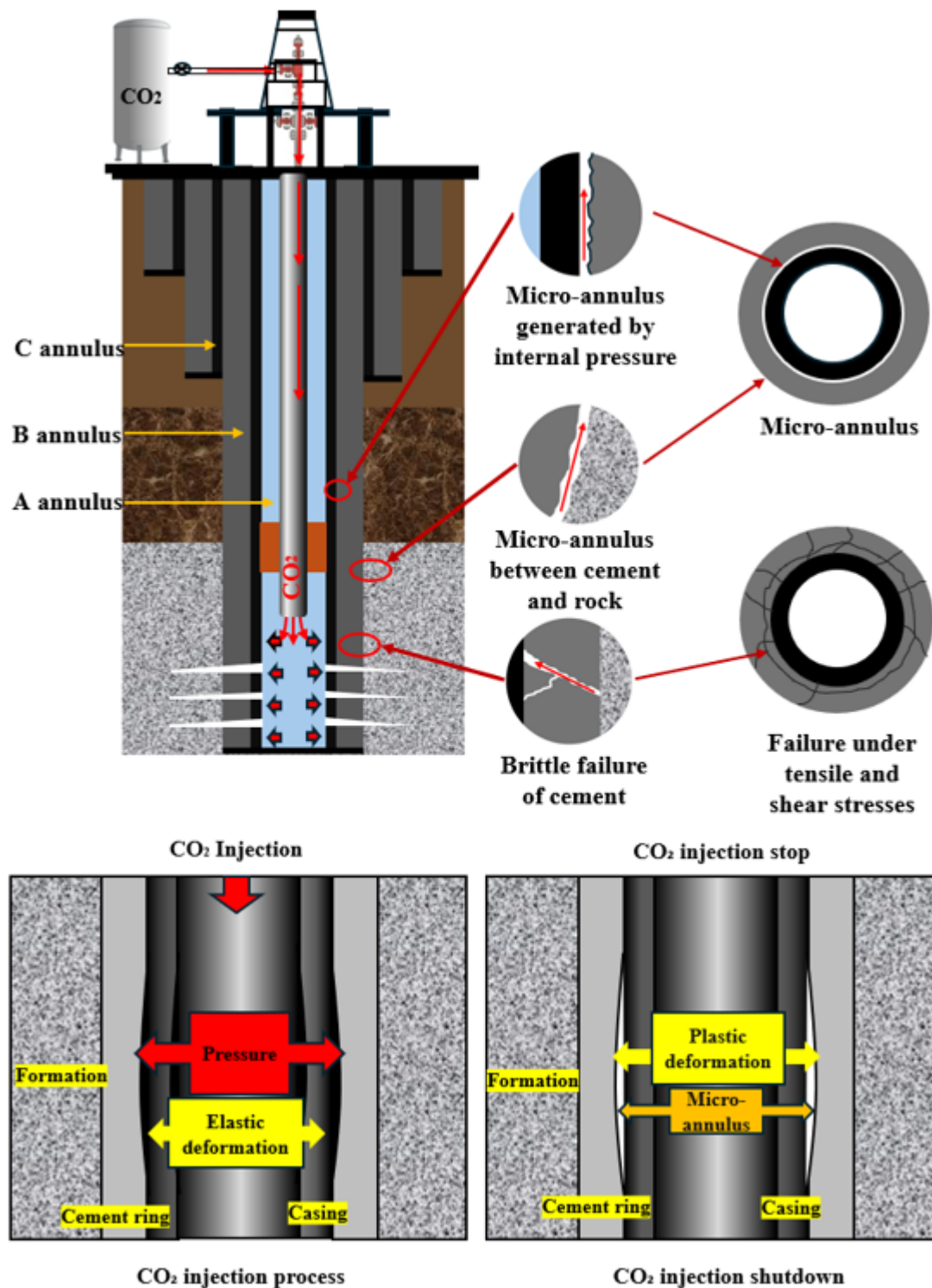


Figure 1. Schematic illustration of B-annulus sealing failure during CO₂ injection in a CCUS well.

2. Characteristics of Sn58Bi Alloy and Plugging Technology Overview

2.1. Properties of the Sn58Bi Alloy

Sn58Bi alloy is a low-melting-point metallic material composed of 58 wt% tin (Sn) and 42 wt% bismuth (Bi), commonly used in electronic soldering and specialized sealing applications. It can melt and resolidify at relatively low temperatures, exhibiting excellent fluidity and reusability. The equilibrium phase diagram of the Sn–Bi binary alloy (Figure 2). As illustrated, this system exhibits the characteristics of a typical eutectic phase diagram. Pure Sn melts at approximately 232 °C, while pure Bi melts at around 271 °C. As the Bi content increases, the melting temperature of the alloy decreases progressively and reaches its minimum value of 139 °C at 43 wt% Bi, corresponding to the Sn–Bi eutectic composition. At this composition, the liquid phase solidifies simultaneously into Sn-rich and Bi-rich solid solutions during cooling, undergoing a synchronous liquid–solid transformation. The region to the left of the eutectic point is dominated by a Sn-rich solid solution (α -Sn), whereas the right side consists mainly of a Bi-rich solid solution (β -Bi) [13]. The specific phase distribution is shown in Table 1.

For near-eutectic alloys such as Sn58Bi, partial melting may occur during heating, providing superior fluidity and wettability that enable effective filling of microcracks and formation of a dense and conformal interfacial contact. These characteristics make the Sn–Bi alloy system highly promising as a sealing material for CO₂ geological sequestration wells. Some key properties of the alloy are summarized in Table 2.

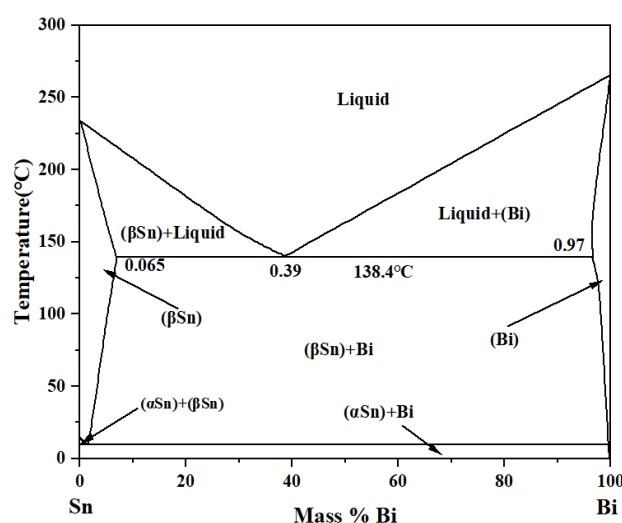


Figure 2. Phase diagram of the Sn–Bi binary alloy system.

Table 1. Phase composition of the Sn–Bi alloy system.

Phase Composition	Phase Transition Temperature (°C)	Phase Region
0	231.9	(β Sn) $\leftrightarrow$ Liquid
6.5%Bi	200	(β Sn) + Liquid
39%Bi	139.4	(β Sn) + (Bi)
97%Bi	200	(Bi) + Liquid
100%Bi	271.3	(Bi) $\leftrightarrow$ Liquid

Table 2. Characteristics of Sn58Bi alloy [14–16].

Property	Melting Point (°C)	Viscosity (mPa·s)	Coefficient of Linear Expansion(K)	Density at 25 °C (g/cm ³)	Elastic Modulus (GPa)	Tensile Strength at 25 °C (MPa)	Elongation at 25 °C (%)
Material Data	138	4.38	1.5×10^{-5}	8.72	5	71.7	20.1%

The key properties of Sn58Bi alloy are summarized as follows:

- (1) Low melting temperature: With a melting point of approximately 138 °C, the alloy can be easily melted, injected, and resolidified in the wellbore through controlled heating.
- (2) Elastic–plastic deformability: Unlike brittle cement-based materials, the Sn58Bi alloy can accommodate stress through elastic deformation, thereby reducing the risk of interfacial cracking.
- (3) Volumetric stability after solidification: The alloy exhibits a volumetric expansion of about 3.5% during solidification, enabling it to exert active radial compressive stress on the wellbore wall, which effectively minimizes the formation and propagation of interfacial micro-annuli [17].
- (4) High hardness and wear resistance: The alloy demonstrates significantly higher hardness and lower wear rates compared with cement, making it a strong and wear-resistant candidate for downhole sealing applications [18].

Therefore, the Sn58Bi alloy, with its low-temperature meltability, excellent flowability, and favorable elastic–plastic behavior, offers a promising material option for ensuring the long-term sealing integrity of CO₂ geological storage wells.

Therefore, Sn58Bi alloy, characterized by its low-temperature heating sealability, favorable fluidity, and superior elasto-plastic properties, provides a promising material option to ensure the long-term sealing integrity of wellbores in geological CO₂ storage.

2.2. Overview of the Pre-Embedded Sn58Bi Alloy Sealing Technique for the B Annulus

The pre-embedded Sn58Bi alloy sealing method for the B-annulus involves placing a preformed Sn58Bi low-melting-point alloy within the annular space between the casing and the cement sheath. The alloy is melted by lowering an electric heating tool into the wellbore (Figure 3). In its molten state, the alloy infiltrates downward and fills the annular gaps under the combined effects of gravity and capillary forces. Upon cooling and solidification at downhole temperature, a dense and continuous metallic sealing layer is formed (Figure 4), thereby achieving effective isolation of the B-annulus.

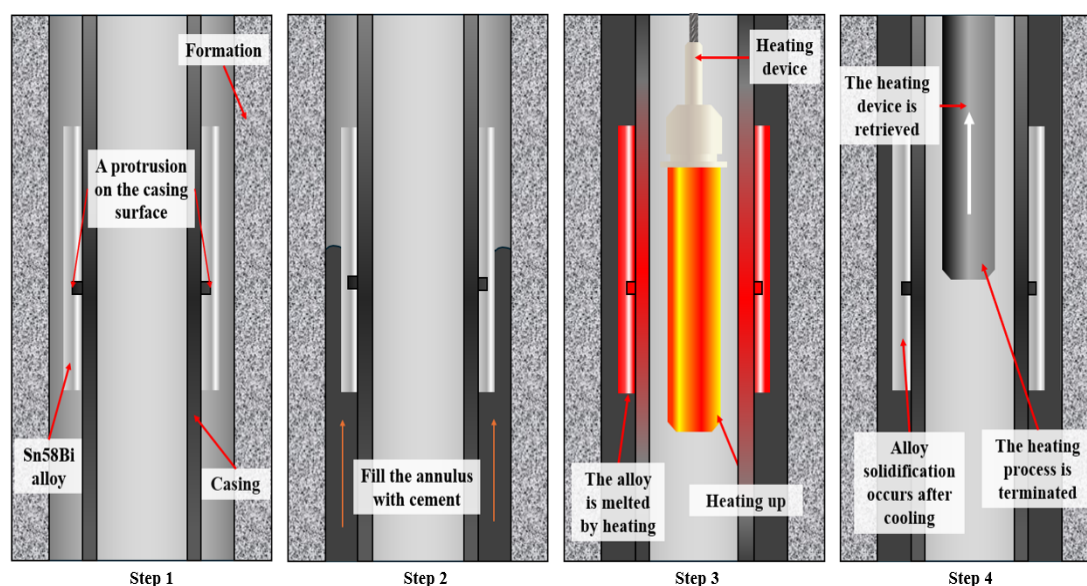


Figure 3. Schematic illustration of the embedded molten Sn58Bi alloy sealing process in the B-annulus.

The sealing procedure using the Sn58Bi alloy consists of the following steps:

- (1) Preparation stage: The Sn58Bi alloy block is accurately positioned at the target location within the cement sheath using a dedicated placement structure. A heating tool is then deployed to the position of the alloy block in preparation for subsequent thermal activation.
- (2) Heating and melting stage: The heating tool elevates the local temperature to the melting point of the Sn58Bi alloy (approximately 138 °C), causing the alloy to rapidly melt and flow into micro-annuli or fractures.
- (3) Cooling and solidification stage: After the molten alloy infiltrates and fills the gaps, the heating process is stopped and the heating device is retrieved. The downhole temperature enables the alloy to gradually cool and solidify, forming a dense metallic sealing structure that achieves effective isolation.

Sn58Bi is a eutectic low-melting-point alloy with excellent fluidity and re-meltability. Upon solidification, it forms a metallic structure with high density, good corrosion resistance, and strong resistance to CO₂ penetration, which can potentially extend the service life of the wellbore system and enhance long-term integrity for carbon sequestration. During cyclic CO₂ injection, alternating loads are induced within the casing, and the sealing performance of the Sn58Bi alloy under such conditions has yet to be thoroughly validated. To address this issue, a dedicated experimental apparatus was designed and constructed to simulate the sealing behavior of the alloy under cyclic loading conditions representative of CCUS wells. The setup also considers the influence of environmental factors such as temperature and load amplitude on the overall sealing performance.

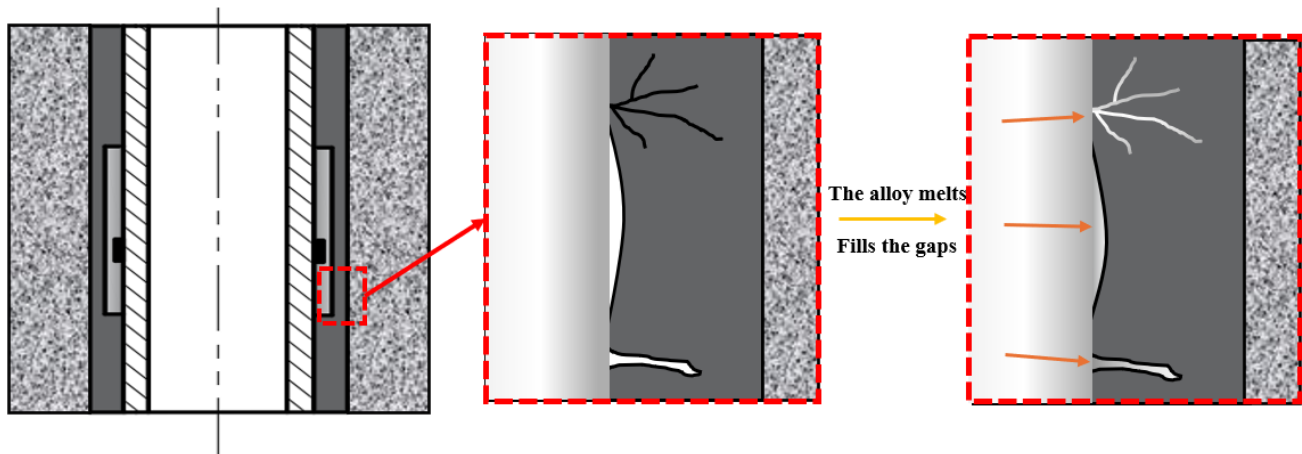


Figure 4. Effect of Embedded Molten Alloy Plugging in the B-Annulus.

3. Experimental Device

3.1. Experimental Apparatus for Gas Channeling Sealability

3.1.1. Experimental Apparatus and Testing Principle

The sealing performance gas-channeling apparatus consists of the device body, a hydraulic loading system, a gas injection and monitoring system, and a temperature-controlled chamber. The apparatus was designed and fabricated in our laboratory (Beijing, China). The body is composed of an inner and outer sleeve, upper and lower end caps, sealing rings, gaskets, and the tested material (Sn58Bi alloy or cement). The configuration forms an annular space where the sealing material is placed, with rings and gaskets ensuring integrity.

Cyclic pressure is applied to the inner sleeve through the hydraulic system to simulate wellbore loading, while gas is injected into the annulus and monitored by a pressure gauge to detect leakage. Under controlled temperature, the sealing material fills the annulus, and pressure variations in the gauge indicate sealing failure or gas channeling (Figures 5 and 6).

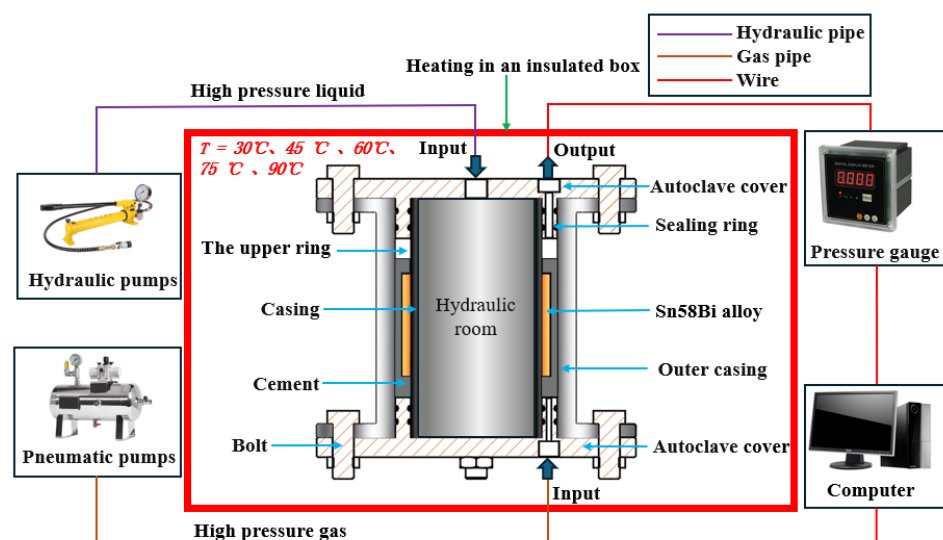


Figure 5. Schematic diagram of the sealing gas-channeling experimental apparatus.

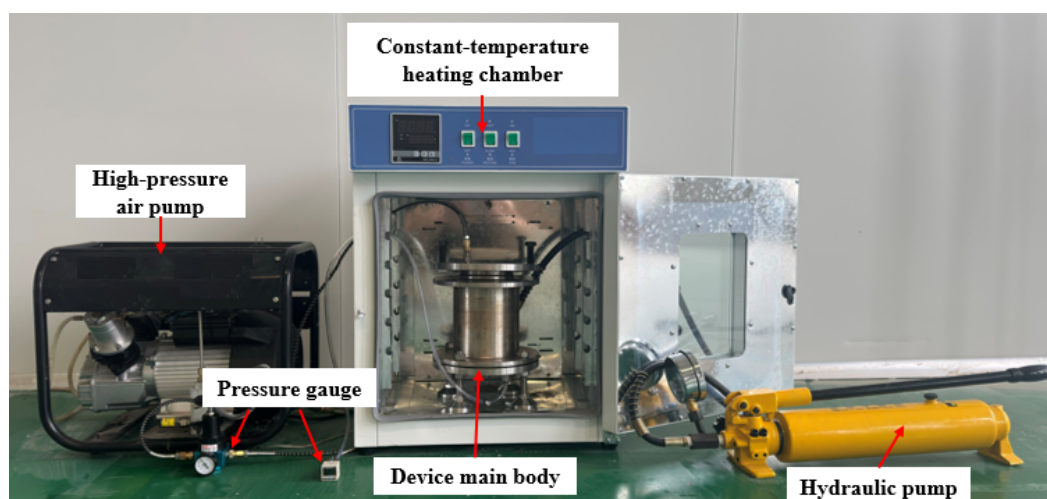


Figure 6. Photograph of the sealing gas-channeling experimental apparatus.

3.1.2. Similarity Analysis and Field Representativeness

The objective of the laboratory-scale experiment was not to replicate the full dimensions of a field wellbore, but to reproduce the key physical processes governing annular sealing integrity. Therefore, the experimental design focused on maintaining similarity in the dominant controlling parameters, including temperature, pressure loading, cyclic stress variation, and confinement conditions. These factors are considered the primary drivers of deformation and leakage evolution in annular sealing materials during CCUS operations. In practical CCUS operations, injection pressure fluctuations commonly occur during start-up, shut-in, and cyclic injection processes. The selected pressure range of 20–30 MPa was designed to represent the typical pressure variation experienced by deep saline aquifer storage wells. Although the absolute field pressures may vary among projects, the selected loading conditions are representative of the stress amplitudes encountered in engineering applications. In practical CCUS operations, injection pressure fluctuations commonly occur during start-up, shut-in, and cyclic injection processes. The selected pressure range of 20–30 MPa was designed to represent the typical pressure variation experienced by deep saline aquifer storage wells [19]. Although the absolute field pressures may vary among projects, the selected loading conditions are representative of the stress amplitudes encountered in engineering applications. Table 3 presents the parameters obtained through a 1/4 scale reduction in the wellbore structure reported in [3], while maintaining geometric similarity to ensure consistency with field conditions. These parameters allow the plugging process to be simulated under representative and mechanically similar wellbore environments. The specifications of the main components of the experimental apparatus are given below.

Table 3. Experimental setup parameters.

Inner Casing Inner Radius (mm)	Inner Casing Outer Radius (mm)	Outer Casing Inner Radius (mm)	Outer Casing Outer Radius (mm)	Inner Casing Pressure (MPa)	Casing Length (mm)
44.45	49.01	61.125	65.95	20–30	180

3.2. Experimental Investigation of Gas Channeling in Alloy Seals

3.2.1. Action of Sn58Bi Alloy and Cement Specimens

In conventional oil well cementing, Class G cement is typically used to achieve long-term sealing between the casing and the formation. For comparative evaluation, both

cement and alloy sheaths were prepared in this study, and their performance was tested using the same experimental apparatus. The preparation procedures are as follows:

(1) Preparation of Sn58Bi Alloy Samples

The Sn58Bi alloy was placed on a heating stage and heated to 200 °C until fully molten. The Sn58Bi alloy was heated to the injection temperature at a controlled heating rate of 30 °C/min, and subsequently cooled at a rate of 10 °C/min after injection to ensure stable solidification behavior. During melting, the alloy was gently stirred with a glass rod. The molten alloy was then slowly injected into the annular space to ensure uniform filling under the influence of gravity. After injection, the entire apparatus was maintained at 200 °C using an electric heating coil to prevent rapid cooling caused by temperature differences, which could result in uneven filling.

(2) Preparation of Cement Samples

G-class oil well cement was mixed at a water-to-cement ratio of 0.44 using a mechanical stirrer for 5–10 min to achieve a homogeneous slurry. The cement slurry was poured into molds for shaping, followed by a 2-day curing period after initial setting to ensure sufficient strength and stability.

The samples were made as shown in Figure 6. Once the Sn58Bi alloy and cement had fully solidified, the resulting samples were used for subsequent sealing performance tests and investigations of micro-annulus formation under cyclic loading conditions.

3.2.2. Experimental Procedure

To simulate alternating loads generated within the casing during CO₂ injection, the upper part of the apparatus was connected to a hydraulic pressurization system, allowing high-pressure fluid to enter the inner casing from the top. The lower part was connected to a gas pressurization system to evaluate the gas-tightness of the alloy or cement sheaths. If gas breaches the interface between the sealing material and the casing, it escapes through the annulus to the upper chamber, while pressure changes are recorded to obtain experimental data. The specific procedure is as follows:

- (1) Open the bottom pressurization system and inject gas at the base of the alloy/cement ring, adjusting the bottom pressure to 0.5 MPa for initial gas-tightness testing.
- (2) Activate the top pressurization system to inject hydraulic fluid into the casing. Once the target test pressure of 20 MPa is reached, open the relief valve to depressurize. The control system and sensors automatically record pressure variations during the test.
- (3) Monitor the pressure at the base of the alloy sheath. A pressure drop indicates sealing failure of the alloy sheath, whereas stable pressure suggests that the cement sheath remains sealed. Step 2 is then repeated for subsequent cycles. Each test group undergoes 20–30 cycles of load and unload. After completion, the experimental data are saved for analysis (Figure 7). The cyclic internal pressure loading tests were conducted under a controlled loading program consisting of 20–40 pressure cycles. Each cycle included a pressurization stage, a pressure-holding stage, and a depressurization stage. The loading rate was set to 2 MPa/s, while the unloading rate was maintained at 2 MPa/s. During each cycle, the maximum pressure was held constant for 60 s to ensure pressure stabilization before unloading. This loading scheme was designed to minimize transient pressure fluctuations and to ensure repeatable mechanical response of the Sn58Bi alloy, considering its sensitivity to strain rate effects. All cyclic tests were performed under identical loading parameters to guarantee experimental consistency.

To ensure the reliability of experimental data, all tests were conducted with multiple parallel groups, and the arithmetic mean of the measured data was taken as the final result.

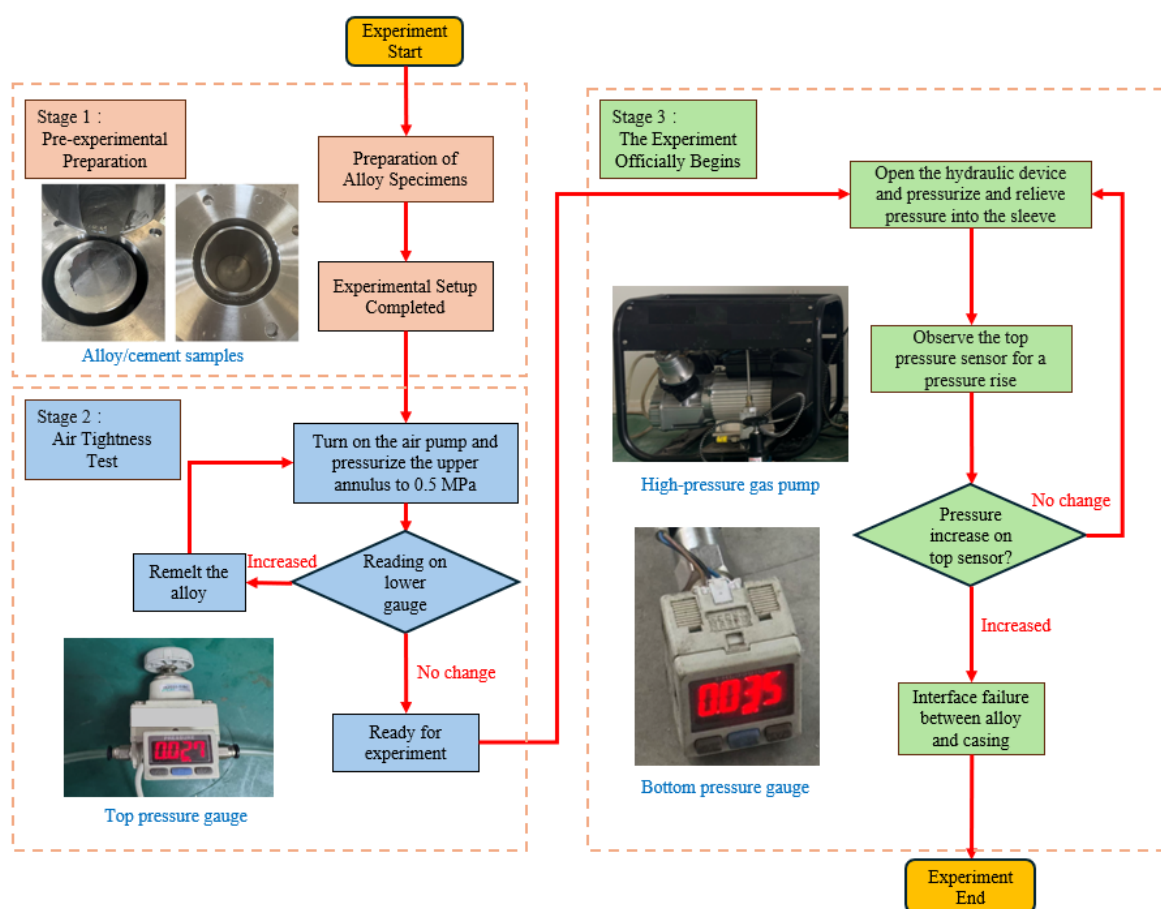


Figure 7. Schematic flowchart of the gas-channeling sealing experiment.

4. Experimental Analysis of Sn58Bi Alloy for Annulus Sealing

4.1. Comparison of Alloy and Cement Annulus Sealing Performance

Under identical cyclic pressure and temperature conditions, 20 cycles of alternating load were applied to both the Sn58Bi alloy sealing structure and the conventional G-class cement sealing structure. Figure 8 shows the cyclic loading of the internal pressure from 0 to 20 MPa. The pressure variations at the lower gas port were recorded after each loading cycle. The experimental parameters for the alloy and cement annulus sealing tests are listed in Table 4. Each experiment under identical conditions was repeated three times to ensure data reliability. The reported results represent the arithmetic mean value, and the error bars shown in the figures correspond to the standard deviation of the repeated measurements.

Table 4. Experimental test parameters.

Test Group	Sealing Materials	Casing Inner Pressure (MPa)	Temperature (°C)	Cycle Rounds	Unloading Pressure (MPa)
1-1	Sn58Bi	20	30	20	0
1-2	Cement	20	30	20	0

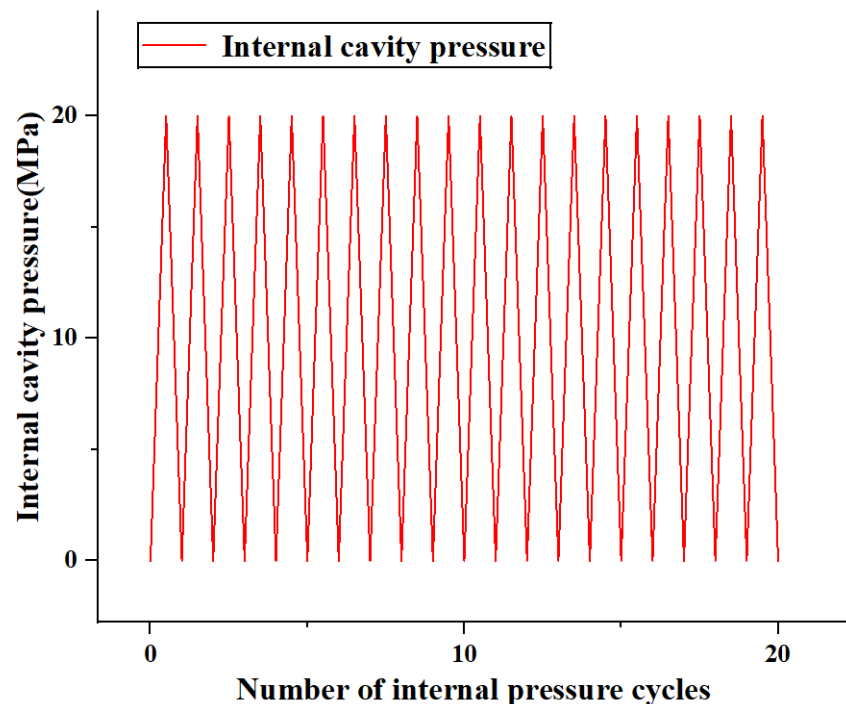


Figure 8. Internal gas pressure variations in alloy and cement under cyclic loading.

The experimental results demonstrated that the Sn58Bi alloy samples maintained a stable bottom-hole pressure during the initial 16 cycles without any noticeable decline. Moreover, no gas penetration into the lower annulus was detected, confirming the favorable sealing performance of the alloy.

In contrast, the G-class cement samples showed a gradual increase in bottom pressure at the 5th cycle. Gas began to leak, suggesting micro-annulus channels had formed at the interface. Leakage was detected at 0.03 MPa for cement. For Sn58Bi, leakage occurred at the 16th cycle, at 0.5 MPa. This shows that Sn58Bi has stronger resistance to gas penetration during early cycles.

For cement, gas leakage occurred after the fifth cycle, with a relatively low leakage pressure of 0.02 MPa. From the 6th cycle, it increased gradually. At the 11th cycle, it reached 0.18 MPa. By the 15th cycle, it sharply rose to 0.5 MPa and remained high. This indicates failure of the cement seal. Micro-cracks or micro-annuli likely developed, allowing gas to escape (Figure 9).

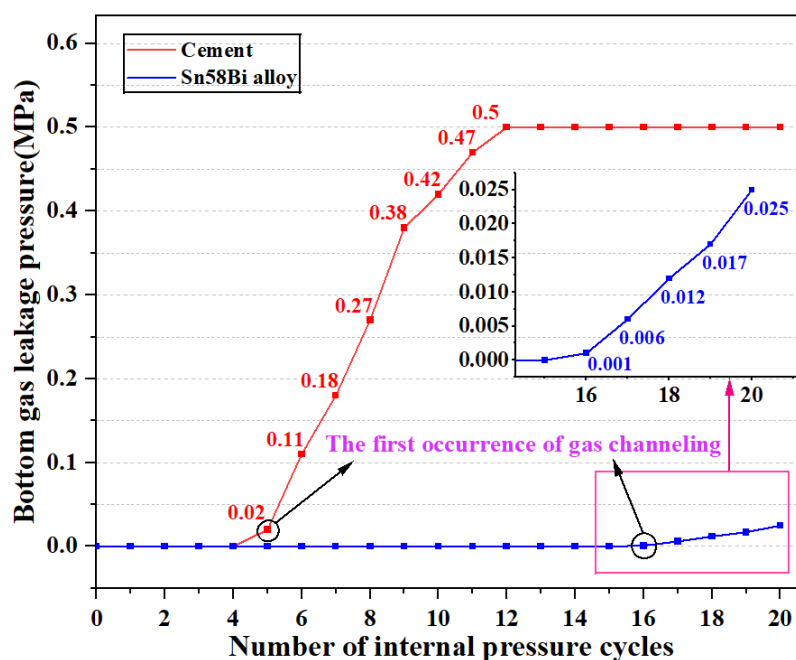


Figure 9. Gas pressure trends of alloy and cement under cyclic loading.

For Sn58Bi, leakage pressure remained near 0 MPa during cycles 0–15. After the 16th cycle, it slightly increased to 0.001 MPa. By the 20th cycle, it reached only 0.025 MPa. Overall, Sn58Bi maintained stable sealing performance. Its integrity was preserved, effectively preventing gas leakage even under multiple cyclic loads.

4.2. Effect of Environmental Temperature on Alloy Annulus Sealing Performance

To investigate the influence of environmental temperature on the sealing performance of the alloy plug, systematic comparative experiments were conducted to evaluate the gas breakthrough pressure and the critical yield cycles of the alloy sealing structure under different temperatures. Kong et al. reported that high-temperature mechanical testing of Sn58Bi alloy shows a sudden strength reduction of approximately 30% when the temperature increases from 75 °C to 100 °C, and temperatures above 100 °C lead to abnormal coarsening of the Bi-rich phase and significant creep softening, resulting in a sharp decline in the overall load-bearing capacity of the alloy [20]. Therefore, to avoid interference from high-temperature softening in the evaluation of sealing performance, the experimental temperature in this study was maintained below 90 °C. The experimental parameters are listed in Table 5.

Table 5. Experimental test parameters.

Test Group	Sealing Materials	Casing Inner Pressure (MPa)	Temperature (°C)	Cycle Rounds	Unloading Pressure (MPa)
2-1	Sn58Bi	20	30	0-40	0
2-2	Sn58Bi	20	45	0-40	0
2-3	Sn58Bi	20	60	0-40	0
2-4	Sn58Bi	20	75	0-40	0
2-5	Sn58Bi	20	90	0-40	0

As the temperature increases from 30 °C to 90 °C, the initial gas breakthrough pressure of the alloy sealing structure under no cyclic loading rises significantly from 1.61 MPa

to 2.82 MPa. However, after 20 and 40 internal pressure cycles, the breakthrough pressure decreases markedly, with the most severe degradation occurring in the low-temperature range (30–45 °C), where the maximum reduction reaches 75%. In contrast, the high-temperature range (75–90 °C) retains approximately 46–89% of the initial sealing capacity. The red curve in the figure indicates the critical yield cycle, defined as the number of pressurization cycles at which irreversible plastic deformation begins. This critical cycle increases linearly with temperature, from 16 cycles at 30 °C to 37 cycles at 90 °C, suggesting that higher temperatures enhance the alloy's yield resistance, effectively delaying fatigue damage and prolonging sealing life (Figure 10).

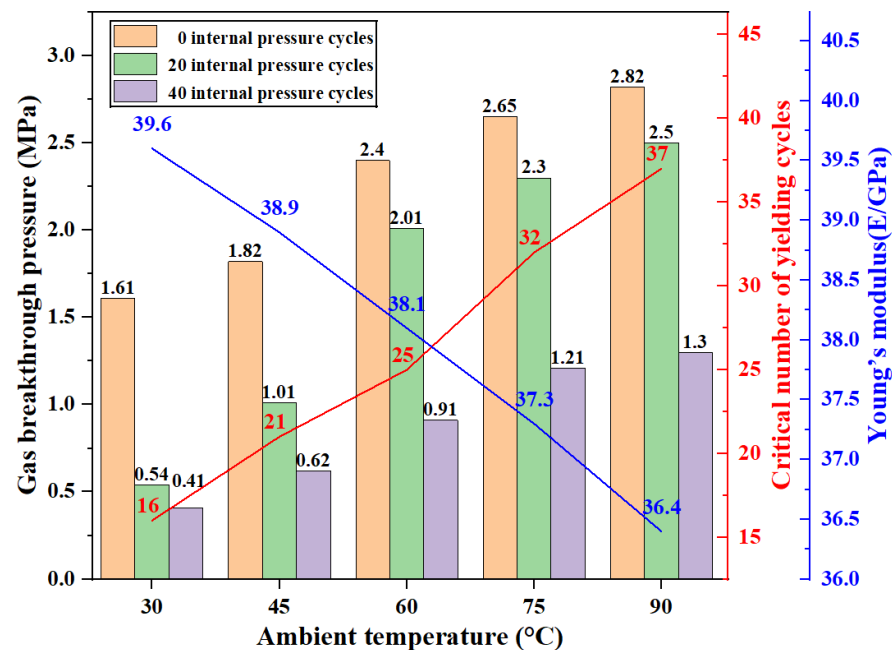


Figure 10. Gas breakthrough pressure of Sn58Bi at varying temperatures.

The Sn58Bi low-melting-point alloy demonstrates excellent sealing stability under high-temperature and high-pressure wellbore conditions, which is intrinsically related to its creep behavior. Creep refers to the progressive plastic deformation of a material under constant stress over time, and for Sn58Bi alloy, this phenomenon is particularly pronounced within the downhole temperature range of 40–110 °C. The mechanical property changes in Sn58Bi between 30 and 90 °C—including reduced hardness, enhanced ductility, and increased creep—contribute to the observed advantage in wellbore sealing experiments: higher initial sealing at elevated temperatures and prolonged life under cyclic loading. Kong et al.'s high-temperature mechanical data indicate an intrinsic evolution of the alloy within 30–90 °C characterized by “decreasing hardness, enhanced creep, and increased ductility,” which explains the experimental observation that the initial sealing performance improves with temperature while retaining higher breakthrough pressure and greater critical yield cycles after multiple cycles [20]. According to Hmadeh et al., when the temperature reaches approximately 0.3–0.4 times the material's melting point (around 80–110 °C), the alloy enters a steady-state creep stage, exhibiting substantial stress relaxation and improved interface conformity [21]. Although 30–90 °C is well below the eutectic melting point of 138 °C, it is sufficient to reduce the elastic modulus and induce micro-creep. The reduction in local yield stress at elevated temperature allows minor plastic flow under external compressive forces, filling interface roughness and micro-voids, thereby improving gas tightness.

Furthermore, the elastic modulus of Sn58Bi decreases with increasing temperature, as shown in Figure 10 [22]. As temperature rises, the elastic modulus drops from approximately 39.6 GPa to 36.4 GPa, reducing material stiffness and allowing better accommodation of thermal expansion deformations of the casing and cement sheath. This mitigates cracking or debonding of brittle materials under cyclic loading. The lowered elastic modulus enables the alloy to undergo elastic–viscoplastic deformation at the microscale, facilitating adaptive filling of interface irregularities or micro-gaps, thereby enhancing interfacial contact and gas tightness. During loading and unloading, Sn58Bi can more effectively recover its shape and maintain tight interfacial contact.

4.3. Influence of Internal Pressure on Sn58Bi Alloy Sealing

To investigate the effect of different cyclic internal pressures on the sealing performance of the alloy annulus, comparative experiments were conducted to measure the gas leakage pressure through the Sn58Bi alloy sealing structure under varying cyclic pressures. At the same environmental temperature, the alloy seal was subjected to 20 cycles of alternating load under different internal pressures.

Table 6 lists the experimental parameters for the alloy under various cyclic internal pressure conditions.

Table 6. Parameters for alloy integrity testing.

Test Group	Sealing Materials	Casing Inner Pressure (MPa)	Temperature (°C)	Cycle Rounds	Unloading Pressure (MPa)
3-1	Sn58Bi	20	30	0-20	0
3-2	Sn58Bi	25	30	0-20	0
3-3	Sn58Bi	30	30	0-20	0

Under all cyclic internal pressure conditions, the Sn58Bi alloy sealing structure exhibited excellent sealing performance during the initial cycles. The bottom gas leakage pressure remained extremely low (below 0.001 MPa), indicating effective prevention of gas penetration.

However, as the number of loading cycles increased, a clear inflection point appeared in the leakage pressure, followed by a rapid rise, indicating the onset of seal failure.

It can be seen that higher internal pressure reduces the number of cycles required for gas to penetrate the alloy seal. At 20 MPa, leakage pressure began to rise noticeably after the 16th cycle and reached 0.038 MPa by the 21st cycle. In contrast, at 25 MPa and 30 MPa, the critical cycles occurred earlier, at the 14th and 10th cycles, respectively. By the 20th cycle, the bottom leakage pressure reached 0.025 MPa and 0.1 MPa for 25 MPa and 30 MPa, respectively (Figure 11).

Under the 30 MPa condition, the leakage pressure increased earlier and exhibited a steeper growth trend in subsequent cycles. These results indicate that high internal pressure combined with multiple cyclic loads accelerates the loss of elastic capacity and accumulation of plastic damage in the alloy, significantly reducing the durability and reliability of the sealing system.

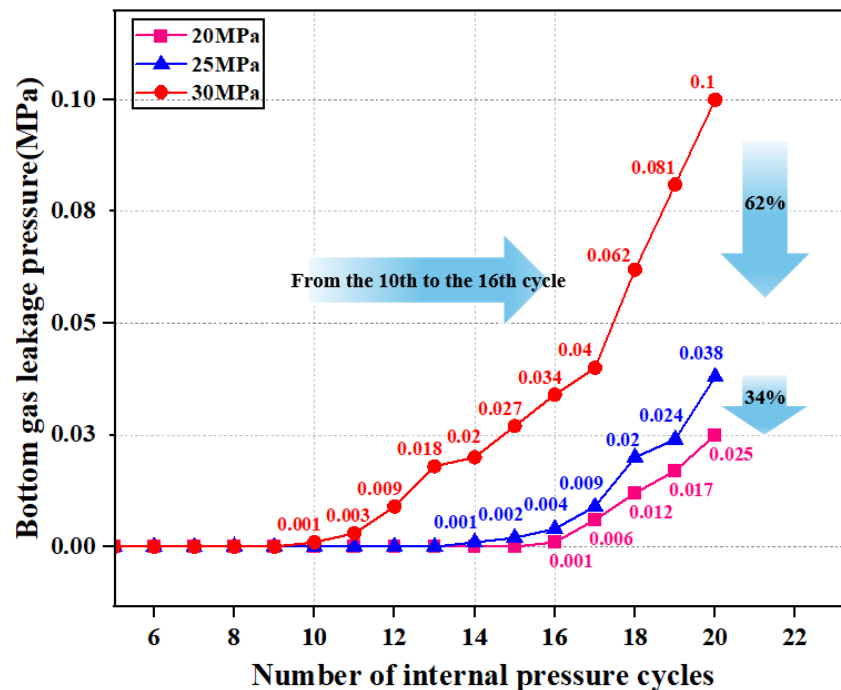


Figure 11. Gas-tightness of Sn58Bi under varying internal pressures.

5. Comparison of Alloy and Cement Seal Failure

5.1. Model Assumptions and Applicability

To ensure physical consistency, the radial displacement calculated in this study is directly related to the evolution of annular sealing integrity. An increase in residual radial displacement indicates the progressive development of micro-annular gaps at the casing–sheath and sheath–formation interfaces, which serve as preferential pathways for gas migration. Therefore, the displacement magnitude can be used as an effective mechanical indicator of sealing degradation under cyclic loading.

Although the present model does not explicitly incorporate time-dependent creep behavior, the accumulation of residual displacement under cyclic loading effectively captures the macroscopic manifestation of irreversible plastic deformation. In this context, the cyclic loading process is represented as a stepwise elastic–plastic response, where each cycle contributes to incremental permanent deformation, leading to progressive contact stress reduction and eventual micro-annulus formation. Time-dependent behaviors such as creep and cyclic damage are neglected due to the short duration of cyclic loading and the focus on immediate elastic response.

Thus, the proposed analytical framework provides a mechanically consistent approximation of sealing degradation, focusing on the dominant deformation mechanism governing short-term cyclic performance rather than long-term rheological effects.

5.2. Establishment of the Three-Layer Coupled Elastic Model

To compare the interfacial integrity of Sn58Bi alloy and conventional Grade G cement in CCUS wellbores, this study adopts a three-layer coupled casing–annulus–formation analytical model originally proposed by Zhang et al. [23] to calculate the radial displacement of the alloy sheath and cement sheath under cyclic loading at 30 °C and a casing pressure of 20 MPa.

As shown in Figure 12, the system consists of casing, alloy sheath, cement sheath, and surrounding formation.

The inner and outer radii of the casing are denoted as a and b , the outer radius of the alloy sheath is c , and the outer radius of the cement sheath is d . The internal casing pressure is P_i , while the interface contact stresses are defined as P_{c1} (casing–alloy), P_{c2} (alloy–cement), and P_{c3} (cement–formation), respectively.

All governing equations are derived under linear elastic assumptions using thick-walled cylinder theory under plane strain conditions.

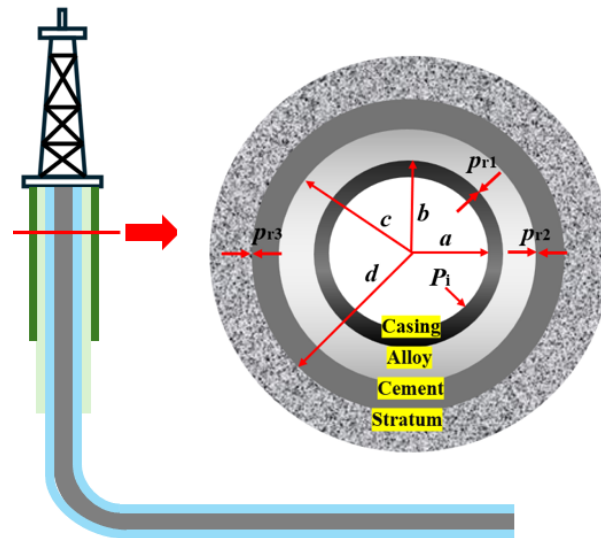


Figure 12. Schematic diagram of the interaction among casing, alloy ring, and formation.

5.3. Displacement Distribution

To quantitatively describe the deformation behavior of cement sheaths and Sn58Bi alloy sheaths, this study adopts the elastic solution of the casing–annulus–formation three-layer coupled model established by Zhang et al. [23]. Based on the thick-walled cylinder elasticity theory under plane strain conditions, the radial displacement analytical expression derived for annular sheath s is introduced. For any coaxial annular sheath (inner radius r_i , outer radius r_o ; inner surface subjected to internal pressure p_i , outer surface subjected to external pressure p_o), the radial and circumferential stresses are expressed as follows:

$$\sigma_r(r) = A - B/r^2 \quad (1)$$

$$\sigma_\theta(r) = A + B/r^2 \quad (2)$$

The constants A and B are determined from the boundary conditions:

$$A = p_i r_i^2 - p_o r_o^2 / (r_o^2 - r_i^2) \quad (3)$$

$$B = (p_i - p_o) r_i^2 r_o^2 / (r_o^2 - r_i^2) \quad (4)$$

The corresponding radial displacement of the annular sheath:

$$u(r) = 1/E[(1 - \nu^2)Ar + (1 + \nu)B/E] + (1 + \nu)\alpha\Delta T r/E \quad (5)$$

5.4. Boundary Conditions and Basic Assumptions

(1) Casing layer: $a < r < b$

The inner wall is subjected to the casing internal pressure P_i (expressed in the stress formula as $p_i^{(1)} = P_i$), and the outer wall is in contact with the alloy, with a contact pressure of $p_o^{(1)} = P_{c1}$.

- (2) Alloy: $b < r < c$

The inner wall is subjected to the casing–alloy contact pressure $p_i^{(2)} = P_{c1}$, and the outer wall is subjected to the alloy–cement contact pressure $p_o^{(2)} = P_{c2}$.

- (3) Cement: $c < r < d$

The inner wall is subjected to the alloy–cement contact pressure $p_i^{(3)} = P_{c2}$, and the outer wall is subjected to the cement–formation contact pressure $p_o^{(3)} = P_{c3}$.

- (4) Formation: $r \geq d$

The formation is usually treated as a semi-infinite domain, with the far-field radial stress denoted as p_f .

Displacement continuity conditions:

$$u_r^{ring}(b) = u_r^{casing}(b) \quad (6)$$

$$u_r^{ring}(c) = u_r^{casing}(c) \quad (7)$$

$$u_r^{ring}(d) = u_r^{casing}(d) \quad (8)$$

Substitute the parameters in Table 7 for calculation:

Table 7. Material parameters.

Materials	E/GPa	ν
Casing	210	0.3
Cement	15	0.22
Sn58Bi	23	0.32
Formation (Limestone)	40	0.25

5.5. Calculation Results and Discussion

Using the developed linear elastic analytical model, radial displacement distributions of the casing–annulus–formation system were calculated for both the Sn58Bi alloy sheath and the conventional cement sheath under 30 °C and 20 MPa casing pressure.

As shown in Figure 13, the results demonstrate significant differences in deformation accumulation behavior between the two materials.

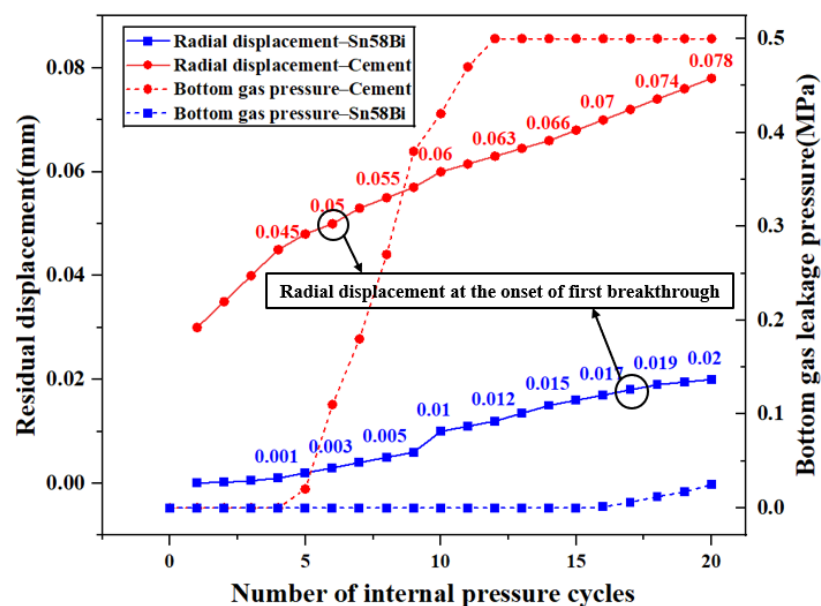


Figure 13. Comparison of radial displacement at the inner wall for Sn58Bi alloy and cement sheaths.

The cement sheath exhibits progressively increasing residual radial displacement, rising from 0.03 mm initially to 0.078 mm at the 20th cycle. Micro-annulus initiation is observed when displacement reaches approximately 0.05 mm at the 6th cycle, indicating the onset of interfacial separation and sealing degradation.

In contrast, the Sn58Bi alloy sheath shows a much slower increase in residual displacement, from 0.001 mm to 0.02 mm over the same loading cycles. Micro-annulus initiation occurs later (16th cycle) at a displacement of 0.018 mm, and the maximum leakage pressure remains limited to 0.025 MPa.

These results indicate that cement exhibits stronger accumulation of irreversible deformation under cyclic loading, leading to earlier interfacial debonding and micro-annulus formation. The Sn58Bi alloy, however, maintains lower residual deformation accumulation, resulting in improved interfacial stability and enhanced sealing performance.

Overall, the linear elastic coupled model combined with residual displacement evolution provides a consistent mechanical explanation for sealing degradation under cyclic loading conditions in CCUS wellbores.

6. Discussion

6.1. Sealing Mechanism and Comparative Behavior

This study systematically investigated the sealing performance of Sn58Bi low-melting-point alloy for B-annulus applications under cyclic internal pressure conditions, with comparison to conventional G-grade cement. The results clearly demonstrate that the Sn58Bi alloy exhibits significantly enhanced sealing stability and resistance to cyclic degradation compared with cement systems.

Under identical loading conditions (20 MPa, 30 °C), the alloy maintained stable sealing for up to 16 cycles, whereas cement failure occurred at the 5th cycle. This difference is primarily attributed to the distinct deformation characteristics of the two materials. Cement exhibits brittle behavior with limited strain accommodation capacity, leading to microcrack initiation and propagation under cyclic stress. In contrast, the Sn58Bi alloy responds through recoverable elastic deformation and stable volumetric behavior, enabling better accommodation of interfacial irregularities and suppression of early leakage pathways.

These results confirm that material compliance and deformation compatibility are key controlling factors governing annular sealing performance under cyclic loading conditions.

6.2. Temperature and Pressure-Dependent Sealing Evolution

Temperature and cyclic internal pressure are identified as two dominant external factors governing sealing performance evolution. Increasing temperature from 30 °C to 90 °C enhances both initial breakthrough pressure and the number of critical failure cycles. This behavior is associated with the reduction in elastic modulus and enhanced micro-scale deformation ability of Sn58Bi alloy at elevated temperatures, which improves interfacial conformity and reduces stress concentration.

Conversely, increasing cyclic pressure (20–30 MPa) accelerates sealing degradation by promoting cumulative interfacial separation and reducing elastic recovery capability. At higher pressure levels, earlier leakage initiation is observed, indicating that stress amplitude is a key driver of interface damage accumulation. Despite this, the alloy still maintains significantly lower leakage permeability compared to cement under identical conditions, confirming its superior robustness under aggressive cyclic loading environments.

6.3. Mechanism of Interfacial Degradation

The underlying sealing degradation mechanism can be explained from the perspective of interfacial contact evolution under cyclic elastic mismatch. During repeated loading–unloading cycles, the Sn58Bi alloy undergoes reversible radial deformation, while the surrounding casing and cement sheath exhibit comparatively lower deformation compatibility. This mismatch leads to progressive deterioration of interfacial contact conditions at both casing–alloy and alloy–formation interfaces.

As cycling continues, localized contact loss accumulates and develops into micro-gaps (micro-annuli), which act as preferential pathways for gas migration. The evolution of sealing performance is therefore governed by progressive interfacial separation rather than irreversible plastic failure. The proposed elastic analytical model successfully captures this mechanism by linking radial deformation evolution to contact pressure reduction and micro-annulus formation, providing a consistent explanation for experimentally observed trends in leakage pressure and residual displacement.

6.4. Engineering Implications and Field Applicability

From an engineering perspective, the Sn58Bi alloy demonstrates strong potential as an alternative B-annulus sealing material for CCUS well integrity applications, particularly in environments characterized by cyclic injection and shut-in operations. Compared with conventional cement systems, the alloy exhibits superior resistance to cyclic degradation and more stable long-term sealing behavior, indicating improved potential for mitigating micro-annulus-related integrity failures.

The observed performance under temperatures of 30–90 °C and pressures up to 30 MPa is representative of conditions commonly encountered in deep CO₂ storage formations. Therefore, the results provide meaningful insight into the mechanical reliability of alternative sealing materials under realistic operational stress regimes.

However, the present study is based on a laboratory-scale geometrically scaled model with simplified boundary conditions. Field-scale systems involve additional complexities such as geological heterogeneity, long-term chemical reactions, and multi-physics coupling effects, which are not explicitly considered in this work. In addition, the model is based on linear elastic assumptions and does not account for time-dependent phenomena such as creep or fatigue damage.

Accordingly, the results should be interpreted as capturing the dominant mechanical mechanism of sealing degradation rather than providing direct quantitative prediction of field performance. Nevertheless, the proposed framework provides a useful basis for preliminary material evaluation and mechanism understanding. Future work should focus on large-scale validation, long-term durability testing, and incorporation of thermo-chemo-mechanical coupling effects to improve field-scale applicability.

7. Conclusions

This study investigated Sn58Bi alloy's annulus sealing performance under molten infiltration, focusing on temperature and internal pressure effects, with findings providing theoretical support for its application in CCUS well B-annulus sealing. Key conclusions are as follows:

- (1) Under 20 loading cycles, the alloy sheath's residual radial displacement was significantly smaller than cement's—first leakage occurred at the 16th cycle (0.019 mm) vs. cement's 5th cycle, indicating superior cyclic deformation resistance.
- (2) The alloy's molten-to-solid transition during solidification enhances casing/wellbore conformity; its interface structure remains stable under cyclic internal pressure, prolonging sealing integrity and suppressing micro-annuli.

- (3) Elevated temperatures improve the alloy's interface filling (relieving stress concentrations), but increased internal pressure intensifies plastic deformation and accelerates seal failure (a primary control factor).
- (4) The three-layer casing–alloy–formation elastoplastic coupled model shows the alloy better absorbs casing radial expansion-induced deformation stresses, buffering formation impact and ensuring long-term sealing mechanical stability.

This study systematically investigates the sealing performance of Sn58Bi alloy in B-annulus applications under cyclic internal pressure loading conditions by integrating experimental testing with a linear elastic theoretical model to quantitatively analyze its sealing response behavior. A three-layer coupled elastic model was developed to describe the radial deformation evolution and micro-annulus formation of the Sn58Bi sealing structure under cyclic loading, and an integrated experimental–theoretical framework was established to enable quantitative characterization of sealing behavior. Meanwhile, the effects of temperature and loading conditions on sealing integrity were systematically examined, revealing the thermo-mechanical coupling mechanism governing micro-annulus evolution. The results indicate that cyclic loading significantly accelerates sealing degradation, while the proposed model can effectively capture the evolution of residual radial displacement and leakage behavior under elastic deformation assumptions. Overall, this work provides a mechanistic and quantitative understanding of Sn58Bi alloy sealing behavior in B-annulus environments and offers a theoretical basis for the design and evaluation of sealing materials under cyclic loading conditions.

Author Contributions: C.Z.: conceptualization, data organization, formal analysis, investigation, and methodology. J.S.: writing—review and editing, data collation, visualization, writing—draft preparation, formal analysis, and project management. W.W.: data collation, visualization, project management, and validation. G.L.: supervision and writing—review and editing. J.L.: writing—review and editing and project management. W.L.: resources, software, and funding acquisition. All authors have read and agreed to the published version of the manuscript.

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