HiLL PUBLISHING

Engineering Advances, 2026, 6(3), 167-172
https://www.hillpublisher.com/journals/ea/
ISSN Online: 2768-7961

Failure Analysis and Maintenance Improvement of a High-pressure Steam Gate Valve in Superheated Steam Service

Jingdi Wu

Technical & Maintenance Department, BASF-YPC Company Limited, Nanjing 210048, Jiangsu, China.

How to cite this paper: Jingdi Wu. (2026) Failure Analysis and Maintenance Improvement of a High-pressure Steam Gate Valve in Superheated Steam Service. *Engineering Advances*, 6(3), 167-172.
DOI: 10.26855/ea.2026.09.007

Received: May 28, 2026
Accepted: June 25, 2026
Published: July 22, 2026

***Corresponding author:** Jingdi Wu, Technical & Maintenance Department, BASF-YPC Company Limited, Nanjing 210048, Jiangsu, China.

© 2026 by the author(s).
This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution-NonCommercial-NoDerivatives (CC BY-NC-ND) license, which permits non-commercial use, distribution, and reproduction in any medium, provided the original work is properly cited and is not modified or adapted.
https://creativecommons.org/licenses/by-nc-nd/4.0/

Abstract

High-pressure steam gate valves are critical isolation barriers in petrochemical units, especially during shutdowns, emergency isolation, and major maintenance. This paper presents a practical failure analysis and maintenance improvement case involving two large gate valves installed in series on the high-pressure steam line of an ethylene cracking unit. The valves operated in superheated steam service at approximately 525 °C and 12 MPa and had experienced recurrent leakage after overhaul. Based on maintenance history, disassembly inspection and operating feedback, the dominant external leakage path was identified as the upper sealing system, including the backseat, stem, packing and self-sealing region. The root causes included backseat deformation under steam erosion, excessive stem clearance, thermal fatigue and scoring of the stem, insufficient packing resistance to thermal settling and steam attack, and limited maintainability of the original metallic self-sealing arrangement. Corrective actions included redesigning the backseat as a more rigid 45° line-contact sealing head, upgrading the stem material and reducing the diametral clearance from approximately 3 mm to 0.5 mm, increasing the stuffing box depth from 140 mm to 167 mm, adopting a composite reinforced graphite and metal-support packing structure, and replacing the original hard self-sealing concept with a more tolerant graphite-based sealing arrangement. Preventive maintenance was also performed on the wedge and actuator, and staged hot retightening was applied during startup. Post-overhaul inspection and operating feedback indicated that the repaired valves met the required technical criteria and no visible leakage was observed during subsequent site operation. The case shows that recurrent leakage in severe steam service should be addressed as a complete sealing-system problem rather than as an isolated packing failure.

Keywords

High-pressure steam valve; failure analysis; corrective maintenance; sealing reliability

1. Introduction

Industrial gate valves in high-pressure steam systems may remain fully open for long periods, but reliable closure is critical during shutdowns, emergencies, and major maintenance. External leakage can release high-temperature steam and endanger personnel, while internal leakage can prevent complete downstream isolation. Valve failure commonly results from interacting leakage, wear, corrosion, fracture, and structural factors rather than a single defect [1].

In petrochemical plants, steam-driven compressor trains depend on a stable high-pressure steam supply, making

isolation valves important safety and maintenance barriers. Valve configuration, materials, pressure-temperature rating, sealing structure and operating requirements must therefore be considered together [2, 3]. Post-overhaul performance also depends on interactions among the backseat, stem guidance, packing, self-sealing components, actuator condition and startup tightening.

This technical note presents a maintenance case involving two large gate valves installed in series on the high-pressure steam line of an ethylene cracking unit. The valves operated in superheated steam at approximately 525 °C and 12 MPa and had experienced recurrent post-overhaul leakage. A systematic failure analysis was therefore conducted to improve the complete sealing path rather than replace individual components. For rising-stem valves, sealing performance is affected by packing material and compression, stem surface condition, temperature, and operating cycles [4].

2. Equipment Background and Failure Description

The two gate valves were installed in series on the steam line supplying a compressor train. Under normal operation, both valves were fully open. During planned shutdowns or abnormal events, the valves had to close reliably to isolate the steam line and allow downstream equipment to be inspected or repaired. This operating mode created a typical challenge for normally open isolation valves: the valves experienced severe thermal and pressure service for long periods, but their sealing performance was only fully tested when isolation was required.

The main operating medium was superheated steam. The nominal valve size was large, and the valves were equipped with pneumatic motor actuators. Because the valve ends were butt-welded into the pipeline, full replacement was not preferred during normal maintenance. Repair and upgrade of replaceable internal components were therefore selected as the practical maintenance strategy. The basic gate-valve construction and butt-welding-end arrangement were considered with reference to the applicable gate-valve design requirements [5].

Maintenance history showed repeated leakage-related repairs. Earlier work included packing replacement, stuffing box repair, stem surface restoration, and weld repair or grinding of wedge sealing surfaces. These measures improved performance temporarily, but leakage risk remained under severe temperature and pressure conditions. During the 2025 turnaround, both valves were disassembled for detailed inspection. The inspection confirmed that the dominant failure path for external leakage was associated with the upper sealing system: the backseat, stem, packing, and self-sealing region.

Figure 1 illustrates the leakage path and major sealing interfaces in the upper valve structure. Once high-pressure steam passed the backseat, it could migrate upward along the stem and attack the packing system. If the packing had insufficient compression margin or structural support, the leakage could develop into visible external leakage. This observation shifted the maintenance focus from a single packing replacement to a sealing-system improvement.

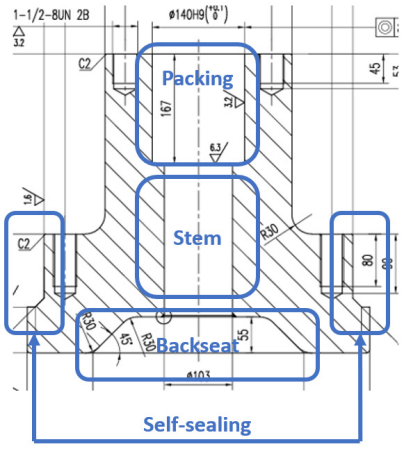

Figure 1. Leakage path and sealing interfaces in the upper valve sealing system.

3. Failure Mechanism Analysis

3.1 Backseat Degradation

The backseat was the first barrier against steam migration toward the packing area. The original design used a relatively thin metallic sealing element. After long-term exposure to high-pressure and high-temperature steam, this

element was vulnerable to compression deformation and erosion. Once the backseat lost its sealing stability, the downstream packing system was exposed to direct steam attack.

This mechanism explains why packing damage appeared repeatedly in previous maintenance cycles. The packing was not necessarily the first root cause; rather, it became the final barrier after failure or weakening of the backseat. Under this condition, any reduction in packing compression margin could lead to external leakage.

3.2 Stem Condition and Clearance

The stem also contributed to the leakage path. The original stem material was F6, which was not ideal for long-term exposure to the actual service temperature of approximately 525 °C. Inspection found signs of thermal fatigue and scoring on the stem surface. Surface damage increased the possibility of local leakage paths and reduced the stability of the stem-packing contact condition.

Another important factor was the clearance between the stem and the surrounding stuffing box or guiding structure. The original diametral clearance was approximately 3 mm. This relatively large clearance allowed steam to bypass upward more easily after backseat degradation. Steam migration along this path increased the thermal and erosive load on the packing area. High-temperature valve failure investigations have also shown that cyclic thermal and mechanical loading can interact with local material or manufacturing defects and promote progressive fatigue damage [6].

3.3 Packing System Limitations

The original packing system used graphite packing. In earlier repair campaigns, reinforced graphite packing with metallic mesh was introduced and provided better performance than the original arrangement. However, the packing system still had limited resistance to long-term thermal settling, compression loss, and upward steam attack. Compression packing performance depends on maintaining adequate radial contact pressure against both the stem and the stuffing-box wall, while temperature, stem finish, gland loading and the number of packing rings can affect leakage and operating resistance [4].

The lower part of the packing stack was particularly vulnerable because steam entered the packing chamber from below once the backseat was compromised. If the lower packing layers were damaged or lost compression, the remaining upper layers had to carry a larger sealing load. Over time, this mechanism reduced the available compression margin and increased the probability of leakage after startup. The selection and qualification of the upgraded packing should therefore consider the applicable temperature and mechanical-cycle testing principles for process-valve packing [7].

3.4 Self-sealing Arrangement Sensitivity

The stuffing box side seal used a metallic self-sealing concept in the original design. This arrangement required good cylindricity, surface finish, and dimensional compatibility. In field maintenance, restoring all these conditions consistently is difficult, especially after repeated service at high temperature.

The original hard-seal concept was therefore sensitive to surface condition and assembly deviation. A more tolerant sealing structure was needed to improve maintainability and post-overhaul reliability [8].

4. Maintenance Improvement Measures

4.1 Backseat Redesign

The first improvement was to redesign the backseat. The thin metallic sealing element was replaced by a more rigid integrated sealing head. The new sealing interface adopted a 45° line-contact design. This geometry improved centering during assembly and reduced the risk of local distortion under load.

By improving the first sealing barrier, the modification reduced the likelihood that high-pressure steam would reach the packing system. This was considered the most important change because it addressed the initial stage of the leakage path.

4.2 Stem Material Upgrade and Clearance Reduction

The second improvement was the stem upgrade. The original F6 stem was replaced by a higher-temperature alloy suitable for the actual steam service. In the original maintenance plan, 25Cr2MoVA was selected for the new stem

because of its improved high-temperature capability compared with the original material.

The running clearance was also reduced. The diametral clearance between the stem and the stuffing box region was reduced from approximately 3 mm to 0.5 mm. This tighter fit limited steam bypass, improved stem guidance, and reduced direct steam attack on the packing structure.

4.3 Composite Packing Arrangement

The third improvement was the redesign of the packing system. Figure 2 shows the composite soft-hard sealing concept used in the upgraded stuffing box. The packing chamber depth was increased from 140 mm to 167 mm. Reinforced graphite packing was used as the main sealing medium, while a metallic support element was added at the lower side of the packing stack.

The design intent was to combine adaptability and strength. The graphite layers provided sealing conformity, while the metallic support resisted the first impact of high-pressure steam from below. Compared with a simple graphite packing system, the composite arrangement provided better resistance to blow-by, extrusion, and thermal settling [4, 7].

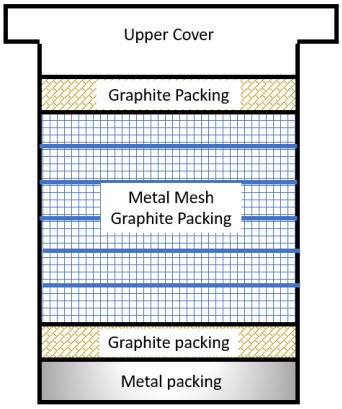

Figure 2. Composite soft-hard packing arrangement used in the upgraded stuffing box.

4.4 Modified Self-sealing Concept

The fourth improvement was to replace the original metallic hard self-sealing concept with a graphite-based sealing structure reinforced by metallic gaskets. Figure 3 shows the modified self-sealing arrangement. The outer diameter of the stuffing box bottom section was increased from 515 mm to 519 mm, reducing the side clearance and improving sealing consistency.

The original inclined sealing geometry was also simplified to a right-angle compression profile. This change provided more uniform compression on the graphite-based seal and made the structure less sensitive to minor dimensional variation during maintenance.

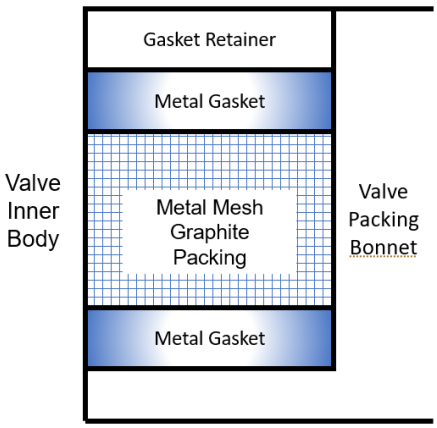

Figure 3. Modified self-sealing concept with reinforced graphite-based structure.

4.5 Preventive Maintenance on Wedge and Actuator

Although the main leakage path was located in the upper sealing system, preventive maintenance was performed on the wedge and actuator. Surface defects on the wedge, including cracks and local pores in the hard-facing layer, were repaired by hard-facing and grinding. During reassembly, red lead was used to check the contact condition between the wedge and the seat. A continuous and clear sealing line indicated acceptable contact quality.

The actuator system was also improved. The original thread arrangement required approximately 90 minutes for full opening or closing. After upgrading the mechanism and matching a new pneumatic motor, the operating time was reduced to about 45 minutes. A stainless-steel protective cover was added to reduce the risk of debris entering the actuator mechanism and causing jamming.

Table 1. Summary of failure causes and corrective actions

Area	Observed problem	Failure contribution	Corrective action
Backseat	Thin metallic sealing element deformed under service	Loss of first sealing barrier and upward steam migration	Rigid integrated sealing head with 45° line-contact interface
Stem	Thermal fatigue, scoring and relatively large clearance	Steam bypass and increased packing load	Higher-temperature stem material and clearance reduction from about 3 mm to 0.5 mm
Packing	Compression loss and limited resistance to steam attack	External leakage after thermal settling	Increased chamber depth and reinforced graphite-metal composite packing
Self-sealing region	Hard metallic self-seal sensitive to geometry and surface condition	Reduced maintainability and inconsistent sealing after overhaul	Graphite-based self-sealing structure with metallic reinforcement and reduced side clearance
Actuator and wedge	Surface defects and long operating time	Secondary reliability and maintainability risks	Wedge hard-facing/grinding, sealing-line check, actuator upgrade and protection cover

5. Startup Retightening and Reassembly Control

Reassembly control was an important part of the repair. The wedge, stem, stuffing box and upper bonnet were installed in sequence. The lifting bolts and packing bolts were tightened using a staged and symmetrical method to avoid uneven loading. Staged and symmetrical tightening was used to reduce uneven preload and local distortion during assembly [9]. During assembly, field technicians adjusted and checked the position of key components to ensure that the sealing parts were properly seated.

Hot retightening during startup was treated as a critical maintenance step. As steam temperature and pressure increased, the packing and self-sealing components continued to settle under load. If this settlement was not compensated, the newly improved sealing structure could lose compression during the early operating period. Maintenance personnel therefore performed repeated staged hot retightening until the operating conditions stabilized.

This practice is one of the key lessons from the case. Hardware improvement alone is insufficient for high-temperature steam valves. Reassembly sequence, tightening method, and startup retightening must be included in the repair strategy.

6. Results and Discussion

After the overhaul, inspection confirmed that the repaired valves met the project-specific technical acceptance criteria. Where applicable, valve pressure and leakage testing principles may be referenced to API 598, ISO 5208 and MSS SP-61 [10-12]. During subsequent site operation, no visible external leakage was observed. The maintenance results indicated that the recurrent leakage tendency was significantly reduced.

The improvement was not caused by a single modification. The result was achieved through the combined effect of backseat strengthening, improved stem guidance, composite packing, a more tolerant self-sealing arrangement, preventive repair of the wedge, and actuator improvement. These measures addressed both the original leakage path and several secondary reliability risks.

The case also shows the importance of viewing a valve as a system. In previous repairs, packing replacement alone could improve performance temporarily but could not remove the root cause. Once the backseat degraded, steam could reach the packing again. Similarly, a new stem would not have been sufficient without packing and

self-sealing improvements. Therefore, recurrent leakage in severe steam service should be analyzed from the complete sealing path.

7. Conclusions

A recurrent leakage problem in a high-pressure steam gate valve was analyzed based on maintenance history, disassembly inspection, and operating feedback. The main leakage path was identified as the backseat–stem–packing/self-sealing region.

The root causes included backseat deformation, excessive stem clearance, stem thermal damage, limited packing resistance to thermal settling and steam attack, and the maintenance sensitivity of the original metallic self-sealing concept.

The maintenance improvement strategy included a rigid 45° line-contact backseat, stem material upgrade, clearance reduction from approximately 3 mm to 0.5 mm, increased stuffing box depth, reinforced graphite-metal composite packing, a modified graphite-based self-sealing arrangement, and staged hot retightening during startup.

The repaired valves met service requirements, and no visible leakage was observed during subsequent site operation. The case demonstrates that reliable post-overhaul performance of critical steam isolation valves requires treatment of the complete sealing system rather than isolated component replacement.

References

[1] Yao HY, Jiang CH, Jin ZJ, Qian JY. Research progress on valve failure. Fluid Mach. 2021;49(10):74-83, 90. doi:10.3969/j.issn.1005-0329.2021.10.011.

[2] Smith P, Zappe RW. Valve selection handbook: engineering fundamentals for selecting the right valve design for every industrial flow application. 5th ed. Amsterdam: Gulf Professional Publishing; 2004.

[3] ASME. ASME B16.34-2025: valves—flanged, threaded, and welding end. New York: American Society of Mechanical Engineers; 2025.

[4] Sotoodeh K. A review of valve stem sealing to prevent leakage from the valve and its effect on valve operation. J Fail Anal Prev. 2021;21(1):9-16. doi:10.1007/s11668-020-01050-1.

[5] API. API Standard 600: steel gate valves—flanged and butt-welding ends, bolted bonnets. 14th ed. Washington, DC: American Petroleum Institute; 2021. Errata 1, 2024.

[6] Kishore K, Kushwaha S, Lal D, Sharma A, Prabhakaran A, Adhikary M, et al. Failure investigation of a hot blast valve of stove of blast furnace. J Fail Anal Prev. 2021 Jul 14. doi:10.1007/s11668-021-01200-z.

[7] API. API Standard 622: type testing of process valve packing for fugitive emissions. 3rd ed. Washington, DC: American Petroleum Institute; 2018. Addendum 1, 2022.

[8] Chen YQ, Yu H, Fu SW, Li A. Study on sealing performance of main gate valve of marine nuclear power plant based on fluid-solid-thermal coupling method. Front Energy Res. 2024;12:1375806. doi:10.3389/fenrg.2024.1375806.

[9] Bickford JH. Introduction to the design and behavior of bolted joints: non-gasketed joints. 4th ed. Boca Raton, FL: CRC Press; 2007. doi:10.1201/9780849381874.

[10] API. API Standard 598: valve inspection and testing. 11th ed. Washington, DC: American Petroleum Institute; 2023.

[11] ISO. ISO 5208:2015: industrial valves—pressure testing of metallic valves. 4th ed. Geneva: International Organization for Standardization; 2015.

[12] MSS. MSS SP-61-2019: pressure testing of valves. Vienna, VA: Manufacturers Standardization Society of the Valve and Fittings Industry; 2019.