On the Code-Based Design of Clamping Systems for Reactor Pressure Vessels

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Abstract

This article establishes a rigorous, code-compatible basis for sizing and assessing longitudinal clamping systems for pressure vessels. Motivated by large-bore, high-pressure service, we evaluate four closure families: (i) conventional studded flanges designed by ASME Section VIII, Division 1, Appendix 2; (ii) external clamp-ring quick-opening closures; (iii) breech-lock (segmented helical-thread) closures; and (iv) split-band collars. The methodology integrates closed-form Design-by-Rules relations for bolt/gasket loads and preliminary capacity checks with a Design-by-Analysis (DBA) acceptance framework for plastic collapse, local failure, ratcheting, and fatigue. Assembly guidance (preload targets and scatter) follows ASME PCC-1; hydrostatic test requirements follow UG-99.

A representative baseline envelope ($P = 15\,\mathrm{MPa}$, $D_i = 5\,\mathrm{m}$, $T = 270\,^\circ\mathrm{C}$) yields a governing hydrostatic end force $F = P\pi D_i^2/4 \approx 2.95 \times 10^8\,\mathrm{N}$. Results show: (1) Appendix 2 studded flanges become infeasible due to extreme required bolt area, impractical stud counts, and flange proportions; (2) external clamp-rings consolidate load into a continuous section and are the most credible path at scale, contingent on tapered-hub contact management and full DBA; (3) breech-lock concepts require substantial increases in segment area and careful tribological control to be viable; and (4) split-band collars are unsuitable at this diameter/pressure. Scaling trends are unfavorable with increasing bore ($A \propto D_i^2$, mass $\propto D_i^3$), making reduction of effective closure diameter the single most effective design lever.

We recommend a segmented external clamp-ring with reduced effective bore as the reference concept, supported by elastic–plastic contact DBA, fatigue assessment, interlock design per quick-opening provisions, and prototype testing to validate seating forces, relaxation, and operational repeatability.

1 Introduction

1.1 Purpose

This report establishes the engineering basis for *longitudinal clamping* of pressure-vessel closures, i.e., the structural systems that react the internal pressure end force while maintaining a qualified, leak-tight seal and enabling repeatable opening/closing for inspection, refueling, maintenance, or testing. The design space examined comprises four closure families that cover most practical applications across small, medium, and large diameters:

1. Conventional studded flanges designed by the bolt/gasket method of ASME BPVC Section VIII, Division 1, Mandatory Appendix 2, with qualification by Section VIII, Division 2 Design-by-Analysis (DBA) where warranted [ASM23e, ASM23d].

2. External clamp-ring (Grayloc/Bandlock-style) quick-opening closures (QOC), meeting the quick-actuating/quick-opening requirements of Section VIII, Division 1 and demonstrated by DBA for geometry outside tabulated proportions [ASM23f, ASM23d, Gra21, GD 20].

3. Breech-lock (segmented helical-thread) closures, preliminarily sized by shear/bearing checks and qualified via elastic–plastic analysis and fatigue assessment per Section VIII, Division 2 [ASM23d].

4. Split-band collars (Tri-Clamp analogues) for small to moderate diameters, screened for capacity and stiffness, with applicability bounded by roundness control and seal line stability [ASM23c].

1.2 Problem Statement and Design Drivers

A longitudinal closure must transmit the hydrostatic end force

$$F = P \frac{\pi D_i^2}{4}, \tag{1}$$

preserve the required gasket or metallic-seal compression under all governing load combinations, and remain inspectable, maintainable, and operable across the service life. In nuclear and other high-hazard services, additional drivers include: (i) minimization of radiation exposure (ALARA) through reduced manipulation time and reliable actuation; (ii) positive interlocks that prevent opening with any residual internal pressure; (iii) materials, fabrication, and NDE compliance with the construction code of record; and (iv) auditable analysis records and acceptance checks. A representative operating envelope motivating this study is in the range $P \sim 10$–$15\,\mathrm{MPa}$ and $T \sim 250$–$300\,^\circ\mathrm{C}$ for large-bore vessels, which pushes conventional studded solutions toward impractically large stud counts and flange diameters and motivates clamp-ring or breech-lock concepts with more favorable scaling [ASM23e, ASM23d].

1.3 Applicable Codes and Qualification Philosophy

The construction code of record is the ASME Boiler and Pressure Vessel Code (BPVC):

- **Design-by-Rules (DBR) for bolted flanges:** Appendix 2 of Section VIII, Division 1 defines seating and operating bolt loads (W_{m2}, W_{m1}) based on gasket parameters m, y, b, together with practical layout constraints and flange proportion checks [ASM23e]. Material allowables are taken from ASME Section II, Part D [ASM23a].
- **Quick-opening/quick-actuating closures:** Section VIII, Division 1 prescribes specific requirements for closure classification, safety devices, and proof testing/interlocks; these are mandatory for clamp-ring and similar mechanisms [ASM23f].
- **Design-by-Analysis (DBA):** When geometry or service falls outside DBR scope, Section VIII, Division 2, Part 5 requires elastic–plastic analysis and checks for protection against failure modes (primary membrane, local membrane+bending, ratcheting, fatigue), with weld/structural detail categories and fatigue usage evaluation [ASM23d].
- **Nuclear Class 1 service (if applicable):** Section III, Subsection NB provides the stress limits, service-level load combinations, materials, and QA requirements for Class 1 pressure-retaining components and bolting; equivalency or Code Cases may be required when adopting non-traditional closures [ASM23b].

1.4 Engineering Objectives

This report establishes:

1. Closed-form, code-compatible relations for: (a) bolt/gasket preload and required bolt area for Appendix 2 flanges; (b) clamp-ring net area and preliminary section sizing for external clamping mechanisms; (c) breech-lock segment shear/bearing capacity with preliminary geometry targets; and (d) split-band collar capacity, stiffness, and roundness constraints [ASM23e, ASM23d].
2. A consistent data model for temperature-dependent allowables $S(T)$ for common materials (e.g., SA-193 B7, SA-182 F22, SA-508 Cl.3, 17-4PH), with traceable interpolation and audit-ready references to Section II, Part D [ASM23a].
3. Quantities of interest (QoIs) for early trade studies: required bolt area and count, feasible pitch-circle diameter (PCD) and flange outside diameter (OD), clamp-ring area and width, breech-lock segment geometry and utilization, collar band thickness/width, and approximate mass/cost roll-ups [ASM23c, ASM23d, Gra21, GD 20].
4. A verification and validation path based on elastic–plastic finite-element analysis to Section VIII, Division 2, Part 5 and, where applicable, Section III NB-3200, including fatigue assessment and acceptance documentation suitable for regulatory audits [ASM23d, ASM23b].

1.5 Design Options Considered

The following options are carried forward:

Studded flange (Appendix 2). Standard ring-type metallic gasket joints sized from $W = \max\{W_{m2}, W_{m1} + 2\pi bGmP\}$, with stud layouts meeting spacing and pitch-circle constraints and rim/hub proportions for rigidity and access [ASM23e, ASM23a].

External clamp-ring (Grayloc/Bandlock-style). A continuous or segmented ring reacts F through tapered hubs and a self-energizing seal; preliminary ring area $A_{\mathrm{req}} = F/\{\eta S_{\mathrm{allow}}(T)\}$ informs section size prior to DBA of contact/hub stresses and fatigue. Positive interlocks are mandatory [ASM23f, ASM23d, Gra21, GD 20].

Breech-lock (segmented helical thread). Shear/bearing area across n segments is matched to F, with checks on thread bending, galling risk, and anti-rotation; DBA addresses local stresses and fatigue for the final geometry [ASM23d].

Split-band collar. Circumferential band(s) react axial force through hoop tension; applicability is bounded by achievable stiffness and roundness control and is most suitable for smaller diameters and moderate pressures [ASM23c].

1.6 Safety, Interlocks, and Operations

Quick-opening designs shall include positive mechanical interlocks (and, where appropriate, pressure-sensing interlocks) to preclude unlatching with any internal pressure present. Code provisions require prevention of inadvertent opening, proof testing where specified, and operating procedures that ensure depressurization and seal integrity prior to actuation [ASM23f]. Industry practice emphasizes redundant locking devices, operator-proof latch sequences, and qualification of clamp/segment relaxation and seal reuse over representative thermal–mechanical cycles [Gra21, GD 20].

1.7 Project Deliverables and Traceability

This work product includes: (i) a requirements baseline tied to specific code paragraphs and protection-against-failure-mode checks, (ii) a parameterized computation package that generates first-pass dimensions and margins for each closure family, and (iii) a set of DBA load cases and acceptance checks (stress categorization, plastic collapse/ratcheting/fatigue) suitable for regulatory review [ASM23d, ASM23b].

1.8 Boundaries and Interfaces

Out of scope here are detailed nozzle loads, external piping anchor loads, seismic/SSE combinations, thermal transients beyond a bounding ΔT, and local mechanisms (keys, pins, hinge arms, davits). These are addressed later in the Technical Data, Results, and DBA sections. Materials, NDE, fabrication tolerances, and QA/QC follow the governing BPVC sections and procurement specifications [ASM23a, ASM23c].

1.9 Document Organization

The remainder is organized as follows: Section 2 states baseline assumptions and load cases; Section 3 provides technical data, governing equations, and code references for each closure family; Section 4 presents sizing outputs and margins; Section 5 discusses feasibility, scaling, operability, and licensing; Section 6 summarizes conclusions and recommended next steps.

2 Assumptions

This section defines the baseline assumptions used for first-pass sizing and screening of longitudinal closures (studded flanges, external clamp-ring, breech-lock, split-band). Assumptions are grouped by loads, geometry, materials/allowables, joint details, assembly, analysis scope, and acceptance criteria. All symbols are defined where first used; SI units throughout.

2.1 Design Conditions and Load Cases

1. **Design pressure and temperature.** The vessel closure is sized for internal design pressure P and coincident metal design temperature T at the joint. The dominant longitudinal action is the hydrostatic end force
$$F = P\,\frac{\pi D_i^2}{4},$$
where D_i is the vessel inside diameter at the closure bore.

2. **Hydrostatic test.** Hydrotest pressure P_t follows Section VIII, Division 1, UG-99: $P_t \geq 1.3\,\mathrm{MAWP} \times \big(S(T_t)/S(T)\big)$, where T_t is the test temperature and $S(\cdot)$ is the applicable allowable stress at temperature [ASM23g, ASM23a]. Components whose controlling load is bolt preload rather than pressure (e.g., metallic seals) are verified not to exceed assembly limits at P_t.

3. **Service levels.** Operating combinations are Level A/B unless otherwise specified; upset, emergency, and faulted (Level C/D) cases are addressed by Design-by-Analysis (DBA) when required. Fatigue evaluation is deferred to DBA (stress ranges from thermal and pressure cycling).

4. **External loads.** Nozzle reactions, pipe anchors, external moments, and seismic/SSE are excluded from the DBR sizing but are included in the DBA load sets. Weight and handling loads on local hardware (hinges, davits, clamps) are excluded here and addressed by vendor data and DBA.

2.2 Geometry, Tolerances, and Seal Line

1. **Nominal geometry.** Inputs: D_i (bore), t (shell thickness at the closure), hub angles/proportions per concept, and required clearances for tooling and interlocks. For studded flanges, the pitch-circle diameter (PCD/BCD) and available rim width are bounded by a practical flange OD.

2. **Gasket/seal line.** For Appendix 2 flanges, the gasket mean diameter G and effective width b define the load path. The Appendix 2 method is used with seating/operating loads:
$$W_{m1} = P\frac{\pi G^2}{4}, \qquad W_{m2} = \pi b G\, y, \qquad W_{\mathrm{op}} = W_{m1} + 2\pi b G\, m\, P,$$
and required bolt preload $W = \max\{W_{m2}, W_{\mathrm{op}}\}$ [ASM23e].

3. **Out-of-roundness and flatness.** Roundness/flatness tolerances follow fabrication drawings; joint analyses assume roundness within typical shop tolerances for the given diameter. Split-band applicability requires roundness and stiffness such that seal compression remains within vendor limits.

4. **Corrosion and mill tolerances.** Corrosion allowance (CA) and mill tolerance (MT) on section properties are included in shell/closure thicknesses but neglected in preliminary joint capacity unless explicitly noted (conservative for capacity).

2.3 Materials and Allowables

1. **Allowables.** Temperature-dependent allowables $S(T)$ are taken from ASME Section II, Part D for the selected materials (e.g., SA-193 B7 studs, SA-182 F22 or SA-508 hub/flange/clamp, 17-4PH for breech-lock segments). Interpolation is linear between tabulated temperatures [ASM23a].

2. **Bolt allowables.** For Appendix 2, required total bolt area is $A_{\mathrm{bolt,req}} = W/S_{\mathrm{bolt}}(T)$ using the Section II-D allowable for the stud material at the joint temperature. Proof or yield fractions used for assembly targets are treated separately under assembly assumptions.

3. **Clamp ring and bands.** Preliminary clamp/band cross-section $A_{\mathrm{req}} = F/\big(\eta\, S(T)\big)$, with efficiency $\eta \in [1.0, 1.2]$ to cover non-uniform load paths and contact effects prior to DBA. Final acceptability is by DBA (primary/local membrane, bending, ratcheting, fatigue) [ASM23d].

2.4 Gasket/Seal Parameters

1. **Gasket constants.** Appendix 2 calculations use m and y factors and an effective width b representative of the selected gasket. Project default values are provided by gasket manufacturers; if unavailable, conservative provisional values are used and justified in design notes [ASM23e].

2. **Metallic seals / connector-style hubs.** For Grayloc/Bandlock-style seals, seat geometry and self-energizing behavior are per vendor data; sizing herein treats the ring as the axial load path while seal seating/energization forces are confirmed against vendor limits in DBA and vendor qualification [Gra21, GD 20].

2.5 Bolting Assembly and Preload

1. **Assembly practice.** Bolted-joint assembly follows ASME PCC-1: controlled lubrication, calibrated tools or hydraulic multi-stud tensioners (MST), cross-pattern passes, and verification tightening. The joint factor K (nut factor) is assumed per lubricant class with variability managed per PCC-1 [ASM22].

2. **Preload target and scatter.** Target initial bolt load W_0 is set to meet $W = \max\{W_{m2}, W_{\mathrm{op}}\}$ with margin for relaxation; when torque methods are assumed, preload scatter of $\pm 20\%$ is carried; with MST, $\pm 10\%$ is assumed [ASM22]. Joint relaxation from gasket creep and embedment is included as a lumped loss fraction where applicable.

3. **Proof/yield limits.** Assembly targets do not exceed recommended fractions of proof or yield per PCC-1 and material specification; final confirmation is by stress check of stud shank and thread bearing.

2.6 Concept-Specific Simplifications (Screening Stage)

1. **Studded flange.** Appendix 2 rigidity and proportion checks are deferred to the Technical Data section; flange rotation, hub stress, and leakage tightness are verified by DBA if the layout approaches tabulated limits.

2. **External clamp-ring.** The ring is idealized as a continuous section carrying F in axial tension; contact pressures, hub taper stresses, and wedge effects are resolved in DBA.

3. **Breech-lock.** Segment capacity is checked by shear/bearing area $A_{\mathrm{shear}} = nwh$ against F; thread bending, galling, and anti-rotation devices are handled by DBA and vendor practices.

4. **Split-band collar.** Hoop-tension capacity is used for screening with an eccentricity factor ϕ to account for hinge/latch geometry; stiffness and roundness control are later confirmed by DBA.

2.7 Acceptance Criteria and Analysis Method

1. **DBR checks.** Appendix 2 bolt/gasket sizing satisfied with required margins; material allowables from Section II-D at temperature [ASM23e, ASM23a].

2. **DBA checks.** Where DBR is insufficient or not applicable (clamps, breech-locks), elastic–plastic analysis per Section VIII, Division 2, Part 5 is used to demonstrate protection against plastic collapse (P_m, P_L), local failure (P_b), ratcheting, and fatigue [ASM23d]. For nuclear applications, Section III NB methodology and limits are used when designated [ASM23b].

3. **Leak tightness.** Leak criteria are per gasket/seal vendor qualification and Appendix 2 intent (maintaining required seating pressure); quantitative leakage rates, if specified, are verified via vendor data or dedicated testing.

2.8 Conservatism Summary

The screening models bias toward safety: no credit is taken for load sharing beyond primary paths; efficiency factors (η, ϕ) are applied ≥ 1.0 as noted; preload scatter and relaxation are explicitly carried; flange/segment stress intensification is deferred to DBA with full categorization and fatigue assessment.

3 Technical Data

This section provides the equations, data definitions, and step-by-step calculation procedures used to size and assess longitudinal clamping systems for pressure vessels: (i) Appendix 2 bolted flanges, (ii) external clamp-ring (Grayloc/Bandlock-style) quick-opening closures, (iii) breech-lock (segmented helical-thread) closures, and (iv) split-band collars. Where Design-by-Rules (DBR) does not directly apply, equations are provided for preliminary sizing, with final acceptability established by Design-by-Analysis (DBA) per Section VIII, Division 2, Part 5 [ASM23e, ASM23d].

3.1 Notation, Units, and General Relations

SI units are used unless stated otherwise; stresses are positive in tension.

P	internal design pressure (Pa)	(2)
D_i	vessel inside diameter at the closure bore (m)	(3)
t	shell thickness at the closure (m)	(4)
F	longitudinal hydrostatic end force (N)	(5)
$F = P\left(\frac{\pi D_i^2}{4}\right)$	(primary axial force to be reacted)	(6)

Hydrostatic test pressure (UG-99) and temperature correction:

$$P_t \;\geq\; 1.3\,\mathrm{MAWP}\,\frac{S(T_t)}{S(T)}, \qquad S(\cdot) = \text{allowable stress at temperature from Section II-D.} \tag{7}$$

Equation (7) provides the governing test case; joint integrity at test is verified not to exceed assembly or gasket limits [ASM23g, ASM23a].

3.2 Appendix 2 Bolted Flange Method (Ring-Type Gaskets)

3.2.1 Geometric definitions and gasket parameters

Let G be the gasket mean diameter, w the nominal gasket width (radial), and b the effective gasket width; m and y are the gasket factors per Appendix 2 (or per ASME B16.20 for spiral-wound/RTJ families) [ASM23e, ASM17, ASM20b, ASM20a]. Then

$$A_p = \frac{\pi G^2}{4} \quad \text{(projected area of internal pressure at the gasket line),} \tag{8}$$

$$W_{m1} = P\,A_p \quad \text{(hydrostatic end force at the gasket line),} \tag{9}$$

$$W_{m2} = \pi\,b\,G\,y \quad \text{(gasket seating load),} \tag{10}$$

$$W_{\mathrm{op}} = W_{m1} + 2\pi\,b\,G\,m\,P \quad \text{(operating bolt load).} \tag{11}$$

The required total bolt preload is

$$W \;=\; \max\bigl(W_{m2},\, W_{\mathrm{op}}\bigr). \tag{12}$$

Effective width b. Take b from gasket standard/manufacturer data consistent with Appendix 2 treatment; for many metallic/spiral-wound gaskets, b is the effective seating width associated with y (use B16.20 tables as applicable). When only w is known, use a conservative $b \leq w$ consistent with the gasket family [ASM23e, ASM17].

3.2.2 Bolt area, count, and layout

Let $S_{\mathrm{bolt}}(T)$ be the allowable stress for the stud material at joint temperature T (Section II-D) [ASM23a]. The total required tensile-stress area is

$$A_{\mathrm{bolt,req}} \;=\; \frac{W}{S_{\mathrm{bolt}}(T)}. \tag{13}$$

For a chosen nominal stud size with tensile-stress area A_1, select an even number of studs n such that $n\,A_1 \geq A_{\text{bolt,req}}$ and satisfy practical constraints (typical DBR practice and PCC-1 guidance):

$$s \geq 2.5\,d \qquad \text{(minimum pitch spacing)}, \tag{14}$$
$$e \geq 1.5\,d \qquad \text{(edge distance to flange rim)}, \tag{15}$$
$$R_b \in \left[G/2 + \Delta_{\min},\ (D_{\text{OD}} - e)/2\right] \qquad \text{(feasible bolt circle radius)}. \tag{16}$$

Here d is the stud nominal diameter, s the circumferential pitch at the bolt circle, e the radial edge margin, R_b the bolt circle radius, and D_{OD} the flange outside diameter.

3.2.3 Flange moment and simplified rigidity checks

For preliminary proportioning, treat the bolt group centroid at radius R_b and the gasket load at radius $G/2$. Seating and operating bending moments on the flange ring about a radial neutral axis through the bolt circle are

$$M_{\text{seat}} = W_{m2}\,(R_b - G/2), \tag{17}$$
$$M_{\text{op}} = W_{\text{op}}\,(R_b - G/2). \tag{18}$$

A conservative ring-bending section modulus for a flange rim of effective radial width b_f and thickness t_f is

$$Z_f \;\approx\; \frac{t_f\,b_f^2}{6} \quad \Rightarrow \quad \sigma_f \;\approx\; \frac{M}{Z_f} \quad \text{(screening)}. \tag{19}$$

Final flange stresses (at the hub, rim, and groove) and rotation/leakage checks shall be performed per Appendix 2 ring-bending equations (using the Appendix 2 geometric coefficients) or by DBA with stress categorization [ASM23e, ASM23d].

3.2.4 Bolt stresses and assembly torque (PCC-1)

The average bolt stress at assembly and under operation:

$$\sigma_{b,0} = \frac{W_0}{n\,A_1}, \qquad \sigma_{b,\text{op}} = \frac{W_{\text{op}}}{n\,A_1}, \tag{20}$$

with W_0 the target initial preload (including allowances for relaxation/creep). If torque tightening is used, PCC-1 torque estimation:

$$T_{\text{thread}} = F\,\frac{d_m}{2}\,\tan(\varphi + \alpha), \qquad T_{\text{bearing}} = \mu_b\,F\,\frac{D_b}{2}, \tag{21}$$
$$T_{\text{total}} = T_{\text{thread}} + T_{\text{bearing}} \;\approx\; K\,F\,d, \tag{22}$$

where F is the desired preload per stud, d_m is the nut/bolt thread mean diameter, α the thread helix angle, $\varphi = \arctan \mu_t$ the friction angle (threads), μ_b the bearing friction coefficient under the nut face, D_b the effective bearing diameter, and K the nut factor calibrated per lubricant and surface finish [ASM22, BN19]. Use hydraulic multi-stud tensioners (MST) where practicable to reduce preload scatter.

3.3 External Clamp-Ring (Grayloc/Bandlock-Style) Closures

3.3.1 Axial equilibrium and preliminary section sizing

Assume the clamp ring reacts the entire axial end force F (Eq. 6). For a net metallic section area A of the ring,

$$\sigma_{\text{ring}} \;=\; \frac{F}{A} \;\leq\; S_{\text{ring}}(T). \tag{23}$$

Introduce an efficiency factor $\eta \geq 1$ to cover load-path nonuniformity and local contact effects in screening:

$$A_{\text{req}} \;=\; \frac{F}{\eta\,S_{\text{ring}}(T)}. \tag{24}$$

For a square ring section $w \times w$, $w = \sqrt{A_{\text{req}}}$. For a rectangular section $w \times t_r$, choose w, t_r meeting assembly and clearance constraints.

3.3.2 Tapered hub contact and seal seating

Let each hub interface be tapered with half-angle β (two symmetric tapers). Under axial load F, the normal reaction per interface (neglecting friction) is

$$N = \frac{F}{2\sin\beta}. \tag{25}$$

If the contact annulus has mean diameter D_c and axial (projected) contact length L_c, the average contact pressure is

$$p_c = \frac{N}{\pi D_c L_c} = \frac{F}{2\pi D_c L_c \sin\beta}. \tag{26}$$

Self-energizing metallic seals typically require a minimum seating load F_{seat} and limit pressure $p_{c,\max}$; verify $p_c \geq F_{\text{seat}}/(\pi D_s b_s)$ at assembly and $p_c \leq p_{c,\max}$ under test/operation, where D_s and b_s characterize the seal contact [Gra21, GD 20]. Friction increases the required locking effort for opening; for conservative seating sizing in screening, neglect friction (use DBA for detailed contact).

3.3.3 Local bending and fillet stresses

Peak stresses in the ring at hinge slots/segments and in the tapered hub at the groove/fillet shall be checked by DBA:

$$\text{Check: } P_m,\ P_L,\ P_b \text{ vs. limits;} \quad \text{ratcheting under pressure/thermal cycles;} \quad \text{fatigue usage.} \tag{27}$$

Seal groove stresses (bearing and bending) must satisfy vendor limits; use elastic–plastic contact analysis with appropriate seal constitutive models [ASM23d].

3.4 Breech-Lock (Segmented Helical-Thread) Closures

3.4.1 Helix geometry and load components

Let D_m be the mean thread diameter, p the lead, and α the helix angle:

$$\alpha = \arctan\left(\frac{p}{\pi D_m}\right). \tag{28}$$

For a square/modified-square flank with n segments engaged, each segment of circumferential length L_e and flank height h, the gross shear area on one flank is $A_{s,1} = L_e h$. If both flanks share load, use $2A_{s,1}$.

3.4.2 Segment shear and bearing checks (screening)

Resolve axial load F to flank shear (neglecting friction for capacity):

$$\tau_{\text{seg}} = \frac{F}{n\,A_{s,\text{eff}}\,\cos\alpha} \leq \tau_{\text{allow}}(T), \tag{29}$$

$$\sigma_{\text{bear}} = \frac{F}{n\,L_e\,t_b\,\sin\alpha} \leq \sigma_{\text{bear,allow}}(T), \tag{30}$$

where $A_{s,\text{eff}} \in \{A_{s,1},\, 2A_{s,1}\}$ depending on whether one or both flanks carry load, and t_b is the effective bearing thickness at the flank interface. The $\cos\alpha$ and $\sin\alpha$ factors account for load orientation relative to the flank.

3.4.3 Anti-rotation and thread bending

Provide an anti-rotation key/stop sized for the peak thread torque. For a power-screw analogue with friction,

$$T_{\text{thread}} = F\,\frac{D_m}{2}\,\tan(\varphi + \alpha), \qquad \varphi = \arctan\mu_t, \tag{31}$$

with μ_t the flank friction coefficient. Local thread-root bending and fillet stresses must be checked by DBA with contact and nonlinear material models; galling risk requires material/coating selection and lubrication per vendor practice [ASM23d, BN19].

3.5 Split-Band Collar Closures

3.5.1 Axial equilibrium and band tension

Idealize the collar as two symmetric tension legs reacting F. The tensile force per leg is

$$T_{\text{leg}} \;\approx\; \frac{F}{2}. \tag{32}$$

For a band of width w_b and thickness t_b (metallic net), the average band stress is

$$\sigma_{\text{band}} \;=\; \frac{T_{\text{leg}}}{w_b\, t_b\, \phi} \;\leq\; S_{\text{band}}(T), \tag{33}$$

where $\phi \in (0, 1]$ is an efficiency factor (eccentricity, hinge holes, local taper). Rearranged,

$$w_b \;\geq\; \frac{F}{2\, t_b\, \phi\, S_{\text{band}}(T)}. \tag{34}$$

Provide hinge/latch pins sized for combined shear and bending; check bearing on lugs and local shell reinforcement by DBA.

3.5.2 Roundness and stiffness constraints

Let the allowable radial seal compression variation be $\Delta c_{\max}$. The band and shell must maintain roundness such that

$$\Delta r_{\max}(P,\, T,\, T_{\text{leg}}) \;\leq\; \frac{\Delta c_{\max}}{2}, \tag{35}$$

where $\Delta r_{\max}$ is the maximum radial deviation under combined pressure, thermal, and actuation loads. Evaluate by DBA with contact to confirm seal line uniformity.

3.6 Materials, Allowables, and Temperature Interpolation

Allowables $S(T)$, $\tau_{\text{allow}}(T)$, and bearing limits are taken from Section II-D or material specifications at the relevant metal temperature. For discrete tables $\{(T_k,\, S_k)\}$,

$$S(T) \;\approx\; S_k + (S_{k+1} - S_k)\frac{T - T_k}{T_{k+1} - T_k} \quad \text{for } T \in [T_k, T_{k+1}]. \tag{36}$$

Use the governing joint temperature (bolt/stud for σ_b, clamp ring for σ_{ring}, etc.) [ASM23a].

3.7 Acceptance and Verification Framework (Summary)

1. **DBR (Appendix 2):** Eqs. (9)–(12), bolt area Eq. (13), layout constraints; flange rigidity per Appendix 2 ring-bending coefficients; leakage/rotation checks.

2. **QOC (Clamp/Breech/Collar):** Preliminary capacity Eqs. (24), (26), (29), (30), (34); *mandatory* DBA for P_m, P_L, P_b, ratcheting, fatigue (Eq. (27)), seal contact and interlocks [ASM23f, ASM23d].

3. **Assembly:** PCC-1 torque/tension per Eq. (22); lubrication and scatter controls [ASM22].

4. **Hydrotest:** UG-99 per Eq. (7) [ASM23g].

3.8 Implementation Notes for Calculation Workflow

The computational workflow accepts $\{P,\, D_i,\, t,\, T\}$; gasket $\{G,\, b,\, m,\, y\}$; material selections with $S(T)$; and concept-specific geometry. It returns: (i) required bolt area and feasible n, d, R_b; (ii) clamp ring net area/section and contact pressures; (iii) breech-lock segment geometry utilization (τ, σ_{bear}); (iv) split-band w_b, t_b; and (v) flags requiring DBA where margins or geometry approach limits.

4 Results

This section reports the first–pass numerical results for the baseline case used to screen closure concepts. Unless otherwise noted, values are directly reproduced from the example run of the sizing script accompanying this report.

4.1 Baseline Input Case

Inside diameter at bore, D_i	5000 mm
Shell thickness at closure, t	120 mm
Design pressure, P	15 MPa
Design metal temperature, T	270 °C
Hydrostatic end force, $F = P\pi D_i^2/4$	2.945×10^8 N

Table 1: Input case used for the screening calculations (units SI).

4.2 Appendix 2 Studded Flange (bolt/gasket method)

Selected stud diameter	24 mm
Required stud count	11 146
Recommended flange outside diameter (OD)	212 960.9 mm
Estimated flange mass	50 300 100.9 kg
Estimated stud mass	5699.9 kg
Material cost (flange + studs)	$251 534 703
Machining cost (rough+finish)	$201 223 203
Total estimated cost	**$**452 757 906

Table 2: Studded flange—sizing, mass, and rough cost roll-up for the baseline case.

4.3 External Clamp-Ring (Grayloc/Bandlock-style)

Preliminary required ring width (square section)	1873.0 mm
Estimated clamp-ring mass	777 391.0 kg
Material cost	$5 053 041
Machining cost	$3 109 564
Total estimated cost	**$**8 162 605

Table 3: External clamp-ring—section width proxy, mass, and rough cost for the baseline case.

4.4 Breech-Lock (segmented helical-thread) Closure

Number of thread segments engaged	6
Thread flank width, w	200.0 mm
Thread flank height, h	300.0 mm
Screening shear safety factor (segments)	0.13
Estimated lock-ring mass	7704.2 kg
Material cost	$92 450
Machining cost	$30 817
Total estimated cost	**$**123 267

Table 4: Breech-lock—segment geometry utilization and mass/cost for the baseline case.

4.5 Split-Band Collar

Band thickness (rule-of-thumb)	36.0 mm
Required band width (screening)	50 582.9 mm
Estimated band mass	236 935.6 kg
Material cost	\$1 540 082
Machining cost	\$947 742
Total estimated cost	**\$**2 487 824

Table 5: Split-band collar—required width, mass, and rough cost for the baseline case.

4.6 Notes on Interpretation

- The studded flange results indicate an extremely large stud count and flange OD for this high-P, large-D_i case, driving mass and cost to impractical values at the screening stage.
- The clamp-ring consolidates axial load into a continuous section; the preliminary width is large, but mass and cost are orders of magnitude lower than the studded-flange roll-up for this envelope.
- The breech-lock's screening shear safety factor (≈ 0.13) shows that additional segments, larger flanks, and/or higher-strength materials (with DBA) would be required to reach acceptable margins.
- Split-band collars do not scale favorably here due to the required band width, consistent with their typical use on small-to-moderate diameters.

All costs are coarse, mass-proportional estimates intended solely for comparative screening. Final design acceptability must be established by Design-by-Analysis and vendor qualification, as detailed in the Technical Data and Discussion sections.

5 Discussion of the Results

5.1 Overall Interpretation and Scale Effects

The baseline envelope ($P = 15\,\mathrm{MPa}$, $D_i = 5.0\,\mathrm{m}$, $T = 270\,^\circ\mathrm{C}$) produces a longitudinal hydrostatic end force

$$F \;=\; P\,\frac{\pi D_i^2}{4} \;\approx\; 2.95\times10^{8}\ \mathrm{N}, \tag{37}$$

which is extraordinary for a single closure. All concepts evaluated are, therefore, governed by first-order force equilibrium rather than secondary stiffness refinements. The dominant scaling relations are:

$$\text{Bolted flange:}\quad W \sim F + 2\pi b G m P \;\Rightarrow\; A_{\mathrm{bolt,req}} = \frac{W}{S_{\mathrm{bolt}}(T)} \propto D_i^2, \tag{38}$$

$$\text{Clamp ring:}\quad A_{\mathrm{req}} = \frac{F}{\eta S_{\mathrm{ring}}(T)} \propto D_i^2, \quad w \sim \sqrt{A_{\mathrm{req}}} \propto D_i, \tag{39}$$

$$\text{Breech-lock:}\quad n\,A_{s,\mathrm{eff}} \sim \frac{F}{\tau_{\mathrm{allow}}\cos\alpha} \;\Rightarrow\; \text{segment area} \propto D_i^2, \tag{40}$$

$$\text{Split band:}\quad w_b \ge \frac{F}{2\,t_b\,\phi\,S_{\mathrm{band}}(T)} \propto D_i^2. \tag{41}$$

Because the mass of a circumferential component is roughly $M \propto A\,(\pi D)$ with $A \propto D^2$, both clamp rings and large flanges exhibit $M \propto D^3$ scaling, rapidly rendering monolithic closures unwieldy as D_i grows. This trend explains the impracticality of the Appendix 2 flange and the marginal feasibility of even a very large clamp ring for the baseline.

5.2 Appendix 2 Studded Flange

The computed stud count ($\mathcal{O}(10^4)$) and flange OD indicate this concept is infeasible at the given envelope.

1. **Bolt/gasket load partition.** The operating requirement $W_{\text{op}} = W_{m1} + 2\pi bGmP$ is dominated by the end force term $W_{m1} \propto D_i^2$, but the gasket term can be non-negligible for metallic gaskets with high m. Even if a favorable gasket is selected (lower m, optimized b at fixed leakage performance), the count reduction is small relative to the order-of-magnitude gap.

2. **Layout constraints.** Minimum pitch $s \geq 2.5d$ and edge distance $e \geq 1.5d$ enforce a large bolt circle and flange OD. Increasing stud size d reduces count but inflates flange OD and rim bending moments $M \sim W(R_b - G/2)$.

3. **Rigidity & leakage.** Appendix 2 bending/rotation limits are likely exceeded unless an extremely thick rim/hub is adopted. Rotation at the gasket line compromises tightness, and DBA would likely show local membrane+bending (P_b) hot spots exceeding limits [ASM23e, ASM23d].

4. **Assembly/ALARA.** Torque-based assembly at this scale is impractical; MST would be mandatory, yet the sheer quantity of studs defeats outage-time goals [ASM22].

Conclusion: For the baseline envelope, a conventional studded flange is eliminated.

5.3 External Clamp-Ring (Grayloc/Bandlock-Style)

The clamp ring consolidates F into a continuous metallic section with width $w \approx \sqrt{F/(\eta S)}$, giving a more favorable manufacturing and assembly profile than tens of thousands of studs.

1. **Section sizing.** The required net area is large but single-piece or segmented rings are conceptually fabricable. The reported square-section width in the results reflects this: $w \propto D_i$.

2. **Contact and seal seating.** Tapered hub contact pressure $p_c = \dfrac{F}{2\,\pi D_c L_c \sin\beta}$ must (i) exceed seal seating requirements at assembly and (ii) stay below groove/seat limits at hydrotest and operation. At the present scale, p_c can be managed by increasing L_c and choosing a moderate β, but DBA is mandatory to resolve local stresses and contact nonlinearities [ASM23d, Gra21, GD 20].

3. **Segmented designs.** Multi-segment clamp rings reduce handling mass and facilitate opening without full-ring removal. However, segmentation introduces slot/finger stress raisers; DBA must show P_m, P_L, P_b acceptability and fatigue life under thermal/pressure cycles.

4. **Quick-opening compliance.** As a QOC, the design requires positive interlocks, proof/cycle testing, and prevention of opening under pressure [ASM23f]. Interlock design must consider residual seal energization and frictional wedging.

5. **Manufacturing.** Forging or built-up weldments with qualified procedures are feasible; NDE access around the tapered hubs and ring segments should be planned (UT, volumetric NDE for heavy sections).

Conclusion: Among the four options, the clamp ring remains the most credible path provided the closure diameter or design pressure is moderated, or the ring is heavily optimized and segmented, and the joint is qualified by DBA.

5.4 Breech-Lock (Segmented Helical-Thread)

The screening shear factor (~ 0.13) shows that the present n, w, h are insufficient. Capacity can be increased by:

1. **Geometry.** Increasing n (segments), flank width w, and height h to raise $A_{s,\text{eff}} = n\,w\,h$. Because $F \propto D_i^2$, large multipliers are required to close the gap.

2. **Helix angle.** A moderate α reduces the $\cos\alpha$ penalty in shear and the $\sin\alpha$ denominator in bearing; however, α also drives torque via $T = F\frac{D_m}{2}\tan(\varphi+\alpha)$ and affects galling risk [BN19].

3. **Materials and coatings.** Switching to high-strength precipitation-hardened stainless or Ni-based alloys raises τ_{allow}, but galling becomes a major concern. Coatings (e.g., nitriding, MoS_2), lubrication control, and surface finishes are essential.

4. **Local failure modes.** DBA must demonstrate no local plastic collapse at thread roots, no ratcheting under cyclic pressure/thermal gradients, and acceptable fatigue usage; contact non-linearity is intrinsic [ASM23d].

Conclusion: Feasible in smaller sizes or lower pressures; at the baseline envelope the required segment area and torque management make this option challenging.

5.5 Split-Band Collar

The band-width requirement from $w_b \geq F/(2t_b\phi S)$ exceeds practical values even with generous thickness t_b and efficiency ϕ. Additional concerns include:

1. **Roundness/stiffness.** Maintaining seal-line uniformity over 5 m diameter with a band actuator is difficult; small ovalization induces large variations in seal compression.

2. **Hinge/latch details.** Pins and lugs concentrate load and demand thick, heavy fittings, eroding the simplicity advantage; DBA would likely show P_b exceedance near lugs.

Conclusion: Not viable at the baseline; reserved for small-to-moderate diameters and lower pressure classes.

5.6 Hydrostatic Test vs. Operating Conditions

UG-99 requires $P_t 1.3\,\text{MAWP} \times S(T_t)/S(T)$ [ASM23g]. Because $F \propto P$, hydrotest magnifies the axial force; if $S(T_t) > S(T)$, the net effect on required areas may be partially offset, but local contact and groove stresses generally increase. Seal seating at test must avoid over-compression; clamp-ring and breech-lock details often govern under test rather than operation.

5.7 Assembly, Preload Scatter, and Leak-Tightness

For bolted joints, PCC-1 recommends controls on nut factor K and lubrication to control preload scatter; MST can reduce scatter to $\sim \pm 10\%$ [ASM22]. Although the baseline flange concept is eliminated, the same philosophy applies to clamp-ring bolting (if any auxiliary bolts exist) and to breech-lock anti-rotation keys/locking devices. Leak-tightness for metallic seals is primarily governed by contact pressure distribution (DBA) and by vendor limits; conservative seating forces should be validated by testing [Gra21, GD 20].

5.8 Sensitivity and Parametric Trends

The following sensitivities guide redesign:

1. **Reduce effective closure diameter.** If a transition hub reduces the closure bore by a factor $\kappa < 1$, then $F \to \kappa^2 F$. For clamp rings, $w \propto \kappa$, and mass $\propto \kappa^3$. Reducing D_i by even 20% ($\kappa = 0.8$) cuts mass by $\sim 49\%$.

2. **Reduce design pressure or change design class.** If process constraints allow lowering MAWP (or categorizing pressures as occasional), F reduces linearly with P.

3. **Increase material allowables.** For concepts governed by $A \propto 1/S(T)$, raising S by 30% reduces A by 23% and mass accordingly; trade against weldability, toughness, and temperature capability per Section II-D [ASM23a].

4. **Segmentation.** Segment count in clamp rings reduces handling mass and improves maintainability but increases local stress intensification at slots; DBA drives the optimum.

5. **Seal selection.** Lower m and reasonable y reduce W_{op} for Appendix 2 flanges (if reconsidered at smaller D_i). For clamp-style metallic seals, geometry controls seating rather than m/y, but seal hardness and profile strongly affect contact pressures.

5.9 Risk, Uncertainty, and Required DBA

Principal uncertainties are in (i) gasket/seal performance at scale, (ii) contact pressure distribution and friction in tapered hubs, (iii) preload losses from relaxation/creep, (iv) local stress intensification at slots, grooves, and fillets, and (v) fatigue from cyclic pressure/thermal loads. The following DBA tasks are required for any retained concept [ASM23d]:

- Elastic–plastic contact analysis of hub–ring (or thread) interfaces at assembly, hydrotest, and operation; extraction and categorization of P_m, P_L, P_b.
- Shakedown/ratcheting evaluation under thermal/pressure cycles representative of operation.
- Fatigue usage per Part 5 using stress ranges at critical details; include thermal gradients and clamp actuation cycles for QOC.
- Sensitivity study on friction coefficients, tolerances (ovality/flatness), and preload scatter.
- Verification of quick-opening interlock requirements, proof/cycle testing plans (for clamp/breech concepts) [ASM23f].

5.10 Recommendations and Path Forward

1. **Eliminate the Appendix 2 flange** at the baseline envelope; reconsider only if D_i and/or P are substantially reduced.
2. **Advance the clamp-ring concept** with the explicit goal of reducing effective closure bore by internal transitions (e.g., hub insert) to drive F down; adopt a segmented ring to manage handling.
3. **Material screening:** Evaluate high-strength, high-toughness alloys for the ring and hubs to increase $S(T)$ while maintaining weldability and fracture resistance (Section II-D, vendor experience) [ASM23a, Gra21].
4. **Seal and taper optimization:** Optimize β, D_c, and L_c for contact pressure targets; coordinate with seal vendor for groove geometry and allowable ranges [Gra21, GD 20].
5. **DBA program:** Execute Part 5 analyses for assembly/test/operation; include fatigue, ratcheting, and misalignment cases; define acceptance maps for segmentation and slot geometry [ASM23d].
6. **Qualification testing:** Plan a subscale or reduced-D_i prototype to validate seating forces, relaxation, and reusability across cycles consistent with quick-opening provisions [ASM23f].
7. **ALARA/operations:** Engineer lifting, alignment, and interlocks to minimize manipulation time; document MST procedures (if any) per PCC-1 [ASM22].

5.11 Closing Statement

The results decisively favor a quick-opening, clamp-ring–type closure as the only realistic option at the baseline envelope, *provided* that (i) the effective closure diameter is reduced and (ii) a rigorous DBA and test program demonstrate compliance with Part 5 criteria and quick-opening requirements. Breech-lock concepts remain candidates only if the envelope is moderated or if significant increases in segment count/size and material strength are feasible with acceptable manufacturability and operability. Split-band and conventional flanges are out of scope for the present scale.

6 Conclusions

6.1 Key Findings

1. The governing design driver for any longitudinal closure is the hydrostatic end force $F = P\pi D_i^2/4$; for the baseline envelope ($P = 15\,\mathrm{MPa}$, $D_i = 5\,\mathrm{m}$, $T = 270\,°\mathrm{C}$), $F \approx 2.95 \times 10^8$ N. This magnitude dominates sizing, assembly strategy, and feasibility across concepts.

2. **Appendix 2 studded flange:** The required bolt area translates to an impractical stud count and flange outside diameter at the baseline; rigidity and rotation constraints would not be met without extreme proportions. This option is eliminated for the present envelope (see Section 4).

3. **External clamp-ring (QOC):** Consolidating load into a continuous (or segmented) ring is the most credible path at scale. Preliminary section requirements are large but manufacturable; acceptability hinges on contact pressure management at tapered hubs and full Design-by-Analysis (DBA) for local stresses and fatigue (Section 3).

4. **Breech-lock (segmented helical-thread):** Screening shows inadequate segment shear/bearing capacity with the trial geometry; feasibility at the baseline would require substantial increases in segment number/size and careful control of torque, galling, and contact—still to be proven by DBA.

5. **Split-band collar:** Required band width is non-physical at the baseline; the concept is unsuitable for large diameters/high pressures but remains useful at small to moderate sizes.

6. Scaling trends are unfavorable with increasing D_i: required areas $\propto D_i^2$ and closure mass $\propto D_i^3$. Any reduction of effective closure bore provides disproportionate benefit to weight, cost, and DBA margins.

6.2 Recommended Concept and Conditions for Viability

1. Proceed with a **segmented external clamp-ring** quick-opening closure as the reference concept, subject to:

   (a) Reducing the *effective* closure bore via an internal transition or hub insert (target reduction $\geq 15\%$ on D_i).

   (b) Selecting high-strength, weldable materials with qualified allowables at T for the ring and hubs.

   (c) Optimizing taper angle, contact length, and seal groove geometry to meet seating and peak-pressure limits.

   (d) Implementing positive mechanical and pressure-sensing interlocks per quick-opening requirements.

2. Retain breech-lock only as a *secondary* concept for moderated envelopes (smaller D_i and/or P), contingent on demonstrated DBA compliance and tribological risk control.

6.3 Qualification and Verification Program (Mandatory for Downselect)

1. Execute elastic–plastic contact DBA for assembly, hydrotest, and operation to demonstrate protection against plastic collapse (P_m, P_L), local failure (P_b), shakedown/ratcheting, and fatigue usage at critical details.

2. Quantify sensitivity to friction, tolerances (ovality/flatness), preload scatter, and thermal gradients; define acceptance maps for ring segmentation and slot geometry.

3. Validate seating forces, relaxation, and reusability via subscale or reduced-bore prototype testing consistent with quick-opening provisions; confirm interlock performance and prevention of opening under pressure.

6.4 Operational and ALARA Considerations

1. Favor segmented rings to limit single-lift masses and reduce manipulation time; design lifting, alignment, and locking features for repeatable, low-exposure operation.

2. Where bolting remains (auxiliary fasteners or retainers), apply PCC-1 practices or multi-stud tensioners to minimize preload scatter and turnaround time.

6.5 Applicability Boundaries

1. **Studded flanges:** Consider only for substantially reduced D_i and/or P, where Appendix 2 proportions and rotation limits can be satisfied without extreme mass.

2. **Clamp-rings:** Primary candidate at large D_i, provided bore reduction and DBA-confirmed contact/stress control.

3. **Breech-locks:** Candidates for mid-size envelopes with careful thread geometry, materials/coatings, and torque management.

4. **Split-bands:** Limited to small-to-moderate diameters and pressure classes; not suitable for the baseline.

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