Flange thickness, head to vessel main flanges: D. Shuman June 18, 2012

inner radius max. allowable pressure

$R_{i\_pv} = 0.68\,\text{m}$ $P = 15.4\,\text{bar}$ (gauge pressure)

The flange design for O-ring sealing (or other self energizing gasket such as helicoflex) is "flat-faced", with "metal to metal contact outside the bolt circle". This design avoids the high flange bending stresses found in a raised face flange (of Appendix 2) and will result in less flange thickness. The rules for this design are found only in sec VIII division 1 under Appendix Y, and must be used with the allowable stresses of division 1. Flanges and shells will be fabricated from 316Ti (ASME spec SA-240) stainless steel plate. Plate samples will be helium leak checked before fabrication, as well as ultrasound inspected for flat laminar flaws which may create leak paths. The flange bolts and nuts for a metal C-ring gasket seal will be inconel 718, (UNS N77180) as this is the highest strength non-corrosive material allowed for bolting. For O-ring sealing we can use 304 bolts, temper B. We design the flanges for both cases, using the parallel calculation mode of MathCAD in which the possible values for a parameter are expressed as a matrix. Calculations are then performed in parallel for each row index. Where necessary (multiple vectors in an expression) an arrow over the expression enforces this paralllelism

Maximum allowable material stresses, for sec VIII, division 1 rules from ASME 2010 Pressure Vessel code, sec. II part D, table 2A (division 1 only):

Maximum allowable design stress for flange

$S_f := S_{max\_316Ti\_div1}$ $S_f = 137.9\,\text{MPa}$ $S_f = 2 \times 10^4\,\text{psi}$

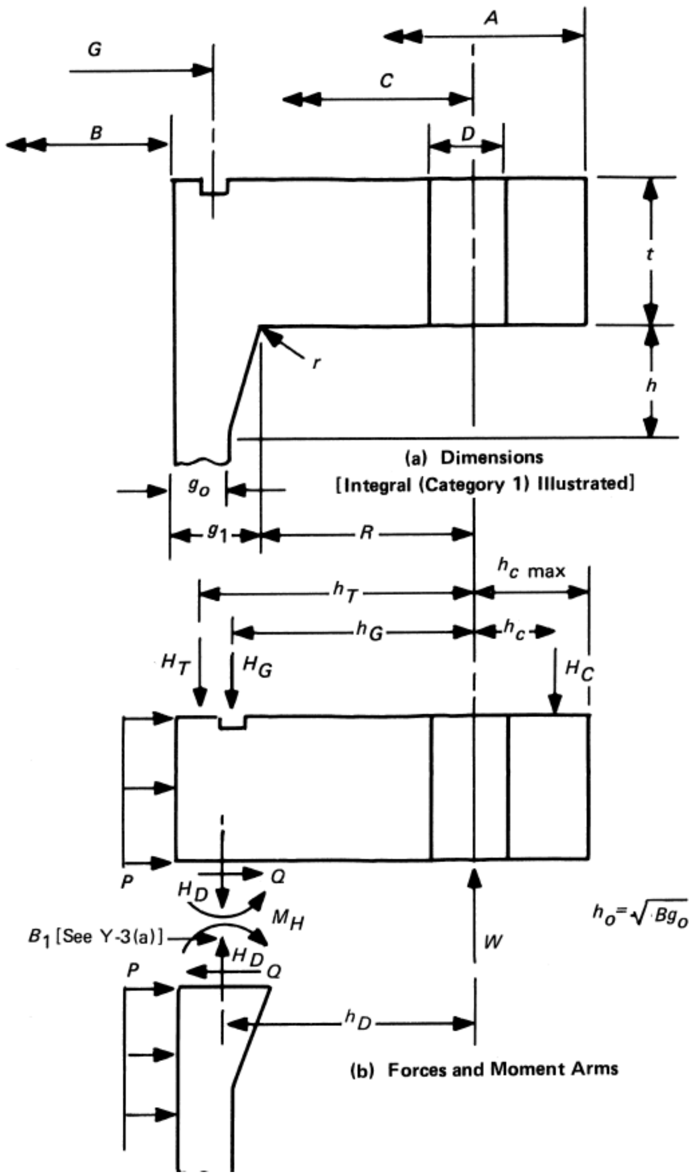
Maximum allowable design stress for bolts, from ASME 2010 Pressure Vessel code, sec. II part D, table 3

Inconel 718 (UNS N07718) $S_{max\_N07718} := 37000\text{psi}$ $S_{max\_304\_B} := 25000\text{psi}$ for bolts less than 3/4 in

$S_b := \begin{pmatrix} S_{max\_304\_B} \\ S_{max\_N07718} \end{pmatrix}$ $S_b = \begin{pmatrix} 172.4 \\ 255.1 \end{pmatrix}\text{MPa}$ $S_{max\_316\_2} := 22000\text{psi}$ for bolts less than 3/4 in

From sec. VIII div 1, non-mandatory appendix Y for bolted joints having metal-to-metal contact outside of bolt circle. First define, per Y-3:

FIG. Y-3.2 FLANGE DIMENSIONS AND FORCES



hub thickness at flange (no hub) corner radius:

$g_0 := t_{pv}$ $g_1 := t_{pv}$ $g_0 = 10\,mm$ $g_1 = 10\,mm$ $r_1 := \max(.25g_1, 5mm)$ $r_1 = 5\,mm$

Flange OD

$A := 1.495m$ this is the maximum possibel, given our plate stock

Flange ID

$B := 2R_{i\_pv}$ $B = 1.36\,m$

define:

$B_1 := B + g_1$ $B_1 = 1.37\,m$

Bolt circle (B.C.) dia, C:

$C := 1.43 \cdot m$

Gasket dia

$G := 2(R_{i\_pv} + .65cm)$ $G = 1.373\,m$ O-ring mean radius as measured in CAD model: $68.65 \cdot 2 = 137.3$

Note: this diameter will be correct for Helicoflex gasket, but slightly higher for O-ring, which is fluid and "transmits pressure" out to its OD, howqever the lower gasket unit force of O-ring more than compensates, as per below:

Force of Pressure on head

$H := .785G^2 \cdot MAWP_{pv}$ $\qquad H = 2.31 \times 10^6 N$

Sealing force, per unit length of circumference:

for O-ring, 0.275" dia., shore A 70 F= ~5 lbs/in for 20% compression, (Parker O-ring handbook); add 50% for smaller second O-ring, and another 50% for 30% compression. Helicoflex and HTMS have equivalent formulas using Y as the unit force term and gives several possible values.

for 4.78mm C-ring, M surface hardness:

$Y_2 := 65 \frac{N}{mm}$ recommended value for large diameter seals, regardless of pressure or leak rate

for O-ring only

$Y_1 := 10 \frac{lbf}{in}$ min value for our pressure and required leak rate (He) $\qquad Y_1 = 1.751 \frac{N}{mm}$

for gasket diameter $\quad D_j := G \qquad D_j = 1.373 m$

Force is then either of:

$F_m := \pi D_j \cdot Y_1$ $\qquad$ or $\qquad F_j := \pi \cdot D_j \cdot Y_2$

$F_m = 7.554 \times 10^3 N$ $\qquad F_j = 2.804 \times 10^5 N$

Start by making trial assumption for number of bolts, nominal bolt dia., pitch, and bolt hole dia D,

$n := 140$ $\qquad d_b := 16mm$ $\qquad$ maximum number of bolts possible, using narrow washers: $\quad n_{max} := \mathrm{trunc}\left(\frac{\pi C}{2.0 d_b}\right) \qquad n_{max} = 140$

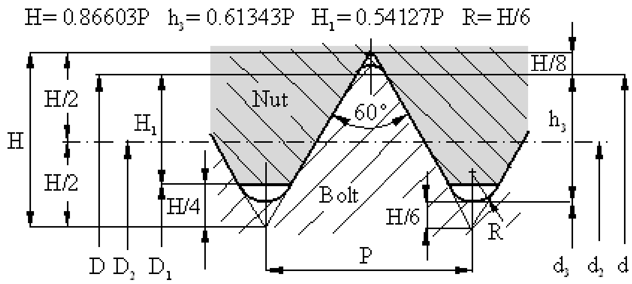
Check strength restriction: d_b <3/4in

$d_b \le 0.75in = 1$

Choosing ISO fine thread pitch of 1mm, to maximize root dia.; thread depth, h_3 is:

$p_t := 1.0mm \qquad h_3 := .6134 \cdot p_t$

using nomenclature and formulas from this chart at http://www.tribology-abc.com/calculators/metric-iso.htm



metric screw threads ISO 724 (DIN 13 T1)								
Nominal diameter d = D	Pitch P	root radius r	pitch diameter d2=D2	minor diameter d3	minor diameter D1	thread height h3	thread height H1	drill diameter mm
M 1.00	0.25	0.036	0.838	0.693	0.729	0.153	0.135	0.75
M 1.10	0.25	0.036	0.938	0.793	0.829	0.153	0.135	0.85
M 1.20	0.25	0.036	1.038	0.893	0.929	0.153	0.135	0.95
M 1.40	0.30	0.043	1.205	1.032	1.075	0.184	0.162	1.10
M 1.60	0.35	0.051	1.373	1.171	1.221	0.215	0.189	1.25
M 1.80	0.35	0.051	1.573	1.371	1.421	0.215	0.189	1.45
M 2.00	0.40	0.058	1.740	1.509	1.567	0.245	0.217	1.60
M 2.20	0.45	0.065	1.908	1.648	1.713	0.276	0.244	1.75
M 2.50	0.45	0.065	2.208	1.948	2.013	0.276	0.244	2.05
M 3.00	0.50	0.072	2.675	2.387	2.459	0.307	0.271	2.50
M 3.50	0.60	0.087	3.110	2.764	2.850	0.368	0.325	2.90
M 4.00	0.70	0.101	3.545	3.141	3.242	0.429	0.379	3.30
M 4.50	0.75	0.108	4.013	3.580	3.688	0.460	0.406	3.80
M 5.00	0.80	0.115	4.480	4.019	4.134	0.491	0.433	4.20
M 6.00	1.00	0.144	5.350	4.773	4.917	0.613	0.541	5.00
M 7.00	1.00	0.144	6.350	5.773	5.917	0.613	0.541	6.00
M 8.00	1.25	0.180	7.188	6.466	6.647	0.767	0.677	6.80
M 9.00	1.25	0.180	8.188	7.466	7.647	0.767	0.677	7.80
M 10.00	1.50	0.217	9.026	8.160	8.376	0.920	0.812	8.50
M 11.00	1.50	0.217	10.026	9.160	9.376	0.920	0.812	9.50
M 12.00	1.75	0.253	10.863	9.853	10.106	1.074	0.947	10.20
M 14.00	2.00	0.289	12.701	11.546	11.835	1.227	1.083	12.00
M 16.00	2.00	0.289	14.701	13.546	13.835	1.227	1.083	14.00
M 18.00	2.50	0.361	16.376	14.933	15.394	1.534	1.353	15.50
M 20.00	2.50	0.361	18.376	16.933	17.294	1.534	1.353	17.50

<---use h3 for 1.0 mm pitch

<--- use H1 for 1.5mm pitch

Bolt root dia. is then:

$d_3 := d_b - 2h_3$ $\qquad d_3 = 14.7732\,\text{mm}$

Total bolt cross sectional area:

$A_b := n \cdot \frac{\pi}{4} d_3^{\;2}$ $\qquad A_b = 239.976\,\text{cm}^2$

Check bolt to bolt clearance, here we use narrow thick washers (28mm OD) under the 24mm wide (flat to flat) nuts (28mm is also corner to corner distance on nut), we adopt a minimum bolt spacing of 2x the nominal bolt diameter (to give room for a 24mm socket) :

$d_w := 2d_b$ $\qquad d_w = 32\,\text{mm}$

$\pi C - n \cdot d_w \geq 0 = 1$ $\qquad$ actual bolt to bolt distance: $\frac{\pi C}{n} = 32.089\,\text{mm}$

Check nut, washer, socket clearance: $OD_w := 2d_b$ $\qquad$ this is for standard narrow washers, and for wrench sockets which more than cover the nut width across corners

$0.5C - \left(0.5B + g_1 + r_1\right) \geq 0.5OD_w = 1$

Check minimum bolt circle

$0.5B + g_1 + r_1 + 0.5 \cdot d_w \leq 0.5C = 1$

Flange hole diameter, minimum for clearance :

$D_{tmin} := d_b + 2mm \qquad D_{tmin} = 18\,mm$

We will thread some of these clearance holes for lift fixture bolts of size (db+4mm) to allow the head retraction fixture to be bolted up the the flange. The effective diameter of these holes will be the average of nominal and minimum diameters. To avoid thread interference with flange bolts, the flange studs will be machined to root diameter per **UG-12(b)**.in between threaded ends of 1.5x diameter in length. The actual clearance holes will be db+2mm, depending on achievable tolerances, so as to allow threading where needed.

$d_{lfb} := d_b + 4mm$

$H_1 := .812mm$ from chart above, for 1.5mm thread pitch

$d_{min\_lfb} := d_{lfb} - 2\cdot H_1 \qquad d_{min\_lfb} = 1.838\,cm$ this will be max bolt hole size or least material condition (LMC)

$d_{min\_lfb} \geq D_{tmin} = 1$

effective threaded clearance hole diameter:

$D_e := 0.5\left(d_{lfb} + d_{min\_lfb}\right) \qquad D_e = 1.919\,cm$

Set:

$D_t := D_e \qquad D_t \geq D_{tmin} = 1$

Compute Forces on flange:

$H_G := \begin{pmatrix} F_m \\ F_j \end{pmatrix} \qquad H_G = \begin{pmatrix} 7.554\times 10^3 \\ 2.804\times 10^5 \end{pmatrix} N$

$h_G := 0.5(C - G) \qquad h_G = 2.85\,cm$ from Table 2-6 Appendix 2, Integral flanges

$H_D := .785\cdot B^2\cdot P \qquad H_D = 2.266\times 10^6\,N$

$R_. := 0.5(C - B) - g_1 \qquad R_. = 2.5\,cm$ radial distance, B.C. to hub-flange intersection, int fl..

$h_D := R_. + 0.5g_1 \qquad h_D = 3\,cm$ from Table 2-6 Appendix 2, Int. fl.

$H_T := H - H_D \qquad H_T = 4.353\times 10^4\,N$

$h_T := 0.5\cdot\left(R_. + g_1 + h_G\right) \qquad h_T = 31.75\,mm$ from Table 2-6 Appendix 2, int. fl.

Total Moment on Flange

$M_P := H_D\cdot h_D + H_T\cdot h_T + H_G\cdot h_G \qquad M_P = \begin{pmatrix} 6.958\times 10^4 \\ 7.736\times 10^4 \end{pmatrix} J$

Appendix Y Calculation

$P = 15.4\,bar$

Choose values for plate thickness and bolt hole dia:

$t := 4.2cm \qquad D := D_t \qquad D = 1.919\,cm$

Going back to main analysis, compute the following quantities:

$$\beta := \frac{C + B_1}{2B_1} \qquad \beta = 1.022 \qquad h_C := 0.5(A - C) \qquad h_C = 3.25\,\text{cm}$$

$$a := \frac{A + C}{2B_1} \qquad a = 1.068 \qquad AR := \frac{n \cdot D}{\pi \cdot C} \qquad AR = 0.598 \qquad h_0 := \sqrt{B \cdot g_0} \qquad h_0 = 11.662\,\text{cm}$$

$$r_B := \frac{1}{n}\left(\frac{4}{\sqrt{1 - AR^2}}\,\text{atan}\left(\sqrt{\frac{1 + AR}{1 - AR}}\right) - \pi - 2AR\right) \qquad r_B = 8.438 \times 10^{-3}$$

We need factors F and V, most easily found in figs 2-7.2 and 7.3 (Appendix 2)

since $\frac{g_1}{g_0} = 1$ these values converge to $F := 0.90892 \; V := 0.550103$

Y-5 Classification and Categorization

We have identical (class 1 assembly) integral (category 1) flanges, so from table Y-6.1, our applicable equations are (5a), (7) - (13), (14a), (15a), (16a)

$$J_S := \frac{1}{B_1}\left(\frac{2 \cdot h_D}{\beta} + \frac{h_C}{a}\right) + \pi r_B \qquad J_S = 0.092 \qquad J_P := \frac{1}{B_1}\left(\frac{h_D}{\beta} + \frac{h_C}{a}\right) + \pi \cdot r_B \qquad J_P = 0.07$$

(5a) $$F' := \frac{g_0^{\,2}(h_0 + F \cdot t)}{V} \qquad F' = 2.814 \times 10^{-5}\,\text{m}^3 \qquad M_P = \begin{pmatrix} 6.958 \times 10^4 \\ 7.736 \times 10^4 \end{pmatrix} \text{N} \cdot \text{m}$$

$$A = 1.495\,\text{m} \qquad B = 1.36\,\text{m}$$

$$K := \frac{A}{B} \qquad K = 1.099 \quad Z := \frac{K^2 + 1}{K^2 - 1} \quad Z = 10.598$$

$f := 1$ hub stress correction factor for integral flanges, use f =1 for g1/g0=1 (fig 2-7.6)

$t_s := 0\text{mm}$ no spacer between flanges

$l := 2t + t_s + 0.5d_b \quad l = 9.2\,\text{cm}$ strain length of bolt (for class 1 assembly)

Y-6.1, Class 1 Assembly Analysis

http://www.hightempmetals.com/techdata/hitempInconel718data.php

Elastic constants:

$$E := E_{SS\_aus} \qquad E = 193\,\text{GPa} \qquad E_{Inconel\_718} := 208\text{GPa} \; E_{bolt} := \begin{pmatrix} E_{SS\_aus} \\ E_{Inconel\_718} \end{pmatrix}$$

Flange Moment due to Flange-hub interaction

$$M_S := \frac{-J_P \cdot F' \cdot M_P}{t^3 + J_S \cdot F'} \qquad M_S = \begin{pmatrix} -1.8 \times 10^3 \\ -2 \times 10^3 \end{pmatrix} \text{N} \cdot \text{m} \qquad (7)$$

Slope of Flange at I.D.

$$\theta_B := \frac{5.46}{E \cdot \pi t^3}\left(J_S \cdot M_S + J_P \cdot M_P\right) \qquad \theta_B = \begin{pmatrix} 5.734 \times 10^{-4} \\ 6.375 \times 10^{-4} \end{pmatrix} \qquad (8)$$

opening half gap = $\theta_B \cdot 3\text{cm} = \begin{pmatrix} 0.017 \\ 0.019 \end{pmatrix} \text{mm}$

$$E \cdot \theta_B = \begin{pmatrix} 110.674 \\ 123.04 \end{pmatrix} \text{MPa}$$

Contact Force between flanges, at h_C:

$$H_C := \frac{M_P + M_S}{h_C} \qquad H_C = \begin{pmatrix} 2.086\times 10^6 \\ 2.319\times 10^6 \end{pmatrix} N \tag{9}$$

Bolt Load at operating condition:

$$W_{m1} := H + H_G + H_C \qquad W_{m1} = \begin{pmatrix} 4.403\times 10^6 \\ 4.909\times 10^6 \end{pmatrix} N \tag{10}$$

Operating Bolt Stress

$$\sigma_b := \frac{W_{m1}}{A_b} \qquad \sigma_b = \begin{pmatrix} 183.5 \\ 204.6 \end{pmatrix} MPa \qquad S_b = \begin{pmatrix} 172.4 \\ 255.1 \end{pmatrix} MPa \tag{11}$$

$$r_E := \frac{E}{E_{bolt}} \qquad r_E = \begin{pmatrix} 1 \\ 0.928 \end{pmatrix}$$ elasticity factor

Design Prestress in bolts

$$S_i := \overrightarrow{\left[\sigma_b - \frac{1.159\cdot h_C^{\,2}\cdot(M_P + M_S)}{a\cdot t^3\, l\cdot r_E\cdot B_1}\right]} \qquad S_i = \begin{pmatrix} 175.2 \\ 194.6 \end{pmatrix} MPa \tag{12}$$

Radial Flange stress at bolt circle

$$S_{R\_BC} := \frac{6(M_P + M_S)}{t^2(\pi\cdot C - n\cdot D)} \qquad S_{R\_BC} = \begin{pmatrix} 127.7 \\ 141.9 \end{pmatrix} MPa \tag{13}$$

Radial Flange stress at inside diameter

$$S_{R\_ID} := -\left(\frac{2F\cdot t}{h_0 + F\cdot t} + 6\right)\cdot\frac{M_S}{\pi B_1\cdot t^2} \qquad S_{R\_ID} = \begin{pmatrix} 1.533 \\ 1.704 \end{pmatrix} MPa \tag{14a}$$

Tangential Flange stress at inside diameter

$$S_T := \frac{t\cdot E\cdot\theta_B}{B_1} + \left(\frac{2F\cdot t\cdot Z}{h_0 + F\cdot t} - 1.8\right)\cdot\frac{M_S}{\pi B_1\cdot t^2} \qquad S_T = \begin{pmatrix} 2.58 \\ 2.87 \end{pmatrix} MPa \tag{15a}$$

Longitudinal hub stress

$$S_H := \frac{h_0\cdot E\cdot\theta_B\cdot f}{0.91\left(\frac{g_1}{g_0}\right)^2 B_1\cdot V} \qquad S_H = \begin{pmatrix} 18.82 \\ 20.922 \end{pmatrix} MPa \tag{16a}$$

Y-7 Bolt and Flange stress allowables: $S_b = \begin{pmatrix} 172.4 \\ 255.1 \end{pmatrix} MPa \qquad S_f = 137.9\,MPa$

(a) $\overrightarrow{(\sigma_b \le S_b)} = \begin{pmatrix} 0 \\ 1 \end{pmatrix}$

(b)

(1) $\overrightarrow{(S_H \le 1.5S_f)} = \begin{pmatrix} 1 \\ 1 \end{pmatrix}$ S_n not applicable

(2) not applicable

(c) $\overrightarrow{(S_{R\_BC} \le S_f)} = \begin{pmatrix} 1 \\ 0 \end{pmatrix}$

$$\overrightarrow{(S_{R\_ID} \le S_f)} = \begin{pmatrix} 1 \\ 1 \end{pmatrix}$$

(d) $$\overrightarrow{(S_T \le S_f)} = \begin{pmatrix} 1 \\ 1 \end{pmatrix}$$

(e) $$\overrightarrow{\frac{S_H + S_{R\_BC}}{2} \le S_f} = \begin{pmatrix} 1 \\ 1 \end{pmatrix}$$

$$\overrightarrow{\frac{S_H + S_{R\_ID}}{2} \le S_f} = \begin{pmatrix} 1 \\ 1 \end{pmatrix}$$

(f) not applicable

Bolt force

$$F_{bolt} := \sigma_b \cdot .785 \cdot d_b^{\ 2} \qquad F_{bolt} = \begin{pmatrix} 3.687 \times 10^4 \\ 4.111 \times 10^4 \end{pmatrix} N$$

Bolt torque required, minimum:

$$T_{bolt\_min} := 0.2 F_{bolt} \cdot d_b \qquad T_{bolt\_min} = \begin{pmatrix} 118 \\ 131.6 \end{pmatrix} N \cdot \text{ı}\ T_{bolt\_min} = \begin{pmatrix} 87 \\ 97 \end{pmatrix} lbf \cdot ft$$

for pressure test use 1.5x this value

This is the minimum amount of bolt preload needed to assure joint does not open under pressure. An additional amount of bolt preload is needed to maintain a minimum frictional shear resistance to assure head does not slide downward from weight; we do not want to depend on lip to carry this. Non-mandatory Appendix S of div. 1 makes permissible higher bolt stresses than indicated above when needed to assure full gasket sealing and other conditions. This is consistent with proper preloaded joint practice, for properly designed joints where connection stiffness is much greater than bolt stiffness, and we are a long way from the yield stress of the bolts

$$M_{head} := 2500 kg \qquad \mu_{SS\_SS} := .7$$

typ. coefficient of friction, stainless steel (both) clean and dry

$$V_{head} := M_{head} \cdot g \qquad V_{head} = 2.452 \times 10^4 N$$

$$F_n := \frac{V_{head}}{\mu_{SS\_SS}} \qquad F_n = 3.502 \times 10^4 N$$

this is total required force, force required per bolt is:

$$F_{n\_bolt} := \frac{F_n}{n} \qquad F_{n\_bolt} = 250.17 N$$

this is insignificant compared to that required for pressure.

Let bolt torque for normal operation be then 25% greater than minimum:

$$T_{bolt} := 1.25 T_{bolt\_min} \qquad T_{bolt} = \begin{pmatrix} 147 \\ 164 \end{pmatrix} N \cdot m \qquad T_{bolt} = \begin{pmatrix} 109 \\ 121 \end{pmatrix} ft \cdot lbf$$

It is recommended that a pneumatic torque wrench be used for tightening of bolts. Anti-seize lubricant (checked for radiopurity) should be used on threads and washers. Fasteners should not be plated, as Inconel is very sensitive to hydrogen embrittlement. Bolts should be tightened in 1/3 full torque increments, but there is no specific tightening pattern to be used, as gasket compression is not determined by bolt tightness. However there may be a recommendation for tightening a helicoflex gasket in the initial stages of compression, at low bolt loads where the joint is still closing.

Bolt torque required to close joint with Helicoflex gasket (initial gasket compression)

$$F_{bg} := \frac{H_G}{n} \qquad F_{bg} = \begin{pmatrix} 53.957 \\ 2.003 \times 10^3 \end{pmatrix} N$$

$$T_{bg} := 0.2 F_{bg} \cdot d_b \qquad T_{bg} = \begin{pmatrix} 0.173 \\ 6.408 \end{pmatrix} N \cdot m \qquad T_{bg} = \begin{pmatrix} 0.1 \\ 4.7 \end{pmatrix} ft \cdot lbf$$

The head lift fixture must be used to prealign the head to the flange faces and bolt holes prior to attachement. this