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Comparison of Russian and European Design Rules for FBR Piping Systems

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1. ABSTRACT

In the framework of an ECC contract between European and Russian Engineering Companies (FRAMATOME, ANSALDO, NNC, CEA, AEA and MINATOM), a comprehensive investigation was carried out upon FBR standard design-by-analysis procedures currently used in Europe and in Russian Federation, with reference to the French RCC-MR Code and to the Russian National Standards: this paper is focused on the comparison between corresponding design criteria for low pressure thin wall pipes fabricated from austenitic stainless steel.
After a synthesis of the basic rules used in both practices for the prevention of damages from excessive deformation or plastic instability, buckling, ratcheting and fatigue (with or without creep significance), the final discussion is issued from a benchmark application of the two sets of criteria to the design of a typical FBR hot leg secondary pipe (under an operational loading cycle) and highlights the main differences potentially affecting the reactor safety and lifetime.

2. SYMBOLS AND ABBREVIATIONS

D_a , D = outside pipe diameter
D_m , r = mean diameter, mean radius
E = YOUNG modulus of elasticity
ν = POISSON ratio
f , λ = elbow flexibility factor
h , (s-c) = efficient pipe thickness
h_c , s = conventional pipe thickness
L = pipe run length
M_1 , M_z = torsion moments
$M_{2,3}$, $M_{x,y}$ = bending moments
N_z = axial force
p = internal pressure
R = elbow bend radius
R_m^{20} = min. tensile strength at 20°C
R_m^T = min. tensile strength at temp. T
R_{mt}^T, $S_r(\theta,t)$ = min. stress-to-rupture at temp. T, (θ) for load duration t
$R_{p0.2}^{20}$;$R_{0.002}^{20}$=min. yield strength at 20
$R_{p0.2}^T$;$R_{0.002}^T$= min. yield strength at T
t = load duration time
T, θ = mean pipe wall temperature
T_t = transition temperature
Z ,W= section inertia modulus

α = mean thermal expansion (20°C to T)
θ^a,θ^b = θ at gross discontinuity sides a,b
θ_1 = linear thermal gradient through h
θ_2 = non linear thermal gradient through h
σ_{ffs} = stress of secondary creep end
$\sigma_{1\%}$ = 1% total strain minimum stress
σ_m ,($\sigma_{m,ml}$)=general (local) membrane stress
σ_r = radial stress
σ_ψ ,($\sigma_{\psi p}$) = hoop stress comp. (due to p)
σ_z ,(σ_{zp}) =axial stress component (due to p)
σ_{T0} = axial thermal stress at a discontinuity
$(\sigma)^*_T$ = bending thermal stress
τ = shear stress
ECC = European Community Commission
FBR = Fast Breeder Reactor
LWR = Light Water Reactor
DE = Design Earthquake (1/100 y)
MDE = Max. Design Earthquake ($1/10^4$ y)
OBE = Operating Basis Earthquake \
SSE = Safe Shutdown Earthquake
NOC =Normal Operating Conditions (A/B)
NOCV = NOC Variations (Level B/C)
ES = Emergency Situations (Level C/D)

3. MAIN ANALYTICAL FORMULATIONS

Hereinafter, reference is made to the Russian PNAE Norms (henceforward referred to as "the Norms"), Ref.(1), and to the French RCC-MR Code (referred to as "the Code"), Ref.(2).
The given formulations are relevant to Safety Class 1 thin wall pipes under internal pressure load: they apply to piping current sections, excluding bolted or welded joints. severest
Unlike the Code, the Norms use the same set of rules for pipelines of any safety class; the agreement is not absolute as regards as well service level definitions and ES conditions (covering Level D situations) are not taken into account in Russian pipe verification.
For each considered damage, a distinction is made between the two domains of negligible or significant creep; creep significance is assessed according to the following criteria:

a) in Russian practice, whenever maximum temperature T exceeds $T_t = 450°C$:
b) in European practice, whenever conformity to RB3613.1 of the Code is not met.

We observe that, in both practices, ratcheting criteria for significant creep (long-term static strength) are to be verified in addition to short-term static strength criteria. European rules require as well the preliminary verification against excessive deformation and buckling, including the limitation of the monotonous elastic follow-up due to imposed displacements and of the cyclic follow-up due to thermal expansion during the severest loading cycle.

3.1 Rules for the Prevention of Excessive Deformation and Plastic Instability

a) Negligible Creep

Items	Russian Practice Ref.(1)			European Practice Ref.(2)		
Membrane Stress Intensity $(\sigma)_1$; P_m	Straight pipes and elbows: $(\sigma)_1 = \sigma_\psi = \sigma_{\psi p} = p\,\frac{[D_a - 2\,(s\text{-}c)]^2}{2(D_a\text{-}s\text{+}c)(s\text{-}c)}$			Straight pipes: $P_m = p(D_e - 0.8h)/2h$ Elbows (with $K = R/r$): $P_m = \frac{K\text{-}0.5}{2h(K\text{-}1)} \cdot p(D_e - 0.8h)$		
Membrane plus Bending Stress Intensity $(\sigma)_2$, by the maximum shear stress criterion (TRESCA method) ; $P_m + P_b$	$(\sigma)_2$, from components of stress: $\sigma_\psi = \sigma_{\psi p} = 2\sigma_{zp}$ $\sigma_{zp} = p\,\frac{[D_a - 2\,(s\text{-}c)]^2}{4(D_a\text{-}s\text{+}c)(s\text{-}c)}$ $\sigma_z = \pm\frac{\sqrt{M_x^2 + M_y^2}}{W} + \frac{N_z}{A} + \sigma_{zp}$ $\sigma_r = -p/2 \qquad \tau = \frac{M_z}{2W}$ For elbows with $\lambda \leq 1.4$: $(\sigma)_2 = \frac{\Omega}{\Psi}\frac{1}{W}\sqrt{M_x^2 + M_y^2 + M_z^2}$ Ω/Ψ, stress index from A5.2			$P_m + P_b = B_1 p(D_e/2h_c) + < B_2/Z, M >$ where, for straight pipes or elbows : $<B_2/Z,M> = \left\langle \begin{array}{l} (B_2/Z)\cdot M_R \\ \frac{\sqrt{B_2^2 M'^2_R + 1.21 M_1^2}}{Z} \end{array}\right.$ B_1 and B_2 being the primary stress indices from RB3680 $M_R = \sqrt{M_1^2 + M_2^2 + M_3^2}$ $M_R' = \sqrt{M_2^2 + M_3^2}$		
Allowable Stress Limits $[\sigma]$; S_m	$[\sigma] = \min\left\{\frac{R_m^T}{2.6} ; \frac{R_{p0.2}^T}{1.5}\right\}$			$S_m = \min\left\{\frac{R_{0.002}^{20}}{1.5} ; 0.9R_{0.002}^T ; \frac{R_m^{20}}{3.0} ; \frac{R_m^T}{2.7}\right\}$		
Verification Criteria	Load Condition	Membrane	Membrane + Bending	Load Condition	Membrane	Membrane + Bending
	NOC	$(\sigma)_1 \leq [\sigma]$	$(\sigma)_2 \leq 1.3[\sigma]$	Level A	$P_m \leq S_m$	$P_m + P_b \leq 1.3S_m$
(index "s" for seismic loads)	NOCV NOC+DE	$(\sigma)_1 \leq 1.2[\sigma]$ $(\sigma_s)_1 \leq 1.2[\sigma]$	$(\sigma)_2 \leq 1.6[\sigma]$ $(\sigma_s)_2 \leq 1.6[\sigma]$	Level C (with OBE)	$P_m \leq \min[1.35\,S_m ; R_{0.002}^T]$	$P_m + P_b \leq 1.9\,S_m$
	NOC + MDE	$(\sigma_s)_1 \leq 1.4[\sigma]$	$(\sigma_s)_2 \leq 1.8[\sigma]$	Level D (with SSE)	$P_m \leq \min[2S_m ; 0.7R_m^T]$	$P_m + P_b \leq [3S_m ; 0.9R_m^T]$

b) Significant Creep

Items	Russian Practice Ref.(1)			European Practice Ref.(2)		
Membrane Stress	$(\sigma)_1$ as for negligible creep			P_m as for negligible creep		
Membrane plus Bending $(\sigma)_2$; $P_m + \Phi P_b$	$(\sigma)_2$ as for negligible creep			$P_m + \Phi P_b$ where: $\Phi = 0.88$ (bending stress redistribution ratio due to creep)		
Allowable Stress Limits $[\sigma]$; S_t	$[\sigma] = \frac{R_{mt}^T}{1.5}$			$S_t = \min[2/3 S_r(\theta,t) ; 0.8\sigma_{ffs} ; \sigma_{1\%}]$ (reduced in Level A/C conditions to account for creep usage due to thermal expansion, in case of non negligible relaxation follow-up effects, accordingly to RB3652.11)		
Verification Criteria	Load Condition	Membrane	Membrane + Bending	Load Condition	Membrane	Membrane + Bending
	NOC + NOCV	$(\sigma)_1 \leq [\sigma]$	$(\sigma)_2 \leq K_t[\sigma]$ with $K_t = 1.25 - 0.25\sigma_m/[\sigma]$	Level A and C	$P_m \leq S_t$	$P_m + \Phi P_b \leq S_t$
				Level A, C, D	$P_m \leq \frac{1}{1.35} S_r$	$P_m + \Phi P_b \leq S_r/1.35$

3.2 Rules for the Prevention of Buckling

a) Negligible Creep

Items	Russian Practice Ref.(1)		European Practice Ref.(2)	
Critical Stress σ_c ; $s_m + s_b$	For cylindrical shells under axial compression load (F) with: $0.05 \leq (s\text{-}c)/D_m \leq 0.2$: $\sigma_c = \frac{F}{\pi D_m(s\text{-}c)}$ (from Sect.5.5.2)		$s_m + s_b = D_1 p(D_e/2h_c) + \langle D_2/Z, M+gm \rangle$ D_1,D_2 (stress indices) and g (ratio for displacement controlled moment m), from RB3680 and RB3651.114 $\langle D_2/Z, M+gm \rangle$, from RB3651.113	
Allowable Stress Limit $[\sigma_c]$; S^*	$[\sigma_c] = \min\{[\sigma_c]_1 ; [\sigma_c]_2\}$ where: $[\sigma_c]_1 = 0.5\,\xi_1\,\sigma_{kr1}$ $[\sigma_c]_2 = 0.5\,\xi_2\,\sigma_{kr2}$ with: σ_{kr1}(global buckling) $=1.2\,E\left(\frac{D_m}{\pi L}\right)^2$ σ_{kr2}(local buckling)$=1.2\,E\,(s\text{-}c)/D_m$ ξ_1, ξ_2 material dependent factors		Comprehensive rule for plastic instability and buckling, accounting for monotonous elastic follow-up effects : $s_m + s_b \leq S^*$ with: $S^* = \min[0.8R_{0.002}^T ; 0.4(R_m^T]$	
Verification Criteria	Load Condition	Criteria	Load Condition	Criteria
	NOC, NOCV	$\sigma_c \leq [\sigma_c]$	Level A	$S \leq S^*$
			Level C	$S \leq 1.25S^*$
			Level D	$S \leq 1.9S^*$

b) Significant Creep

Items	Russian Practice Ref.(1)	European Practice Ref.(2)
Critical Stress	Same as for negligible creep	Same as for negligible creep
Allowable Stress Limit (NOC+NOCV)	$[t] = \min\{[t_1] ; [t_2]\}$ where: $[t_1]$ = limit for global buckling $[t_2]$ = limit for local buckling (from Sect.5.5.8.5)	

3.3 Rules for the Prevention of Ratcheting

a) Negligible Creep

Items	Russian Practice Ref.(1)	European Practice Ref.(2)
Short-term Stress Range $(\sigma)^{ST}_{RK}$ (TRESCA method) Efficient Stresses P_1 ; P_2	$(\sigma)^{ST}_{RK} = (\sigma)^{\circ}_{RK} + (\sigma)_{T0}$, with $(\sigma)_{T0}$ drawn from A5.2.3.2.4 For straight pipes or elbows with $\lambda \geq 1.4$, $(\sigma)^{\circ}_{RK}$ is drawn from stress components: $\sigma_\psi = 2\sigma_{zp} = 2p\frac{[D_a - 2(s-c)]^2}{4(D_a-s+c)(s-c)}$ $\sigma_z = \pm\frac{\sqrt{M_x^2 + M_y^2}}{W} + \frac{N_z}{A} + \sigma_{zp}$ $\sigma_r = 0 \qquad \tau = \frac{M_z}{2W}$ At elbows with $\lambda \leq 1.4$, it is the largest of: $(\sigma)^{\circ}_{RK} = \frac{1}{W}\sqrt{[\lvert M_x\rvert\gamma_m + \lvert M_y\rvert\beta_m + W\sigma_{zp}]^2 + M^2_z}$ $(\sigma)^{\circ}_{RK} = \frac{1}{W}\sqrt{[\lvert M_x\rvert\beta_m + \lvert M_y\rvert\gamma_m + W\sigma_{zp}]^2 + M^2_z}$ $(\sigma)^{\circ}_{RK} = \frac{1}{W}\sqrt{[\lvert M_x\rvert\gamma_m + BW\sigma_{\psi p}]^2 + M^2_z}$ $(\sigma)^{\circ}_{RK} = \frac{1}{W}\sqrt{[\lvert M_y\rvert\gamma_m + BW\sigma_{\psi p}]^2 + M^2_z}$ with β_m and γ_m secondary stress indices from A5.2.6.1 and $B = (2R-r)/2(R-r)$	Preliminary verification of cyclic follow-up effects ($r_c < 3$, with r_c defined in RB3643.32) Stress intensity range (between load sets j and j') : $q(j,j')=(C_2/Z)[m(j,j')]_R+E\alpha\theta_1(j,j')/[2(1-v)]+C_3\cdot\lvert(E_a\alpha_a\theta^a-E_b\alpha_b\theta^b)(j,j')\rvert$ where: C_2, C_3 secondary stress indices from RB3680 m(j,j') displacement controlled moment range between j and j' Secondary ratios : SR_1= Max q(j,j') /Max P_m SR_2=Max q(j,j') /Max (P_m+P_b) Efficient stresses : P_1= Max P_m/v_1 P_2= Max $(P_m+P_b)/v_2$, v_1 and v_2 being the efficiency indices from SR_1 ,SR_2 and RB3661.12
Shakedown Criterion	$(\sigma)^{ST}_{RK} \leq \min[(2.5-R_{p0.2}{}^T/R_m{}^T)R_{p0.2}{}^T ; 2R_{p0.2}{}^T]$ (not mandatory)	Max q(j,j')+Max $(P_m+P_b) \leq 3S_m$
Efficiency Diagram Rule		$P_1 \leq 1.2\ S_m$ $P_2 \leq 1.56\ S_m$

b) Significant Creep

Items	Russian Practice Ref.(1)	European Practice Ref.(2)
Long-term Stress Range $(\sigma)^{LT}_{RK}$ (TRESCA method) Efficient Stresses P_1 ; P_3	For straight or curved pipes with $\lambda \geq 1.0$, $(\sigma)^{LT}_{RK}$ is evaluated as for negligible creep; for elbows with $\lambda < 1.0$, it is the largest of: $\frac{1}{W}\sqrt{[\lvert(0.6M_x + M_\theta)\rvert\gamma_m + \lvert 0.6M_y\rvert\beta_m + W\sigma_{zp}]^2 + M^2_z}$ $\frac{1}{W}\sqrt{[\lvert(0.6M_x + M_\theta)\rvert\beta_m + \lvert 0.6M_y\rvert\gamma_m + W\sigma_{zp}]^2 + M^2_z}$ $\frac{1}{W}\sqrt{[\lvert(0.6M_x + M_\theta)\rvert\gamma_m + BW\sigma_{\psi p}]^2 + M^2_z}$ $\frac{1}{W}\sqrt{[\lvert 0.6M_y\rvert\gamma_m + BW\sigma_{\psi p}]^2 + M^2_z}$ with M_θ moment due to pressure and section ellipticity percentage	q(j,j'), as for negligible creep Secondary ratios : SR_1= Max q(j,j') /Max P_m SR_3=Max q(j,j') /Max $(P_m+\Phi P_b)$ Efficient stresses : P_1= Max P_m/v_1 P_3= Max $(P_m+\Phi P_b)/v_3$ with v_1 and v_3 efficiency indices from SR_1 ,SR_3 and RB3661.12
Shakedown Criterion	$(\sigma)^{LT}_{RK} \leq K'_t[\sigma]$ (mandatory) where: $[\sigma] = \frac{R_{mt}{}^T}{1.5}$ and $K'_t = 1.75 - 0.25\sigma_{m,mL}/[\sigma]$	
Efficiency Method		$P_1 \leq 1.2\ S_m$ $P_2 \leq 1.56\ S_m$,and : $P_1 \leq 1.2\ S_t$ $P_3 \leq 1.2\ S_t$.

3.4 Rules for the Prevention of Fatigue

a) Negligible Creep

Items	Russian Practice Ref.(1)	European Practice Ref.(2)
TRESCA Alternating Stress Intensity $(\sigma_{aF})_K$ VON MISES Equivalent Strain Range $\Delta\varepsilon$ (including NEUBER cyclic effects and triaxiality))	$(\sigma_{aF})_K = (\sigma_{aF})^{o}_{K} + ½(\sigma)^{*}_{T} + ½(\sigma)_{T0}$ For straight or curved pipes with $\lambda \geq 1.0$ $(\sigma_{aF})^{o}_{K}$ is evaluated from $(\sigma)^{o}_{RK}$ stress components, as $(\sigma_{aF})^{o}_{K} = ½(\sigma)^{o}_{RK}$ At elbows with $\lambda \leq 1.0$ $(\sigma_{aF})^{o}_{K}$ is essentially drawn from the previous formulas for ½ $(\sigma)^{LT}_{RK}$, with bending moments reduced by the factor 0.7 , instead of 0.6 (see Sect.5.2.3.3.2) The effect of plasticity is taken into account by reevaluating the peak stress intensity $(\sigma_F)_K$ accordingly to Sect.5.3.8 with material parameters from Sect.A1	Accordingly to RB3661.24: $\Delta\varepsilon = \Delta\varepsilon_1 + k\,\Delta\varepsilon_2$ where : $\Delta\varepsilon_1$(elastic strain range) = $\frac{2}{3}\frac{1+\nu}{E}\, s_p(j, j')$ $\Delta\varepsilon_2$ = plastic amplification due to primary stress range $k = (K_\varepsilon - 1) + K_\nu$ where : K_ε depends on primary plus secondary stress range $s_n(j,j')$ K_ν depends on total stress range $s_p(j,j')$ (K_ε , K_ν from A3.59, with $s_n(j,j')$ and $s_p(j,j')$ evaluated from RB3661 and RB3680)
Verification Criteria	The allowable number of cycles N_i is evaluated by entering $(\sigma_{aF})_K$ into curves of Sect.5.6 for austenitic steels or into formulas 5.25 or 5.30 (the least value is retained). The cumulated fatigue damage a is given by: $a = \Sigma_i(n_i/N_i)$ with: n_i = occurrences of i-th cycle	$V(\Delta\varepsilon) \leq 1$ The allowable number N_k for the k-th cycle is issued by entering $\Delta\varepsilon_k$ into curves A3.64. The cumulated fatigue usage factor for all cycles is given by : $V = \Sigma_k(n_k/N_k)$ with: n_k = occurrences of k-th cycle

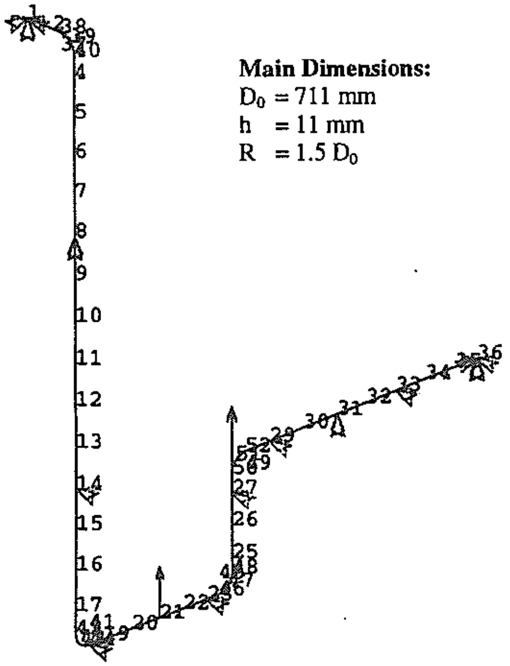
b) Significant Creep

Items	Russian Practice Ref.(1)	European Practice Ref.(2)
Stress Intensity Range and Equivalent Strain Range $(\sigma_{aF})_K$; $\Delta\varepsilon$	Same formulations as for negligible creep, but R_{pe}^{T} (proportionality limit), ν (hardening index) and material ductility parameters, accounting for elastoplastic effects in the evaluation of local peak stresses $(\sigma_F)_K$, are drawn from Sections A6 and A7.	$\Delta\varepsilon = \Delta\varepsilon_{cl+pl} + \Delta\varepsilon_{fl}$ $\Delta\varepsilon_{cl+pl}$ = elastoplastic strain range ($\Delta\varepsilon$ of negligible creep verification) $\Delta\varepsilon_{fl}$ = creep amplification, from equations of A3.63 and from σ_K , depending on the mean primary stress during the k-th cycle and on the equivalent stress range associated to $\Delta\varepsilon_{cl+pl}$ (from A3.59) A less conservative evaluation of $\Delta\varepsilon_{fl}$ including stress relaxation is allowed according to RB3662.23.
Verification Criteria	The allowable number for the i-th cycle is evaluated by entering $(\sigma_{aF})_K$ into equations of Sect.5.6.6 (with parameters from Sect.A7) or design fatigue curves for $2{\cdot}10^5$hours of loading duration (from Sect.A7.4). The cumulative damage is estimated as for negligible creep.	V from total $\Delta\varepsilon$ and curves A3.64, as for negligible creep ; W (cumulative creep damage) from RB3626.3: $W = \Sigma_K(\sigma_K/0.9)$ The creep-fatigue damage envelope is then estimated by entering V and W into A3.58 interaction diagram (giving the allowable domain).

4. DISCUSSION

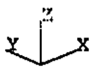
4.1 Benchmark Application

A typical hot leg secondary piping between the IHX and the SGU of a FBR unit is chosen for the benchmark analysis. Considered material is the AISI316LN Stainless steel (corresponding to the Russian 08X16H11M3), the characteristics of which are taken from the Code, in order to set aside any discrepancy potentially coming from different material data.
Geometry and input data for the analysis with the finite element computer program ANSYS, Ref.(3), are shown here below. Internal pipe pressure is assumed as negligible.
Verification is carried out according to Safety Class 1 criteria for Level A (NOC) conditions and significant creep (maximum T > 450°C), at straight and curved pipe sections with the highest primary stresses (nodes 31 and 46) or secondary stresses (nodes 2 and 38).



Main Dimensions:
D_0 = 711 mm
h = 11 mm
R = 1.5 D_0

BENCHMARK3 PIPING RUN
ANSYS F.E.M. MODEL



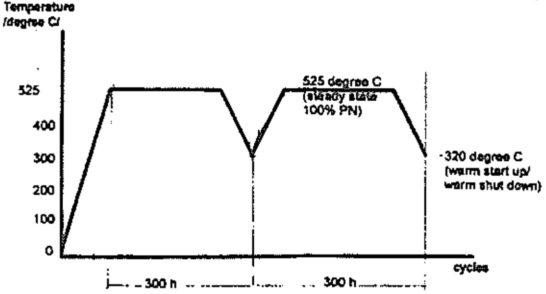
Rigid Supports:

Nodes 14,23,27,29,33,44	Uy=0
Nodes 8,31	Uz=0
Node 1	Ux=Uy=Rx=Ry=Rz=0
Node 36	Uy=Rx=Ry=Rz=0

Constant Support Springs :

Node 21	z-Force=47350 N
Node 27	z-Force=63000 N

Loading Cycle: Warm Start Up - Steady State 100% Pn - Warm Shut Down (10^3 occurrences)



Data for Scram at 100%P_N: θ_1=30°C; θ_2=30°C

Displacements at IHX and SGU Locations

Component	Load case	Temp. [°C]	Displacement[mm] X	Y	Z
IHX outlet	100%P_N	525	-5.6	0.0	32.5
	shutdown	320	-5.6	0.0	20.4
SGU inlet	100%P_N	525	0.0	0.0	115.3
	shutdown	320	0.0	0.0	82.0

4.1 Primary Stress Analysis

a) Limitation of Excessive Deformation

The main verification items at the selected locations are given in the following table:

Node	M_I (N · m)	M'_R (N · m)	M_R (N · m)	N_z (N)	$(\sigma)_2$ (MPa)	P_m+P_b (MPa)	$P_m+\Phi P_b$ (MPa)	S_m+S_b (MPa)
2	5680	8332	10084	9481	2.8	2.5	2.2	271.5
38	5680	2438	6181	9481	9.4	9.2	8.1	214.7
31	21.4	181870	181870	3358	43.8	43.6	38.4	87.1
46	135.7	22041	22041	3358	33.5	32.8	28.9	45.7

As to the short-term verification, the allowable limit for $(\sigma)_2$ (Russian practice) and P_m+P_b (European practice) is $1.3S_m$=1.3[σ] (with S_m=103 MPa from the Code, Sect.A3.1S.51).
The stress values evaluated from the two sets of rules are quite close everywhere and allowable limits are respected with a good margin in both practices (min. ~67% at node 31).
The long-term allowable limits ($R_{mt}^T/1.5 = S_t = 111$ MPa) are also fulfilled, as (at node31):

a) from Russian practice, $(\sigma)_2$= 43.8 MPa < $K_t[\sigma]=1.25\cdot 111=138.75$ MPa;

b) from European practice, $P_m+\Phi P_b$= 38.4 MPa < 111 MPa.

The Norms seem slightly less conservative (margin 68.4% versus 65.4%), due to a 10% lower bending stress redistribution factor for creep ($1/K_t$=0.80 against Φ=0.88 for the Code).

b) Buckling (Stability) Verification

The Code criteria for the prevention of buckling and plastic instability are not met at nodes 2 and 38, where the limit (S^*= 91.2 MPa) for s_m+ s_b is exceeded: the pipeline verification should be completed by a refined thin shell analysis of the pipe portion near the SGU inlet nozzle. As to the Norms, the simplified stability rules allowed for cylindrical shells under axial loading give at node 40 (first elbow) a maximum axial compression only slightly above the allowable limit $[\sigma_c]$ (from N_z = -583670N, σ_c= 24.1 MPa > $[\sigma_c] = [\sigma_c]_1$= 22.4 MPa).

4.2 Secondary Stress Analysis

a) Prevention of Creep-Ratcheting

For the severest loading cycle, between steady-state (j) and warm shutdown (j'), we get:

Node	M_x(j,j) (N·m)	M_y(j,j)' (N·m)	M_z(j,j') (N·m)	N_z(j,j') (N)	$(\sigma)^{ST}_{RK}$ (MPa)	$(\sigma)^{LT}_{RK}$ (MPa)	q(j,j') (MPa)	P_2 (MPa)	P_3 (MPa)
2	787910	1341	23838	10730	189.5	189.5	248.6	25.0	23.7
38	414920	416.2	23838	10730	857.9	514.8	988.3	97.0	90.1
31	30831	335.1	158.8	1460	7.5	7.5	66.9	58.1	53.3
46	4780	30.8	4154	1460	10.0	6.0	73.7	50.5	47.3

Russian $(\sigma)_{RK}$ are lower than European q(j,j') values, due to thermal bending stresses not included by the Norms in secondary stress range evaluations and, at elbows (nodes 38 and 46), also to the slightly lower Russian stress indices (γ_m=8.614 against C_2=9.316). Nevertheless, the Russian approach is by far more pessimistic, as , with the same material data, the allowable limits (respectively for short-term and long-term verifications) are given by: $(\sigma)^{ST}_{RK} \leq 2R_{p0.2}^T=3S_m$=309MPa, $(\sigma)^{LT}_{RK} \leq 1.75\ (R_{mt}^T/1.5) = 1.75S_t$= 194.25MPa for the Norms and $P_2 \leq 1.56S_m$=160.7MPa, $P_3 \leq 1.2S_t$= 133.2MPa for the Code. As a result, at locations with high secondary stresses, Russian long-term static strength limits are either approached (straight portion, node 2) or exceeded (elbow, node 38), whereas Code criteria are met everywhere.

b) Prevention of Creep-Fatigue

Main verification items for the considered loading cycle are given in the following table :

Node	$(\sigma_{aF})_K$ (MPa)	$(\sigma_{aF})_K^{(*)}$ (MPa)	N_0	s_p(j,j') (MPa)	$\Delta\varepsilon_{el+pl}$ (%)	σ_K (MPa)	$\Delta\varepsilon_{fl}$ (%)	$\Delta\varepsilon_{tot}$ (%)	N	V	W
2	134.5	139.4	2355	268.5	0.181	158.6	0.022	0.203	1.1e5	.009	1.34
38	340.0	511.9	77	1008.	1.111	330.6	0.456	1.567	37	26.9	2155
31	43.0	43.0	$>10^7$	86.8	0.051	136.9	0.012	0.063	$>10^9$	~0	0.74
46	43.2	43.2	$>10^7$	93.6	0.055	132.8	0.011	0.066	$>10^9$	~0	0.69

(*) after reevaluation taking into account elastoplastic effects

At straight portions (nodes 2 and 31), the values of $(\sigma_{aF})_K$ from the Norms are very close to the corresponding $\frac{1}{2}s_p(j,j')$ from the Code; the lower values at elbows (nodes 38 and 46) reflect the 0.7 factor for bending moments (and, to a lesser extent, the lower stress indices γ_m). In the fatigue assessment, the Russian practice seems more pessimistic at straight portions (node 2) and a little less conservative at elbows (node 38), but the most significant difference is related to the different approach in evaluating creep effects. As a matter of fact, Code limits are exceeded at node 38 (where verification criteria are not met in both practices) and even at node 2 (because of excessive creep), where according to the Norms the allowable number of cycles is fulfilled ($1000 < 2355$); differences, also found at nodes 31 and 46, are somewhat enhanced by the Code conservative evaluation of $\Delta\varepsilon_{fl}$ (here neglecting strain relaxation).

5. CONCLUSIONS

The most significant issues of the comparative analysis upon Russian and European design criteria for FBR low pressure piping systems may be resumed as follows:

- Criteria for excessive deformation limitation are basically the same in both practices, but lower allowable limits are set in the Norms for NOCV conditions or under seismic loads.
- A significant difference concerns buckling prevention: unlike the Code, which provides rules for the cumulative risk assessment of buckling and plastic instability along the pipeline (including elastic follow-up effects), the Norms do not give any specific criteria for piping buckling analysis, but only simplified rules for axisymmetric shell stability.
- The Russian approach for ratcheting prevention is essentially based upon the $3S_m$ shakedown criterion, with a compulsory extension to high temperatures, which seems to be too pessimistic, since it involves a total secondary-to-primary transformation of stresses. Instead, European criteria are mainly founded on the efficiency diagram method (the $3S_m$ criterion being only allowed at low temperatures).
- The Russian fatigue assessment makes use of alternating stress intensities, whereas the Code estimate is based on equivalent strain ranges: apart from different methods of taking into account material non-linearity effects (the Norms use a reevaluation of local elastic stresses, whereas the Code applies a simplified elastoplastic analysis), Russian rules seem globally more conservative in the non-significant creep regime. The main difference is found in creep-fatigue analysis criteria: while the Code requires separate evaluations for fatigue (though considering a creep strain amplification) and creep damages, for a final envelope assessment through a creep-fatigue interaction diagram, in the Norms long-term effects are basically taken into account by modified fatigue curves or equations. In some cases, as in the benchmark application, the Russian approach could be non-conservative.

Future work on the presented subject should be focused on the following topics:

1) providing background information for a better understanding of Russian rules, with particular regard to prevention of ratcheting and its interaction with creep-fatigue;
2) extending the comparison to high pressure piping (as used in LWR power plants).

6. REFERENCES

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