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Temporal Evolution of the Steel Pipes Quality Requirements for the Natural Gas Transmission Pipelines

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Abstract

In this paper there is outlined the analysis performed by the authors regarding the temporal evolution of the steel pipes quality requirements for the natural gas transmission pipelines. It shows the history of the implementation of prescriptions regarding the chemical composition and the tensile mechanical characteristics, focusing mainly on the implementation of requirements regarding the toughness in the standards that refer to the pipe quality, but also on the qualitative evolution of these prescriptions, consisting in passing from the toughness checkings based on the impact energy (determined by the notched-bar impact test), to checkings based on the percet shear area (having a fibrous appearance) on the impact fracture surface (determined by the drop-weight tear test – DWTT) and to the checkings based on the crack tip opening displacement (determined by fracture mechanics tests).

Key words: *transmission pipeline, steel pipes, chemical composition, strength and toughness requirements*

Introduction

According to the definition, pipelines are assemblies of components (pipes, fittings, valves, flanges etc.) which separate from the environment a closed and sealed tubular space used mainly to convey a fluid. Thus, any pipeline is operated fully safely as far as it keeps its attributes as closed and sealed tubular space stated in the definition and it can become the location of undesired events (technical accidents) if it loses these attributes and if a part of the conveyed fluid leaks in the environment; obviously the risk associated to the operation of a pipeline, defined by the probability and the consequences of technical accidents, is directly connected to the characteristics used for describe the conveyed fluid as a dangerous substance.

In case of natural gas transmission pipelines – NGTP, the injuriousness of the conveyed fluid identifies with the injurious character of the methane, main component of natural gas; consequently, natural gas is a substance characterized by the following: a) it pollute the air; b) it is non toxic, but it has asphyxiant potential; c) it is extremely flamable (+F) and has explosive potential (in combination with oxygen or air). [1] presents the event tree by means of which one can assess the technical risk associated to the NGTP operation.

The previously shown issues suggest that the steel pipes quality requirements for the natural gas transmission pipelines (NGTP) have been continuously formulated and developped (by applying the principle of continual improvement of the quality) by designers, constructors and operators, being perceived as new challanges by the pipe producers; the temporal evolution of these requirements was determined and influenced by: a) the requirements (within legislative and normative documentations) regarding the increase of the operating safety and the diminution of the risk associated to the use of NGTP; b) the technical progress in steel making and pipe manufacturing and in the performing of welded joints (necessary for manufacturing pipes and for pipelines construction); c) requirements regarding the reducing of the costs associated to the construction / installation, operating and maintenance of NGTP. In table 1 there is synthetized the available information regarding the normative documents referring to the quality characteristics of NGTP and of steel pipes necessary for construct these pipelines; this information has to be considered together with the following completions: a) actual edition of ISO 3183 canceled and replaced ISO 3183-1:1996, ISO 3183-2:1996 and ISO 3183-3:1999; b) EN 14161: 2011 is identical with ISO 13623:2009 modified; c) BS PD 8010-1 has a supplement: PD 8010-3:2009 – Code of practice for pipelines. Steel pipelines on land. Guide to the application of pipeline risk assessment to proposed developments in the vicinity of major accident hazard pipelines containing flammables; d) for BS 6990, the first edition is DD 39, July 1974 and the first published as BS 6990 is February 1989 [2, 3].

This paper intends to offer an image of the temporal evolution of the prescriptions regarding the chemical composition and the strength and toughness properties of steel pipes for natural gas transmission pipelines.

Strength and Chemical Composition of NGTP Pipes

The technical conditions (operating pressures, temperature rates, chemical characteristics of conveyed gases) and the safety requirements imposed to NGTP led to the decision of construction these pipelines by using steel pipes with assured strength properties.

Consequently, the pipes for NGTP were and still are made of steel grades defined according to the assured degree of mechanical strength. The strength degrees of the pipes for NGTP have always been described and coded by the specified minimum value of the yield strength $R_{t0.5}$ of the steel they are made of, defined as the mechanical stress for which the total strain registered during the tensile test reaches the value ε_t = 0.5 %). The information in Figure 1 and in tables 2 and 3 illustrates the temporal evolution of the strength degrees of steel pipes used for construction NGTP belonging to the Romanian natural gas transport (NTS) and to other pipeline systems of this kind worldwide. It has to be specified that before 1989 the NGTP belonging to the SNT were mainly made of pipes of Romanian steel grades: a) seamless pipes (having the quality characteristics imposed by STAS 404/2; STAS 530/1,2; STAS 715/2), made of the steel grades OLT 35 or OLT 45, and of Grade A25, Grade A or Grade B steels, regulated by STAS 8183; b) longitudinally welded pipes (having the quality characteristics imposed by STAS 7657) or helically welded pipes (having the quality characteristics imposed by STAS 6898/1,2 and by STAS 11082) made of rolled tapes of OL 32.2k steel (equivalent to Grade A steel), of OL 37.2k,kf steel (equivalent to Grade B steel), of OL 44.2k,kf and 15Mn11 steels (equivalent to the X42 steel), and of the OL52.2k,kf steel (equivalent to X52), all theses kinds of steel having the quality regulated by STAS 500. The pipes (with smooth ends) for the NGTP could be ordered in the category M (by maintaining the mechanical properties) or in the category CMH (by maintaining the chemical composition, the mechanical properties and the strength at hydrostatic pressure test); besides, for (longitudinally or helically) welded pipes one could choose the category S (pipes having the quality factor of welded joints φ = 1) or the category O (welded pipes with φ = 0.9) [3,4].

Table 1. Main normative documents regarding NGTP and pipes these lines are made of

Normative document	Document title	Actual edition	Year of the actual edition	Year of the first edition
ASME B31-8	*Gas Transmission and Distribution Piping Systems*	-	2010	1952
CSA Z662	*Oil and Gas Pipeline Systems*	6th	2011	1994
IGEM/TD/1	*Steel Pipelines and Associated Installations for High Pressure Gas Transmission*	5th	2008	1965
49CFR192	*Safety requirements for pipeline transportation of natural gas*	-	2012	1952
ISO 15649	*Petroleum and natural gas industries – Piping*	1st	2001	2001
EN 1594	*Pipelines for Maximum Operating Pressure over 16 bar – Functional Requirements*	2nd	2013	2009
EN 12732	*Welding Steel Pipework – Functional Requirements*	-	2013	2000
EN 14161	*Pipeline Transportation Systems*	-	2011	2003
ASME B31-8S	*Managing System Integrity of Gas Pipelines*	-	2012	2004
API 570	*Piping Inspection Code Inspection, Repair, Alteration, and Rerating of In-service Piping Systems*	2nd	1998/2003	1993
EN ISO 16708	*Pipeline Transportation Systems – Reliability-based Limit State Methods*	1st	2006	2006
CEN/TS 15174	*Guideline for Safety Management Systems for Natural Gas Transmission Pipelines*	1st	2006	2006
ASME B31G	*Manual for Determining the Remaining Strength of Corroded Pipelines*	-	2012	1984
API 579-1 ASME FFS-1	*Fitness-For-Service*	3rd	2013	2000
BS 7910	*Guide to methods for assessing the acceptability of flaws in metallic structures*	3rd	2013	1999
ISO/TS 12747	*Pipeline transportation systems. Recommended practice for pipeline life extension*	1st	2011	2011
API Spec 5L	*Specification for Line Pipe*	45th	2010	1924 (!?)
ISO 3183	*Steel Pipe for Pipeline Transportation Systems*	3th	2010	1996/1999
EN 10208-2	*Steel Pipes for Pipelines for Combustible Fluids. Technical delivery conditions. Part 2: Pipes of Requirement class B*	3th	2009	1998
API Std 1104	*Welding of Pipelines and Related Facilities*	20th	2013	1984
EN ISO 15607	*Specification and Qualification of Welding Procedures for Metalic Materials – General Rules*	2nd	2005	2003
EN 1011-2	*Recommendations for Welding of Metallic Materials – Part 2: Arc Welding of Ferritic Steels*	1st	2001	2001
BS 4515-1	*Specification for Welding of Steel Pipelines on Land and Offshore – Part 1: Carbon and Carbon Manganese Steel Pipelines*	-	2009	1995
BS 6990	*Code of Practice for Welding on Steel Pipes Containing Process Fluids or their Residuals*	1st	1989	1989
ISO/DIS 13847	*Pipeline Transportation Systems – Welding of Pipelines*	1st	2011	2011
ASME PCC-2	*Repair of Pressure Equipment and Piping*	1st	2011	2011

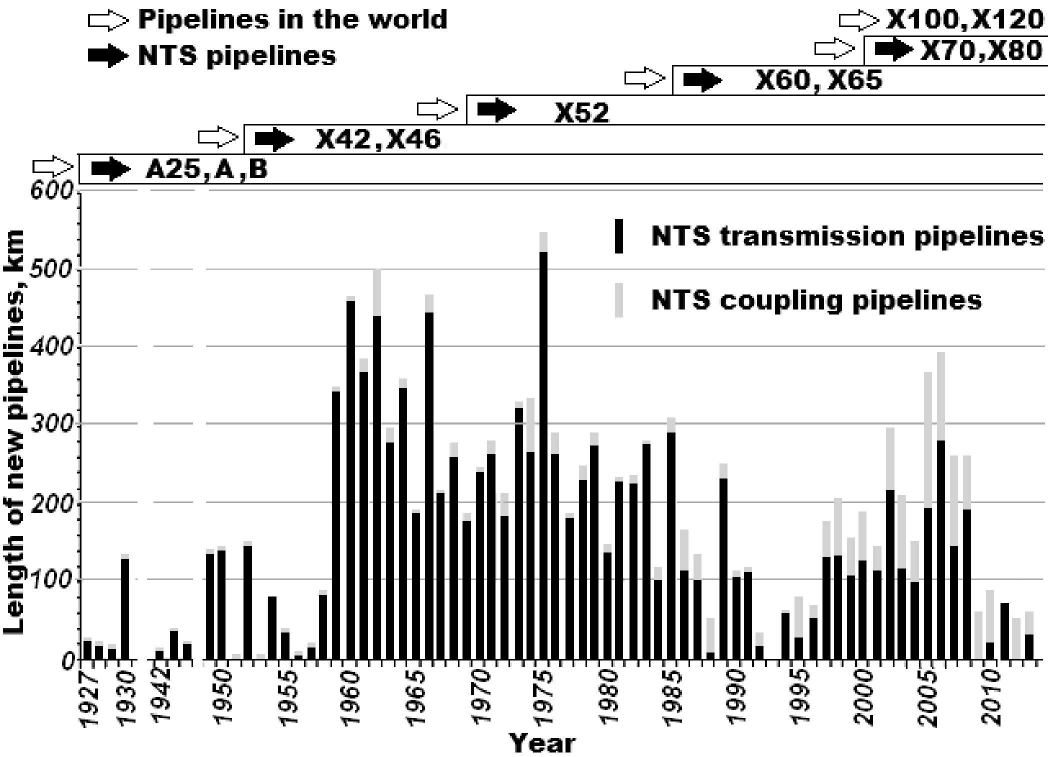

Fig. 1. Temporal evolution of the NGTP net belonging to the SNT and the strength degrees of steel pipes used for constraction these pipelines

In order to assure the specified strength propertiess for the pipes made of the steel grades presented in Table 2 there were used, over time, different combinations of the following technological solutions for steel-making, for half-finished materials (such as blanks and slabs) and for pipe manufacturing: a) the convenient choosing of the carbon concentration %C in order to assure a pearlitic-ferritic equilibrium structure, with the fraction of pearlite f_P (f_P = 1,33%C – 0,027) convenient for obtaining the specified value of the yield strength $R_{t0.5}$; b) the limiting of the carbon concentration in order not to compromise the weldability and the compensation of this limitation by an adequate increase of the manganese concentration; c) the drastic diminutipon of the concentration of impurities (S and P) and the microalloying with elements (Ti, Zr, Ce etc.) in order to modify the type, the form, the dimensions and the dispersion degree of non metallic inclusions (mainly sulphides); currently the steels for pipes are made only by means of basic procedures, in basic oxygen converters or in electric arc furnaces and are subjected to advanced purification technologies (%S ≤ 0.005 % and %P ≤ 0.020 %), and for the making of primary / starting semiproducts (such as round billets and piercing or hollow shells used for seamless pipes or slabs and blooms used for hot rolled tapes or coils necessary for longitudinally or helically / spiral welded pipes) there is used the continuous casting (instead of the ingot casting); d) the advanced finishing of the grains by using the microalloying (with Nb, Mo, V, N, Al, Ti etc.) and/or by using the controlled / thermomechanical rolling M (rolling with high degrees of deformation, where the operating temperatures, the heating and cooling rates, the deformation degrees and rates for each passing are strictly controlled), that can assure the obtaining of some rolled tapes (for longitudinally or helically welded pipes) with nanometric grains (20...100 nm); e) the obtaining of some complex microstructures by using the thermomechanical rolling, which assures structures with acicular ferrite (low carbon bainite) and hardening submicroscopic precipitates (carbides, nitrides or carbonitrides of the alloying elements) and/or by completing the rolling process with a heat treatment of quenching and tempering – Q, with an accelerated cooling – ACC or a direct intensive cooling – DIC; these solutions are used instead of the classical rolling (normalizing rolling or rolling followed by normalization N) [5].

Table 2. Tensile properties of steel pipes for the NGTP (API Spec 5L / ISO 3183)

Grade of steel pipe [a]	Tensile requirements [b,c]				Notes
	$R_{t0.5}$, N/mm^2		R_m, N/mm^2		
	min.	max.	min.	max.	
A25 (A25R,N)	**175**	-	**310**	-	Currently not used anymore for the NGTP of the NTS
A (AR,N)	**210**	-	**330**	-	
L245R,N,Q,M sau BR,N,Q,M	**245**	450 [d]	**415**	760	Used for the NGTP of the NTS in the R or N state
L290R,N,Q,M sau X42 R,N,Q,M	**290**	495	**415**	760	
L360N,Q,M sau X52 N,Q,M	**360**	530	**460**	760	Used for the NGTP of the NTS especially in the N state Currently used for the NGTP of the NTS also in the M state
L415N,Q,M sau X60 N,Q,M	**415**	565	**520**	760	
L450Q,M sau X65Q,M	**450**	600	**535**	760	
L485Q,M sau X70Q,M	**485**	635	**570**	760	
L555Q,M sau X80Q,M	**555**	705	**625**	825	
L625M sau X90M	**625**	775	**695**	915	Were not used and are not recommended for the NGTP of the NTS
L690M sau X100M	**690**	840	**760**	990	
L830M sau X120M	**830**	1050	**915**	1145	

a) R – classic rolling; N – rolling or normalizing forming or rolling + heat treatment of normalization or of normalization + tempering; Q – rolling + final heat treatment quenching and tempering; M – rolling or thermomechanical forming; b) For pipes having D_e > 323.9 mm the maximum value of the ratio $d_t = R_{t0.5}/R_m$ has to be d_t = 0.93 for L245...L555; d_t = 0.95 for L625; d_t = 0.97 for L690 and d_t = 0.99 for L830; c) the minimum specified elongation A_f, measured at a distance between the tensile specimen marks of 50.80 mm (2 in), is determined by rounding off to the closest whole value the value obtained by using the relation: $A_f = 1940S^{0.2}/R_m^{0.9}$, $S = \min(S_0;\ 485\ \text{mm}^2)$, where S_0 is the area of the cross section of the gauged section of the tensile tested specimen, in mm^2, and R_m – the minimum specified tensile strength, in N/mm^2, of the steel the analyzed pipe is made of; d) For the pipes having D_e < 219.1 mm, $R_{t0.5}$ max is 495 N/mm^2;

The way the previously specified technological solutions contributed to the development of the production of steel semiproducts necessary for making pipes used in construction NGTP is illustrated suggestively in Figure 2 and the modifications over time of the prescriptions regarding the chemical composition and the tensile properties of the steels for such pipes are suggested by the information in Table 3.

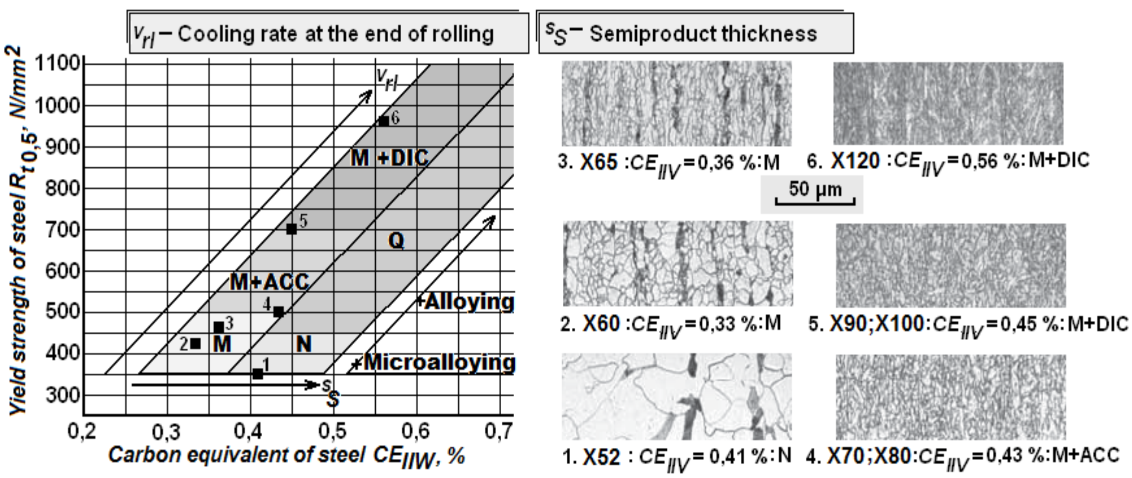

Fig. 2. Effects of the technological solutions used in order to increase the performance of pipes the NGTP are made of

Table 3. Temporal modification of the prescriptions regarding the properties of steel pipes for the NGTP

Type of steel pipe[a]	Chemical composition, %					Tensile and ductility requirements[b]			CE_{IIW} max %
	C[c]	Mn	P	S	Alloying	$R_{t0.5}$ min/max N/mm²	R_m min/max N/mm²	d_t max	
API 5LX and API 5LS Edition !? (1970) – API Spec 5L Edition 36 (1987)[e]									
B/S-W/-	0.27	1.15	0.04	0.05	-	241/-	413/-	0,85	-
X52/S/L	0.31	1.35	0.04	0.05	-	358/-	455/-	0,85	-
X52/S/E	0.29	1.25							
X52/W/L	0.30	1.35							
X52/WL/E	0.28	1.25							
X60/S-W/L-E	0.26	1.35	0.04	0.05	*d*	413/-	517/-	0,85	-
API Spec 5L Edition 40 (1992)[i]									
B/S/L-E	0.27	1.15	0.03	0.03	*f*	241/-	413/-	-	-
B/W/L-E	0.26	1.15							
X52/S/L	0.31	1.35	0.03	0.03	*g*	358/-	455/-	-	-
X52/S/E	0.29	1.25							
X52/W/L	0.30	1.35							
X52/WL/E	0.28	1.25							
X60/S-W/L-E	0.26	1.35	0.03	0.03	*h*	413/-	517/-	-	-
X80/S-W/L-E	*j*					551/-	620/827	-	-
X80/S-W/L-E	0.18	1.80	0.03	0.018	*h*				
EN 10208-2:2009[i]									
B/S-W/N	0.16	1.10	0.025	0.020	*k*	245/440	415/-	0.80	0.42
B/W/Q	0.16	1.50			*k,l*			0.85	0.40
X52/W-S/N	0.20	1.60	0.025	0.020	*f,k*	360/510	460/-	0.85	0.45
X52/S/Q	0.16	1.40						0.88	0.42
X52/W/M	0.16	1.60						0.85	0.41
X60/S-W/N	0.20	1.60	0.025	0.020	*f,k*	415/565	520/-	0.85	*m*
X60/S/Q	0.16	1.60						0.88	0.43
X60W/M	0.16	1.60						0.85	0.42
X80/S/Q or W/M	0.16	1.80	0.025	0.020	*f,k,n*	555/675	625/-	0.90	*m*
API Spec 5L Edition 44 (2007) / ISO 3183:2007[p,q]									
B/S-W/R-N	0.24	1.20	0.025	0.015	*f,k,n*	245/450	415/760	0.93	0.43
B/S-W/Q	0.18	1.40							0.43
B/W/M	0.22	1.20							0.43
X52/S-W/N	0.24	1.40	0.025	0.015	*f,k,n*	360/530	460/760	0.93	0.43
X52/S-W/Q	0.18	1.50							0.43
X52/W/M	0.22	1.40							0.43
X60/S-W/N	0.24	1.40	0.025	0.015	*f,k,n*	415/565	520/760	0.93	0.43
X60/S-W/Q	0.18	1.70							0.43
X60/W/M	0.12	1.60							0.43
X80/S-W/Q	0.18	1.90	0.025	0.015	*f,k,n*	555/705	625/825	0.93	0.43
X80/W/M	0.12	1.85							0.43

a) S – seamles pipe; WL – welded pipe (longitudinal seam); WH – welded pipe (helical seam); W – welded pipe (longitudinal or helical seam); S-W – seamless or welded pipe; L – nonexpanded pipe; E – cold expanded pipe; L-E – nonexpanded or cold expanded pipe; R; N; Q; M – see table 2; b) for elongation requirements – see table 2; ductility $d_t = R_{t0.5}/ R_m$; c) for grades X42 through X65, for each reduction of 0,01 % below the specified max. %C, an increase of 0.05% above the specified max. Mn content is permissible, up to a max. of 1.45% for X52 and lower and up to a max. 1.60...2.0 % for grades higher than X52; d) microalloying: max 0.05% Nb; max 0.02% V and max 0.03% Ti; e) API Spec 5L Edition 36 contain steel pipes Grade A25 through X65; f) Nb, V, Ti or combinations thereof, may be used by agreement between purchaser and manufacturer; g) Nb, V, Ti or combinations thereof, may be used at the discretion of the manufacturer; h) other chemical composition may be furnished by agreement between purchaser and manufacturer; i) this document contains steel pipes Grade A25 through X80; j) chemical composition by agreement between purchaser and manufacturer; k) $0{,}015\% \le Al_{tot} < 0{,}060\%$; $N \le 0{,}012\%$; $Al/N \ge 2/1$; $\%Cu \le 0.25\%$; $\%Ni \le 0.30\%$; $\%Cr \le 0.30\%$ and $\%Mo \le 0.10\%$; l) microalloying: max 0.04% Nb; max 0.04% V; m) by agreement; n) $V + Nb + Ti \le 0.15\%$; $Mo \le 0.35\%$; p) see table 2; q) if $C > 0{,}12\%$, the weldability criteria is $CE_{IIW} \le 0.43\%$; if $C \le 0.12\%$, the weldability criteria is $CE_{Pcm} \le 0.25\%$.

Ductility, Toughness and Weldability of Pipes for the NGTP

The requirements regarding the safe operation and the diminution of the gravity as a consequence of possible technical accidents on NGTP led to the necessity of implementing for steel pipes designed for this type of lines of some adequate conditions regarding the ductility and the toughness, so that they have a ductile behaviour at the minimum operating temperatures of the NGTP (in other words a brittle fracture during operation to be actually impossible) and to have a good strength while ductile fracture propagates (to have a good capacity to inhibit / arrest cracks).

The conditions regarding the ductility imposed to steel pipes for the NGTP were initially expressed in form of some specified minimum values for the elongation A_f (determined by means of the relation specified in the foot-note c) in Table 2) and recently completed (see the information in Table 3) by the stipulation of some specified maximum values for the ratio $d_t = R_{t0.5}/R_m$.

The conditions regarding the toughness imposed (beginning with the sixties) to steel pipes the NGTP are made of were initially taken from the field of metallic constructions [3] and were adjusted by taking into consideration the loading particularities and the operating conditions of the NGTP. These conditions were and are still formulated by using the following general terms: a) the toughness is tested by the notched-bar impact test, on transversal T (oriented on the direction of the circumference of the pipe they are taken from) specimens (of normal or reduced sizes), with a V notch, made on the normal direction on the pipe wall; b) the impact test is performed at a temperature t_t specified in the NGTP design documentation; c) the pipe toughness is considered adequate if the impact energy absorbed KV, determined as the average of the impact test results (at the temperature t_t) of three normal specimens ($KV = \frac{1}{3}\sum_{i=1}^{3} KV_i$), complies with the condition $KV \geq CV$, where CV is the specified minimum value of the energy absorbed, the fulfillment of this condition is validated only if each of the values KV_i, $i = 1...3$, by means of which the average energy KV was calculated fulfills the condition $KV_i \geq f_s CV$, where f_s has a prescribed value $f_s < 1$.

Over time the conditions (previously mentioned) regarding the pipe toughness for the NGTP knew different customizations: a) at the beginning (the sixties) it was recommended to choose a test temperature $t_t \leq 20^oC$, then (see API Spec 5L:1992 and the following editions) this recommendation was modified to $t_t \leq 10^oC$, and recently (see API Spec 5L / ISO 3183:2007) the recommendation was $t_t \leq 0^oC$; b) before the seventies, the toughness condition of pipes was formulated considering $CV = 27$ J and $f_s = 0,75$ (respectively $f_s CV = 21$ J), and with the diversification of pipes for the NGTP and the manufacturing of pipes with degrees of strength superior to the X60 grade, it was recommended to determine the minimum toughness value CV according to the characteristic dimensions of pipes (the outer diameter D_e and the wall thickness s_n), to the level of hoop stresses σ_θ, generated in the pipe wall by the action of the pressure of the conveyed gas and the grade of the steel the pipes are made of; currently (see API Spec 5L / ISO 3183:2007 and the next edition), CV is defined by a condition of the form: $CV = \max[CV_f; CV_0]$, using the data in table 4.

API Spec 5L / ISO 3183 also recommends the substantiation of the minimum CV level imposed to NGTP pipes toughness by applying the Battelle two curve method. When elaborating this method they started from the idea that because the gases conveyed through the NGTP are compressible, the failure, accidentally initiated on the pipeline and which causes its loss of tightness, propagates as long as it is maintained by the energy released during the transitory process of gas pressure drop; in other words, the length of the propagation of ductile fracture initiated on a NGTP is longer or shorter, depending on the toughness of the material (steel) the pipes are made of, which determine the level of the energy necessary for the extension of the failure. The method consists of representing on the same flow chart, as it can be seen in Figure 4, of a crack velocity curve – *CVC*, relationship between the pressure at crack tip p_c and the crack velocity v_c, $v_c = f(p_c)$ and a gas decompression curve – *GDC*, relationship between the pressure p_d and the gas decompression velocity v_d, $v_d = g(p_d)$, defined analytically by the following formulae:

$$v_c = C\frac{R_{t0,5}}{\sqrt{KV}}\left[\frac{p_c}{p_a}-1\right]^{\alpha}; \quad v_d = v_{sg}\frac{\gamma_g+1}{\gamma_g-1}\left[\left(\frac{p_d}{p_o}\right)^{\frac{\gamma_g-1}{2\gamma_g}}-\frac{2}{\gamma_g+1}\right], \tag{1}$$

where C is a constant depending on the presence and type of backfill, α = 1/6, if the steel pipeline toughness is expressed by the level of absorbed energy at Charpy impact test KV, v_{sg} – sound speed in transported gas, γ_g – specific gas heat ratio, p_o – maximum operating pressure and p_a the pressure which generates a hoop stress with σ_{ha}, the maximum hoop stress intensity for which the prevention of a fracture growth takes place [6]. If no intersection exists between the *CVC* and *GDC* curves, gas decompression velocity exceeds crack velocity for all pressure levels, the pressure at the crack front will decrease and the crack will arrest; on the other hand, if an intersection exists between the two curves, the pressure level where crack and gas decompression run together at the same velocity exist, no further decrease of the pressure at the crack tip is possible and the crack will continue to propagate. Thus, the tangent condition between the two curves represents the boundary between arrest and propagation and the corresponding toughness level *CV* is referred to as the arrest toughness by BTCM (see fig.3) [6].

Table 4. Data necessary for determining the minimum values of toughness *CV* * for the NGTP pipes

Formula for CV_f **	CV_0, J	Validity criteria of formula	
		D_e, mm	Steel pipe
$CV_f = 2{,}67\cdot10^{-4}\sigma_\theta\sqrt{D_e\sigma_\theta}$	27	$D_e \le 762$	L245...L450
	40	$762 < D_e \le 1219$	L245...L450
	40	$1219 < D_e \le 1422$	L245...L415
	54	$1219 < D_e \le 1422$	L450
$CV_f = 3{,}21\cdot10^{-4}\sigma_\theta\sqrt{D_e\sigma_\theta}$	27	$D_e \le 762$	L485
	40	$762 < D_e \le 1219$	L485
	54	$1219 < D_e \le 1422$	L485
$CV_f = 2{,}83\cdot10^{-5}\sigma_\theta^2\sqrt[3]{D_e s_n}$	40	$D_e \le 1219$	L555
	54	$1219 < D_e \le 1422$	L555

* the data are valid for NGTP with the design / operating pressure $p_o \le 8{,}0$ MPa, made of pipes having the wall thickness $s_n \le 25$ mm; ** *CV* results in J, if D_e and s_n are introduced in mm, and σ_θ in N/mm^2.

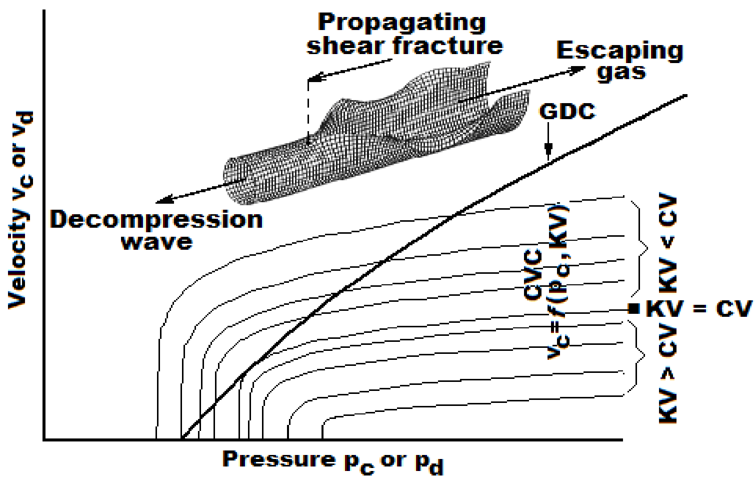

Fig. 3. Way of determining the *CV* toughness by using BTCM

The conditions regarding the toughness based on the level of the absorbed energy *KV* were completed over time with additional conditions regarding the percentage rate F_{sa} of the areas having a fibrous appearance (shear fracture areas) on the fracture surface of the specimens subjected to impact bending testing; these conditions were formulated as follows: a) F_{sa} is expressed as arithmetical mean of the rate of the areas with sfear appearance ($F_{sa,i}$, i = 1…3) on the fracture surfaces of the three specimens subjected to the testing at t_t ($F_{sa} = \frac{1}{3}\sum_{i=1}^{3} F_{sa,i}$); b) the toughness of a pipe is considered to be adequate if the condition $F_{sa} \geq F_T$ is fulfilled, where F_T is the specified minimum value for F_{sa}; beginning with the 1987 edition of API Spec 5L, it was introduced the toughness condition previously mentioned, with F_T = 60 %, and in API Spec 5L / ISO 3183:2007, the condition was modified, the specified minimum level of toughness was F_T = 85 %.

With the increase in diameter and strength characteristics of NGTP steel pipes, the toughness conditions based on the level of the absorbed energy *KV* (determined by using the impact test) were completed with additional conditions based on the results of other toughness tests. So,: a) API Spec 5L:1992 (and the following editions) stipulated the testing of the pipe toughness, where the pipes had the $D_e \geq 508$ mm (20 in), and were made of X80 steel also on the basis of the results of the Drop Weight Tear Test – DWTT, and the condition that has to be fulfilled in order to estimate whether the toughness of pipes is satisfactory was: at t_t = 0 °C, $F_{saDWT} = (F_{saDWT,1} + F_{saDWT,2} + F_{saDWT,3})/3 \geq F_{TDWT}$ = 60 %, and $F_{saDWT,i} \geq 40$ %, i = 1…3, F_{saDWT}, $F_{saDWT,i}$, i = 1…3 and F_{TDWT}, having similar significations F_{sa}, $F_{sa,I}$ and F_T; b) API Spec 5L:2004 (and recent editions) stipulate the DWTT testing in order to determine the toughness of pipes having $D_e \geq 508$ mm (20 in), made of X52 steels or with higher strength, and the basic condition for determining whether the toughness of pipes is satisfactory is: at t_t = 0°C, $F_{saDWT} \geq F_{TDWT}$ = 85 %, where F_{saDWT} is determined as an average of the DWTT results for two specimens.

Because NGTP are welded constructions, built by butt seam welding of pipes (welded or seamless) and other components (bends, elbows, tees, reductions etc.), the development of welded pipe production for these pipelines, as well as the construction of pipelines imposed the adequate solving of the following problems: a) assurance of the weldability of steels used in making pipes (and other components) for the NGTP; b) assurance of the strength, ductility and toughness of welded joints (necessary for manufacturing NGTP pipes and components and/or for the connection of pipes and components for building NGTP). In order to assure the weldability all steels used in making the pipes for NGTP must have the carbon concentration limited and as low as possible level of equivalent carbon *CE*, determined by the formula:

$$CE_{IIW} = \%C + \frac{\%Mn}{6} + \frac{\%Cr + \%Mo + \%V}{5} + \frac{\%Ni + \%Cu}{15}, \quad (2)$$

recommended if the concentration of the carbon is %C > 0,12 %, or by the formula :

$$CE_{Pcm} = \%C + \frac{\%Mn}{20} + \frac{\%Si}{30} + \frac{\%Cr + \%Cu}{20} + \frac{\%Ni}{60} + \frac{\%Mo}{15} + \frac{\%V}{10} + 5\%B, \quad (3)$$

recommended if %$C \leq 0,12$ %. The pipes for the NGTP have an appropriate weldability and metallurgical behaviour while welding, if the *CE* values are at most equal to those specified in table 3; yet, the weldability is also influenced by the used welding procedure and by the quality of the filler materials used while welding.

The main technological problem while fuse welding steel pipes with moderate strength (X60 or lower), obtained by classical rolling procedures (variants R, N – see table 2) and which, as previously mentioned, were the first used for construction NGTP consists of obtaining in the heat affected zone – HAZ of welded joints of some higher hardness values than those corresponding to the base material (of the pipes that are being welded) – BM and to the welds – WLD. In order to solve this problem it is necessary to check the welding technologies (regimes) to see how well these correlate with the behaviour while welding BM and with the quality requirements imposed to welded joints. The main criterion for validating the welding technologies is to assure in the welded joints some structures of high toughness which prevent the occurance of enbrittlement phenomena and/or cold / hydrogen cracking, and for the qualification of the welding procedures the condition $HV_{\max} \leq HM$ has to be fulfilled, where HM is the maximum hardness in the HAZ for which the cold cracking risk is insignificant, determined according to the diffusable hydrogen content H_D of the filler materials FM used for welding, as it can be seen in table 5; the technological measures that assure the fulfillment of the condition are: a) adequate choosing of FM filler materials used for welding (see table 5); b) making up of the WDS from an appropriate number of weld runs and layers c) assurance of some high enough heat input levels while welding *EL*; d) preheat welding at moderate temperatures t_{pr} (t_{pr} = 80...150 ^{0}C), correlated with *HL* of FM used for welding (t_{pr} determined by applying the procedures recommended by EN ISO 15607 and EN 1011-2). It has to be mentioned that EN 1011-2 recommends the condition $HV_{\max} \leq HM$ to be supplemented with a condition regarding the HAZ toughness: a) formulated similarly as for BM ($KV \geq CV$), considering that the testing of the HAZ toughness is performed by using the impact test (at the same temperature t_t as for BM); b) formulated on the basis of a fracture mechanics concept; one can use, for instance, the condition $CTOD \geq \delta_{CT}$, where $CTOD$ is the crack tip opening displacement (considering a crack existing in the HAZ), determined by using the test described by ASME E 1290 and ASME E 1820, and δ_{CT} is the specified minimum value for $CTOD$ (API Std 1104 suggests, for instance, for the NGTP pipes and welded joints, δ_{CT} = 0.12…0.25 mm) [5].

The weldability of pipes made of steels characterized by a high strength (X60…X120), obtained by modern rolling procedures previously mentioned (thermomechanical rolling M, completed with Q, ACC or DIC) is good, due to the reduced concentration of carbon and to the very low levels of the concentration of impurities (S and P). When manufacturing welded pipes or when constructing NGTP with pipes made of these kinds of steel (by using fusion welding processes), the following problems occur: a) to assure in the WLD strength characteristics similar to those of the BM it is necessary to use FM with carbon concentrations higher than those corresponding to BM (because WLD cannot be subjected after welding to a thermomechanical treatment similar to that experienced by the BM), in combination with the increase of the Mn concentration to 1.4...1.5 %, alloying with 0.2...0.5 % Mo, Cr (max. 0.2 %), Ni (max. 1 %) and, eventually, other elements which assure WLD wirth fine grains and high strength; b) in the HAZ of welded joints there is formed a deconsolidation band, where the hardness values obtained are lower than those assured in the WLD and the BM (because BM is reheated and coalescence phenomena occur together with an increase of the dimensions of precipitates in the acicular ferrite microstructure, process which diminishes the hardening effect of the presence of precipitates); this problem can be solved as followed (experimentally validated solution): the deconsolidation area in the HAZ can be accepted (it doesn't prejudice the behavior when subjected to mechanical loads of the welded joints, assuring a unitary ratio between the strength of the BM and the strength of welded joints), if the ratio k_D between its width l_D and the thickness s of the components that are welded is kept under 0.22 ($k_D = l_D/s \leq 0.22$), condition fulfilled if the welding is performed with reduced heat input (WLD is formed from a big number of filliform layers and raws) and without preheating or with preheating at t_{pr} = 30…60 ^{o}C [5].

Table 5. Correlations between *HL* and *HM* while performing joint welding on pipes and NGTP made of steels with moderate strength (X52 or lower)

Hydrogen scale – HS	Hidrogen level – HL	Diffusable hydrogen content H_D, ml H/100 g of deposited metal	Maximum allowable hardness in HAZ of welded joints, *HM*
A	High – **H**	$15 < H_D$	**350 HV**
B	Medium – **M**	$10 < H_D \leq 15$	375 HV
C	Low – **L**	$5 < H_D \leq 10$	400 HV
D	Very Low – **VL**	$3 < H_D \leq 5$	425 HV
E	Very Very Low – **VVL**	$H_D \leq 3$	450 HV

The technological problems (previously described) that have to be solved in order to perform the welding operations when manufacturing welded pipes or when building NGTP are shown comparatively in Figure 4.

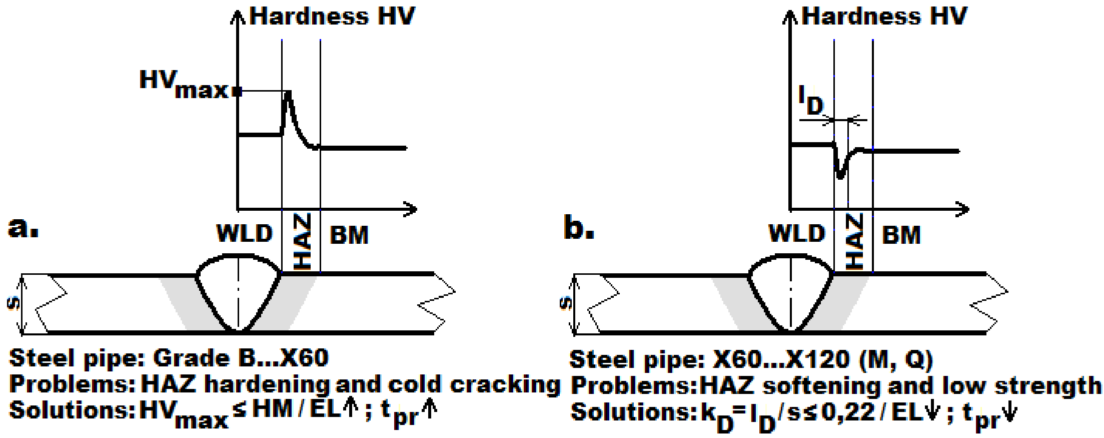

Fig. 4. Schematic outline of the technological problems that occur during welding operations when manufacturing welded pipes and/or when constructing NGTP

The prescriptions regarding the strength, the ductility and the toughness of welded joints of the NGTP have been simply formulated: mechanical strength, ductility and toughness of welded joints must be at least equal to those of the BM (the components connected by welding are made of). Consequently, most of the tests by means of which the mechanical stength, the ductility and the toughness of welded joints of NGTP are assessed, which are performed when qualifying the welding procedures, are completed by qualitative estimations. The following are performed: a) the tensile test (for determining the strength of welded joints, that has to be at least equal to the specified minimum value for R_m of BM, but, as it is also stipulated in API Spec 5L:1992 and in all the following editions, also in the last editions of API Std 1104, without determining the yield strength and the elongation); b) the flattening test, for evaluating the ductility of welded pipes (stipulated in API Spec 5L:1992 and in all the following editions); c) the bend test and/or the guided bend test (stipulated in API Spec 5L:1992 and in all the following editions, and also in the last editions of API Std 1104, for assessing the ductility of welded joints of pipes or of NGTP pipes; d) the impact test or the fracture mechanics tests, when it is demanded by the pipeline design or by the procedure for the qualification of welding technologies (not stipulated in API Spec 5L nor in API Std 1104) [5-7].

Conclusions

The issues discussed within this paper led to the following conclusions regarding the temporal evolution of the steel pipes quality requirements for the natural gas transmission pipelines:

- The existing concern, beginning with the twenties of the previous century, in the development of natural gas transmission pipelines, together with the continuous technical progress in steel-making and pipe manufacturing for pipelines and the performing of welded joints (necessary in manufacturing pipes and construction pipelines), led to the drawing up of normative documents (standards, norms, technical prescriptions etc.) that regulate now the quality of steel pipes for NGTP.
- The system of criteria for assessing the quality of pipes for NGTP has been continuously developped over time and has now a coherent and complex form, including both criteria referring to the assurance of the strength, and criteria regarding the assurance of ductility, toughness and weldability; the use of this system of criteria in designing, construction, testing, operating and maintainance NGTP determined an increase of the operating safety and a diminution of the risk associated to the use of NGTP.

- The contemporary NGTP designers and constructors have the possibility to choose two types of solutions regarding the selection of steel pipes: a) pipes with moderate strength (up to X52 or X60), for which the manufacturing and welding technologies are simple and cheap, but the use of which implies, for a given diameter and operating pressure of the NGTP, great wall thicknesses and dimensions and, consequently high costs for transportation and handling, low productivity when building NGTP etc.; b) pipes with high strength (from X60 up to X120), the use of which leads, for a given diameter and operating pressure of the NGTP, to small wall thicknesses and dimensions and, consequently, to low costs for transportation and handling, high productivity when building NGTP etc, but the manufacturing and welding technologies are complex and expensive. Under these circumstances the selection of pipes for NGTP has to be based on the economic criterion of minimum total costs for the acquisition of pipes and for the construction of NGTP; in some cases the use of high strength steels is not the most convenient solution.

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Evoluția temporală a cerințelor de calitate impuse țevilor din oțel pentru conductele de transport al gazelor naturale

Rezumat

Lucrarea prezintă analiza efectuată de autori privind evoluția de-a lungul timpului a condițiilor privind calitatea impuse țevilor din oțel destinate construirii conductelor aparținând sistemelor de transport al gazelor naturale. Se prezintă istoricul introducerii prescripțiilor privind compoziția chimică şi caracteristicile mecanice la tracțiune, insistându-se mai ales asupra introducerii cerințelor privind tenacitatea în standardele referitoare la calitatea țevilor pentru conducte, cât şi asupra evoluției calitativă a acestor prescripții, constând în trecerea de la verificările de tenacitate bazate pe energia de rupere (determinată prin încercarea la încovoiere prin şoc), la verificările bazate pe ponderea zonelor cu aspect fibros pe suprafețele de rupere prin şoc (determinate prin DWTT) şi la verificările bazate pe deplasarea de deschidere la vîrful fisurii (determinate prin încercări de mecanica ruperii).