

# Methods for Determining the Remaining Strength Factor of Pipelines with Volumetric Surface Defects

GHEORGHE ZECHERU<sup>1</sup>, PETRO YUKHYMETS<sup>2</sup>, GHEORGHE DRAGHICI<sup>1</sup>, ANDREI DUMITRESCU<sup>1\*</sup>

<sup>1</sup> Petroleum-Gas University of Ploiesti, 39 București Blvd., 100680, Ploiesti, Romania

<sup>2</sup> E.O.PATON Electric Welding Institute of the National Academy of Science of Ukraine, 15 Bogenko Str, 03150, Kiev, Ukraine

*Knowing the values of the Remaining Strength Factor – RSF constitutes a mostly useful tool for the application of the proactive maintenance principles and for programming the maintenance (repair) works for the liquid and gas transmission pipelines. This paper proposes and analyses the pertinent modalities for the definition and determination of RSF for the transmission pipelines whose steel pipes have volumetric surface defects, i.e. of the type local metal loss (locally thin areas, pittings, grooves or gauges-like flaws). The mechanical strength of the pipes, with and without flaws, of a pipeline (through which liquids or gases under pressure are flowing) is quantitatively expressed by: - the pressure value for which the pipeline reaches the serviceability limit state, named Maximum Allowable Operating Pressure – MAOP; - the pressure value for which the pipeline reaches an ultimate limit state (global yielding / plastic collapse, fracture following crack growth or failure / bursting of pipes). The equations presented in the paper for the determination of the pressure at which the pipelines (with and without flaws) reach the ultimate limit state have been analysed on the basis of the results of their application for the case of pipes (with and without flaws) that have been the object of some experimental programs, consisting of their internal pressure testing, up to bursting; the validation and qualification criterion for each equation has been constituted by the concordance between the bursting pressure values obtained by using the equation and those determined experimentally. The results available in literature regarding such experimental programs have been used, together with the results of an experimental program performed by the authors and presented thoroughly in the paper.*

*Keywords: Pipeline (with or without flaws), Serviceability / ultimate limit state, Maximum Allowable Operating Pressure (MAOP), Burst Pressure (BP), Remaining Strength Factor (RSF)*

The flaws of the type metal loss (Locally Thin Areas – LTA, Pittings – PIT, Grooves – GLF or Gauges – GAU), which consist of the general or local thinning of the steel pipes wall of the transmission lines, by means of material loss, due to corrosion and/or erosion processes, represent one of the most important failure causes of these pipelines during their operation [1-3].

If, at the periodic inspection of the technical condition of a pipeline, flaws of the type metal loss are detected on its steel pipes, it is needed to evaluate the remaining mechanical strength of the pipeline and to ascertain which one from the following decisions is pertinent: a) the qualification of the flaws as being imperfections and maintaining the pipeline in service, without performing maintenance works and without decreasing the operating pressure; b) the qualification of the flaws as being defects and the reduction of the pipeline operating pressure, until some corrective maintenance works are applied, with or without removing the pipeline from service, consisting of the consolidation (by applying patches, sleeves, composite materials wraps etc.) or the replacement of the pipes with flaws.

A simple and efficient modality to express the degree in which the flaws existing on the steel tubes of a transmission pipeline affect its loading capacity and the measure in which it is acceptable to operate a pipeline whose tubes contain flaws is represented by the Remaining Strength Factor (RSF), defined as the ratio between the value of a characteristic that expresses the mechanical strength (or the maximum allowable mechanical load) of the pipeline with flaws and the value of the same characteristic for the pipeline without flaws.

In the case of the onshore (buried) transmission pipelines, the main mechanical load is given by the internal pressure (of the transported fluid) and RSF is therefore correlated with the ratio of the pressures from the pipeline with and without flaws for which, in its steel pipes, the conditions of a serviceability limit state are attained. Because the serviceability limit state of a pipeline is the condition beyond which the pipeline does not meet its functional requirements, and in the design process it is required that stresses and strains generated in the steel tubes wall during pipeline operation should be of elastic nature only, RSF is correlated with the pressures at which it is reached the limit state characterized by the occurrence of plastic deformations in the most loaded areas of the pipeline, determined by the fact that the intensity of the stresses generated in these areas attains the level of the (effective) yield strength  $R_p$  of the steel from which the pipes are manufactured.

Nevertheless, when designing the pipelines, a serviceability limit state is (conservatively) considered; such condition is reached before the one previously defined: the state for which the stresses in the pipes walls attain the level corresponding to an allowable stress  $\sigma_a = F_d R_{pm}$ , where  $R_{pm} \leq R_p$  is the specified minimum yield strength of the steel from which the pipes are made, and  $F_d < 1$  is the design factor, defined as a function of the location class of the pipeline, the quality of the welded joints on the pipeline etc. As a result, the pipelines designed and constructed adequately have a loading capacity reserve which allows for the small flaws generated during their construction and operation to be able to be tolerated, that is to be qualified

\* email: andrei.upg@gmail.com; Tel. 0723 298 506

as imperfections, whose presence does not affect the operational safety and their functional characteristics, and one can define a (minimum) allowable level for  $RSF$ , with the symbol  $RSF_u$  ( $RSF_u = 0.8...0.9$  [2]). In these conditions, the Maximum Allowable Operating Pressure of a pipeline with flaws (damaged)  $MAOP_d$  can be determined using the formula:

$$MAOP_d = \min \left[ \frac{RSF}{RSF_u}; 1 \right] \cdot MAOP, \quad (1)$$

$MAOP$  being the Maximum Allowable Operating Pressure of the pipeline without flaws (new). The decisions that can be taken after the evaluation of the technical condition of a pipeline containing flaws are:

a) if  $RSF \geq RSF_u$ , the damaged pipeline may be placed back into and maintained in service without the modification of the operating regime for which it has been designed ( $MAOP_d = MAOP$ );

b) if  $RSF < RSF_u$ , the damaged pipeline must be subject to corrective maintenance (repairs), and until their application  $MAOP_d$  shall be decreased to the level determined by applying equation (1).

The criteria for decisions making that have been presented above are effectively applicable, because the standards, Codes and Norms referring to the structural integrity analysis of transmission pipelines specify the modalities of determining  $RSF$  taking into account the stress concentration or intensification effects determined by the configuration and the characteristic dimensions of the flaws detected on their steel pipes; usually, the characteristic dimensions of the metal loss flaws detected on the steel tubes (with the outside diameter  $D_e$  and the wall thickness  $t_t$ ) of the transmission pipelines are the ones indicated in figure 1: maximum depth  $d_p$ , length or longitudinal extent  $s_p$  and width or circumferential extent  $c_p$ , while the formula used to determine  $RSF$  is [1,2]:

$$RSF = \frac{1 - k_d d_{rp}}{1 - \frac{k_d d_{rp}}{M_d}}, \quad (2)$$

$k_d$  being a coefficient taking into account the configuration of the longitudinal profile of the flaw ( $k_d = 0.67...1$ ),  $d_{rp}$  - relative depth of the flaw  $d_{rp} = \frac{d_p}{t_t}$ , and  $M_d = f(s_{rp})$  - a factor depending on the relative length flaw  $s_{rp} = \frac{s_p}{\sqrt{D_e t_t}}$ , which is

commonly calculated with the recommended formula (together with  $k_d = 0.85$ ) in [1]:

$$M_d = \sqrt{a_0 + a_1 s_{rp}^2 + a_2 s_{rp}^4}, \text{ if } s_{rp} \leq 7 \text{ or} \\ M_d = b_0 + b_1 s_{rp}^2, \text{ if } s_{rp} > 7, \quad (3)$$

with  $a_0 = 1$ ;  $a_1 = 0.6275$ ;  $a_2 = -0.003375$ ;  $b_0 = 3.3$ ;  $b_1 = 0.032$ . Equation (2) can also be used for a more exact assessment of  $RSF$ , in case some flaws with a complicated configuration are present on the tubes of the pipelines, if we replace  $d_{rp} = A_{rp}$ ,  $A_{rp}$  being the relative area of the flaw,  $A_{rp} = \frac{A_d}{A_0}$  (fig. 1).

When assessing the technical condition of the pipelines transporting combustible fluids (crude oil, liquid petroleum products or natural gas) it is important to assess the remaining strength not only in relation with the attainment of the serviceability limit states previously defined, but also in relation with the achievement of an ultimate limit state (failure / bursting of pipes etc.); the attainment of the ultimate limit state, accompanied by the explosive failure of the pipes, by the leakage and, eventually, the ignition of a quantity of transported fluid from the pipeline, represents the event (of maximum gravity) whose probability of occurrence and whose consequences are taken into account when assessing the technical risk attached to the operation of transmission pipelines. Consequently, when assessing the mechanical strength of the transmission lines containing pipes with local surface flaws of the type metal loss, it is necessary to take into account both the value of  $RSF$  determined with equation (2) and also the value of a remaining strength factor related to the attainment of an ultimate limit state (of pipeline failure), with the symbol  $RSF_u$ , defined by the ratio between the Bursting Pressure of the pipes with flaws  $BP_d$  and the Bursting Pressure of the pipes without flaws  $BP_f$ :

$$RSF_u = \frac{BP_d}{BP_f}, \quad (4)$$

For the assessment of  $MAOP_d$  for the pipelines with such flaws, the following formula is proposed:

$$MAOP_d = \min \left[ \min \left[ \frac{RSF}{RSF_u}; 1 \right]; \min \left[ \frac{RSF_u}{RSF_{ua}}; 1 \right] \right] \cdot MAOP, \quad (5)$$

$RSF_{ua}$  being the (minimum) allowable level of  $RSF_u$  ( $RSF_{ua} = 0.7...0.9$ ).

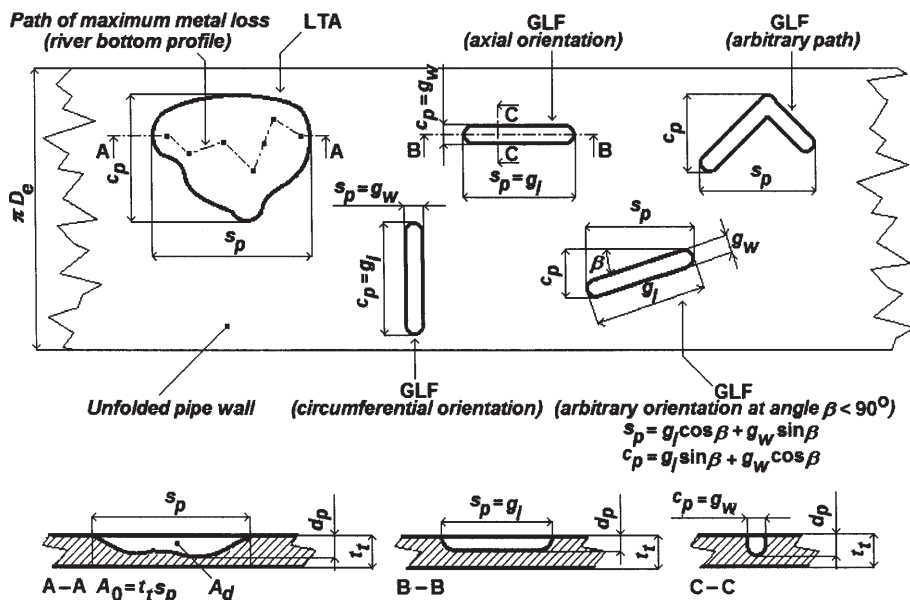


Fig. 1. Characteristic dimensions of the metal loss flaws from the pipes of transmission lines

## Experimental part

In order to determine  $RSF_u$  by means of applying the definition equation (4), it is necessary to know the Bursting Pressures  $BP_d$  and  $BP_r$ . In literature, a multitude of formulae are proposed for the assessment of the bursting pressure of the pipes with or without flaws of the type metal loss, all developed on the basis of the statistical interpretation of the results of some experimental programs [4-10]. In order to select the formulae recommended for the determination of  $BP_d$  and  $BP_r$  for the transmission pipelines, the authors have only considered the results of several experimental programs which aimed at determining the bursting strength of some steel tubes (with or without flaws) for pipelines intended for the transportation of combustible fluids (of the type of the ones recommended by [11]), at which they have also added the results obtained by performing their own experimental program. Using these results, two experimental databases have been developed: a) a database containing the results of the pressure testing up to bursting of  $n_r = 46$  new steel pipes (without flaws); b) a database containing the results of the pressure testing up to bursting of  $n_d = 57$  steel pipes with flaws of the type metal loss. The content of the experimental database is summarised in tables 1 and 2.

Our own experimental program has been achieved using full-scale pipe specimen taken from pipes extracted from a transmission line build for natural gas, on the occasion of performing corrective maintenance works on this pipeline. The pipes (spiral welded, with the outside diameter  $D_e = 508$  mm and the wall thickness  $t_r = 9.52$  mm) from which the specimens subject to internal pressure testing were cut had on their external surface multiple metal loss flaws,

of the type LTA, PIT or GLF, generated by corrosion or of the GAU type, obtained by local machining of the pipes surface when cutting – with abrasive disks – some auxiliary parts, assembled by welding and used (probably) for pipes manipulation. Two pipe segments without flaws have been selected, from which the specimens marked TF1 and TF2 have been made, while 6 pipes with flaws, marked T1...T6, have been selected, and from each one a full-scale specimen has been made. After selecting the pipes, removing the corrosion protection layers from them and cleaning their external surfaces, the pipes T1...T6 have been examined and the characteristic dimensions of the local surface flaws have been measured:  $d_p$ ,  $s_p$  and  $c_p$ . As an example, figure 2 presents the external appearance and the details of the main flaws existing on pipe T1. Table 3 summarises the main information regarding the characterization of the flaw state of all pipes (with flaws) from which specimens have been taken [8, 9].

From the pipes ends, samples have been cut for the determination of the tensile mechanical properties of the steel used to make the rolled strip from which the spiral welded pipes have been manufactured. After performing the tensile tests of these samples, it resulted that the steel has: the yield strength  $R_p = R_{p0.2} = 375...390$  MPa, the tensile strength  $R_m = 500...530$  MPa and the elongation after fracture  $A_{p5} = 18...20$  %. On this basis, it has been assessed that this steel corresponds to the grade X52 (L360 NB).

The full-scale pipe specimens have been provided at both their ends with an ellipsoidal bottom (assembled by welding), after which the connections needed to perform the internal pressure testing have been welded

Pipe symbol	$D_e$ , mm	$t_r$ , mm	$R_p$ , MPa	$R_m$ , MPa	$BP_{f,exp}$ , MPa	Source
AA00	88.9	4.0	336	486	42.7	[5]
AA01	88.9	4.0	336	486	47.0	
CA00	88.9	4.0	512	642	57.9	
CAA01	88.9	4.0	512	642	61.8	
T1	206.0	2.0	900	1200	24.8	[6]
T2	206.0	2.0	900	1200	24.5	
T3	206.0	2.0	900	1200	26.0	
T4	206.0	2.0	900	1200	24.7	
T5	206.0	2.0	900	1200	25.0	
T6	206.0	2.0	900	1200	26.5	
T7	206.0	2.0	900	1200	26.8	
T8	206.0	2.0	900	1200	24.5	
T9	206.0	2.0	900	1200	26.0	
T10	206.0	2.0	900	1200	25.0	
ZHENG1	39.8	1.9	235	375	49.2	[3]
ZHENG2	38.9	2.1	235	375	55.2	
ZHENG3	39.2	2.1	235	375	52.4	
ZHENG4	38.9	2.2	235	375	50.0	
ZHENG5	40.0	2.3	235	375	60.5	
ZHENG6	39.8	2.4	235	375	67.5	
ZHENG7	40.1	2.5	235	375	66.8	
ZHENG8	39.9	2.5	235	375	63.2	
ZHENG9	39.89	2.5	235	375	61.6	
ZHENG10	40.0	2.5	235	375	64.0	
ZHENG11	39.9	2.5	235	375	62.0	
ZHENG12	39.9	2.5	235	375	60.8	
ZHENG13	39.8	2.6	235	375	66.0	
ZHENG14	40.0	2.7	235	375	66.4	
ZHENG15	40.1	2.7	235	375	64.0	
ZHENG16	40.0	0.3	235	375	6.28	
ZHENG17	40.0	0.3	235	375	5.83	
ZHENG18	40.0	0.2	235	375	5.32	
ZHENG19	40.0	1.9	285	484	47.8	
ZHENG20	40.0	0.2	235	375	5.12	
ZHENG21	40.0	1.9	285	484	47.6	
ZHENG22	40.0	1.9	285	484	45.1	
UPG1	508.0	9.5	375	500	22.0	[8]
UPG2	508.0	9.5	390	530	24.5	
SOL-1	323.6	8.5	356	469	25.1	[7]
SOL-3	323.6	8.6	356	469	24.4	
SOL-5	324.1	8.5	356	469	25.0	
SOL-7	321.6	8.3	356	469	22.5	
SOL-8	323.6	8.7	356	469	23.9	
SOL-9	324.1	8.4	356	469	23.3	
SOL-14	323.9	8.6	356	469	24.5	
NOR-3	273.1	5.3	389	502	17.2	

**Table 1**  
CONTENT OF THE EXPERIMENTAL  
DATABASE WITH PRESSURE TESTS FOR  
PIPES WITHOUT FLAWS

Pipe symbol	$D_e$ , mm	$t_i$ , mm	$d_p$ , mm	$s_p$ , mm	$R_p$ , MPa	$R_m$ , MPa	$BP_{d,exp}$ , MPa	Source
AA3I	88.9	4.0	0.8	79.0	336	486	39.0	[5]
AA3H	88.9	4.0	2.0	45.0	336	486	34.1	
AA4A	88.9	4.0	2.0	93.0	336	486	26.7	
AA3B	88.9	4.0	1.1	66.0	336	486	33.4	
AA4F	88.9	4.0	2.0	20.0	336	486	36.0	
AA3G	88.9	4.0	2.1	220.0	336	486	21.2	
AB14B	88.9	8.8	6.1	134.0	324	457	42.7	
AB14E	88.9	8.8	6.2	240.0	324	457	31.4	
AB6E	88.9	8.8	4.3	266.0	324	457	56.7	
AB7I	88.9	8.8	6.1	128.0	324	457	47.1	
AB1K	88.9	8.8	4.6	82.0	324	457	60.8	
AK3E	101.6	10.0	7.5	70.0	337	433	56.0	
AK3F	101.6	10.0	8.0	200.0	337	433	28.3	
AK3D	101.6	10.0	8.0	180.0	337	433	26.0	
GWFO4	711.2	8.2	6.2	250.0	543	695	6.0	
GWFO6	914.4	10.6	7.2	250.0	529	670	6.4	
BMI27	184.5	9.7	6.2	143.6	201	500	16.6	
846077	1422.4	19.2	10.4	180.0	795	840	15.4	
846014	1422.4	20.1	3.8	385.0	795	840	20.1	
99457	914.4	16.4	9.0	150.0	739	813	21.4	
99437	914.4	16.4	6.0	450.0	739	813	24.0	
UPG1	508.0	9.5	5.5	32.0	375	500	18.0	
UPG21	508.0	9.5	6.0	40.0	375	500	17.5	
UPG22	508.0	9.5	6.0	40.0	375	500	16.0	
UPG3	508.0	9.5	5.5	12.0	390	530	18.0	
UPG4	508.0	9.5	5.2	15.0	390	530	16.0	
UPG5	508.0	9.5	5.5	150.0	390	530	15.0	
SOL-2	323.3	8.6	2.2	63.5	356	469	24.4	
SOL-10	323.6	8.6	3.3	144.8	356	469	23.9	
SOL-11	323.6	8.6	2.7	127.0	356	469	21.7	
SOL-12	323.1	8.5	2.2	50.8	356	469	21.6	
NOR1	273.1	5.2	1.9	408.9	389	502	16.7	
NOR2	273.1	5.3	1.7	139.7	389	502	18.1	
TNG-01	273.1	8.3	4.0	241.3	409	481	21.2	
RLK-1	611.4	6.6	3.3	901.7	402	534	9.4	
RLK-2	612.5	6.4	3.6	1432.6	402	534	7.9	
RLK-3	611.5	6.4	2.6	1371.6	402	534	9.8	
BCG-1	273.3	5.0	3.3	182.9	351	454	13.7	
BCG-2	273.0	4.7	2.6	48.3	351	454	13.8	
BCG-3	273.5	4.8	1.6	30.5	351	454	13.7	
BCG-4	273.1	4.9	2.2	101.6	351	454	15.2	
BCG-5	273.9	4.9	1.6	45.7	351	454	15.0	
BCG-6	274.1	5.0	2.2	124.5	351	454	13.3	
BCG-7	274.4	4.6	2.7	66.0	351	454	12.7	
BCG-8	274.1	5.0	2.7	38.1	351	454	14.8	
BCG-9	274.5	4.8	2.1	157.5	351	454	12.6	
ESS-01	323.9	5.1	3.7	99.1	373	472	9.7	
NOV01	506.7	5.7	3.0	132.1	462	587	10.7	
NOV02-2	505.0	5.7	3.3	462.3	462	587	8.1	
NOV03-2	508.0	5.7	3.8	619.8	462	587	8.6	
NOV04	508.0	5.7	3.8	533.4	462	587	9.9	
NOV04-2	508.0	5.7	3.0	416.6	462	587	10.9	
NOV05	508.3	5.6	3.4	596.9	462	587	8.0	
NOV06	508.0	5.6	2.5	170.2	462	587	11.5	
TCP01	863.6	9.6	3.6	213.4	400	508	10.8	

**Table 2**  
CONTENT OF THE EXPERIMENTAL  
DATABASE WITH PRESSURE TESTS FOR  
PIPES WITH FLAWS

on each specimen. The specimens prepared in such way have been subject to internal pressure testing (up to bursting) on the stand presented in figure 3, and the obtained results have been synthesised in table 4. It has to be mentioned that the experimental program achieved had more objectives (emphasising the stress concentration / intensification effect induced by the metal loss flaws, by determining the state of stress and strain around them with the help of strain gauges, ascertaining the conditions for fracture triggering in the area of the metal loss flaws by means of measuring pipes deformations before bursting etc. [8]); however, this paper presents and uses only the results regarding the bursting pressures of the pipes with and without flaws.

### Results and discussions

The experimental results inscribed in the databases we have compared with the results obtained with the different equations proposed in literature for determination the bursting pressure of the pipes with and without flaws [12-23].

The relationship recommended in various papers for the assessment of  $BP_f$  and  $BP_d$  have been processed and brought to the following general forms, better adapted for use:

$$BP_f = R_{fx} f(t_{rt}, R_{rx}); \quad BP_d = R_{dx} g(t_{rt}, R_{rx}, d_{rp}, s_{rp}), \quad (6)$$

in which  $R_{fx}$  and  $R_{dx}$  represent one of the tensile properties of the steel from which the pipes are made; that is the yield strength  $R_p$ , the tensile strength  $R_m$  or the yield stress (in the area of stress concentrators, such as the flaws of the type metal loss)  $R_{pd}$ , which can be considered  $R_{pd} = 1.1R_p$  or  $R_{pd} = R_p + 69$  MPa or  $R_{pd} = \min[1.1R_p; R_p + 69; \frac{R_m + R_p}{2}]$ , while  $f$  and  $g$  are functions having only dimensionless variables:

$t_{rt} = \frac{t_t}{D_e}$ ;  $R_{rx} = \frac{R_p}{R_m}$ ;  $d_{rp} = \frac{d_p}{t_t}$ ;  $s_{rp} = \frac{s_p}{\sqrt{D_e t_t}}$ . The characteristic  $R_{fx}$  and the analytical expressions of the function  $f = f_i, i = 1 \dots 12$ , from the  $n_f = 12$  formulae proposed in literature for the determination of  $BP_f = BP_{f,i}$ , along with the characteristic  $R_{dx}$  and the analytical expressions of the function  $g = g_j, j = 1 \dots 11$ , from the  $n_g = 11$  formulae recommended for the determination of  $BP_d = BP_{d,j}$  are shown in table 5. The values of the strain-hardening exponents  $n_{sp}$  and  $n_{exp}$ , which intervene in the analytical expressions of the functions  $f_i$  and  $g_j$ , have been obtained with the formulae  $n_{sp} = 0.224 \left(\frac{1}{R_{rx}}\right)^{0.604}$  and  $n_{exp} = 0.239 \left(\frac{1}{R_{rx}} - 1\right)^{0.596}$ .

Using the information from the databases presented in tables 1 and 2, we have drawn, considering one at a time each of the formulae described in table 5, the statistical correlation diagrams

$$BP_{f,exp} \leftrightarrow BP_{f,i}, i = 1 \dots 12 \quad \text{and} \quad BP_{d,exp} \leftrightarrow BP_{d,j}, j = 1 \dots 11$$

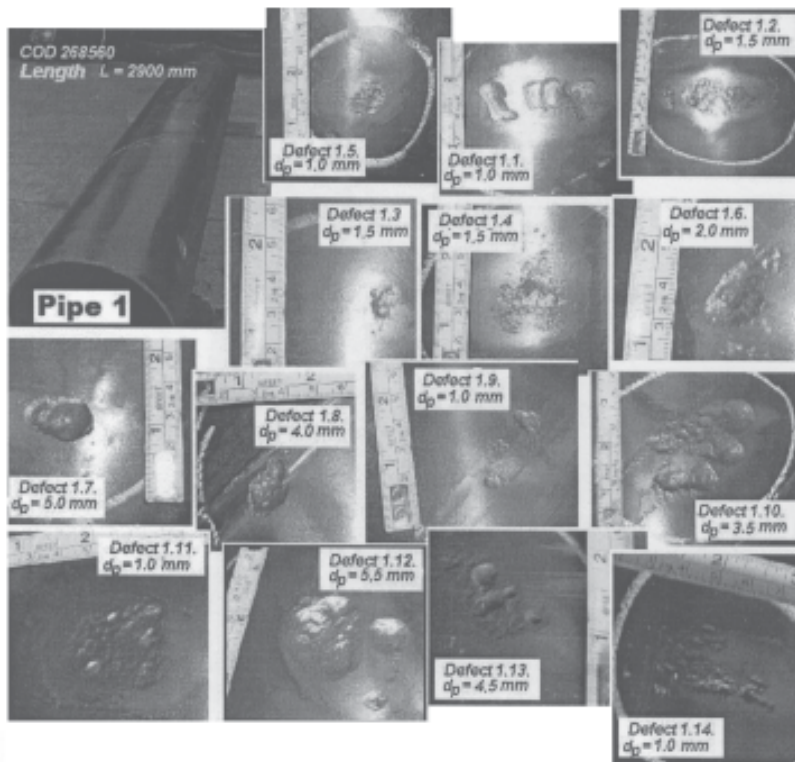


Fig. 2. The flaws of one of the pipes (Pipe 1) from which the specimens used within the experimental program have been taken

Pipe	Number of flaws	Depth of flaws, mm	Main dimensions of the maximum depth flaw			Type of flaws
			$d_p$ , mm	$s_p$ , mm	$c_p$ , mm	
T1	14	1.0...5.5	5.5	32	25	14LTA
T2	20	1.0...6.0	6.0	40	20	19LTA + 1GAU
T3	4	2.6...5.5	5.5	12	12	3LTA + 1GAU
T4	7	1.8...5.2	5.2	15	12	6LTA + 1GAU
T5	9	1.2...5.5	5.5*	150	55	9LTA

\* group of interacting flaws

**Table 3**  
CHARACTERISTICS OF THE FLAWS OF THE PIPES FROM WHICH SPECIMENS HAVE BEEN CUT

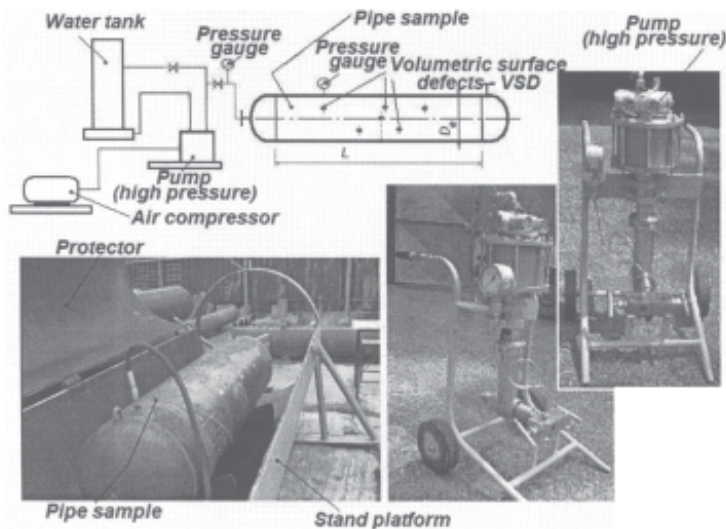


Fig. 3. Stand for internal pressure testing up to bursting of the full-scale pipe specimens

Pipe specimen	T1	T2	T2	T3	T4	T5
Burst Pressure $BP_d$ , bar	180	175	160	180	160	150
Type of flaw on which failure initiated	LTA	GAU	LTA	GAU	GAU	LTA

**Table 4**  
RESULTS OBTAINED AT THE INTERNAL PRESSURE TESTING UP TO BURSTING OF THE SPECIMENS CUT FROM PIPES WITH FLAWS

and we have calculated the linear regression coefficients

$$BP_{f,exp} = m_{f,i} BP_{f,i}, i = 1 \dots 12 \text{ and}$$

$BP_{d,exp} = m_{d,j} BP_{d,j}, j = 1 \dots 11$  and the correlation coefficients  $r_{ci}$  and  $r_{cj}$  associated to them. It resulted that, with very few exceptions  $r_{ci}, r_{cj} > 0.9$  and  $m_{fi}, m_{dj} > 1$ , which shows that the level of trust of the values  $BP_{f,exp}$  and  $BP_{d,exp}$  provided by the linear regressions is very high and that

the formulae for  $BP_{fi}$  and  $BP_{dj}$  are conservative (leading to values of the pressures  $BP_{fi}$  and  $BP_{dj}$  lower than the real / experimental values).

Based on the results previously obtained and applying the definition relationship (4), a multitude (with  $n_f = n_{fd} \times n_{cd} = 132$ ) of formulae for  $RSF_u$  can be obtained:

Formulae for $BP_f$ ( $BP_{fi} = R_{f,i} f_i(t_{rt}, R_{rx}, d_{rp}, s_{rp})$ , $i = 1...12$ )					
$BP_{fi}$	$R_{f,i}$	$f(t_{rt}, R_{rx}) = f_i(t_{rt}, R_{rx})$	$BP_{fi}$	$R_{f,i}$	$f(t_{rt}, R_{rx}) = f_i(t_{rt}, R_{rx})$
$BP_{f1}$	$R_p$	$(2 - R_{rx}) \frac{2}{\sqrt{3}} \ln \left( \frac{1}{1 - 2t_{rt}} \right)$	$BP_{f7}$	$R_p$	$\frac{2}{\sqrt{3}} \ln \left( \frac{1}{1 - 2t_{rt}} \right)$
$BP_{f2}$	$R_m$	$\left( \frac{1}{2} \right)^{n_{sp}+1} \frac{4t_{rt}}{1 - 2t_{rt}}$	$BP_{f8}$	$R_m$	$\frac{2}{\sqrt{3}} \ln \left( \frac{1}{1 - 2t_{rt}} \right)$
$BP_{f3}$	$R_m$	$\left( \frac{1}{\sqrt{3}} \right)^{n_{sp}+1} \frac{4t_{rt}}{1 - t_{rt}}$	$BP_{f9}$	$R_p$	$\frac{2}{\sqrt{3}} [1 + 0.65(1 - R_{rx})] \ln \left( \frac{1}{1 - 2t_{rt}} \right)$
$BP_{f4}$	$R_m$	$\left( \frac{1}{4} + \frac{1}{2\sqrt{3}} \right)^{n_{sp}+1} \frac{4t_{rt}}{1 - t_{rt}}$	$BP_{f10}$	$R_{pd}$	$\ln \left( \frac{1}{1 - 2t_{rt}} \right)$
$BP_{f5}$	$R_m$	$\frac{4}{(\sqrt{3})^{n_{sp}+1}} \frac{t_{rt}}{1 - 2t_{rt}}$	$BP_{f11}$	$R_{pd}$	$\frac{2}{\sqrt{3}} \ln \left( \frac{1}{1 - 2t_{rt}} \right)$
$BP_{f6}$	$R_m$	$\frac{1}{4n_{sp} + 0.88} \left( \frac{e}{n_{sp}} \right)^{n_{sp}} \ln \left( \frac{1}{1 - 2t_{rt}} \right)$	$BP_{f12}$	$R_m$	$\frac{4}{(\sqrt{3})^{n_{exp}+1}} \frac{t_{rt}}{1 - 2t_{rt}}$
Formulae for $BP_d$ ( $BP_{dj} = R_{d,j} g_j(t_{rt}, R_{rx}, d_{rp}, s_{rp})$ , $j = 1...10$ )					
$BP_{dj}$	$R_{d,j}$	$g(t_{rt}, R_{rx}, d_{rp}, s_{rp}) = g_j(t_{rt}, R_{rx}, d_{rp}, s_{rp})$			
$BP_{d1}$	$R_p$	$(2 - R_{rx}) \frac{2}{\sqrt{3}} \ln \left( \frac{1}{1 - 2t_{rt}} \right) [1 - 0.945t_{rt}^{0.2} d_{rp}^{1.6} s_{rp}^{0.4}]$			
$BP_{d2}$	$R_m$	$\left( \frac{1}{2} \right)^{n_{sp}+1} \frac{4t_{rt}}{1 - 2t_{rt}} \left\{ 1 - d_{rp} \left[ 1 - \exp \left( -0.222 \frac{s_{rp}}{\sqrt{1 - d_{rp}}} \right) \right] \right\}$			
$BP_{d3}$	$R_m$	$1.9t_{rt} \left\{ 1 - d_{rp} \left[ 1 - \exp \left( -0.222 \frac{s_{rp}}{\sqrt{1 - d_{rp}}} \right) \right] \right\}$			
$BP_{d4}$	$R_p$	$\frac{2t_{rt}}{1 - t_{rt}} \frac{1 - d_{rp}}{1 - \frac{d_{rp}}{M_{F4}}}; M_{F4} = \sqrt{1 + 0.743 \frac{s_{rp}}{\sqrt{1 - t_{rt}}}}$			
$BP_{d5}$	$R_m$	$2t_{rt} [1 - d_{rp} (1 - \exp(-0.111s_{rp}))]$			
$BP_{d6}$	$R_{pd}$	$\frac{2t_{rt}}{1 - t_{rt}} \left[ 1 - d_{rp} \left( 1 - \frac{1}{M_{F6}} \right) \right]; M_{F6} = \sqrt{1 + 0.805 \frac{s_{rp}^2}{d_{rp}(1 - t_{rt})}}$			
$BP_{d7}$	$R_{pd}$	$\left[ \frac{2t_{rt}d_{rp}}{(1 - 2t_{rt}d_{rp})M_{F7}} + \ln \left( \frac{1 - 2t_{rt}d_{rp}}{1 - 2t_{rt}} \right) \right]; M_{F7} = \sqrt{1 + 0.805 \frac{s_{rp}^2}{d_{rp}(1 - 2t_{rt}d_{rp})}}$			
$BP_{d8}$	$R_{pd}$	$\frac{1}{M_{F8}+1} \left[ M_{F8} \ln \left( \frac{1}{1 - 2t_{rt}} \right) + \ln \left( \frac{1 - 2t_{rt}d_{rp}}{1 - 2t_{rt}} \right) \right]; M_{F8} = \frac{t_{rt}d_{rp}(d_{rp}-1)}{M_{F7}(1 - 2t_{rt}d_{rp}) \ln(1 - 2t_{rt}d_{rp}) + 2t_{rt}d_{rp}}$			
$BP_{d9}$	$R_{pd}$	$\left[ \frac{1}{M_{F9}} \ln \left( \frac{1}{1 - 2t_{rt}d_{rp}} \right) + \ln \left( \frac{1 - 2t_{rt}d_{rp}}{1 - 2t_{rt}} \right) - \frac{1 - t_{rt}d_{rp} - \sqrt{(1 - t_{rt}d_{rp})^2 + t_{rt}^2 d_{rp}^2}}{1 - 2t_{rt}} \right]$			
$BP_{d10}$	$R_{pd}$	$\frac{1}{M_{F9}-d_{rp}} \left[ (1 - d_{rp}) \ln \left( \frac{1}{1 - 2t_{rt}} \right) + (M_{F9} - 1) \ln \left( \frac{1 - 2t_{rt}d_{rp}}{1 - 2t_{rt}} \right) \right]; M_{F9} = \sqrt{1 + 0.625 \frac{s_{rp}^2}{d_{rp}}}$			
$BP_{d11}$	$R_m$	$\frac{2.1t_{rt}}{1 - t_{rt}} \frac{1 - d_{rp}}{1 - \frac{d_{rp}}{M_{F11}}}; M_{F11} = \sqrt{1 + 0.31s_{rp}^2}$			

**Table 5**  
THE CHARACTERISTIC  $R_i$  AND  
THE ANALITICAL EXPRESSIONS  
OF FUNCTIONS  $f$  AND  $g$   
FROM EQUATION (6)

$i$	1	5	2	5	5	5
$j$	1	1	2	2	3	4
$k_{cij}$	1.0016	0.9210	1.0005	1.1989	1.0950	1.2750
$i$	5	5	5	5	5	5
$j$	5	6	7	9	10	11
$k_{cij}$	1.0360	1.1580	1.1430	1.1550	1.1580	0.9710

**Table 6**  
VALUES OF THE CORRECTION  
FACTORS  $k_{cij}$  FROM THE  
FORMULAE  $RSF_u = RSF_{ui,j}$

$$RSF_u = RSF_{ui,j} = \frac{BP_{d,exp}}{BP_{f,exp}} = k_{ci,j} \frac{BP_{d,j}}{BP_{f,i}} = k_{ci,j} \frac{R_{d,x,j} g_j}{R_{f,x,i} f_i} \quad (7)$$

the values of the correction factors  $k_{cij}$  ( $i = 1...12$ ;  $j = 1...11$ ) being defined in such way that the following condition is observed  $\lim_{s_{rp}, d_{rp} \rightarrow 0} RSF_u = 1$ .

In order to illustrate the manner of using the new procedure proposed for the definition of  $RSF_u$ , we have considered the case of the transmission pipelines with  $D_e = 508$  mm and  $t_t = 8$  mm ( $t_t = 0.01575$ ), build with pipes made of X52' (L360 NB) steel, having  $R_{0.5} = 360$

MPa,  $R_{pd} = 396$  MPa and  $R_m = 450$  MPa ( $R_{rx} = 0.8$ ). The followings results have been obtained:

a) the values  $k_{cij}$  to be used in the main equation for  $RSF_{ui,j}$  tested in view of their application for the case of these pipelines are the ones presented in table 6;

c) the diagrams for the evaluation of  $RSF_{ui,j}$  for the pipelines with flaws characterized by different values of the relative depth  $d_{rp}$  and relative length  $s_{rp}$ , containing the graphical representations of the curves  $RSF_{ui,j} = k_{ci,j} \frac{R_{d,x,j} g_j(t_{rt}=ct, R_{rx}=ct, d_{rp}, s_{rp})}{R_{f,x,i} f_i(t_{rt}=ct, R_{rx}=ct)}$ , are of the types presented for exemplification in figure 4. It can be

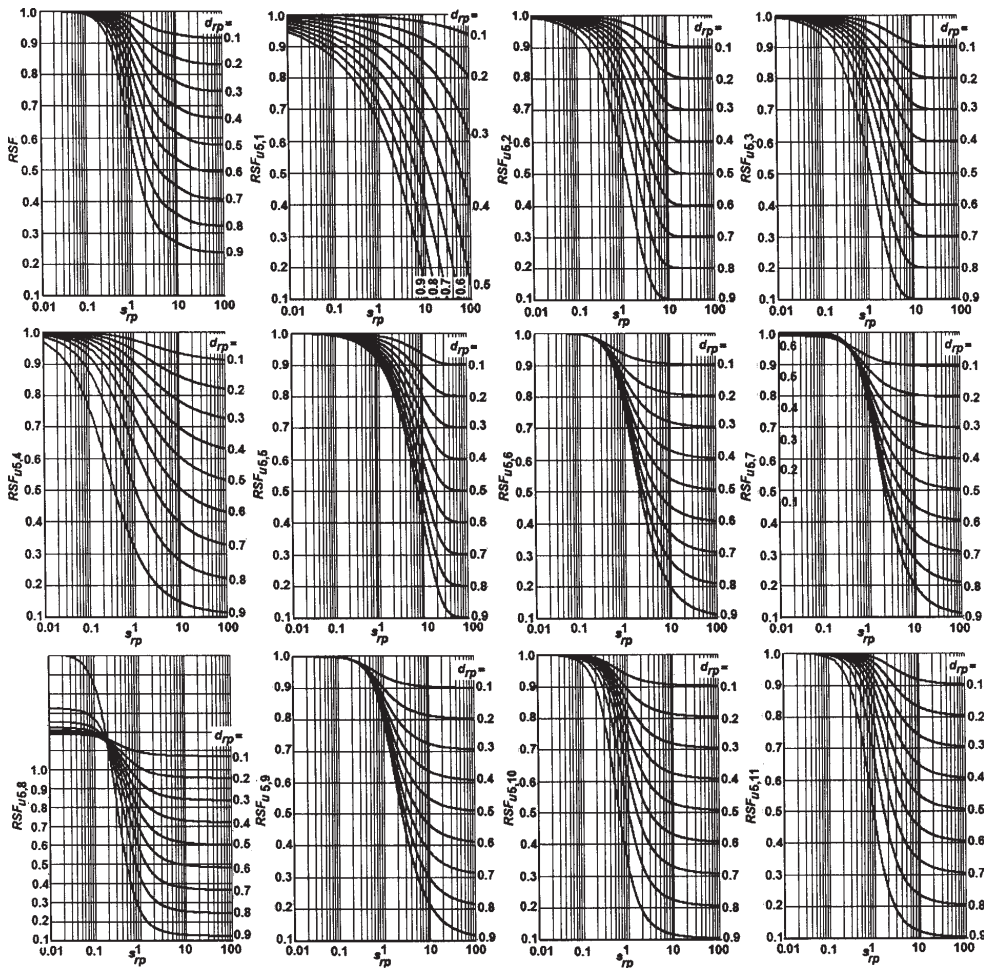


Fig. 4. Examples of diagrams for the evaluation of  $RSF_{ui}$  for the pipelines with flaws

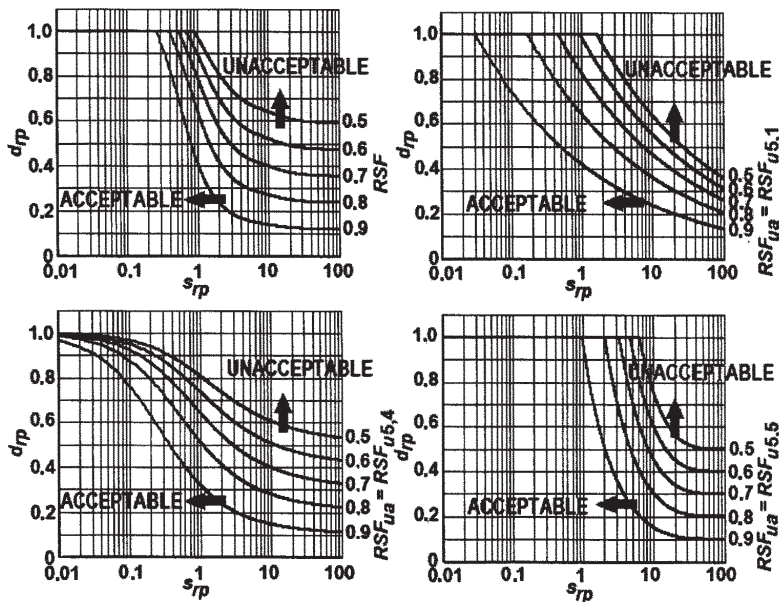


Fig. 5. Examples of Flaw Acceptance Diagrams

observed that these diagrams differ from the  $RSF$  evaluation diagram, having the curves described analytically by equation (2). The usage of  $BP$  is not recommended, because, for values  $s \leq 0.2$ ,  $RSF_u$  is a monotonically increasing function with  $d$ ;

d) considering an allowable level ( $RSF_{ua}$  or  $RSF_{ua}^d$ ) of  $RSF$  or  $RSF_u$  and describing analytically the conditions  $RSF \geq RSF_{ua}$  and  $RSF_u \geq RSF_{ua}^d$  with the equations (2) and (7), Flaw Acceptance Diagrams, of the type of those presented as an example in figure 5, can be build.

### Conclusions

The magnitude of the remaining strength factor can characterize the degree in which the local flaws of the

type metal loss existing on the steel pipes of the transmission lines affect their loading capacity.

In order to correctly assess the remaining mechanical strength of the pipelines with metal loss flaws, it is recommended to determine both  $RSF$ , defined as the ratio between the operating pressures for which in the pipeline with flaws and in the pipeline without them a serviceability limit state is attained (characterised by the development in the pipe wall of stresses reaching the level of the yield strength or allowable strength of the steel from which it is manufactured), and  $RSF_{ua}$ , defined as the ratio between the pressures for which in the pipeline with flaws and in the pipeline without flaws the ultimate limit state (bursting / failure) is reached.

The relationships presented in this paper for the bursting pressure of the steel pipes with and without flaws of the type metal loss, ascertained on the basis of the results interpretation for some experimental programs (of the type of the one presented in this paper), allow for the definition of a consistent multitude of formulae for  $RSF$ . The calculation results for  $RSF$  and  $RSF_u$  can be synthesised under the form of evaluation diagrams for the metal loss flaws, extremely useful for a fast assessment of the remaining mechanical strength of the pipelines with flaws and for an operative decision making process regarding the maintenance work interventions.

*Acknowledgments: The research leading to these results has received funding from the European Union Seventh Framework Programme FP7-PEOPLE-2012-IRSES, under grant agreement n° 318874 "INNOPIPES – Innovative Nondestructive Testing and Advanced Composite Repair of Pipelines with Volumetric Surface Defects".*

## References

- 1.\*\*\*, ASME B31G-2009, Manual for Determining the Remaining Strength of Corroded Pipelines.
- 2.\*\*\*, API 579-1/ASME FFS-1, Fitness-For-Service, 2007.
- 3.ZHENG, Ch.-X., LEI, Sh.-H., Journal of Zhejiang University SCIENCE A, **7** (Suppl.II), 2006, p. 277.
- 4.LABOUREUR, D., Experimental Characterization and Modeling of Hazards: BLEVE and Boilover, Ph.D. Dissertation, Ecole Polytechnique de Bruxelles, 2012.
- 5.STAAT, M., Nuclear Engineering and Design, **234**, 2004, p. 25.
- 6.RAJAN, K.M., DESHPANDE, P.U., NARASIMHAN, K., Journal of Materials Processing Technology, **125-126**, September 2002, p.228.
- 7.CRONIN, S.D., Assessment of Corrosion Defects in Pipelines, Ph.D. in Mechanical Engineering Thesis, University of Waterloo, Ontario, Canada, 2000.
- 8.\*\*\*, Raport Contract de cercetare nr. 38/2007, Universitatea Petrol – Gaze din Ploiesti, Ploiesti, 2008.
- 9.ECHERU, G., LAȚA, E. I, DRĂGHICI, G., BÂRSAN, F., DUMITRU G., vol. Mecanica ruperii. Lucrările celui de-al XV-lea Simpozion național de Mecanica ruperii, Sibiu, 6-7 nov. 2009, p. 95.
- 10.\*\*\* STAAT, M., International Journal of Pressure Vessels and Piping, **82**, 2005, p. 217.
- 11.\*\*\*, ISO 3183:2007 Petroleum and natural gas industries. Steel pipe for pipeline transportation systems.
- 12.\*\*\* DNV – RECOMMENDED PRACTICE – F101, Corroded Pipelines, October 2010
- 13.WILLOUGHBY, A.A., DAVEY, T.G., ASTM STP 1020, 1989, p. 390.
- 14.MILLER, A.G., International Journal of Pressure Vessels and Piping, **32**, 1988, p. 197.
- 15.BHINGARE, Y.K., HEGNE, A.V., International Journal of Latest Trends in Engineering and Technology (IJLTET), **2**, May 2013, p.303.
- 16.DINIZ, J.L., VIEIRA, R.D., FREIRE J.L., Experimental mechanics, **46**, No.6, 2006, p.765
- 17.OH, C.K., KIM, Y.J., BACK, J.H., KIM, Y.P., KIM, W.S., International Journal of Pressure Vessels and Piping, **84**, 2007, p. 512.
- 18.NOOR, N., NOR, A.N.O., YAHAYA, N., Journal of Sustainability Science and Management, **6**, No. 1, June 2011, p. 69.
- 19.VELAZQUEZ, J.C., COLEYO, F., HALLEN, J.M., ROMERO-MERCADO, O., HERRERO-HERNANDEZ, H., International Journal Electrochemical Science, **8**, 2013, p.11356.
- 20.ASEER BRABIN, T., CHRISTOPHER, T., NAGESWARA RAO, B., International Journal of Pressure Vessels and Piping, **88**, 2011, p.119.
- 21.STAAT, M., VU, D. K., Engineering Fracture Mechanics, **74**, No. 3, 2007, p.431.
22. XUE, L., WIDERA, G., SANG, Z., Transactions of ASME, Journal of Pressure Vessel Technology, **130**, No. 1, 2008, p. 1
- 23.ZHU, X., LEIS, B.N., Transactions of ASME, Journal of Pressure Vessel Technology, **129**, No.4, 2007, p. 644.

Manuscript received: 24.07.2014