ISSN 1310-3946

НАУЧНИ ИЗВЕСТИЯ на НТСМ
SCIENTIFIC PROCEEDINGS
"NDT days 2014"/"Дни на безразрушителния контрол 2014"
Year/Година XXII ❐ Number/ Брой 1 (150) June/Юни 2014

DEVELOPMENT OF AN EXPERIMENTAL PROGRAMME AIMED AT EMPHASIZING THE CONSOLIDATION EFFECTS OF COMPOSITE MATERIAL WRAPS APPLIED FOR THE REPAIR OF TRANSMISSION PIPELINES WITH VOLUMETRIC SURFACE DEFECTS

РАЗРАБОТКА ЭКСПЕРИМЕНТАЛЬНОЙ ПРОГРАММЫ ПОВЫШЕНИЯ УКРЕПЛЯЮЩЕГО ЭФФЕКТА КОМПОЗИТНЫХ БАНДАЖЕЙ ДЛЯ РЕМОНТА НАГНЕТАТЕЛЬНЫХ ТРУБОПРОВОДОВ С ОБЪЕМНЫМИ ПОВЕРХНОСТНЫМИ ДЕФЕКТАМИ

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Abstract
The present paper describes a planned experimental programme to be performed jointly by the authors, with the aim of studying the reinforcement (consolidation) effects of repair systems using composite materials wraps (sleeves) developed for damaged transmission pipelines (intended for petroleum, liquid petroleum products or natural gas), with defects of the type metal loss (volumetric surface defects - VSD). The results (briefly described in the paper) of experimental tests previously executed within research activities in both our institutions have emphasized the need to define and perform a new set of tests for the composite repair systems. The selection of the materials (pipe steel, composite) to be tested, the testing conditions and their parameters are detailed in the followings and the plan and objectives of such experimental programme are explained.
KEYWORDS: COMPOSITE MATERIAL WRAP, VOLUMETRIC SURFACE DEFECT, TRANSMISSION PIPELINE REPAIR

1. Introduction
The transmission pipelines (normally made of steel) used to transport natural gas, petroleum or liquid petroleum products are providing services of great importance and therefore their maintenance and repair activities need special attention. Among the most common defects that might be detected on these pipelines are the ones of the type metal loss (also called VSD – volumetric surface defects), due to corrosion and/or erosion processes.

In the last years, the repair of the pipeline areas with such defects was frequently performed by means of applying composite materials sleeves/wraps, because such repair technology does not required welding operations and can be applied without removing the pipelines from service [6]. However, the problems afferent to the application of this repair procedure did not found yet technical solutions fully underlain and unanimously accepted [7].

For this reason, the authors are carrying out, within the INNOPIPES FP7 Project, an extended research programme that studies both theoretically and experimentally the transmission pipeline repair systems using composite materials. One of the main goals of our research programme is to investigate experimentally the effectiveness of the repair systems using composite materials applied on transmission pipelines with VSDs made by machining, under various loading conditions (internal pressure, low cycle loading). The main objectives of our past and future experimental work are the following:

1) to evaluate the consolidation effect, considered as a measure of their effectiveness, for some composite repair systems used for damaged pipelines, by investigating the stress-strain state in the damaged area under the operational (internal) pressure, and also by determining the burst pressure value;
2) to validate numerical and analytical models used to evaluate the remaining strength of a pipeline with volumetric surface defect reinforced using composite repair systems and also the design procedures for the composite wraps to be applied for pipelines repair; some models and procedures [7] have been developed by the authors and their research partners;
3) to compare the obtained experimental data and results with similar investigations performed by other research teams.

In the followings, after a brief description of the experimental results obtained separately by the authors, the definition of the parameters for the future tests (pipe material and geometry, VSD geometry, loading conditions etc.) is detailed and the plan for the experiments to be carried out jointly by both our institutions is described.

2. Previous experimental tests
The authors of the present paper have been involved in the past in similar tests regarding pipeline repair systems using composite materials, performed within both the Petroleum-Gas University and the E.O. Paton Welding Institute. These tests constituted the starting point for the development of the experimental programme described in the following sections. A brief description of the results of these tests is included below.

Among the analyses regarding the repair methods intended for transmission pipelines, a repair system using composite materials conceived by ICECHIM Bucharest, named IWR (ICHECHIM Wrap Repair) has been the object of investigations under an extensive research program carried out in the University of Ploiesti. The IWR material is made of a multilayer composite material, in which the reinforcement component consists of layers of fibre glass fabric, and the matrix is the polymeric material used to impregnate the fabric. This polymeric resin has been conceived as a modified polymeric system with flexibilisators with small molecular weight and with mineral fillings.

The IWR mechanical properties (E_C – elastic modulus, R_{mC} – tensile strength, A_C – elongation at fracture) are compared in Table 1 with the ones of other composite repair systems developed for transmission pipelines.

Table 1. Comparison between the mechanical characteristics of IWR, KPB and other composite materials for pipeline repair

Composite material	Reinforcement material	Mechanical characteristics of the composite material *		
		E_C, GPa	R_{mC}, MPa	A_C, %
IWR	Fiberglass	17.5...22.7	265...315	1.32...1.60
KPB	Fiberglass	2.8…3.1	30…31	0.90…1.10
EC10 1680	Fiberglass	41.4…43.0	884…1025	2.44…3.27
Perma Wrap	Fiberglass	34.0…38.0	580…620	1.00…1.10
Fiba Roll	Fiberglass	7.9...8.7	86...72	2.60...3.10
Clock Spring	Fiberglass	33.8...34.5	630...650	1.06...1.36
TDW RES-Q	Carbon fibre	68.8	1028	-

* measured in the direction corresponding to the pipeline circumference when applying the composite material wrap

The IWR repair has the structure shown in Figure 1, and its achievement requires three steps: 1) pipeline preparation for repair (cleaning etc.); 2) rehabilitation of the pipe external configuration (filling the defects using a polymeric filler); 3) rehabilitation of the pipe mechanical strength, applying the reinforcing composite wrap in the defects area.

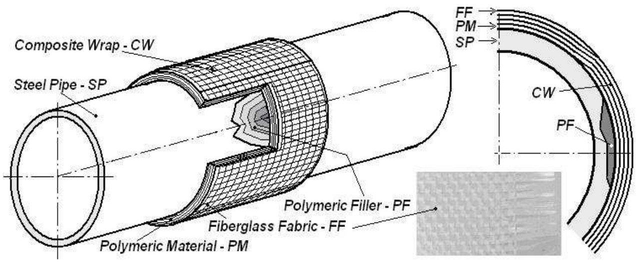

Fig. 1. Structure of IWR composite repair system for pipelines

The IWR research program included, but was not limited to, the experimental testing of the IWR system applied to three full-scale pipe specimens, all made of steel grade L245/B ($R_{t0.5}$ = 245 MPa, R_m = 415 MPa) and with one or several machined VSD, subjected to internal pressure loading (maximum allowable operating pressure MAOP = 5.5 MPa). Figures 2-6 illustrate the test method applied and the behaviour of specimens 1 and 3, reinforced with composite wraps, after being subjected to bursting tests.

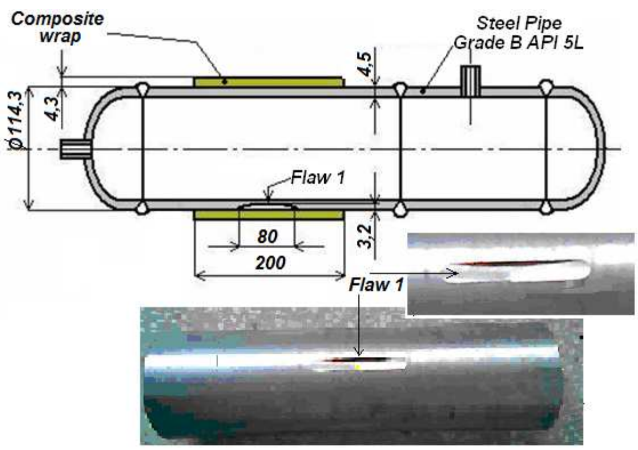

Fig. 2. Geometry of specimen 1 (with only one VSD)

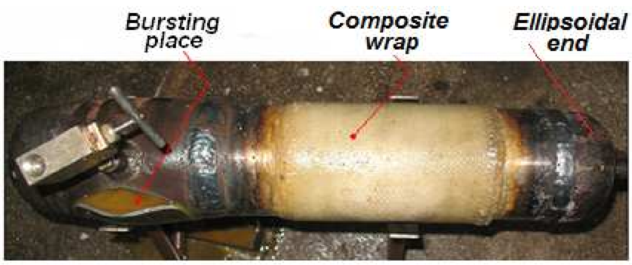

Fig. 3. Specimen 1 after testing (burst pressure: 39.5 MPa)

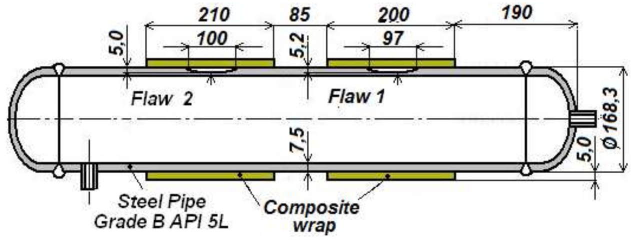

Fig. 4. Geometry of specimen 3 (with two VSDs)

The research team form E.O. Paton Institute in Kiev also carried out an important research program regarding the KPB composite repair system, which included experimental testing of two full-scale pipe specimens after repair. The KPB material, provided by Kailas Ltd., is made of a multilayer composite material, in which the reinforcement component consists of layers of fibre glass fabric, and the matrix is the polymeric resin used to impregnate the fabric.

Fig. 5. Specimen 3 before repairing

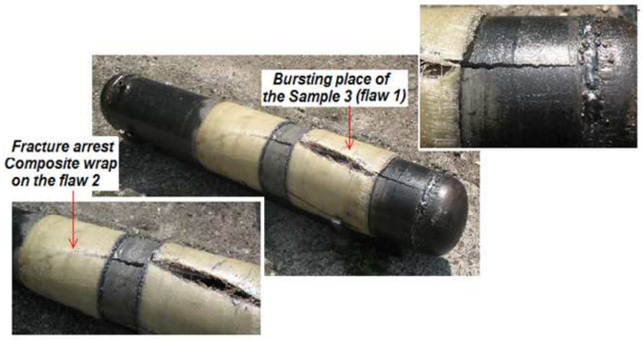

Fig. 6. Specimen 3 after testing (burst pressure: 31.5 MPa)

KPB wrap repair has the structure shown in Figure 7, and its achievement requires four steps: 1) pipeline preparation; 2) rehabilitation of the pipe external configuration (using REM-steel filler); 3) covering the pipeline surface using a polymeric primer (MB); 4) rehabilitation of the pipe mechanical strength, applying the composite wrap (KPB) for reinforcement in the defects area.

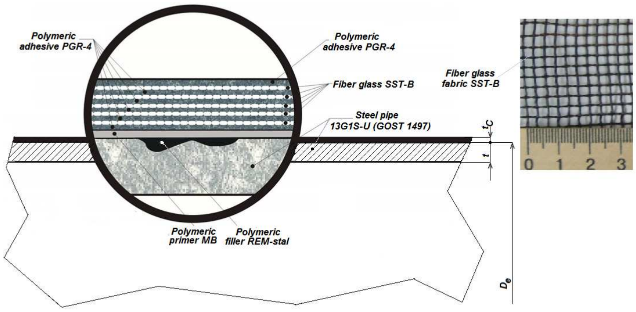

Fig. 7. Structure of KPB composite repair system for pipelines

The testing method and parameters are illustrated in Figures 8-9 for specimen 1 (specimen 2, made of the same steel grade, similar to L360/X52, had the outside diameter D_e = 720 mm and the wall thickness t_n = 9.9 mm), while the mechanical behaviour of the pipes reinforced with KPB composite wraps during the bursting test is summarised in Figure 10.

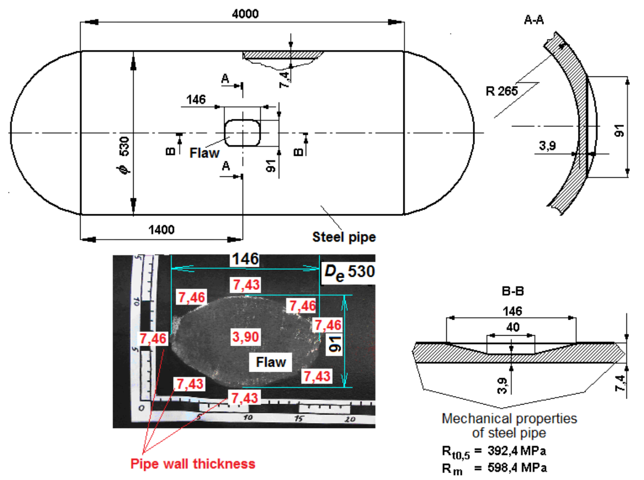

Fig. 8. Geometry of specimen 1 before repair with VSD details

The reason for which the achievement of a new set of tests has been decided has been to investigate additional issues regarding composite wrap repair systems (behaviour under low cycle internal pressure loading, test of specimens repaired while the pipe is subjected to internal pressure, validation of the composite wrap design method proposed in [7] as the wrap thickness to be applied will be calculated accordingly) and also to enrich our database of experimental results.

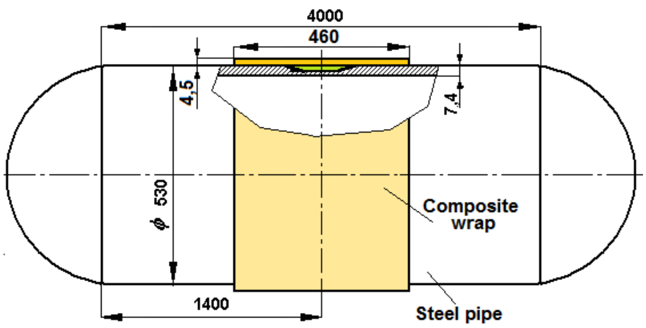

Fig. 9. Geometry of specimen 2 after repair (with KPB wrap)

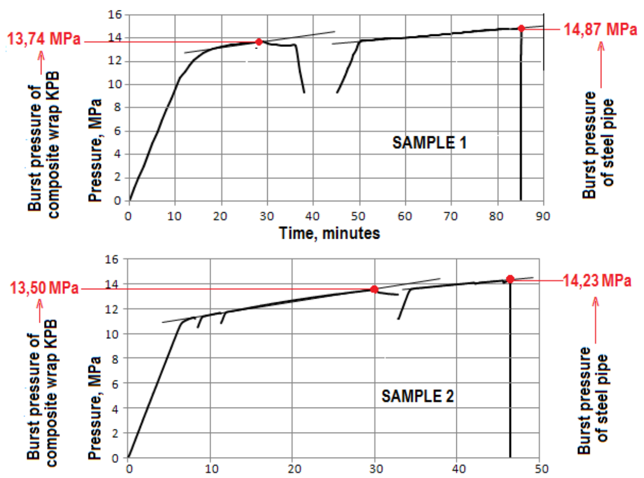

Fig. 10. Test results for both specimens

3. Definition of the experimental parameters

In the first place, the most adequate pipe materials to be tested have been considered the steel grades L290/X42 and L360/X52 (or equivalent) [1], because they range among the most frequently used steel grades in both Romanian and Ukrainian gas pipelines systems, especially in the older ones that usually present VSD and therefore require repair systems. For the same reason, the most suited values for the outside diameter of the pipes to be tested have been considered: D_e = 219.1; 323.9; 508.0; 711.0 mm.

The pipe specimens finally selected for testing, based also on available pipe materials and dimensions, are made of Steel 20 (according to GOST 550-75 [5]), very similar to L290, and have the outside diameter D_e = 219.0 mm. Table 2 compares the mechanical properties of steels L290, L360, Steel 20 given in their standards [1, 5] with the ones determined by performing tensile testing on samples cut in the axial and circumferential direction for the specimens material.

Table 2. Mechanical properties comparison

Pipe grade / sample direction		SMYS *, $R_{t0.5}$ (MPa)	Tensile strength, R_m (MPa)
L290 / X42		290	415
L360 / X52		360	460
Steel 20	GOST	255 **	431
	axial sample	320	464
	circumf., straightened	323 **	474
	circumf., not straightened	312 **	477

* specified minimum yield strength
** $R_{c0.2}$ (corresponds to residual elongation 0.2%)

In order to be able to compare the results of our research work with the ones of other similar activities, we have decided to select a pipe wall thickness and to define a defect geometry equivalent to the ones used within an extensive experimental program currently underway, organized by Pipeline Research Council International – PRCI [9, 10]. This program, sponsored by PRCI and thirteen composite manufacturers from around the world, is a response to questions from the pipeline industry regarding the long term performance of composite repair systems.
The program consisted of the preparation of grade L290/X42 test specimens with welded end caps and machined VSD (their geometry is shown in Figure 11), repaired by the participating manufacturers. All manufacturers repaired specimens for a three-year test period, while five of the manufacturers elected to participate for a 10-year study.

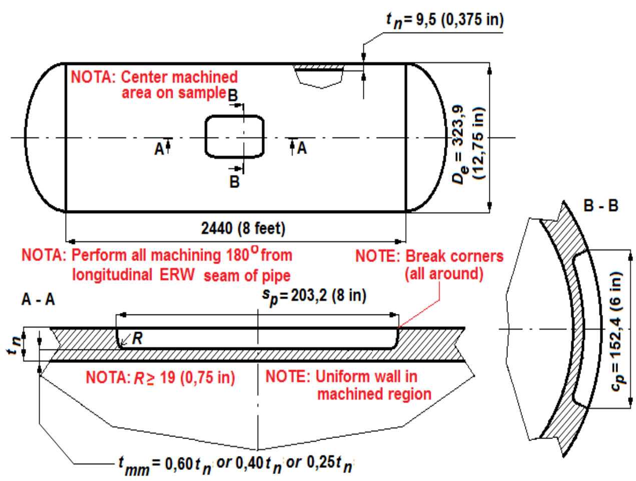

Fig. 11. PRCI full-scale test specimen [9]

Burst tests were planned for all the repaired specimens at 0, 1, 2, and 3 years. The 10-year participants will have additional burst periods at 5, 7.5, and 10 years. While 36 samples were burst immediately after repair, 144 samples were buried in the ground at Stress Engineering's Waller, Texas Test Facility. Samples will be continuously pressurized at 36% SMYS and cycled 75 times once per month at 36% SMYS and once per quarter at 72% SMYS. Burst test samples will be removed from the buried trenches at the designated test periods. Figure 12 includes the test field layout.

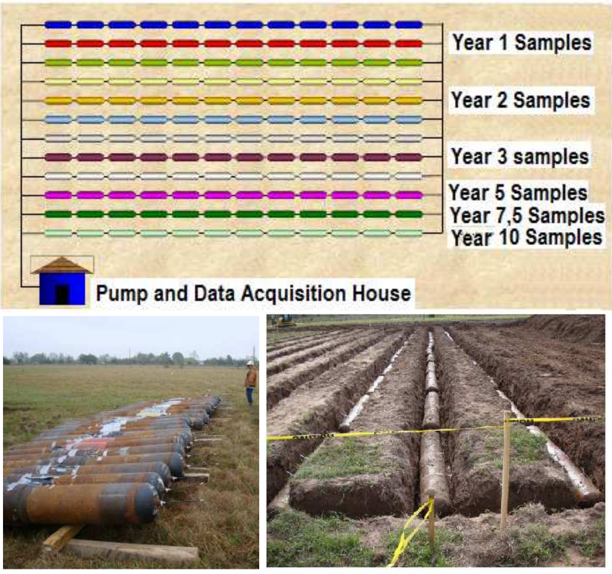

Fig. 12. PRCI test field layout and pictures [10]

During the testing period, strain gages will be used to monitor strain in the corroded steel beneath the composite repairs. The strain gages from each specimen are connected to a central data acquisition system that will collect data once per month over a 10-year period. Among the participant manufacturers, we mention: Armor Plate, EMS Group, T.D. Williamson (10 years programme); Clock Spring Company, Pipe Wrap (3 years programme).

The nominal wall thickness of the pipe specimens, t_n, has been selected such that to obtain approximately the same *SDR* (Standard Dimensional Ratio – $SDR = D_e/t_n$) as the PRCI pipes. As these pipes have $SDR = 34.09$, the resulting value for the nominal wall thickness has been $t_n = 6.0$ mm.

The defect dimensions have been determined to obtain the same values as per the PRCI experimental program (including three different values for the defect depth corresponding to 40%, 60%, and 75% respectively of the thickness t_n) for the non-dimensional parameters of the defect defined in the standard API 579 [2] characterizing its depth, length and width, respectively:

$$h_d = \frac{d}{t_n}\ , \quad \lambda = \frac{1.285 \cdot s_p}{\sqrt{D_e \cdot t_n}}\ , \quad \lambda_c = \frac{1.285 \cdot c_p}{\sqrt{D_e \cdot t_n}}\ , \qquad (1)$$

where d is the defect depth, s_p – axial extent or length of defect, c_p – circumferential extent or width.

Applying equations (1-3) for the PRCI pipes (with the defect dimensions shown in Figure 11) and then for our pipes, we have obtained the following defect dimensions values: $s_p = 133$ mm; $c_p = 103$ mm; $d = 2.4$, 3.6, 4.5 mm. The pipes used as specimens are shown in Figure 13 before machining the VSDs and in Figure 14 after machining the defects. The specimen geometry will be the same as the one used by PRCI (Figure 11).

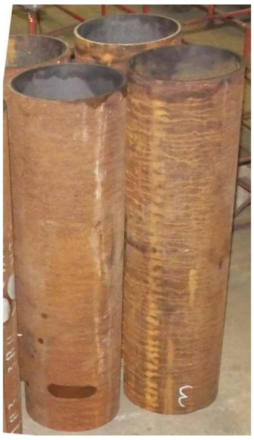

Fig. 13. Blank pipes used for specimens

Fig. 14. Defects machined on two specimens

4. Description of the planned experimental programme

Two composite repair systems are intended to be investigated in our experiments, the ICECHIM wrap repair (described in section 2, while its main properties are indicated in Table 1) and a system using fibre glass EC10 1680, combined with the polymeric resin КДА-XI (its properties are also shown in Table 1). We plan to use this system instead of KBP as its properties are more suitable for pipeline repair. However, further tests will be performed to better define the values of the composites properties. The composite wrap thickness will be defined according to the recommendations of ISO / TS 24817 [4] and the design procedure detailed in [7].

The test planned will comprise hydraulic burst tests of 4-6 specimens and also testing under cyclic pressure loading. Bursting tests will be performed in the first stage for a bare pipe specimen without defect, then for a specimen without defect and a composite wrap applied and also for a third specimen with VSD but without composite repair. In the second stage, several specimens with VSD and repaired with composite wraps (using both investigated systems, IWR and EC10 1680) will be tested.

During the first stage of pressure loading (from zero up to the strain limit of gage), the measurement of pipe strains will be done using strain gauges preliminary installed on each specimen surface. Two gauges (one in the axial direction and one in circumferential direction) will be placed outside the repaired area of the specimen and another two in the VSD areas, before applying the filler and composite wrap. Strain measurement of repaired specimens will be done before (in the elastic region) and after applying the wrap.

We are considering also the possibility to apply composite wrap on a specimen with VSD subjected to internal pressure (thus simulating an in-service pipeline repair) and to analyse the effect of a pressure decrease on the system pipe-wrap.

In most cases, the main load of a transmission pipeline is the internal pressure, that is not constant in service and changes most significantly during pumping starts/stops and periodical hydraulic tests. This creates the prerequisites for low-cycle failure in the zones of stress concentration, among which VSDs. Furthermore, any cyclic loading could adversely influence the reinforcement effect of composite wraps applied in the damaged zone. Therefore, we regard the cyclic testing of full-scale specimens with composite wrap repair system as another important direction of our experimental activity, especially taking into account the important experience in this field accumulated by the research team from E.O. Paton Welding Institute [8].

In the end, we mention that recent testing has shown fatigue lives for pipelines repaired with composite wraps ranging from 20,000 to 500,000 cycles, at a pressure level equivalent to 36% SMYS and VSDs with a depth equal to 75% of the wall thickness [10].

5. Conclusions

The repair of the areas with metal loss local defects of the transmission pipelines applying composite materials wraps has been used from some time, but the problems regarding it did not found yet technical solutions fully underlain and unanimously accepted.

For this reason, the authors of this paper intend to perform an experimental programme with the aim of studying the reinforcement effects of such repair systems. This programme will complete previous results obtained separately by the authors and will investigate also new problems, among which the behaviour of repaired pipelines under low cycle pressure.

6. Acknowledgements

The research leading to these results has received funding from the European Union Seventh Framework Programme FP7-PEOPLE-2012-IRSES, under the grant agreement n° 318874 "*INNOPIPES*" – ***Inno****vative Nondestructive Testing and Advanced Composite Repair of* ***Pipe****lines with Volumetric* ***S****urface Defects.*

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