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REVIEW ARTICLE

Critical and Comprehensive Evaluation of High Pressure Pipeline Rehabilitation Methods and Patents for Seeking Innovation Trends

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Abstract: ***Background:*** Fluid transport pipelines are subjected to operating conditions that generate their continuous deterioration. The deterioration rate is of great significance when the pipeline is considered a high pressure line (above 200 psi), which can lead to major loss of life and assets in case of any system's failure.

Objective: This study seeks for innovative pressure pipeline intervention methods used in industry, like the oil & gas.

Methodology: An exhaustive revision of literature from diverse sectors of pressurized fluid transport through pipelines was performed, with special emphasis on oil & gas sector. The traditional criteria were reviewed including the possibility of implementing the intervention while in service, the possibility of application of the method with leakage, the classes of defects in which the method is effective, material classes, user-friendliness, and risks associated with the implementation of the methods. The new principle depends on the ability of the method to relieve the stresses of the intervened area immediately. A patent review of trench technologies was also performed to emphasize innovation evolution and possible investigation trends referring to "active" interventions.

Conclusion: The selection of rehabilitation methods is dependent on the degree of the integrity improvement, operability and the desired increase in the remaining life. Most of the developed technologies are applied with the common defects found in the pressurized transportation pipelines. There has been an important change in the generated patents for the industry that shows the evolution from mere mechanical containments to hybrid rehabilitation methods that lead to the "active" trend.

Keywords: Gas pipelines, pressure pipeline rehabilitation methods, repair methods, active rehabilitation, passive rehabilitation, patents.

1. INTRODUCTION

In the transport of flammable fluids through pipelines, due to the high and potential costs that result from a failure in these systems (loss of life, damage to people or property and penalties from service´s interruption), it is important to develop and to have rehabilitation techniques that ensure the integrity of these installations over time in a cost-effective way.

Fluid transport pipelines are subjected to operating conditions that generate their continuous deterioration; such as physical, mechanical or chemical external actions of people, machinery, nature, soil or surroundings as well as the severity, physical-chemical aggressiveness, levels and variability of the flow parameters of the transported fluid.

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These interactions can cause defects in the piping and all the system's elements. These flaws affect the integrity and safety of the installation, making it necessary according to international standards and codes, the execution of interventions to remedy this situation.

It is important to define the types of possible interventions and their scope. The definitions are presented in a paper by Grigg *et al.* [1] concerning the purpose and scopes of the interventions made in the water transport industry, which include pressurized transport pipelines, such as oil and gas:

Repair: It is defined as a focused action or actions performed on transport pipelines, developed to restore the temporary and total loss of operational capacity at specific points of pipelines due to leakage, rupture or damage. For this reason, as it comes to restoring the operation of a pipeline that is temporarily out of service, these targeted actions must be imminent and temporarily used to restore the service or operation of the affected line immediately.

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Rehabilitation: It involves generalized and planned actions that are performed on an existing pipeline that is in service. It starts with a general diagnosis of its state, to restore, potentiate and update it to a condition similar or superior to the original. This allows both the significant extension of service life, of at least 20 years and the restoration or increase in the safety factors due to the reduction in the operating stresses.

Replacement: It involves actions to provide and install a "new replacement" of an existing transport pipeline or segment thereof. It necessarily implies the suspension of the service during the development of the intervention.

A first classical criterion of characterization and/or classification of repair techniques is related to the purpose of the intervention, concerning the level of restitution of the integrity, safety, and operability of the restored element.

In general, this form of classification of the interventions developed in pipes has been presented in the majority of revisions and previous characterizations found in the specialized literature on the subject.

Analyzing the variety of requirements of the operators and maintainers of these assets, this study presents new classification and analysis criteria that are relevant for the sector. The proposed criteria and primary factors for the selection and classification of intervention methods can be divided into two main categories: Traditional and Non-Traditional criteria. Traditional classification criteria are those usually implemented by the industry and literature. Non-traditional criterion states for a novel classification for the rehabilitation methods which have not been found in the literature.

A traditional selection criterion is the characterization of the defects for the selection of an effective intervention method for each specific flaw. Another traditional approach corresponds to the need to perform the intervention with or without the suspension of the service. According to Pinzon *et al.* [2]:

Hot Rehabilitation Methods: Methods that can be made in service without suspending or modifying the operating parameters of the pipeline, are called **hot rehabilitation methods**. For example, compression clamps applied to pipe leaks.

Warm Rehabilitation Methods: These include rehabilitations that are made in service, reducing the level of some operating parameters. For example, the application of composite reinforcement sleeves over a pipe defect.

Cold Rehabilitation Methods: These are rehabilitation methods that require the suspension of the service for its implementation. For example, cutting and replacing a pipeline section.

A final traditional classification criterion is the ease of execution and the risk generated during the intervention, which will depend on the number and complexity of the necessary steps, the training level of the operators and the level of exposure to mechanical, chemical or electrical risks associated with the intervention, among others.

Finally, a non-traditional criterion of selection and/or classification of rehabilitation methods was proposed. This criterion is novel in relation to the analyzed literature and refers to the need for the rehabilitation method to immediately generate a relief in the stress level of affected element, or by default, work as a backup when a total or partial failure occurs in the affected section. Under these circumstances, those methods that immediately relieve the effects of the service condition on the affected region, are here called as active rehabilitation methods; while the latter, which act as a backup, are referred here as passive rehabilitation methods.

When a pipeline segment has a defect and it is subjected to operation to dynamic pressure or operates with static stresses under a corrosive media, it is important to immediately or “in the short period of time” relief the stresses in the substrate material, by reducing the pressure or applying an “active” rehabilitation method that produces this effect, according to the basic principles of fracture mechanics. This active criterion is convenient in situations with progressive damage growth, very close to the limit values established by standards or when the rate evolution of the failure mechanism grows exponentially with the level of stresses in the intervened area. According to what was previously said, active interventions avoid further damage or eventual collapse of damaged pipeline segment.

Some examples of the active rehabilitation methods are the outer reinforcing sleeves with separating mechanisms between the tube and the sleeve that immediately propitiates the total or partial transmission of load from the tube towards the reinforcing element. On the other hand, examples of passive rehabilitation methods are outer sleeves or bandages made of composite materials that do not immediately propitiate the total or partial transmission of the load unless an evolution of the failure occurs so that the reinforcement is a back-up.

Based on the fact that traditional criteria are the most used in the pressure pipeline industry for intervention classification and selection, the following sections provide a precise and in-depth analysis of typical defect and rehabilitation methods implemented. A final review of rehabilitation and repair patents is made in order to point out opportunities based on the restoration of the pipeline performance and the novel classification criterion of active and passive solutions.

2. DEFECTS

Pipelines are prone to particular kind of failures based on the type of material, physical design, age, functionality, and the internal and external environment to which they are subjected. The damage and collapse of a pipe are the results of a complex interaction between several mechanisms occurring in and around the tube according to Sihna *et al.* [3]. The impact of the deterioration of a pipeline system is dependent on factors such as size, complexity, topography and service provided. It is almost impossible to predict the moment of collapse of a pipe; however, it is possible to estimate if a pipe has deteriorated sufficiently for the collapse to be probable. It is relevant to define the terminology related defects in pipes:

- **Anomaly:** It corresponds to a deviation of a characteristic condition in the pipeline from the one specified in the standard. All materials contain anomalies, which may or may not be detrimental to material’s performance.

- **Imperfection:** It is defined as an anomaly with dimensions or characteristics that do not exceed acceptable limits.
- **Defect:** A defect is defined as an anomaly with dimensions or characteristics that exceed the acceptable limits.

Pipelines have anomalies classified as incorporated or anomalies generated in the long term. The built-in anomalies are those that result from the construction of the pipe and represent conditions that affect the performance of the line after installation. These can be deviations in alignment, uncorrelated or loose joints due to vibrations, flattened or oval tubes, falls due to positioning, stresses caused by dynamic fill loads, removal of trench lining and piles, compaction upon overloading, *etc*. Cossio *et al.* [4]. Long-term anomalies are a result of the regular process of pipe deterioration. Some causes of long-term pipe deterioration are sulfate corrosion due to pipe gasses, excessive hydraulic flows, structural failure, soil weakening, environment, leakage, infiltration, and erosion. The industry responsible for transporting flammable products such as natural gas and oil, has used pipes as a preferred means of transportation; which are generally made of ferrous metals that are susceptible to corrosion and even more so if they are operating in highly corrosive environments such as those in the depths of the sea or other areas of water.

According to Shamsuddoha *et al.* [5], corrosion is undoubtedly one of the major challenges for the industry of transporting liquid products and flammable gasses, as it triggers other failure mechanisms that can lead to a collapse of the structure and multiple effects on people and the environment. As reported by Ossai *et al.* [6], there have been 360 fatalities, 1368 damages and 894 incidents that were related to failures in pipelines transporting oil, gas or some dangerous fluid between 1995 and 2014 in the United States.

Piping breaks are likely to occur when environmental and operational stresses act on pipelines whose structural integrity has been compromised by corrosion, degradation, installation or manufacturing defects. The types of pipe breaks are classified into three categories: (a) circumferential breaks, caused by longitudinal stresses; (B) longitudinal breaks, caused by transverse stresses (strain tensions); and (c) bell cracks, caused by transverse stresses in the pipe joint. In addition to these types, pits are present due to corrosion or impact. Circumferential ruptures due to longitudinal tension are typically the result of one or more of the following occurrences: (i) thermal contraction (eg, due to the low fluid temperature in the pipe and the piping environment), (ii) stress (Especially in clay soils) or large voids in pipe foundations as a result of leakage, (iii) inadequate excavation and foundation practices, and, (iv) interference from third parties as accidental breaks [7].

According to the above mentioned types, the types of defects that can be found in the pipes can be classified as:

- Loss of outer material: It is usually the result of external corrosion and is characterized by bites or large visible irregular depressions.
- Internal defects: These are the result of internal corrosion. It can only be detected from the outside through ultrasonic inspection techniques, by measuring the wall thickness.
- Indented faults: Contact with excavation equipment usually causes these defects. They can be dents, crevices or scratches. They may contain cracks that can lead to or cause fatigue, stress corrosion, or arc burn (welding).
- Cracks, scratches, notches or slots oriented longitudinally.
- Defects oriented transversely (not in a welded joint).
- Cracks oriented along a spiral.
- Buckles or wrinkles
- Arc burns.
- Blisters.

Consequently, maintaining the integrity of transport systems is crucial, given the explosive nature of the fluids to be transported, any failure could have catastrophic consequences, with supremely high costs. Due to the above reasons, there is a growing awareness and concern among pipeline operators and maintainers of developing effective and low-cost repair and rehabilitation methods that will reduce the economic losses associated with both the consequences of accidents and maintenance costs of the structure.

Considering that the expected life of a new gas pipeline is 30 years, rehabilitation should lead to a significant extension of operational life. According to the literature, this extension should be at least 2/3 of the initial life*, i.e.,* 20 years so that can be an attractive alternative to substitution, Mannesmann *et al.* [8]. Therefore, the selection of an effective and efficient method of rehabilitation requires both a critical and comparative evaluation of state of the art in rehabilitation methods and the correlation of its effectiveness with the most representative pathologies or defects that have been identified after a rigorous assessment of the pipeline to intervene.

3. REHABILITATION METHODS

The following presented techniques can be used for rehabilitation labors in gas transportation pipelines. It is important to keep in mind that some practical principles of the repair methods are the same used in rehabilitation techniques, what changes is the purpose of their implementation.

The rehabilitation of pipes can be performed, in general terms, in two ways: (i) from inside the pipe; and (ii) from the outside of the tube. The former does not require the construction of trenches around the tube, thus avoiding excavation processes and alterations that affect surrounding areas; however, a service interruption is necessary during this type of operation. On the contrary, the methods that are implemented on the outside, require the construction of ditches (except in aerial sections), but it is not necessary to interrupt the service.

Due to the characteristics of the gas pipeline layout and the need to ensure the availability of the fuel supply, rehabilitation processes are usually done with methods that intervene the outside of the pipe.

The following are the main techniques that are currently used to rehabilitate pipe sections without interruption in the service, referred in Farrag [9], which are as follows:

1. Grinding.
2. Full Encirclement Sleeve.
3. Mechanical Clamps.
4. Composite Wraps.
5. Deposited Weld Metal.
6. Patch.
7. Hot Tapping.

The application of each of these methods depends on the type of failure and the operating conditions to which the pipe will be exposed. It is a challenging task to choose a particular repair method since there are many relevant variables in the selection process. But without a doubt, to make a right choice, it is necessary to know the relevant technical information for each alternative, to know what the best solution for each specific case is.

3.1. Grinding

Grinding is a technique that consists of smoothing down the surface of the pipe to remove imperfections and then coating the tube to protect it against corrosion. It is usually done using an abrasive disk in the areas where superficial flaws are located. This method is applied mainly when the pipe has defects such as dents or cracks and is only used if it is possible to eliminate the stress concentrator.

Care must be taken to avoid reducing too extra surface of the pipe so that it can withstand the pressure in which it is operating. It is also important to control the amount of heat supplied to the pipeline because it is possible that the transported fluid will ignite. When this type of operation is carried out, the working pressure is reduced by approximately 20%.

The ASME B31.4 code allows this type of repair to be performed up to 10% of the nominal pipe thickness without limiting the extension of the grinding zone and up to 40% of the thickness, just if the size of the defect does not exceed the specified limit given by the standard.

The following Table **1** summarizes the advantages and disadvantages of this rehabilitation method.

Table 1. Advantages and disadvantages of grinding.

GRINDING	
ADVANTAGES	**DISADVANTAGES**
Quick procedure	Pressure must be lowered
Low cost	Size limitations of defects
It does not require highly specialized personnel and/or equipment	Only for external defects
Can be used in conjunction with other repair or rehabilitation techniques	It requires further inspection by penetrating inks or magnetic particles

3.2. Full Encirclement Sleeve

When the pipe presents severe signs of wear, deterioration or damage, it is recommended to use a reinforcement sleeve that is composed of two circular caps, typically of steel, that are located around the pipe and are then joined longitudinally by welding (to butt or overlap welding).

Reinforcing sleeves are classified as Type A and Type B. Type A sleeves (Fig. **1a**) are not welded to the transport pipe and do not contain pressure. Therefore, they are only used for defects where there are no leaks. Types B sleeves (Fig. **1b**) are welded to the transport pipe and can be used to repair leaks or reinforce areas with circumferentially oriented defects. Depending on the design, this type of reinforcement can partially or entirely withstand the pressure of the pipe. This type of method requires greater technical control in the manufacture and inspection of its integrity.

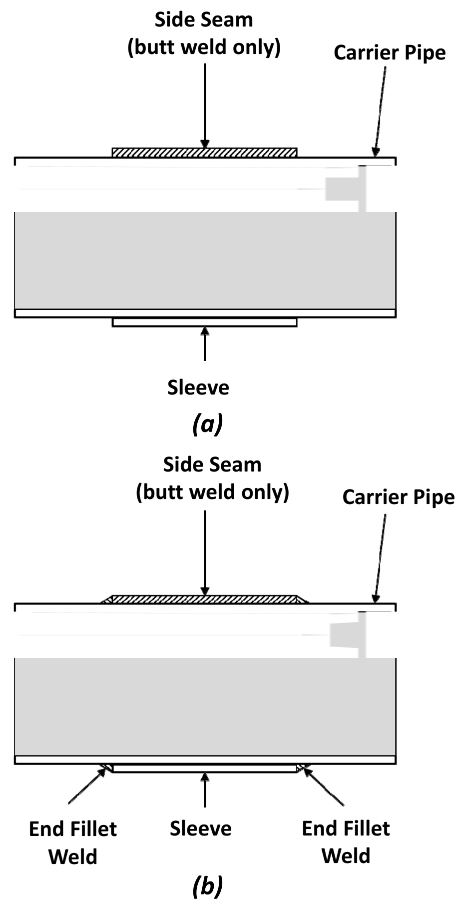

Fig. (1). a) Representation of sleeve type A. **b**) Representation of sleeve type B.

3.2.1. Conditions to Ensure an Effective Reinforcement

Type A: The function of the sleeve is to reinforce the defect area, restricting bulging or radial swelling as much as possible. The sleeve must be installed minimizing the free space with the pipe.

To ensure the effect of the reinforcement, the following conditions must be guaranteed:

- The pressure of the pipe must be reduced during the installation of the sleeve.

- External load must be applied to the sleeve to force the sleeve against the surface of the pipe.
- A material should be used to fill the annular space between the sleeve and the pipe.

Type B: This sleeve configuration is connected to the tube, allowing the repair of leaks and reinforcing the areas with circumferentially oriented defects.

It is recommended to butt weld in any of the three variants shown in the following Fig. (**2**). Fillet welding is not recommended.

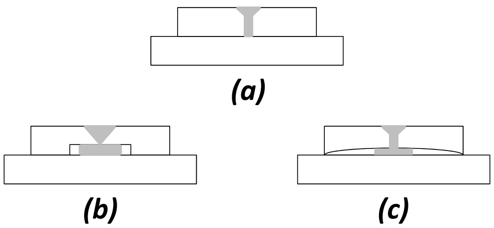

Fig. (2). Acceptable butt weld in Type B sleeves. (**a**) Without backing plate; (**b**) With backing plate and slot; (**c**) With backing plate without slot.

The sleeve type B must be designed to withstand the same pressure with the transport pipe, which implies that both the wall thickness and the material (Grade) of the sleeve must be at least the same of the tube. It is acceptable to use thinner or greater thicknesses depending on the strength of the material being used. In case the type of welded joint is the option (b), a greater sleeve thickness is recommended to compensate for the thickness loss due to the groove.

When the thickness of the sleeve exceeds the pipe's measure by more than 2.4 mm, it is recommended to include a chamfer with a slope of 4: 1.

The diameter of the sleeve should be slightly bigger than the pipe's diameter so that the two shells can fit over the pipe. Another alternative is to use the same pipe diameter but to extend the halves beyond a half circle. In this case, a greater free space will be generated between the sleeve and the pipe surface.

Type B sleeves require a more precise manufacturing than Type A sleeves. Poor fitment could lead to a diminished load-absorbing capacity in the sleeve, reducing the reinforcing effect. In addition, qualified technical personnel and a suitable welding procedure are required. For welding in pipelines in service, consideration should be given to cooling speeds and depth of penetration.

The length of the sleeve must extend at least 50 mm at each end of the defect. If there are several sleeves along the pipe, they must be installed with a minimum weld spacing of half of the diameter of the pipe to avoid a concentration of stress between the two sleeves.

When the length of the intervention is greater than four times the diameter of the pipe, supports must be considered in the pipe during the rehabilitation operation.

The advantages and disadvantages of each reinforcing sleeve are summarized in the following Table **2**.

3.3. Mechanical Clamps

This method consists of two shells or caps that are mechanically joined, typically by bolts, to form a shell, reinforcing the affected area of the pipe. It can be used in imperfections such as leaks or damages caused by high loads.

This type of solution is characterized by being very robust since bolts are used to generate the compression force on the pipe and to prevent crack growth, which could induce

Table 2. Advantages and disadvantages of type A and type B sleeves.

TYPE A	
ADVANTAGES	**DISADVANTAGES**
High structural integrity with short defects ($L < \sqrt{20\,Dt}$) D: diameter; t: thickness.	Not suitable for circumferentially oriented defects.
Simple manufacturing.	Not suitable for leakage repair.
It does not require rigorous nondestructive inspection.	It generates an annular space that can be difficult to protect against corrosion.
It may have smaller thicknesses than the pipe (2/3 t).	Difficult installation in accessories or curved sections.
TYPE B	
ADVANTAGES	**DISADVANTAGES**
It can be used to repair leaks.	It requires careful manufacturing.
Suitable for circumferentially oriented defects.	It requires rigorous nondestructive inspection.
It absorbs longitudinal loading by lateral loads.	Requires the same thickness as the pipe.
Long pipe lengths can be rehabilitated.	It can induce microstructural changes (pipelines in service).
Suitable for reinforcing areas with internal corrosion.	Effort concentration should be considered in the fillets at the ends of the handle.
	Difficult installation in accessories or curved sections.

additional stresses in the pipe, according to Oh *et al.* [10]. Its ease of installation and low level of training required for operators make it a very useful type of intervention.

It is possible to find some clamps capable of producing sealing by themselves without welding, using some material as the interface between the pipe and the casing. There is a great variety of clamps, although most are elements that occupy a great volume, these can be in different forms and configurations depending on each manufacturer. Hopkins *et al.* [11] reported that some can be installed in curved sections of the pipe without any problem.

Its great weakness is corrosion, since the metallic components with which the solution is made, are not suitable for working in highly corrosive environments, problems with sealing may also occur, but this can be solved by applying welding [12].

Usually, the clamps have an elastomeric component that can act as a seal in case of leakage in the pipe.

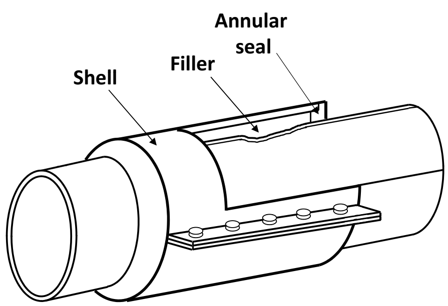

Fig. (3). Mechanical clamp.

The advantages and disadvantages of the use of mechanical clamps (Fig. **3**) as a rehabilitation technique are summarized below in Table **3**.

Table 3. Advantages and disadvantages of the use of mechanical clamps.

MECHANICAL CLAMPS	
ADVANTAGES	**DISADVANTAGES**
They can be adapted to any material and pipe diameter.	Great size and weight.
Quick and easy installation.	A high cost of implementation.
They can repair leaks.	
It does not require rigorous inspection.	

3.4. Composite Wraps

Composite materials have been used for decades in structural applications in the aerospace, naval and construction industries. Different types of sleeves or reinforcement linings with composite materials have been developed over the last years. This type of reinforcement has become attractive in the industry due to its simplicity in installation, which requires a lower level of expertise in the personnel, the installation is faster and is done in continuous operation. They are currently used to repair defects in non-leaky pipes.

In these types of methods, at least two components are required: one that will be the matrix and another that will be the reinforcing fiber. The matrix is usually a polymer resin, while the reinforcement is generally glass fiber, and in some cases carbon fiber.

This type of method is allowed by current regulations to repair thickness loss defects, including the United States Department of Transportation and the CSA standard Z662 (Oil and Gas pipeline systems).

In general, composite reinforcements can be installed in straight, curved or connecting sections because of their flexibility before curing. During installation, it is important to keep the roll tensioned.

Besides the use of fiberglass, aramid and carbon fiber are also used, because they increase the piping resistance, durability, and anticorrosion properties, in agreement with Toutanji *et al.* [13].

In general terms, the design of a composite reinforcement should consider at least four aspects:

- The minimum thickness required for the reinforcement.
- The pressure at which the repair system must be installed.
- The pre-tension to be applied to the composite material.
- The minimum length of reinforcement needed beyond the ends of the defect.

It is recommended that the composite reinforcement extends at least 50 mm beyond the edge of the defect. This type of support requires preliminary tests of cathodic disbondment to ensure its future functionality.

According to the studies conducted by Duell *et al.* [14], it was estimated that on average, these systems are 24% cheaper than soldered solutions and about 73% cheaper than replacing the damaged pipe section. Also, the use of this type of reinforcement has demonstrated a significant reduction in the corrosion of the pipe.

The following table (Table **4**) summarizes the advantages and disadvantages of this rehabilitation technique.

3.5. Deposited Weld Metal

This method (Table **5**) seeks to restore the pipe by applying welding on its surface.

It cannot be implemented if there is a leak and because it is such a risky procedure, special preventive measures have to be taken, such as the use of a particular electrode that reduces hydrogen emissions. Hydrogen in large quantities could lead to rupture of the structure.

Another important aspect is the technique used to apply the weld and the number of passes, since in many occasions due to improper practices; inclusions are generated inside the weld that can lead to brittle bonding [15]. It is important then to correctly select the sequence in the welding process.

In pipelines in service, the pressure and the flow of the fluid can generate high rates of cooling of the welded area. This can cause brittleness in the pipe.

Table 4. Advantages and disadvantages of composite wraps.

COMPOSITE WRAPS	
ADVANTAGES	**DISADVANTAGES**
They can be used in straight sections, curved or in accessories.	They cannot be used to repair leaks.
Fast installation in straight or curved sections.	Tension should be applied to the reinforcement during installation.
Lower intervention costs.	Preliminary tests of cathodic disbondment are required.
They require less trained personnel than in welding techniques.	Limitations in operating temperatures.
	The storage, transport, and handling of the materials must be done under strict conditions.
	Preparation of the pipe surface is required.

Table 5. Advantages and disadvantages of deposited weld metal.

DEPOSITED WELD METAL	
ADVANTAGES	**DISADVANTAGES**
Adaptable to curved or accessories sections.	Cannot be used to repair leaks.
Rapid rehabilitation.	Highly trained personnel are required.
It only requires filler metal as an input.	Risk of penetrating the pipe (minimum required thickness of 3.2 mm).
	Possible microstructural changes in the pipe.

3.6. Patch

Patches can be used to repair leaks. Typically a patch covers a limited region of the surface up to half of the circumference of the pipe. They can be made of metal or composite material. This method is very sensitive to manufacturing defects and is limited to low-pressure applications.

3.7. Hot Tapping

This method can be used to repair defects in pipelines in service. The hot tapping procedure consists of attaching a bypass and a valve to the outside of a running pipe. The pipe wall is then cut into the bypass, and the wall section is removed through the valve. The use of hot taps prevents the loss of product, the emissions of fuel transported and the interruption of the service to the consumers.

On the other hand, it should be ensured that when performing the section cutting operation, the entire defect is covered in the pipe and that the installed hot tap can withstand the stresses to which it will be subjected in the pipeline [12].

4. DISCUSSION: EVOLUTION OF PIPELINE REHABILITATION METHODS

This evolution analysis is based on a review of the patents related to the rehabilitation and repair solutions developed for the pressurized transport pipeline industry. This review is focused on trench interventions. Trenchless patents are not included because of the need of interruption in the service for their implementation. The developments and patents have been oriented to the implementation of removable sleeves capable of containing leaks and provide structural support to the pipeline infrastructure.

Among the first inventions available before the 1970s, there are leakage containment solutions for pipes that integrate basic mechanical tightening systems. The patents from James and Alice [US2651329A] [16] and Palmer [US865056A] [17] consist of cylinder caps coupled to flammable fluid transport steel pipe. The caps are secured and tight against the tube, employing mechanical elements for the generation of locks or using screws. The patent [US3496963A] [18] proposed by Bardgette *et al.,* implements a joint bladder with a conventional clamp. This bladder is filled with gaseous or liquid fluid, posterior to the mounting of the clamp, generating pressure in the affected area. This innovation is one of the first systems that implements active rehabilitation principles in pipes.

In the 1980s, inventions were made incorporating the active rehabilitation principle for sealing leaks. The British Gas Corp patent [GB2093146A] [19] integrates the use of injectable resin under pressure inside a jacket, generating tightening pressure and sealing on the external surface of the defective pipe. The patent from Manfred [US4448218A] [20] incorporates the use of jackets with a flexible inner wall, in addition to the injection of resins of cold solidification, for the stoppage of leaks or superficial defects. The injection of resins in these solutions seeks to generate tightening contact between the jacket and the tube, to stop a leak. Stig's patent [US4647072A] [21] utilizes the mechanical principle of the spring to generate compressive forces on a jacket element that covers the pipe. These developments have the disadvantage that the external pressure generates by the resin in liquid state disappears when the resin suffers a great volumetric shrinking during the curing process. Therefore these solutions offer an active effect of short duration. Finally, the invention from Keith [US4653782A] [22] is made of a clamp with internal walls that seek to retain leakage in pipes with defects. The two halves of caps are fastened between them, generating the required seal.

In the 1990s, the patents developed were similar to those created in the previous decade. The patents from Gilleland [US5042532A] [23] and Charles [US5118139A] [24] are

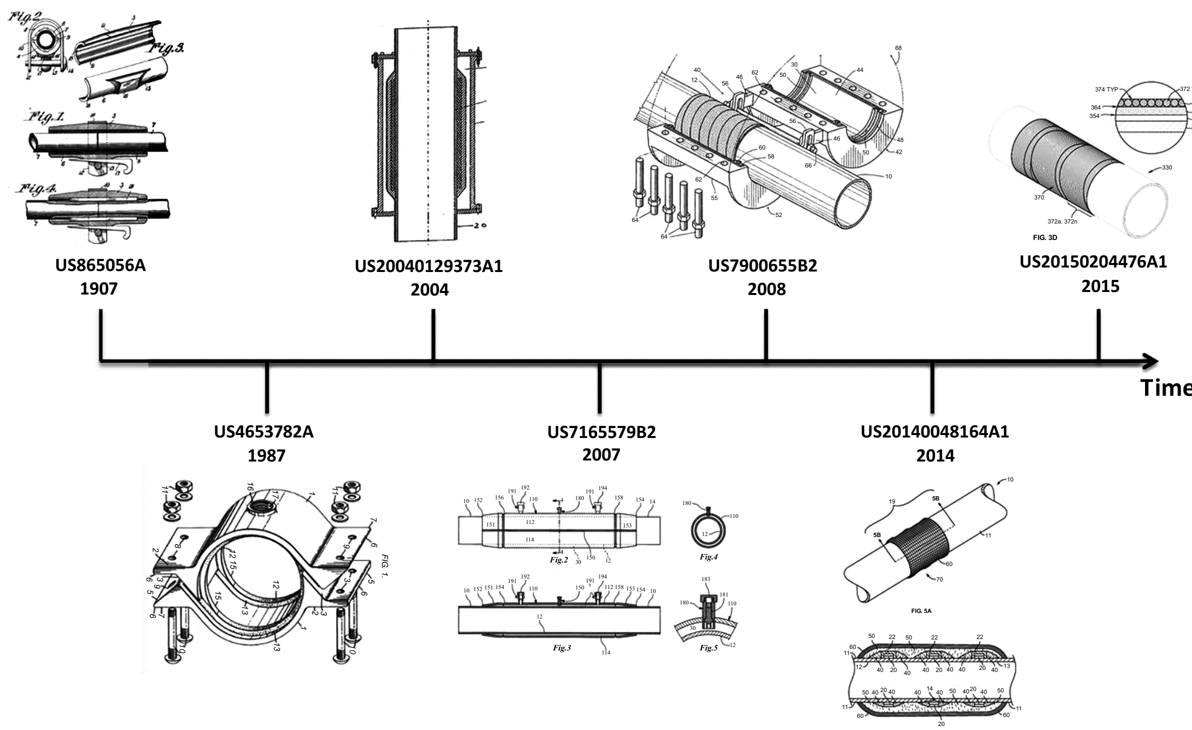

Fig. (4). Timeline of patents designed for rehabilitation and repair of natural gas pipelines.

based on sleeves and clamps, respectively. These inventions seek to generate tightness for the sealing of leaks. The G. Alfeo and P. Valentino´s patent [US5345972A] [25] represents a breakthrough in the development of active rehabilitation solutions in the presence of defects in the pipe. It consists of welded caps around the defective tube, with circumferential seals at the ends. Subsequently, pressure resin is injected into the interstitial space between the pipe and the repair sleeve.

In the next decade, the inventions by Jim [US6220302B1] [26], Ronald A. [US6276726B1] [27] and Gaston *et al.* [US6675836B1] [28] seek to repair leaks by implementing mechanical sealing clamps against the pipe. The inventions by Laurence S., *et al.* [US6305719B1] [29] and Abdulaziz K. [US7617843B1] [30] integrate the use of pressure fillers resins of fast-setting properties, within sleeves or metal clamps. These patents are focused on repairing leaks in natural gas transport pipelines. These developments replicate what was patented in the 1990s. Nevertheless, some patents are proposed which use a hybrid system of resin-filled sleeves alongside with a mechanical tightening system to the defective pipe. Patents by Nagendran *et al.* [US20040129373A1] [31], Boulet *et al.* [FR2851635A1] [32], Станислас *et al.* [RU2300045C2] [33] and D'Auria *et al.* [US20060162797A1] [34] are constituted by composite materials or steel rods helically arranged on the pipe, which compress the tube while in operation. These elements are then covered by a removable sleeve having an interstitial space which is filled with pressurized resin. These inventions implement hybrid systems for leakage repair in pipelines. In the second half of the decade of 2000s, a significant advancement was made in the development of active solutions. Kakoschke *et al.* provided a patent [US7066210B2] [35] that generates a compression pressure on the pipe by the implementation of sleeves with mechanical tightening systems. This alternative has the power to carry out a permanent rehabilitation reducing the stress state of the defect and the pipe, becoming an active solution. The solution proposed by Morton *et al.* [US7900655B2] [36] integrates the use of composite material for defect repair. The composite casing is then covered by a removable jacket that allows the injection of a gaseous or liquid fluid that reaches the same pipe's pressure. The composite fiber is tensioned and then cured under these conditions. Subsequently, the sleeve is removed, leaving a composite material wrap that relieves the stresses of the defective area. Finally, Borland *et al.* [US7165579B2] [37] follows the principle of an active repair, relieving the tube stresses by introducing fluid under pressure into a metal jacket.

In the last decade, at the beginning of 2010, the inventions by Skellern *et al.* [US20110241342A1] [38], Venero *et al.* [US20110284115A1] [39], Benson *et al.* [US20130255816A1] [40], Patriarca [US20160109050-A1] [41] and Clark *et al.* [US8210210B2] [42] continued to be mechanical tightening clamps with filling grooves for containment of leaks. Solutions proposed by Wolf and Peschka [US7950418B2] [43], Rice [US7673654B2] [44] and Morton [US7673655B1] [45] are composed of composite liners which are based on the pressure curing of the fiber and resin previously injected into the repair. The protective seal invention by Lazzara *et al.* [US8522827B2] [46] introduces the use of various composite fibers that cure and protect the surface of steel joints and pipes against corrosion. Neptune research's patent [US20150204476A1] [47] shows the application of unidirectional fiber layers joined by the application of resins, forming a single composite reinforcing sleeve element. Finally, in 2014, a hybrid system was developed by Souza [US20140048164A1] [48], which consists of compressive bands that generate tightness in the pipe, covered by epoxy resins that avoid the penetration of humidity. The entire system is then covered by a composite wrapping material that protects against corrosion.

It can be seen that most of the generated patents started with the use of clamps of mere mechanical containment to more complex reinforcements based on sleeves that implement composite materials. The latest advances implemented a hybridization of the solution alternatives, integrating the use of mechanical options along with the composite materials in the presence of a defect. In the last developments, the importance of creating a similar effect as the reduction of the internal pressure is contemplated to relieve the substrate's stresses, using external mechanisms. This fact highlights the importance of the application of active rehabilitation systems to increase the reliability of the repairs in pressure pipelines or natural gas transport pipelines based on fracture mechanic principles. This thesis is also is shared by *PRCI* [12] where the importance of the pressure reduction during the repair method implementation is stated.

Based on the aforementioned facts, a timeline summarizing the development of patents for the repair and rehabilitation of flammable fluid transport pipelines is shown in Fig. (**4**).

CONCLUSION & FUTURE DEVELOPMENTS

After analyzing state of the art concerning the defectology that occurs with greater recurrence in the pipelines and the existing methods of rehabilitation, it is identified that the most common defects according to statistics and consulted literature are: dents, scratching, indentations, corrosion and cracking under corrosive stress. At the same time, it can be concluded that the most explored methods have been the rehabilitations using sleeves type A and the external rehabilitations using composite materials. These techniques apply to a wide variety of defects in the pipe, and besides, their implementation is economical and safe compared to line replacement or welding operations on flammable fluid transport pipelines.

With respect to the alternatives of sleeves, the following opportunities for innovation and improvement are presented as a result of the patent review:

- The benefit of stress relief of the defective area is to be achieved during worksite repair, without reducing the operating pressure of the pipeline.
- Different resins or composite fillers must be explored for sleeves that allow a better structural performance of the solution system.
- Active resin solutions with implementation procedure must be developed that allows extending the active effect of the sleeves filled with resins in spite of the resin shrinking.

Concerning composites, the following innovation opportunities are initially visualized:

- The trend in repairs that implement composite materials is to make systems lighter, stronger and less expensive. Chemical compatibility, corrosion resistance and ease of application are requirements that must be taken into account.
- Current compounds are good regarding stress, flexibility, and resistance to chemical attack. They consist of glass, carbon or aramid fibers [49]. The major problems encountered in the composite pipe repair industry are those associated with resin limits, both in high temperature and low temperature (cryogenic) applications. The resin strength, elongation and thermal expansion will vary depending on the formulation thereof.
- It is a matter of interest to develop low-cost cement resins or pastes that can operate properly under high-pressure conditions. The most economical resins are polyesters and vinyl esters. There are also, the epoxy resins with a more intermediate cost. Epoxy resins have an average performance better than those previously stated under severe operating conditions, regarding corrosion and temperature endurance.
- There is an innovation opportunity developing a cement paste from the commercial offer of dental cement or construction cement. It is desirable that the inventions be either rapid curing or rapid hydration, with high resistance or with short setting time, type II-R and III commercial types of cement. For corrosion resistance, type II or V cement may be used which behaves well under corrosion. Also to improve the waterproofing, it is possible to use waterproofing additives or nano-additives. The curing time of a resin or cement can be reduced with additives or by another curing acceleration mechanism, such as photocuring depending on the adhesive or cement. Usually, hydration hardened cement requires more time for this than other types of resins.
- It is important to find or determine which low-cost fiber could sufficiently improve the integrity of the pipeline when it is applied to correct defects present in the pipeline. In this sense, alternatives with fiberglass or new reinforcing fibers with cables, rods or steel meshes of high strength should be explored, without dismissing the use of organic fibers. The study for the latter case will requires a larger experimental phase.
- An important and obvious challenge is the development of active rehabilitation solutions with composite sleeves.
- An even greater challenge is the development of the active composite rehabilitation methods.

CONSENT FOR PUBLICATION

Not applicable.

CONFLICT OF INTEREST

The authors report no conflict of interest and have received no payment in the preparation of this manuscript.

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