Pipeline Technology Today and Tomorrow

*By T. CALLAN**

Transportation of liquid or gaseous hydrocarbons via buried cross-country pipeline generally represents the safest and most economic method of bulk movement of such products. In 2005 there existed worldwide a total length of over 1.5 million km of high pressure transport pipelines, not including water transmission pipelines or smaller bore distribution networks. By 2030, this figure is predicted to almost double, with much of the increase due to the construction of new gas transmission and distribution pipelines.

Historically, the development of pipeline technology has been driven by either technical challenges, or by the need to reduce cost. Key influences today are:

– Mitigation of environmental impact
– Acceptance by the public and authorities
– Competition with tanker transport (LNG, crude).

New applications, such as use of CO_2 pipelines in carbon capture, transport and storage (CCS) projects, represent a new challenge for the industry.

This article reviews the current status of onshore pipeline technology and makes some predictions regarding future trends. The presentation, which is an update of a similar status report prepared by ILF Consulting Engineers in 2001 [1], follows the life cycle path of a pipeline.

1 Introduction

The first main oil and gas pipelines were constructed in the late 1800's. Since then over 1,500,000 km of high pressure transport pipelines have been constructed worldwide, not including water pipelines, flow and gathering lines and low pressure gas distribution piping. This figure is expected to double over the next 25 years, as existing fields are depleted and ever more remote sources are developed. Furthermore, the increasing energy demand in developing countries such as China and India, as well as the moves of established markets to diversify energy supplies, will drive the need for new oil and gas pipeline transport corridors to be constructed.

The main historical factors driving development of pipeline technology have either been to meet new technical challenges, such as developing higher grades of steel to meet higher transportation pressures, and/or the need to reduce cost.

In recent years, the main factors driving development have been:

– Mitigation of environmental impact, including increased awareness of HSE issues. This has resulted for instance in the development of new methods and tools for risk assessment and minimisation during pipeline design, as well as implementation of sophisticated systems for leak detection and monitoring of pipeline integrity during the life time of the system.
– Acceptance by the public and authorities, whereby this is an area that has sometimes been underestimated by the designer or project owner in the past. The trend towards increased public awareness and sensitivity has been mirrored by the introduction of new legislation, such as requirements for more detailed Environmental & Social Impact Assessments of pipeline projects, including public hearings prior to issuing authority approval of a project.
– Competition between pipeline transport and other options such as tanker transport of Liquefied Natural Gas (LNG) or crude oil, which has been a continued incentive to drive down pipeline costs.

Given the need for increased pipeline construction in the near future, it is useful to take stock of the current status of pipeline technology and to analyse possible trends in the industry. This review follows the main steps in the life cycle of a pipeline following project conception, including: route engineering, pipeline design and selection of materials, construction, operation and maintenance. Only onshore pipeline technology is considered in this review, whereby it is recognised that offshore pipeline construction represents in itself a significant area of development.

2 Route Engineering

One of the first main activities following conception of a pipeline project is the route engineering. This defines how to connect the source, such as an oil or gas field, with a supply point, such as a tank farm or refinery for liquids, or take-off point to a local distribution network for gas. Although the easiest and cheapest way to connect supply and source is obviously via a straight line, in reality it is necessary to consider a large number of other constraints before being able to define the optimum pipeline route.

The most common practice today is to evaluate all these issues using GIS-based constraint maps, of which an example is shown in Figure 1. The different colours represent different types of constraint, such as nature reserves or archaeological areas, land use planning areas and geohazards.

Typical considerations regarding constraints include:

– Constructability, for instance consideration of the different type of terrain (geomorphology) and soil conditions (geology) through which the pipeline must be constructed. Rock conditions, may for instance be a constraint that leads to rerouting of a pipeline
– Safety of the route in regard to geohazards, such as seismic areas and fault crossings, areas of landslide, karst, erosion, liquefaction
– Minimum environmental impact, considering water table (hydrology), local nature reserves, special flora and fauna, biotopes, etc.
– Minimum resistance from affected stakeholders, general public and authorities, for instance, avoidance of inhabited areas and existing infrastructure as far as feasible, and consideration of historical or archaeological sites
– Finally it must be possible to acquire the right of way and easements required for construction and ongoing operation. This requires detailed information on catastral boundaries, land use and zoning to assist in land acquisition negotiations.

In the last 10 years route engineering has been revolutionized by the use of new mapping technologies using GPS (Global Positioning System) technology and use of satellite imagery and aerial photography. Furthermore, the development of GIS (Geographic Information Systems) based systems has allowed a huge variety of information to be digitally imported as background layers within the traditional pipeline alignment drawings. In particular for constraints mapping, it is possible to overlay information from a number of different sources onto a single map and so find the "path of least resistance".

The availability of aerial flight, satellite and shuttle imagery has allowed further development of the so-called Digital Elevation or Digital Terrain Models (DTM). Such models give a digital representation of ground

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Fig. 1 **Typical constraint map showing land use**

surface topography including geographical features such as vegetation, buildings and other infrastructure. Incorporation of the pipeline route into such a model is of great value for the route engineering, allowing for instance structural analysis of the pipeline, investigation of geohazards, flood and drainage modeling, as well as preparation of 3-D visualizations. It is noted that continuing improvements in the availability and resolution of satellite imagery may in the future negate the current advantages of aerial survey.

Of course traditional on-ground terrestrial surveying is still also necessary, in particular for detailed design of special points such as crossings, identification of third-party obstacles, as well as augmentation of DTMs where necessary. New developments, such as 3-D Laser scanning have improved the information available and reduced the time required for terrestrial surveying.

By integrating imagery, as well as topographical, environmental, land-use and catastral layers, with supplementary traditional survey data, is possible to generate all maps and alignment sheets required for pipeline construction. The availability of all this data in an integrated database simplifies any revision that may be required, for instance due to re-routings. Finally, this forms the basis of the Pipeline Information database that will eventually be handed over to the Pipeline Owner/Operator to support operations and maintenance activities.

One area of route engineering where there is still the opportunity for development in the future is to find a similar cost effective method for geological soil survey. Research has concentrated on infrared or radar-based surveys, but acquisition of data is still limited to upper soil layers. Investigations are ongoing into the use of seismic refraction surveys and satellite data for this purpose.

Finally, as already stated earlier, it is important during the route engineering to have an open communication with authorities and the public. As common-place as it now may seem, the increasing use of the internet has allowed a greater dissemination of information regarding potential pipeline projects, contributing to a general improvement in "public relations".

3 Pipeline Design and Materials

The route optimisation exercise defines an optimum pipeline corridor which may range from 10 km to 100 m width, depending on the stage of study and design. This gives the approximate pipeline length which is then used by the pipeline designer to define other

Table 1 **Steel tonnage for 1000 km pipeline 90 bar operating pressure**

Steel grade	Tonnes
X52	856,000
X70	639,000
X80	560,000

technical parameters of the pipeline, such as diameter and pipe wall thickness. One of the main parameters that the pipeline designer can adjust is the grade of steel to be used. As per the well known "hoop stress formula", the higher the grade of steel, the lower the theoretical pipe wall thickness necessary for a defined operating pressure. Lower wall thickness directly results in lower tonnage of steel that has to be purchased, transported and welded.

Over recent years, manufacturing improvements have resulted in an increase of the yield strength of pipeline steel commercially available, so that now API grade X80 is considered a viable option for high pressure pipelines, with X100 already in trial operation. Research is continuing into X120 grade and it is expected that this grade will become commercially available within the next 10 years. Welding procedures and consumables must also of course be developed to match the new materials.

Table 1 highlights the advantage in using a higher grade steel for a hypothetical transmission pipeline.

Clearly large savings in steel tonnage are possible. There is however a physical limit as to how thin a pipeline can be designed, based on manufacturing, handling and constructability considerations. The generally accepted limit is that minimum wall thickness should not be less than 1% of diameter. This corresponds for instance to 10 mm wall thickness on a DN1000 pipe. Although thinner walled pipes have been and are being constructed, it is necessary to have very strict control regarding handling, trenching, bedding and back-filling, in order to avoid problems such as denting and ovality of the line pipe. Furthermore, manufacturing techniques for the higher grade steels may limit the available minimum wall thickness: one pipe supplier, for instance, recommends a minimum thickness of 12 mm for X80 and 16 mm for X100 pipe.

Particularly for gas pipelines, there is an incentive to increase the operating pressure in combination with higher steel grade [2]. Figure 2 gives a set of curves showing the relationship between specific gas transport cost and annual gas throughput for a theoretical pipeline using grade X80 steel, comparing 56″ and 64″ pipeline diameter for various design pressures. In each case the compressor station pressure ratio (and hence number of compressor stations) has been optimised to give best efficiency. Specific transport cost is calculated as the discounted cost of investment (CAPEX) and operating / maintenance costs (OPEX) over 20 years. The curves confirm that for higher transportation pressure, the potential throughput increases for a given pipe diameter, while the specific transport cost reduces. For a "typical" intra-regional gas transport volume of 30 BCM (billion cubic meters per year), for instance, the curves show that a 56″ pipeline operated at 140 barg has an economic advantage over a 64″ pipeline operated at 90 barg. The 56″ pipeline could optimally transport even 40 BCM at a lower specific cost than the 64″ pipeline.

One of the difficulties associated with high pressure cross-country pipelines is the ability to get planning permission. A de-facto limit of between 80–90 barg maximum operating pressure seems to have become established in public and approval authority perception (sometimes partly defined by in-country legislation), although there is no significant technical reason why this limit should be the case. There is still a considerable amount of technical justification required in order to convince authorities and the general public of the safety of high pressure pipelines exceeding 100 barg. In particular, there is an increasing role for the use of Quantified Risk Assessment (QRA) in order to analyse risk scenarios, such as leakage, and to define mitigation measures in a transparent way.

Over recent years, there has been further development in the use of computer models to simulate pipeline hydraulics, as well as to analyse pipeline integrity and safety. Use of such computer models has also allowed more detailed monitoring and control of pipeline systems in operation. Particularly for crude oil and product transport, the accuracy of on-line leak detection systems has significantly improved over recent years.

One application of such software models during the planning stage is the analysis of environmental risk. Figure 3 shows the type of considerations that can be made for a crude oil pipeline for instance. The bottom axis shows the pipeline profile and location of block valve stations which may be closed in case of pipeline leak. The other axes show various factors such as potential leak quantity at each location, as well as location-specific sensitivity factors such as: ground water; land use; archaeology and so on. The top axis shows the environmental risk calculated as a factor. By placing block valve stations at optimum locations it is possible to minimise the overall environmental risk factor.

Use of sophisticated non-linear finite element models to investigate geohazards such as active seismic faults and splices has improved design of such crossings, whilst at the same time allowing to minimise construction costs.

Furthermore, pipe sections are now almost always provided with factory-applied high resistance tri-laminate coatings. When a high quality coating is combined with an impressed Current Cathodic Protection (CP) system in an installed pipeline, the possibil-

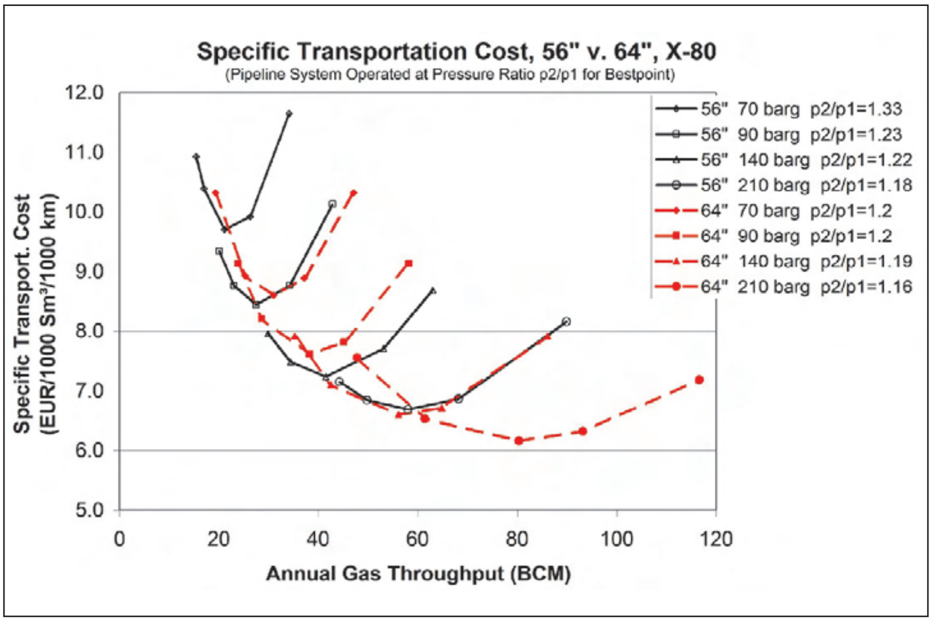

Fig. 2 Comparison of specific transportation cost for a gas pipeline at different operating pressures

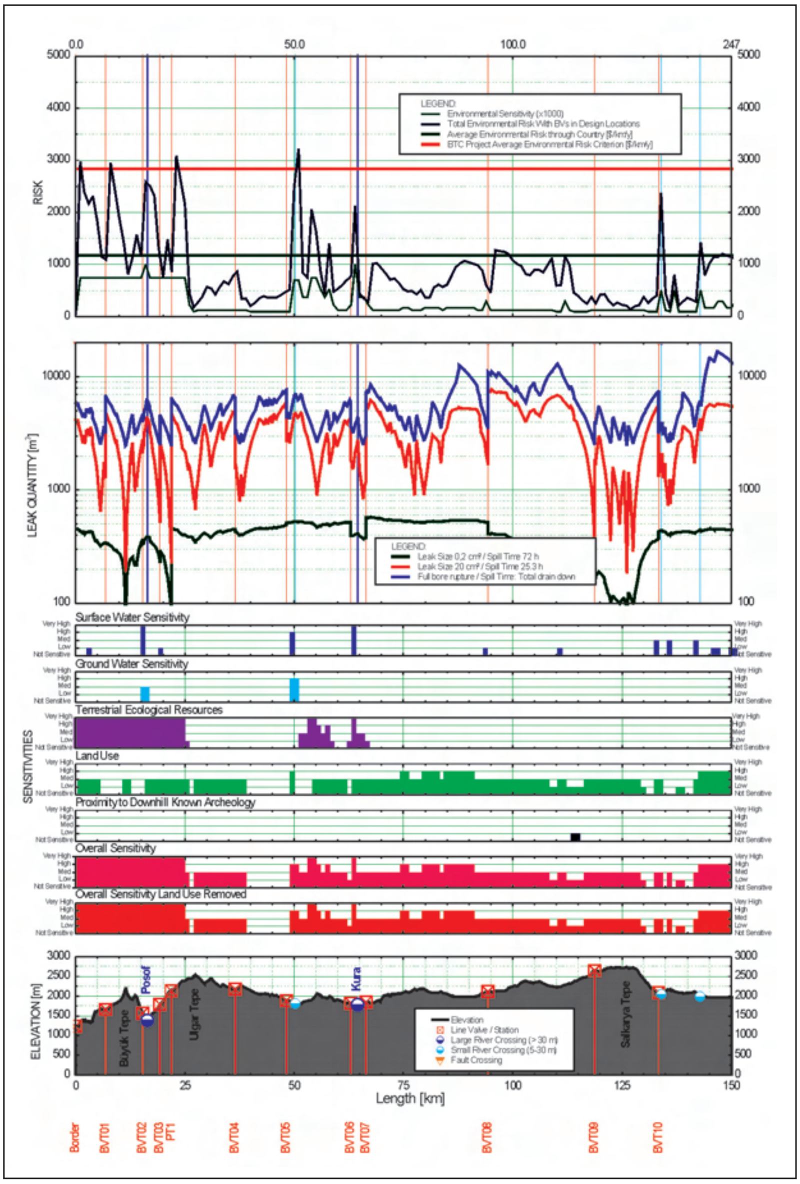

Fig. 3 Environmental risk assessment based on theoretical leak quantities

ity of external corrosion is virtually eliminated.
Internal corrosion, however, is still a problem, especially for applications such as multiphase flow lines. Use of exotic steels such as duplex is becoming more common; however, there exists the potential for further research and optimization of the metallurgy in order to improve corrosion resistance.
New pipeline applications, such as transportation of supercritical CO_2, or of highly corrosive substances such as liquid sulphur, also provide a challenge for the corrosion engineer. For such specialist applications, it is vital that the chemical composition of the transported product is exactly defined, considering potentially harmful contaminants.

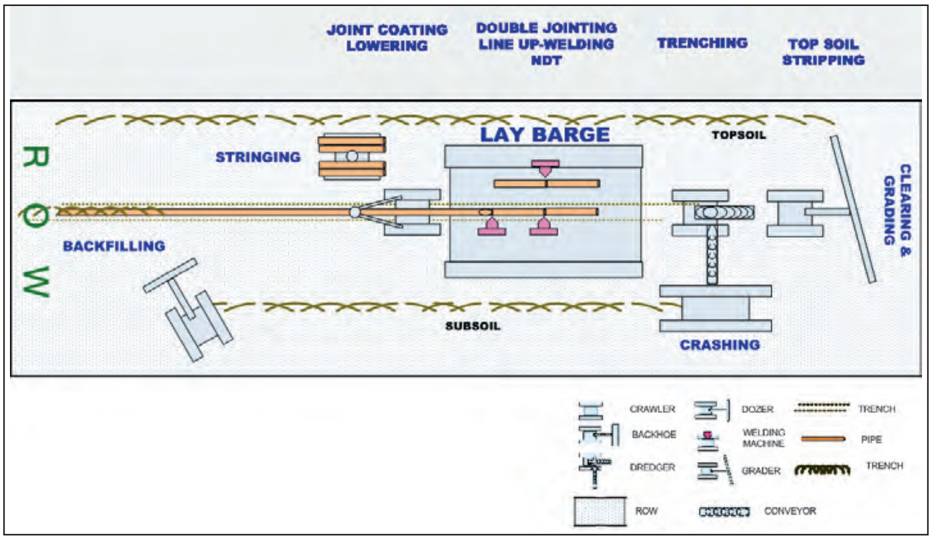

Fig. 4 Typical land lay barge configuration [3]

Construction

One of the major costs of establishing a new pipeline is the construction cost. Over the last few decades there has been relatively little innovation in the construction methods of onshore pipelines, except in a few key areas.
One of these is the development of new techniques for constructing crossings, such as horizontal drilling (HDD) and micro-tunneling. The limits of HDD have in the meantime been extended to greater than 1000 m for 56″ pipe diameter. Other techniques have been developed allowing simultaneous tunnelling and thrusting of the prefabricated pipeline into the drill hole (e. g. Direct Pipe™), further reducing time and cost for such crossings and at the same time reducing the risk of execution.
In regard to pipeline construction, manual arc welding is still the most common method. The use of mechanised or automated welding combined with ultrasonic testing has increased, although, use is probably not as widespread as many would have predicted. Laser-based welding techniques show some promise, but are still in the development stage.
Finally, there have been some innovations in the area of trenching equipment, such as auto-trenchers and “No-Dig” systems. Many of these systems may still be considered to be under development.
Considering the future, great efforts are underway to reduce the cost of pipeline construction. One application for the construction of large cross-country pipelines in relative easy terrain is the use of the so-called “Land Lay Barge”. This is based on the offshore approach where all activities such as double-jointing, welding, NDT and laying are combined onto a moving platform (i. e. a ship in case of offshore construction). Figure 4 shows an illustration of a typical land lay barge configuration.
The land lay barge concept aims to concentrate the logistics of ROW clearing, trenching, pipe stringing, welding, NDT, lowering and back-filling into the most compact area practicable. Operations, which on a typical pipeline construction site may be offset by several weeks, are timed to occur ‘just-in-time’ for the subsequent construction step. In particular, the co-location of jointing, welding, NDT and coating operations on a single moving platform eliminates a large amount of equipment logistics and movement of personnel.
Use of such lay barge techniques, however, is generally limited to relatively flat and unobstructed terrain, where it is not necessary to frequently dismantle the barge in order to traverse crossings or to circumvent other obstacles. For more complicated routes incorporating steeper slopes, the traditional side booms are still used, whereby there have been some developments in the manoeuvrability and operability of these units in recent years.
Furthermore, it is clear that the trend of increased HSE (Health, Safety, Environment) requirements will continue, giving associated improvements in construction safety, but also coupled with increasing compliance costs.
The new pipelines will be constructed in ever more remote areas, with difficult terrain and adverse weather conditions. Associated infrastructure, such as compressor and pump stations, must also be planned with the pipeline systems. Many of the aspects mentioned above relating to the pipeline itself, such as selection of optimum location, analysis of environmental risk, etc. also apply to the associated stations and facilities.
GIS technologies, as already mentioned for route engineering, are also now already implemented during the procurement and construction phases. Pipe tracking systems allow monitoring progress of single pipe lengths from mill to welded location in the pipeline and can be later integrated into overall Pipeline Information Management Systems (PIMS).

5 Operation and Maintenance

As for route engineering, modern information technology has lead to major advances in the operation and maintenance phase of a pipelines lifetime. Use of hydraulic simulators, leak detection systems and GIS-based emergency response plans are just some examples.
Implementation of on-line monitoring systems allows the Operator to obtain more detailed information in regard to actual threats or events impacting pipeline integrity than have been achievable by traditional visual ROW surveillance methods. Use of such systems is becoming more critical, considering the growing present-day threats of illegal taps, intentional sabotage and terrorism. Several such systems exist, one example being the use of acoustic sensors mounted onto the pipeline at regular intervals to monitor and localise impacts on the pipeline itself or even within the right-of-way.
For new pipeline systems, consideration may be given to co-laying special Fibre Optic Cable (FOC) in the pipeline trench. In this method, the FOC is used as a continuous sensor to monitor small changes in temperature, strain or acoustic footprint. Each method relies on the fact that a change in conditions will cause light transmission along the cable to be disrupted. Leaks or other incidents can be accurately pinpointed by monitoring the timing of reflections caused by this scattering of light. It should be noted that the location and method of FOC installation in relation to the pipe is critical, depending on the transported medium and leak characteristic or deformation to be expected.
Other advances in terms of operation include the use of flow improvers to increase transport capacity through existing oil pipeline systems. In a current project, for instance, it is predicted that a 60% increase in throughput can be achieved through an existing crude oil pipeline system by using new generation suspension-based Drag Reducing Agents.
Although intelligent pigs have been used for a number of years, the type of information that can be obtained by such methods is in-

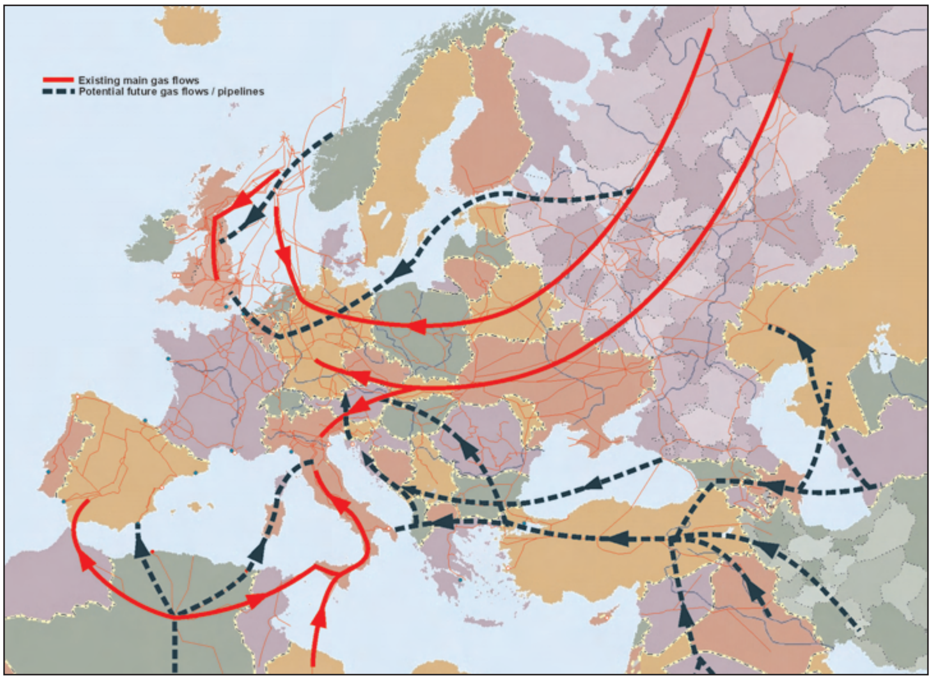

Fig. 5 Current and future main gas flows to Europe

creasing. Information from intelligent pigging is one aspect of a detailed monitoring and inspection programme that can be implemented even for quite old existing pipeline systems. In a number of recent projects in Germany, for instance, it has been possible to demonstrate the integrity of pipeline systems built in the 1960´s to the satisfaction of the respective Authorities, allowing extending the operating permits of such systems.
As mentioned above, GIS-based systems are now implemented to support operations and maintenance activities. Such systems integrate physical and geographical information about the pipeline assets with real-time information and embedded organisational procedures. Graphical tools provide a user-friendly interface for quick and easy access to information.

6 Perspective for the Gas Sector

It is apparent that the pipeline market will develop significantly over the next few years. In Europe, there are several strong factors driving activity, particularly in the gas transport sector.
A number of recent incidents have increased awareness of gas supply security. Of the three main gas sources currently supplying Europe, the North Sea reserves are declining, while supplies from Russia and sub-Saharan Africa have their own security issues. Although Germany in particular seems to be building up its reliance on Russian gas via the Nord Stream pipeline, it is the stated aim of the EU to diversify gas supplies to Europe. This will mean building large intra-regional pipelines from the Middle East, Asia and Africa. The dashed lines on the map in Figure 5 show some of the well-known pipelines that are currently in various stages of planning (e. g. Nabucco, SCP-Expansion, Trans-Adriatic, Trans-Arab, Trans-Caspian).
Liberalization of the European gas market, including common carrier and free access legislation, should theoretically lead to further interconnection of individual country networks. Furthermore, the continuing development of LNG in order to diversify supply, as well as increased underground gas storage for security purposes, will also require the construction of new gas pipelines to interconnect the new terminals and storage facilities to transport infrastructure.
A new application is the predicted future increase in installation of CO_2 pipelines, used to transport carbon captured from fossil-fuel power stations and other industrial plants to underground storage reservoirs. A significant safety aspect associated with such applications is the potential contamination of CO_2 with impurities such as H_2S and SO_2 which could lead to a health hazard if released. Here there is a need for detailed risk analysis to evaluate potential leak scenarios and define mitigation measures.
In conclusion, there have been some significant developments in pipeline technology in recent years. Further innovation is continuing in order to meet the technical demands of a growing sector, while at the same time demonstrating the ongoing safety and environmental acceptability of this technology to the general public.

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