Compressing costs

Gurdial Singh and Michael Moore, CB&I UK Limited and Stephen Gower, BP Exploration, UK, discuss reducing the cost of onshore pipeline systems.†

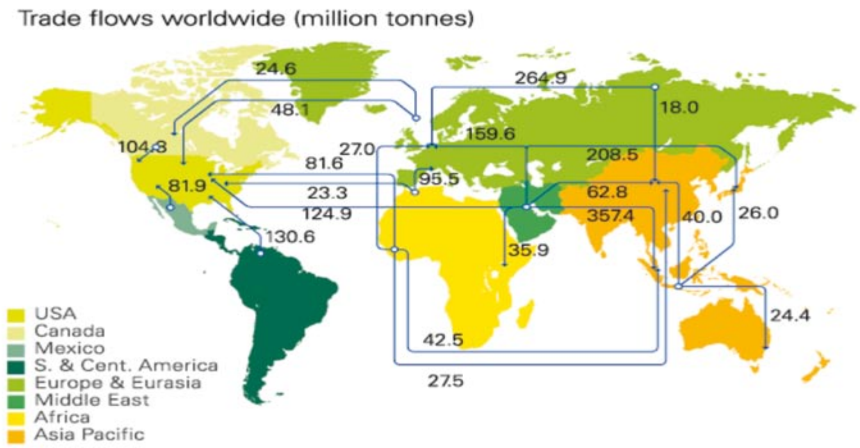

Figure 1. Oil movement (BP Statistical Review of World Energy 2005).

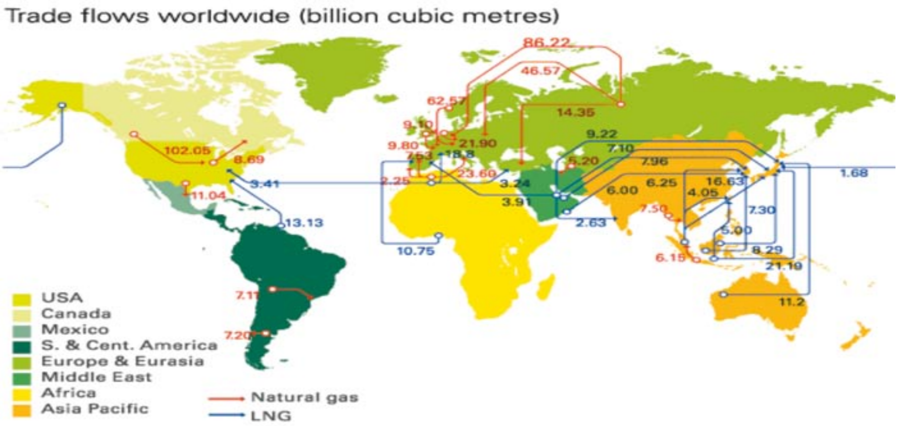

Figure 2. Gas movement (BP Statistical Review of World Energy 2005).

Growing demand for energy, coupled with production capacity constraints in the established oil and gas regions, has led to the exploration and production of hydrocarbons in more remote and challenging environments. This trend has inevitably resulted in the transportation of hydrocarbons over longer distances (Figures 1 and 2 illustrate the current world movement of oil and gas), prompting energy companies to look at new ways of building and operating pipelines in a more economical fashion[1].

In an effort to reduce the cost of new pipeline infrastructure, BP, working closely with all sectors of the oil and gas industry, launched the Pipeline Cost Reduction project in 1997. To date, this initiative has involved more than 200 individual operators, consultants, contractors, research associations and universities, and it has resulted in the establishment of new industry design guidelines, new welding techniques and operational tests for higher grade pipe.

While the project initially focused on line pipe and construction[2,3], further analysis of the data revealed that pipeline facilities are a source of significant cost. A look at recent project costs (Figure 3), prior to the implementation of any cost reduction methods, indicated that material costs typically account for

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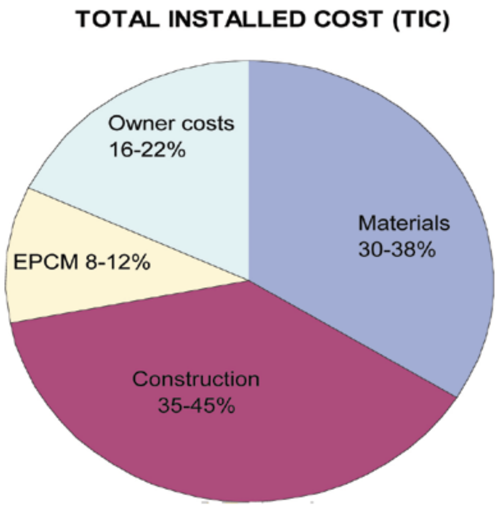

Figure 3. Typical cost breakdown of BP long distance, large diameter pipelines.

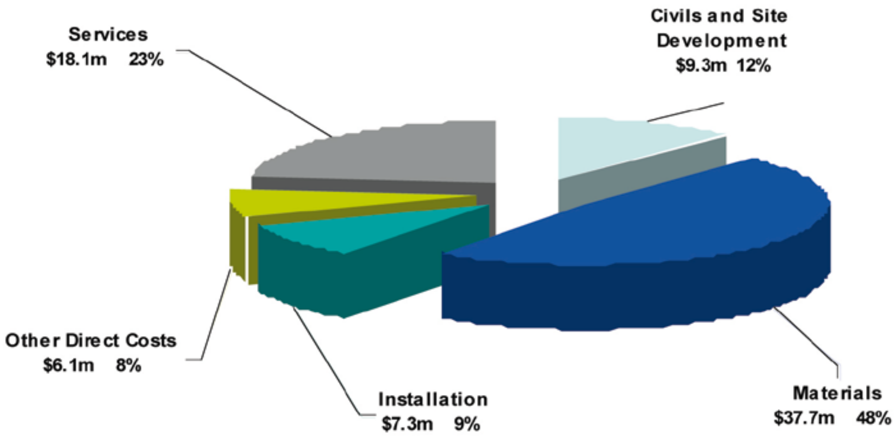

Figure 4. Typical cost breakdown of facilities.

30 - 38% of total pipeline costs, construction approximately 35 - 45%, and the remainder consisting of risk related costs, contractor's profits, and owner's costs (which typically include project management costs, financing and insurance).

Subsequent analysis showed that a significant part of pipeline system costs is taken up by the cost of the facilities that house pump/compressor stations, which can represent between 25 - 30% of the overall cost of a project. For several years, BP has worked closely with rotating equipment suppliers Solar Turbines, MAN Turbo, Rolls Royce and Dresser Rand to develop more efficient, reliable and competitively priced machinery for these facilities.

In 2002, BP engaged the services of engineering, procurement and construction contractor CB&I - which had been active in a number of cost reduction studies with BP - working with them and the rotating equipment suppliers to lead a study that would offer a fresh perspective on how pipeline facilities costs could be reduced. The result of preliminary work indicates that installing spare machinery is not always the most appropriate solution. Further development of this essential theme led to the identification of several other cost reduction methodologies, including remote operation, modularisation and process optimisation. The results of this study follow.

Study development

The study was comprised of three stages:

- An initial analysis of the costs of pipeline facilities.
- The collection of data from the rotating equipment suppliers, various interested bodies within BP and other organisations with interests or technologies appropriate to the study.
- Data analysis and derivation of methods.

The first stage identified the relationship between total installed power and facilities costs and also identified other practices, such as levels of site manning and methods of control, that needed to be challenged.

The second stage involved data gathering, using questionnaires and detailed discussions, both collectively and individually, with the rotating equipment suppliers, BP and other parties. The results were then analysed and developed in the third stage, data analysis and derivation of methods, which was divided into the following activities:

- Generating generic, non-dimensional performance maps for compressors and pumps in order to optimise pipeline and facility design and specify preferred equipment characteristics generically.
- Conducting Reliability, Availability and Maintainability (RAM) studies that would help generate an availability model for a typical transmission pipeline and provide data on equipment reliability and repair.
- Examining the experience of rotating equipment suppliers, operating companies and electronic communications specialists with regards to remote operation.
- Developing modularisation concepts based on:
    - Manufacturing in a shop environment and simplifying the installation and transportation of equipment.
    - Providing modularised components that are simple to change out and are not limited by transportation methods due to their size.
- Implementing process optimisation, which consisted of thinking 'outside the box' and finding new ways of reducing onsite personnel support.

The effects of any facilities cost reductions found in the study have been reflected in the overall pipeline optimisation process. While the original intent was to develop an optimisation procedure applicable to all pipelines, it became evident as the study progressed that oil pipelines could not be analysed generically due to topographical effects. Consequently, the current optimisation procedure is limited to gas pipelines. However, the cost saving principles described hereafter can also be applied to oil pipelines once topographical data is available.

Cost reduction on facilities

In the first stage, an analysis of recent major projects was used to establish the approximate costs of facilities (a breakdown of which is shown in Figure 4). Based on these costs, study participants identified areas where potential savings could be achieved.

For instance, the total installed power required for each facility is optimised against the pipeline diameter for minimum cost and, traditionally, standby machinery trains are then added at each station. This practice was called into question by study participants who began to closely examine the interdependency between the availability of a standby unit and the overall performance of a pipeline.

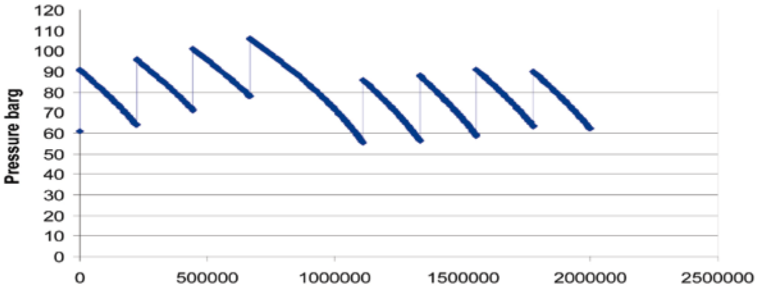

Figure 5. Single station failure recovery - 24 in. optimisation study.

Their work soon focused on understanding the relationship between the number of compressor stations on a gas pipeline, the number of compressors on each station and the consequences of failure of one of the stations or machine trains. Several investigations determined that, while a station with two 100% machine trains (200% installed power) has a higher availability than one with three 50% trains (150% installed power), the initial investment is clearly a 33% increase in installed power.

Not only was the availability of individual stations considered, but also the availability of the total pipeline system. To this end, the concept of residual flow loss (RFL) was developed. This is the loss in pipeline throughput in the event of a single machine train failure, ignoring the mitigation of pipeline packing or unpacking.

In addition, the reliability of modern machinery was also taken into account. Several members of the original equipment manufacturers (OEMs) confirmed that current models and equipment have much higher availability than typically used in availability modelling. Discussions with pipeline operators likewise confirmed this improvement and suggested that the causes of failure were most frequently not associated with the machinery trains themselves.

Based on these initial findings, the main cost reduction concept was to eliminate standby machines. The initial study showed that it was possible to remove all standby units except at the first site and still achieve the design throughput, by optimisation of facility spacing in conjunction with prudent machine selection. A typical example is shown in Figure 5.

Another cost-saving method investigated was the increased use of remote monitoring techniques. Remote operation removes the personnel support infrastructure. Combined with the removal of standby trains, a reduction of more than 70% in plot size could be realised. The study identified up to 30% in cost reductions resulting from reduced plot size and equipment.

Modular construction was also considered, since ease of equipment installation and removal is particularly attractive with remotely operated sites. Other benefits include ease of construction and a shorter schedule. Modularised components are also easier to maintain, and repairs can be carried out by semi-skilled staff that may be more readily available for travel to remote sites. However, to fully realise these savings, maintenance centres would have to be placed strategically along the pipeline.

Thus, it was determined that the minimisation of standby units, the increased use of remote monitoring techniques and modularisation could all result in significant savings in facility capital expenditures if different design, operating and maintenance philosophies were adopted. It was also recognised that such large cost reductions would change the optimum mix of pipelines and compression facilities.

Performance review

For the next stage of the study, methodologies were developed to allow the design of new equipment configurations without prior knowledge of any particular machine construction or station configuration. These were specifically developed for gas turbine driven compressor systems in gas pipelines.

Figure 6 shows a typical compressor operating map and its normal operating range. The boundary to the top of the map is the maximum speed limit of the compressor, which is normally 5% higher than design. The boundary to the left is the surge control line that defines the usable operating range at lower flowrates. Beyond this, there is also the surge line which, if crossed, can cause severe physical damage to the machine. Approaching this boundary will also result in a penalty in terms of compressor efficiency. The boundary to the right is less rigid and is very machine dependent; however, severe efficiency losses will accrue in the region. The lower boundary, however, is a function of power and represents 50% power. This power limit is for gas turbine driven compressors and is slightly below the level at which most gas turbine manufacturers cannot guarantee to meet the NOx emission standards required in most countries of the world.

This operating map can be used to represent either a station with many parallel compressor trains or a station with just one compressor train; thus allowing the investigation of using multiple trains for varying conditions.

For the transmission of 100% of the design flow of gas, all the compressor stations must be operational. However, in situations where reduced throughput is required - either on a frequent basis or during the early life of the pipeline - different combinations of stations and machinery trains can be used. For example, operating with one 50% train on every fourth station can provide 40 - 50% flow on the same system.

To analyse a scenario of pipeline systems during the design phase, it is convenient to use non-dimensional parameters, so that the solutions are independent of any machine type. The methodology developed to achieve this is described below.

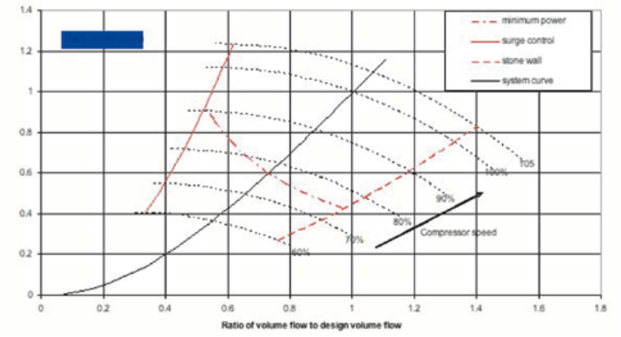

Figure 6. Compressor performance map with system curve for compression ratio (Pr) of 1.4.

Non-dimensional head vs. volume flow equation

The following equation can be used to describe centrifugal compressor performance:

$$h = S^2 \left\{ 1 + a \left[\left(\frac{v}{S^n} \right)^m - \left(\frac{v}{S^n} \right)^{2m} \right] \right\} \qquad (1)$$

Where *h* is the ratio of the head at a given volume flow and speed to the head at the design point, *v* is the ratio of the volume flowrate to the volume flowrate at the design point, and *S* is the ratio of the compressor speed to the design speed.

By analysis of the equation above, it can be shown that the meanings of parameters *a*, *m* and *n* are as follows:

- *a* determines the head rise to surge from the highest efficiency point at any given speed.
- *m* governs the 'flatness' of the compressor curve at a given speed. In turn, this determines the range of volume flow between the high efficiency point and the surge line. The flatter the curve, the wider the range, which is better for single machines. For multiple machines, however, this may not be as important as the slope of the curve, which needs to be steeper to allow multiple machine control.
- The product *am* is the slope at the design point on the 100% speed line.
- The index *n* is the locus of the highest efficiency operation for the compressor at any speed. It can be shown that an ideal operational curve can be identified as head equal to volume flow to the power of *2/n*.

All of the information above is dimensionless and can be applied to both compressor trains and stations with a number of trains.

System curve analysis

A simple, dimensionless system curve can be generated using the Fanning equation. Ignoring gravitational and acceleration effects, the pressure gradient can be stated as:

$$\frac{dP}{dz} = -4f\frac{G^2}{2\rho D} \qquad (2)$$

Where *P* is the pressure, *z* is the distance along the pipeline, *f* is the Fanning friction factor, *G* is the mass velocity ($=4\dot{m}/\pi D^2$, where $\dot{m}$ is the mass flowrate), ρ is the gas density and *D* is the pipe inside diameter.

The variation of friction factor, particularly in high pressure gas systems, can be considered negligible. However, for a gas pipeline, the density will change due to pressure, temperature and compressibility. The most significant of these is pressure and, for the initial estimate, the temperature and compressibility can also be considered constant. With these assumptions, equation (2) can be integrated to give:

$$P_1^2 - P_2^2 = C.L \qquad (3)$$

Where P_1 is the pressure into the section of pipeline of length *L*, P_2 is the pressure out and the 'constant' *C* is given by:

$$C = \frac{64 fZRT\dot{m}^2}{MW\pi^2 D^5} \qquad (4)$$

Where *Z* is the mean gas compressibility, *R* is the universal gas constant, *T* is the absolute temperature and *MW* is the gas molecular weight.

For a series of compressor stations equally spaced along a pipeline, P_1 is the discharge pressure from one station, and P_2 is the suction pressure at the next. The pressure ratio over each compressor is given by:

$$\frac{P_1}{P_2} = \sqrt{\frac{1}{1 - \frac{C.L}{P_1^2}}} \qquad (5)$$

Therefore, in the design case, the choice of pressure ratio across the machine is either governed by or dictates the design of the pipeline, depending on which parameter is chosen first.

In the situation where the philosophy is to maintain the discharge pressure at the design pressure regardless of throughput, it can be shown that the pressure ratio is related to fraction *F* of the design mass flow, which can be stated as:

$$\left(\frac{P_1}{P_2}\right) = \sqrt{\frac{1}{1 - \frac{F^2 C.L}{P_1^2}}} \qquad (6)$$

And the volume flow relative to the design is given by:

$$v = \frac{P_2}{P_1}.F.\left(\frac{P_1}{P_2}\right) \qquad (7)$$

To use in conjunction with the compressor performance, the relationship between head and flow needs to be determined. In its dimensionless form, this can be expressed as:

$$h = \frac{\cdot\left[\left(\frac{P_1}{P_2}\right)'\right]^{k'} - 1}{\left[\frac{P_1}{P_2}\right]^{k'} - 1} \qquad (8)$$

Where k' is the polytropic index in the gas equation.

Application to station design

Using the equations above, a system curve can be drawn on the same axes as the compressor curve, such as in Figure 6, where the design pressure ratio is 1.4. From there, the value of the compressor parameter *n* that fits this curve can then be determined. A preliminary assumption that can be made is that this curve is orthogonal to the 100% compressor speed line at the design point. This fixes the slope and thus the product *am*.

At this point, a theoretical design can be developed and examined in detail before the pipeline design becomes fixed, with the confidence that the prospective equipment suppliers would all be able to meet the project requirements.

Using this methodology, the effect of losing one machine train can be considered for a number of configurations, station spacing (L), design pressure ratios and additional stations, as shown in Table 1. The values for RFL in Table 1 are the loss of production in percentage terms during a single machine shutdown.

According to Table 1, RFL is reduced when both the number of stations and the number of compressor trains at each station are increased. However, this action leads to increased costs. Hence, a balance needs to be achieved between costs and overall availability, which can be found using such tools as the RAM analysis. It should be further noted that the impact of compression ratio is of a lower order.

RAM studies

RAM studies were carried out to investigate the influence of RFL on overall pipeline availability. Of particular importance was the reliability data for the major compressor station components. Two sources of data were used: the Offshore Reliability Data (OREDA) database and the latest information from the OEMs, to investigate the influence of compressor train configurations, repair response times and the differences between the OREDA and OEM data. The influence of spare components and maintenance regimes was also considered.

The RAM model includes the effect of all items of equipment on the station in its normal configuration, such as power generation and compressed air supply. The results are expressed in terms of overall pipeline availability, which, in this case, is defined as the total gas throughput achieved in one year as a percentage of the total pipeline throughput capability over one year. The model considers each failure of a piece of equipment and the time taken to bring that equipment back online. During periods of machine or station breakdown, the line throughput is assumed to be reduced by the RFL previously described in Table 1.

Figure 7 compares pipelines that have stations without spare machinery trains at different RFL values with a pipeline provided with dual machine (operating and standby) compressor stations. It should be noted that even with an RFL of 0%, there is a finite loss of availability because the probability of another station failing coincidentally is not zero. Also, a coincidental loss of both compressors or the failure of a common ancillary component would result in a station failure. Failure of one station in this configuration would produce an RFL of about 24%. Through appropriate compressor specification and the spacing of stations such that the pipeline RFL is small despite the loss of a single station, pipelines with single unit compressor stations can have similar availabilities as those pipelines with dual unit stations.

For pipelines utilising highly reliable machines, the availability advantage of providing spare machines at each station becomes minimal. As previously stated, experience confirmed from discussions both within and outside of BP suggest that spare machine trains may not be appropriate for many pipeline designs.

Remote operation

Information gleaned from experienced operators confirmed that remote operation is a preferred practice. The principle that the pipeline should be operated as a single entity rather than a group of individual stations becomes even more apparent when consideration is given to currently available communications equipment and techniques. However, remote operation must be built into the base design, as each pipeline owner - depending on their location, climate and culture - will have particular requirements with regards to operation, maintenance and security.

While remote operation with maintenance teams based in one or more central locations (not necessarily one of the pipeline stations) can provide greater efficiency, this is more easily achieved if the stations and equipment share a common design. Establishing service agreements with suppliers of major equipment trains can produce significant benefits, particularly if the supplier is prepared to carry replacement spares, take a failed component to repair and replace operators' stock. For gas turbines, spare gas generators have been available to operators with this type of agreement for some time. Many machinery suppliers already have the technical capability to monitor equipment condition and performance remotely; thus, providing scope for preventative maintenance on a planned basis.

A major reduction in buildings and personnel support systems can stem from such a philosophy, and this approach can provide significant savings in both capital and operating costs. It is important to note that the ability to achieve these savings is available now and is, to some extent, already being realised.

Modularisation concepts

Two aspects of modularisation were considered: modularisation for construction and modularisation for maintenance. While the former has been used to a large extent in the offshore sector, it has also been used for large onshore plants and, by some organisations, for pipeline stations. Based on discussions with experienced operators, this is very much a beneficial route. The extent of modularisation to be undertaken and the parties selected to do this work need careful consideration, as the responsibility for modularisation is often placed on companies that have no real expertise or even experience in this area. Packages supplied by compressor and/or turbine suppliers can often be a module in themselves, but further packaging should be evaluated carefully.

Modularisation for maintenance, by contrast, is closely linked to remote operation. The intent would be to have small modules - encompassing high technology equipment - that can be removed and replaced readily by a competent maintenance worker who would not need to know the details of the enclosed components. This method is used successfully in other industries. Replacement and/or repair of the components within the module can be performed by skilled technicians in a central establishment, which may well be carried out by the suppliers. Additional benefit could also be gained from the practice of keeping common spares.

Table 1. Variation of RFL with compression ratio and configuration

Pipeline design pressure ratio	Station spacing	1 x 100%	2 x 50% parallel	3 x 33.3% parallel	4 x 25% parallel	Spare on alter-nate*	2 x 50% series
1.2	L	23.8%	9.6%	6.2%	4.6%	6.5%	9.5%
	0.9*L	20.0%	6.2%	2.6%	0.9%	2.3%	6.0%
	0.8*L	15.5%	2.1%	0	0	0	2.0%
1.4	L	24.8%	9.7%	6.2%	4.6%	12.3%	9.5%
	0.9*L	21.0%	6.1%	2.4%	0.7%	8.3%	6.0%
	0.8*L	16.5%	1.9%	0	0	3.6%	2.0%
1.6	L	25.6%	9.6%	6.0%	4.4%	15.5%	9.3%
	0.9*L	21.8%	5.9%	2.1%	0.5%	11.3%	5.6%
	0.8*L	17.3%	1.5%	0	0	6.4%	1.5%

For stations with one 100% machine, the limitation is due to the compressor map.
For multiple machine configurations the limitation is power.
** Alternate sites with one 100% on odd numbered stations and two 100% on even numbered stations. Spare machines arranged to operate in series when preceding single machine station fails. The limitation is power on one machine and position on the compressor map on the other.*

Process optimisation

Process optimisation may offer some of the greatest benefits to pipeline cost reduction in the future. For any pipeline system, the basic operation should be that there is a requirement to move gas, that some device is needed to provide this movement and that some form of energy must be applied to achieve the movement. Anything other than this basic system should be considered surplus until a valid and unshakable argument is put forward.

Many pipeline stations are equipped with emergency generators, building complexes, water supply and treatment, back up fuel supplies, etc., that often require as much, if not more, maintenance than the machinery trains themselves. Buildings require heating, lighting and often air conditioning, which use up energy and require maintenance. The removal of these buildings and personnel support systems further reduces the complexity and power and maintenance requirements of the station, leaving the machinery train as a self-contained and sustained entity. By using the capabilities of the machinery train, such as the energy available from the exhaust heat, secondary drivers or even the incoming air supply, much of the extra energy required by the machinery train can be provided without additional fuel use. Thus, the availability of the train depends on its own reliability and not that of an ancillary piece of equipment.

It is recognised that this philosophy is an ideal that would be difficult to achieve immediately, primarily due to lack of commitment to such a concept. There are also some systems, particularly for start-up, that would be needed in some form. However, the ultimate aim should be to minimise all equipment that does not fulfil the basic premise previously mentioned.

Environmental benefits

While the initial thrust of the study focused on cost reductions, it became apparent that the techniques proposed in the study would also produce considerable environmental benefits due to the following:

- A reduction in manufactured equipment for each facility.
- A reduction in construction activities at each site due to the installation of fewer buildings and equipment.
- A reduction in energy consumption at sites that adopt remote operation.
- Improved fuel utilisation due to improved machinery design.

Application to projects

The concepts proposed in the study were tested against various BP in-house projects that not only confirmed that considerable savings can be achieved, but they also identified areas where further design optimisation could be realised. Presently, the concepts of modularisation, remote operation and process optimisation are already being used on several BP gas pipeline projects, and a similar analysis has been carried out for oil pipelines.

Conclusion

As a result of the studies performed,[4] it was concluded that the costs of pipeline facilities can be greatly reduced, in some cases by more than 20%, by a combination of eliminating standby machines, remotely operating pipeline stations and developing modularised components. Such cost reduction will alter the balance between pipeline size and compression facilities. Methodologies for station performance can be used to carry out a thorough design analysis, while RAM techniques can address complex issues such as sparing philosophies and the impact of mobilisation and repair times.

It should be recognised, however, that in order to achieve these benefits, a number of steps have to be in place in the early phases of the project. These include specifying the availability requirements in the design philosophy and commercial agreements, a wider acceptance of the principle of remote operation with its associated service agreements with equipment suppliers, and a genuine commitment to modular construction and maintenance.

The effect of pipeline facility cost reductions has to be reflected in the overall pipeline optimisation process. To that end, a pipeline optimisation procedure has been developed that is applicable to large diameter, long distance gas pipelines. However, many of the principles for cost savings relating to remote operation and modularisation are applicable to all pipelines. Application to oil pipelines is more dependent on topographical constraints, and consequently, the opportunities to reduce the number of standby units will be fewer. Nonetheless, the use of drag reducing agent (DRA) in conjunction with these concepts is an area that still has to be explored.

It should also be noted that there are a number of technologies, both new and established, in other fields that can be applied to pipeline facilities. Offshore practices could provide some techniques that are applicable but not commonly used. Alternative accommodation strategies in remote locations should also be considered.

Once the initial design has started, it is paramount that a strong partnership between the operator, designer and the equipment suppliers is formed to fully realise the cost-saving benefits. The methods described above can assist in clarifying the interfaces involved.

References

1. GOWER, S and HOWARD M., *Changing Economics of Gas Transportation*, Paper TF 9-C, IGU 22nd World Gas Conference, Tokyo, Japan, 1-5 June, 2003.
2. FREETH, G and PIRANI, R, *BP- IPLOCA: Novel Construction Methods*, Energy Institute, London, UK, 25th February 2005.
3. *Novel Construction Methods,* BP-IPLOCA presentation, Paris, France. 30th - 31st March 2005.
4. *BP Facilities Optimization Study,* Phase 2, Final Report, November 2004.

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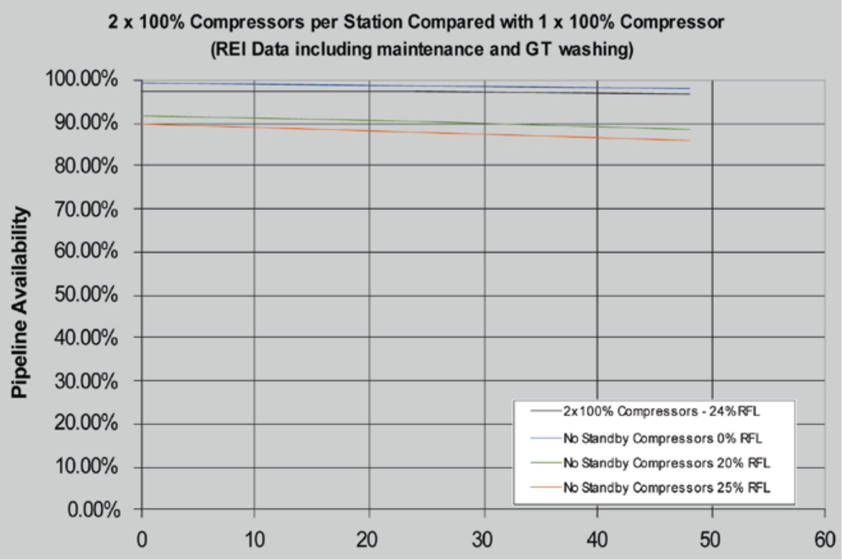

Figure 7. Variations of RFL with machinery configuration and time to repair, with mobilisation time for repair along the bottom axis.