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## COMPRESSOR STATION AVAILABILITY
## - MANAGING ITS EFFECTS ON GAS PIPELINE OPERATION

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### ABSTRACT

As competitive market for gas transmission becomes more and more dynamic and we face an increase of regulatory agencies influence, the pressure on cutting down cost of service without affecting reliability and safety is a consequence. Notwithstanding this trend, transportation companies must act in a way that guarantees a fair return on investment and optimizes assets and operation costs. Contractual obligations play an important role since most of the contractual capacity is on a firm basis and subject to liabilities related to capacity shortage or interruption. Compressor stations availability study play a fundamental role in providing information that will support decision making in terms of defining a criterion for installing stand-by units. This paper presents two methods adopted for the Bolivia-Brazil Gas Pipeline Project: (1) Monte Carlo Simulation and (2) Scheduled and Unscheduled Maintenance. A technical end economic feasibility study is also presented to support the decision of installing stand-by units.

### INTRODUCTION

This paper presents the work developed for the Brazil section of the Bolivia-Brazil Gas Pipeline Project – Gasbol. The Gasbol transmission system (Santos, S. P., 1997) has 4 compressor stations in Bolivia side and 10 compressor stations in Brazil side as shown in ***figure 1***.

We have adopted two methods to evaluate the availability of the gas pipeline (1) Scheduled and Unscheduled Maintenance and (2) Monte Carlo Simulation. Additionally, compressor unit's unavailability was calculated by using binomial distribution for the purpose of comparing its results with the other two methods.

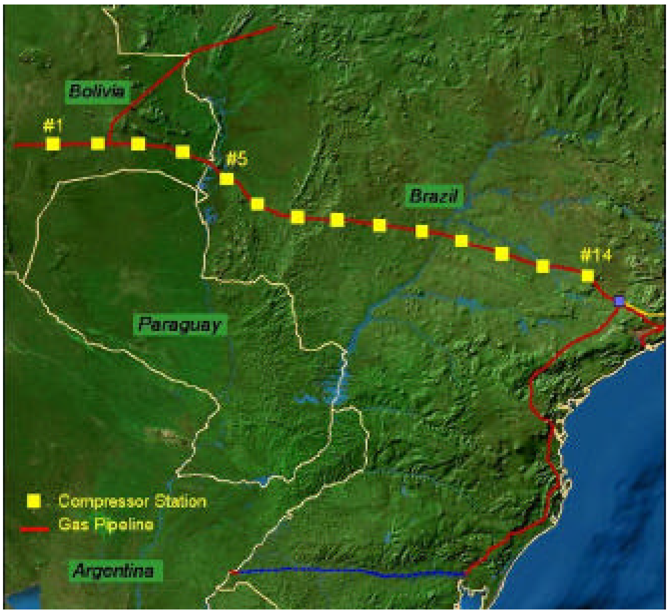


Figure 1 – Bolivia-Brazil Gas Pipeline

The objective of the study was to quantify the availability of the transmission system and to identify the required quantity of the stand-by compressor units to be installed to fulfill contractual obligations for firm capacity. An optimum number of stand-by compressor units where defined, taking into account contractual liabilities (as a result of failure to provide total required firm capacity) and also the total investment and operating cost for the new stand-by compressor units.

Although to commit the maximum capacity of a gas pipeline transmission system is not a recommended procedure, the Gasbol project has adopted a contractual ship-or-pay of 100% of the gas pipeline maximum capacity to reduce the transportation rate and transfer the commercial risk to the shipper. Capacity ramp up was planned to start at 2 MMm3/d and to increase up to 30 MMm3/d over 10 years time since gas market was not fully developed in Brazil. The installation of stand-by compressor units were postponed until gas pipeline capacity was close to maximum.

## BOLIVIA-BRAZIL GAS PIPELINE CHARACTERISTICS

The current configuration of the Gasbol project is described below:

| | |
|---|---|
| Pipeline Length: | 1813 km |
| Pipeline Diameter: | 32” |
| MAOP | 99.84 kgf/cm2g. |
| Transportation Capacity: | 30.08 MMm$^3$/d |

## COMPRESSOR STATION CONFIGURATION

The compressor station configuration consists mostly of two parallel compressor units per station. Bolivia side stations #1, 2 and 3 have two parallel 25000 hp and #4 three parallel 7000 hp plus one 15000 hp compressor units.

Brazil side stations #5, 6, 7, 9, 10, 11, 13 and 14 have two parallel 15000 hp compressor units installed and stations #8 and 12 have four parallel 7000 hp compressor units installed.

This paper focus on the Brazil section of the GASBOL as presented bellow:

| | |
|---|---|
| Compressor stations in Brazil | 10 |
| Compressor units per station: | 2 |
| Compressor Units Installed Power: | 15000 hp ISO |
| Maximum Compressor Ratio: | 1.8 |
| Mean spacing btw compressor sta.: | 125 km |

## REFERENCES FOR AVAILABILITY EVALUATION

The availability values for the compressor station units were defined based on the following criteria:

(a) Obtained from the EPRI Report No. RP 4CH2983 as 0.971 for installed compressor stations with centrifugal compressor and gas turbine driver.

(b) Obtained by the following equation and without stand-by units:

| | |
|---|---|
| Reliability | = 100 - FOF |
| Availability | = 100 – (FOF + SOF) |
| FOF | = (FOH / PH) x 100 |
| SOF | = (SOH / PH) x 100 |
| FOF | = Forced Outage Factor |
| FOH | = Forced Outage Hours |
| PH | = Period Hours |
| SOF | = Scheduled Outage Factor |
| SOH | = Scheduled Outage Hours |

The values of FOF and SOF presented below were taken from the North American Electric Reliability Council – NERC Report of January 2005 for gas turbine drivers.

| | |
|---|---|
| FOF | = 2.82% |
| SOF | = 4.24% |

| | |
|---|---|
| Reliability | = 100 – FOF = **0.9720** |
| Availability | = 100 – (FOF + SOF) = **0.9294** |

(c) Obtained from Binomial Distribution based on the availability value taken from NERC report for the gas turbine driver.

(d) Obtained from the scheduled maintenance as recommended by gas turbine manufacturer.

(e) Obtained from Monte Carlo simulation, and considering the availability number for the gas turbine drivers taken from the NERC report. The simulation considered the compressor stations operating initially without stand-by units and then defined the number of stand-by units to be installed to guarantee an adequate level of availability for the pipeline to cope with contractual obligations related to firm transportation capacity and also to mitigate liabilities.

Specialized software that simulates the reliability, availability and maintenance analysis incorporates a lot of equipment details and maintenance schedules provided by manufactures and from transportation company experience. The simulation results, when all of these data are put together gives the overall availability value for the compressor station or even for the complete transmission system.

The approach we adopted has proved to be quick, reliable and adequate in providing information that allowed making a decision on the number of of stand-by compressor units to be installed.

## GAS PIPELINE AVAILABILTY EVALUATION

The information and procedures described above where used with emphasis on (b) scheduled maintenance and (e) Monte Carlo simulation, as detailed below.

The GASBOL gas pipeline is operated by two different transmission companies: one in Bolivia side and one in Brazil side. This paper only addresses the Brazil section of the gas pipeline with 10 compressor stations.

## BINOMIAL DISTRIBUTION

For the purpose of comparing the two different approaches adopted and presented in this paper, a model simplification was made, as shown below, assuming two compressor units per station, for all 10 stations in Brazil size. Stations #8 and 10 with four smaller units of 7000 hp were replaced in the model by 2 bigger units of 15000 hp.

The binomial distribution equation and availability data taken from NERC report has provided the results detailed onward.

$$P(X) = \frac{n!}{X!(n-X)!} p^X (1-p)^{n-X}$$

$$P(X) = probabilit\,y\_of\ \_X\ \_unavailabl\,e\_units$$

$$n = sample\ \_size$$

$$p = unavailabi\ lity\ \_value$$

$$1- p = availabili\ ty\ \_value$$

$$X = number\ \_of\ \_unavailabl\,e\_units$$

| | |
|---|---|
| p | = 0.0706 (Unavailability value) |
| 1-p | = 0.9294 (Availability value) |
| n | = Compressor stations total units |
| X | = unavailability of 0, 1, 2, 3… n units |

### Actual Gas Pipeline Comp. Stations Configuration

Stations #5, 6, 7, 9,10,11,13 and 14 have 2 units of 15000 hp ISO compressors while stations 8 and 12 have four 7000 hp ISO units as ***figure 2***.

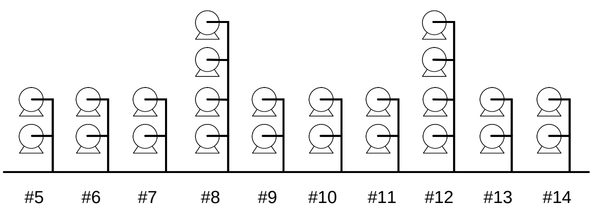


Figure 2 – Current Compressor Stations Units Arrangement

### Gas Pipeline Simplified Configuration

The simplified gas pipeline configuration shown in ***figure 3*** was necessary to allow the binomial distribution evaluation for compressor units unavailability. In this model all units are exactly the same. The purpose of doing the binomial distribution evaluation was to compare its result with the one from Monte Carlo simulation.

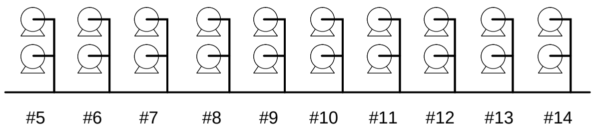


Figure 3 – Simplified Compressor Stations Units Arrangement

### Binomial Distribution for All Units

| | |
|---|---|
| n, Number of units | = 20 |
| p, Unavailability | = 0.0706 |
| 1-p | = 0.9294 |
| X | = simultaneous units unavailable |
| BC(X,n) | = Binomial coefficient |

$$BC(X,n) = \frac{n!}{X!(n-X)!}$$

**Units Unavailability**

| X | *BC* (X,n) | P(X) | Unavailability (days/year) |
|---|---|---|---|
| 0 | 1 | 0.231235 | 84.40 |
| 1 | 20 | 0.351306 | 128.23 |
| 2 | 190 | 0.253519 | 92.53 |
| 3 | 1140 | 0.115549 | 42.18 |
| 4 | 4845 | 0.037304 | 13.62 |
| 5 | 15504 | 0.009068 | 3.31 |
| 6 | 38760 | 0.001722 | 0.63 |
| 7 | 77520 | 0.000262 | 0.10 |
| 8 | 125970 | 0.000032 | 0.01 |
| 9 | 167960 | 0.000003 | 0.00 |
| 10 | 184756 | 0.000000 | 0.00 |
| 11 | 167960 | 0.000000 | 0.00 |
| 12 | 125970 | 0.000000 | 0.00 |
| 13 | 77520 | 0.000000 | 0.00 |
| 14 | 38760 | 0.000000 | 0.00 |
| 15 | 15504 | 0.000000 | 0.00 |
| 16 | 4845 | 0.000000 | 0.00 |
| 17 | 1140 | 0.000000 | 0.00 |
| 18 | 190 | 0.000000 | 0.00 |
| 19 | 20 | 0.000000 | 0.00 |
| 20 | 1 | 0.000000 | 0.00 |
| | | 1.000000 | 365.00 |

Table 1 – Unavailability Results for up to 20 units

From ***table 1***, we can see that the probability of having an unavailability of exactly 1 compressor unit along the year is 0.351306, which corresponds to 128.23 days per year. All units will be simultaneously available 84.4 days per year. All the probabilities need to add to 1 and consequently the days/year should add up to 365 days.

To allow a better study of compressor station behavior we did the statistical evaluation of a compressor station with 2 units, following the same method as presented above.

**<u>Compressor station availability</u>**

The method used to evaluate the availability number for a station with 2 compressor units is presented below:

n, Number of units = 2
p, Unavailability = 0.0706
1-p = 0.9294
X = compressor units unavailable
BC(X,n) = Binomial coefficient

$$BC(X,n) = \frac{n!}{X!(n-X)!}$$

**Station Availability**

| X | BC(X,n) | P(X) |
|---|---|---|
| 0 | 1 | 0.863784 |
| 1 | 2 | 0.131231 |
| 2 | 1 | 0.004984 |
| | | 1 |

Table 2 – Compressor Station Unavailability

With the probability values taken from ***table 2*** we can use model simplification and calculate the unavailability of the gas pipeline compressor stations . We can now have 10 compressor stations to be evaluated in the following scenarios:

(a) No unit per station unavailable
(2) One unit unavailable per station
(3) Two units unavailable per station.

The following tables show the results.

**<u>Gas transmission pipeline availability</u>**

The Brazil and Bolivia sections of the GASBOL are operated by independent transportation companies.

The following tables present the binomial statistical results for some selected scenarios. With these results we run the thermo-hydraulic simulation software to identify the impact of compressor units and stations unavailability on pipeline capacity.

**<u>Compressor Stations with no unit unavailable</u>**

From ***table 2***, we get the probability of having no unavailable units in a station as 0.863784. From this value we calculate the probability for a series arrangement of 10 compressor stations with no units unavailable, P(0), as:

P(0) = (0.863784)^10 = 0.231233 or 84.40 days.

This value matches the one we got from the ***table 1*** for no units unavailable for the total of 20 compressor units.

**<u>Compressor Stations with 1 unit unavailable</u>**

n, Comp. Stations = 10
p, 1 Unit unavailable = 0.131231
1-p = 0.868769
X = compressor units unavailable

**1 Unit per Station**

| X | *BC* (X,n) | P(X) | Unavailability (days/year) |
|---|---|---|---|
| 0 | 1 | 0.244930 | 89.40 |
| 1 | 10 | 0.369977 | 135.04 |
| 2 | 45 | 0.251490 | 91.79 |
| 3 | 120 | 0.101303 | 36.98 |
| 4 | 210 | 0.026779 | 9.77 |
| 5 | 252 | 0.004854 | 1.77 |
| 6 | 210 | 0.000611 | 0.22 |
| 7 | 120 | 0.000053 | 0.02 |
| 8 | 45 | 0.000003 | 0.00 |
| 9 | 10 | 0.000000 | 0.00 |
| 10 | 1 | 0.000000 | 0.00 |
| | | 1.000000 | 365.00 |

Table 3 – Compressor Stations with 1 Compressor Unit Unavailable per Station

**Compressor Stations with 2 units Unavailable**

The occurrence of two units unavailable at one station means compressor station outage. As can be seen in ***table 4*** this event could happen 17 days per year.

n, Comp. Stations = 10
p, 2 Units unavailable = 0.004984
1-p = 0.995016
X = simultaneous compressor units unavailable

**2 Units per Station**

| X | *BC* (X,n) | P(X) | Unavailability (days/year) |
|---|---|---|---|
| 0 | 1 | 0.951260 | 347.21 |
| 1 | 10 | 0.047652 | 17.39 |
| 2 | 45 | 0.001074 | 0.39 |
| 3 | 120 | 0.000014 | 0.01 |
| 4 | 210 | 0.000000 | 0.00 |
| 5 | 252 | 0.000000 | 0.00 |
| 6 | 210 | 0.000000 | 0.00 |
| 7 | 120 | 0.000000 | 0.00 |
| 8 | 45 | 0.000000 | 0.00 |
| 9 | 10 | 0.000000 | 0.00 |
| 10 | 1 | 0.000000 | 0.00 |
| | | 1.000000 | 365.00 |

Table 4 – Compressor Stations with 2 Compressor Units Unavailable per Station

**Two contiguous Compressor Stations with 1 unit unavailable at each station.**

This unavailability condition is based on the results presented in ***table 3***. From that table, the probability of having 2 simultaneous occurrences of 1 unit unavailable per station, in any of the 10 compressor stations, is exactly 0.251490 representing 91.79 days per year.

Since the combination of 2 occurrences in 10 compressor stations equals 45 and the combination of two consecutive occurrences (e.g.: unavailability of 1 unit in station #6 and also 1 unit in station #7) in 10 equals (10-2+1 = 9) then, the probability of 2 consecutive occurrences, P(2cu), is:

$$P(2cu) = (9/45)*0.251490 = 0.050298 = 18.35 \text{ days/year}$$

**Binomial distribution calculations versus Monte Carlo simulation.**

The compressor unit unavailability frequency from binomial distribution and Monte Carlo Simulation are shown in ***figure 4*** for comparison.

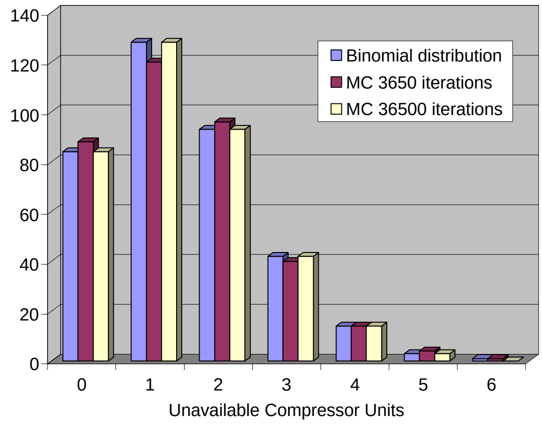


Figure 4 – Frequency comparison between Binomial Distribution and Monte Carlo Simulation

**SCHEDULED MAINTENANCE**

The maintenance contract with the gas turbine manufacturers for all the compressor units covers preventive inspection, unscheduled repairs and overhauls. The following average outage time are adopted for the services:

| Maintenance Services | Qty. per Year | Outage Hours / Year |
|---|---|---|
| Basic Quarterly Inspections | 4 | 48 hours Total |
| Semi-Annual Inspections | 1 | 110 hours |
| Annual Inspections | 1 | 150 hours |

Turbine overhauls are expected to happen each 30000 running hours. Assuming that a spare engine will be available, the estimate is 5 days (120 hours) for removal & replacement of the turbine.

| Expected Simultaneous Occurrence of Engine Overhauls (*) | Outage Hours per Unit |
|---|---|
| 2 - 3 | 120 |

(*) Three MARS-100 and three TAURUS 60 kept as spare.

The scheduled maintenance is shown on ***figure 5*** for reference with four different activities, as recommended by the equipment manufacturer (some months hidden for clarity).

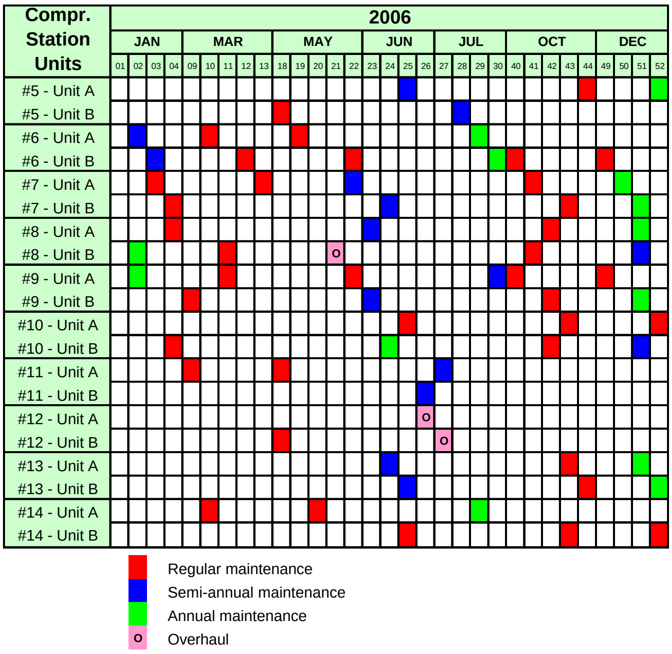


Figure 5 - Scheduled Maintenance

***Figure 6*** represents the available gas transmission capacity (gray area below graphic line) versus time, for a period of two years.

30.08 $MMm^3$/day is the firm contractual gas transmission capacity, and ***figure 6*** shows the significant capacity reduction of 2.48 $MMm^3$/d due to maintenance outage hours. From this evaluation the resulting average capacity is about 27.5 $MMm^3$/day.

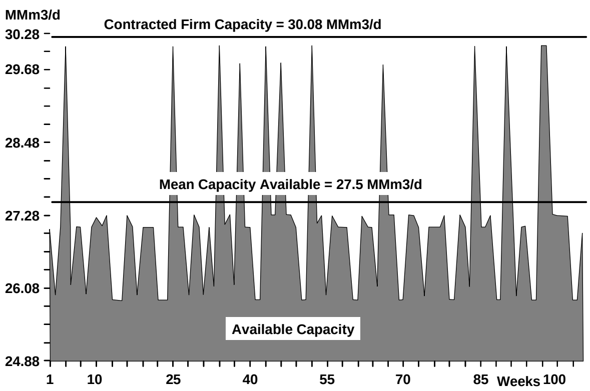


Figure 6 – Capacity loss due to maintenance services with no stand-by compressor units

However, as additional units are installed as stand-by, the overall pipeline availability increases, as the stand-by units overrides the unavailable ones without causing capacity shortage on the stations where they are installed.

***Figure 7*** presents the situation when five additional units are installed in five compressor stations. The gray area below graphic line now extends up, covering almost 100 % of the required firm gas transmission capacity. By this approach the expected average capacity is now very close to 30.08 $MMm^3$/day.

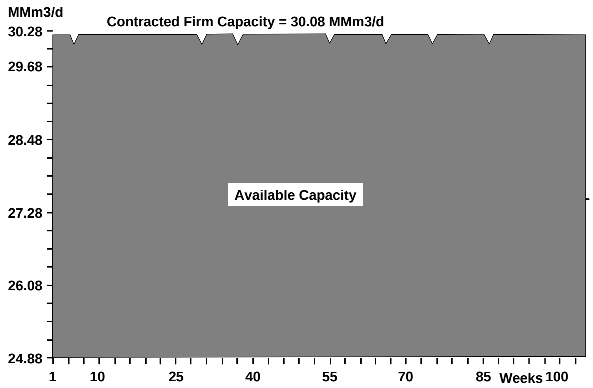


Figure 7 – Capacity recovery with the installation of five stand-by compressor units

## MONTE CARLO SIMULATION

Monte Carlo simulation is a very practical, simple and straightforward tool in predicting compressor station units unavailability that would expose the Gas Transmission Company to capacity shortage and consequently revenue losses and contractual liabilities, as a result of failure to provide the firm capacity to the shippers.

The software @Risk® from Palisade was used in conjunction with Excel® for Windows® to run all the Monte Carlo simulations.

We have adopted an availability value of 0.9294 for each compressor station unit, and then applied Monte Carlo simulation to the gas pipeline compressor station model for three cases: (a) No stand by units, (b) Five stand by units and (c) Ten stand by units.

The criterion to evaluate the gas pipeline availability has considered the available capacity taken from the thermo-hydraulic simulation software of the gas pipeline under different unavailability scenarios. Pipeline Studio® from Energy Solutions was used to run the scenarios. The maximum capacity taken from the simulation software for each scenario divided by the contractual firm transmission capacity provides the availability of the transmission system.

Stand-by compressor units were defined based on feasibility analysis and also on transportation company experience in handling market demand and operation risk.

### Monte Carlo simulation results

The Monte Carlo simulation was run for a configuration of a total of 10 compressor stations, with 2 compressor units per station, and the failure outcomes are presented in the ***tables 1, 2 and 3,*** respectively for (a) no stand by units, (b) 5 stand by units for the first 5 compressor stations (1 at each compressor station) and also (c) 10 stand by units (1 in all compressor stations) for comparison purpose only. The feasibility study was performed to identify the best number of stand-by units to mitigate the exposure to contractual liabilities. The Monte Carlo simulation has performed 36500 iterations.

From the average firm transportation capacity taken from ***tables 5, 6 and 7*** of 27.77, 29.36 and 29.99 $MMm^3/d$, respectively the availability of the gas pipeline transmission system was evaluated by simply dividing this capacity value by the firm contractual capacity of 30.08 $MMm^3/d$ with the following results:

- No stand by compressor units: 0.9231
- 5 stand by units (for the first 5 stations): 0.9761
- 10 stand by units (1 to each station): 0.9971

| Unavailable Compressor Units | Frequency days/year | Capacity, MMm3/d | Compressor Station #5 | #6 | #7 | #8 | #9 | #10 | #11 | #12 | #13 | #14 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | unavailable days per year | | | | | | | | | |
| 0 | 88 | 30.08 | | | | | | | | | | |
| | | 25.90 | 11.8 | | | | | | | | | |
| | | 26.10 | | 12.6 | | | | | | | | |
| | | 26.70 | | | 12.2 | | | | | | | |
| | | 26.70 | | | | 11.8 | | | | | | |
| 1 | 120.4 | 27.20 | | | | | 11.6 | | | | | |
| | 133.6 | 27.50 | | | | | | 13.0 | | | | |
| | 254 | 28.70 | | | | | | | 10.5 | | | |
| | | 29.80 | | | | | | | | 11.6 | | |
| | | 29.30 | | | | | | | | | 13.8 | |
| | | 25.80 | | | | | | | | | | 11.5 |
| | | 25.90 | 0.70 | | | | | | | | | |
| | | 26.10 | | 0.50 | | | | | | | | |
| | | 26.70 | | | 0.60 | | | | | | | |
| | | 26.70 | | | | 0.20 | | | | | | |
| 2 | 5.6 | 27.20 | | | | | 0.50 | | | | | |
| | | 27.50 | | | | | | 0.80 | | | | |
| | | 28.70 | | | | | | | 0.50 | | | |
| | | 29.80 | | | | | | | | 1.00 | | |
| | | 29.30 | | | | | | | | | 0.30 | |
| | | 25.80 | | | | | | | | | | 0.50 |
| | | | Compressor Station 5&6 | 6&7 | 7&8 | 8&9 | 9&10 | 10&11 | 11&12 | 12&13 | 13&14 | |
| | | 21.60 | 2.6 | | | | | | | | | |
| | | 21.70 | | 1.1 | | | | | | | | |
| 1+1 | | 21.90 | | | 1.7 | | | | | | | |
| (at two | | 22.00 | | | | 1.8 | | | | | | |
| contiguous | 16.4 | 23.00 | | | | | 2.7 | | | | | |
| stations) | | 23.70 | | | | | | 2.5 | | | | |
| | | 24.40 | | | | | | | 1.4 | | | |
| | | 24.90 | | | | | | | | 1.8 | | |
| | | 21.90 | | | | | | | | | 0.8 | |
| | 364.3 | 27.77 | | | | | | | | | | |
| System Availability | | 0.9231 | | | | | | | | | | |

Note: For the case of *one unit unavailable per station* the quantity of 133.6 days are related to others non contiguous stations that also have one unit unavailable that do not reduce the pipeline simulated capacity.

Table 5 – Failure Simulation Results of Compressor Station Units with no Stand by using Pipeline Studio®.

| Unavailable Compressor Units | Frequency days/year | Capacity, MMm3/d | Compressor Station #5 | #6 | #7 | #8 | #9 | #10 | #11 | #12 | #13 | #14 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | unavailable days per year | | | | | | | | | |
| 0 | 58 | 30.08 | | | | | | | | | | |
| | | 30.08 | 11.2 | | | | | | | | | |
| | 67.7 | 30.08 | | 14.1 | | | | | | | | |
| | 101.6 | 30.08 | | | 13.1 | | | | | | | |
| | 169 | 30.08 | | | | 15.3 | | | | | | |
| 1 | | 30.08 | | | | | 14.0 | | | | | |
| | | 27.50 | | | | | | 9.4 | | | | |
| | | 28.70 | | | | | | | 8.8 | | | |
| | 112 | 29.80 | | | | | | | | 7.9 | | |
| | | 29.30 | | | | | | | | | 7.6 | |
| | | 25.80 | | | | | | | | | | 10.5 |
| | | 25.90 | 1.6 | | | | | | | | | |
| | 5 | 26.10 | | 1.1 | | | | | | | | |
| | | 26.70 | | | 0.6 | | | | | | | |
| | | 26.70 | | | | 0.5 | | | | | | |
| 2 | | 27.20 | | | | | 1.1 | | | | | |
| | | 27.50 | | | | | | 0.6 | | | | |
| | 2 | 28.70 | | | | | | | 0.7 | | | |
| | | 29.80 | | | | | | | | 0.5 | | |
| | | 29.30 | | | | | | | | | 0.2 | |
| | | 25.80 | | | | | | | | | | 0.0 |
| 3 | 0 | | 0 | 0 | 0 | 0 | 0 | | | | | |
| | | | Compressor Station 5&6 | 6&7 | 7&8 | 8&9 | 9&10 | 10&11 | 11&12 | 12&13 | 13&14 | |
| | | 30.08 | 3.1 | | | | | | | | | |
| | 11 | 30.08 | | 2.9 | | | | | | | | |
| 1+1 | | 30.08 | | | 2.1 | | | | | | | |
| (at two | | 30.08 | | | | 2.7 | | | | | | |
| contiguous | | 27.50 | | | | | 1.5 | | | | | |
| stations) | | 23.70 | | | | | | 1.9 | | | | |
| | 9 | 24.40 | | | | | | | 1.9 | | | |
| | | 24.90 | | | | | | | | 2.1 | | |
| | | 21.90 | | | | | | | | | 1.3 | |
| | 365.5 | 29.36 | | | | | | | | | | |
| System Availability | | 0.9761 | | | | | | | | | | |

Note: For the case of *one unit unavailable per station* the quantity of 101.6 days are related to others non contiguous stations that also have one unit unavailable that do not reduce the pipeline simulated capacity.

Table 6 – Failure Simulation Results of Compressor Station Units with 5 Stand-by Units (1 at each first 5 station) using Pipeline Studio®.

| Unavailable Compressor Units | Frequency days/year | Capacity, MMm3/d | Compressor Station #5 | #6 | #7 | #8 | #9 | #10 | #11 | #12 | #13 | #14 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | unavailable days per year | | | | | | | | | |
| 0 | 40 | 30.08 | | | | | | | | | | |
| | | 30.08 | 9.8 | | | | | | | | | |
| | | 30.08 | | 9.5 | | | | | | | | |
| | | 30.08 | | | 9 | | | | | | | |
| | 94.0 | 30.08 | | | | 7.4 | | | | | | |
| 1 | 206.0 | 30.08 | | | | | 10.1 | | | | | |
| | 300 | 30.08 | | | | | | 9 | | | | |
| | | 30.08 | | | | | | | 10 | | | |
| | | 30.08 | | | | | | | | 8.5 | | |
| | | 30.08 | | | | | | | | | 10.6 | |
| | | 30.08 | | | | | | | | | | 10.1 |
| | | 25.90 | 0.9 | | | | | | | | | |
| | | 26.10 | | 0.7 | | | | | | | | |
| | | 26.70 | | | 0.6 | | | | | | | |
| | | 26.70 | | | | 0.5 | | | | | | |
| 2 | 6 | 27.20 | | | | | 0.7 | | | | | |
| | | 27.50 | | | | | | 0.7 | | | | |
| | | 28.70 | | | | | | | 0.4 | | | |
| | | 29.80 | | | | | | | | 0.4 | | |
| | | 29.30 | | | | | | | | | 0.6 | |
| | | 25.80 | | | | | | | | | | 0.9 |
| 3 | 0 | | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | | 30.08 | Compressor Station 5&6 | 6&7 | 7&8 | 8&9 | 9&10 | 10&11 | 11&12 | 12&13 | 13&14 | |
| | | 30.08 | 2 | | | | | | | | | |
| | | 30.08 | | 2 | | | | | | | | |
| 1+1 | | 30.08 | | | 2 | | | | | | | |
| (at two | 18 | 30.08 | | | | 1 | | | | | | |
| contiguous | | 30.08 | | | | | 2 | | | | | |
| stations) | | 30.08 | | | | | | 3 | | | | |
| | | 30.08 | | | | | | | 2 | | | |
| | | 30.08 | | | | | | | | 1 | | |
| | | 30.08 | | | | | | | | | 3 | |
| | 365 | 29.99 | | | | | | | | | | |
| System Availability | | 0.9971 | | | | | | | | | | |

Note: For the case of *one unit unavailable per station* the quantity of 206 days are related to others non contiguous stations that also have one unit unavailable that do not reduce the pipeline simulated capacity.

Table 7 – Failure Simulation Results of Compressor Station Units with 10 Stand by Units (1 at each first 10 station) using Pipeline Studio®.

## ECONOMIC ANALYSIS

The economic analysis to define the quantity of stand by units was based on Monte Carlo simulation runs performed for each gas transmission system configuration: (a) no stand by units, (b) 5 stand by units and (c) 10 stand by units. The objective was to identify the adequate quantity of stand-by units to provide a manageable level of risk exposure to contractual liabilities due to non-delivered capacities. The discounted cash flow - DCF method was used (Ross & Westerfield, 1999) and compared for the three configurations to identify the one that would give the better net present value – NPV. The avoided losses and liabilities were considered as revenues and the stand-by units as capital investments. No additional costs related to fuel gas plus operation and maintenance were accounted for since the units will operate as stand-by units.

## Economic Assumptions

For the purpose of this paper the following assumptions were adopted:

| | |
|---|---|
| Firm contractual capacity: | 30.08 MMm$^3$/d |
| High Heat Value: | 36480 BTU/m3 |
| Transportation rate: | 1.20 US$/MMBTU |
| Loss of revenue: | 1 time the non-delivered capacity |
| Contractual liability: | 1 time the non-delivered capacity |
| Contractual term: | 15 years |
| Discount rate: | 15% per year |
| 1 installed stand by unit: | US$ 12,900,000.00 |

## Economic Evaluation Results

(a) No Stand by Units – Base Case

| | |
|---|---|
| System availability: | 0.9231 |
| Potential loss of capacity | 2.28 MMm$^3$/d |
| Potential loss of revenue: | 182.8 MMUS$ |
| Potential loss in liabilities: | 182.8 MMUS$ |

(b) 5 Stand by Units

| | |
|---|---|
| System availability: | 0.9761 |
| Remaining Loss of capacity: | 0.85 MMm$^3$/d |
| Remaining yearly exposure: | 136.3 MMUS$ |
| Recovered capacity: | 1.43 MMm$^3$/d |
| Avoided loss of revenue: | 114.7 MMUS$ |
| Avoided contractual liability: | 114.7 MMUS$ |
| Capex for stand by units: | 64.5 MMUS$ |
| NPV: | 164.8 MMUS |

(c) 10 stand by units (1 at each 10 compressor station)

| | |
|---|---|
| System availability: | 0.9971 |
| Remaining Loss of capacity: | 0.07 MMm$^3$/d |
| Remaining yearly exposure: | 11.2 MMUS$ |
| Recovered capacity: | 2.21 MMm$^3$/d |
| Avoided loss of revenue: | 177.2 MMUS$ |
| Avoided contractual liability: | 177.2 MMUS$ |
| Capex for stand by units: | 129 MMUS$ |
| NPV: | 225.4 MMUS$ |

The results obtained for configurations (b) and (c), above, points to an opportunity to install stand-by units for all the compressor stations.

Although the capital investment in stand-by units was not considered to be included in the original capital expenditure - Capex for the gas pipeline project they are still necessary to mitigate the risk exposure associated with the loss of revenues and contractual liabilities.

These investments in stand by units also provide a potential increase of the gas transmission system capacity of around 4 MMm$^3$/d on an interruptible basis. This additional capacity will allow to a certain level the recovery of the investment in stand by units.

## CONCLUSIONS

Based on the information presented on the tables 1, 2 and 3 we the following conclusions can be drawn:

(a) stand by units are necessary to provide contractual firm capacity to the shipper;

(b) 5 stand by units have given an availability value of 0.9716 and 10 stand-by compressor units have given an availability value of 0.9978 that is very close to 1.

(c) the assumed exposure level to penalties will always be dependent on the risk profile of the Transportation company and company experience in dealing with such situation;

(d) This kind of evaluation would be recommended during the design phase of the gas pipeline project so as to define the appropriate load factor to be adopted for the project, or to negotiate appropriate level of commitment of contractual firm capacity.

(e) The Monte Carlo simulation method associated with Scheduled and Non-scheduled Maintenance gives quick and reliable results to be used by the decision makers in defining the necessary level of redundancy for the gas pipeline transmission system.

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