PSIG 0405

Series or Parallel Arrangement for a Compressor Station? - A Recurring Question that needs a Convincing Answer

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This paper was prepared for presentation at the PSIG Annual Meeting held in Palm Springs, CA, United States, 20 October – 22 October 2004.

ABSTRACT

Long distance gas pipelines compressor stations play an important role in providing natural gas transportation capacity at the same time that allow the pipeline capacity expansion in conjunction with the option of installing loop lines along its length.

This subject has attracted the attention of many authors (Santos, 1997 and 2000; Kurz et all, 2003) with papers addressing the pros and cons of adopting a specific compressor station units arrangement, whether series, parallel or parallel-series, with conclusions not always comprehensive and converging.

This paper brings back this important subject to our attention and presents an evaluation of the best arrangement for a compressor station not as a theoretic and isolated design but as part of an entire gas transportation system.

A case study is presented base on the expansion design for the Bolivia-Brazil Gas Pipeline Project – Gasbol for the Station #5, in Brazil side. Gasbol pipeline has a design capacity of 30 MMm3/d (1,059 MMcfd) resulted from a ND 32”, 1813 km (1127 miles) pipeline and 14 compressor stations with 4 units, each of them originally designed with 7000 hp ISO, starting at Rio Grande, Bolivia up to São Paulo, Brazil.

This paper also covers the Gasbol capacity expansion studies from 34 (1201) and then to 40 (1413), 50 (1766) and 68 MMm3/d (2402 MMcfd) by means of retrofitting its compressor stations and by adding looping on incremental basis.

The subject of which arrangement to adopt has been considered and simulated at the design phase of the project and was again performed by the time we started the expansion design.

Such analysis has even considered the opportunity of using variable speed driver with electric motor as an alternative against gas turbine drivers (Santos, 2000). Failure analysis in transient mode was also performed to identify the pros and cons of the compressor station units arrangement

This paper presents a technical and economic approach to help deciding on which compressor station arrangement to adopt.

INTRODUCTION

When the Bolivia-Brazil Gas Pipeline design has started in 1993 there were some uncertainties to be addressed such as the certified volumes for the gas reserve, closure of transportation agreements, creation and implementation of gas distribution companies, gas selling agreements and market growth projections. The design started assuming a transportation capacity of 16 MMcm/d (565 MMdfd) from a 28” pipeline diameter that proved to be unfeasible.

The design capacity was defined latter on to be 30 MMcm/d (1059 MMcfd) from a 32” pipeline diameter with extension of 1813 km (1127 miles) and 14 compressor stations. The expansion project based solely on new compressor stations design has improved the capacity from 30 (1059) to 34 MMm3/d (1201 MMcfd).

METHODOLOGY

As part of the design phase we adopted a methodology that proved to be of fundamental importance for the project success that includes the following steps:

1. Perform thermo-hydraulic simulation – steady state
2. Pre-select compressor units
3. Perform thermo-hydraulic simulation – transient state
4. Perform failure analysis

Thermo-hydraulic Simulation – Steady State

The pipeline was modeled using generic compressor with trans-thermal and steady state modes for each operation year and adopted the following steps:

- Simulation from maximum to minimum capacity
- Definition of compressor station quantity and spacing

Pre-selection of Equipment for Series and Parallel Arrangements

With the data collect from each operation year from steady state simulation for the compressor station we were able to pre-select the turbo-compressor units to be used in series or in parallel arrangement. We have favored the selection of larger units and fewer quantities per station since the concentration of power per unit drops the capital investment per station, presents higher thermodynamic performance and therefore enhances the project economics.

Thermo-hydraulic Simulation – Transient

With the performance maps defined from the pre-selection of the turbo-compressor units for series and parallel arrangements and with the flow demand profiles for each gas delivery points we run the transient analysis for each operation year to check the pipeline sizing (Santos, 1997 and 2000) and compressor station overall performance.

Failure Analysis

Another important step while designing a gas pipeline and selecting the compressor station, whether series or parallel, is the failure analysis. The failure analysis allows quantifying exactly which arrangement will present the higher transportation capacity under failure conditions and also allows identifying the one that will be more desirable in terms of reducing liabilities due ship-or-pay agreements clauses.

CASE STUDY

The case study is based on the Expansion Project of the Bolivia-Brazil Gas Pipeline – Gasbol that we have applied all the aforementioned procedures. This case study considers an evaluation of two parallel arrangements and one series arrangement as described below:

Parallel arrangements:

- Two centrifugal compressor per station
- Four centrifugal compressor per station

Series arrangement:

- Two centrifugal compressors per station

Technical Assumptions

Gas Specific Gravity	0.6
Pipeline	
Diameter:	DN 32”
Design code:	ANSI B31.8
Max. Allowed Working Pres. – MAOP:	1440 PSIG
Pipe material:	API 5L X70
Pipe internal roughness (epoxy painted):	350 μinches
Pipeline Inlet Pressure:	1420 psig
Minimum Pipeline Delivery Pressure:	700 psig
Pipeline overall heat transfer:	0.39 Btu/h.ft2.F
Soil temperature:	61 to 86 F
Depth of burial:	3 feet
Compressor Station	
Maximum Compression ratio:	1.6
Suction and Discharge Header pressure drop:	5 psi
After cooler pressure drop:	5 psi
After cooler outside temperature:	127 F
Site elevation	341 feet
Site Temperature	82 F
Flow Equation:	Colebrook

Centrifugal Compressors - Performance Maps

- Two Units in Series – 2 x 15000 hp ISO, ***figure 1***
- Two Units in Parallel – 2 x 15000 hp ISO, ***figure 1***
- Four Units in Parallel – 4 x 7800 hp ISO, ***figure 1***

Thermo-Hydraulic Simulation Results for the Station Configurations

The simulations results for all the arrangements can be seen on ***table 1***.

FAILURE ANALYSIS

For the purpose of this case study the compressor station has been considered as a business unit (see ***figure 2***) with contractual obligations to guarantee the nominal transportation capacity. In this model the Service Co is a company that holds property of the compressor station and provides a compression service under an agreement with the transportation company – TransCo.

Based on gas turbine reliability of 97.5% we can anticipate a down time of 219 hour or 9.125 days per year per unit assumed that the failures may happen to one unit at a time. We also considered that the station have 1 (one) spare driver that would be used as a replacement. The replacement time was taken as 48 hours. The detrimental effect on capacity reduction is associated with loss of revenue and contractual liabilities assumed as the same amount as the revenue losses as detailed onward.

Transient Results

As can be seen from the graphic show on ***figure 3*** the parallel arrangement with 4 compressor units is the one that presents a much better result along the 48 hours of failure.

The effect of one unit failure in Station #5 over the Station #6 can be observed on ***figure 4*** for all arrangements under analysis. ***Figures 5*** to ***11*** explain the amount of capacity recovered as a function of the operation variables of the remaining compressors such as available power and maximum speed. In some cases we can observe that the compressor power or speed goes to maximum and as a consequence discharge pressure can no longer be maintained at the set pressure of 99.84 kgf/cm2g (1420 psig). For the purpose of this case study Station #6 was considered as 4 x 7800 hp ISO and all downstream part of the gaspipeline was maintained unchangeable for all the cases analysed so as not to affect the comparative evaluation of Station #5. For the series arrangement (2 x 15000 hp ISO) one unit failure analysis, ***figure 6*** shows the recycling time that the remaining compressor unit will run until its compression ratio overcomes the station compression ratio. During this recycling time the station flow will be zero. This situation was modeled by shuting down both units and starting one unit thereafter. This effect is not observed in ***figure 5*** since graphic time scale is larger and this effect is very short in time.

Comparative Table

With the tabular format (see ***table 2***) from the previous graphic for failure analysis we can quantify the capacity loss for each configuration, in MMm3/d as shown in

Capacity Loss due to Failure

The capacity loss per year is equal to the failure days per unit/year times the number of units times the average capacity loss. The result must be doubled to allow for contractual liabilities (see ***table 3***).

ECONOMIC EVALUATION

Technical and economic evaluation is necessary to support the decision on which arrangement to adopt since there are some items that affect significantly the overall result of the analysis. The economic evaluation assumed the compression station #5 as a Business Unit under a compression service contract with a Shipper on 100% availability. The spreadsheet (see ***figure 12***) calculation considered the following assumptions and is shown below:

- Capital investment requirements for each configuration
- Investment done in two years time – 50% each year.
- O&M cost (overhaul and spare parts included) as 5% of the total station investment
- Compression rate for each Station arrangement in US$/MMBTU
- Fuel price @ 1.25 US$/MMBTU
- Pipeline capacity under failure analysis
- Taxes of 40%
- Return rate of 12% a year un-leveraged.
- Project life of 10 and 15 years

Capital Investment and O&M

The compressor station capital investment shown on the ***table 4*** represents the expected costs and includes engineering, importation, taxes and construction and assembling and may vary from country to country. Reader should get the accurate figures for his own project configuration prior to apply the methodology presented in this paper.

Economic Evaluation – Table of Results

The economic evaluations have been made for the station with and without stand by units and the results are shown on ***table 5***. With all the information for each configuration the compression service rate was calculated to recover all the capital expenditure - Capex and operation expenditures - Opex using the economic assumptions defined previously.

The discounted cash flow – DCF approach (Ross, Westerfield, 1999) was performed by using an excel spreadsheet to evaluate the net present value – NPV of each compressor station configuration. The series arrangements with 2 units of 15000 hp ISO with and without stand by unit were taken as reference arrangements and the correspondent compression service rates were calculated to zero the NPV. For the other configuration we kept the compression service rate as constant to evaluate the NPV effect due to changes in capital investment, capacity loss, fuel usage, O&M and depreciation.

The two reference arrangements, that are the 2 units in series with stand by units and 2 units in series without stand by units, had their compression service rate calculated to give NPV equal zero for comparison purpose. To keep a stand by unit the Shipper will have to pay for this operational compressor station availability increase that would affect the competitiveness of a compression service provider or the Business Unit we considered to apply for the Station #5 as reflected on the compression service rate of 0.0377 versus 0.0314 US$/MMBTU – 20.06% higher, for a economic life of 10 years.

GAS PIPELINE EXPANSION

Gas pipeline expansion is something that we should expect to happen along the life of a project. As we acknowledge the natural gas market potential growth studies has been made for incremental capacity expansion. The Bolivia-Brasil Gas pipeline Project started with a capacity of 16 MMm3/d (565

MMcfd) then we decided on a design capacity of 30 MMm3/d (1059 MMcfd). Later on we redesigned the compressor stations to increase capacity to 34 (1201), 40 (1413), 50 (1766) and 68 MMm3/d (2402 MMcfd). Associated with the compressor station redesign we also considered the installation of loop lines to the pipeline in incremental lengths of 1/3, 2/3 and finally doubling the gas pipeline section between the compression stations. Up to 34 MMm3/d (1201 MMcfd) the expansion relied only on compressor station redesign without loop lines.

The Compressor station arrangement whether series or parallel has attracted our attention in terms of having a configuration that would be flexible enough and that would minimize capital investment, fuel usage, O&M costs and therefore would maximize economic results for the project. The thermo-hydraulic simulation results from this analysis are presented on ***tables 6 and 7***.

Parallel arrangement was adopted as the best selection for the project.

In case we start a project with a series arrangement and latter on we need to expand the capacity we must be aware of the limitations associated with the units capacity range since all the gas flow goes through each compressor and we also have the available power from the driver that may be just enough for the original design with no allowance to be used for the expansion and in that case the options would be a replacement for the units or to add parallel units that would be one unit or even two additional units in series as illustrated in ***figure 13***, that shows an optimization scheme with suction and discharge headers and set of valves that allows a flexible parallel-series arrangement for a compressor station with just one unit (any unit) as a stand by.

CONCLUSIONS

As can be seen from the simulation results and confirmed by the economic evaluation for this case study, series arrangements provides better results when compared with parallel arrangements when no stand by units is considered and parallel units provides better results than series when stand by units is a requirement and more flexibility is desirable.

The impact of transportation capacity shortage and capital investment associated with the stand by unit play an important role on this kind of analysis and must be considered whenever a design selection is to be made.

The methodology presented if adopted accordingly will provide a convincing economic answer to the recurrent question related to the compressor station arrangement and therefore will allow a good decision making.

REFERENCES

1. Santos, S. P., 1997, "Transient Analysis – A Must in Gas Pipeline Design", Pipeline Simulation Interest Group
2. Santos, S. P., 2000, "Series or Parallel – Tailor Made Design or a General Rule for a Compressor Station Arrangement?" Pipeline Simulation Interest Group
3. Kurz, R., Ohanian, S. and Lubomirsky, M., 2003, "On Compressor Station Layout", Proceedings of ASME TURBOEXPO 2003.
4. ROSS, S.A.; WESTERFIELD, R.W.; JAFFE, J.F. - Corporate Finance, fifth edition: The McGraw-Hill Companies, Inc., 1999.

ACKNOWLEDGEMENTS

The authors want to thank PETROBRAS for making this information available to the PSIG members and also Sebouh Ohanian, Senior Project Manager of Solar Turbines for reviewing the paper and providing pertinent comments.

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TABLES

Station Arrangement		Series		Parallel	
		1x15000	1x15000	2x15000	4x7800
Up pressure	psig	*939.2*	*1156*	*939.2*	*938.5*
Down pressure	psig	*1156*	*1420*	*1420*	*1420*
Up temperature	F	*94.16*	*122.7*	*94.16*	*94.14*
Down temperature	F	*122.7*	*152.1*	*153.5*	*166.1*
Max. disch. pressure	psig	*1420*		*1420*	*1420*
Station Inlet flow rate	MMscfd	*1117*		*1117*	*1117*
Station Outlet flow rate	MMscfd	*1117*		*1117*	*1117*
Unit flow rate	MMscfd	*1117*		*558.39*	*279.20*
Unit Actual flow rate	ft3/min	*11008*	*9486*	*5504*	*2754*
Head	ft-lbf/lbm	*9054*	*9546*	*18565*	*18623*
Speed	RPM	*7540*	*7470*	*8148*	*13119*
Adiabatic efficiency	%	*87*	*88*	*85.2*	*79.7*
Power required	hp	*11083*	*11671*	*11792*	*6325*
Power available	hp	*12620*	*12598*	*12757*	*6438*
Fuel Gas	MMscfd	*5.024*		*5.068*	*5.702*
Mechanical efficiency	%	*99*	*99*	*99*	*98*
Auxiliary load	hp	*0*	*0*	*0*	*0*
Compressor type	Centrifugal				
Driver type	Gas Turbine				

Table 1 – Thermo-hydraulic Simulation Results for the Station #5

Station Arrangement		Time in hours: 0	6	12	18	24	30	36	42	48	Mean	Capacity Loss
2x15000 Series	MMSCFD	1117	1039	1050	1056	1059	1061	1062	1063	1063	1058	59.15
2x15000 Parallel	MMSCFD	1117	1012	1025	1030	1033	1035	1036	1037	1037	1032	84.77
4x7800 Parallel	MMSCFD	1117	1062	1068	1073	1077	1078	1079	1080	1081	1075	41.57

Table 2 – Failure Analysis Results

Station Arrangement [A]	Failures days per unit/year [B]	Total Failures (unit-days/year) [A x B]	Capacity loss MMm3/d [C]	Capacity loss per year, MMm3 [D]=[A x B x C]	Total Capacity loss (failure + penalties) [E]=2 x [D] (*)
2x15000 Series	9.125	18.25	59.15	1079.6	2159.2
2x15000 Parallel	9.125	18.25	84.77	1547.0	3094.0
4x7800 Parallel	9.125	36.50	41.57	1517.4	3034.9

(*) Service Co is penalized with the same amount as the capacity loss due to station failures.

Table 3 – Compression Capacity Loss

Compressor Station Units	hp	Station Cost (US$)	Engineering & Management (5%)	Taxes & Transportation (17%)	Total (US$)	O&M (US$)/year
4	7800	28,800,179	1,440,009	4,896,030	35,136,218	1,756,811
5	7800	33,769,979	1,688,499	5,740,896	41,199,374	2,059,969
2	15000	28,005,517	1,400,276	4,760,938	34,166,731	1,708,337
3	15000	37,399,612	1,869,981	6,357,934	45,627,527	2,281,376
Spare Driver						
1	7800	1,600,000	80,000	272,000	1,952,000	
1	15000	2,276,949	113,847	387,081	2,777,878	

Table 4 – Capital Investment and O&M

Compressor Station Units	hp	Arrangement	Total (US$)	O&M (US$)/year	Fuel Cost (US$)/year	Compression Service Rate (US$/MMBTU) 10 years	15 years	NPV 10 years (US$)/year	NPV 15 years (US$)/year
Without Stand by									
4	7800	Parallel	37,088,218	1,756,811	2,687,388	0.0314	0.0277	(1.3070)	(1.5413)
2	15000	Parallel	36,944,609	1,708,337	2,388,580	0.0314	0.0277	(0.1546)	(0.1734)
2	15000	Series	36,944,609	1,708,337	2,367,843	0.0314	0.0277	-	-
With Stand by									
5	7800	Parallel	43,436,134	2,059,969	2,687,388	0.0377	0.0331	1.3347	1.2737
3	15000	Parallel	45,627,527	2,281,376	2,388,580	0.0377	0.0331	(0.0628)	(0.0757)
3	15000	Series	45,627,527	2,281,376	2,367,843	0.0377	0.0331	-	-

Table 5 – Comparison of NPV Results

		Parallel Arrangement			
Units		3x15000	3x15000	4x15000	5x15000
Station Flow	MMSCFD	1201	1413	1766	2402
Loop Length		-	1/3	2/3	3/3
Gas Sp. Gr.		0.6	0.6	0.6	0.6
Suc. Press	psig.	884	922	842	881
Disch. Press	psig.	1420	1420	1420	1420
Suc. Temp.	F	92.57	90.97	88.42	92.54
Actual Flow	ft3/min	4201	4694	4827	5060
Adiabatic Eff.	%	0.85	0.85	0.85	0.85
Head	ft –lbf/lbm	21476	19284	23624	21648
Unit Req. Power	hp	9703	10251	11772	11737
Fuel Gas	MMSCFD	5.735	6.059	9.278	11.563

Table 6 – Expansion Simulation Results for Parallel Arrangement

		Series		Parallel-Series	
Units		2x19500		(**2x2**)19500	
Station Flow	MMSCFD	1201		2402	
Loop Length		-		3/3	
Gas Sp. Gr.		0.6		0.6	
Suc. Press	psig	884	1120	881	1120
Disch. Press	psig	1120	1420	1120	1420
Suc. Temp.	F	92.58	126.17	92.55	126.64
Actual Flow	ft3/min	12598	10644	12645	10657
Adiabatic Eff.	%	0.85		0.85	
Head	ft-lbf/lbm	10401	11150	10560	11164
Unit Req. Power	hp	14098	15114	14314	15132
Fuel Gas	MMSCFD	5.468		11.023	

Table 7 – Expansion Simulation Results for Series and Parallel-Series Arrangement

FIGURES

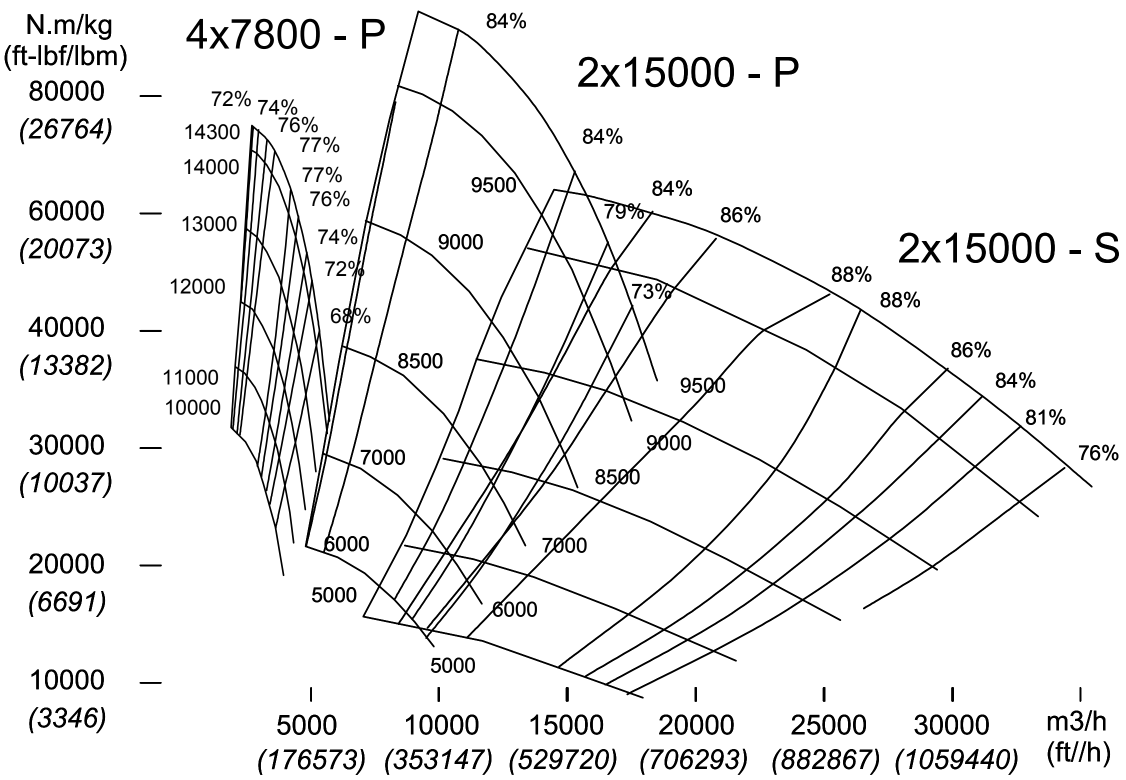

Figure 1 – Compressors Performance Map for each arrangement

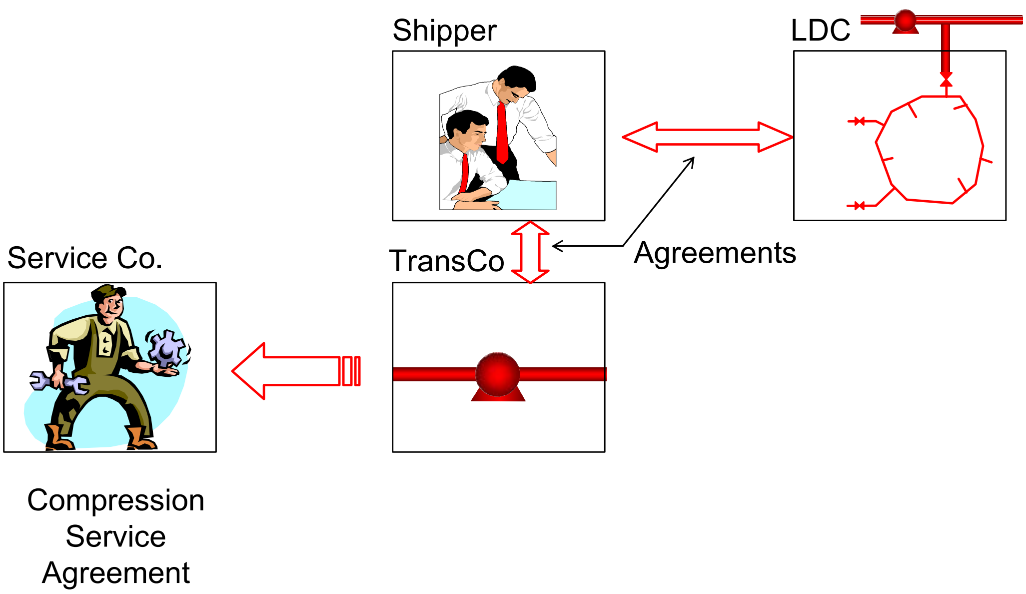

Figure 2 – Compressor Station #5 – Business Model

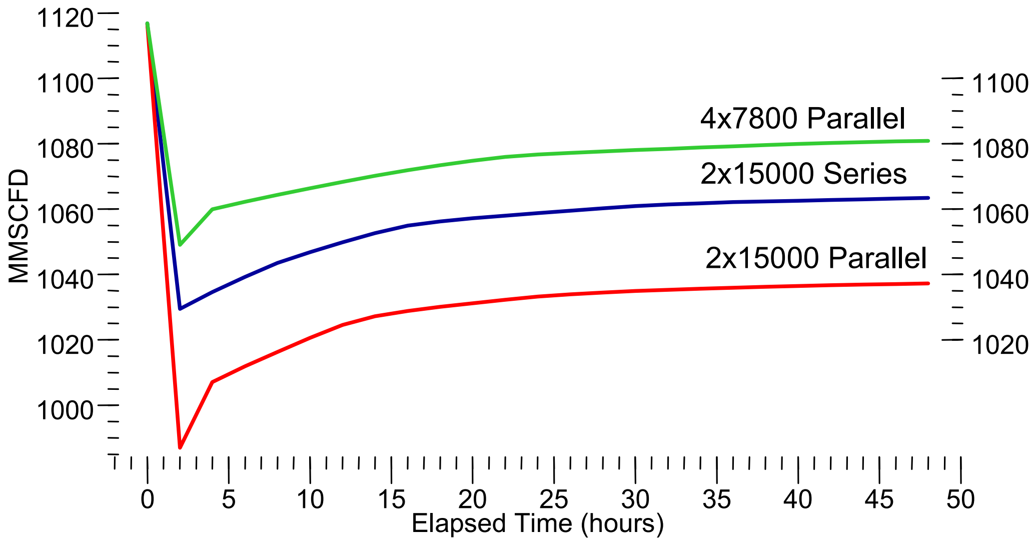

Figure 3 – Transient Analysis of One Unit Failure of Station #5 for each Arrangement

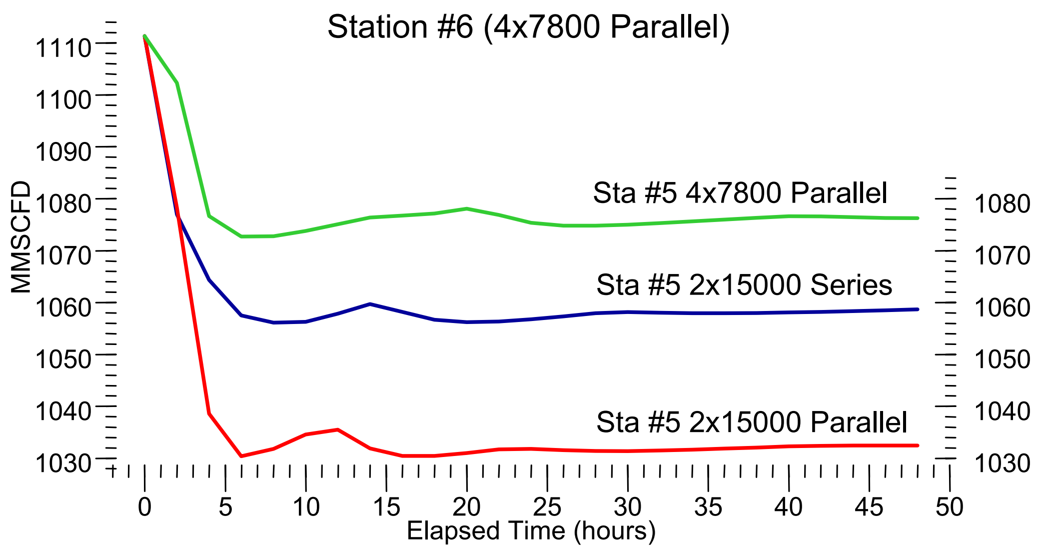

Figure 4 – Effect of Station #5 One Unit Failure for Each Arrangemente on Station #6 Capacity

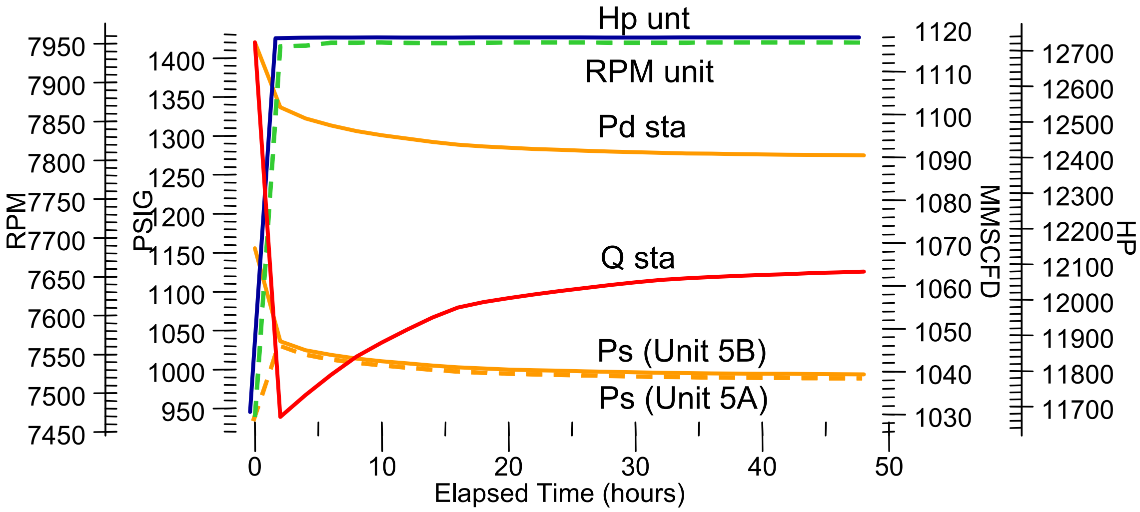

Figure 5 – 2x15000 hp Series - Station #5 Performance After One Unit Failure

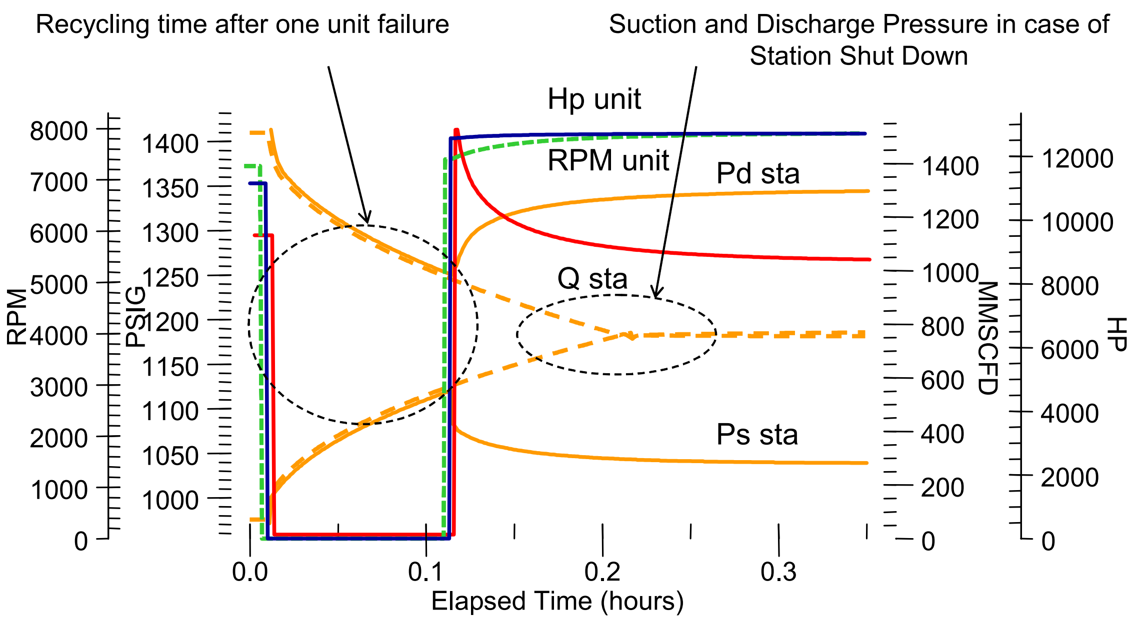

Figure 6 – 2x15000 hp Series - Station #5 Recycling Time after One Unit Failure

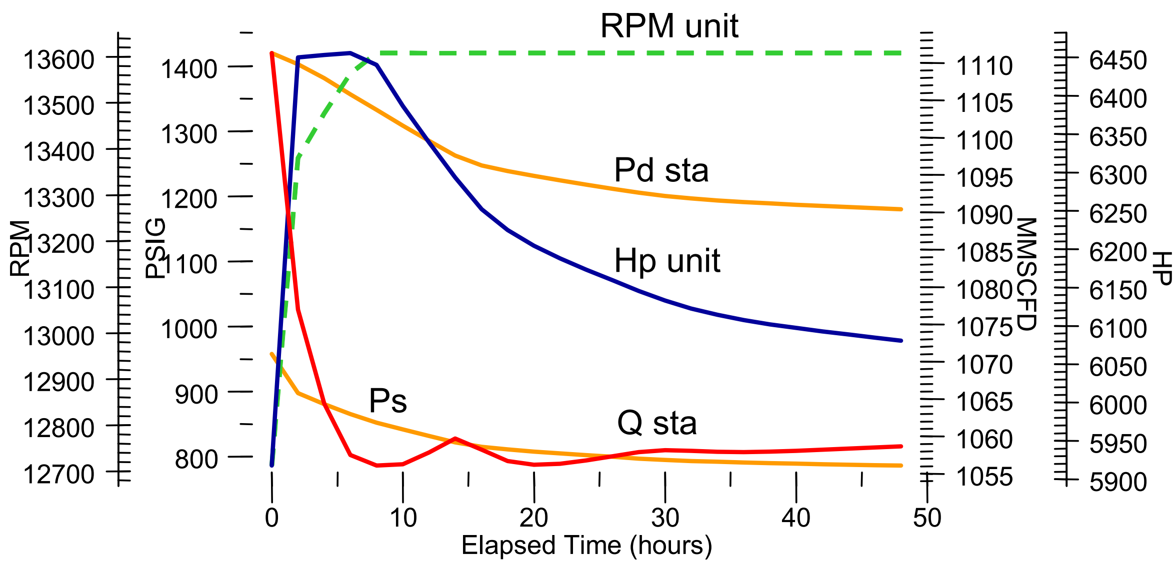

Figure 7 – 2 x 15000 hp Series – Effect on Station #6 due Station #5 One Unit Failure

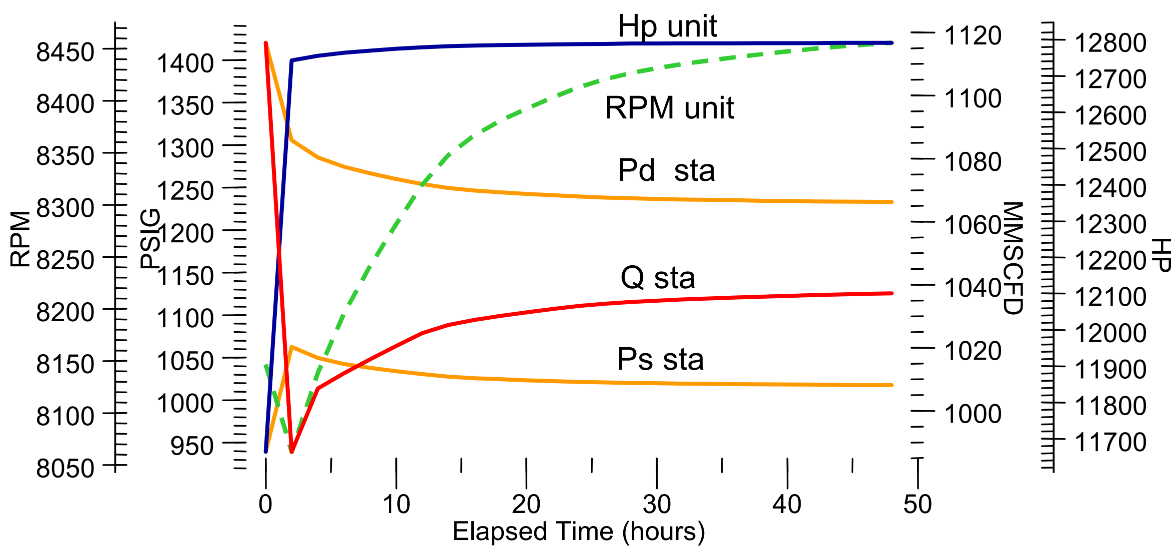

Figure 8 – 2 x 15000 hp Parallel - Station #5 Performance After One Unit Failure

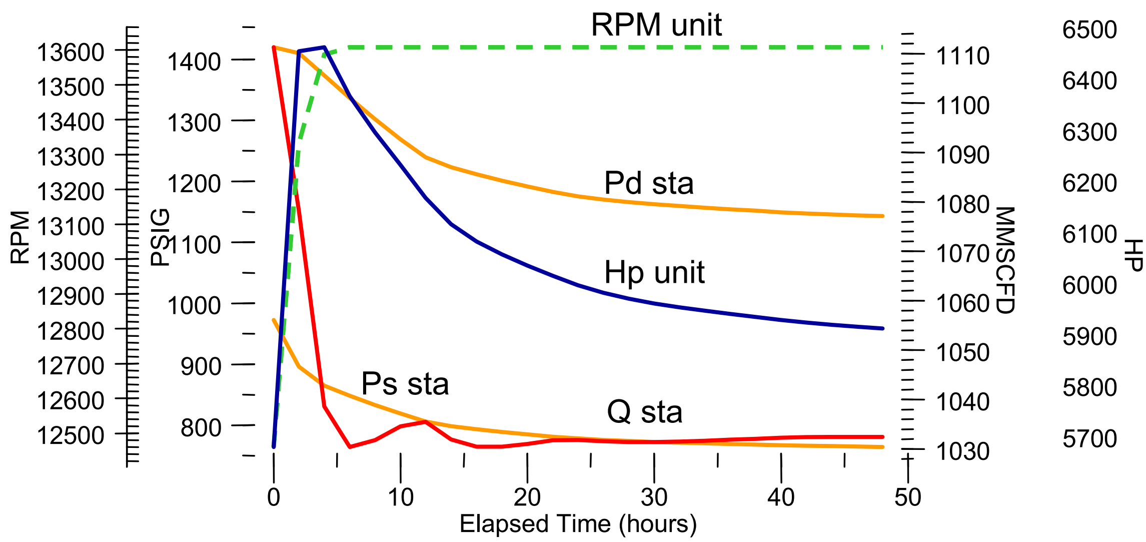

Figure 9 – 2 x 15000 hp Parallel – Effect on Station #6 due Station #5 One Unit Failure

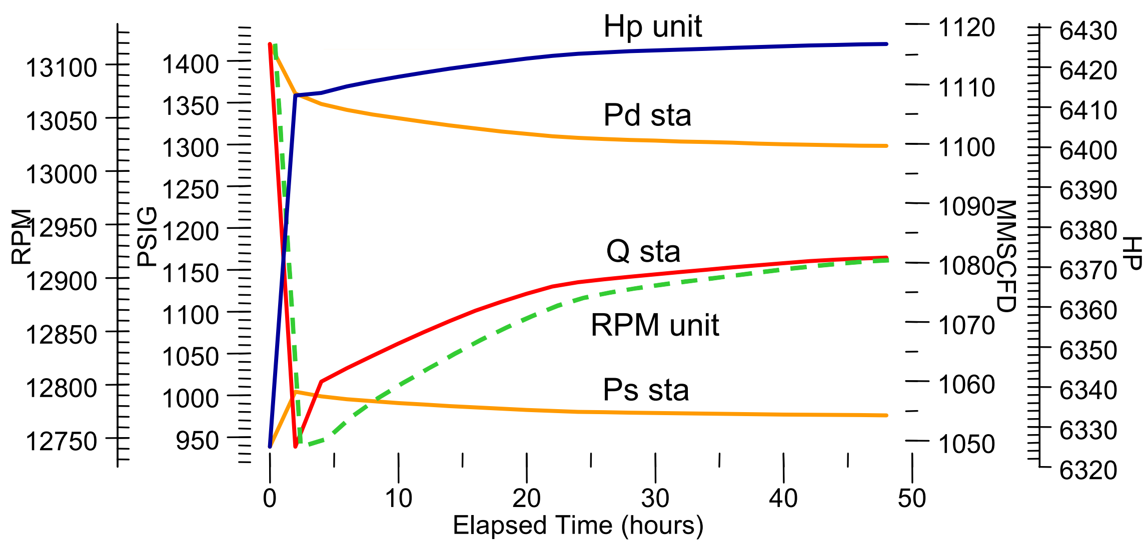

Figure 10 – 4 x 7800 hp Parallel - Station #5 Performance After One Unit Failure

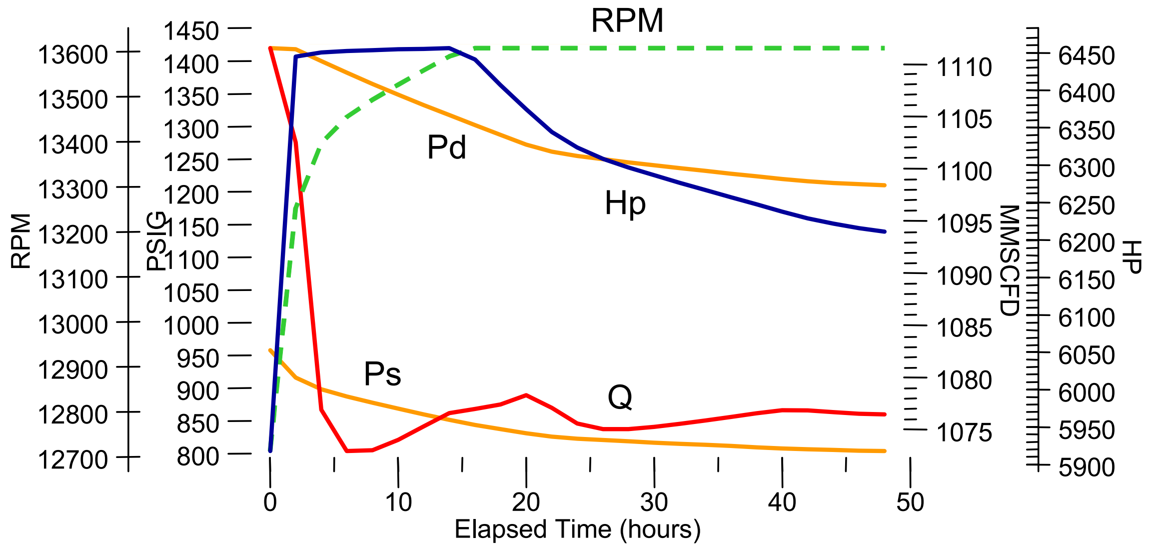

Figure 11 – 4 x 7800 hp Parallel – Effect on Station #6 due Station #5 One Unit Failure

Number of Years	**15**	(1)	-	1	10	11	15
Income Statement, million US$		-					
Contractual Transportation **Capacity**, MMSCFD				1,117	1,117	1,117	1,117
Loss of capacity due to failure, MMSCF	2,159			5.92	5.92	5.92	5.92
Compression Service Rate (US$/MMBTU)	0.0277			0.028	0.028	0.028	0.028
Operational Revenues				11.62	11.62	11.62	11.62
O&M costs				1.71	1.71	1.71	1.71
Fuel costs				2.37	2.37	2.37	2.37
Fuel consumption, MMSCFD	5.024						
Fuel gas price, US$/MMBTU	1.25						
Earnings before Interest/Tax/Deprec./Amortiz.(EBITDA)				7.54	7.54	7.54	7.54
Depreciation				3.69	3.69	-	-
Earnings before Interest and Tax (EBIT)				3.85	3.85	7.54	7.54
Interest paments on debt				-	-	-	-
Earnings before Tax (EBT)				3.85	3.85	7.54	7.54
Taxes	40.00%			1.54	1.54	3.02	3.02
Profit after tax				2.31	2.31	4.52	4.52
Cashflow Statement				1	10	11	15
Profit after tax				2.31	2.31	4.52	4.52
(+) Depreciation				3.69	3.69	-	-
(-) Debt Service Payments				-	-	-	-
Free Cash		-		6.00	6.00	4.52	4.52
(-) Total Equity **Investments**		(18.47)	(18.47)	-	-	-	-
(=) Project After-tax Free Cash Flow	12.00%	(18.47)	(18.47)	6.00	6.00	4.52	4.52
Project IRR	12.00%						
NPV (12% and Year -1)		**0.00**					

Figure 12 – Tipycal Economic Evaluation Spreadsheet (some years ommited for better display)

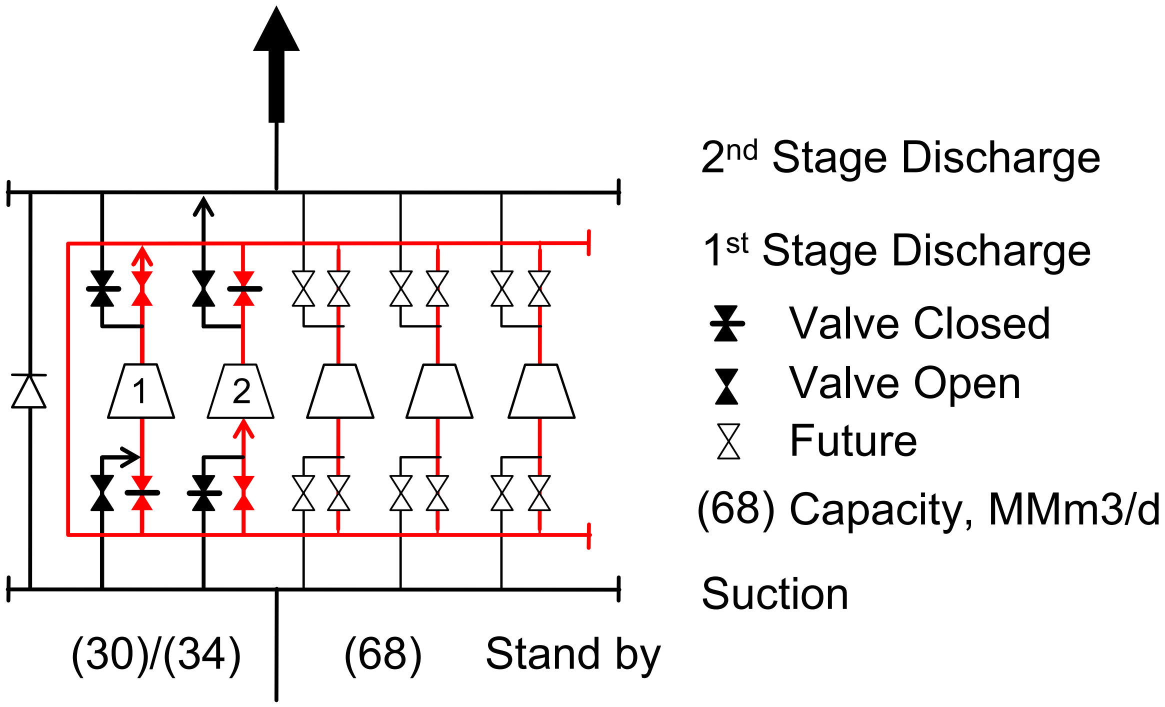

Figure 13 – Parallel-Series Arrangement