FCC HOT GAS EXPANDER RELIABILITY UPGRADE EVALUATION

by

Shailendra K. Gupta

Reliability Engineer

David L. Boomer

Manager, Engineering Projects

and

Lynn C. Fulton

Reliability Engineer

BP Amoco Corporation

Whiting, Indiana

Shailendra K. Gupta is a Reliability Engineer at BP Amoco Corporation, in Whiting, Indiana. He has more than 15 years' experience in the industry and is presently responsible for reciprocating compressors at Whiting Refinery. Prior to joining BP Amoco, he worked at Sunoco's Toledo Refinery where he was responsible for developing and implementing a reliability program. Mr. Gupta also worked at Syncrude Canada Ltd., in the areas of reliability, maintenance, and design.

Mr. Gupta has a B.Sc. degree (Mechanical Engineering, 1984) from the University of Detroit. He is a registered Professional Engineer in the Province of Alberta, Canada. He presently serves as BP Amoco's representative on the NPRA Maintenance Committee and has coauthored three technical papers.

David L. Boomer is Manager, Engineering Projects, for BP Amoco Corporation, in Whiting, Indiana. He has more than 26 years of refining industry experience with Amoco and BP Amoco. He has held a variety of technical, maintenance supervisory, operation management, and project leadership positions at several refinery locations and corporate headquarters.

Mr. Boomer received a B.S. degree (Civil Engineering, 1974) from the University of Nebraska, Lincoln, and is a registered Professional Engineer in the State of Virginia.

Lynn C. Fulton is a Reliability Engineer at the BP Amoco Whiting Refinery, in Whiting, Indiana. His current role includes root cause failure analysis of chronic problems and knowledge management for the future. He has held a variety of positions in engineering and maintenance within the Whiting refinery and as a Rotating Machinery Engineer with Amoco Petroleum Products. He has more than 20 years' experience in rotating machinery.

Mr. Fulton received a B.S. degree (Psychology, 1973) from Western Illinois University and a B.S. degree (Mechanical Engineering, 1977) from the University of Illinois in Chicago. He is a member of API Task Forces 614, 670, and RP686. Mr. Fulton is a registered Professional Engineer in the States of Illinois and Indiana.

ABSTRACT

The hot gas expander (PRT) is an integral part of the refinery's fluid cat cracker unit's PRT train. Since 1995, the PRT has experienced four unplanned outages due to blade and steam baffle bolting failures.

These failures were extensive and very expensive. The cost (mechanical repair and lost opportunity) added up to tens of millions of dollars along with tremendous stress and strain on the organization, to which no cost can be attributed.

A PRT reliability upgrade project was initiated to improve the reliability of the PRT train with the objective of achieving back-to-back four-year reliable runs. The project was also to evaluate potential opportunities for debottlenecking without compromising reliability.

The purpose of this paper is to share the methodology and various tools used to carry out a vigorous technical and economic assessment and to share results for a PRT upgrade project. As a result, key indicators and activities have been established to keep this machine available.

INTRODUCTION

A hot gas expander (PRT) train with a hot gas expander, an axial compressor, and a steam turbine was installed in the early 1980s at this refinery on one of the two fluid cat cracker units (FCCU). This train is intended to supply the combustion air to the larger FCCU, and at times to provide combustion air to our adjacent FCCU. The axial air compressor is driven primarily by the hot gas PRT. Power for the PRT comes from the flue gas generated by the FCCU catalyst regenerator. This regenerator flue gas is considered a "free energy source." This was used as the economic basis for incentives for the original installation of the PRT train. A steam turbine is also part of the train and is used as a supplemental horsepower device to the train. Soon after the startup, the new PRT case bolting developed a series of failures, and after 10 years of service and many case flange repairs, it was decided to replace the intake and exhaust case system. This replacement scope included a new intake case, transition or intermediate case, nosecone, stator, shroud, diffuser, inner exhaust case, exhaust case, and rotor blades. The existing rotor and rotor support system was reused. Figure 1 shows the PRT train flow diagram and Figure 2 shows the modifications made in 1992.

The new PRT was commissioned in late 1992 with a rerated stationary case and new blades. This configuration was in service until a blade failure on the PRT in 1995 that wrecked the entire

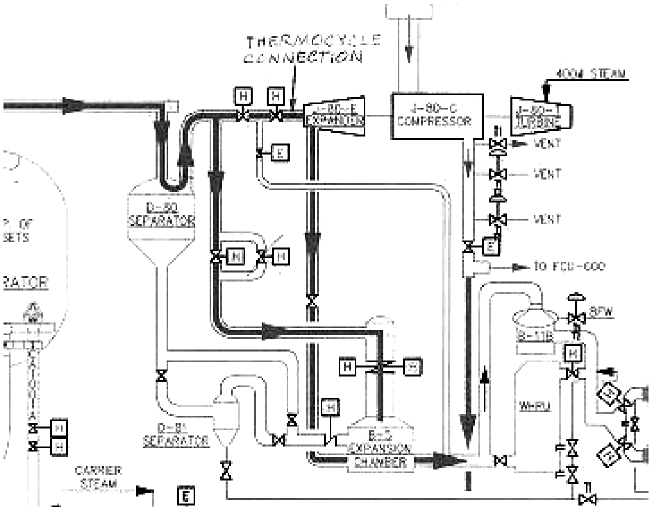


Figure 1. The PRT Train Flow Diagram.

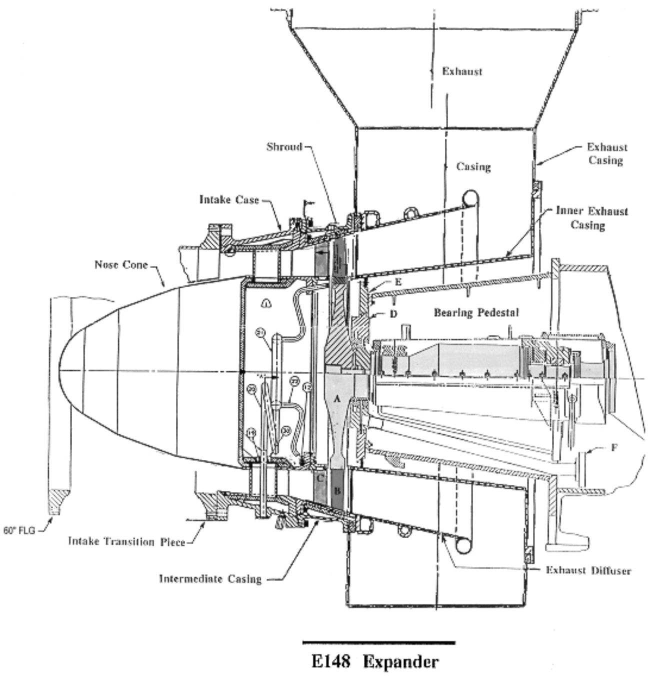


Figure 2. The PRT Cross Section. (All stationary parts and blades except for the base support were replaced in 1992.)

train. Considerable repair expense and several weeks of lost opportunity resulted. An analysis of the failure was completed before recommissioning and changes were made to the design as a result of this. Another failure occurred early in 1996 (bolting on the steam baffle on the backside of the nosecone), and yet another blade failure occurred in late 1996. In 1998 another blade failed after radial tip rubs were observed. Each failure was caused by unique conditions that had not been seen in previous failures.

Since the startup after the 1995 failure, radial vibration trip detection sensors on the PRT have been in service so the subsequent failures after 1995 involve only the PRT.

The PRT train at this refinery was installed such that the FCCU needs to generate flue gas before the PRT can be placed in service. Smaller backup air compressors are used to start the FCCU until sufficient flue gas is generated to bring the PRT and the axial compressor online. Consequently, the PRT train can be isolated from the FCCU, and the FCCU can operate without the PRT, although at reduced rates. As such significant energy and process penalties exist when the PRT is not in service with the FCCU in operation. Most other PRT trains include a motor generator for motor startup of the compressor. In those configurations, the axial compressor is the only combustion air blower in the unit.

DESIGN AND OPERATING BASIS

A review of both 1982 and 1992 PRT operating and design parameters was conducted (Table 1). The 1982 vintage PRT was replaced in 1992 to address casing leak problems and to increase the horsepower output. The new PRT was rated for 25,500 hp at 4050 rpm compared with 16,750 hp at 3950 rpm for the original installation.

Table 1. Design and Actual Parameters for 1992 PRT.

Parameter	Max. Design	Min. Design	Actual
Mass Flow (lbs./hr.)	850,000	650,000	725,400
Inlet Pressure (psig)	25	20	29
Exhaust Pressure (psig)	0.7	0.3	1
Inlet Temperature (9 mos.) (°F)	1,330	1,220	1,330
Inlet Temperature (3 mos.) (°F)	1,330	1,330	1,330
Speed (RPM)	4,050	3,850	4,150
Shaft Horsepower	25,500		>26,000

Comparison Versus Industry

The 1982 PRT was "middle-of-the-pack" in the world of PRT installations as far as horsepower and severity of operating conditions. It ran at an almost constant speed of 3950 rpm and never had a blade failure. Conversely, the 1992 machine had longer and heavier cross-section blades and at its design speed (4050 rpm) it was among the most highly stressed machines in the world. By late 1993 the operating speed was higher than design and for most of 1994 it operated near 4150 rpm, which, according to a PRT consultant, created the highest operating blade stresses of any machine in the world. Please refer to Figure 3 for a Goodman diagram for blade stresses and Figure 4 for a blade Campbell diagram. As can be seen from the Goodman diagram, blade outer neck and inner neck were operating above the recommended design stresses.

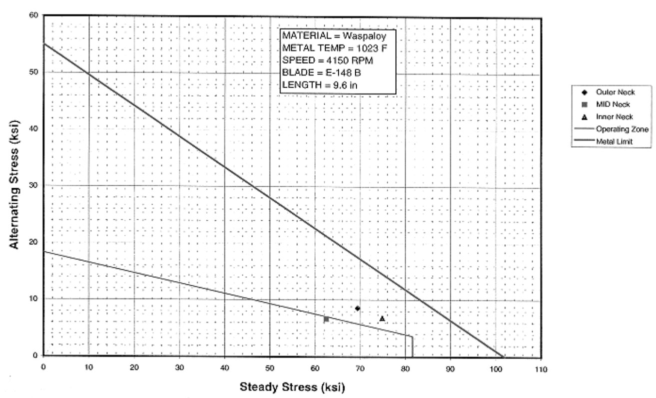


Figure 3. Blade Attachment Goodman Diagram.

After the 1995 blade failure (Figure 5), which was caused by hot corrosion and high stresses, the blade length was shortened to reduce stresses, to avoid interference of resonant frequencies with known excitations, and to increase the gap between the shroud and the blades. The 1996 failures were due to internal fastener failures on the nosecone baffle plate. These bolts contacted the lead edge of the rotating blades, knocking off the hard coating surface. Later in the year, metallic aluminum contamination in the fresh FCCU catalyst formed a very brittle "Waspaluminoy" material at the high stress area of the blade (Figure 6). This blade failure was

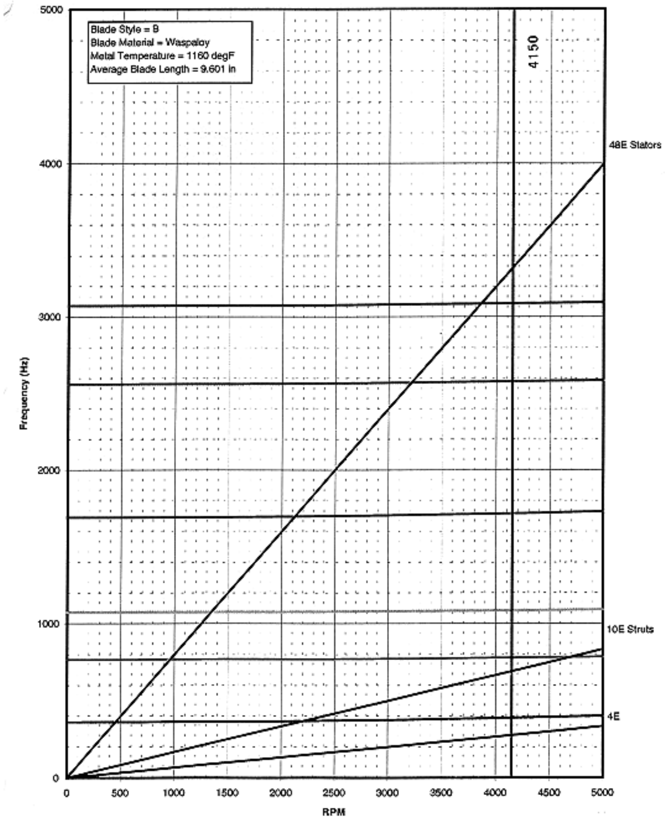


Figure 4. The PRT Campbell Diagram.

exacerbated by continued operation at maximum allowable blade stress limits due to high operating speed (4150 rpm) and also by periodic low operating speed (less than 3600 rpm) which excited blade resonances (Figures 7 and 8).

Following the 1997 rebuild of the machine we limited operating speed to 4050 rpm, which, according to the consultant, is the highest operating speed of any machine in the world except for one machine operating at 4350 rpm with blades half the length of ours. Operating stresses in 1997 continued to be at the design limit for the material used and, when we experienced blade tip rubs due to catalyst buildup, another failure occurred early in 1998.

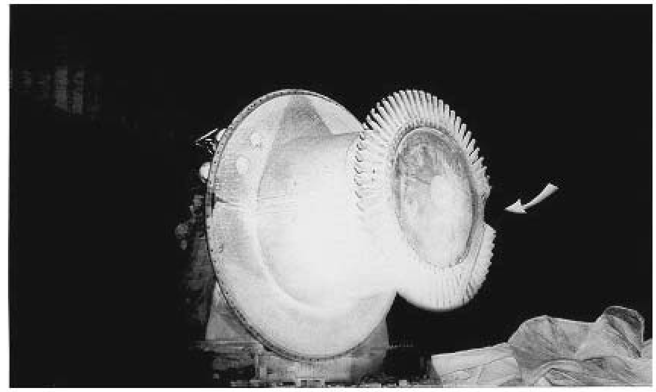
In 1998, blade material was changed and blade tip clearances were increased. A commitment was made to thermal cycle the PRT to remove catalyst buildup before any future blade tip rubs, with minimal operating interruptions. It has been proven that the increased gap between the shroud and the blades has extended the time between thermal cycles (Figures 9 and 10).

Erosion damage to rotor blades is the most common cause of premature shutdowns and PRT failures. On the 1998 failure there was evidence of erosion of the blade's hard-surface coating. Blades removed in Spring 2000 were found to have considerable erosion as shown in Figures 11, 12, 13, and 14.

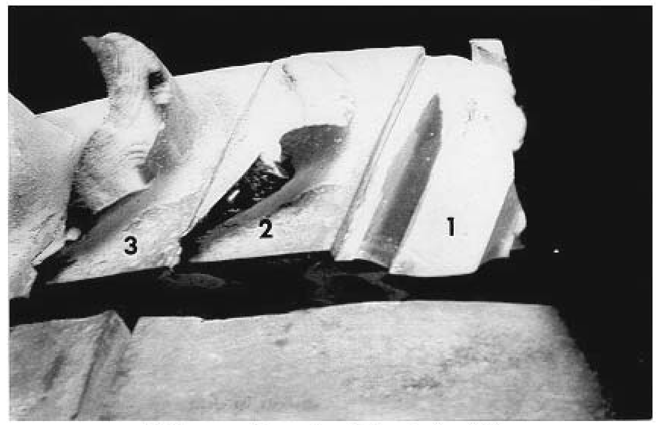
Third Stage Separator Performance Review

The sole purpose of the third stage separator (TSS) is to protect the PRT blades from rapid erosion by removing most of the 10 micron and larger catalyst particles from the PRT inlet flue gas. As the TSS performance deteriorates in removing the large particles, the PRT blade erosion rate increases. This leads to premature blade erosion and possible PRT failure.

To better understand TSS performance, an isokinetic test was carried out in June 1998. A consultant was contracted to review and analyze the 1998 and previous isokinetic test results. The study compared the test results with the TSS original design and with a database containing performance of other TSS in operation



(a) Overall view of the rotor.



(b) Close-up of the section with the missing airfoils.

Figure 5. 1995 Rotor Wreck Due to Blade Failures.

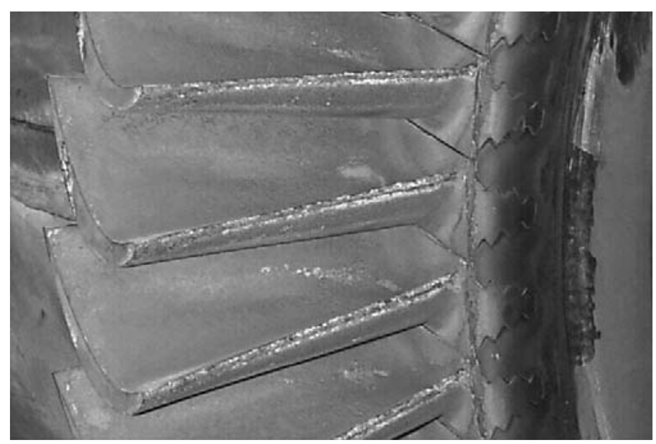


Figure 6. 1996 Blade Failure with Waspaluminoy on Leading Edge.

worldwide. The TSS performance analysis and the PRT blade hard surfacing erosion rate indicated that the TSS performance has deteriorated over the years as shown in Figure 15. The consultant recommended improvements to the future isokinetic test procedure. It was also learned that there was very little mechanical inspection history available due to minimal or no inspection of the TSS internal in the past.

PROJECT DEVELOPMENT

Due to four major failures in less than three years, the refinery management lost faith in the previous approaches to solving the reliability problems of the PRT and demanded a different and systematic approach to resolving the issue. As a result, a project

Figure 7. 1996 Blade Failure (View One).

Figure 8. 1996 Blade Failure (View Two).

was initiated to develop and implement a long-term solution using capital value process (CVP).

> The CVP is a key part of the business investment process with a structured and integrated approach to project selection and capital efficiency. The CVP supports the achievement of distinctive investment performance through successful development and execution of projects as aligned with business objectives (CVP Standard).

CVP is a corporate standard for project management.

The CVP is a structured process based on the following features (quoted directly from CVP Standard):

- Project is divided into stages, each of which corresponds to a key decision point.

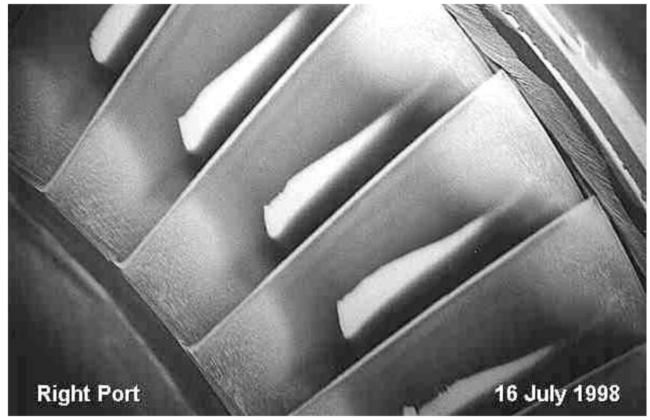


Figure 9. Online Photo of Catalyst Deposit on Blades and Shroud Used for Thermal Cycling.

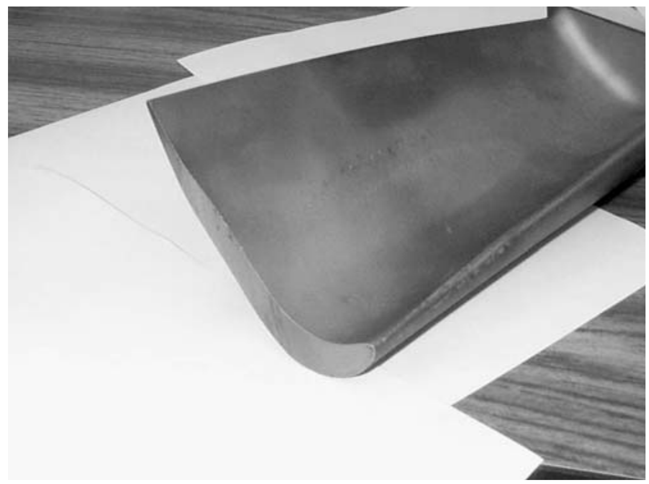


Figure 10. Blade Tip Eroded Due to Rub with Catalyst Deposit on the Shroud.

Figure 11. Rotor Blade Erosion, February 2000 (View One).

- Each stage has a gate that must be passed, which forces the Gatekeeper and the project team to make appropriate decisions.
- These decisions and the rationale behind them are captured in a Decision Support Package (DSP) document.
- The activities required within each stage are only those necessary to develop the information required for the DSP.

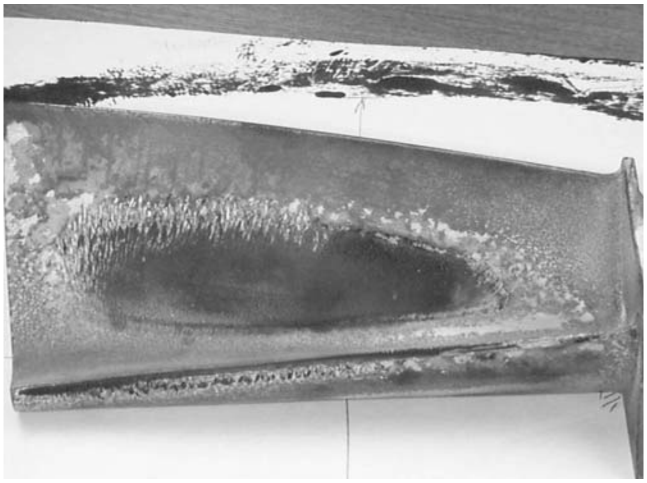


Figure 12. Rotor Blade Erosion, February 2000 (View Two).

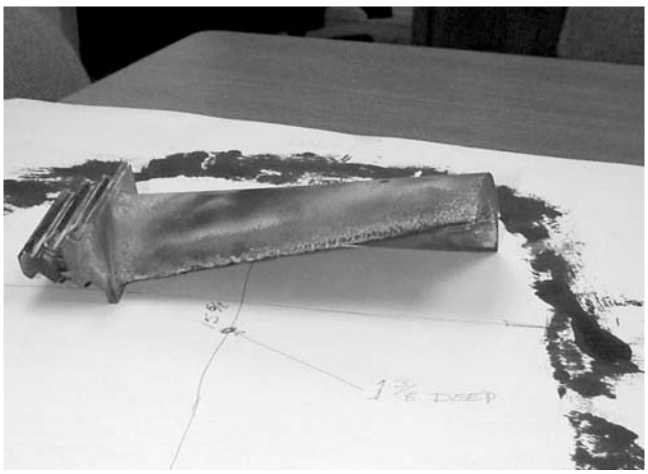


Figure 13. Rotor Blade Erosion Seen on Backside of Leading Edge, February 2000.

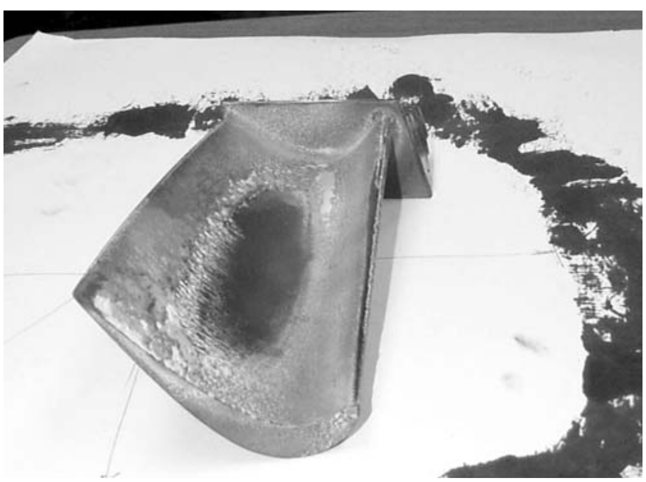


Figure 14. Rotor Blade Erosion Seen from Blade Tip, February 2000.

- Successful implementation requires behaviors which permit effective cross functional teams.
- A Front-End Loading (FEL) assessment is completed at the end of the Define stage.

A CVP flow diagram is shown in Figure 16.

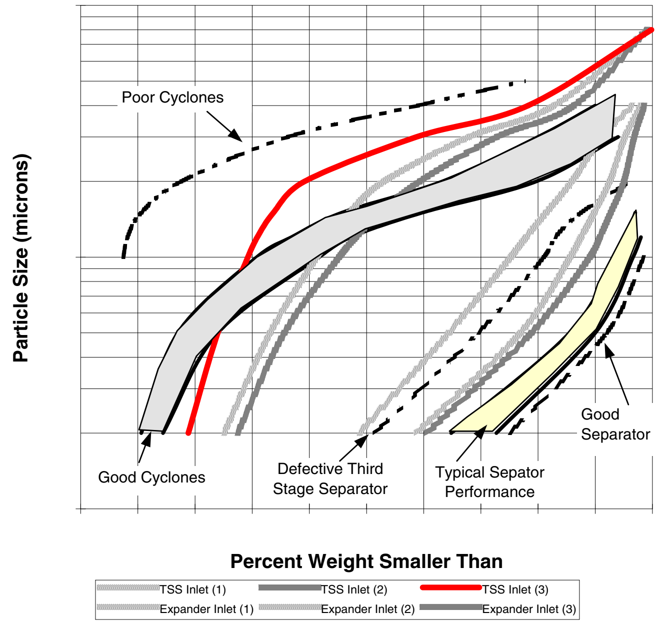


Figure 15. FCCU Third Stage Separator Performance, June 1998. (Courtesy of Carbonetto, CONMEC)

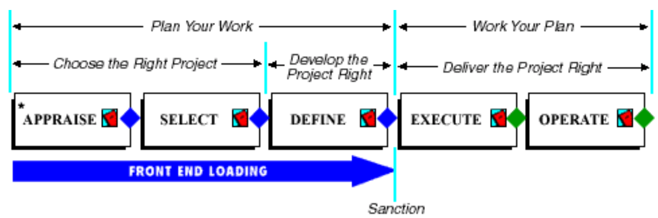


Figure 16. The CVP Flow Diagram.

Project Goals

Once it was decided to take a project approach to solve the PRT reliability issues, the following mission statement was developed:

- Provide a cost effective reliable upgrade to the FCCU PRT train to enable safe four-year continuous operating runs.

To complete this mission, business objectives were developed and prioritized as follows:

1. Increase reliability of PRT train to enable four-year continuous operating runs.
2. Complete upgrade scope of work prior to the next PRT train failure.
3. Improve condition monitoring/shutdown capability to reduce probability of catastrophic failure.
4. Improve condition monitoring/shutdown capability to reduce the extent of collateral equipment damage due to catastrophic failure.
5. If feasible without compromising reliability, improve the PRT energy transfer efficiency.
6. If feasible without compromising reliability, increase the PRT horsepower transfer capacity.
7. If feasible without compromising reliability, optimize/debottleneck PRT train.

PRT Train Economic Basis

Due to the frequent PRT failures, it was asked whether there was an economic justification either to make major modifications or to replace the PRT with a more reliable machine. The capital and operating costs of replacing the PRT driver with an electric motor driver were reviewed. The economic evaluation provided major incentives to operate a reliable PRT over the installation of a new electric motor.

For project evaluation purposes, the PRT train economic analysis included four components.

1. *Reliability cost*—defined as the total cost of an unplanned outage caused by a PRT train failure. It included both the maintenance repair (parts and labor) and the lost opportunity components.

2. *Capital cost*—defined as the installed cost of the proposed modifications, including spares.

3. *Routine maintenance cost*—defined as the maintenance repair costs required to maintain the PRT during a planned outage.

4. *Debottleneck incentives*—defined as additional revenue/savings due to improved efficiency and/or increased capacity.

The maintenance cost component was estimated based on actual costs. An average cost of $75 M/day was used for the lost opportunity component. This was arrived at by averaging a higher penalty for a summer unplanned outage and a lower penalty for a winter unplanned outage. Based on past experience, a 40 day unplanned outage was used for a PRT blade failure. The capital costs for various options were provided by a major third party PRT/compressor rerate/repair firm (“OEM”).

Debottleneck incentives were based on maximizing air from the PRT driven compressor and maximizing the PRT horsepower. Other incentives were derived from minimizing air from air compressors and minimizing horsepower from the helper turbine on the PRT. For air and horsepower requirements, eight month summer operation and four month winter operation scenarios were used.

Project Cost and Schedule

Cost and schedule were the two key project drivers. As described later in the paper, a detailed cost-benefit analysis was carried out for each option considered.

Since the project-recommended upgrade had to be implemented before the next failure, the issue of schedule was somewhat tricky. A replacement PRT required as much as 44 to 54 weeks of lead time. Extra monitoring and contingent plans were put in place to manage the schedule risks.

Project Scope of Work

The following scope of work was developed to meet the project goals:

- Carry out a thorough review of the previous PRT failures and identify failure root causes and contributory factors.
- Review mechanical design and performance of the third-stage separator, the PRT, and the air compressor.
- Review the entire PRT train as a system and identify any reliability issues.
- Review and implement changes to the operating parameters and guidelines, if necessary, to avoid any failures in the short term.
- Develop future process and mechanical requirements.
- Develop and evaluate options.
- Recommend and implement the selected option.

PRT TRAIN RELIABILITY MODEL

The impact of a PRT train failure on the refinery operation is very significant. Although the past PRT train failures were due to the PRT blade failure, other PRT train equipment failures could easily shut down the train. Therefore, it was decided not to look at the PRT itself in isolation, but to address the reliability concerns of the entire PRT train.

Risk Analysis/Reliability Matrix

In order to fully understand and appreciate the issues that had affected the availability of the PRT train and could affect the train in the future, the entire train was broken into 14 subsystems. Each subsystem was reviewed for potential issues and a total of 85 issues were identified. The subsystems and issues breakdown is summarized in Table 2.

Table 2. PRT Train Subsystems and Number of Issues Identified.

System Description	Number of Impact Issues
Expander	16
Compressor	4
Steam Turbine	4
D-80	7
Inlet Gas Control	7
S/D Trip Control	4
"Star Wars" Control Panel	7
Cooling Systems	6
Lube Oil Systems	6
Air Control	7
Duct Work	7
On-Line Cleaning Systems	4
Catalyst	3
Spare Parts	3
Total Items/Issues --	85

A reliability matrix was developed to evaluate each subsystem and define issues and concerns that could adversely impact the reliability and operation of the train. Reliability and risk for each impact issue were assessed and possible upgrade/corrective actions were developed, evaluated, and prioritized based on the “Weighted Value of Upgrade” as shown in APPENDIX A. An action plan was developed and implemented for most of the issues based on priority.

There was a fair amount of information available from the scientific analysis, such as physical test and material microanalysis. However, a large amount of information came out during the interview/discovery process from the people that were involved with this machine including operators, maintenance and instrument mechanics, technical experts, and the PRT consultant. It must be emphasized that this information was not all physical evidence, but was based on observations, perceptions, and opinions. The key was to translate this information into meaningful data for assessment and options evaluation.

Historical Failure Analysis

Using the reliability matrix as a guide, a thorough analysis of the past failures was carried out. A failure history/factor correlation analysis matrix was developed to understand, define, and establish root causes and contributing factors for the past failures as shown in APPENDIX B. This afforded an all-encompassing review of the 14 subsystems and the 85 issues for their impact on failures and near misses.

Design and manufacturing errors were identified as the single biggest and most common root cause for the past failures. Excessive blade stress, catalyst buildup, blade erosion, high temperature corrosion, and blade quality control were some other root causes that were identified to specific failure(s).

Availability Model

An effort was launched with a specialty consultant to develop a statistical-based availability model of the train to simulate how each component affected the availability of the entire train. This modeling effort, however, did not produce desired results due to limited statistically significant life-cycle reliability data of the many individual components.

Recommended New Design Parameters

Table 3 details the desired process operating conditions for a replacement PRT. These conditions have accounted for higher future regenerator pressure and optimized the PRT train operation.

Table 3. New PRT Design Parameters.

Parameter	Operating Condition
Mass Flow (lbs./hr.)	867,000
Inlet Pressure (psig)	33
Exhaust Pressure (psig)	1
Inlet Temperature (oF)	1,330
Speed (RPM)	>4,050
Shaft Horsepower	30,000

PROJECT OPTIONS DEVELOPMENT AND EVALUATION

In working with an OEM, options were developed during the course of the project ranging from "do nothing" to replacing with a "brand new state-of-the-art PRT." The compressor and the PRT debottleneck opportunities were explored and incorporated in these proposals. Various retrofit and upgrade variations offered new options, and the task of evaluating this large number of options became increasingly challenging. A summary of these options is provided in APPENDIX C. Both qualitative and quantitative assessment methods were used to evaluate the vast array of options.

Kepner-Tregoe Decision Analysis

Kepner-Tregoe (K-T) analysis is a qualitative assessment tool. It takes into account two kinds of parameters—"Musts" and "Wants"—to evaluate each option. Valid options have to meet all the "Must" requirements. The options are then evaluated based on how best they meet the "Want" requirements. "Want" requirements are first assigned a value between one and 10, one being of low importance and 10 being of high importance. Each option is then evaluated against these parameters and a value, again between one and 10, is assigned based on how best the option in consideraton meets the need of the parameter. Please refer to APPENDIX D for the K-T analysis results.

The qualitative evaluation of the options did provide direction. However, this analysis was deemed too subjective. It did not account for many technical uncertainties and did not fully appreciate various economic factors and consequently resulted in recommending the most expensive option for a new "gold-plated" PRT. Obviously, this recommendation was challenged and a thorough quantitative evaluation was prescribed.

GRisk Analysis

The corporation had developed a sophisticated tool called "GRisk" for a quantitative evaluation of its medium to large investments.

> GRisk is a powerful, general-purpose Monte Carlo statistical program designed to support all types of uncertainty modeling, from technical assessments to complex financial scenarios. The program provides an environment in which a user can quickly and easily (a) define input and output variables; (b) generate realistic distributions for all input; (c) specify the "recipe" for relating outputs to inputs, and run a Monte Carlo analysis for any number of iterations; and (d) generate graphical and statistical results, as well as perform sophisticated sensitivity analysis to determine which inputs are the principal "drivers" in the analysis (Hammond, 1999).

Although, this tool was used extensively within the corporation to evaluate large projects, its use at the refinery, especially for a smaller project of this size, was somewhat new. It proved to be a very powerful tool in evaluating various options that were considered for this project.

Capital cost, maintenance cost, reliability (failure) data, and related costs and incentives were input into the GRisk model. The model provided risk weighted net present value (NPV) (shown in Figure 17), cash flow, internal rate of return (IRR), and sensitivity analysis (shown in Figure 18) as outputs. Scheduled maintenance and turnaround activities were also included in the model. The analysis was done on a project life of 20 years. Financial data such as depreciation scale, inflation, hurdle rate, etc., were used as prescribed by the corporation. The software program results for the final six options are summarized in Table 4.

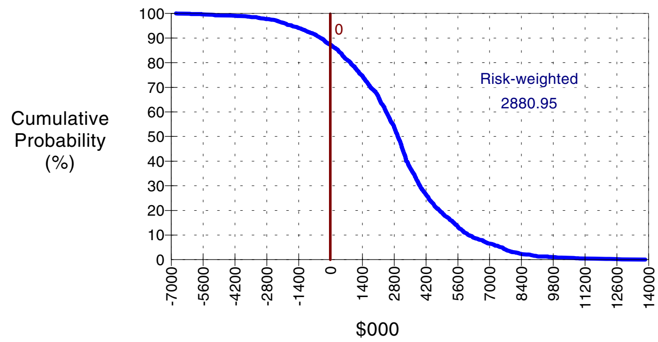


Figure 17. Risk Weighted NPV for Option 5 Relative to Option 1.

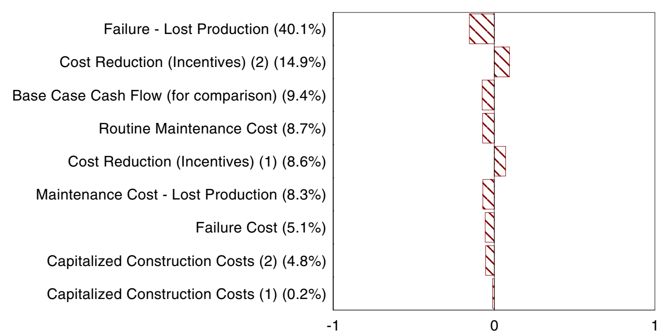


Figure 18. Sensitivity Analysis for Option 5.

Table 4. PRT Upgrade Option. (Includes NPV relative to option 1.)

Option #	Reblade	Replace PRT	Capital Investment ($000)	Risk Weighted NPV ($000)	NPV at 50% ($000)
1[1]	Every 2 year	Year 8 (2007)	$5500 in 2007	($ 6,944)	($ 6,221)
				$ 0	$ 0
2[1]	Every 4 year	Year 8 (2007)	$5500 in 2007	($ 9,506)	($ 8,922)
				($ 2,464)	($ 2,211)
3[1,2]	Every 2 year	Year 1 (2000)	$5500 in 2000	($ 4,811)	($ 4,239)
				$ 2,346	$ 2,280
4[1,2]	Every 4 year	Year 1 (2000)	$5500 in 2000	($ 6,885)	($ 6,453)
				$ 157	$ 373
5[1,3]	Every 2 year	Year 8 (2007)	$5500 in 2007	($ 4,266)	($ 3,548)
				$ 2,880	$ 2,957
6[1,3]	Every 4 year	Year 8 (2007)	$5500 in 2007	($ 6,238)	($ 5,689)
				$ 822	$ 1,131

Notes:

1. **These options assume a PRT reblade in 1999 TAR and that D-80 preformance will be as designed after 1999 TAR.**
2. Compressor debottleneck incentives are based on current operation. It does not include FCCU-600 Cat Cooler incentives.
3. Compressor debottleneck incentives are based on 50% of current operation. It does not include FCCU-600 Cat Cooler incentives.

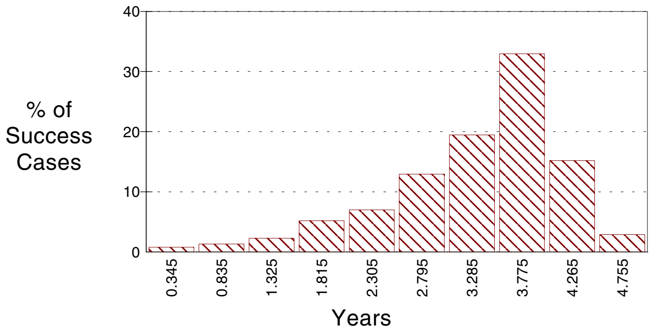


Figure 19. Failure Distribution with Peakedness of 4.

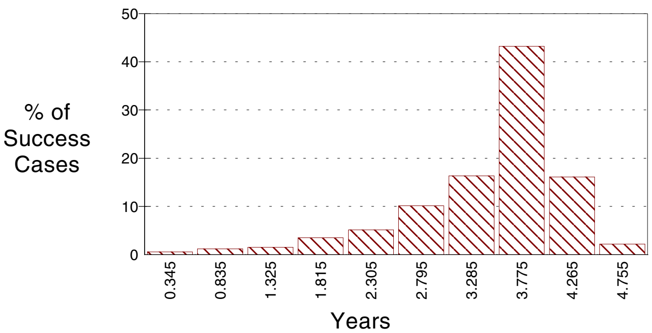


Figure 20. Failure Distribution with Peakedness of 7.

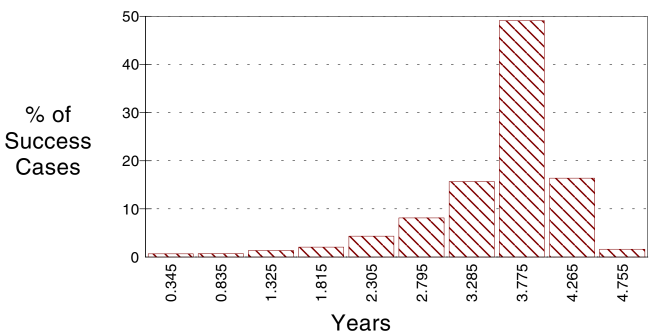


Figure 21. Failure Distribution with Peakedness of 10.

During the software analysis, one of the biggest issues the team wrestled with was of the reliability data for various options. There was not a great deal of PRT reliability data available. The reliability data were arrived at after considerable discussion and analysis from the project team and the PRT consultant. One of the key features of the model was the ability to define the confidence factor (“peakedness”) of individual assumptions and distribution of the input data. Figures 19, 20, and 21 illustrate the effect of “peakedness” on reliability data distribution. The model ran over 2000 iterations of the input distributions to generate an integrated output. Please refer to APPENDIX E for sample input and output data from the software. The sensitivity analysis (Figures 18) clearly showed that “Lost Production” due to a PRT train failure was the biggest single variable that influenced the IRR and net present value (NPV) results.

PROJECT RESULTS AND RECOMMENDATIONS

As options were being developed and evaluated, surprisingly, it became apparent that the objective of achieving back-to-back four-year runs was not a realistic optimum run length, either with the existing PRT or with a new state-of-the-art PRT.

After a few rounds of recycling of over 50 options, six most likely options emerged from the K-T and the preliminary GRisk. These six were then rigorously evaluated using the software program for a final recommendation as shown in Table 4. It was recommended to proceed with option 5:

- Carry out a PRT maintenance in the fall 1999 turnaround and every two years thereafter and replace the PRT in 2007 to meet future operating requirements.

The assessment results were surprising. Prior to the start of this project it was felt that either a major redesign of the existing PRT or a brand new state-of-the-art PRT would be required to achieve the desired reliability. However, the project assessment concluded that there was no justification to replace the PRT in the near future even with the debottleneck incentives. The project also recommended to spinoff four other small focused projects to deal with specific issues. These were:

1. Assess and improve TSS performance.
2. Upgrade the PRT train trip control system.
3. Modify compressor intake filter housing.
4. Upgrade the PRT torquemeter.

Other Recommendations

A performance monitoring plan was put together to keep a close eye on the key operating parameters: vibration, flue gas pressure and temperature, blade pictures, etc. Blade pictures must be taken at a fixed interval to monitor catalyst deposition on the shroud and the rotor blades on a regular frequency to identify and project catalyst buildup rates. These photos would be used to schedule the thermal cycle of the PRT to remove the catalyst deposit from the shroud. It was expected that a PRT thermal cycle would be required once every six months.

CONCLUSIONS

Perhaps the most obvious conclusion that can be drawn from this project is that because of a disciplined and rigorous quantitative analysis a major capital investment was avoided. It was decided not to replace the existing PRT with a new “gold-plated” PRT. The new PRT would not have solved all the reliability problems of the PRT train as envisioned at the beginning of the project. In addition, the following conclusions can be drawn from this project:

- It was learned that the reliability objective was too aggressive. Only a few PRT’s in operation worldwide have made one or two back-to-back four-year runs and these were operating at much less severe conditions.
- GRisk proved to be a very powerful quantitative assessment tool to evaluate complex projects such as this.
- The software model was used later to evaluate turnaround repair options and provided effective results. This model will be used for future PRT evaluations.
- This software program has become a standard evaluating tool for all the projects at our refinery.
- The refinery developed a better set of key performance/ maintenance indicators to keep the existing machine available.
- Review of the entire PRT train identified other reliability concerns that were not known.

APPENDIX A— PRT RELIABILITY AND RISK MATRIX

		A	B=4/A	C	D=B*C			E	F	G=4/F	H=C*G	I=(D-H)/E
Item No.	Description of Item/Issue Impacting Reliability	Present MTTF (Yrs.)	Run Failure Frequency	Failure Impact, $ M	Present Run Risk, $ M	Possible Corrective Action	Possible Item/Issue Upgrade Action	Upgrade Cost, $ M	Upgraded MTTF (Yrs.)	Upgraded Failure Frequency	Upgraded Run Risk, $ M	Weighted Value of Upgrade
1	Excess Blade Stresses @ steady state condition	1.50	2.67	3,880	10,347	Redesign blade	Revise blade metallurgy, style, fur tree design, and cooling	500	11.0	0.36	1,411	17.9
2	Catalyst build up on shroud & blades	0.75	5.33	3,800	20,267	On-line cleaning	Thermal cycle (once every 6 month at a cost of $75 M/event)	600	11.0	0.36	1,382	31.5
		0.75	5.33	3,800	20,267		Nut blasting (once every 3 months at a cost of $20 M/event	320	1.5	2.67	10,133	31.7
3	Blade erosion	2.00	2.00	3,800	7,600	Flow path, Reduce catalyst, Hard surfacing	Redesign flow path	2,200	3.0	1.33	5,067	1.2
		2.00	2.00	3,800	7,600		Improve D-80 performance	2,000	4.5	0.89	3,378	2.1
		2.00	2.00	3,800	7,600		Improved hardsurfacing	N/A	N/A	N/A	N/A	N/A
4	High temperature corrosion	10.00	0.40	3,800	1,520		Surface coating	N/A	N/A	N/A	N/A	N/A
		10.00	0.40	3,800	1,520		Cooling	N/A	N/A	N/A	N/A	N/A
		10.00	0.40	3,800	1,520		C.O. control	N/A	N/A	N/A	N/A	N/A
		10.00	0.40	3,800	1,520		Lower operating temperature	21,900	22.0	0.18	691	0.0
5	Blade quality control	4.00	1.00	3,800	3,800	Improve quality control	Improve QA/QC and follow-up	100	8.0	0.50	1,900	19.0
6	Casing flange leaks	10.00	0.40	3,800	1,520		Replace inner exhaust case	200	20.0	0.20	760	3.8
7	Gas flow path changes	0.75	5.33	3,800	20,267	Change flow path	Redesign casing	2,300	3.0	1.33	5,067	6.6
8	Operating temperature fluctuations	8.00	0.50	3,800	1,900	Better temperature control	Operator training	40	8.0	0.50	1,900	0.0
9	Nose Cone support struts/stability	4.00	1.00	3,800	3,800		Inspect and repair,	100	4.0	1.00	3,800	0.0
		4.00	1.00	3,800	3,800		Change design	500	11.0	0.36	1,382	4.8
10	Catalyst flow-thru in gas stream	2.00	2.00	3,800	7,600	Reduce catalyst in the gas flow	Redesign D-80	2,000	4.5	0.89	3,378	2.1
11	Flow path finish effecting catalyst buildup	0.75	5.33	3,800	20,267		Finish shroud to better finish	50	2.0	2.00	7,600	253.3
12	Rate & control of cooling steam into machine	2.50	1.60	3,800	6,080		Increase steam flow and quality	50	5.0	0.80	3,040	60.8
13	Distribution of cooling steam within machine	2.50	1.60	3,800	6,080		Improve steam distribution	250	5.0	0.80	3,040	12.2
14	Oil leaks from coupling causing possible fires	10.00	0.40	675	270		Redesign oil system	50	20.0	0.20	135	2.7
15	On-line catalyst sloughing system efficiency	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
16	Inability to monitor drive shaft torque - old devise doesn't work	10.00	0.40	3,800	1,520	Install reliable detection system	Replace Torque Tube with improved design unit	40	20.0	0.20	760	19.0
17												

Notes: Analysis is based on a 4 year run and includes capital and lost opportunity costs.

1. Analysis is based on a 4 year run and includes capital and lost opportunity costs.
2. Lost opportunity cost is estimated at $75 M/day
3. Faileure impact is calculated as: Maintenance cost + (Maintenance downtime+Operations downtine)*75

APPENDIX B— PRT TRAIN FAILURE HISTORY/ FACTOR CORRELATION ANALYSIS

LEGEND

"XX" - Root Cause of Failure
"X" - Contributing factor or consequence of failure
"?" - Possible contributing factor in a failure
"N" - Nuisance problem not contributing to failure

	Reliability Risk Factors			PRT Failure Incidents Correlation of Probable Contributing Failure Factors				
	Sub-System/Issue	Weighted Value of Upgrade		March 1995	June 1996	December 1996	February 1998	Near Misses SIRs
	PRT J-80E							
0	Design & manufacturing errors			XX	XX	?	XX	1+
1	Excess Blade Stresses @ steady state condition	17.5		XX		X	X	
2	Catalyst build up on shroud & blades	31.5/31.7		?			XX	
3	Blade Erosion (loss of protective hard coating)	1.2/2.1			X	XX	?	
4	High temperature corrosion	N/A		XX		?	?	
5	Blade quality control	19.0		X		X	XX	
6	Casing flange leaks	3.8		N	N	N	N	
7	Gas flow path changes	6.6			?	XX	?	
8	Operating temperature fluctuations	0.0		XX	?	?		
9	Nose Cone support struts/stability	0/4.8			?			
10	Catalyst flow-thru in gas stream	2.1						
11	Flow path finish effecting catalyst buildup	253.3		?		?	X	
12	Rate & control of cooling steam into machine	60.8		?	?			
13	Distribution of cooling steam within machine	12.2		?	?			
14	Oil leaks from coupling causing possible fires	2.7		X		X		1+
15	On-line catalyst sloughing system efficiency	N/A		?			X	
16	Inability to monitor drive shaft torque - old devise doesn't work	19.0		?				
17	Aluminum contamination in the catalyst				?	XX		
	Air CompressorJ-80C							
0	Inaccurate stator positioner - no control			X		X	X	
1	Erosion/corrosion of fixed & rotating blades (1st	1.3/1.8		?		?	?	
2	Stator control linkage not exercised and may bind	N/A						
3	Oil leakage from support system onto hot case causing fires	N/A		N				1
4	Lack of detailed vibration data collection for analysis	0.3					N	
5	Inlet expansion joint failure	5.3						
	Steam Turbine J-80T							
0	Torque limiter at low RPMs							2 Failures
1	Non-redundant old Tri-Sen governor controls	1.5				N		1
2	Internal diaphragm configuration makes installation/clearance checks difficult at keyup	9.5		N		N		2
3	Mechanical Trip & Throttle linkage for overspeed could bind/fail							
4	Coupling spare parts not inventoried - 6 month lead time	N/A						
	Third Stage Separator D-80							
1	Unknown condition of internals			?		?	?	
2	Unknown performance of catalyst removal at single point			?		?	?	
3	Unknown impact of operating variables on removal efficiency			?		?	?	
4	Undefined preventative maintenance program			?		?	?	
5	Sizing of Underflow Orifices uncertainty			?		?	?	
6	Underflow system isolation valves do not hold						?	
7	Lack of sample/test data on D-80 performance			?		?	?	

Reliability Risk Factors			PRT Failure Incidents Correlation of Probable Contributing Failure Factors				
	Sub-System/Issue	Weighted Value of Upgrade	March 1995	June 1996	December 1996	February 1998	Near Misses SIRs
	Inlet Gas Control						
1	Poor history of reliability of valve positioners	1.0	X		X		
2	Stack Slide Valve taking excessive pressure drop	N/A					
3	60" Stack Bypass valve inoperable due to unreliable positioner	2.0			X		
4	16" Vent valve actuator not functional	4.0	X				
5	Inability to on-stream verify "16 Vent valve system will function	1.3	N		N	N	
6	Need for control logic on 60" Bypass valve to open when PRT trips	N/A			X		
7	Inadequate gas path temperature measurement points	73.7	?	?	?	?	
	S/D Trip Control						
1	Steam Turbine mechanical trip cannot be tested on-line	0.2	N	N	N	N	
2	High reliability on "Star Wars" panel - poor knowledge of logic	54.7/48.1			N		1
3	Lube Oil Supply to Governor Dump control valve fails at yoke	N/A					1
4	Cannot/do not test Governor Oil Accumulator pressure bladder	0.5					
5	Expander bearing probe wire failure caused by overheating from the flue gas leaks	9.8/8.7/200				N	
	Interlock Trip Control Panel						
1	Field location of panel and corrosion of internal electronics (circa 1985)	54.7/48.1					Future Prob.
2	Lack of knowledge/documentation of control logic	See #1	X				1
3	High reliance on 1 or 2 individuals to understand/maintain	See #1					Future Prob.
4	Lack of redundancy in processors, power supplies, etc.	See #1					Future Prob.
5	Mixture of alarm, monitor and trip circuitry in same panel exposes potential to trip system accidentally during routine work	See #1				?	1+
6	General age of equipment reached end of life	See #1					
7	Early 1980s technology	See #1	N	N	N	N	
	Cooling Sysytem						
	STEAM SYSTEM						
1	Cooling steam supply piping not adequately trapped	N/A	?		?		
2	Steam supply block valve not tight shutoff	8.1	N	N	N	N	
3	Steam flow orifice proper sizing & condition	See #2	?				
	AIR SYSTEM						
4	Not sufficient air flow at S/U	2.0	N	N	N	N	
5	Possible error in aligning air during S/U - Operating Procedures?	N/A	?				
6	Area Plant Air header sizing inadequate for stable supply pressure	See #1	N	N	N	N	
	Lube Oil System						
1	Oil Coolers plugage on water side	3.6	N	N	N	N	
2	Very poor cooling water quality	3.6			N	N	
3	Miss set-up of Aux. Lube Oil Pump Dual power feed/auto transfer at S/U	N/A					1
4	Possible long delay in Aux. Lube Oil pump startup timing on pressure loss	N/A					
5	Poor/fluctuating quality of Lube Oil Filter cartridge elements	1.8					Future Prob.
6	Do not have accumulator pressure bladder set-up/Running monitoring & preventative maintenance	6.0					
	Air Control						
1	No isolation capability on compressor automatic Vent Valve	N/A					1
2	No on-line testing of compressor automatic Vent Valve system/logic	N/A	N		N	N	
3	TAR priorities push valve testing back until on critical path - then dropped	N/A	?				
4	Unknown condition/integrity of Silencer internals	0.0				?	
5	Compressor discharge line has unnecessary in-line straightening vane section	N/A					Not True
6	Unknown Inlet Filter housing/support condition for remaining life	0.9/10.1					Future Prob.
7	Unknown condition of Steam heater coil condition for remaining life	45.6				?	1
	Duct Work						
1	Poor condition/functioning of Expansion Joints	1.4					2
2	Poor condition/functioning of Gimbel Joints	43.1					
3	Question remaining life of duct - weld embrittlement? Concern that cold-hot-cold cycle stress not fully understood, causing early failure.	0.2		cause S/D			
4	Concern that extensive piping loads on Inlet Duct not fully considered	N/A					
5	Concern that Spring Hanger/Expansion Joint Movement Lock-Out procedures/practices not adequate	N/A					
6	Inability to measure Expander Inlet Gas temperature adequately	73.7	?	?	?	?	
	On-Line Cleaning Systems						
1	Nut Blasting system is only a valve - no design considerations	N/A				?	
2	Do not understand impact/parameters for thermal-cycling	N/A				X	
3	Do not have sufficient Gas path temperature indication to fully understand/control thermal-cycling	N/A				?	
4	Cannot thermal-cycle without major process changes due to poor performance/reliability of FCCU stack slide valves	N/A					
	Catalyst						
1	Lack of understanding of impact of catalyst elements on PRT metallurgy	15.8	?		XX		
2	Lack of understanding of catalyst changes to D-80 performance	15.8	?	?	?	?	
3	Lack of communication of catalyst changes to REG for revised equipment condition monitoring	11.1	?		?	?	
	Spare Parts						
1	No analysis of lead times versus probability of failure to establish parts inventory	N/A					Not True
2	Concern/experience of vendor mis-fabrication of upgraded design parts	N/A	X	X	X	X	
3	Concern/experience of vendor fabricating obsolete parts from mis-documention of upgrades	N/A	X		X	X	
4	Lost or misplaced spare parts				N		

APPENDIX C— LIST OF PROJECT OPTIONS

Option #	Reblade	Replace PRT	Capital Investment ($000)	Risk Weighted NPV ($000)	NPV at 50% ($000)
1[1]	Every 2 year	Year 8 (2007)	$5500 in 2007	$ (6,944)	$ (6,221)
2[1]	Every 4 year	Year 8 (2007)	$5500 in 2007	$ (9,506)	$ (8,922)
3[1,2]	Every 2 year	Year 1 (2000)	$5500 in 2000	$ (4,811)	$ (4,239)
4[1,2]	Every 4 year	Year 1 (2000)	$5500 in 2000	$ (6,885)	$ (6,453)
5[1,3]	Every 2 year	Year 8 (2007)	$5500 in 2007	$ (4,266)	$ (3,548)
6[1,3]	Every 4 year	Year 8 (2007)	$5500 in 2007	$ (6,238)	$ (5,689)

Notes:
1. **These options assume a PRT reblade in 1999 TAR and that D-80 performance will be as designed after 1999 TAR.**
2. Compressor debottleneck incentives are based on current operation. It does not include FCCU-600 Cat Cooler incentives.
3. Compressor debottleneck incentives are based on 50% of current operation. It does not include FCCU-600 Cat Cooler incentives.

Option #	OPTION	Capital Investment ($000)	R.W. NPV ($000)
Base	TSS Inspection and PRT reblade in 1999 and reblade every 2 year thereafter	$650 in 1999	$(30,828)
1	Reblade in 1999, 2001, 2003, 2005; new PRT in 2007; reblade every 2 year thereafter[1]	$2500 in 1999, $5500 in 2007	$ (9,244)
2	Reblade in 1999, 2003; new PRT in 2007; reblade every 4 year thereafter[1]	$2500 in 1999, $5500 in 2007	$(11,511)
3	Reblade in 1999; new PRT with compressor debottleneck in 2000; reblade PRT in 2003 and every 2 year thereafter[1,2]	$2500 in 1999, $5500 in 2000	$ (7,022)
4	Reblade in 1999; new PRT with compressor debottleneck in 2000; reblade PRT in 2003 and every 4 year thereafter[1,2]	$2500 in 1999, $5500 in 2000	$ (9,243)
5	Reblade in 1999, 2001, 2003, 2005; new PRT in 2007; reblade every 2 year thereafter. Run PRT at higher HP[1,3]	$2500 in 1999, $5500 in 2007	$ (6,221)
6	Reblade in 1999, 2003; new PRT in 2007; reblade every 4 year thereafter. Run PRT at higher HP[1,3]	$2500 in 1999, $5500 in 2007	$ (8,338)
	Notes:		
	1. It is assumed that TSS performance will be as designed after the 1999 TAR.		
	2. Compressor debottleneck incentives are based on current operation. It does not include FCCU-600 Cat Cooler incentives.		
	3. Compressor debottleneck incentives are based on 50% of current operation. It does not include FCCU-600 Cat Cooler incentives.		

DESCRIPTION	OPTIONS										
	1	2	3	4	5	6	7	8	9	10	11	12
Do nothing	X											
Minimum TSS in 1999		X		X	X	X	X	X	X	X	X	X
100% TSS in 1999			X									
Reblade PRT in 1999		X	X		X	X	X	X	X	X	X	X
PRT (Opt. D) in 1999				X								
PRT (Opt. D) in 2000					X	X						
Reblade PRT in 2001		X		X				X	X	X	X	X
PRT (Opt. D) in 2001							X					
100% TSS in 2003				X	X	X	X	X	X	X	X	X
Reblade PRT in 2003		X	X	X	X	X	X				X	X
PRT (Opt. D) in 2003								X	X	X		
Reblade PRT in 2005		X										
PRT (Opt. D) in 2005											X	
PRT (Opt. D) in 2007												X
Air Compressor Expansion w. new PRT				X	X	X	X		X	X	X	X
Air Compressor Expansion w. cat coolers in 2003						X				X		
NPV												

Notes:
1. PRT option D is NEW MACHINE WITH EXTENDED BLADES, INTERLOCK TRIP CONTROL PANEL AND FILTER MODIFICATIONS.
2. Potential FCCU Cat coolers project air requirements are estimated to begin in 2003.

Option #	Option Description	NPV ($,000)
1	Do Nothing	
1A	PRT reblade in 1999	
2	Repair TSS with 10% replacement parts in 1999.	
3	Repair TSS with 100% internal replacement (latest design)	
4	1999 - 10% TSS internal replacement; 2003 - 100% TSS internal replacement and new PRT (option 8G)	
5	1999 - 10% TSS internal replacement; 2003 - 100% TSS internal replacement; 2007 - New PRT (option 8G)	
5A	Modify PRT to pre-1992 blade design to reduce stress with 10% TSS case	
6	**Repair TSS with 10% replacement parts with**	
6A	New machine with new flow path	
6B	New machine with new flow path, but reuse existing pedestal	
6C	Machine with new flow design, but reuse existing casing and pedestal. Replace casing in 2003	
6D	New machine with EXTENDED BLADES	
6E	New machine with EXTENDED BLADES, but reuse existing pedestal	
6F	Machine with EXTENDED BLADES, but reuse existing casing and pedestal. Replace casing in 2003	
6G	New machine with NEW WIDE DISCS and EXTENDED BLADES	
6H	New machine with NEW WIDE DISCS and EXTENDED BLADES, but reuse existing pedestal	
6I	Machine with NEW WIDE DISCS and EXTENDED BLADES, but reuse existing casing and pedestal. Replace casing in 2003	
7	**Repair TSS with 10% replacement parts, replace Filters and Interlock Trip Control Panel**	
7A	New machine with new flow path	
7B	New machine with new flow path, but reuse existing pedestal	
7C	Machine with new flow design, but reuse existing casing and pedestal. Replace casing in 2003	
7D	New machine with EXTENDED BLADES	
7E	New machine with EXTENDED BLADES, but reuse existing pedestal	
7F	Machine with EXTENDED BLADES, but reuse existing casing and pedestal. Replace casing in 2003	
7G	New machine with NEW WIDE DISCS and EXTENDED BLADES	
7H	New machine with NEW WIDE DISCS and EXTENDED BLADES, but reuse existing pedestal	
7I	Machine with NEW WIDE DISCS and EXTENDED BLADES, but reuse existing casing and pedestal. Replace casing in 2003	
8	**Repair TSS with 10% replacement parts, replace Filters and Interlock Trip Control Panel and debottleneck J-80C Compressor**	
8A	New machine with new flow path	
8B	New machine with new flow path, but reuse existing pedestal	
8C	Machine with new flow design, but reuse existing casing and pedestal. Replace casing in 2003	
8D	New machine with EXTENDED BLADES	
8E	New machine with EXTENDED BLADES, but reuse existing pedestal	
8F	Machine with EXTENDED BLADES, but reuse existing casing and pedestal. Replace casing in 2003	
8G	New machine with NEW WIDE DISCS and EXTENDED BLADES	
8H	New machine with NEW WIDE DISCS and EXTENDED BLADES, but reuse existing pedestal	
8I	Machine with NEW WIDE DISCS and EXTENDED BLADES, but reuse existing casing and pedestal. Replace casing in 2003	

APPENDIX D—
K-T DECISION ANALYSIS RESULTS

Musts

1. Implementation during October 1999 FCCU turnaround. Upgraded machine must fit on the existing baseplate with no piping modifications.
2. Four-year reliable run on PRT train including compressor and turbine.
3. 4050 rpm maximum speed.
4. Maximize return on investment over the life of the project.

Wants

1. Minimize helper turbine horsepower requirements. (Weight—1)
2. Install within 25 (mechanical) days turnaround window. (5)
   - Field execution
   - Number of people working in the area
   - Interference with other work in the area
   - Equipment/Manpower availability
3. Reduce blade stress. (10)
4. Reduce blade erosion. (9)
5. Reduce corrosion. (7)
6. Reduce catalyst buildup. (8)
7. Minimize cost. (4)
8. Maximize air rate. (4)
9. Minimize job risk—field execution and new design (used in PRT). (3)

Alternatives

1. New machine with new (existing design) blades.
2. New machine with new (existing design) blades, but reuse existing pedestal.
3. Machine with new (existing design) blades, but reuse existing casing and pedestal.
4. New machine with new design (extended) blades.
5. New machine with new design (extended) blades, but reuse existing pedestal.
6. Machine with new design (extended) blades, but resue existing casing and pedestal.
7. New machine with new design (extended) blades and wide discs.
8. New machine with new design (extended) blades and wide discs, but reuse existing pedestal.
9. Machine with new design (extended) blades and wide discs, but reuse existing casing and pedestal.

	1		***2***		***3***		***4***		***5***		***6***		***7***		***8***		***9***	
1	1	1	1	1	1	1	8	8	8	8	8	8	10	10	10	10	10	10
2	10	50	7	45	1	5	10	50	7	35	1	5	10	50	7	35	1	5
3	6	60	6	60	6	60	5	50	5	50	5	50	10	100	10	100	10	100
4	5	45	5	45	5	45	5	45	5	45	5	45	10	90	10	90	10	90
5	1	7	1	7	1	7	6	42	6	42	6	42	10	70	10	70	10	70
6	10	80	10	80	5	40	10	80	10	80	10	80	10	80	10	80	10	80
7	3	12	3	12	4	16	2	8	2	8	3	12	1	4	1	4	1	4
8	4	16	3	12	2	8	6	24	5	35	1	4	8	32	7	28	3	12
9	10	30	8	24	6	24	4	12	4	12	1	4	6	18	3	9	4	12
Score		301		286		206		319		315		250		454		426		383

APPENDIX E— GRISK MODEL INPUT AND OUTPUT

Table E-1. Input Summary Table.

	Minimum	Most Likely	Maximum	Flat	Peak	Clip	COF
Category: Constants / Economic Results							
Last Period for Analysis	.	19	.	.	10	.	.
Turnaround Time	.	4	.	.	10	.	.
Max Acceleration of Maint to TAR	.	1.25	.	.	10	.	.
Effective Tax Rate	.	37	.	.	10	.	.
MTI Rate	.	4	.	.	10	.	.
UCC Rate	.	9.94	.	.	10	.	.
Discount Rate for NPV Calculation	.	10	.	.	10	.	.
Depreciation Schedule	Time Series Variable					.	.
Base Case Cash Flow (for comparison)	.	0	.	.	10	.	.
Category: Capital Exp / Incent (1) & Outputs							
Capex Period (1)	.	0	.	.	10	.	.
Capitalized Construction Costs (1)	500	550	650	.	7	.	.
Cost Reduction (Incentives) (1)	625	800	870	.	5	.	.
Category: Capital Exp / Incentives (2)							
Capex Period (2)	.	8	.	.	10	.	.
Capitalized Construction Costs (2)	5300	5500	6500	.	5	.	.
Cost Reduction (Incentives) (2)	1250	1600	1745	.	7	.	.
Category: Capital Exp / Incentives (3)							
Capex Period (3)	.	-1	.	.	10	.	.
Capitalized Construction Costs (3)	.	-1	.	.	5	.	.
Cost Reduction (Incentives) (3)	.	-1	.	.	7	.	.
Category: Capital Exp / Incentives (4)							
Capex Period (4)	.	-1	.	.	10	.	.
Capitalized Construction Costs (4)	.	-1	.	.	5	.	.
Cost Reduction (Incentives) (4)	.	-1	.	.	7	.	.
Category: Timing (1) & Outputs							
Timing / Cost Period (1)	.	0	.	.	10	.	.
Time Between Routine Maint (1)	**.**	**2**	**.**	**.**	**5**	**.**	**.**
Time Between Failures (1)	**0.1**	**4**	**5**	**.**	**4**	**.**	**.**
Time Between Thermal Cycle (1)	**.**	**.5**	**.**	**.**	**5**	**.**	**.**
Category: Timing (2)							
Timing / Cost Period (2)	.	8	.	.	10	.	.
Time Between Routine Maint (2)	**.**	**2**	**.**	**.**	**5**	**.**	**.**
Time Between Failures (2)	**.1**	**4**	**5**	**.**	**7**	**.**	**.**
Time Between Thermal Cycle (2)	**.**	**1**	**.**	**.**	**10**	**.**	**.**
Category: Timing (3)							
Timing / Cost Period (3)	.	-1	.	.	10	.	.
Time Between Routine Maint (3	.	-1	.	.	10	.	.
Time Between Failures (3)	.	-1	.	.	10	.	.
Time Between Thermal Cycle (3)	.	-1	.	.	10	.	.
Category: Timing (4)							
Timing / Cost Period (4)	.	-1	.	.	10	.	.
Time Between Routine Maint (4)	.	-1	.	.	10	.	.
Time Between Failures (4	.	-1	.	.	10	.	.
Time Between Thermal Cycle (4)	.	-1	.	.	10	.	.
Category: Timing (5)							
Timing / Cost Period (5)	.	-1	.	.	10	.	.
Time Between Routine Maint (5)	.	-1	.	.	10	.	.
Time Between Failures (5)	.	-1	.	.	10	.	.
Time Between Thermal Cycle (5)	.	-1	.	.	10	.	.
Category: Costs							
Routine Maintenance Cost	500	750	1000	.	6	.	.
Maintenance Cost - Lost Production	1200	1500	2000	.	0	.	.
Failure Cost	1000	1300	1700	.	4	.	.
Failure - Lost Production	1000	3000	10000	.	0	.	.
Thermal Cycle - Lost Production	.	100	.	.	10	.	.

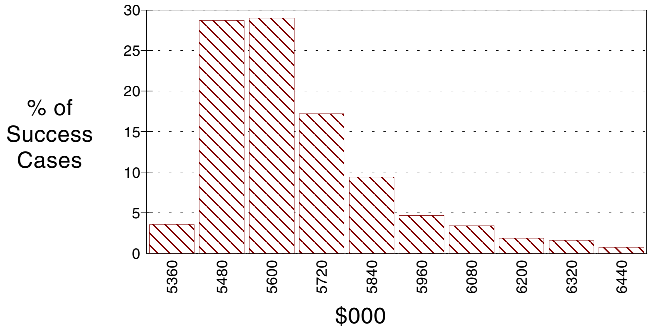


Figure E-1. Capitalized Construction Costs (2), Option 5.

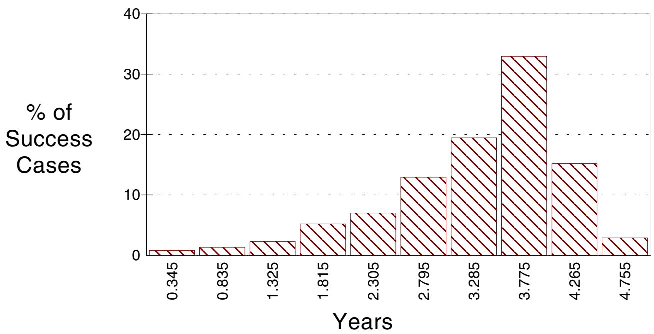


Figure E-2. Time Between Failures (1), Option 5. (0.1, four, five years between failures with peakedness of 4.)

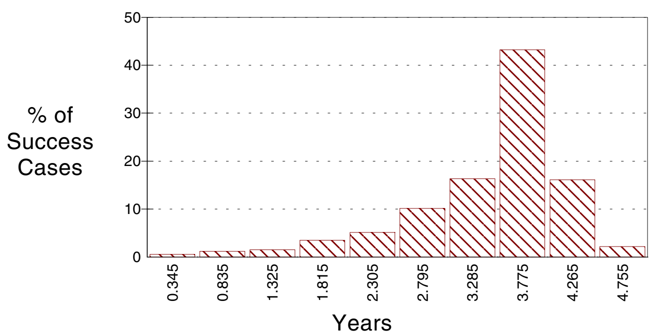


Figure E-3. Time Between Failures (2), Option 5. (0.1, four, five years between failures with peakedness of 7.)

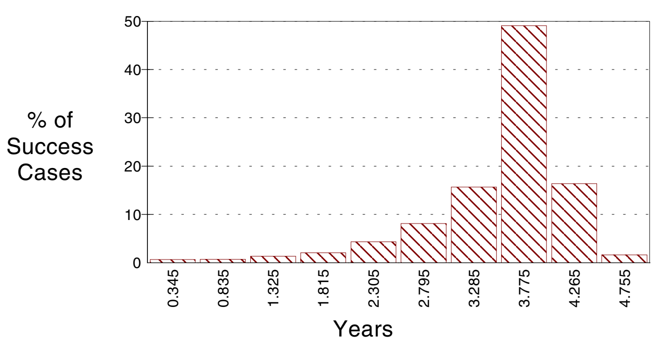


Figure E-4. Time Between Failures (2), Option 5. (0.1, four, five years between failures with peakedness of 10.)

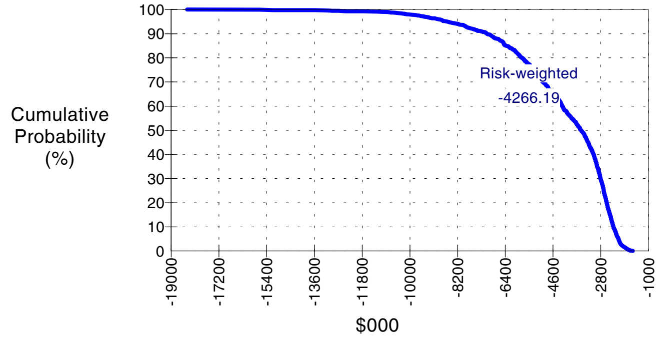


Figure E-5. Net Present Value, Option 5.

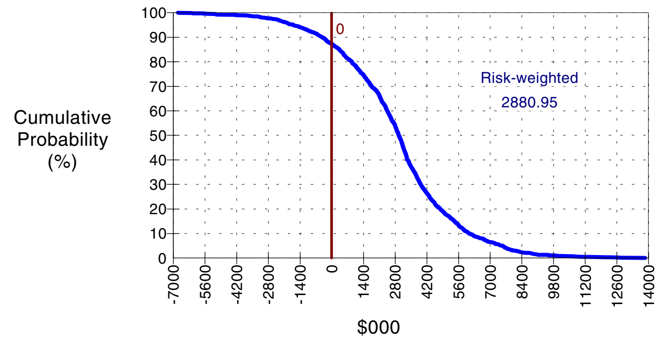


Figure E-6. NPV Relative to Option 1, Option 5.

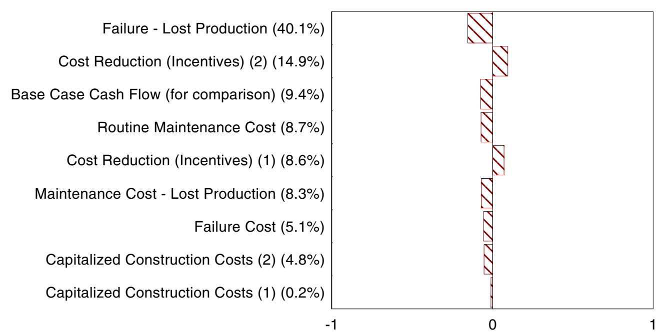


Figure E-7. Sensitivity Analysis for NPV Relative to Option 1, Option 5.

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"CVP Standard," BP Amoco Corporation.

Hammond, P., 1999, "GRisk Description," BP Amoco Corporation correspondence.

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