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Experience with Industrial Gas Turbine Overhaul: Economy Study

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Abstract For the owner of gas turbines (GT) with top in class good history of preventive, and predictive maintenance practices, able to manage its operations efficiently within the time-between-overhaul (TBO) interval, will the repair versus replacement decisions during overhaul, be same, with an owner of questionable maintenance practices with several cases of breakdowns within the TBO interval? And, for both owner types, when is the right time to decide on, and the method to be applied for a "displacement" policy - complete replacement of old gas turbine equipments for new equipments as a result of technological changes, operational inefficiency, or increased maintenance costs? Such Costs and Usage Values, Decisions Analysis is essential in consideration of alternatives in the maintainable equipment overhaul plan. While the GT overhaul repair versus replacement decisions are present economy studies, the "displacement" decision is based on future economy studies of capital recovery. In this paper an approach to assist with the repair versus replacement economic value decision planning is shown through an example in the overhaul of a turbo-compressor, and a basic guide to assist in a gas turbines displacement policy formulation is also given.

Keywords Gas Turbine Overhaul; Turbo-machinery Maintenance; Overhaul Planning; Replacement Value Analysis.

Introduction

The economy study presented is based on the overhaul of a turbo-compressor (Frame 1 and 3 gas turbine units' driving centrifugal natural gas compressors). The study presented is based on the work of Jack [1]. Table 1 shows the spares required and the procurement costs. In Table 2 is given the support materials and costs. Table 3 shows labour costs per man for main, sub- and support contractors. The costs values given are based on 1990 Dollar rates.

Labour Costs

Machine Running Time (TBO) = 32000 hours (Manufacturer Recommendation)
= Time from initial commissioning to overhaul ≈ 3.5 years.
Anticipated Overhaul/Repair time: 60 days, with each man working at 10 hours per day per seven days week.
No overtime charge.

Main Contractor:	\$650 x 60 (10 hour/day) x 3 men:	= \$117,000.00
Sub-Contractor:	\$136.73 x 60 (10 hour/day) x 2 men:	= \$ 16,407.60
Support Casual Labour gang:	\$4/day x 60 (10 hour/day) x 1 man:	= \$ 2,400.00
Total Labour Costs = \$117,000.00 + \$16,407.60 + \$2400.00		= \$135,807.60

Table 1 Replacement Spares for Turbo-compressor Overhaul.

S/N	Materials/Component	Quantity	Unit Price ($)	Total Price ($)
1	Axial Compressor Inboard & Outboard Bearings	2	4,072.02	9,140.04
2	Centrifugal Compressor Tilt-Pad thrust bearings			12,262.58
3	Combustion Chamber Liner	1	55,514.40	55,514.40
4	Compressor seals			1,598.78
5	Dowel Pins	16	6.60	105.60
6	Exhaust Plenum Jacket	1	164.85	164.85
7	First Stage Nozzle			47,214.09
8	Fuel filter	1		2,621.22
9	Journal Bearings	1	1,378.74	1,378.74
10	Labyrinth Seals (brass type)	4	189.34	757.36
11	Main lube oil pump coupling assembly			104.61
12	Oil Filter	6	124.77	748.62
13	O-Rings	2	13.19	26.38
14	Seal Oil Filter	2	2.34	4.68
15	Shim kit			160.35
16	Spark Plugs	1		148.74
17	2-Stage barrier filter	20	52.29	1,045.80

Source: Jack [1]

Table 2 Support Materials and Special Tools.

S/N	Materials	QTY	Unit Price ($)	Total ($)
1	Alignment Tool			1,278.95
2	Anti-rust Liquid	1	120.13	120.13
3	Anti-Seize Compounds	1	12.52	12.52
4	Combustor Puller	1	1,136.83	1,136.83
5	Dye-Penetrant			169.38
6	Engine Detergent Washer			1.60
7	Safety Gears			60.06
8	Silicone Gasket Sealant	10	16.28	160.28

Source: Jack [1]

Table 3 Per man per day Labour cost.

S/N	Expert Service	Rate	No. of Personnel
1	Main Contractor (OEM Field Representatives)	$650.00 per day	3
2	Sub-Contractor Technical Representatives	$136.73 per day	2
3	Support Labour	$4.00 per day	1

Source: Jack, [1]

Economy Study (Repair *versus* Replacement Decision Analysis)

The repair versus replacement decision is often referred to as the Repair Level Analysis [2, 3].

Alternative 1: – Replace Damaged Parts with New Parts:

Total Material Costs (Materials to be replaced): = $131,618.10

Cost of Support materials/Tools:	= $ 2,927.20
Total Cost of Materials = $$131,618.10 + $2927.20	= $134,545.30
Parts Shipment or Import from OEM ($131,618.10, Cost & Freight)	
Custom Duty @ 10%	= $ 13,454.53
Shipment Port handling Charges	= $ 119.65
Government surcharge @ 7%	= $ 9,418.17
Transportation from Shipping Port to Company warehouse	= $ 377.83
Clearing Expenses	= $ 107.05
Agency Fee @ $0.20 per kg	= $ 71.79
Hence, Total Cost of Overhaul for ***Alternative 1*** is:	
Cost of Items	= $ 134,545.30
Shipment Costs per Importation	= $ 23,548.99
Labour Costs	= $ 135,807.60
Total	= $ 293,901.89

Alternative 2 – Repair Damaged Parts

Based on plan, repairable materials are, Combustion Liners, First Stage Nozzle, Axial Compressor inboard and outboard bearings.

Jacobson in Bloch, *et al.* [4], states that, typically the parts to be repaired can be recovered in the "as new" condition for between 30% - 60% of the cost of a new part

If for this project an optimistic rate of 55 % of the new part is assumed (using the new part prices for the three repairable items listed in Table 1):

Cost of Materials	= $ 82,656.00
Cost of Support Materials	= $ 2,927.20
Total Cost of Materials	= $ 85,583.20

Shipment of parts to OEM facility for repair – "Re-Export"

Air Freight to OEM facility @ $3.15/kg + 5% tax	= $ 1,256.30
Transport from Field Site through Shipment Port to OEM facility @	= $ 314.86
Shipment Port handling Charges	= $ 62.97
Custom re-importation certificate	= $ 81.86
Agency Fee @	= $ 71.79
Sub-Total	= $ 1,787.78

Shipment of Repaired parts from OEM facility to Field Site – "Re-import"

($85,583.20 Cost & Freight)

Custom Duty @ 10%	= $ 8,558.32
Shipment Port handling Charges	= $ 119.65
Government surcharge @ 7%	= $ 5,990.82
Transportation from Port to Company warehouse	= $ 377.83
Clearing Expenses	= $ 107.05
Agency Fee @	= $ 71.79
Sub-Total	= $ 9,833.72
Total Shipment Cost	$ 1,787.78 + $ 9,833.72 = $11,621.50

Allow extra 30 days, waiting time for repair of damaged parts:
Hence, extra labour costs = 0.5 ($ 135,807.60) = $ 67,903.80

Therefore:
Total Cost is made up of:

Labour	\$ 67,903.80 + \$ 135,807.60	= \$ 203,711.40
Shipment		= \$ 11,621.50
Repair Cost		= \$ 85,583.20
Total		= \$ 300,916.10

Decision: - ***Alternative 1*** (Replace with New parts) *compared* to ***Alternative 2*** (*Repair* damaged parts):
[\$ 300,916.10 = Expense on ***Alternative 2**-Repair*] > [\$ 293,901.89 = Expense on ***Alternative 1**-Replace*]
Savings = \$ 7,014.21

Hence, ***Alternative 1***, of replacing the damaged parts with new parts is more economical.
Even though, the replacement *Alternative 1* is chosen, it might still be necessary in some instances for an equipment population of same model type of GT machines, that repairable items that are replaced, are not discarded, but sent for repair and used for the next overhaul, if the economic analysis favours such a decision.

Costs of Lost Production/Downtime, and overtime

The economic analysis done is for the GT overhaul expenses for the maintenance and overhaul of a turbo-compressor unit, and excludes cost of lost production due to downtime or overtime labour charges. Jack [1] reported and treated such cases.

Slack-Chart Manning Analysis

The Slack-Manning chart [5], in Table 4, can be used to estimate the required number of workers for the overhaul project. The example uses range day analysis: 0-8, 8-16, 16-24, 24-32, 32-40, 40-48, using the total times (45) along the critical path as a guide.
Approximate Computations for needed manning were estimated based on numbers falling within, and just around a range. Exact computations will require a proper days' spread from 0-45.
The Slack column is obtained from the relation:

$$[LatestFinish(LF)] - [duration(d)] - [EarliestStart(ES)] \qquad (1)$$

The required minimum number of workers for the project is: 6.
There will usually be cost consequence (penalty cost) in exceeding the estimated minimum workers number required for the project, since the labour costs are on daily personnel contract. *On-site managers will need to assign tasks around this minimum manning to ensure that the overhaul is completed on time, allowing for possible moderation to the next manning level which is 9 and so on. In that case the plan is oscillating between extreme optimism (lowest labour costs) and conservative cost management to stay within budget.*
Can job times vary? Possibly! Can new critical jobs not anticipated in planning arise? Possibly! The responsibility of the team leader is to ensure, personnel/tasks assignments are done in line with the determined (planned), and uncertain (unanticipated) estimated tasks times, with savings in time and cost at completion.

Table 4 Slack – Manning Chart for Disassembly, Inspection and Assembly of Gas Turbine Overhaul

Activity Number	Activity Description	Duration *d*, (Days)	Earliest Start Time (*ES*)	Latest Finish Time (*LF*)	Slack (*LF-d-ES*)	Men	Days					
							8	16	24	32	40	48
							(On-site Required No. Of Men)					
D1	Check Operating Data	4	0	4	0	1	1					
D2	Shut Down Unit	4	4	8	0	1	1	1				
D3	Disassemble Package	7	8	15	0	4	4	4				
D4	Remove Combustion Chamber Cover	0.5	0.5	18.5	17	2	~~2~~	~~2~~	2			

D5	Disassemble Coupling	1	15	16	0	2		2					
D6	Pull-out Chamber Liner	0.5	0.5	19	18	2	~~2~~	~~2~~	2				
D7	Check Alignment	1	16	17	0	2		2					
D8	Disassemble Combustion Chamber/Diffuser Casing	1	1	20	18	3	~~3~~	~~3~~	3				
D9	Disassemble Exhaust Housing	0.5	17	17.5	0	4		4					
D10	Remove First Stage Seal Rings	0.5	2	20.5	18	2	~~2~~	~~2~~	2				
D11	Disassemble Exhaust Plenum with Low Pressure Rotor and Mount on Stand	4	17.5	21.5	0	5			5				
D12	Remove Transition Piece	0.5	2.5	21.2	18.2	3	~~3~~	~~3~~	3				
D13	Remove Low Pressure Rotor from Plenum	0.5	21.5	22	0	3			3				
D14	Remove Labyrinth Seals	0.5	22	22.5	0	2			2				
D15	Disassemble Axial Compressor Upper Half Casing	1	3	27.3	23.3	4	~~4~~	~~4~~	~~4~~	4			
D16	Remove Variable Nozzle Upper Casing	0.33	4	27.5	23.2	2	~~2~~	~~2~~	~~2~~	2			
D17	Remove Bearings	0.33	22.5	22.8	0	2			2				
D18	Remove Upper Half of First Stage Nozzle	0.33	3	22.7	19.4	2	~~2~~	~~2~~	2				
D19	Check Rotor, Stator Blade Clearances	0.5	3.3	23.2	19.4	2	~~2~~	~~2~~	2				
D20	Remove Axial Compressor Rotor and Place on Stand	0.33	3.8	23.5	19.4	6	~~6~~	~~6~~	6				
I1	Inspect Bearings	1	22.8	23.8	0	1			1				
I2	Combustion Liner Check for Crack(s), Corrosion, and Erosion	0.5	1	39	37.5	2	~~2~~	~~2~~	~~2~~	~~2~~	2		
I3	Steam Wash Rotor and use Dye Penetrant for Crack Test	0.5	24	24	0	3			3				
I4	Steam wash Low Pressure Rotor and Check Turbine Wheel for Crack(s)	0.5	22.8	25.8	2.5	4			~~4~~	4			
I5	First Stage Nozzle Check for Crack	0.5	3.3	23.7	20	2	~~2~~	~~2~~	2				
A1	Reinstall Lower Half	0.25	23.8	24	0	2			2				

	Bearings and Seals											
A2	Refit Liner Housing	0.5	1.5	39	37.5	2	~~2~~	~~2~~	~~2~~	~~2~~	2	
A3	Reinstall First Stage Nozzle	0.25	3.8	24	19.9	3	~~3~~	~~3~~	~~3~~	3		
A4/A10	Reinstall Axial Compressor	0.5	24	24.5	0	6			6			
A5	Reinstall Seals and Bearings on Low Pressure Rotor	0.25	23.3	26	2.15	3			~~3~~	3		
A6	Reinstall Low Pressure Rotor in Exhaust Plenum	2	23.6	28	1.4	3			~~3~~	3		
A7	Refit Liner	0.5	2	39.5	37	2	~~2~~	~~2~~	~~2~~	~~2~~	~~2~~	2
A8	Refit Liner Cover	0.25	2.5	39.8	37	2	~~2~~	~~2~~	~~2~~	~~2~~	~~2~~	2
A9	Refit Spark Plugs, Gas Ducts	0.25	2.8	41	37.7	3	~~3~~	~~3~~	~~3~~	~~3~~	~~3~~	3
A11	Reinstall Upper Seal Halves	0.5	24.5	25	0	2				2		
A12	Check Axial Compressor Blade Clearance	0.5	25	25.5	0	2				2		
A13	Reinstall Seal Rings	0.5	25.5	26	0	2				2		
A14	Reinstall Transition Piece	0.5	26	26.5	0	3				3		
A15	Reinstall Combustion Chamber/Diffuser Casing	1	26.5	27.5	0	3				3		
A16	Reinstall Variable Nozzle Upper Casing	0.5	27.5	28	0	2				2		
A17	Reinstall Exhaust with Low Pressure Rotor	3	28	31	0	3				3		
A18	Reinstall Exhaust Housing	2	31	33	0	4				4	4	
A19	Align Machine	2	33	35	0	2					2	
A20	Repackage Unit and Connect all pipes	6	35	41	0	4					4	4
A21	Start-up	4	41	45	0	1					1	1
Anticipated Guide for estimating minimum Required GT Overhaul Crew Size based on work progress, Σ =							6	9	47	39	15	12

The Displacement Question

The displacement question relies on issues in productivity as discussed by Humphrey's [6]. Such productivity considerations in this case will bother on: efficient operational performance, ease of sourcing for maintenance repair/spares, obsolescence, and increased cost of maintenance.

Answers to the displacement question in facilities with large gas turbine equipment population (>>2), will be different from that of an owner with two units, one in operation, and a standby. The concerns:

a) What is the history of preventive and predictive maintenance practices of the GT equipment owner?

b) For the owner of several units, should the displacement question be group displacement or individual displacement?

(i.) If group displacement, should there be a phased displacement with initial fewer number of new installed units?
(ii.) Is there enough real estate at the field site location of the existing facility for such new installations alongside the existing ones?
(iii.) Will there be a need to acquire new real estate nearby to benefit from some existing support services such as gas pipeline delivery?

c) If individual unit displacement, are there proper records of operational performance history of each and every unit?

One multi-facility public power utility company with a GT equipment population of 19 units at one of its Generation locations, was at one point successfully operating only two units at the particular field site, with other units having being shutdown for otherwise maintainable reasons ranging from, excessive vibration, worn out journal bearings-spares no longer in production, to compressor blade failure amongst others. These were recorded in its executive summary status report of operations. One interesting record was a whole unit awaiting overhaul for 19 years! A search though the equipment maintenance records in other Generation locations of this public power utility, show similar patterns of equipment breakdowns and unavailability. It was also found from enquiry that one other challenge of the operator was poor spare parts sourcing practice.

This utility power operator is a classic example for total displacement which will also include the complete overhaul of its maintenance practices.

The Displacement question will also involve looking at alternative gas turbine equipment manufacturers, different from the manufacturers of existing installed units.

Answers to the displacement question based on GT unit operational performance is centered on inefficient performance, with the operating history as a guide, and applying the phased displacement policy decision, the least performing equipment will be the first to be taken out from the GT equipment trains population.

DeGarmo, Sullivan, and Canada [5], suggest the application of Replacement Value Theory to the Displacement Question, by the method of capital recovery, using uniform annual cost of capital invested approach (*Unacost* [6]). Humphrey's [6] discusses various attempts at formulating different mathematical models for the displacement question. The gas turbine equipment overhaul planner must work alongside existing and other OEM representatives to get good value for his Company's operational needs. This writer is unaware of a computer program for proposals evaluation and selection of gas turbines from different competing suppliers. For Centrifugal Compressors, a computer program for performance analysis of several bids was developed by Alignagraphics. Such a model may be extended to gas turbines performance evaluation from several bid proposals if one is not currently in the open market.

Conclusion and Discussion

Proper Repair level economic analysis with up to date and current spare parts cost data is recommended for good cost estimate value decisions. Spares costs are affected by the time value of money. Analysis done with a long lead time to the actual overhaul project implementation may need to be reviewed. So, a factor of inflation and price variation must be provided for. It will be good practice for the planners to work with the materials requisition team.

It will be observed from the Maintenance DisIA Network Diagram in [7], and also from slack chart and manning Table 4 that, the time from overhaul project start, activity ST – to – activity A21 (completion and start-up commissioning) was 45 days. This implies additional savings in Labour costs of $ 33,411.90. With ***Alternative 1*** selected, the total Dollar cost savings is $40,426.11.

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