Machinery Management Services to Improve Reliability, Plant Safety & Return on Investment

Manjul N Saxena, Principal Engineer, GMC, Australia

We make it happen

Tel: + 61 456 980 655 E-mail: manjuln_saxena@hotmail.com

Manjul N Saxena – Global Machinery Consultants Pty Ltd.

32 years of machinery design, engineering, erection, commissioning and maintenance experience - a global career spanning across India, Australia, Japan & UK:

1. Erection / Commissioning of IPCL - MGCC (Now Reliance), Nagothane
2. Exxon-Mobil, Bass Strait, Australia facilities – Troubleshooting fleet of 70 machinery trains
3. Al-Shaheen Offshore platforms FEED Compressors, Pumps, Expanders & Turbines
4. Exxon-Mobil PNG – LNG Early Concept Study (led to the development of $20B project)
5. Ichthys LNG (INPEX) – led Concept, FEED & Early Engineering of Machinery ($50B project)
6. BP, UK – Machinery Troubleshooting & Design Review – Worldwide – 6 of the 8 regions

Tel: + 61 456 980 655 E-mail: manjuln_saxena@hotmail.com

Classifying Operational Risk?

Risk is any known or unknown threat which can affect the business bottom line / profitability, reputation and in the worst case can potentially wipe out the business.

Known risks of business are:

- Varying cost of finance (interest rates)
- Varying cost of energy input etc.

Known-unknown: (timing unknown)

- Floods,
- Earthquakes,

Unknown-unknown risks are:

- Accidents due to either
  - Man-made events – example uncontrolled process conditions
  - Unknown operating conditions usually occurring in the plant equipment example surge or short circuit or sudden increase in unbalance.

Unknown machinery operating conditions potentially carry the biggest operating risk.

Tel: + 61 456 980 655 E-mail: manjuln_saxena@hotmail.com

We can support the process of identification of Risk

We have supported well-known engineering analyses used in the plant design across many projects worldwide – 3 LNG Trains, FPSOs (after 5 years of it being in Operation), Offshore platforms, Refineries & Petrochemicals:

1. Hazop (Hazardous Operation Analyses) / HAZID (Hazard Identification)
2. Safety Integrity Level (also called SIL) Analysis or LOPA – Layer of Protection Analysis to ascertain whether the instrumentation installed to ensure safe operation can achieve its functionality and with what degree of reliability.
3. SIMOPS - Simultaneous Operation assessment to evaluate safe facility operation.

Tel: + 61 456 980 655 E-mail: manjuln_saxena@hotmail.com

What are the machinery challenges?

Rotating machinery is designed for 20 years of life, from 4 to 8 years of continuous operation before any major servicing overhaul and require availability above 90% of the time.

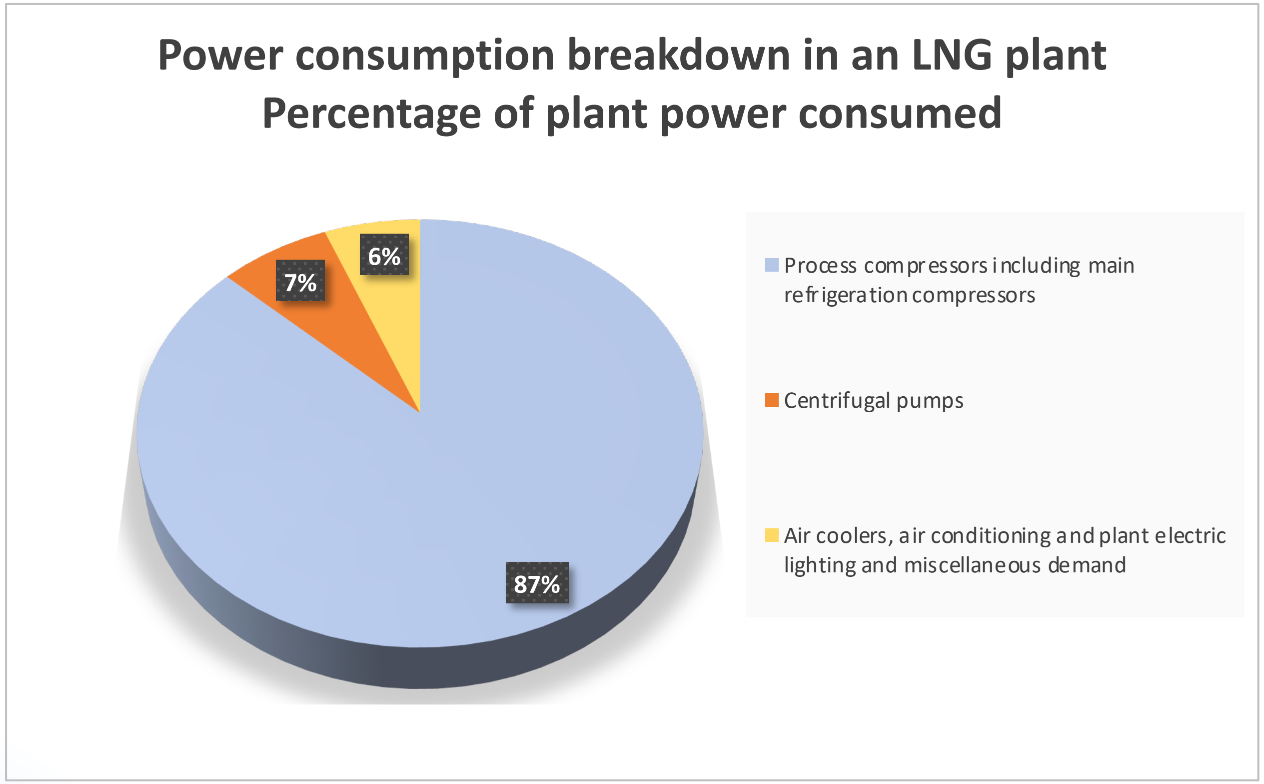
Some challenges are given below.

High power density - gas compressors of power demand > 30,000 to 100,000 kW-hr	This is equal to the combined maximum power generated by 50 to 150 Formula-1 (F1) racing cars
Continuous rotational speed @ 15000 rpm	F1 cars achieve this speed for a few minutes
Balance to less than 25 microns vibration	Human hair is @ 75 microns thick
Impeller tip speed of 300 m/s	Bullet speed is 550 m/s
Controls suitable to overcome surge which can destroy machine in seconds.	

Tel: + 61 456 980 655 E-mail: manjuln_saxena@hotmail.com

Machinery Risk contd.

Power consumption in a 5 million tons per annum capacity LNG plant.
Obviously, with 87% of the power consumed, the reliability of the process compressors is critical.



Tel: + 61 456 980 655 E-mail: manjuln_saxena@hotmail.com

Machinery Risk contd.

Process compressors are expensive and it is uneconomical to install a spare. Hence, the reliability of the design of these machines is paramount. Unscheduled downtime is expensive:

- Trip of the main process compressor in an Ethylene plant of 400,000 tons per annum capacity may result in the flaring of $500,000 of the plant inventory.
- Losses from 1 month downtime of the main compressor(s) in an LNG plant can be in excess of 100 million dollars.
- Trip of the Main Oil Pumps at an Offshore platform producing 100,000 barrels of oil daily would result in a loss of $5 million per day at the Oil price of $50 per barrel.

Tel: + 61 456 980 655 E-mail: manjuln_saxena@hotmail.com

What we offer - Upgrades & Operational Machinery Support Services

- Thermodynamics
    - Pumps – selection, power calculations, footprint, performance
    - Compressors – selection, power calculations, footprint, performance
    - Compressors – selection, power calculations, footprint, performance, auxiliaries.
- Dry Gas Seals and seal support system- engineering & troubleshooting
- CFD – Computational Fluid Dynamics with associate partners
- Compressor Controls with associate partners
- Review of Vibration signatures collected by third parties and provide additional Analysis
- Rotor dynamics
    - Review of third party reports and provide observations
    - Rotor dynamics modelling and analysis with with associate partners
- Compressor & Turbine Hardware
- Bearings and lube oil system design, review and trouble shooting

Tel: + 61 456 980 655 E-mail: manjuln_saxena@hotmail.com

Mitigating Machinery Risk – Design Stage

Machines are designed for specific process conditions

4-stages of checks and tests:

- Verification of supplier's experience to manufacture and supply similar machines
- Desk top design analyses
- Standard quality control testing during manufacturing cycle
- Specialised testing in the supplier shop to mitigate field risk

Tel: + 61 456 980 655 E-mail: manjuln_saxena@hotmail.com

Engineering Review of Supplier's Experience

Experience of multiple suppliers are reviewed

Impeller: Verification of non dimensional values vs flow coefficient

- Mach Number (tip speed/inlet sonic speed)
- Head coefficient (ability to develop pressure)
- Tip speed (stress developed)

Main rotor design verified to

- Predict unbalanced forces
- Ability to dampen the unbalanced forces

Tel: + 61 456 980 655 E-mail: manjuln_saxena@hotmail.com

2nd Stage of Risk Mitigation

For new designs (step change), desk top design studies are carried out to assess

a. Thermodynamic performance of the machine using Computational Fluid Dynamics (CFD),
b. Finite Element Analysis (FEA) to check parts response to various forces and stresses.
c. Rotor dynamic analyses is carried out of all the process compressors including rotor lateral analysis, Train Torsional and transient condition analysis e.g. short circuit
d. Dry gas seal assessment including utility consumptions, alarms and trips review for safety
e. Lube oil system review for suitability for new operating conditions
f. Journal and thrust bearing design assessment
g. Control system including surge control system review
h. Couplings and driver assessment

Tel: + 61 456 980 655 E-mail: manjuln_saxena@hotmail.com

4th Final Stage of Risk Mitigation

In addition to the routine quality control tests (example radiography of welds), customised test can cost upwards of a million dollars and take weeks to conduct. They include:

- PTC 10, Type 1 compressor performance test in the supplier shop,
- Full load string test to verify train rotor behaviour, if possible.
- Field Performance Test

Tel: + 61 456 980 655 E-mail: manjuln .saxena@hotmail.com

Example: Thermodynamics compressor calculations - LNG

MR Compressor – LP+MP+HP for 5MMTPA LNG Train

INPUT	DESCRIPTION	UNIT	GE AGAA LP casing (K02) MR	AGAA MP casing (K03) MR	AGAA HP casing (K04) MR	XXX AGAA LP casing (K02) MR	AGAA MP casing (K03) MR	AGAA HP casing (K04) MR
m	Rated Inlet Mass Flow	Kg/Hr	1160000.0	1160000.0	1160000.0	1160000.0	1160000.0	1159632.0
MW_{gas}	Molecular Weight of Gas (Refer gas property calc)	Kg/Kg-mol	26.29	26.29	26.29	26.29	26.29	26.29
C_p (gas)	Average Specific heat ratio of gas	kJ/Kmol K	50.37	51.50	51.50	50.37	51.50	51.50
P_1 (gas)	Suction Pressure	Kpaa	352.0	2072.0	3682.0	352.0	1801.0	3442.0
T_1 (gas)	Suction temperature	Deg. K	238.5	317.0	317.0	238.5	317.0	317.0
P_2 (gas)	Discharge Pressure	KPaa	2122.0	3700.0	5900.0	1852.0	3500.0	5900.0
Z1	For P1, T1 select Z1	Lee-Kesler-Ploecker	0.963	0.913	0.842	0.963	0.924	0.850
Q1	**Actual inlet flow**	**m^3/hr**	**239239**	**51215**	**26579**	**239239**	**59631**	**28703**
Frame	Frame number - refer engg notes		MCL1404	BCL1003	BCL 804	88M4	60M5	60M4
np	Polytropic Efficiency	% / 100	0.860	0.890	0.870	0.869	0.845	0.866
Nnom	Nominal RPM	RPM	3528	3528	3528	3528	3528	3528
Dnom	Nominal Impeller Diameter	mm	1492.0	1060.0	810.0	1410.0	890.0	871.0
r_p	Compression Ratio	P_2/P_1	6.028	1.801	1.606	5.261	1.939	1.718
k	C_p / (C_p - 8.314)		1.198	1.193	1.192	1.198	1.193	1.192
T_2	**Discharge Temperature °C**		**63.69**	**79.70**	**73.12**	**53.93**	**86.74**	**77.64**
Z_2	For P_2,T_2 select Z_2	Lee-Kesler-Ploecker	0.936	0.898	0.829	0.938	0.909	0.835
Za	Average compressibility	(Z1+Z2)/2	0.95	0.91	0.84	0.95	0.92	0.84
k_a	Average Specific heat ratio	same as k	1.198	1.193	1.192	1.198	1.193	1.192
n_a	Average Polytropic Exponent	same as n	1.238	1.222	1.228	1.234	1.236	1.229
H_p	**Head developed**	**KNm/Kg**	**153.59**	**56.36**	**41.46**	**139.92**	**64.84**	**48.08**
Stg_n	**Number of stages**		**4**	**3**	**4**	**4**	**5**	**4**
N_{oper}	**Operating RPM** [2]	**rpm**	**3525.60**	**3419.28**	**3424.82**	**3482.46**	**3510.14**	**3516.19**
PWR_s	**Total shaft power + losses**	**kW**	**58392**	**20704**	**15582**	**52642**	**25088**	**18151**
TOT PWR	**Total power including all stages+10% margin**				**104146.15**			**105468.96**
u	**Calculated Impeller Tip speed =**	**m/sec**	**275.61**	**195.81**	**149.63**	**260.46**	**164.41**	**160.90**
φ	Flow coefficient		0.138	0.085	0.099	0.166	0.163	0.083
V_2	Discharge Volume from last Impeller		56023.39	31637.35	18071.50	62329.97	34902.13	18481.36
Suc Flange	Size of Suction Flange - Diameter	mm	1750.0	800.0	600.0	1650.0	900.0	600.0

Tel: + 61 456 980 655 E-mail: manjuln_saxena@hotmail.com

E.g. - Thermodynamics calculations – Pipeline Compressor

Machine Configuration			TANAP
INPUT	DESCRIPTION	UNIT	Guarantee case
Std Volume	Flow through Compressor	SM3/hr 101.3 kPaa and 15 oC	655000
m	Rated Inlet Mass Flow	Kg/Hr	518322.5
MW_{gas}	Molecular Weight of Gas (Refer gas property calc)	Kg/Kg-mol	18.68
Pc (gas)	Critical Pressure of Gas (Refer gas property calc)	KPa	4596.64
Tc (gas)	Critical Tempeperature of Gas (Refer gas property calc)	Deg. K	208.10
C_{p1} (gas)	Specific Heat at cons. pres. of Gas (Refer gas property calc)	kJ/Kmol K@15deg C	38.43
C_{p2} (gas)	Specific Heat at cons. pres. of Gas (Refer gas property calc)	kJ/Kmol K@100deg C	43.80
C_p (gas)	Average Specific heat ratio of gas	kJ/Kmol K	41.11
P_1 (gas)	Suction Pressure	Kpaa	6950.0
T_1 (gas)	Suction temperature	Deg. K	302.1
P_2 (gas)	Discharge Pressure	KPaa	13150.0
Z1	For P1, T1 select Z1 Compressibility from charts	LKP	0.860
R	8314/MWgas		445.075
Q1	**Actual inlet flow**	**m^3/hr**	**8623.78**
SELECT COMPRESSOR FRAME FROM TABLE 2 OF FILE			
Frame	Frame number - refer engg notes		Frame A or B
	Frame	Elliott	25MB or 32MB
	Frame	MDT	RB 28 or RB 35
Qnom	Nominal inlet Volume Flow	M^3/Hr.	10050
$H_{pnom.}$	Nominal Polytropic head per stage	KNm/Kg	**30.00**
np	Polytropic Efficiency	% / 100	0.830
Nnom	Nominal RPM	RPM	9505
Dnom	Nominal Impeller Diameter	mm	467.0
$\mathbf{r_p}$	Compression Ratio	P_2/P_1	1.892
k	C_p / (C_p - 8.314)		1.253
T_2	**Discharge Temperature °C**		**79.88**
Z_2	For P_2,T_2 select Z_2 Compressibility from chart	LKP	0.851
Total Polytropic Head			
H_p	**Za*8.314*T1n($r_p^{(n-1/n)}$-1)/ {MWgas (n-1)}**	**KNm/Kg**	**79.36**
Stg_n	**Number of stages: Round of to next higher integer**		**3**
N_{oper}	**Operating RPM = N_{nom} (H_p/H_{pnom}*no. S_{tgn})$^{1/2}$**	**rpm**	**8925**
PWR_{loss}	Mechanical Losses from table3 + gear box losses	%/100	0.030
Power Consumption for gas Compression			
PWR_g	**Power consumed in Kw = m*H_p/(3600*n_p)**	**kW**	**13766**
PWR_s	**Total shaft power including 3% losses**	**kW**	**14179**
u	**Tip speed**	**m/sec**	**232.42**
Suc Flange	Size of Suction Flange - Diameter	mm	400.0
Suc. Vel.	Inlet suction Velocity	m/sec	19

Tel: + 61 456 980 655 E-mail: manjuln_saxena@hotmail.com

Mitigating Risk through studies at Design Stage

A desk top study can cost tens of thousands of dollars and special machinery tests can cost a few million dollars each.

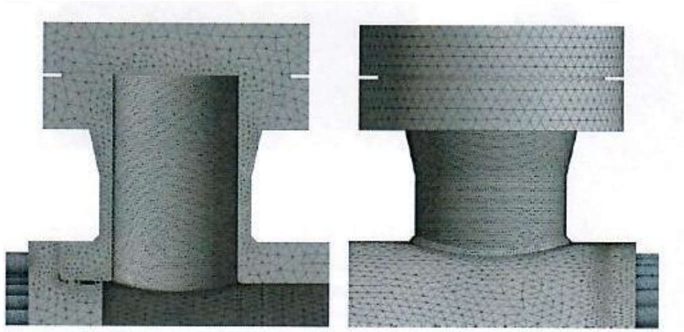
The decision to carry out various studies and tests has to be judiciously taken based on the past experiences and engineer's judgement of the amount of risk. Specialist knowledge of many experts is required.

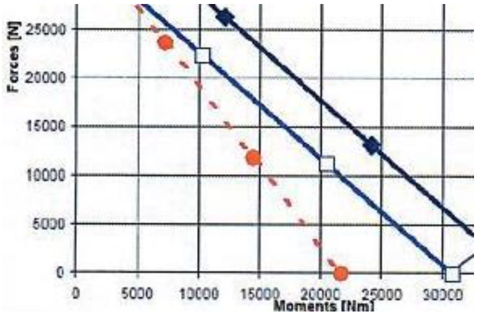
For example in the case of the cryogenic turbines, costing @$12 million for Woodside LNGIV project, increasing LNG plant throughput by 5%, NPV of profits generated > $150 million; some of the specialist engineering studies and test that were carried out were:

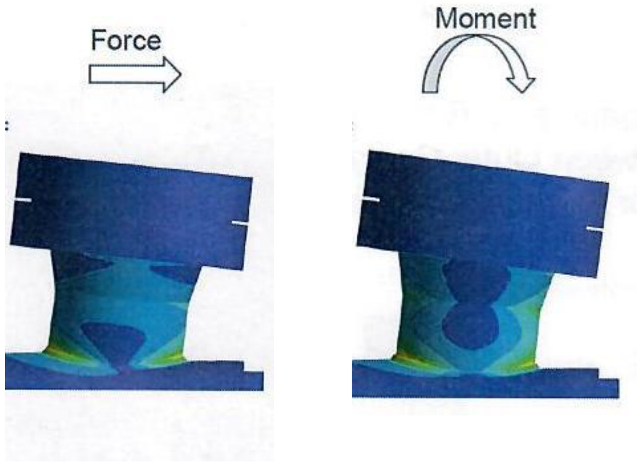
1. Turbine geometry CFD analysis
2. Warm out chamber analysis
3. Rotor overspeed stress analysis etc. and generator rotor high speed balancing

Tel: + 61 456 980 655 E-mail: manjuln_saxena@hotmail.com

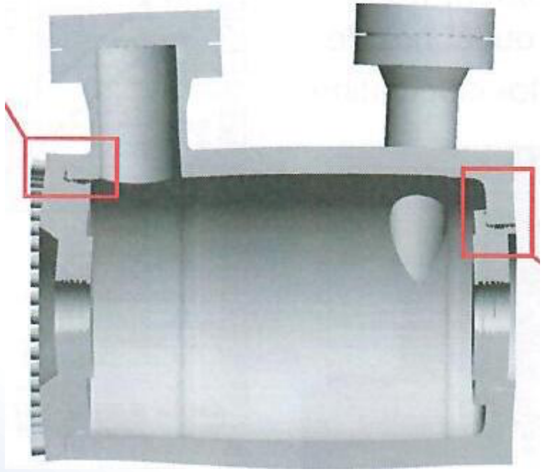
Compressor Casing FEA studies – 25,000 kW duty

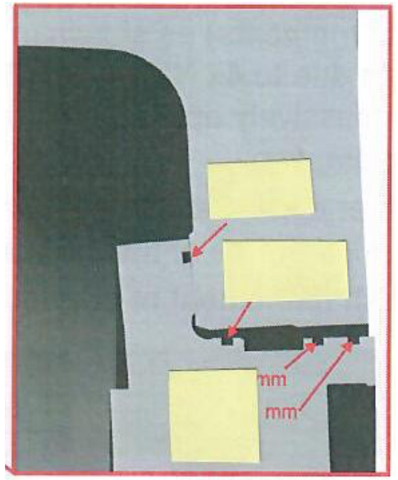






Compressor nozzle and casing mesh to analyze stresses and moments generated under worst design case can be done. The casing is also analyzed to study O-ring relief under pressure. Values hidden.

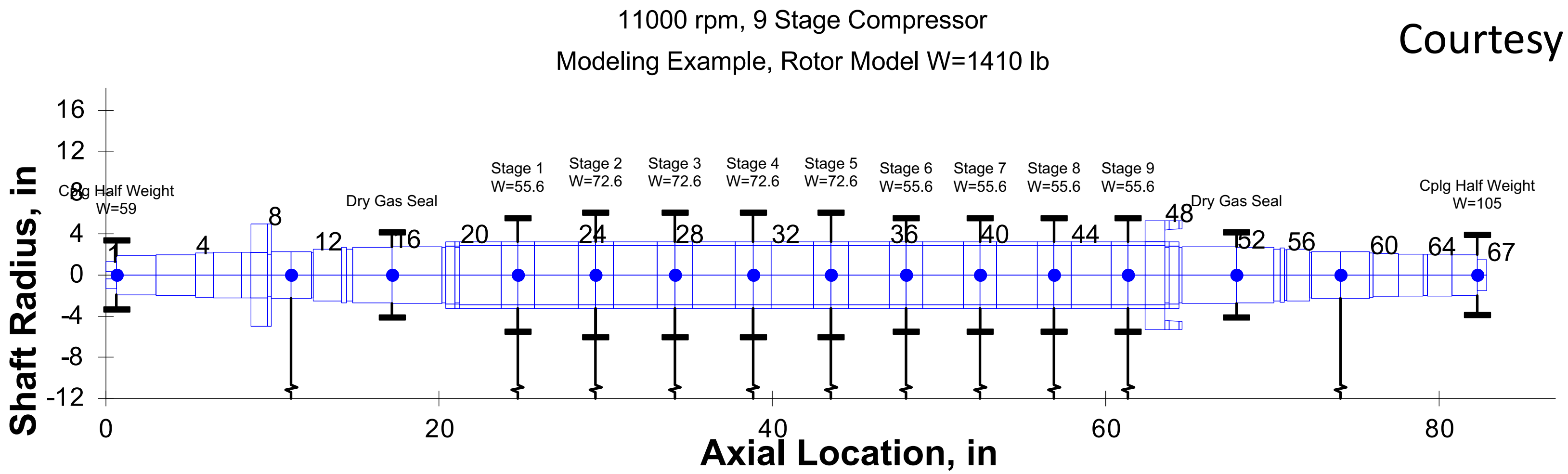


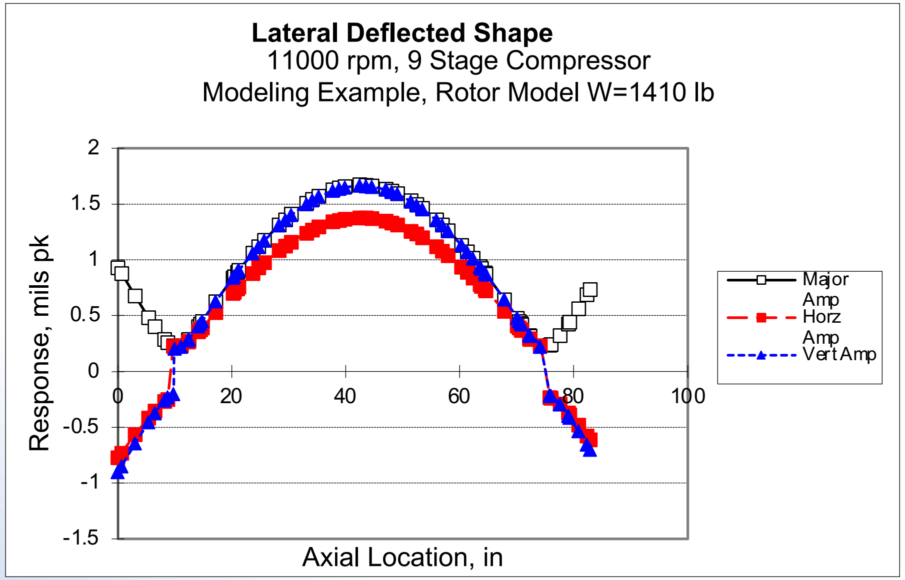


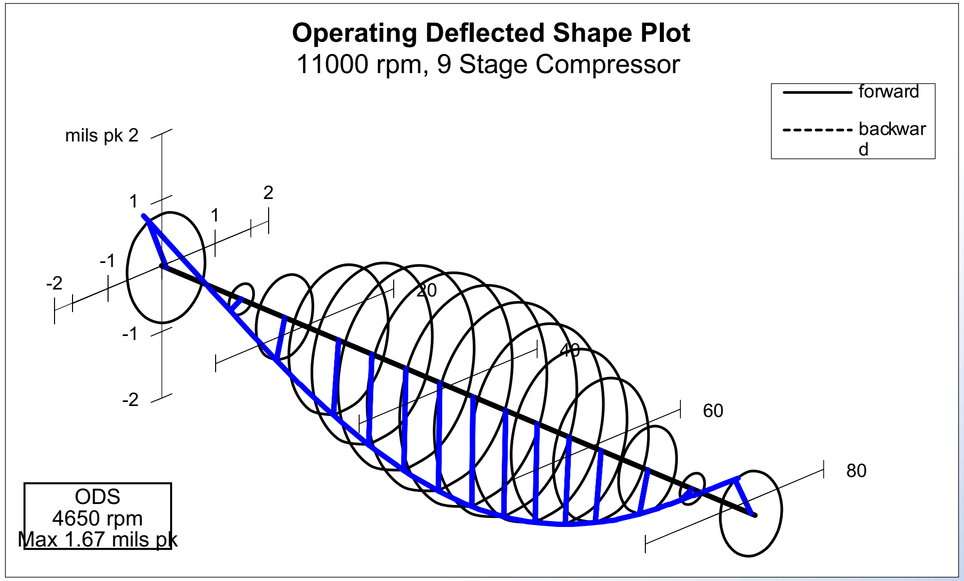
All pictures Courtesy MAN-ES

Compressor Rotor Dynamics studies

Courtesy RMA Inc. - XLROTOR

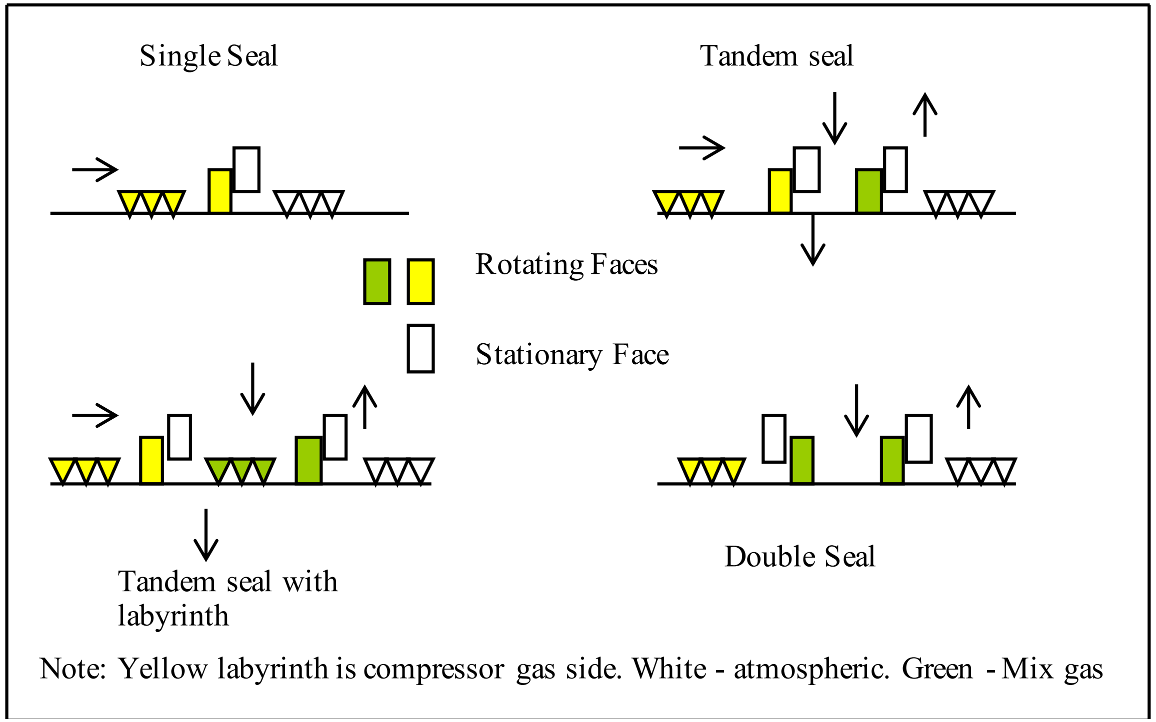






Upgrade to Dry Gas Seals in Compressors

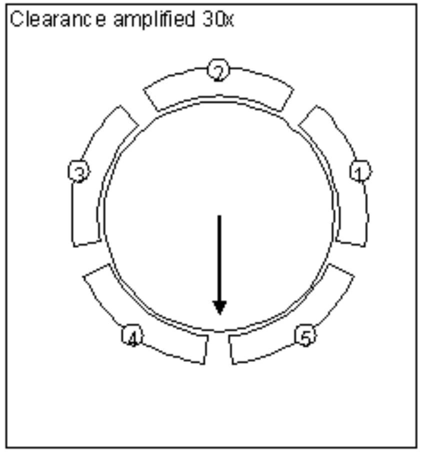
Reduce gas flaring, change from wet oil seals to dry gas seals to save ~$2000 /day /compressor casing at gas price of ~$8 per mmbtu. Improve Compressor uptime by 1.5 days per year. 4 Options available

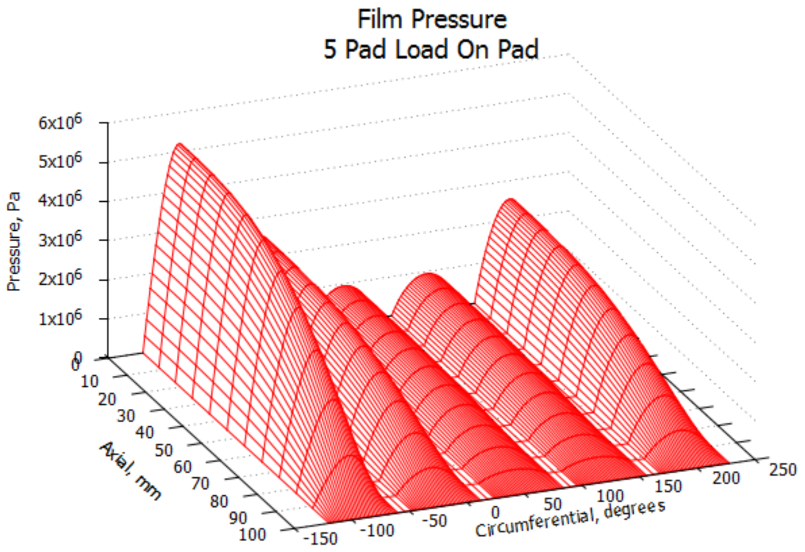


Tel: + 61 456 980 655 E-mail: manjuln_saxena@hotmail.com

Compressor Journal Bearing design review

Courtesy RMA Inc. - XLROTOR





Bearing Diameter	152.4	mm
Pad (Mach.) Diametral Clr	0.3048	mm
Bearing Outer Diameter	198.12	mm

Pad Number	Pad Rotation	Pad Load Normal	Pad Load Tang.	Resultant Preload	Diam Pad Cp	Diam Pad Cb	Pad Inlet T	Pad Inlet Flow	Pad Outlet T	Pad Outlet Flow	Groove T
--	rad	N	N	--	mm	mm	Deg. C	liter/min	Deg. C	liter/min	Deg. C
1	0.000848	68076.15	0.017349	0.5	0.96	0.48	99.3	157.563	121.9	96.469	74.1
2	0.001431	34940.92	0.029182	0.5	0.96	0.48	80.0	226.381	95.5	158.936	76.4
3	0.001111	13630.21	0.018929	0.5	0.96	0.48	72.1	325.73737	81.6	261.89059	72.1

An example of thrust bearing film thickness calculation and oil temperature analysis

Bearing Geometry	Side A	Side B
Bearing Type	Flooded	Flooded
Outer Diameter (mm)	177,8	177,8
Inner Diameter (mm)	88,9	88,9
Area (cm^2)	158,3	158,3
Number of Shoes	6	6
Pad Pivot Offset	50	50
Pad Material	Chrome Copper	Chrome Copper
Sign Convention for Load	+ Load	- Load

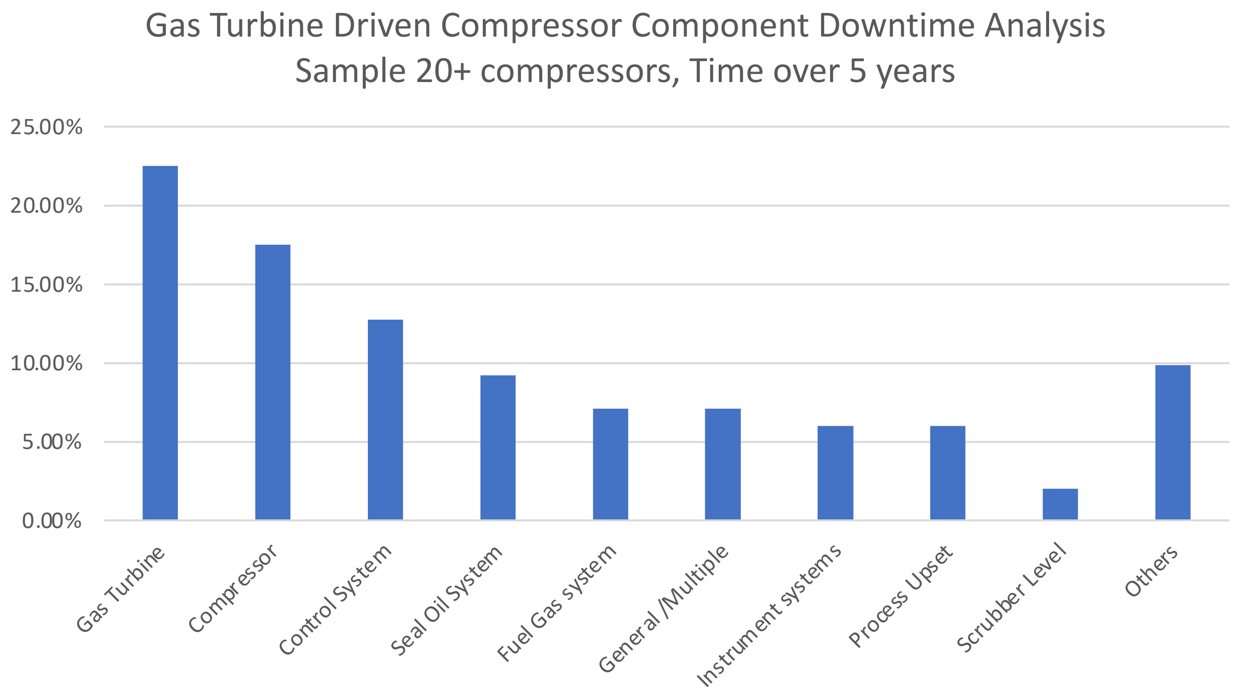
Oil Properties	
Lubricant	ISO VG 46
Oil Viscosity cSt @ 40°C	41,5
Oil Viscosity cSt @ 100°C	6,1
Specific Gravity °API	28,7

	Shaft Speed (rpm)	Shaft Speed (m/sec)	Bearing Load (kN)	Projected Load (MPa)	End-Play (mm)	Oil Flow (liters/min)			Oil Inlet Temp. (°C)	Oil Outlet Temp. (°C)	Power Loss (kW)	Minimum Film (mm)	75/75 Temp (°C)
						Side A	Side B	Total					
nom.	3600	25,1	38,00	2,40	0,165	15,0	15,0	30,0	50,0	55,9	5,3	0,020	82,9
API	3600	25,1	76,00	4,80	0,165	15,0	15,0	30,0	50,0	56,6	6,0	0,012	91,6
accid.	3600	25,1	100,00	6,32	0,165	15,0	15,0	30,0	50,0	56,8	6,2	0,009	95,4

Analysis to reduce bearing pad temperature and ensuring film thickness above 8 microns at maximum load.
Courtesy: Kingsbury Inc.

Assess Operational Risks

Operating plants have their day to day risks. Managers / engineers have to judiciously allocate cost to various maintenance disciplines in an effort to reduce downtime, enhance reliability, safety and profits.



Tel: + 61 456 980 655 E-mail: manjuln_saxena@hotmail.com

Improve Gas Turbine Operational Efficiency

Turbine Inspection and Overhaul Program				
#	Scope of work	K (=1000) hours of operation		
		8K	16K	24/30/48K*1
1	Site Test, Package Safety Functionality Test, Fleet Program			
2	Periodic shutdown checks, inspection and overhaul,			
2.1	Pre-shutdown checks	x	x	×
2.2	Shutdown checks	×	×	×
2.3	Service Overhaul			
	a) Visual inspection Program b) Life assessment of soft parts c) Inspect all air filter elements d) Gas Generator and Power Turbine: • Borescope, • Water wash GG after inspection, • Sample analysis e) Package items functional test	×	×	×
3	Power turbine (hot gas path) overhaul in supplier shop			×

Notes: *1. The third inspection/ major overhaul of the turbine hot gas path. This may be done after 24000, or 30000, 0r 48,000 or 64,000 hours of operation based on the type of turbine (industrial / semi-industrial / aero-derivative). The scope of supplier shop overhaul is based on the inspection report.

Tel: + 61 456 980 655 E-mail: manjuln_saxena@hotmail.com

Alarm & Trip Rationalization – Bringing best practices

(Steam or Gas) Turbine	Driven Equipment
Actuation Systems	Dry gas or Mechanical seal system
Transmission	Control system including surge control
Starting	Vibration (Driver & Driven)
Fuel supply & Control	Lube oil system (Driver & Driven)

Tel: + 61 456 980 655 E-mail: manjuln_saxena@hotmail.com

Upgrade Compressor & Turbine Controls

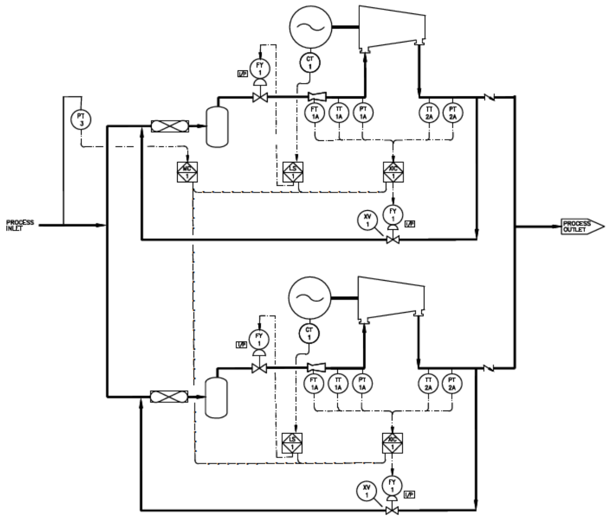
Our study showed Control systems are responsible for more than 12% of machinery downtime. With the improvement in the control cards design and their flexibility we can provide this Open Platform ECT solution through GMC/Nilrekha:

- Change to modern compressor controls to:
  - Control and respond to surge events
  - Multiple compressor train load share
    - Parallel Operation
    - Series Operation
  - Manage performance
- Mount control cards in the control room in the existing DCS / ICSS platform

Tel: + 61 456 980 655 E-mail: manjuln_saxena@hotmail.com

Machine Controls Upgrades – Support from ECT

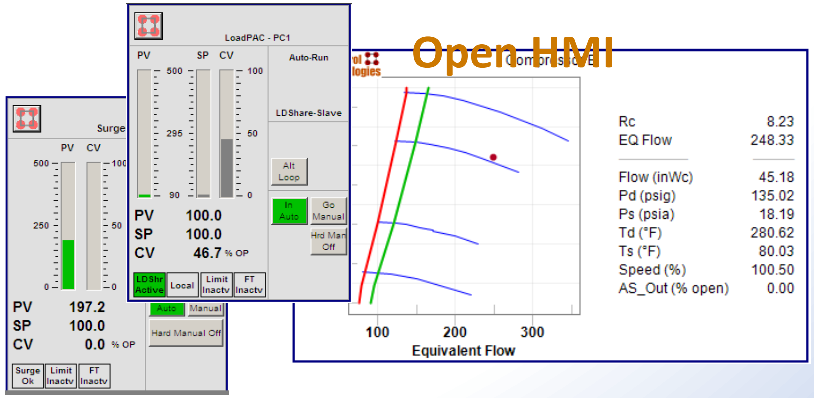
- Organizational Focus on Technology Development and Project Delivery
  - ECT **TurboPAC®** Apps – Application Software Modules installed in open platform
  - Surge/Performance/Speed/extraction/load sharing Apps
- SECURE, RELIABLE PROVEN Control Technology
- OPEN PLATFORM
- Capex & OPEX Saving – Proven across a range of compressor suppliers



+

ECT TurboPAC®
Applications
(Engineered & configured by ECT)

+



Future risks for the Oil & Gas Industry:

Before 2006, project viability was assessed for oil price of $20/ barrel, now @ $40/ barrel. In 2000, US Henry Hub gas price was $5 per MMBTU but in 2021 LNG was sold at $10-30 per MMBTU.

Before the Shale Oil & Gas revolution, OPEC controlled 73% of the global 1.7 trillion barrels of the oil reserves. Now US shale oil reserves alone are estimated at 3.5 trillion barrels. The political implications are huge & countries has to ascertain its role.

Last year USA produced about 13% of its electricity demand from renewable (Wind & Solar) energy. Over the next 10 years by 2030 the renewable may take centre stage and meet about 30% of the global energy demand.

Price may remain volatile, force companies to cut operating cost and could lead to higher risk of incidents in the Oil & Gas industry. Technological improvements in the design analysis of Machinery condition could reduce that risk.

Tel: + 61 456 980 655 E-mail: manjuln_saxena@hotmail.com

Suggestions, Observations & Thanks:

Given many plants were built before 2000 there are many opportunities for the Businesses / Industry to upgrade their machinery to improve their profitability.

Understanding, quantifying and managing machinery risk in one's own area of business will help every manager and engineer to improve their bottom line. We can help in identifying and mitigating that risk.

I wish the you all the very best. Thank you for the opportunity.

We look forward to be of service to your company.

Tel: + 61 456 980 655 E-mail: manjuln_saxena@hotmail.com