65 YEARS EXPERIENCE
WITH CASE HARDENED
& GROUND HIGH SPEED
GEARS

by

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1 Introduction

2 The Development of the Case-carburized Hardened and Ground Turbo Gear

3 Reliability

1 Introduction

This paper discusses the development, and particularly the reliability, of MAAG speed increasing gears which drive turbo compressors of high speeds and powers. An important characteristic of these gears is the case-carburized, hardened and ground gear teeth. The teeth are geometrically corrected to compensate for deflections due to load and thermal effects.

Highest priority has to be given to the assurance of the reliability of such gears. Any breakdown of gears not only may result in large production losses, but also entails the danger of consequential damage to other components of the gear or even to other machinery. Furthermore, many of these gears are installed in locations of difficult access, such as: deserts; arctic regions; or platforms, which may turn a minor problem into a major logistic operation. Based on decades of experience with these gears, a reliability analysis is performed on them and presented in this paper.

2 The Development of the Case-carburized, Hardened and Ground Turbo Gear

The first gear of this type was designed and built by MAAG in 1919 and was installed between a steam turbine and a compressor. At this time surface hardening of steel by carburization had generally been practiced for quite some time. This technique, however, could only be applied to gears that had to operate at low speeds, because of the relatively large distortions that this kind of heat treatment caused.

The engineer Max Maag designed and built the first gear tooth grinding machine in 1916. It enabled the production of accurate hardened gears for every required speed. Max Maag could not know at that time, that his pioneering work would eventually pave the way for the carburized case hardening technique to become superior to all other heat treatment techniques of gears as far as load capacity and wear resistance are concerned.

MAAG, the company Max Maag founded, has improved this technique ever since and developed carburization into an automatic and highly reliable process. More than 65 years of experience with these kinds of gears has been accumulated in the meantime. Today this process is used throughout the machine industry, in aircrafts, for ship propulsion gears, traction, steel and cement mills, etc. Design engineers were often hard to be convinced about the superiority of the hardened toothing. Decades of patient work were necessary to achieve the breakthrough, as reflected in Table 1.

MAAG's development of the turbo gear, of course, profited from the experience gained in all these other fields. It was a process of small steps towards higher speeds and transmitted power. Operating experience, and knowledge gained from the careful investigation of equipment that had failed, was fed back to the design office. For quite some time, the process of "learning by mistakes" was adequate to maintain the leading position in this field.

With increasing pitch line velocities, however, the tooth contact deteriorated due to thermal distortions of the rotors. Temperature measurements, performed experimentally under operating conditions, helped us to evaluate the optimum thermal tooth correction.

New test gears are being built and will be tested at loads and speeds anticipated for the immediate and distant future. The aim of these tests is to be able to calculate compensating tooth corrections accurately for any new application.

Parallel to this development of the toothing, the bearings needed increased attention as well. The ever increasing demands of bearing loads and speeds and the stringent vibrational requirements were, and are, met by continuous improvements in design, all tested on our own bearing test stand, at loads and speeds well over the intended application.

To this date, MAAG has delivered over 2,000 high speed gears, which transmit powers between 1,500 kW and 65,000 kW and with pitch line velocities close to 200 m/s. These gears have proven to be highly reliable as shall be shown in the following chapter. This high level of reliability has been achieved not only by the great efforts made in research and

development, but also through stringent quality assurance and complete after-sales services, including:
- on site erection
- regular inspection and overhauls
- trouble-shooting analysis, including whole trains, if necessary
- schooling of cutsomer's operating and maintenance staff

Furthermore, MAAG is in the fortunate position to be a worldwide leading manufacturer of machine tools and measuring machines used in the manufacturing and quality assurance of such high speed gears.

3 Reliablitiy

The reliability analysis presented here deals with gears in three large separate groups of turbo compressor installations, each group with its own typical ambient and operational conditions but all with high requirement regarding power, pitch velocitiy and ratio. Each group consists of 50 to 80 MAAG gear units in operation. This grouping enables an easier and more meaningful judgment than an overall analysis (see fig. 1 and 2).

The purpose of the analysis is to provide data on the reliability of MAAG's gears that is generally and easily understood and, still meaningful.

For more detailed theories on reliability there is a vast amount of literature available. The following terms on reliability shall be defined for the purpose of this presentation:

Failure is assumed to be an event that causes a gear to become inoperable, so that it can only be put back into service after some corrective maintenance has been performed.

Failure rate (λ) represents the number of failures that occur per unit of operating time, at a certain time during the life time of the components.

Mean Time between Failures (MTBF) represents the average number of operating hours, between failures.

Mean Time to Repair (MTTR) represents the average number of hours it took to repair a gear within its group.

Availability is defined as the probability that at any time the gear is in an operating state.

The above terms are mean values, which will be calculated from data over the entire operating time, up to the present, i.e. April, 1986. The cummulated hours of operation of some gears are not known exactly, especially of installations that are not regularly serviced by MAAG. The yearly production for such installations known to be in operation is conservatively estimated at 4,000 hours. Gear failures or major production stops in such installations are reported to us, however, and are therefore considered in this analysis.

MAAG gears in turbo compressor trains for reinjection plants in Algeria

(Group 1)

A total of 57 MAAG speed-increasing gears are installed between gas turbines and compressors. These installations are situated in two areas of the Sahara desert. The total power installed adds up to 1,300,000 kW.

Table 2 gives some performance data of these gears, as well as hours of operation and the cases of failure up to the present time. Details of these failures are provided in Table 3. From this data the following terms are calculated:

$$\text{Failure rate} = \frac{4 \text{ failures}}{1{,}447{,}000\text{h}} \times 1{,}000 = < 0.003 \text{ failures per 1000 hours}$$

$$\text{MTBF} = \frac{1{,}447{,}000}{4} = 360{,}000 \text{ hours}$$

MTTR = 192 hours per failure

$$\text{Availability} = \frac{\text{MTBF}}{\text{MTBF} + \text{MTTR}} = 0.9994$$

Comments

The MTBF of the gears under consideration is 360,000 hours, i.e. one failure in 360,000 hours of total operation must be expected, or 56 out of 57 gears shall still be in operation after 6,340 hours of operation, one will not.

All four tooth fractures were fatigue failures of the same nature, all on the pinion. In each case, the fatigue crack originated close to the pitch circle on the loaded flank at one or two teeth, slightly to one side from the centre of the toothing. Exact geometrical measurements of the failed pinions and examinations of the steel revealed a metallurgical problem to have been responsible for all four failures. The heat treatment was changed to adapt to the high operating temperatures, which these gears are subjected to. Fortunately, this correction in heat treatment could be introduced in time to cover the bulk of these gears before they were built for these installations. It must be noted, that, when these gears were designed, such high pitch line velocities had never been attempted before for such installations.

No further problems have arisen since the completion of these remedial actions; i.e. since mid 1979 no unscheduled shut-downs were necessary due to the gears. Considering that the four tooth fractures occurred one to five years after start-up, they could be classed as running in failures, i.e. after the elimination of this one problem, reliability and availability of this group of gears has increased sharply.

MAAG gears in turbo compressor trains for off shore oil & gas production platforms

(Group 2)

A large number of MAAG turbo gears are installed offshore, where the demands on reliability are especially exacting. Platforms, with Maag lears installed on them, are scattered all over the world. Although the climate may differ widely among the different sites, other ambient and operating conditions of the gears on platforms are much alike.

Since 1971 MAAG has delivered 123 gears for this type of installation, of which 80 are now in operation, see table 4. Details of the failures that occured up to the present are listed in table 5.

$$\text{Failure rate} = \frac{11}{2{,}014{,}000} \times 1{,}000 = 0.0055 \text{ failures per } 1{,}000 \text{ hours}$$

$$\text{MTBF} = \frac{2{,}014{,}000}{11} = 183{,}090 \text{ hours}$$

$$\text{MTTR} = 91 \text{ hours per failure}$$

$$\text{Availability} = \frac{189{,}090}{183{,}090 + 91} = 0.9995$$

Comments

In at least six out of a total of eleven cases of failure, the gear suffered consequential damage, i.e. the defects originated clearly outside of the gear, as for example failures of the lube oil supply. This fact is not reflected in the above figures, but it points towards the importance of a careful and thorough system design, in close collaboration with the main machinery contractor, and the implementation of the resulting maintenance program as recommended by the gear manufacturer.

In three cases, the corrective measures were able to be undertaken during planned overhaul, i.e. they did not cause production losses.

MAAG gears for turbo compressor trains in gas liquification plants in Saudi Arabia

(Group 3)

In 1960 MAAG delivered the first turbo gears for compressors to Saudi Arabia. To date, 82 units with MAAG gears have been installed with a total power of close to one million kilowatts.

The boom time for new installations was 1977/78, when 45 large speed increasers were built with power between 11,765 kW and 23,162 kW, all being driven by synchronous electric motors.

Table 6 gives all pertinent data for these gears. As reliable information, pertaining to operating hours, is only partly available at this time, the year in which the gears were commissioned is given instead.

Table 7 provides a summary of the cases in which failures occured. This list may be incomplete, because the maintenance work is carried out by the customer, who is well equipped with spare parts. The inspection work is limited to checking the tooth contact annually.

As serious problems would certainly be reported to us, we assume that, to date, no further breakdowns of any kind have occurred. On the other hand, a reliability study, as carried out in the previous chapters is not possible at this time, but it would certainly show similar, or even more favorable figures than in groups 1 and 2.

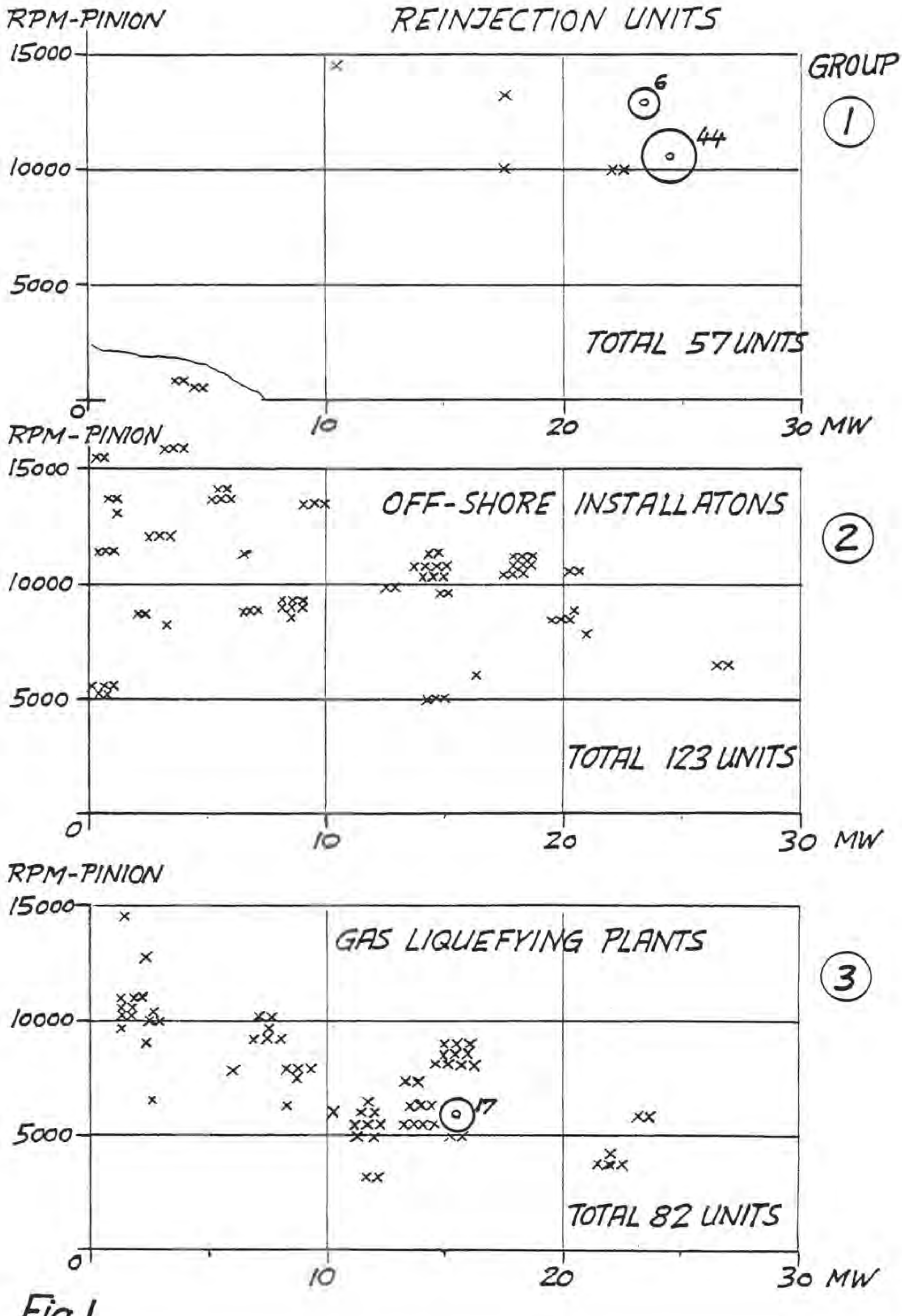
RPM-PINION
REINJECTION UNITS
15000
10000
5000
0
GROUP
①
6
44
TOTAL 57 UNITS
10
20
30 MW
RPM-PINION
15000
10000
5000
0
OFF-SHORE INSTALLATONS
②
TOTAL 123 UNITS
10
20
30 MW
RPM-PINION
15000
10000
5000
0
GAS LIQUEFYING PLANTS
③
17
TOTAL 82 UNITS
10
20
30 MW

Fig. 1

Fig.2

Table 1

Milestones in the Development of the Case-Carburized, Hardened and Ground Gears

1916	First gear tooth grinding machine constructed.
1919	**FIRST HARDENED and GROUND TURBO GEAR**
1932	First hardened and ground marine gear
1946	**TURBO GEAR with PITCH LINE VELOCITY 112 m/s**
1949	Construction of gear grinding machine for 3,600 mm diameter
1952	Largest gear measuring machine, 1000 mm diameter
1952	First locked train gears for ship propulsion, 27,500 HP
1956	**TURBO GEAR 26,838 kW; 2,988/1,000 rpm; 118 m/s pitch line velocity**
1956	First locked train gears for propulsion of tankers
1959	Largest gear grinding machine, 4,600 mm diamter
1960	Development and construction of automatic drip-feed carburization
1964	**TURBO GEAR 62,500 kw; 2,988/1,000 rpm; 137 m/s pitch line velocity**
1965	First automatic synchronzing clutch, 20 MW/3,000 rpm for power station peak power demand
1966	Epicyclic gear for cement mill, torque 3,000 kNm
1968	First COGOG installation, all gas turbine propulsion for naval crafts
1969	**TURBO GEAR 14,560 kW; 5,500/14,837 rpm; 151 m/s pitch line velocity**
1969	Hardened gears for largest steel mill in the world
1972	**TURBO GEAR 17,500 kW, 5,103/13,132 rpm; 173 m/s pitch line velocity**
1974	First CODOG installation, gas turbine/diesel propulsion for naval crafts
1975	Hardened high precision gear drives for the largest telescope in the southern hemisphere (ESO)
1980	Largest gear measuring machine; 2,000 mm diameter
1981	Largest epicyclic gear for cement mill, torque 5,683 kNm
1983	**TURBO GEAR 55,000 kW; 6,340/3,000 rpm; 153.5 m/s pitch line velocity**
1984	**TURBO GEAR (ALASKA) 34,579 kW; 4,670/10,720 rpm, 173 m/s**
1986	**TURBO GEAR 60,000 kW; 6,340/3,600 rpm; 173 m/s pitch line velocity**

Table 2. Reinjection units Algeria

Power kW	Revs. RPM	PLV m/s	Number of Units	Hours of operation by April 1986		Casenumber of Failure
				per Unit	Total	
23 934	4670/10 335	158	6	50 000	300 000	3
24 670	4670/10 335	158	5	30 000	150 000	
24 670	4670/10 335	158	20	25 000	500 000	
24 670	4670/10 335	158	11	20 000	220 000	
24 670	4670/10 335	158	2	1 000	2 000	
23 300	4670/12 924	169	6	5 000	30 000	
17 500	5103/13 132	173	1	65 000	65 000	1
17 500	5103/10 070	160	1	65 000	65 000	2
22 365	3600/10 067	153	1	50 000	50 000	
22 365	3600/10 067	153	1	50 000	50 000	4
10 570	6500/14 589	151	3	5 000	15 000	
1 332 300			57		1 447 000	Total

Table 3

Case-number of failure	Date of start up	Total hours of operation by April 86	Date of shut down Hours of operation up to failure	Reason for shut down	Duration of repair (days)	Spares Available yes/no	Remarks
1	Febr. 1973	65 000	Unscheduled shut down Nov. 1974 6 800	Tooth fracture	5	Yes	
2	Febr. 1973	65 000	Scheduled shut down Sept. 1978 27 800	Routine Inspection	5	Yes	Discovered tooth fracture. Spare gears installed.
3	Dec. 1976	50 000	Unscheduled shut down Jan. 1979 13 700	Automatic shut down because of vibration increase	10	Yes	Fracture of two teeth on pinion.
4	Jan. 1976	50 000	Unscheduled shut down June 1979 15 000	Increased vibration	12	Yes	Cause: Tooth fracture. Spare gears installed.

Table 4. Off-shore installations

Power kW	Rated Speed RPM	PLV m/s	Number of Units	Hours of operation by April 1986		Casenumber of Failure
				per Unit	Total	
16 300	6057/3 /Gener.	105	1	100 000	100 000	1
14 500	5000/10 377	141	3	46 000	138 000	
8 456	1792/ 8 819 E-Mot.	94	1	50 000	50 000	
6 985	1792/ 8 819	94	6	50 000	300 000	2, 3
19 853	3429/ 8 467	128	3	26 000	78 000	4
9 450	6540/13 578	143	3	40 000	120 000	
2 050	1787/ 8 744	56	2	30 000	60 000	
850	8744/13 711	101	2	30 000	60 000	
5 472	9536/13 650	147	5	40 000	200 000	5
3 603	7500/15 849 /21 538	131	3	36 000	108 000	6, 7
6 830	6190/ 8 863	136	3	35 000	105 000	
18 250	3600/10 895	142	3	20 000	60 000	
641	1788/11 372	40	3	20 000	60 000	
17 892	5250/10 619	147	3	20 000	60 000	8, 9
14 200	5000/10 300	127	2	7 000	14 000	
14 816	5200/ 9 609	127	2	28 000	56 000	
3 890	7950/18 972	147	2	10 000	20 000	
3 000	2975/12 092	80	3	10 000	20 000	
14 200	5000/10 521	128	2	15 000	30 000	
4 400	7950/18 754	146	2	14 000	28 000	
220	3580/15 410	49	2	15 000	30 000	
14 630	5004/ 1 800	97	3	14 000	42 000	
26 500	6490/ 3 000	122	2	13 000	26 000	
20 915	3600/ 7 870	122	1	20 000	20 000	
3 200	2970/ 8 188	82	1	12 000	12 000	
20 450	6190/ 8 826	152	1	10 000	10 000	
6 580	1485/11 296	96	1	10 000	10 000	
373	5200/ 1 803	27	5	15 000	75 000	
12 530	5081/ 9 781	126	2	7 000	14 000	
18 250	3600/10 895	142	3	6 000	18 000	
14 775	6178/11 350	151	2	18 000	36 000	
20 220	5200/ 9 672	153	2	18 000	36 000	
1 100	2966/15 708	63	1	18 000	18 000	

786 135			80		2 014 000	Total in Service
575 779			43		0	Total delivered but not yet in service
1 361 914			123	Total delivered		

Table 5

Case number of Failure	Date of start up	Total hours of operation by April 86	Date of shut down Hours of operation up to failure	Reason for shut down	Duration of repair (days)	Spares Available yes/no	Remarks
1	1972	100 000	Unscheduled shut down June 1976 30 000	Bearing failure	3	Yes	Water in lube oil. Toothing and Journals reground
2 2 units	1977	50 000	Unscheduled shut down May 1978 1 000	Increase of shaft vibration	3		Tooth couplings tight due to dirt.
3	1977	50 000	Unscheduled shut down June 1983 25 000	Damage to gear & bearings	5	Yes	Failure of lube system
4	1980	28 680	April 1986 28 680 Scheduled shut down	Slight increase of shaft vibration change of noise	2	No	Tooth fracture on pinion after refurbishing ready for stand-by
5	1980	40 000	Unscheduled shut down April 1984 25 000	Tooth fracture	4	Yes	Severe shaft misalignment
6 2 units	1980	36 000	Unscheduled shut down March 1981 6 300.	Failure of pump drive	3	Partly	
7	1980	36 000	Unscheduled shut down Nov. 1981 7 000	Bearing failure	3	Yes	Oil carbon deposit. Change to lower viscosity oil.
8	1982	16 000	1983 3 000 Scheduled shut down	Corrosion	10	No	Regrinding of gear rotors
9	1982	16 000	April 1984 6 586 Scheduled shut down	Increase of shaft vibration	1		Distorted gear box due to change of foundation. Realigned

Table 6. Liquification plant Saudi Arabia

Rated			Number of Units delivered	Year of Commissioning (approx.)	Total hours of operation	Casenumber of Failure
Power kW	Speed RPM	PLV m/s				
1 306	1730/10 107	56	4	1961		
2 550	4405/ 9 881	90	1	1961		
22 000	2990/ 3 600	107	3	1965	700 000	1, 2, 3
1 500	6440/14 446	103	1	1965		
2 600	6500/ 1 782	53	1	1965/67		
2 575	4440/ 9 952	80	2	1967		
8 750	5100/ 7 465	127	1	1969		
8 460	1800/ 7 686	92	3	1977		
2 310	1788/ 9 055	56	1	1976		
1 200	1785/ 9 789	51	1	1976		
1 200	1785/10 294	51	1	1976		
13 970	1800/ 6 146	102	3	1977		
13 970	1800/ 5 523	100	4	1976/77		
1 850	1792/10 999	58	1	1977		
8 240	1800/ 6 214	88	1	1977		
15 441	1800/ 8 652	116	6	1980/81	150 000	
15 441	1800/ 8 691	116	4			
15 441	1800/ 4 995	100	2			
15 441	1800/ 5 811	104	9	1980	225 000	5
15 441	1800/ 5 886	104	8	1981	152 000	
11 765	1800/ 5 312	99	6	1980		
11 765	1787/ 5 409	99	2	1980		
13 235	1786/ 7 348	105	2	1980		
5 966	1782/ 7 900	76	1	1982		
23 162	1200/ 5 833	102	2			
10 294	1787/ 6 026	104	1	1982		
11 765	1785/ 3 106	86	2	1982		
7 083	1785/10 133	95	2	1982		
1 850	1792/10 999	58	1	1982		
7 463	1800/ 9 218	95	4	1980		
2 238	3575/12 751	82	1	1982		
22 000	2990/ 3 600	107	1	1982		
954 343			82			Total

Table 7

Case-number of failure	Date of start up	Total hours of operation by April 86	Date of shut down Hours of operation up to shut down	Reason for shut down	Duration of repair (days)	Spares Available yes/no	Remarks
1	1965	140 000	Aug. 1966 7 000 Scheduled shut down	Routine Inspection	3		Inadequate tooth contact. Light scuffing - stoning & realigned on foundation
2	1965	140 000	Unscheduled shut down Dez. 1980 109 183	Faulty synchronization	75	No	Total overhaul at MAAG
3	1965	140 000	March 1982 120 000 Scheduled shut down	Routine Inspection	10		Axial bearing repaired Turning gear repair (damage due to misuse).
4	1976		April 1981 Scheduled shut down	Routine Inspection	8	No	Tooth contact 1/3 only. Light pitting on one side. Realigned on foundation.
5	1980	30 000 (one gear)	March 1982 10 000 Scheduled shut down	Routine Inspection	6	No	On one gear only: New keys at pinion coupling hub.