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ESTABLISHMENT OF PREVENTIVE MAINTENANCE SYSTEMS TO INCREASE PRODUCTIVITY OF PHILIPPINE INDUSTRIES

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PHILIPPINES

Technical Report: Tribology and Lubrication Engineering*

Prepared for the Government of the Philippines
by the United Nations Industrial Development Organization,
acting as executing agency for the United Nations Development Programme

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* This document has not been edited.

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INTRODUCTION

UNDP and UNIDO in co-operation with the government of the Philippines are supporting the development of a Preventive Maintenance Project at the National Engineering Centre which is at the University of the Philippines. The objective of the project is to achieve enhanced productivity and efficiency in Philippine industry by raising the standards of preventive maintenance to give increased efficiency and longer life to industrial machinery and equipment.

To support this project the UNDP are funding a number of visits of appropriate experts who can help to train the staff of the centre and can provide them with material for their future guidance in the form of manuals and lists of reference material.

The author of this report spent two weeks at the National Engineering Centre between September 17th and 29th 1990 as a visiting expert in Lubrication Engineering and Tribology. During this period five visits were made to industrial establishments and four lectures were given to the staff at the centre and two on a course for visiting engineers from industry. The remaining time was taken up in discussions with the engineers at the centre giving them assistance with the solution of the various industrial problems with which they were dealing.

This report describes the various technical projects which were worked on, makes recommendations about the operation of the centre and the training requirements of the staff. It also gives an outline of the manuals which were provided for the centre and lists useful publications which the staff should have available for use in carrying out their work.

SUMMARY OF THIS REPORT

1. Industry in the Philippines has a real need for assistance and advice on the improvement of its productivity and efficiency by better preventive maintenance. As a first stage industries require help with solving critical plant and machinery problems. As a second stage they need help with the introduction of improved maintenance philosophies and maintenance management techniques.

2. The UNIDO/Government of the Philippines Project for Preventive Maintenance at the National Engineering Centre, University of the Philippines has the potential for providing the required assistance and advice. It is currently running some useful courses for engineers and managers from industry. To be successful in providing direct help to Philippine industry, the Preventive Maintenance activity at NEC requires major change and review.

3. The Centre requires a new enthusiastic management for its preventive maintenance activities including a plan for developing, applying and marketing its services to industry. The plan needs to be prepared with the help of the staff at all levels who require motivation and a suitable level of financial reward to ensure that their abilities and experience are retained by the centre.

4. The practical experience of the staff needs to be enhanced by including more members with industrial problem solving experience. Further practical training in problem solving is required by all members of the organisation and they need access to more practical reference material to assist them in their work.

5. During the course of this visit three manuals of practical material were made available to the centre and a list of additional reference material required is included in the appendix to this report.

THE TECHNICAL PROJECTS

The Centre is operating a series of pilot projects with various industries to develop their abilities in improving maintenance practices. It is intended that these will provide examples for other companies of the kind of work that the Centre can do and thus increase the use of their services b, industry. The companies that were visited and the related problems which were worked on were a part of these pilot projects. Each company is dealt with in turn below:-

Resins Inc.

This company has plants making sulphuric acid and aluminium sulphate. The plants were of very old and crude design and in a very poor and corroded condition, with acid mist spraying into the atmosphere. The project team are trying to help them improve their maintenance but the plant is really in need of reconstruction and renewal.

However one of the most recurrent problems occurs on a centrifugal pump used to transfer the concentrated acid. This is driven from an electric motor via a vertical shaft about 3 metres long, which has a ball bearing at the top away from the acid and a plain bearing close to the pump and immersed in the acid. The lower bearing consists of a stainless steel shaft running in a nickel chrome alloy bush in a cast iron housing. This bearing wears out in about 1 month from replacement and causes severe vibration, and together with the shaft is a high cost item.

The problem arises because hard metals rubbing together is not a good material combination for use with a water based fluid. An alternative design was suggested based on marine sea water lubricated propeller shaft bearing technology and consisting of about 10 axially arranged rods of acid resistant rubber or plastic inserted in the bore of the housing and rubbing on a smooth non corrodable shaft surface of either plated metal or sprayed ceramic.

The lesson to be learned from this plant is that if NEC want to succeed with good demonstration projects they need to pick those which are likely to be effort effective in terms of the successful results obtained. This plant is not in this category and it is more likely that the plant management could gain by saying they had called in NEC when residential neighbours complain of acid pollution.

Metro Transit Inc.

This organisation runs the Manila Metro trains. They bought 64 new 2 car trains from CFM in Belgium in 1984 and have had continuous trouble with their driving gearboxes. The manufacturers have said that this is due to the use of a lubricating oil which is not quite to specification together with poor wheel maintenance.

The NEC have been working on this problem for about two years but were able to achieve success during the visit with some help on the identification of the problem from the visiting expert. All the failure records were analysed in detail and plotted as a failure rate against the kilometres run. This showed that 75% of the gearboxes had failed and these had a mean distance to failure of about 300,000 km corresponding to about 3 years in service. Also the flexible couplings connecting the gearboxes to the axle shafts were failing at a similar rate. This indicated that the whole bogie drive system had an inadequate capacity to carry the torques that were being applied.

Both gears and bearings were failing and specimens were brought back to the NEC for examination. The gears were measured and the data sent by telefax to the UK for an assessment of the gearbox torque capacity. This was necessary because no gear design data was available at NEC. This study indicated that the gearboxes had ample capacity to carry the motor drive torque. However the design layout used in which the two axles on each bogie were positively coupled together via the gearboxes and motor shaft could give a potential torque windup with practical wheel diameter variations. This windup torque could rise to a level corresponding to wheel slip and the resultant torque was twice the allowable value for the gearboxes.

The basic problem was therefore due to poor bogie drive layout design by the manufacturers. A possible solution was proposed involving driving the bogies on one axle only. Tests are now about to be conducted with this arrangement to check whether the gearboxes run more smoothly at a lower temperature. Manila Metro now have a report on the design analysis to enable them to negotiate from strength with the manufacturers and at the same time to raise the reliability of the Manila Metro service.

A copy of the report is included in the Appendices as an example of the kind of report on maintenance problems that is of assistance to industry.

The lesson to be learned from this is that assisting industry with equipment problems, requires a lot of practical insight together with an adequate usage of design analysis procedures. Engineers who are fully competent in engineering fundamentals need practical training in problem identification by working closely with experienced people. At least one fully experienced person needs to be in the team all the time.

A list of the design analysis procedures which the NEC should have available for reference is listed at the end of this report.

Solid Cement

Solid Cement manufacture cement and have two large rotary kilns together with ball mills to prepare the raw material and grind the cement into fine powder. The kilns are fired with pulverised coal ground up in orbiting roller mills and blown in by air blast.

The plant is basically in good condition and is about 15 years old. The main problems are in the drive gearboxes which have started to show pitting on their teeth. One raw mill gearbox has had its gears reversed to use the other side of the teeth, and the team with the expert confirmed that this was a satisfactory practice. Solid Cement asked for advice on whether it would be worth using a very expensive special lubricant which was stated to be effective in helping with the initial pitting of gears due to alignment errors. It was pointed out that the pitting being experienced was not of this type but was arising simply because the gear teeth had reached the end of the fatigue life of their surfaces, and therefore the use of a special oil would not help.

Advice was also requested on the best place to spray-lubricate gears and they were advised that the spray should be directed at the divergent side of the mesh where the teeth are hottest and the cooling by the oil most effective.

These are all important questions for the company but again the answer needs to be experience based rather than deriving from a fundamental approach, although a knowledge of the basic action of gear teeth and their lubrication is required.

Solid Cement also requested advice on how to monitor the condition of the gear teeth. Magnetic plugs, which can pick up surface fatigue pitting particles were recommended, together with debris collection troughs to enable a small number of magnetic plugs to be used and positioned conveniently for access and inspection.

Reynolds Aluminium

Reynolds roll aluminium sheet and sections and have a large rolling mill with two work rolls of small size supported by two larger backup rolls. The backup roll bearings are Morgoil plain bearings and are lubricated with a locally produced oil, Polybutene 700 selected because it does not stain the product.

The rolls are cooled with a thin paraffin like solvent which washes all over the bearing housings. They have a problem with the oil viscosity in the bearings which can drop from 600 cS to 64 cS in a month resulting in loss of oil pressure and the mill tripping out. The problem was identified as either due to dilution by the coolant or to the use of a lubricating oil made by adding non shear stable thickeners to a thin base oil. A series of simple tests were proposed to determine which of these causes was giving rise to the problem or whether it might be due to both of them.

Coolant splash guards and air purged bearing seals were suggested together with the alternative of accepting the situation, because the oil was cheap, and could always be used as boiler fuel after rejection from the mill.

Calaca Power Station

This is a coal fired power station with sea water cooling located on the coast at Balayan Bay to the south of Manila. The visit was to see whether NEC could help them with maintenance. The station was generally in good condition and two members of staff were currently drawing up a comprehensive computer aided maintenance system.

The main problem with the station was that an incorrect coal sample had been sent to the constructors when the station was ordered, and the actual local coal used causes boiler clogging which requires excessive use of soot blowing. This in turn tends to erode the boiler tubes resulting in leaks, and increased maintenance costs.

Good discussions were held with the station staff but it seems unlikely that they will feel the need to call in the NEC team to help them at this stage.

CONCLUSIONS FROM THE VISIT

It was clear from the visits to industrial sites and from discussions with the staff at the Preventive Maintenance Project that Philippine industries and utilities have a major need to increase the availability of their plant and equipment. The creation of a national centre with the necessary expertise in maintenance management and techniques, and the associated technical problem solving, should therefore make a major contribution to increasing industrial productivity and national prosperity.

The input of expertise from a national maintenance centre to industry tends to be at two levels. At the top management level there is a need to get across the importance of maintenance in order to conserve the assets of a company and keep them available for profitable production. This requires an understanding of the basic economics involved for the various kinds of industries, with examples of successful case studies. The various management methods by which good economical maintenance can be achieved then need to be explained and the company assisted in implementing them. However, this level of approval is only likely to be welcome and effective in companies that are operating reasonably well and wish to raise their standards to a higher and more efficient level. If however the situation is more one of crisis, with various critical problems occurring with the plant and equipment, the immediate need is for help in solving the problems. Assistance of this kind can develop good relations with the centre. Better maintenance philosophies can then be introduced to a receptive audience as a follow on activity.

In the industries in the Philippines the immediate need is for assistance with problem solving rather than for education in improved maintenance management techniques. The immediate urgency, therefore, is an improvement in the skills of the staff of the centre in the identification and solution of technical problems with plant and equipment.

The existing staff have the necessary academic qualifications, proving that they have the essential understanding of the fundamentals of engineering science. These fundamental principles can be readily applied to the solution of a specific problem once it has been identified. However the most difficult part of the work is the problem identification and this is usually confused by various pre-conceived ideas which will be held by the people in the industrial organisation. The skills in doing this problem identification arise from an understanding and feel for the mechanisms of operation of actual plant and equipment, and this is not a basically academic skill. It can be trained by experience and an engineer with good academic qualifications can generally learn these skills in a few years particularly by working with other experienced people. This is an advantage of the use of visiting experts from overseas, but it is vital that it is aiso supported by the full time appointment of industrially experienced engineers in the centre. Organisations outside the Philippines who have attempted to set up similar centres have found that one fully experienced engineer is usually required to work with a maximum of four who only have an academic training.

To help meet this need for practical advice two pre-prepared manuals were handed over to the centre staff to add to their general reference library and to help them is solving practical industrial problems in Lubrication Engineering and Tribology and in Condition Monitoring. These were entitled The Tribology Handbook and A Guide to the Condition Monitoring of Machinery.

Also the lectures given to the staff at the centre were supported by a loose leaf manual of additional data which included lectures on Techniques in Industrial Problem Solving with case studies, Failure Analysis of Plain Bearings, Rolling Bearings, Piston and Rings, and Gears, together with a lecture of Types of Wear and their identification with an additional lecture of Gear Design. There were also two lectures on the condition monitoring of machinery covering both the philosophy and techniques and also guidance on how to help an industrial company introduce these techniques. These are all specimen lectures from a comprehensive training course on solving practical tribological problems in industry which is available from the UK. This course of 64 lectures plus case studies, is of two periods of two weeks duration. It is recommended for the staff of the centre and selected participants from industry.

Another critically important aspect of Centres set up to provide advice and assistance to industry, is that their strength lies in the team of people involved, together with their skills and motivation. The skills can be developed by training, including working with other expert people, but the motivation requires positive leadership and good levels of pay. If these latter aspects are not attended to the staff are unlikely to be retained and for the reasons relating to adequate experience discussed above, their replacement by new inexperienced people will not be effective.

At the present time the Preventive Maintenance Project is organising some useful lecture programmes for industrial participants. This follows on relatively easily from academic lecturing skills, boosted by outside speakers. However the industrial consultancy advice work is not progressing well and needs urgent attention. In particular it needs new enthusiastic management with a full time fully involved manager who is attuned to the needs and timescales of industry, while respecting academic culture. The team needs to generate an exciting and effective plan for its future success with industry with each member of the team respected and integrated into the group and adequately financially rewarded to avoid the loss of rare qualified and experienced individuals.

APPENDICES

1. Manual No. 1. - contents list

2. Manual No. 2. - contents list

3. Manual No. 3 - contents list

4. List of practical reference material required for the solution of problems with plant and machinery and for its improved preventive maintenance.

5. Example of a practical report which can help industry with the solution of maintenance problems.

TRIBOLOGY HANDBOOK

CONTENTS

A. COMPONENT SELECTION, DESIGN AND PERFORMANCE

Wear-resistant components

A41 Wear-resistant parts, material selection	A42 Hard surface coatings, selection and application

Metal forming and cutting tools

A43 Sheet forming and forging tools	A44 Wiredrawing dies A45 Metal cutting tools

High friction components

A46 Selection of belt drives A47 Belt drives, design, materials, performance A48 Selection of friction clutches A49 Friction clutches, design and materials A50 Brakes: performance and selection	A51 Brakes: design data A52 Damping devices A53 Wheels, rails, tyres, performance and life A54 Capstans and drums performance and design A55 Selection of industrial flooring materials

B. LUBRICATION

Lubricants

B1 Selection of lubricant type B2 Mineral oils B3 Synthetic oils	B4 Greases B5 Solid lubricants and coatings B6 Other liquids

Lubrication of components

B7 Plain bearing lubrication B8 Rolling bearing lubrication B9 Gear and roller chain lubrication B10 Slide lubrication	B11 Coupling lubrication B12 Wire rope lubrication B13 Lubrication in metal-working and cutting

Lubrication systems

B14 Selection of lubrication systems B15 Total loss grease systems B16 Total loss oil systems B17 Dip, splash systems B18 Mist systems B19 Circulation systems B20 Design of storage tanks B21 Selection of pumps B22 Selection of filters and centrifuges	B23 Selection of warning and protection devices B24 Selection of heaters and coolers B25 A guide to piping design B26 Lubricant change periods and tests B27 Biological deterioration of lubricants B28 Lubricant hazards; fire, explosion and health B29 Commissioning lubrication systems B30 Running-in procedures

C. PROPERTIES OF MATERIALS FOR TRIBOLOGICAL COMPONENTS AND SURFACES

Materials

C1	Plain bearing materials	C4	Rolling bearing materials
C2	Bearing surface coatings and treatments	C5	Gear materials
C3	Wear-resistant materials and surfaces	C6	Flexure and knife edge materials
		C7	Friction materials
		C8	Frictional properties of materials

D. ENVIRONMENTAL FACTORS

Environmental data for design

D1	World ambient climatic data	D3	Human limits of noise and vibration
D2	Industrial plant environmental data		

Machine design data for particular environments

D4	High pressure and vacuum	D7	Chemical effects
D5	High and low temperatures	D8	Vibration and shock
D6	Dirt and dust	D9	Storage

E. FAILURES AND REPAIR

Failure of common components

E1	Failure patterns	E5	Failures of friction surfaces
E2	Plain bearing failures	E6	Seal failures
E3	Rolling bearing failures	E7	Fretting problems
E4	Gear failures		

Operating and failure limits of components and machines

E8	Failure detection methods	E10	Failure limits of operating temperatures
E9	Failure limits of noise and vibration	E11	Allowable wear limits

Repair and maintenance methods

E12	Repair of plain bearings	E14	Repair of friction surfaces
E13	Repair of worn surfaces	E15	Lubrication maintenance planning

F. BASIC INFORMATION

Basic tribology

General design information

A Guide to the Condition Monitoring of Machinery

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APPENDIX 3

GUIDANCE NOTES ON FAILURE INVESTIGATION AND PREVENTIVE MAINTENANCE

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APPENDIX 4.

LIST OF USEFUL REFERENCE MATERIAL WHICH THE PREVENTIVE MAINTENANCE PROJECT SHOULD HAVE AVAILABLE FOR CONTINUOUS REFERENCE TO ASSIST IN SOLVING INDUSTRIAL PROBLEMS WITH PLANT AND MACHINERY

A. Tribology of Machine Components

1. The Tribology Handbook. M J Neale. Newnes Butterworth.

2. The Tribology Series of Data Items, listed below,
from Engineering Sciences Data Unit
ESDU International plc
27 Corsham Street
London N1 6UA

• 65007	General Guide to the choice of journal bearing type.		
67033	General Guide to the choice of thrust bearing type.		
• 89044	Friction in bearings.		
• 76029	A guide to the selection and design of dry rubbing bearings.		
• 81005	Designing with roller bearings.	Pt. I	Ball and Cylindrical roller bearings.
• 81037		Pt. II	Angular Contact Taper Roller Spherial Roller Bearings.
• 82014		Pt. III	Special types of Bearings.
• 84031	Calculation methods for steadily loaded axial groove hydrodynamic journal bearings.		
• 85028	As 84031 but for super laminar operation.		
• 86008	As 84031 but for process fluid lubrication		
82029	Calculation methods for steadily loaded fixed inclined pad thrust bearings.		

83004	Calculation methods for steadily loaded tilting pad thrust bearings.
67021	The Design of crossed flexure pivot
78026) 78027) 78028) 78029) 79002)	Equilibrium temperatures in self contained bearing assemblies. Methods of calculation.
* 78035) 84017) 85007)	Calculation of Contact stresses and Deflections in non conformal contacts.
68039	Design of tanks for oil circulation systems.
* 78032	Grease life estimation in rolling bearings.
* 83030	Selection of filter rating for lubrication systems.
* 85027) * 89045)	Calculation of film thickness in lubricated non conformal contacts (gears and rolling bearings).
* 80012	Selection of rotary seals.
* 83031	Selection of reciprocating seals.
* 84041	Properties of common engineering materials.
* 86040	Selection of surface treatments and coatings for combating wear of load bearing surfaces.

NOTE: This complete series of practical calculation methods is normally available on lease for a continually updated set of data.

Universities and similar establishments can purchase non updated copies of individual items. The items particularly recommended, which could be obtained in this way are marked *.

3. The American Gear Manufactures Association (AGMA) Standards for Design + Calculation.

Surface Durability (Pitting).

210	Spur Gears
211	Helical Gears
212	Straight Bevel Gears
216	Spiral Bevel Gears

Tooth Bending Strength.

220	Spur
221	Helical Gears
222	Straight Bevel Gears
223	Spiral Bevel Gears

B. Condition Based Preventive Maintenance

A Guide to the Condition Monitoring of Machinery
Michael Neale and Associates. Published in UK by HMSO.

C. General Calculation and Stress Analysis

Formulas for Stress and Strain.
Roark and Young - McGraw Hill.

Stress Concentration Factors.
Peterson - John Wiley

D. Commercial Data

Catalogues from all Rolling Bearing Manufacturers giving bearing dimensions and load capacities.

Data from all Oil Companies listing their lubricants with application and viscosity data.

REPORT

A Study of Gearbox Unreliability Problems on the Metro Transit Vehicles

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September 1990

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ANALYSIS OF GEARBOX FAILURES OF LIGHT RAIL VEHICLES

INTRODUCTION

The Metro Rail Transit Organization operates 64 two car trains, supplied by Constructions Ferroviaires et Metalliques of Belgium. On each train there are 4 bogies consisting of a motor bogie at each end and trailer bogies in the center. The motor bogies have a single 218 KW DC motor mounted longitudinally in the bogies and each end of the motor shaft drives a gearbox manufactured by Thyssen, consisting of a pinion engaging with a crown wheel to provide a 90° reduction drive to each axle with a ratio of 6.125:1. The crown wheels drive the axles via flexible couplings made by Brown Boveri and consisting of rubber bushed tangential links.

The railway started operating at the end of 1984 and by 1986 problems started to occur with the gearboxes and flexible couplings. By August 1990 75% of the gearboxes had failed and a large number of the flexible couplings had failed rubber bushes together with failure of the bush mounting pins.

A failure rate at this level on railway equipment after only about 5 years in service is unacceptable, and the fact that high failure rates are occurring on two associated components made by separate manufacturers suggests that the operating loads in the transmission system have been underestimated by the designers of the system.

This report reviews the failure rates and the system design to detemine the cause of the problem and make appropriate recommendations.

THE FAILURE HISTORY

Accurate records have been kept of all the gearbox failures, and of the 256 gearboxes in service 193 (75%) have failed in the first 5 years. The failure modes comprising this 75% are:

Pinion shaft bearings, pitting and cage failures	34%
Damaged bearings together with broken or pitted gear teeth	19%
Broken teeth on crown gear and associated pinion damage	14%

Pitted teeth on the pinion 8%

Other assorted failures 2%

The incidence of the 193 gearbox failures in terms of the number of kilometers for which they had operated is shown in Figure 1 and this shows a mean life of only about 300,000 kms.

A more detailed Weibull analysis of the failure data in Figure 2 shows a a index of 0.7 for the early failures and 1.5 for the later failures. The indications from this are that all the failures are associated with random overloading, which would correspond to an index of 1. The few early failures appear to have some association with faulty assembly or components, which would be the sole cause if the index were 0.5. The later failures, which are the majority, relate partially to fatigue/wear which would be the sole cause if the index was greater than 3.

The Weibull analysis also suggests that when the remaining 25% of the gearboxes have failed the mean life to failure of the complete set of 256 gearboxes will be of the order ot 450,000 km. This figure can be used as an indicator for the calculation of the future continuing maintenance cost of the gearboxes if they continue to be operated without modification.

EXAMINATION OF FAILED COMPONENTS

A large number of samples of failed gears and bearings were examined at the maintenance workshops of the Metro Transit Organization and samples were collected for more detailed study.

From these investigations it is clear that the double row ball bearing on the pinion shaft is failing due to operation with excessive angular misalignment. This can be deduced from the ball track markings on the outer race together will the positions on these races of the fatigued areas. In addition there is wear in the ball pockets of the cages which is a further indication of angular misalignment. Since the bearings are all fitted together into one sub housing which can be accurately machined, it is very unlikely that the misalignment arises from any assembly error. It is therefore virtually certain that it arises from deflection of the pinion shaft under the load on the pinion from the crown wheel. This misalignment is showing to the greatest extent on the double row ball bearing because from the nature of its design it is more rigid when subject to angular misalignments than its adjacent cylindrical roller bearings. This damage is occuring in spite of the fact that it has a large cylindrical roller bearing between itself and the pinion. The high shaft deflections, which are occuring, do therefore indicate that substantial loads are occuring on the pinion.

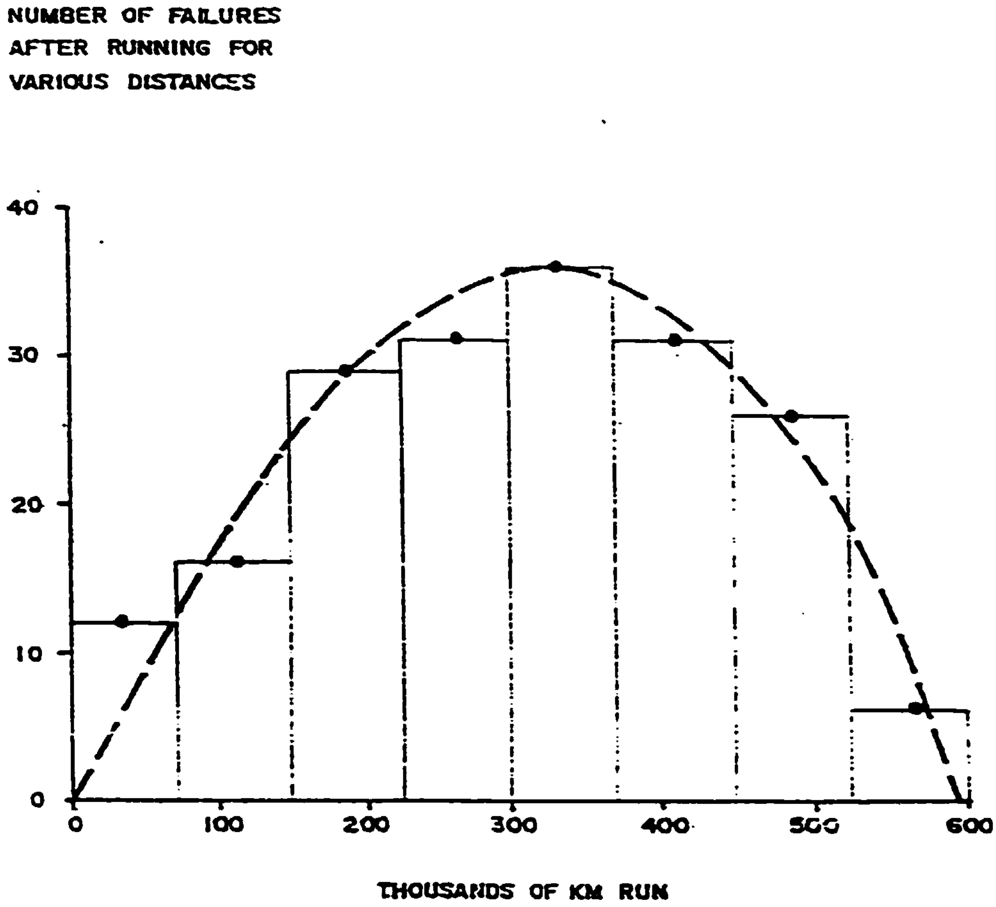
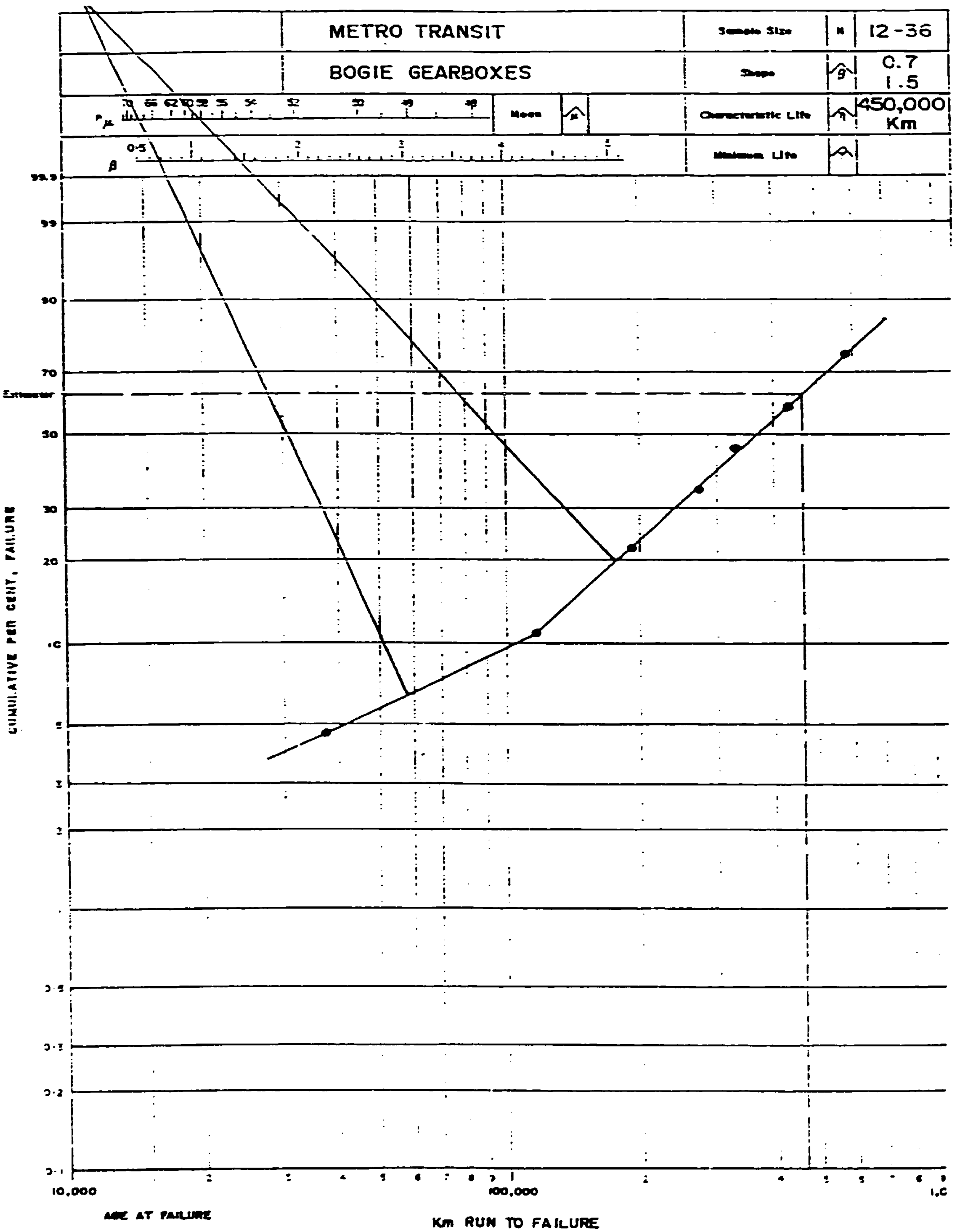


FIGURE 1 - DISTRIBUTION OF GEARBOX FAILURES SHOWING THE FAILURE INCIDENCE AFTER VARIOUS DISTANCES



Km RUN TO FAILURE

FIGURE 2

The gears which were examined showed fracture of the teeth of the crown wheel together, in many cases with pitting on the teeth of the pinion. For gear failures of this kind to occur after a few hundred thousand km indicates that very high torques are being transmitted through these gears. It is important to note that failures of this kind, and particularly the breakage of the crown wheel teeth, cannot be related to lubricant viscosity, so any variations in lubricant viscosity grade or additive content will not have had any effect on the incidence of these failures.

The flexible couplings were also examined and it was observed that some of the failures arose from the rubber bushes and some from fracture of the pins. The pin failures were due in every case to fatigue in bending. The bending moment on these pins is related to the transmitted torque with some additional loads from axle displacements relative to the gearbox. The bending moments on the pins and the associated risk of failures can be readily calculated at the design stage of the couplings and the fact that this failure is occuring in service after a few hundred thousand kilometers again indicates that there are very high applied torque loadings compared with the design load.

ANALYSIS OF THE OPERATING CONDITIONS

Because of the high incidence of gearbox failures it was considered desirable to check the design of the gearbox in order to assess its allowable torque compacity. The detailed dimensions of the gears were therefore recorded together with the measured hardness of the teeth of the gears and pinions. This was used to calculate the allowable torque capacity of the gearbox using AGMA 223.01 for spiral bevel gears. This is a well established design and performance assessment standard for spiral bevel gears and it is interesting to note that for pinions of the size in use in this gearbox its recommends a minimum of 12 teeth while the pinions in fact have 8 teeth.

This analysis shows that the maximum allowable torque on the pinion is 1200 Nm for a life of 10^9 cycles or 333,000 km. This distance corresponds to the typical average failure distance shown in Figure 1 and indicates that if these failures are occurring then the torque applied to the gearbox for a substantial period of its continuous operation must be greater than 1200 Nm.

Moreover, the maximum output torque of the motor at its full rated power is 640 Nm and nominally this is transmitted through two gearboxes in parallel, suggesting an average operating torque per gearbox of 320 Nm under ideal conditions. The load sharing will not always be ideal but the continuous loading on any gearbox would be unlikely to exceed the full motor torque of 640 Nm. Since each gearbox has a design capacity of 1200 Nm no failures would be expected and the gearboxes appear to have an adequate safety factor.

This however assumes that the maximum torque transmitted by the gearboxes arises solely from the motor drive; with the design layout used, this is not the case. In fact greater torque will arise due to relative wind up of the two axles due to differences in their wheel diameters. If the average wheel diameters on the two axles are different the axles will have to rotate by different amounts as the bogie travels down the tracks. This will induce wind up torques in the axles and their driving gearboxes which are only limited by the slip torque of the wheels.

The empty weight of one LRV is 41,000 kg and this can carry 374 passengers who could be assumed to weigh 60 kg each. This corresponds to a total load of 63,440 kg which is carried on 8 axles, so the load per axle is about 8000 kg. The wheel diameter is 660 mm and typical coefficients of friction between rail wheels and rails is in the range 0.3 to 0.5. On the Metro Transit Line values of up to 0.47 have been measured. With this coefficient of friction the slip torque on each axle when carrying 8000 kg is about 12000 Nm which corresponds to a torque at the pinion shaft of about 2000 Nm. This figure exceeds the maximum allowable torque on the gearboxes of 1200 Nm by a substantial margin and the high failure rates which are occurring are therefore to be expected.

DISCUSSION

The preceeding examinations and analysis of the driving gearboxes indicate that the high failure rates are occurring because the overall design layout (in which the two axles of each driving bogie are positively coupled together with the motor shaft) can give rise to high wind up torques which exceed the torque capacity of the gearboxes. These wind up torques also appear to be exceeding the torque capacity of the Brown Boveri flexible couplings.

In theory the wind up torques could be reduced by the precise control of wheel diameters, but it must be remembered that even with very small errors, to the limits of machining accuracy, the torque will still appear provided the bogies continue in a straight path down the track. The design must therefore allow for the possible maximum torque build up even if it does not occur at every position in the track. In practice the torque build up will tend to be reduced by curves which are too tight to be accomodated by the action of the wheel conicity, so that some slip has to occur. During these periods with only one wheel slipping the wind up torque might be reduced to about half the maximum value.

Torque measurements have been made on motor bogies on the Metro Transit line in 1988 which indicate that the maximum pinion torque was related to the differences in wheel diameter according to the following table:

Wheel diameter difference mm	Maximum pinion shaft torque build up. Nm
0	900
1	1800
2	1800
4	2200

This shows that it is not difficult to build up torques which exceed the allowable torque capacity of the gearboxes of 1200 Nm. The test also showed that this torque capacity is exceeded for a substantial continuous period of operating time if the differences in wheel diameter exceed 2 mm.

While new and reconditioned wheels could be installed within this standard of accuracy, bends in the track which are sharp enough to give some relative lateral wheel slip and thus bring the build up torque below the level of 2000 Nm, are also bends which will cause wheel wear and thus give rise to increased errors. It seems clear therefore that the current design layout of the motor bogies is not satisfactory and will inevitably give rise to low reliability and high maintenance, as has already occured in practice.

It is perhaps significant that while solidly coupled paired drive axles have been used successfully on urban tramway systems, all full size railways use individually driven axles, which avoid the wind up problem. It should also be noted that wind up torque is proportional to both wheel load and wheel diameter. This means that although acceptable torques may arise in urban tramways with smaller wheels and lighter loads, there is a severe risk of problems arising when the same system is uprated in wheel size and load to that approaching full size railway practice, as appears to be the case with the current design of Metro Rail vehicles.

At this stage where the fleet of vehicles has already been delivered and is in service the opportunities for modification of the design are limited. Ideally the gearboxes should be uprated to allow them to carry the maximum wind up torque of 2000 Nm, but it is likely to be difficult to achieve this within the existing casings.

An alternative possibility is to modify the system so that the drive in future is only taken on one axle. The torque capacity of the single gearbox would then be 1200 Nm as now, to carry a maximum continuous motor torque of 640 Nm which it should be capable of doing. This arrangement could be achieved by removing the internally splined coupling sleeve which couples the motor to the pinion shaft on one axle of each driving bogie. The drive components of the resulting non driving axle would then effectively constitute a set of "on board spares".

The opinion of Thyssen and of Construction Ferroviaries et Metallique on this proposal should be invited and if they do not consider the gearbox torque capacity to be adequate they should be encouraged to uprate them at their own expense to a sufficient capacity to meet the duty.

A further requirement will be to ensure that adequate adhesion is available with only one driving axle per bogie. The proposal also requires more careful study to ensure that it is compatible will braking and train control requirements, but if these are satisfied at least one train could be modified for adhesion and durability tests.

CONCLUSIONS

1. **The low reliability of the gearboxes and flexible couplings on the driving bogies of Metro Rail vehicles arises because the design allows the build up of wind up torques between the driving axles which exceed the torque capacity of the existing gearboxes and couplings.**

2. **The torque capacity of the gearboxes for an adequate life is 1200 Nm pinion shaft torque while wind up torques may reach 2000 Nm at the pinion shafts.**

3. The failures which have occurred are not related to the oil viscosity grade or additive package that has been used, and are mainly related to the design layout which has been chosen by the vehicle manufacturers.

4. Some alleviation of the problem may be obtained by precise control of wheel diameters on newly overhauled bogies. However with wear in service it is possible that greater wheel diameter variations will occur and this procedure cannot be relied upon to solve the problem.

5. It is possible that the most effective solution may be to modify the bogie drive so that the drive is on one axle only. The manufacturers need to be invited to comment on the potential reliability and general success of this arrangement and to cover the costs or any additional modifications that they may consider necessary.

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