International Journal of Current Engineering and Technology
E-ISSN 2277 – 4106, P-ISSN 2347 – 5161
Available at http://inpressco.com/category/ijcet

Research Article

Methodology to Analyse Power Losses in Off-Highway Power Train Aggregates for Two Different Lubricants

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Received 14 May 2020, Accepted 02 July 2020, Available online 03 July 2020, **Vol.10, No.4 (July/Aug 2020)**

Abstract

Powertrain aggregates used in mining equipment are complex, and it comprises of primary aggregates like an engine, powershift transmission, differential and final drive, which in-turn includes many tribological systems including gears, bearings, and shafts. Evaluating the effect of different lubricants on preliminary design phase is a crucial challenge, especially identifying various power losses such as gear meshing, oil churnings and the bearings losses in several machine elements on single go is a complex one. To identify combined power losses in gear and bearings, an analytical model or analysing individual component and summing up the effect as a complete system loss can cater acceptable result, but in case of accuracy, it significantly lags. The experimental setup, which incorporates the real-time equipment environmental factor takes ample time and cost. In this paper, detailed study and analysis have been carried out to identify power losses and thermal rating factor for gears and bearing on one go for different lubricants (i.e. SAE30 & Tailor-made BEML C6002-44) using a gear train analysis tool called KISSsoft/KISSsys. The result exhibits a significant reduction in power losses & contact temperature for C6002-44. The comparative results illustrate that it is an effective method, and it can be used in a preliminary stage of a planetary transmission design to identify the gear train power losses in a shorter duration. This methodology can also be employed to determine the effect of tailor-made new lubricants.

Keywords: *Gearbox power losses, Thermal Rating, Tailor-made lubricant, KISSsoft, BEML C6002-44.*

1. Introduction

Sustainability has become a driving force in the industry; augmentation of Transmission performance and durability is a vital challenge. Saving energy and resources as well as improving the performance of the transmission becomes central environmental matters. By reducing friction and providing wear protection, which extends machine runtimes and thereby protects raw materials (Franco Concli, *et al*, 2017). So, designers should be careful about selecting lubricant in the beginning phase of design which is efficient and also environment friendly.

The total transmission power losses are the addition of load-dependant and load-independent losses. To determine Load-independent losses, few equations and test methods are available (Martin Andersson *et al,* 2017), Conventional equation method can provide acceptable results. Still, they are not suitable for accurate prediction for industrial design because of various application factors which need to be considered for accurate results, and experimental methods need test facility which is a timing consuming process when it is done during the beginning phase of design.

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DOI: https://doi.org/10.14741/ijcet/v.10.4.2

In an in-depth exploration of the efficiency calculations for gearboxes, the calculations clearly defined for thermal load carrying capacity, which includes churning, meshing losses and heat dissipation in the standards such as ISO 14179. However, there are many works done on past and many programs available in the market to identify the power losses in gears (T. H. Chong, *et al,* 2002). but the efficiency calculations for the many other machine elements such as gears, bearings, seals in the multi-stage planetary gearbox for off-highway equipment with tailor-made lubricants is the new topic. No such standards are established yet. The power losses can be approximated only using field data mapping and experimental data mapped from test rigs. These stipulations lead to a quite big challenge for the power train designers to identify power losses in multi-stage gearboxes for tailor-made lubricants. Therefore, we used commercially available gear train software called KISSsoft which has an in build template named as KISSsys to automate the efficiency calculation and thermal factor of a whole gearbox which includes gears, shafts, bearings, seal and other machine elements.

This template contains two modules; The calculations of the power losses and the calculations of heat dissipation. The above two modules are calculations by referring the standards such as ISO, AGMA, DIN and the research works from the academy & the industry.

Apart from these standards, KISSsys accounts for contact analysis and elastic deformation which plays a significant role in the validation of gear pairs for tailor-made lubricants and brings detailed results including Coefficient of static & dynamic friction and power losses graphs can be extracted from the KISSsys in few clicks.

In this paper, the design methodology carried out using KISSsys simulation is to identify the effect of two different lubricants on off-highway planetary gear train performance and has been validated based on real-time equipment field test data. The results are in very well in accordance with the field data. Further, the results indicate that tailor-made lubricant C6002-44 is superior to commercially available SAE30.

1.1. Power losses in the gearbox.

The thermal rating factor of the gearbox can be defined in two sections, such as power losses and heat dissipation of various mechanical elements. The power loss and heat dissipation can be further divided into load-dependent and load-independent losses, which are usually present when a planetary gearbox unit is operating. Power loss can also be subdivided into machine elements losses, such as gears, bearings and seals losses. Meshing and churning losses are taken into consideration for gears, whereas sliding, rolling, seal and drag friction are taken into consideration for bearings and seal friction losses (Klaus Michaelis, *et al*, 2011). Power loss sources in a gear train associate to various gear parameters such as teeth profile, specific sliding, and lubricant properties. However, the viscosity is the prime element in improving gear train efficiency and performance. Researches show that the use of a lubricant with a suitable viscosity could save up to 20% of power losses (S. Abusaad, *et al*, 2011). Fig.1 and Fig.1.1 show the Transmission Power losses P_T and its contributions:

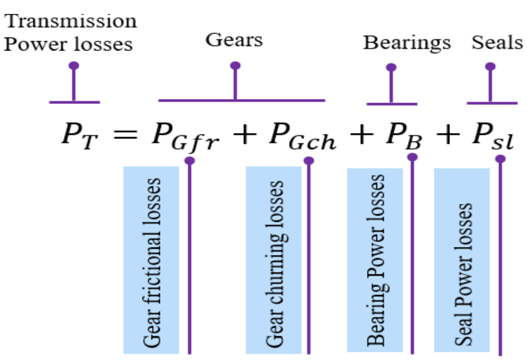

Fig.1 Transmission Power losses and its contributions

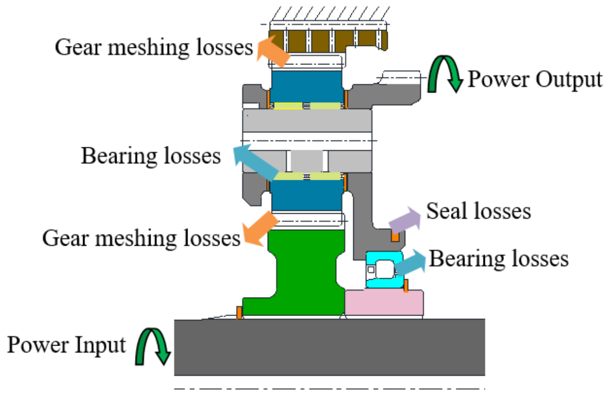

Fig.1.1 Illustration of practical machine element losses

The frictional gear losses are load-dependent and also related to gears geometry, number of teeth in gear and pinion (Z_1, Z_2 respectively) and friction coefficient (μ_m), The frictional gear losses P_{Gfr} can be estimated as follows:

$$P_{Gfr} = \Pi\left(\frac{1}{z_1}+\frac{1}{z_2}\right)\left(1-\left(\frac{g_f+g_a}{p_b}\right)+\left(\frac{g_f}{p_b}\right)^2+\left(\frac{g_a}{p_b}\right)^2\right)P_{in}\mu_m \quad (1)$$

It illustrates that the average friction coefficient has a vital impact on P_{Gfr}. According to studies, the friction coefficient can be calculated from the following equation:

$$\mu_m = 0.048\left(\frac{F_{bt}/b}{v.\rho_c}\right)^{0.2}\eta_{oil}{}^{-0.05}R_a{}^{0.25} - X_L \quad (2)$$

The equation above shows that μ_m is inversely proportional to the lubricant viscosity η_{oil} and velocity v. On the other hand, the churning loss P_{Gch} in gear are load-independent losses; and mainly depend on the oil velocity, geometry of the rotating parts immersed in the lubricating oil and oil density ρ and viscosity η_{oil}, which can be estimated from below equation.

$$P_{Gch} = \frac{\Pi}{30}.n.\left[\frac{1}{2}.\rho\left(\frac{\Pi.n}{30}\right)^2 A_i \left(\frac{d}{2}\right)^3\right]\left[\left(\frac{2.h}{d}\right)^{0.45}\left(\frac{\eta_{oil}}{d}\right)^{0.1}F_R{}^{-0.6}Re^{-0.21}\right] \quad (3)$$

Similarly, the bearing and seal losses can be determined by several equations.

2.Methodology

2.1 Application

A Multi-Stage Planetary gear train (Gearbox) used in Dozer application is taken for the analysing power losses for two different lubricants. Fig.2 shows the schematic power flow of Dozer.

The power generated by engine has its torsional vibration dampened by the damper, and then passes through a universal joint, and is transmitted to transmission through torque converter in accordance with the change in the load. Then power is transmitted to track chain through bevel gear, Steering clutch and Final drive.

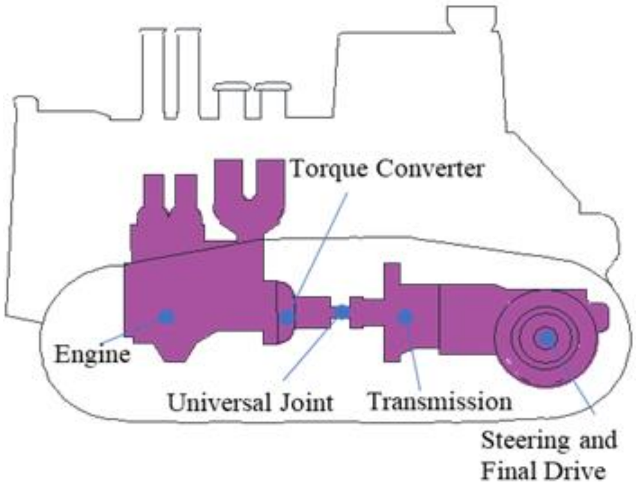

Fig.2 Power train layout

2.2 Design Considerations

The gearbox adopted is a 3 forward and 3 reverse gear speed transmission which consists of the planetary gear mechanisms and the disc clutches. Out of the four sets of planetary gear mechanisms and disc clutches, two clutches are fixed hydraulically to select one direction rotation and at one speed. For the present study One high speed forward(F3) and reverse(R3) gears are taken to identify power losses and thermal rating factor for gears and bearing on one go for different lubricants (i.e. SAE30 & Tailor-made BEML C6002-44). Fig. 3 shows Power flow of F3(Green line) and R3(Redline) of Multi-Stage Dozer Gearbox layout.

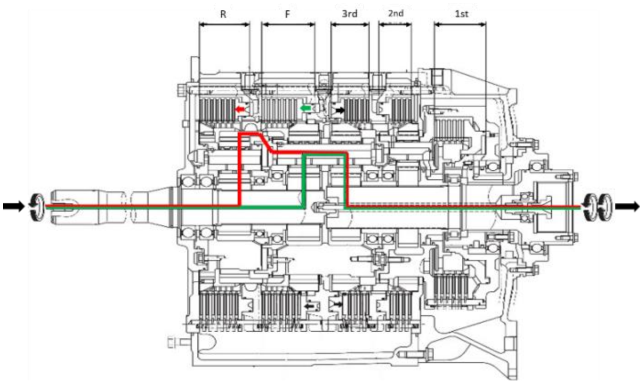

Fig.3 Transmission and Power flow of F3 & R3 gear

Table 1 Input, Output and fixed members of F3 gear

Member	Forward	*3rd*
Sun gear	Input Member	Output member
Carrier	Output member	Input member
Ring gear	Fixed Member	Fixed member

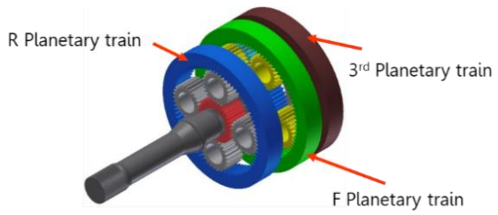

Fig.4 3D schematic of F3 & R3 Gear train

Table 2 Input, Output and fixed members of R3 gear

Member	*Reverse*	*3rd*
Sun gear	Input Member	Output member
Carrier	Fixed Member	Input member
Ring gear	Output member	Fixed member

Table-1 and Table-2 show the input, output and locking member of F3 and R3 planetary set.

Table-3 shows the list of Design inputs considered for analysing power losses in F3 and R3 Gears with two SAE30 and C6002-44 lubricants.

Table 3 Design inputs

Gear Geometry and Rating		
Gear type	Spur Gear type	
No of planets	4	
Normal Module (m_n)	4	
Pressure angle (α_n)	20°	
Input Torque (T_1)	282.9 Kg-m	
Input Speed (n_1)	1881rpm	
F3 Gear Ratio	1.000	
R3 Gear Ratio	0.781	
Gear strength calculation method	ISO6336:2006 (YF Method C)	
Lubrication and Lubricant Data		
Type of Lubricant	SAE30	C6002-44
Lubricant Viscosity ν_{40}	100 mm²/s	110 mm²/s
Lubricant Viscosity ν_{100}	11.1 mm²/s	12.5 mm²/s
Lubricant factor (ZL)	0.966	0.989
Lubrication type	Oil Injection Lubrication	
Lubricant Flow (Q)	160 lpm	
Oil Jet Velocity (Vs)	3m/s	

2.3 Kinematics and Process flow chart

Fig.5 is KISSsys kinematics and simulation carried out for Dozer transmission along with all machine element for two different gear combinations F3 and R3. Using these kinematics, Forward Gear engaged by disengaging Reverse Gear and Vice versa

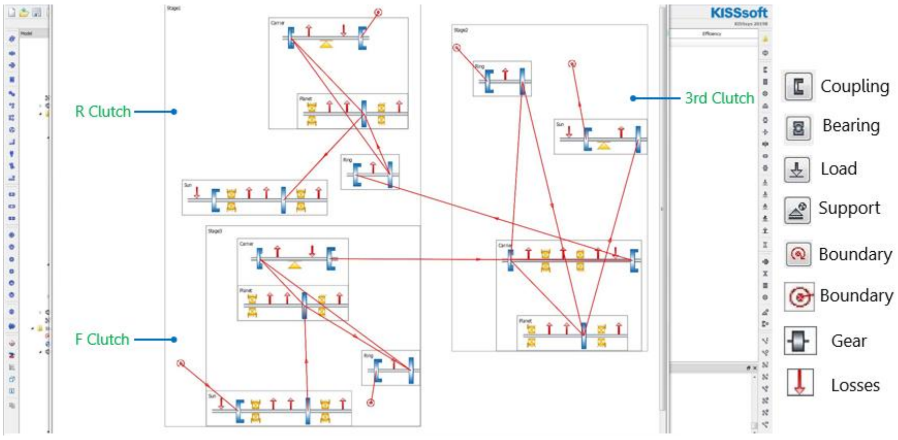

Fig.5 Representation of kinematics on the gear train and power flow (schematic) in KISSsys

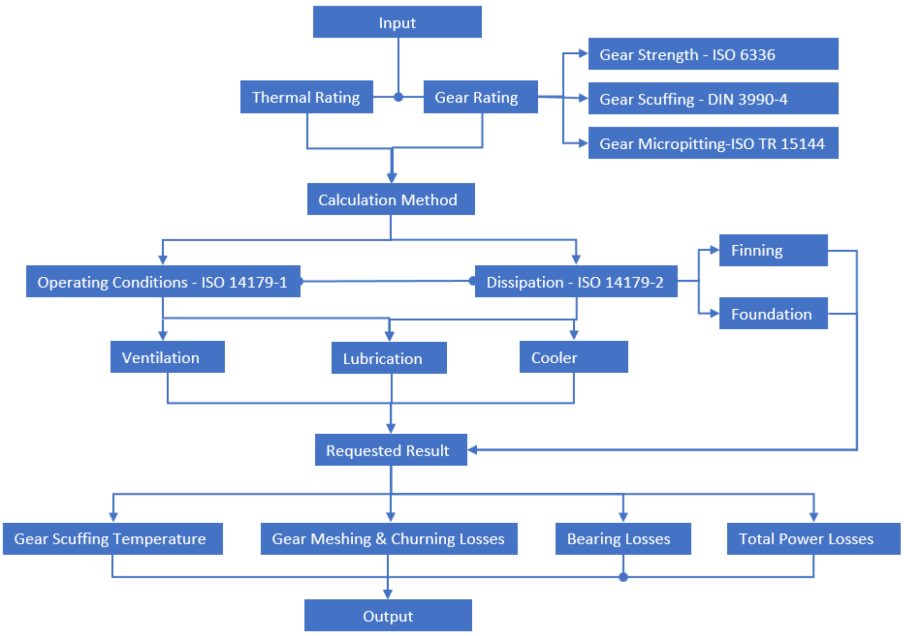

Fig.6 Representation of simulation process flow in KISSsoft/KISSsys

3. Results and Discussion

KISSsys simulation was performed on the gearbox to analyse the effect of two different lubricant performances for identifying gearbox losses and thermal rating.

Table 4 shows the power losses and thermal rating values in two different modes F3 & R3 gear, for SAE30 & C6002-44.

Table 4 Power Losses and Thermal rating of SAE30 & C6002-44

Thermal Rating	**SAE30**	**C6002-44**	**SAE30**	**C6002-44**
	F3		R3	
Power Input (W)	546662.6			
Power Output (W)	536302.5	536874.6	530669.4	531308.3
Gear Churning Losses (W)	1315.1	1229.8	4459.4	4444
Gear Frictional losses (W)	8160.4	7673.2	10456.7	9832.6
Other Losses (W)	884.6	885	1077.1	1077.7
Total Power losses (W)	10360.1	9788	15993.2	15354.3
Thermal effects				
Highest Contact temp (ºC)	168.53	165.41	220.13	214.85
Safety factor for scuffing (Sun & Planet)	2.88	2.90	2.37	2.39
Safety factor for scuffing (Planet & Ring)	4.51	4.50	4.41	4.40

The evaluated result shows the superiority of C6002-44 in terms of gear Churning losses, Gear Frictional losses, machine element losses and improved thermal rating in Planetary Gear train in both Gear combination F3 & R3. Further, the highest gear contact temperature reduced, and lubricant film thickness significantly improved.

Reduction in heat generated per mm during gear meshing along the face width from the start of active profile to end of active profile between planetary members using C6002-44 over SAE30 are represented in Fig.7 & Fig.8.

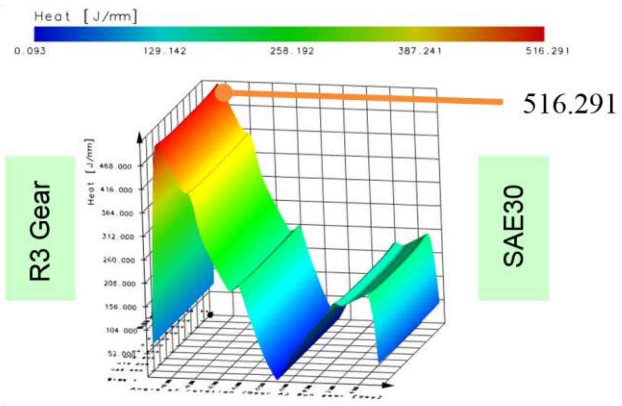

Fig.7 Heat generated per mm in Sun and Planet gear for SAE30 Lubricant in R3 Gear

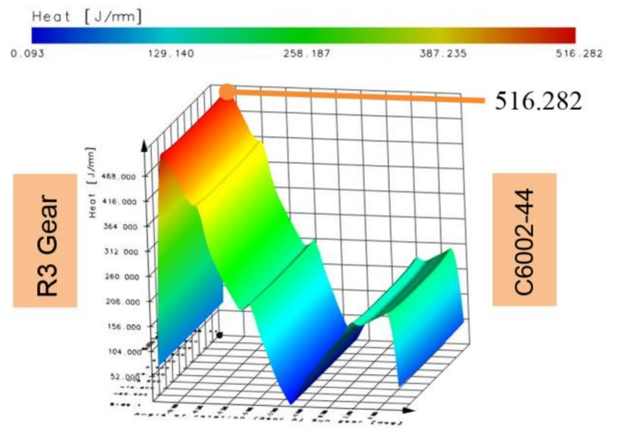

Fig.8 Heat generated per mm in Sun and Planet gear for C6002-44 Lubricant in R3 Gear

Fig.9 shows that the lubricant film thickness range maintained in the range of 0.338~0.744mm during gear meshing along the face width from the start of active profile to end of active profile between planetary members while using SAE30 grade oil.

Fig.10 shows that the lubricant film thickness range maintained in the range of 0.371~0.816 during gear meshing along the face width from the start of active profile to end of active profile between planetary members using BEML tailor-made C6002-44.

The minimum and maximum film thickness for the tailor-made oils show significant improvements.

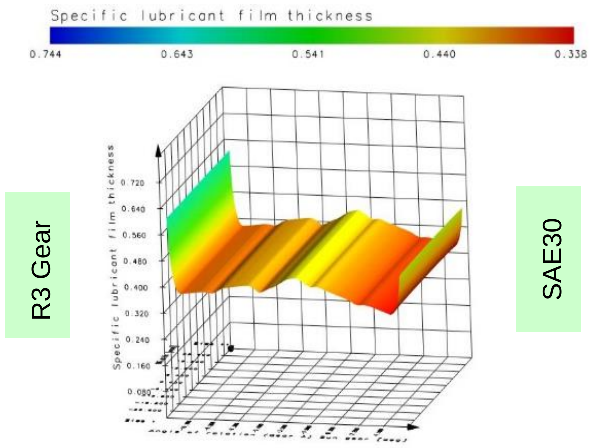

Fig. 9 Lubricant film thickness during Sun and Planet gear meshing for SAE30 Lubricant in R3 Gear

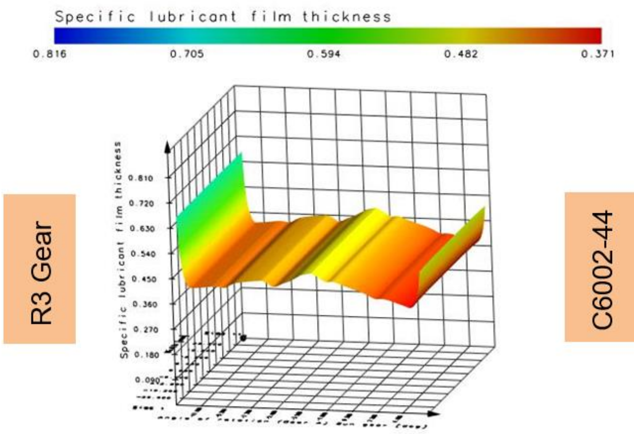

Fig. 10 Lubricant film thickness during Sun and Planet gear meshing for C6002-44 Lubricant in R3 Gear

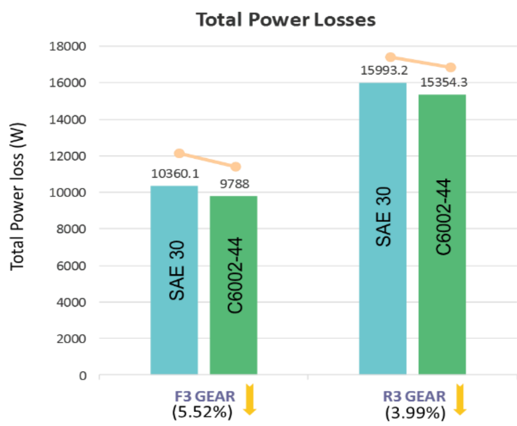

Fig. 11 Total power losses of two different lubricants in F3 & R3 Gear

Fig. 11 illustrates that 5.52% of reduction in total power losses while using BEML tailor-made C6002-44 over SAE30 in F3 gear and 3.99% in R3 Gear.

This method can be adopted to evaluate new tailor-made lubricants to identify power losses and thermal rating factors at the preliminary stage of design.

Further Field trials are under progress on BEML Off-Highway equipment at coal mines with Tailor-made lubricant C6002-44 and found performance satisfactory.

Conclusions

1) Tailor-made BEML C6002-44 lubricant shows sound effects on the tribological characteristics in Multi-stage planetary gear train used in Dozer compared with SAE30, which is pure commercial oil.
2) Besides, power losses, highest gear contact temperature and heat generated per mm of face width during meshing is reduced, which results in improving the overall gearbox efficiency.
3) Due to intense competition the resultant need to provide a high quality and economical product promptly, in which this methodology can be potentially adopted in any multi-stage Planetary gear train for analysing the tribological characteristics of new Tailor-made lubricants.
4) Apart from tribological characteristics, this methodology can be used to Evaluate different layouts by changing positions and parameters of the machine element for various power flow in one window within a short time.

Acknowledgement

We sincerely acknowledge, M/s. Indian Oil Corporation Ltd for developing Tailor-made lubricant for BEML equipment and field trial support. The authors thank S Jeyakumar and B.H Madhusudhan, BEML, R&D for aiding in due course of work

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