UPGRADATION OF ALCO LOCOMOTIVE ENGINE DESIGN - THE IN-HOUSE EFFORT BY INDIAN RAILWAYS

ABSTRACT

2600 HP, 16-Cylinder engine diesel locomotives were introduced on Indian Railways in early 1960's with the transfer of technology from American Locomotive Company (ALCO), USA. The diesel engines of above design continued to be manufactured in the Production Unit of Indian Railways at Diesel Locomotive Works, Varanasi for about 25 years without any modifications. To improve the technology of above engines to achieve improved fuel efficiency and increase in the power without major change in the basic engine configuration, Engine Development Directorate was set up by Indian Railways in 1980's in their R&D Centre (Research Designs & Standards Organisation) at Lucknow. Since then, sustained efforts have been made by Indian Railways to achieve the above objectives.

In the first stage, various modifications were taken up in the original 16-cylinder 2600 HP ALCO engines to reduce its fuel consumption by more than 6% and lube oil consumption by about 15%. These modified engines were called 2600 HP (FE) Engines. In the second stage, the uprating of the engine was carried out from 2600 HP (FE) to 3100 HP along with the improvement in fuel economy to 8% and lube oil consumption reduction to 25%. In the third stage, the technological improvements were made to further uprate the engine to 3300 HP/3600 HP and improve its fuel efficiency by 9.6% and lube oil consumption reduction by 33%. The modifications in the fourth stage are the modifications, which have been tested on test Beds of RDSO but are yet to be implemented on locomotives. The present fuel efficiency of these engines is now comparable to any engine in the world of this design.

INTRODUCTION

Indian Railways manufactures its diesel locomotives at Diesel Locomotive Works (DLW), a premier production unit working under the Ministry of Indian Railways. The above unit was established in 1961 in collaboration with M/s American Locomotive Company (ALCO), USA at Varanasi, the oldest living city of human civilization. Since its inception, DLW has produced 4650 locomotives. Its locomotives not only run in every nook and corner of India, but also in other South East Asia countries.

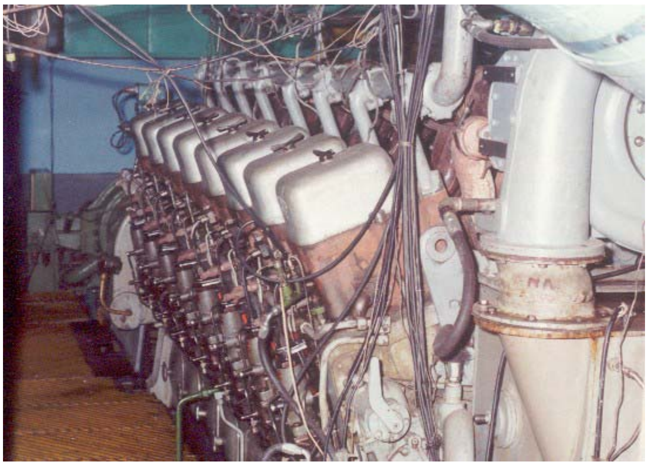
The high-energy costs, world over, have forced the engine manufacturers to substantially improve and optimise the performance and control of the engine. Indian Railways consume approximately two billion litres of diesel fuel annually through its fleet of 4000 no. Freight & Passenger Diesel Electric Locomotives consisting of medium speed 16-cylinder, 12-cylinder and 6-cylinder ALCO Engines.

The above requirement, in the year 1987, led to the creation of test beds at Engine Development Directorate of RDSO at Lucknow having state of the art facilities for developmental testing of all the variants of diesel engines being used by Indian Railways. It included the computer based test facility for both data logging and control of engines. The above facilities comparable to the best facilities in the world were created to meet the following objectives:

- Development of technology for improving existing Rail Traction Diesel Engines for
  - Better Fuel Efficiency
  - Higher Reliability
  - Increased Availability
- Development of technology for increasing power output of existing Diesel Engines.
- Develop capability for designing new Rail Traction Diesel Engines for meeting future needs of Indian Railways.
- To provide effective R&D backup to Railways and Production units to
  - Maintain Quality
  - Facilitate Indigenisation

ENGINE TEST BED FACILITIES

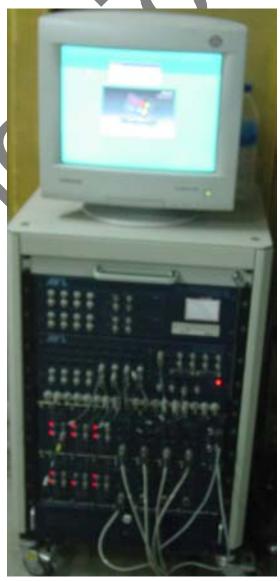
The test bed facilities in RDSO are equipped with four Test Cells. These Test Cells house four (16 cylinder GM-EMD, 16 cylinder ALCO, 12 cylinder ALCO, 6 cylinder ALCO) types of DLW manufactured Engines. Each test cell has its own microprocessor controlled data acquisition and control systems and Video Display Unit (VDU) for pressure, temperature and other parameters. Various transducers relay the information from the test engines to the microprocessor based test commander for further processing with the help of sophisticated software. Each test cell has an instrumentation catering to 60 to 120 pressure / temperature transducers along with sophisticated equipments like gravimetric fuel balance for measurement of fuel consumption and the equipment for measurement of air flow.



Test Bed

These test beds have also been provided with High Speed Data Acquisition System having the capability to acquire data from the engine at the frequency of 100 MHz, 16 channels of analog data can be accessed simultaneously from various transducers such as Cylinder pressure, Valve lift, Fuel injection pressure, Injector needle valve lift etc.

Test Commander



High Speed Data Acquisition System

The following two fuel efficiency indices are popularly used on Indian Railways:

Fuel Consumption on 8th Notch

Since the fuel consumption at 8th notch is highest and also since Locomotives run at this notch for longer duration as compared to other notches, fuel consumption at this notch is one of the important fuel efficiency index. This is measured in terms of gm / bhp - hr.

Fuel Consumption over Duty cycle

An Engine runs in the field at different notch as per requirement of speed / load of the locomotive. The notch-wise percentage running of locomotive over duty cycle for passenger and freight operations of Indian Railways locomotives is as under:

Notch		8	7	6	5	4	3	2	1	Idle
Duty cycle in %	Passenger	21	6	4	8	4	8	5	6	38
	Freight	22	7	5	3.5	3.5	3.5	3	1.5	51

Fuel consumption (in kg/hr) over duty cycle is calculated by taking weighted average of fuel consumption at every notch over duty cycle.

VARIOUS STAGES OF DEVELOPMENT

STAGE-I

During early 90s, fuel - efficient kit for original 16-cylinder DLW manufactured ALCO engines was developed, which reduced specific fuel consumption by more than 6% and lube oil consumption by about 15%. The reduction in fuel consumption at full load was from 166 gm/bhp/hr to 156 gm/bhp/hr at full load. Similarly, there was reduction in the % lube-fuel oil ratio from 1.5% to 1.27%. The major modifications in the design with their estimated contribution to improvement in fuel and lube oil consumption is described below:

Development of Efficient After -Cooler

After-cooler in a turbocharged engine cools the compressed air to engine, thereby increasing the density of charge air. A large after-cooler with higher effectiveness was designed for better cooling of compressed air. The size of the core was increased to get higher contact area between water and air. The new after cooler, called Large After-cooler, also resulted in lower cycle temperatures and lower thermal stresses on the engine.

Large Aftercooler Core

This modification increased cooling effectiveness of after cooler from 50% to 75% and decreased exhaust gas temperature from 600ºC to 520ºC.

It is estimated that this development improved the fuel efficiency by approx. 1% and reduced the lube oil consumption by about 2.5%.

Development of Improved Turbochargers

The original DLW manufactured locomotives were fitted with ALCO A720 turbochargers. These turbochargers were replaced by fuel-efficient

- Napier NA295 A720; and
- ABB VTC-304 VG-13 turbochargers.

Global Efficiency of ALCO turbocharger is in the range of 50%, whereas the new turbochargers have efficiency of more than 60%. The rotor speed of these turbochargers at rated power is also higher (23000 rpm) as compared to the speed of earlier turbo (19000 rpm). With the increase in turbo efficiency, the inlet air density increased without changing the design of combustion chamber. Increase in booster air pressure from 1.2 bars to 1.6 bars with these turbochargers, was achieved.

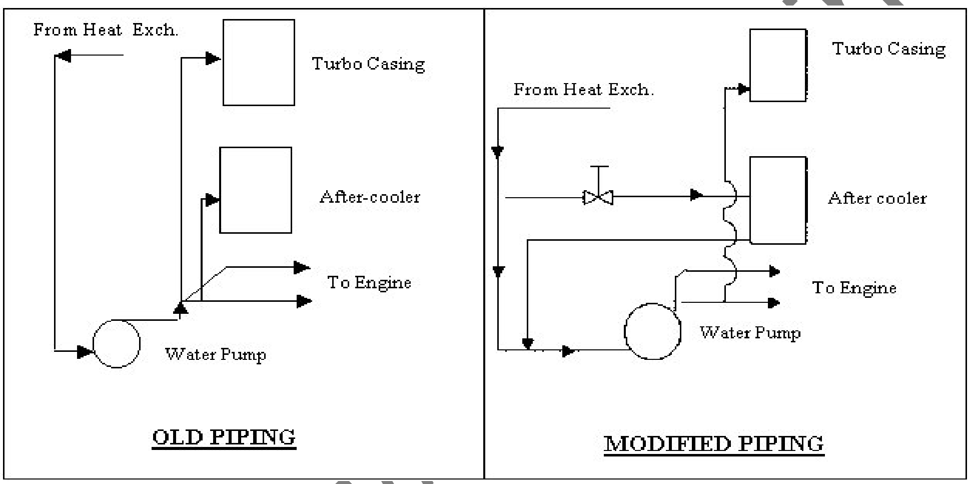
A comparison of the two types of turbochargers is given in the table below:

Stages	1960-90	Stage-I
Technology wise classification of turbochargers	Conventional	High efficiency
Turbo models used by RDSO	ALCO 720A	Napier NA295 A720 ABB VTC-304 VG-13
Turbo global efficiency	50%	60%
Exhaust gas temperature at turbo inlet	>600^{0}C	580^{0}C
Frequency of maintenance	6 months	2 years
Salient features	Bearing interference fit. Thrust on hot side.	Bearing sliding fit. Floating bush. Thrust on cold side.

It is estimated that fuel and lube oil saving with the above modification is approx 1% and 2.5% respectively.

<u>Modification In Cooling Water Piping</u>

The cooling water piping arrangement of the loco was modified for better cooling of charge air. The water inlet to after-cooler was modified to supply water at minimum possible temperature to after-cooler. The water to the after-cooler was fed directly from the radiator and the water from the after-cooler was connected to inlet of the water pump. In original design, water to the after-cooler was being fed from the outlet of water pump. The old and modified connections are shown in schematic diagram below:



Schematic Diagram of Old & Modified

This Modification is estimated to have contributed to 0.5% and 1% improvements in specific fuel consumption and lube oil consumption respectively.

<u>Development of 12.5 Compression Ratio Steel Cap Pistons</u>

Original ALCO engines had aluminium dish top pistons. Use of high efficiency turbochargers and higher capacity fuel injection pumps, as brought out above, led to higher peak firing pressures. As aluminium pistons cannot withstand these higher firing pressures, steel cap pistons were developed. These steel cap pistons were provided with special crown profile for better combustion.

Aluminium Dish

Steel Cap

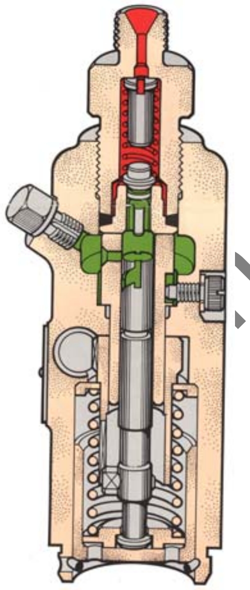
Steel cap pistons have additional advantages of longer life due to lesser wear of ring grooves and ability to withstand higher thermal load due to better cooling.

The estimated saving in fuel and lube oil consumption with use of steel cap piston is about 1.5% and 4% respectively.

<u>Modification of Fuel Injection Pump</u>

The original fuel injection pumps used on ALCO Engines had plunger diameter of 15 mm. The plunger diameter of the fuel injection pump was increased from 15 mm to 17 mm. This modification led to sharper fuel injection i.e. injection at higher-pressure. The modification resulted in increase of peak fuel line pressure from 750 to 850 bars and, thus, improvement in the fuel efficiency.

Fuel Injection Pump



FIP Cut Section

The estimated fuel and lube oil economy with this modification is approx. 1.5% and 4% respectively.

<u>Modification of Cam Shaft</u>

Camshaft with increased overlap of 140 deg in place of 123 deg. was designed to improve scavenging. The exhaust & inlet air cam lobes were modified so that both the inlet and exhaust valves are kept open for longer period. With this modification, pressurised inlet air was able to force out the burnt gases for longer period. This improved quality of charge air had significant effect on fuel efficiency of the engine. The width of fuel cam lobes along with the width of fuel cam roller was also increased to take up higher fuel injection pressure.

The estimated saving in fuel and lube oil consumption with the above change is about 0.5% and 1% respectively.

STAGE-II

Fuel-efficient 2600 HP ALCO Engine was upgraded to 3100 HP by increasing the engine rpm from 1000 to 1050 rpm and introducing high efficiency turbocharger in the year 1992. Apart from upgradation, the above changes further resulted in the reduction in fuel consumption from 156 gm/bhp-hr to 153 gm/bhp-hr at 8th notch and reduction in the % lube-fuel oil ratio from 1.27% to 1.12%.

Development of High Efficiency Turbo Chargers

The High Efficiency Turbochargers available in world market were tested and optimised on 3100 HP upgraded engine. Two new designs of turbochargers, ABB VTC-304 VG-15 and GE 7S1716 (Twin discharge) were introduced for 3100 HP engine. There was increase in the Booster pressure with the use of above turbos from 1.6 to 1.9 bars. The speed of rotor at rated power also increased to 27000 rpm against 23000 rpm of Stage-I turbochargers.

GE 7S1716 Twin Discharge Turbo

A comparison between the turbochargers used in the two stages is given below:

Stages	**Stage-I**	**Stage-II**
Technology-wise classification of turbochargers	Efficient	High efficiency
Turbo models used by RDSO	Napier NA295 IR ABB VTC-304 VG-13	GE 7S1716 ABB VTC-304 VG-15
Turbo over all efficiency	60%	64%
Exhaust gas temp.	580^{0}C	500^{0}C
Frequency of maintenance	2 Years	4 years
Salient features	Bearing sliding fit. Floating bush. Thrust on cold side	Bearing sliding fit. Thrust on both sides

The estimated saving in fuel and lube oil consumption with high efficiency turbocharger is approx. 1% and 4.5% respectively.

Introduction of Fuel Efficient Piston Rings

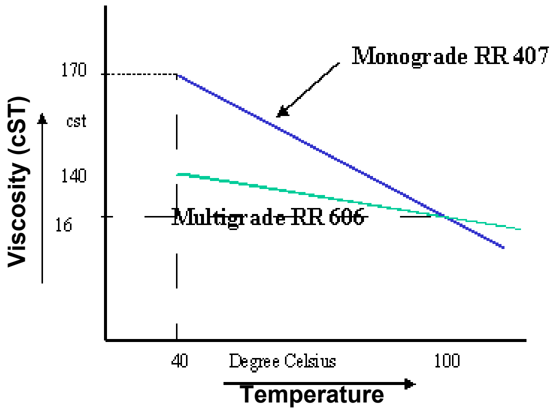
DLW engines conventionally employed a piston ring set of 5-rings having square, taper, taper, oil conformable and oil scraper configuration. Trial with piston ring set of barrel, taper, taper, oil conformable and oil conformable configuration showed considerable reduction in fuel and lube oil consumption. The ring set has been named as fuel-efficient ring set.

Use of these rings is estimated to have reduced the fuel and lube oil consumption by approx 0.5% and 2.5% respectively.

Use of Multigrade Lubricating Oil

Single grade SAE40 lubricating oils, as recommended originally by ALCO, were being used by Indian Railways, up to 1998. Development of 20W40 multigrade oil was taken up by RDSO from 1995 onwards. These oils have an additional additive called Viscosity Index Improver (VII) to reduce the change in viscosity with change in temperature. The mono-grade lube oil has a problem that its lubricating property deteriorates at higher operating temperature. The lubrication of moving components was found to be better at higher temperatures with multigrade lubricating oil.

This behaviour of multigrade oils improves the lubrication properties at working temperatures and also results in savings of fuel.



Viscosity vs. Temperature of oils

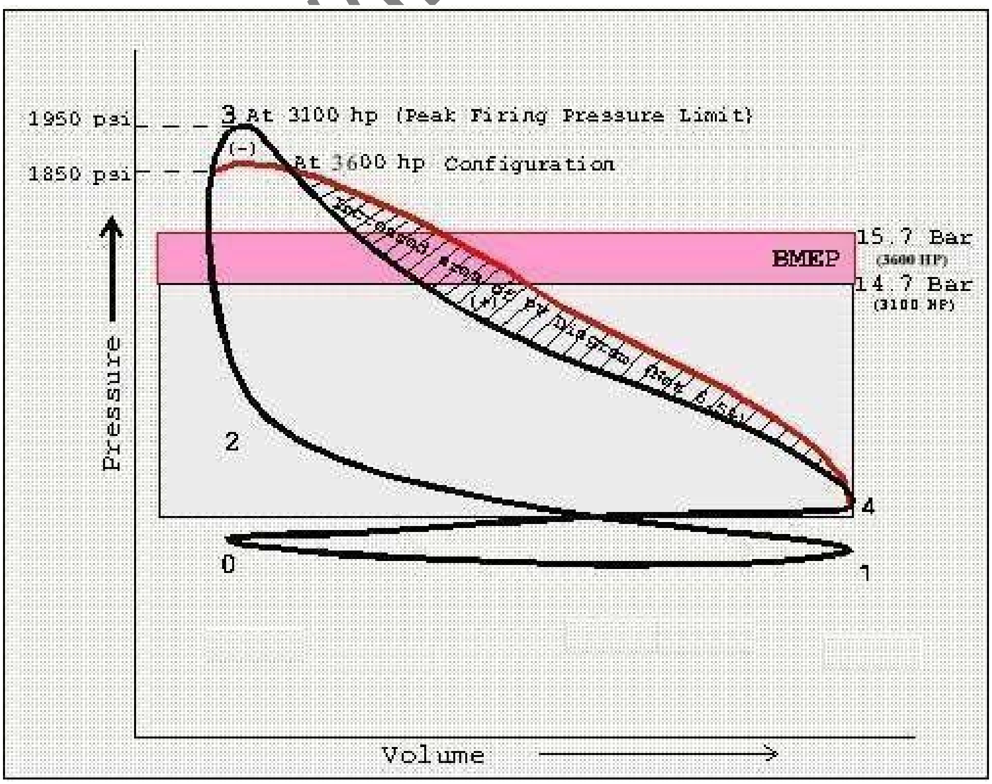
Based on results of extensive field trials of performance of multigrade oils as compared to mono-grade oils, Indian Railways switched over to use of Multigrade oil.

It is estimated that the fuel and lube oil saving with the use of multigrade lube oil is approximately 0.5% and 3% respectively.

STAGE-III

Literature survey showed the worldover use of 3600-3900 HP rating 16-cylinder 251 ALCO engines by Montreal Locomotive Works and Bombardier Corporation. Since M/s GETS, USA are the present holders of ALCO 251 technology, M/s. GE Transportation System, India was consulted, who agreed to associate in the project of 3600 HP upgradation by extending all possible assistance for engine configuration build-up and subsequent testing.

The 3100 HP ALCO Engines has, thus, been upgraded in association with M/s. GE Transportation System, India to 3300 HP in the year 2001 and to 3600 HP in 2002. The fuel consumption of the upgraded ALCO engines was also further reduced from 153 gm/bhp-hr to 150 gm/bhp-hr on top notch. Similarly, there was reduction in the % lube-fuel oil ratio from 1.12% to 1%.



The underlying theoretical approach for the above power upgradation to 3600 HP rating is 16% increase in the area of 3100 HP PV diagram with the peak firing pressure within specified limit by suitable engine configuration selection.

We know $p = \frac{HPxK}{N}$ where, p is BMEP, K is a constant and N is rpm

For 3100 HP, $p_1 = \frac{3100\ K}{1050} = 2.95\ K$ (14.7 bar)

For 3600 HP, $p_2 = \frac{3600\ K}{1050} = 3.43\ K = 1.16\ p_1$ (17.2 bar)
at 1050 rpm

Therefore, for upgradation of power to 3600 HP, BMEP increases by 16% over that at 3100 HP and it would result in corresponding increase in cylinder peak firing pressure and exhaust gas temperatures with the same engine configuration. Hence, there was a need of a suitable configuration to limit these critical parameters.

Following limits of critical parameters were fixed for the development:

i. Mechanical Load: Average peak firing pressure <1950 psi.
ii. Thermal Load: Exhaust gas temperature at turbine inlet <550 ^{0}C.
iii. Specific Fuel Consumption: SFC at rated power <156 gm/bhp-hr.
iv. Surge Margin: >15%.
v. Boost pressure <2.2 bar.

Introduction of New Generation Turbochargers

New generation aircooled turbochargers having global efficiency of 70% were introduced in place of High Efficiency Turbochargers.

ABB TPR-61

HS 5800 NGT

Two New Generation Turbochargers, ABB TPR-61 & HS 5800 NGT were optimised on RDSO's Test Bed for 3100 HP & 3600 HP engines and a broadband matching was established. The booster air pressures on 3300 hp and 3600 hp were found as 2.0 and 2.2 bars respectively. The rotor speed of these turbochargers went up to 30,000 rpm on 3600 hp engines.

The comparison of the two turbochargers of Stage-II & Stage-III is as under:

Stage	Stage -II	Stage -III
Technology-wise classification of turbochargers	High Efficiency	New generation
Turbo models used by RDSO	GE 7S1716 ABB VTC-304 VG-15	HS 5800 NGT ABB TPR-61
Turbo over all efficiency	64%	70%
Exhaust gas temp.	500^{0}C	500^{0}C
Frequency of maintenance	4 years	4-6 years
Salient features	Bearing sliding fit. Thrust on both sides	Bearing sliding fit. Thrust on both sides. No water-cooling.

The estimated saving in fuel and lube oil consumption with New Generation Turbocharger is about 0.6% and 2% respectively.

Development of Stiffer Unit Cam Shaft

For generation of higher horsepower with improved fuel efficiency, fuel cam lobe design needed change for still sharper fuel injection. A new design of camshaft with modified profile of fuel cam lobe was developed. This design was called Stiffer Unit Camshaft. Peak fuel line pressure of 1100 bars was achieved with this camshaft.

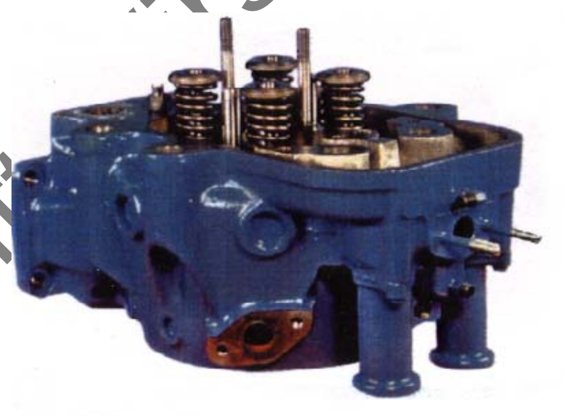
Stiffer Unit Cam Shaft

This camshaft was strengthened to take up the increased stress due to increased fuel line pressure. Other design improvements were also incorporated for longer life and easy maintenance of camshaft. Accessories like FP Support, Push Rod Lifter, Cross-Head Lifter etc. were also required to be redesigned to suit this camshaft.

The estimated saving in fuel and lube oil consumption using stiffer camshaft is approx. 0.5% and 3% respectively.

Development of Plus cylinder head

To take care of increased heat load, Plus cylinder heads have been developed having air intake valve angle of 30 degree instead of 45 degree in the conventional cylinder head. The intake and exhaust ports have been streamlined for improved air flow, minimize flow resistance and improve breathing of cylinder head. Casting quality such as fillet radii and internal surface finish have been improved. The heat transfer rate in the new design has also been enhanced due to thinner flame deck; low gap between the flame deck and the middle deck; and the machined valve bridges. The location of cooling passages has also been changed to give better heat transfer. The valve seat inserts have been press fitted without snap ring, resulting in larger contact area and thus better heat transfer.



Plus cylinder head

The estimated saving in fuel and lube oil consumption using Plus cylinder heads is approx. 0.5% and 3% respectively.

CHANGES IN ENGINE CONFIGURATION AND OPERATING PARAMETERS IN UPGRADATIONS

The above trials have resulted in the following optimum configuration of 16-cylinder ALCO diesel engine for 3600 HP:

- Stiffer Unit Cam Shaft assembly (22^0 BTDC start of injection).
- GE 7S1716 turbocharger (26 sq. inch nozzle) with twin discharge.
- 11.75 Compression ratio Super Bowl steel cap pistons.
- Plus cylinder head assembly.

- High pressure fuel tube for 1200 bar pressure rating.
- 17 mm FIP having fuel rack of 35 divisions.
- Rest of the engine components remain same as existing 3100 HP.

Other recommended Engine Support System for 3600 HP rating diesel engine include:

- Mechanically bonded, louvered fin radiator for 2000 kW heat load.
- Twin aftercooler for 400 kW heat load and >90% effectiveness.
- Plate type lube oil cooler for 500 kW heat load.
- 10"Impeller water pump.
- Stream lined lube oil and water piping network.
- Insulated exhaust gas manifold.

The above 16 Cylinder DLW/ALCO test engine upgraded to 3600 HP rating has also qualified the 100 hours performance test as per codal requirements of UIC623.2/KTA3702.2. The details of 100 hours test sequence is as under:

a. Continuous Power Rating – Duration 80 hrs. – Power x RPM
(100%) 3500 x 1000
3600 x 1050

b. Excess Power Rating – Duration 1 hr. – Power x RPM
(110%) 3825 x 1000
3960 x 1050

c. Partial Load – Duration 10 hrs. – 2 h 30 min 100% 3600 HP
(1000 rpm) 2 h 30 min 75% 2700 HP
2 h 30 min 50% 1800 HP
2 h 30 min 25% 900 HP

d. Cyclic Load Testing – Duration 9 hrs.
(1000 rpm)

5 cycles	2 min 8 min	15% 100%	540 HP 3600 HP
5 cycles	4 min 6 min	25% 100%	900 HP 3600 HP
18 cycles	4 min 6 min	50% 100%	1800 HP 3600 HP
26 cycles	4 min 6 min	75% 100%	2700 HP 3600 HP

During above 100 hours test, conscious efforts were made to load engine to the maximum power and speed limits and it was observed that the engine ran smoothly with all the parameters within prescribed limits without any abnormality in engine operations or any of its sub-systems/components.

While taking up the improvements/modifications/upgradation in above three stages, as detailed above, conscious effort was made to keep the critical engine operating parameters within the limits. A summary of comparison of critical parameters is as under:

Engine Operating Parameters	**Stage-I (2600 FE)**	**Stage-II (3100 HP)**	**Stage-III**	
			3300 HP	**3600 HP**
Peak firing Pressure (psi)	1650	1900	1850	1870
Exhaust Gas Temp. (^{0}C)	600	500	509	525
Boost Pressure (bar)	1.2	1.6	2.0	2.2
BMEP (bar)	13.5	14.7	15.7	17.5
Fuel Injection Pressure (bar)	850	950	1010	1040
Engine speed (rpm)	1000	1050	1050	1050
SFC 8th Notch (gm/bhp-hr)	166	156	154	152

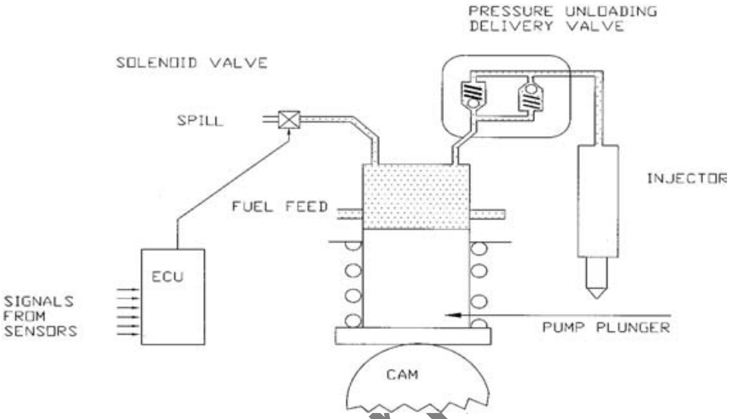
STAGE-IV

This stage consists of the technological improvements, where fuel saving on the locomotive engines have been achieved on the test bed but yet to be implemented in the field. Fuel and lube oil consumption of DLW manufactured ALCO engines have been further reduced by more than 2% and 6% with these modifications.

Electronic Fuel Injection System:

Mechanical fuel injection pumps, which were being used on ALCO Engines, had no provision of changing start of injection at various notches. Since Diesel Engine consumes maximum fuel at 7th and 8th notches, the fuel injection timing on this engine are optimised to give lowest specific fuel consumption at these notches. Electronic fuel injection pump has the advantage of setting the start and end of injection for each cylinder individually, which results in injection of optimum quantity of fuel in combustion chamber at right moment. EFI pump as well as the schematic diagram of the set-up of EFI system is shown hereunder:

EFI Pump



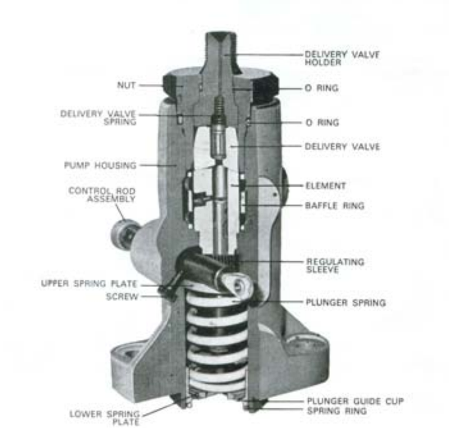
Schematic diagram of the set-up

Apart from reducing fuel consumption of the engine at lower notches, the Electronic fuel injection system also eliminates a number of mechanical engine components, the most prominent being the Governor itself, thereby reducing maintenance effort and resulting in higher reliability. Other advantages of the system include elimination of hot engine alarms; better control and diagnostics; design flexibility; automatic balancing; and lesser exhaust emissions.

The Electronic Fuel Injection System has been developed by RDSO in association with M/s Lucas Bryce, UK as well as M/s MICO at Bangalore in India. The system has been optimised for ALCO Engine at RDSO's Test Bed. The system has given the fuel saving of more than 2% over duty cycle.

Double Helix Fuel Injection Pump

RDSO has also developed double helix pumps for ALCO Engine in association with M/s MICO. In double helix design, helix is provided on the top and bottom edges (both) of FIP plunger, so that opening of spill port is also optimized and controlled resulting in the optimization of start of injection at part load as well.

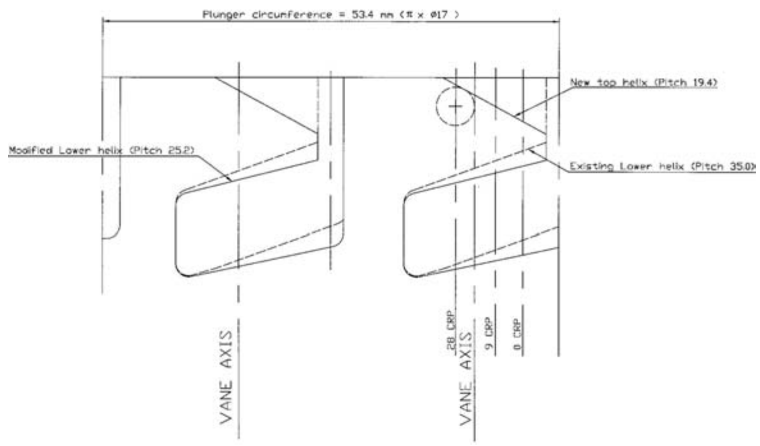


FIP Cut Section

Single Helix Plunger

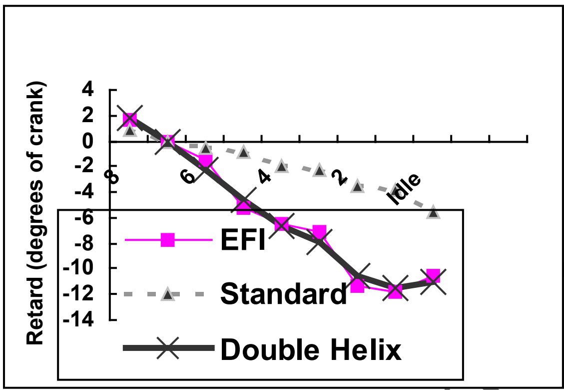
Double Helix Plunger

The helix has been manufactured as a linear approximation of results obtained on Electronic Fuel Injection System. For every mm of movement of fuel control rack, the camshaft has been designed to move 0.35º more for the ports to close.



Development drawing of the Element

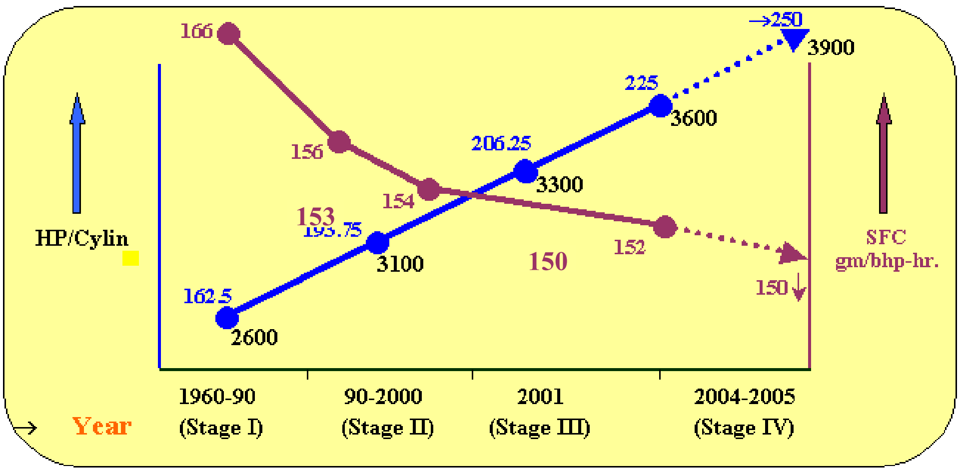
The optimized Notch-wise retard for the Standard, Electronic Injection and Double helix pump is shown hereunder:



Fuel saving of about 1.6 % over duty cycle has been observed with the use of Double Helix Pump. The pay back period of this pump is hardly 1.5 month as against 3 years for Electronic fuel Injection System. However, this system does not offer the other advantages of Electronic fuel Injection System.

CONCLUSIONS

Indian Railways has, thus, made sustained efforts in all the facets of diesel traction technology over past four decades by consistently and continuously improving the diesel locomotive technology of 1950s, entirely through in-house research and development to "State-of-the-art" level. The stage wise improvement in BSFC alongwith increase in horsepower per cylinder is summarised in the graph below:



Stage-wise improvement in BSFC along with increase in Horse-Power per cylinder

Indian Railways' diesel locomotive fleet has, thus, benefited immensely from the various technological inputs in terms of in-house developed new products and designs.