# TRB
# 02-3249

# Retrofit Of Diesel Locomotive with Twin Gas Turbine Power to Achieve Minimum Particulate Emissions and Lower Overall Emissions While Burning Either Diesel #2 Fuel or Liquefied Natural Gas.

**Jerome R. Pier**
**J.R. Pier & Associates**
**22 Woodend Drive**
**Carlisle, Ontario**
**L0R 1H2**

**Tel: 905 690 1892**
**Fax: 905 690 1893**
**E mail:** jrpier@home.com

| | |
|---|---|
| **WORD COUNT** | |
| **TOTAL TEXT-** | **3662** |
| **12 Tables & Figures-** | **3000** |
| **Total** | **6662** |

**Format- MS Word 7**

# Retrofit Of Diesel Locomotive with Twin Gas Turbine Power to Achieve Minimum Particulate Emissions and Lower Overall Emissions While Burning Either Diesel #2 Fuel or Liquefied Natural Gas.

**Jerome R. Pier**
**J.R. Pier & Associates**
**22 Woodend Drive**
**Carlisle, Ontario**
**L0R 1H2**

Abstract**.** The fine particulate matter component of diesel engine exhaust has been declared by the state of California to be a human carcinogen at any concentration and is therefore subject to measures for its reduction or total elimination. (1) The diesel locomotive contribution to this problem is projected to be 46% of the total diesel engine particulate tonnage in 2010 (2).

This paper will discuss a conceptual design substituting gas turbines for the main traction engine and head end power (HEP) engine of a typical diesel electric commuter locomotive. Retention of the existing HEP engine while replacing the traction engine will also be evaluated. Elimination of major reduction of measurable particulate matter as well as significant reductions in other exhaust pollutants is projected while burning conventional diesel #2 fuel oil. Since the gas turbine readily adapts to natural gas as a fuel without any loss in performance, the economics and further emissions benefits will be developed for the use of liquefied natural gas (LNG) fuel as well.

## INTRODUCTION

Diesel locomotives in commuter rail service are a significant contributor to air pollution in urban areas. Over 400 diesel electric commuter locomotives are currently in operation in North America (3) and. by nature of the function; all of these are operating in densely populated areas where air pollution from many sources creates a problem. The fine particulate matter component of diesel engine exhaust gases has been declared a human carcinogen at any concentration (1) and methods for reducing or eliminating this risk are a valid subject for examination. The diesel locomotive contribution to the problem is projected to be 46% of the total diesel engine particulate tonnage for California in the year 2010. (2) There is no reason to believe that projection is not valid for most North American commuter rail operations that use diesel locomotives.

This paper develops a concept for the application of gas turbines to replace the main traction engine and optionally, the head end power (HEP) diesel engine in a typical commuter locomotive with separate HEP. The primary reason for such a retrofit is to take advantage of the much cleaner exhaust offered by the gas turbine including the elimination of measurable particulate matter in the exhaust. A secondary reason is to take advantage of the gas turbine's easy adaptability to an alternate fuel such as liquefied natural gas (LNG) to gain relief from reliance on diesel #2 fuel oil as well as gain additional exhaust emission and maintenance cost advantages. (4) The proposed design is conceptual; a detailed design is beyond the scope of this effort. The reference train is a locomotive hauling ten bi-level cars. The last car in the train, designated a cab car, includes a control cab so that the train can be run in either direction without turning it around. The addition of the cab reduces seated passenger capacity by two but in all other respects the cab car is the same as the other coaches. This is typical of trains operated in urban areas in California (Southern California Commuter Rail Authority), Florida (Tri-County Commuter Rail Authority), Ontario Canada (GO Transit), Chicago (Chicago Commuter rail Services Board). The train is assumed to have an empty weight of 612 tonnes (675 tons) and a seated load of 722 tonnes (796 tons). Crush load is 910 tonnes (1004 tons). Where train weight is a factor in this work, the seated load will be used as representative of average daily experience. The locomotive power train consists of a 12 cylinder, two stroke cycle, 2238 kW (3000 hp) diesel engine driving a 10 pole alternator at 800 rpm which in turn delivers 700 VDC of rectified power to drive four DC traction motors. The HEP unit comprises a 582 kW (780 hp), V-8 four stroke cycle diesel engine driving a 3 phase, 60 Hz, 480 VAC alternator

## The Proposed Gas Turbine

The proposed gas turbine is the TF15, developed and refined for military applications as the AGT1500, specifically for the Abrams Tank. Over 11,000 of this recuperated gas turbines have been built. (5) Completely overhauled zero hours engines are readily available at less than half the cost of a comparable new engine with the same level of performance and efficiency. Figure 1 shows a cut-away view of the TF15 gas turbine illustrating its compact design. The recuperator, which extracts heat from the exhaust and re-introduces it to the thermal cycle, surrounds the final drive of the turbine The gas turbine is designed for maintenance from above providing for the removal of the hot or power turbine end of the engine without disconnecting the output shaft. Other elements can be removed in the same manner. For total rebuild, the entire unit can be removed and replaced in one working shift. The gas turbine is controlled by a Digital Electronic Control Unit (DECU) which regulates fuel flow to provide the required performance and also monitors turbine condition to minimize maintenance costs. (6)

The engine is 1689 mm (66.5 in.) long, 991 mm (39 in.) wide and 808 mm (31.8 in.) high. It produces 1120 kW (1500 hp) for a weight of 1134 kg (2500 lbs.), or

0.99kW/kg (0.6 hp/lb). A typical locomotive diesel produces about 0.024 kW/kg (0.07 hp/lb). Output speed is 21,700 rpm reduced to 3000 rpm by a planetary gear train. For use as an auxiliary power generator, output speed can be controlled at 1800 rpm, normal four pole, 60 Hz alternator speed. Output power is modulated to meet the desired auxiliary power demand while holding the speed constant. Recuperation extracts air at the output of the compressor and passes this air through a counterflow heat exchanger, extracting waste heat from the exhaust gas and adding it to the combustion air prior to its re-introduction to the combustor. This increases overall efficiency at the expense of a slight increase in nitrous oxide (NOx) emissions as a result of the higher combustion temperature. Most importantly it reduces fuel consumption at the less than full power loads encountered in most commuter rail operations. Another feature of this engine is variable blading in the power turbine that maintains power output over a wide temperature range. With this feature, gas turbine output as rated at sea level and 10°C (50°F) remains constant at ambient temperatures from -51°C (-60°F) to 31°C (87°F) rather than varying with changes in air density related to temperature. (6)

## Design Concept

Two gas turbines coupled in parallel are used to replace the 2238 kW (3000 hp) diesel engine. Coupling may be accomplished mechanically by means of a gear train or electrically with individual alternators and rectifiers. For purposes of this paper, only electrical coupling will be discussed since this method offers lighter weight which, in turn, will result in reduced fuel burn.

### *Electric Coupling*

The electric coupling method is shown in Figure 2. In this case, the existing 800 rpm, 2200 kW alternator, its associated rectifier and smoothing reactor are replaced with 3000 rpm, 1100 kW alternators directly coupled to the output shafts of the two TF15 gas turbines. Each alternator has its own rectifier incorporating voltage regulation as well as a smoothing reactor. The rectifier outputs are then joined to provide 2200 kW power at 700 VDC to the locomotive traction system. Either gas turbine can be started or run by itself with the natural diode function in the rectifiers preventing back flow of energy to the idle turbine. This feature is valuable in start-up. It also permits operation with only one gas turbine for those portions of the route where power demand is 1120 kW (1500 hp) or less. An analysis by Southwest Research Institute (7) indicates that such a condition can prevail as much as 44% of the time in a typical commuter rail operation. The advantage in specific fuel consumption between running both turbines at half load and one turbine at full load is about 19%.

The electric coupling solution provides weight savings as a result of replacing the conventional electric generating system with two high speed, lightweight alternators. The lower inertia of the high-speed alternator should also reduce run-up time of the power train. Table 1 shows the build-up of the modified train weight as compared to the standard locomotive hauled train.

## Operating Characteristics

### *Power Modulation*

Conventional diesel electric locomotive throttle control is divided into 8 steps or notches excluding the idle position. Typically, notch 1 calls for 20% of full power; notch

2, 40%; notch 3, 50%; and so on in 10% increments until full power is called for in notch 8. While gas turbine control is essentially continuous, rather than stepped, the DECU can be programmed to deliver the same power response to throttle notch position. The Gross Power chart of Figure 3 illustrates this capability. The chart also includes an optimum speed curve. The intersection of this curve with each power setting represents the turbine speed which will deliver optimum efficiency for the power demand. The optimum speed curve coincides with 100% speed from 80% power to 100% power. This chart can also be used to demonstrate the speed-power relationship for the head end power function. In this case, the DECU will have a fixed speed setting of 60% or 1800 rpm. At this speed maximum demand of 600 kW will be met at 60% power, a point which falls to the left of the optimum speed curve but provides acceptable operation. Lower power demands will follow the 60% speed line downward.

### *Fuel Consumption*

Figure 4 charts the specific fuel consumption as a function of power output for the TF15 as well as for a typical diesel engine and a non-recuperated, or conventional, gas turbine of similar size. The latter is included to illustrate the advantage of recuperation in turbines of similar power output. Note that at 40% power, the fuel consumption for the recuperated gas turbine is 66 g/kWh or 16% lower than the non-recuperated turbine. The lightweight of the turbine drive lowers locomotive weight by as much as 30.5 tonnes, (34 tons) having the effect of lowering specific fuel consumption an additional 18 g/kWh or 4%. From a different aspect, acceleration performance will improve by 4% effecting a reduction in trip time with consequent reduction in fuel burn. A third curve in Figure 4 shows this adjusted effect.

### *Ambient Temperature Compensation*

As noted above, an important feature of the TF 15 gas turbine is variable blading in the power turbine which compensates for changes in ambient air temperature. Figure 5, Power Vs Inlet Temperature, illustrates this feature. Gas turbines are normally rated at 59°F. As ambient temperature rises above this value, power output for the conventional turbine declines rapidly but the TF15 output remains constant up to 31°C (87°F) and at 40°C (104°F) falls off just 10%. The power curve for the conventional 1194kW (1600 hp) turbine without this feature crosses the TF15 turbine's power curve at 17°C (63°F) and at 40°C (104°F) has dropped to 900 kW (1206 hp), 11% below the TF15.

### *Head End Power*

Substitution of the TF15 gas turbine for the auxiliary power (HEP) engine is straightforward. The output speed of the gas turbine will be reduced from 3000 rpm to1800 rpm using the DECU to govern the turbine speed and to adjust fuel flow for the desired power output. This will result in a slight deviation from the optimum speed/power curve but offers simplicity and cost benefits. An alternative is to reduce output rpm to1800 rpm with a new gear train. This is not considered practical in a prototype application but might be cost effective if retrofit volume increases.

## Optimizing the Configuration

### *Emissions*

The Primary purpose of this effort is to present a retrofit which will optimize locomotive emissions with specific attention to particulate matter. The locomotive/train configuration as it now exists, consisting of one locomotive and ten double deck coaches, is considered to be the baseline. If the only consideration were emissions, the best solution would be replacement of both the traction diesel engine and the HEP engine with TF15 gas turbines. For purposes of this discussion, this configuration will be designated Solution 1. Solution 2 replaces the traction engines with two TF15 gas turbines while leaving the HEP unit unchanged. An immediate benefit of the Solution 2 configuration is saving the cost of a third gas turbine at a weight penalty of 845 kg. Since the lighter weight of both turbine solutions should result in reduced trip time as well as elimination of traction engine idling during layover, a comparison of the two proposed solutions to the baseline was done in terms of kg of pollution per trip using the trip time and power distributions developed for SCRRA by the Southwest Research Institute. (7) The bar graph of Figure 6 compares the two possible solutions to the baseline. Note that total emissions per trip for Solution 1 are 60 kg (64%) lower than the Baseline and Solution 2 emissions per trip are 46 kg (50%) lower than the baseline. Solution 1 emits no particulate matter while Solution 2 emits just under 0.4 kg per trip, 82% lower than the baseline.

### *Fuel Burn*

Fuel burn, or fuel consumption per trip, is an important consideration. If a direct comparison of specific fuel consumption is made, the gas turbine configuration shows a disadvantage of 18%. Using the same approach as used for emissions comparison, total fuel burn per trip, including HEP requirements, were calculated for the baseline train and Solutions 1 and 2. It was assumed that the baseline train would have a layover time of one hour between trips and that the traction engine would run at low idle for this period while the HEP unit would run a half power to maintain interior temperatures. For Solutions 1 and 2, the traction engine would be shut down for the layover period but HEP operation would be the same as for the baseline train. In all three cases, the trains would be fully shutdown or on shore power for the overnight period. The result of these calculations appears on the chart of Figure 8. Note that Solution 1 results in a total fuel burn of 622 liters/trip, 96 liters (18%) more than the baseline train while Solution 2 results in a total fuel burn of 560 liters/trip, just 34 liters (7%) above the baseline train. Simulation studies to establish the optimum time for running on one turbine, rather than two, have the potential of lowering this differential even further. Such studies are beyond the scope of this paper but deserve consideration as follow-on work.

Based on the above analysis, it appears that a 50% reduction in emissions for a 7% increase in fuel consumption makes Solution 2 the obvious choice. Subsequent discussions will therefore be confined to the Solution 2 configuration.

### Liquefied Natural Gas (LNG) As an Alternate Fuel

LNG offers an alternative to diesel #2 fuel oil for internal combustion engines. Its lower heating value is 82,295 kJ (78,000 Btu) per gallon as compared to 132,706 kJ (125,780 Btu) per gallon for diesel #2. LNG fuel tanks for equivalent range must therefore be 61% larger than diesel fuel tanks and, in addition, the tanks must be insulated to maintain the LNG at -164°C (-263°F). Since natural gas will not compression-ignite; a diesel engine running on natural gas must use either spark ignition or pilot injection of diesel fuel to ignite the fuel. Difficulty in getting enough gas into the compression chamber results in a loss of power per unit of displacement. Power output for a diesel engine running on LNG is typically 55% of its rating with diesel #2 fuel. The implication of this characteristic is that two LNG fueled locomotives are required to perform the work of one diesl#2 fueled locomotive if performance is to be maintained. A positive outcome is that maintenance periods will be extended and emissions lowered because of the clean burning characteristics of the fuel. Southwest

Research Institute, under contract to Gas Rail USA, has demonstrated a system called LaCHP (late cycle, high injection pressure) which, on the test bed, is claimed to deliver a 50% reduction in NOx without any loss of power output. Unfortunately, funding for this program was cut off before a field service trial could be implemented. (8)

Gas turbines, because of the continuous nature of their combustion cycle, will run on natural gas without any loss of power. Experience has shown that service life of the turbine will be doubled as a result of the clean burning characteristics of the gas. (4)

### *Comparison of Solution 2 Locomotive with LNG Baseline Diesel Locomotive*

For this comparison, it was assumed that only the traction engine of the diesel locomotive would be converted to LNG since conversion of the HEP engine could mean a 45% increase in its size. Use of two HEP units seems impractical because of the complexities of phase matching the two outputs or dividing the train’s auxiliary power systems. Figure 9 is a bar chart comparing the emissions per trip for the diesel locomotive LNG conversion and the Solution 2 diesel#2 fueled TF15 locomotive. Note that nitrous oxide (NOx) emissions are about the same for both configurations but that the Solution 2 total emissions are 26 kg (36%) lower than the LNG diesel locomotive as a result of lower carbon monoxide (CO) and hydrocarbon (HC) emissions.

### *Direct Comparison of LNG Baseline Locomotive and LNG Solution 2 Locomotive*

Although the previous chart indicates that acceptable emissions performance can be attained with the diesel#2 fueled gas turbine, it is worthwhile to show the added benefits of the LNG Solution 2 locomotive. The bar chart of Figure 9 adds the bar graph for the LNG Solution 2 locomotive to permit a direct comparison of the three configurations. Note that all of the emissions of the Solution 2-L locomotive are measurably lower than the Baseline-L resulting in a total emissions reduction of 33 kg/trip (46%) and the benefit for the Solution 2-L conversion is 7 kg/trip (10 percentage points).

Table 3 summarizes the fuel data. Note that the cost per trip for Solution 2, Diesel #2 fueled TF15 gas turbine traction power and diesel HEP, is more than $12 less than the baseline diesel locomotive fueled with LNG and Solution 2 provides a 26% improvement in emissions.

## DISCUSSION

As noted above, a more comprehensive simulation study of a typical commuter route would likely produce more precise data, however, its is unlikely that the relationships developed in this paper would show significant change. Prices of both diesel #2 fuel and LNG tend to fluctuate with market conditions but their relationship can be expected to remain about the same. The primary goal of achieving a major reduction in particulate matter is not only achieved with the proposed retrofit but overall emissions are also reduced 50% with only a 7% increase in diesel fuel consumption. Particulate traps can be used for particulate reduction but their effectiveness is limited and all other pollutants remain unchanged. While the reduced weight of the locomotive will reduce normal axle loading with a consequent reduction in available tractive effort, this is of minor consequence in commuter operations where tractive effort seldom approaches adhesion limits above 15 mph. Modern traction control systems can handle this without difficulty.

Liquefied natural gas is only one of a number of alternative fuels that can be used to fuel gas turbines such as the one described here. As an example, ethanol will provide similar emissions to LNG although the cost per unit of energy is higher. The use of biofuels, including both ethanol and vegetable based ethyl ester fuels, in a gas turbine locomotive was covered in previous work. (9) While the locomotive in that case was for high speed operation, similar results can be anticipated for commuter service with a recuperated gas turbine. The diesel electric commuter services in North America use over 40 million gallons of fuel each year. Conversion to LNG fuel would divert all of this to other uses. Use of a 50% diesel-vegetable biofuel blend would divert 20 million gallons of fossil fuel. The cost of the biofuel diversion would be high, 2.5 times present fuel costs, but this could be expected to decline as volume production of the biofuel reduced its cost.

A service trial on an actual diesel #2 fueled gas turbine locomotive is the next step toward implementing this clean air modification. To accomplish this, a detailed design covering all aspects discussed here plus intake filtering design, exhaust design and acoustics must be developed. A sponsoring agency will be required to bring together the required, funding and skills. The service trial should include full evaluation of the technology plus operation hauling passengers in a commuter train for at least four seasons to develop unique characteristics as well as projected maintenance needs.

## References

1. Air Resources Board, California declaration- ARB1998b
2. Saricks, C. L. et al, Alternatives to Diesel Fuel in California, Fuel Cycle Energy and Emission Effects of Possible Replacements Due to the TAC Diesel Particulate Decision, TRB, National Research Council, Paper 00-0513, Table 1.
3. American Public Transit Authority, Commuter Rail Transit Agencies, http//www.apta.com/stats/modesum/cragency.htm
4. Pier, J. R., Alternative Fuel-Powered Gas Turbine Locomotive, TRB, National Research Council, Annual Meeting, January, 1994

5. Horan, R., Textron Lycoming AGT1500 Engine-Transitioning for Future Applications, ASME 92-GT-436
6. AGT1500 Turbine Technology, Publication 10913000, Textron Lycoming 1991 (Available from Honeywell Engines, P.O. Box 52181, Phoenix, AZ 85072-2181)
7. Fritz, S.G., Southwest Research Institute, Report to Southern California Regional Rail Authority, February, 1992
8. Gas Rail USA Reduces NOx by 75 Percent, Southwest Research Institute News Release, May 29, 1998
9. Pier, Jerome R., Comparison of Biofuels in High Speed Turbine Locomotives, *In Transportation Research Record 1691,* National Research Council, Washington, DC, 1999, pp 24-32.

## LIST OF TABLES AND FIGURES

## TABLE 1 Estimated Train Weight Calculations

| ITEM | WT-TONNES | WT-TONS |
|---|---|---|
| BASELINE TRAIN WEIGHT* | 722.54 | 796.60 |
| LOCOMOTIVE ENGINE | -19.73 | -21.75 |
| EXISTING ALTERNATOR | -9.07 | -10.00 |
| SMOOTHING REACTOR | -0.23 | -0.25 |
| HEP ENGINE | -1.98 | -2.18 |
| THREE GAS TURBINES | 3.40 | 3.75 |
| TWO 3000 RPM ALTERNATORS | 3.50 | 3.86 |
| TWO RECTIFIERS & REACTORS | 1.36 | 1.50 |
| NET WT | 699.79 | 771.52 |
| DELTA WEIGHT | -22.75 | -25.08 |
| % REDUCTION | 3.1% | 3.1% |

*** Baseline Train= Locomotive + 9 Bi-Level Cars, 1 Cab Car and 1618 Seated Passengers**

**TABLE 2 SCRRA*-San Bernardino Line**
**Time Per Throttle Notch Position (7 )**

| NOTCH | Time-Hr | % Time | RPM | kW | BHP |
|---|---|---|---|---|---|
| 8 | 0.356 | 26% | 903 | 2395 | 3210 |
| 7 | 0.014 | 1% | 821 | 1895 | 2540 |
| 6 | 0.096 | 7% | 726 | 1268 | 1700 |
| 5 | 0.069 | 5% | 649 | 1037 | 1390 |
| 4 | 0.178 | 13% | 566 | 791 | 1060 |
| 3 | 0.137 | 10% | 491 | 533 | 714 |
| 2 | 0.096 | 7% | 339 | 276 | 370 |
| 1 | 0.123 | 9% | 339 | 154 | 207 |
| DLE-LOW | 0.302 | 22% | 201 | 7 | 10 |

*** Southern California Regional Rail Authority**
**** Data from Southwest Research Institute 1993 Report**

**TABLE 3 Fuel Data**

| Item | Diesel #2 | LNG |
|---|---|---|
| Lower Heating Value-mJ/L(Btu/Gal) | 36(128,980) | 21.8(78,000) |
| LHV Ratio-D2/LNG | 1.65 | 1 |
| Cost/Liter-$ | 0.24 | 0.17 |
| Cost/Gallon-$ | 0.91 | 0.65 |
| Cost/Trip-Baseline-$ | 127.03 | 147.54 |
| Cost/Trip-Solution 2-$ | 135.24 | 157.08 |

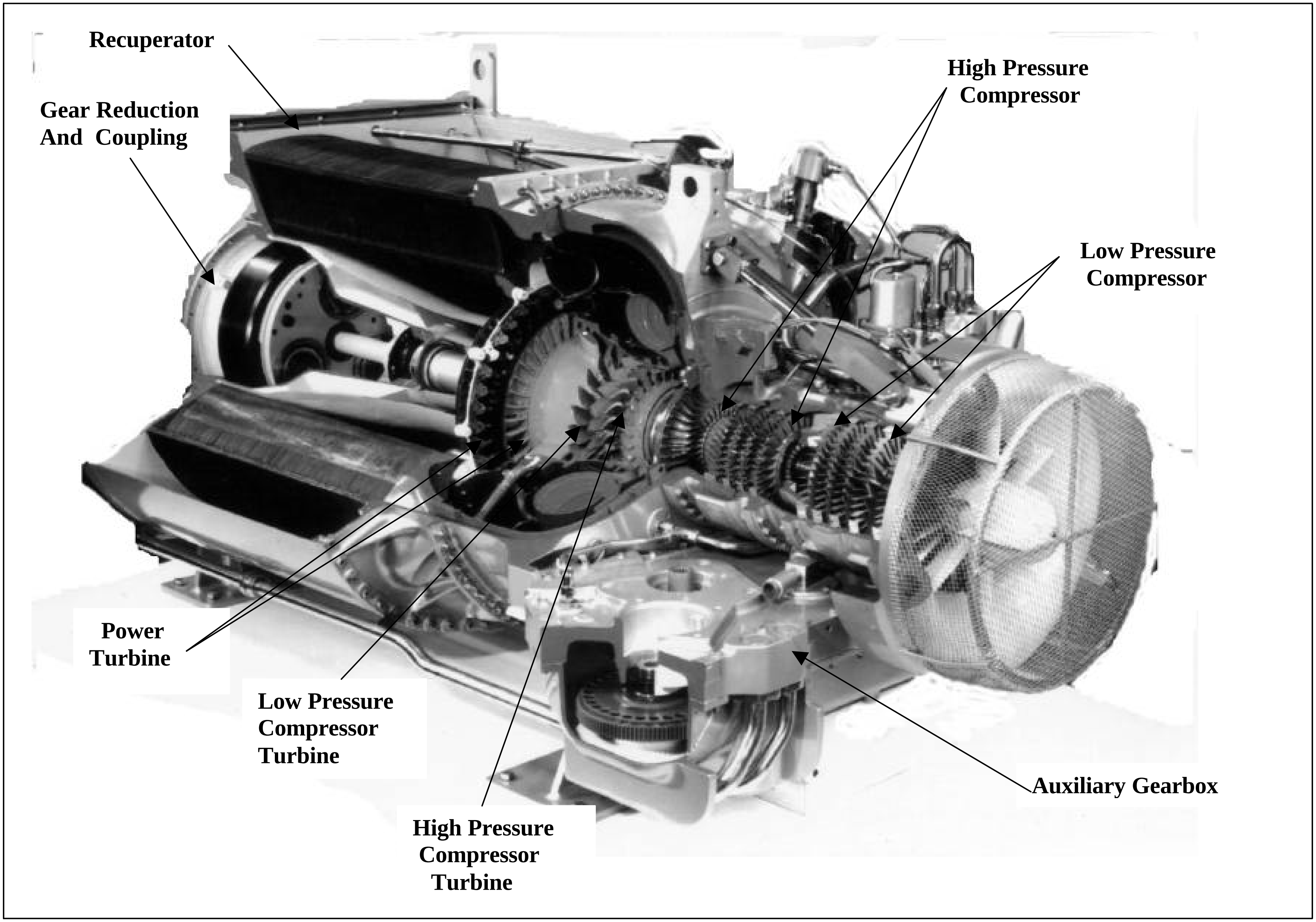


**FIGURE 1 TF15 Gas Turbine, Cut-Away View**

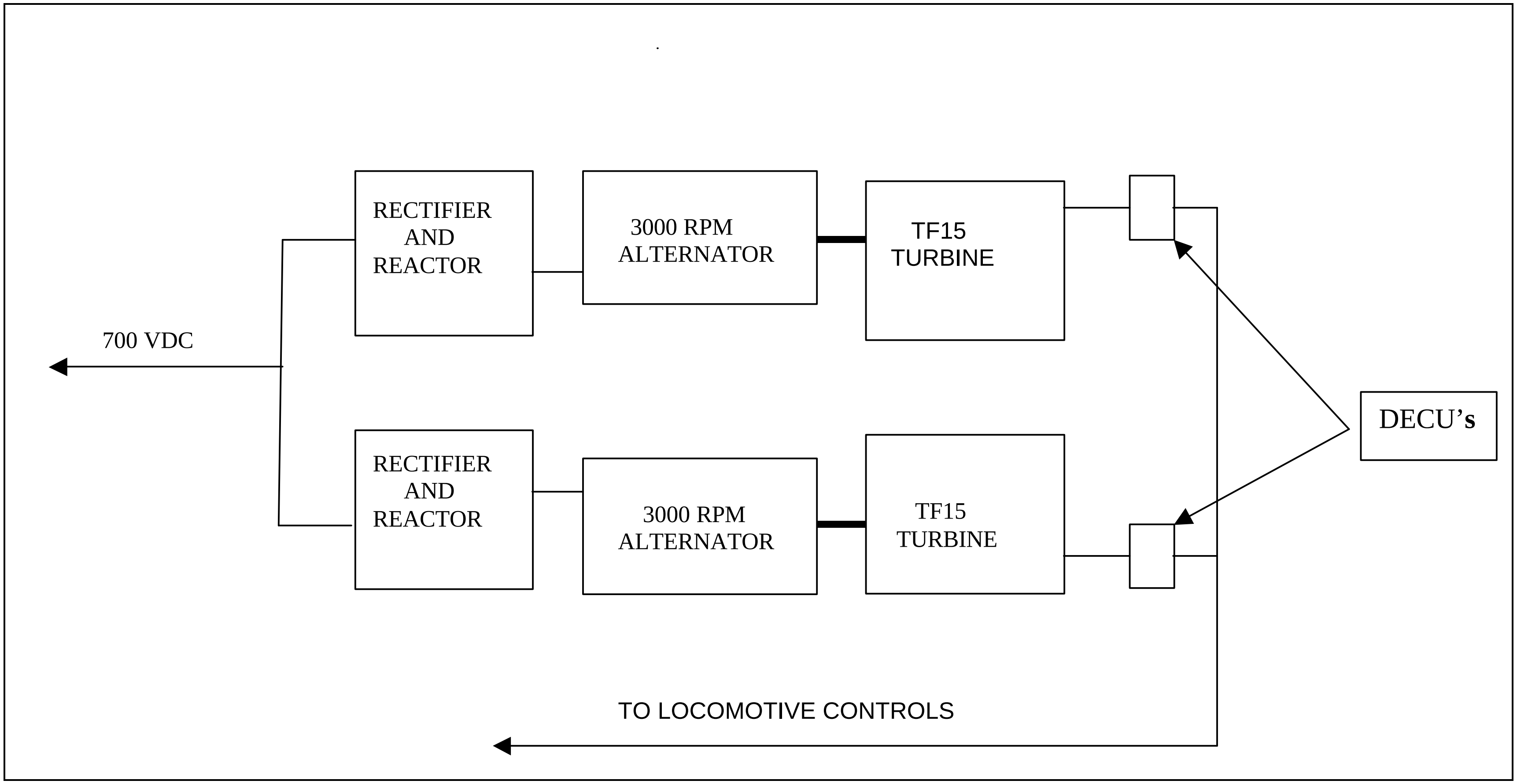


**FIGURE 2 Twin Turbine/Alternator Block Diagram**

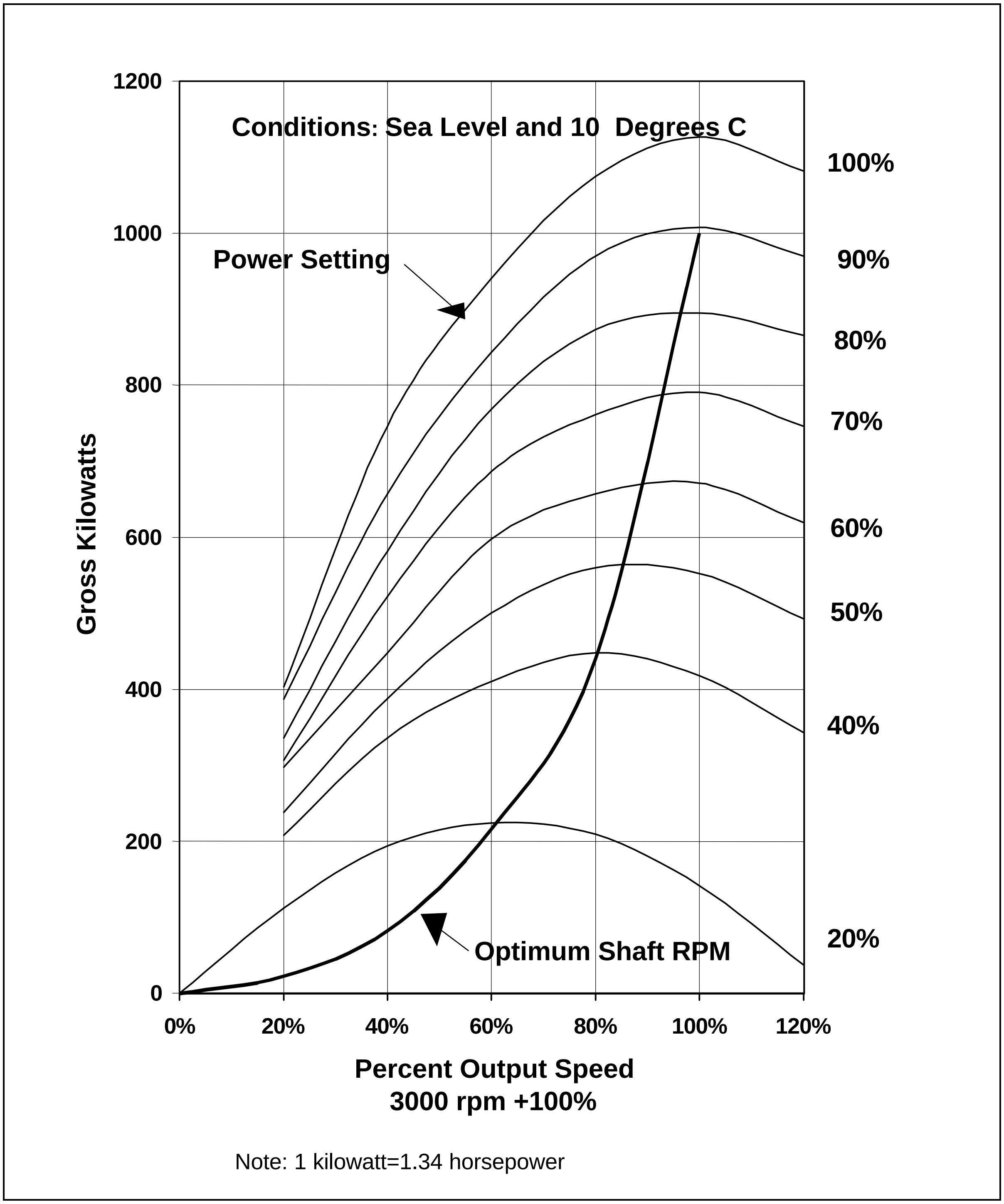
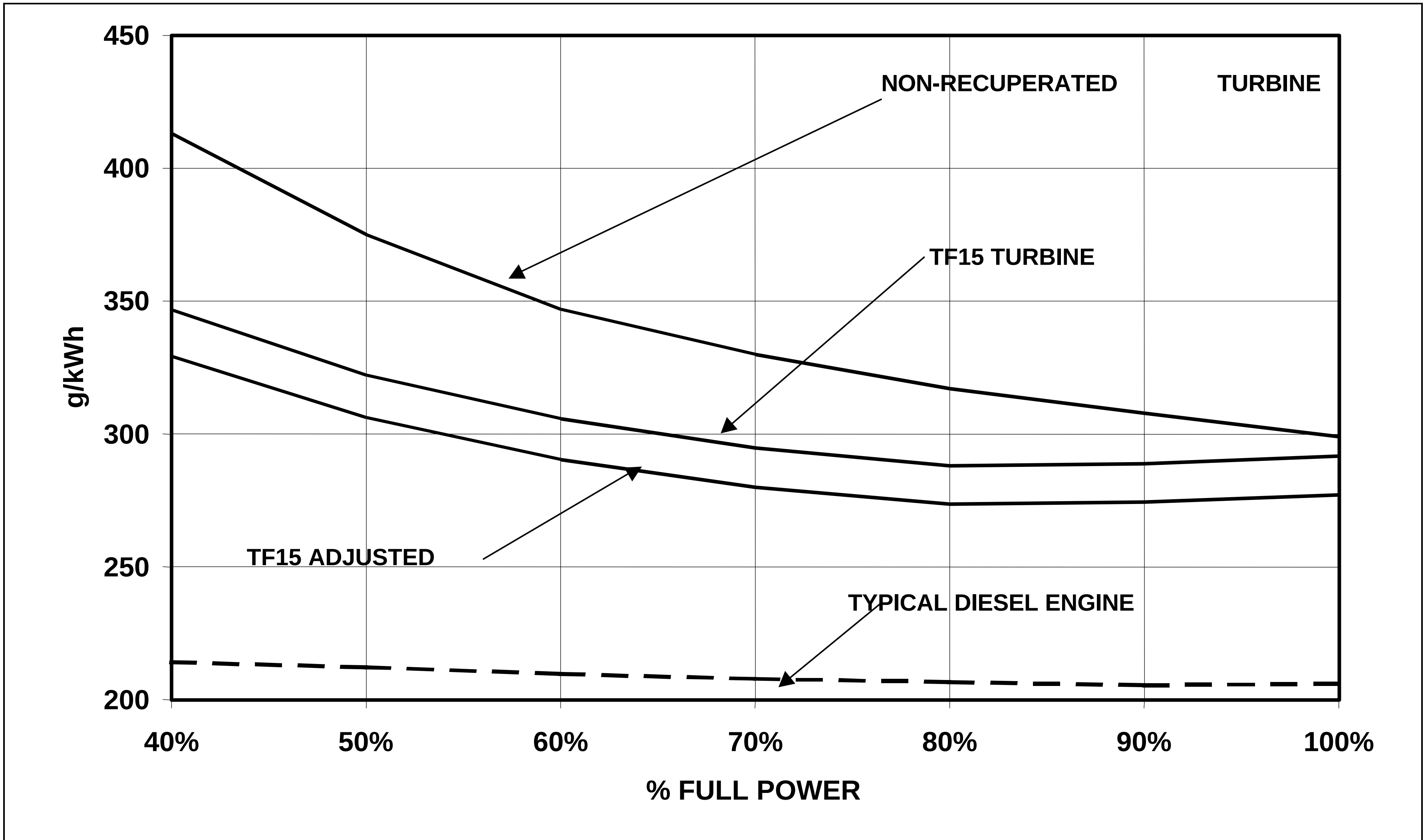
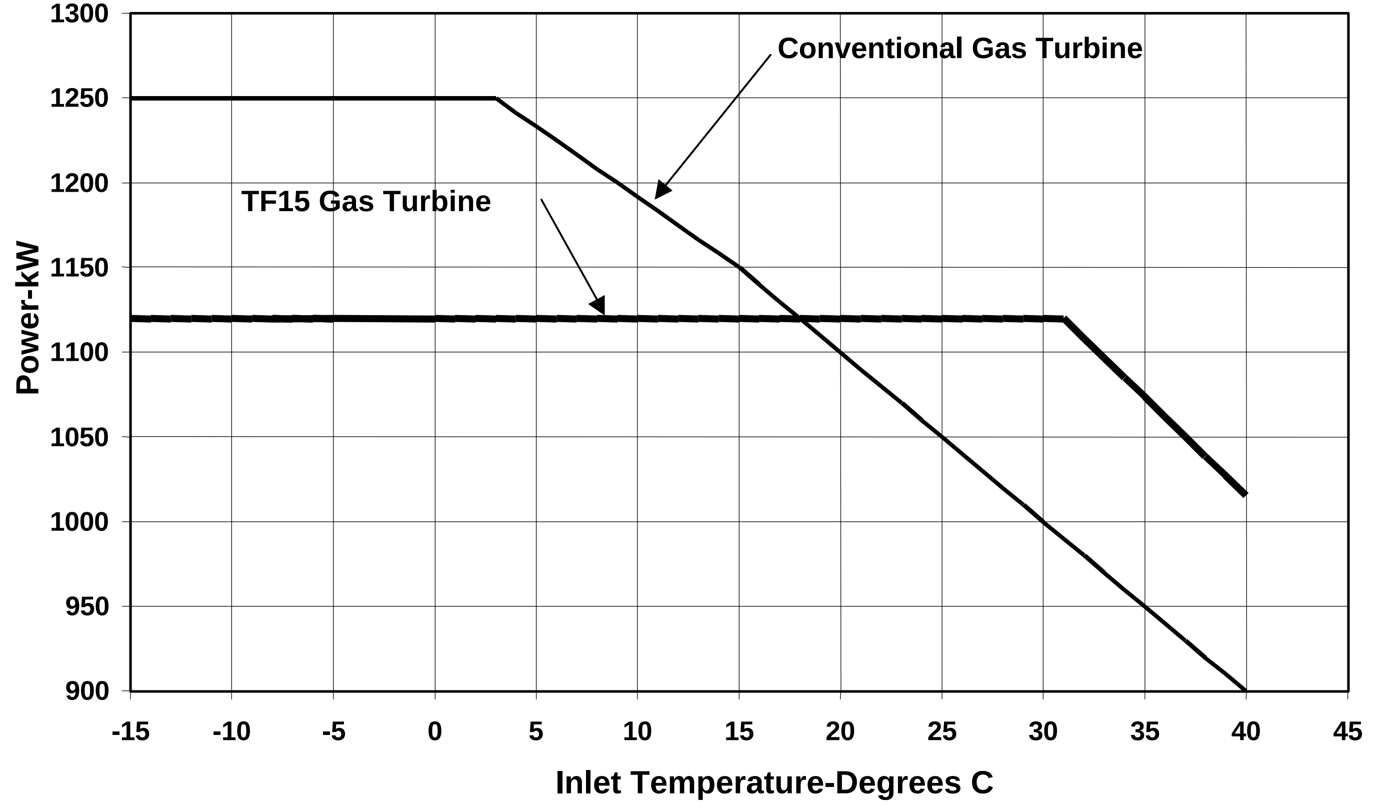


**FIGURE 3 Gross Power Vs Percent Speed**



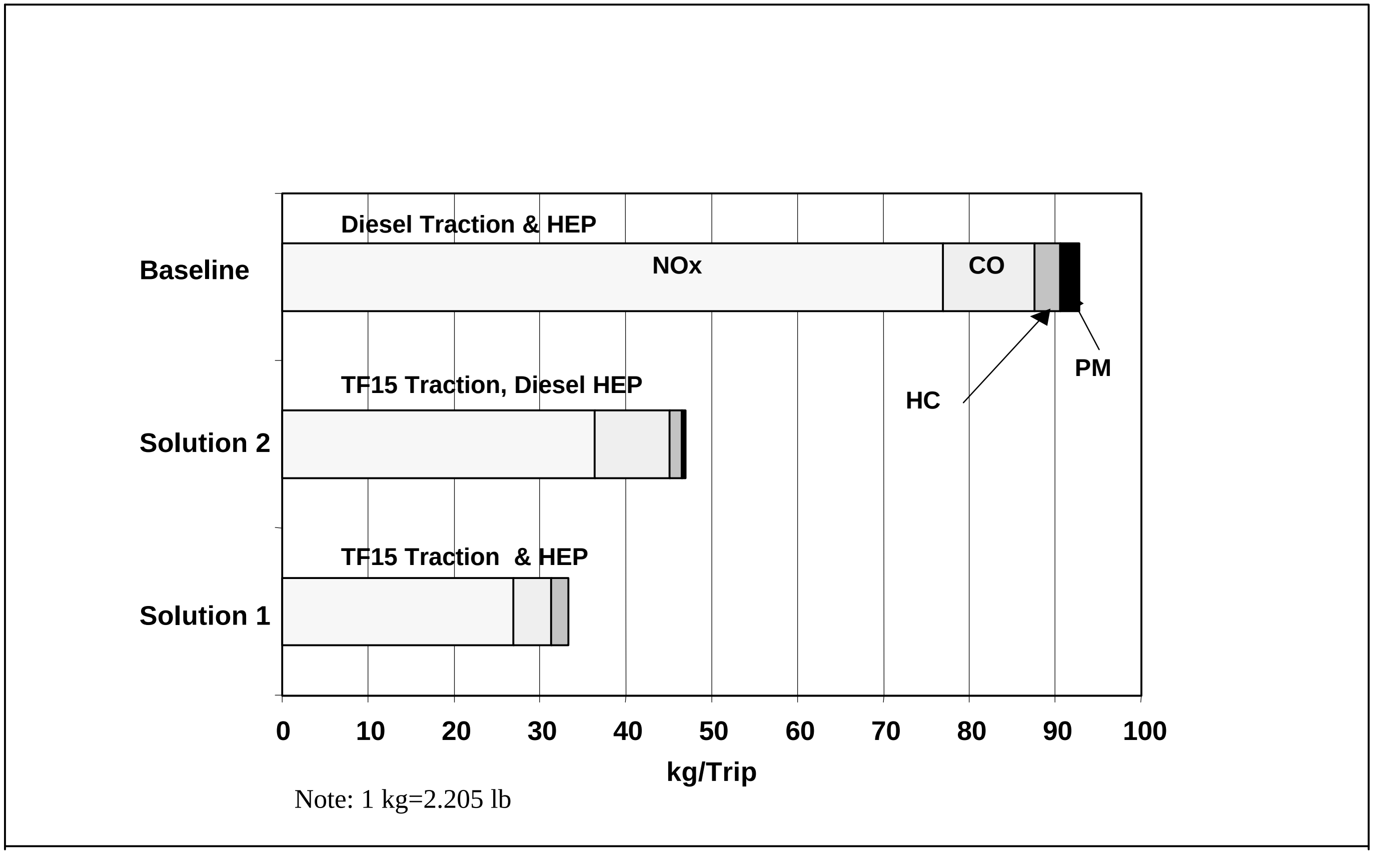
Note: 1 g/kWh= 0.00165 lb/bhp-hr

FIGURE 4 SPECIFIC FUEL CONSUMPTION



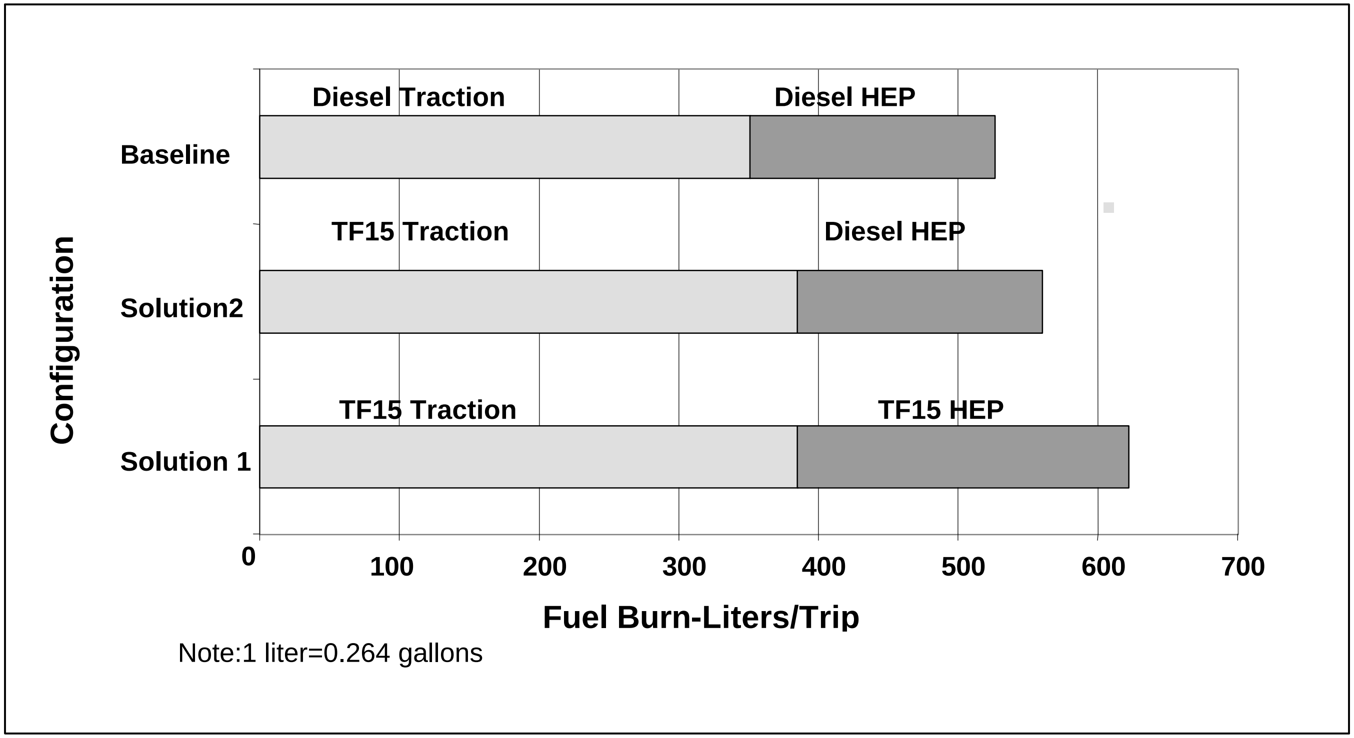
**Note: 1 kW=1.34 HP and 1 degree C=1.8C+32 Degrees F**

**FIGURE 5 Power vs Inlet Temperature**



Note: 1 kg=2.205 lb

**FIGURE 6 Emissions for Various Locomotive Configurations**



Note:1 liter=0.264 gallons

Figure 7 Fuel Burn For Various Locomotive Configurations

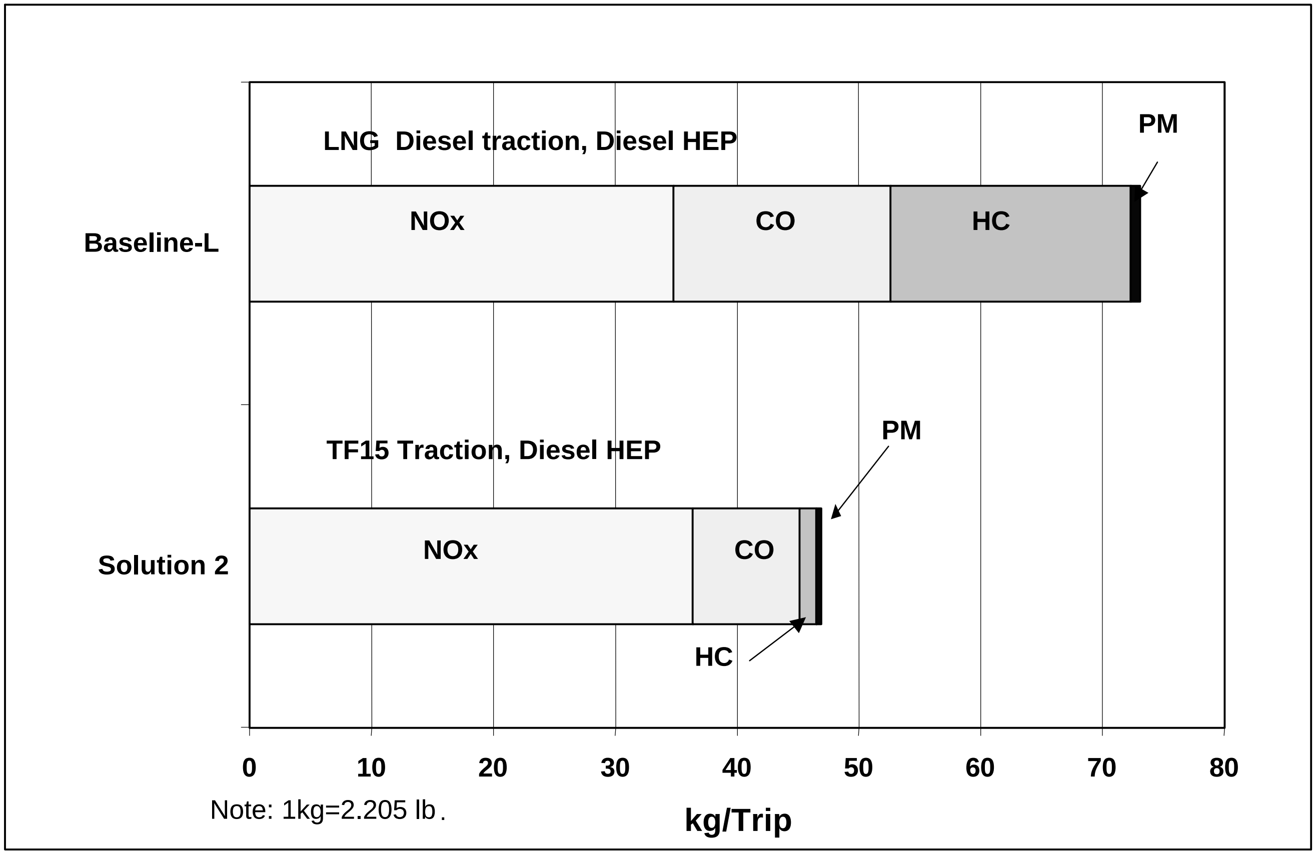


**Figure 8 Solution 2 Emissions Comparison with LNG**

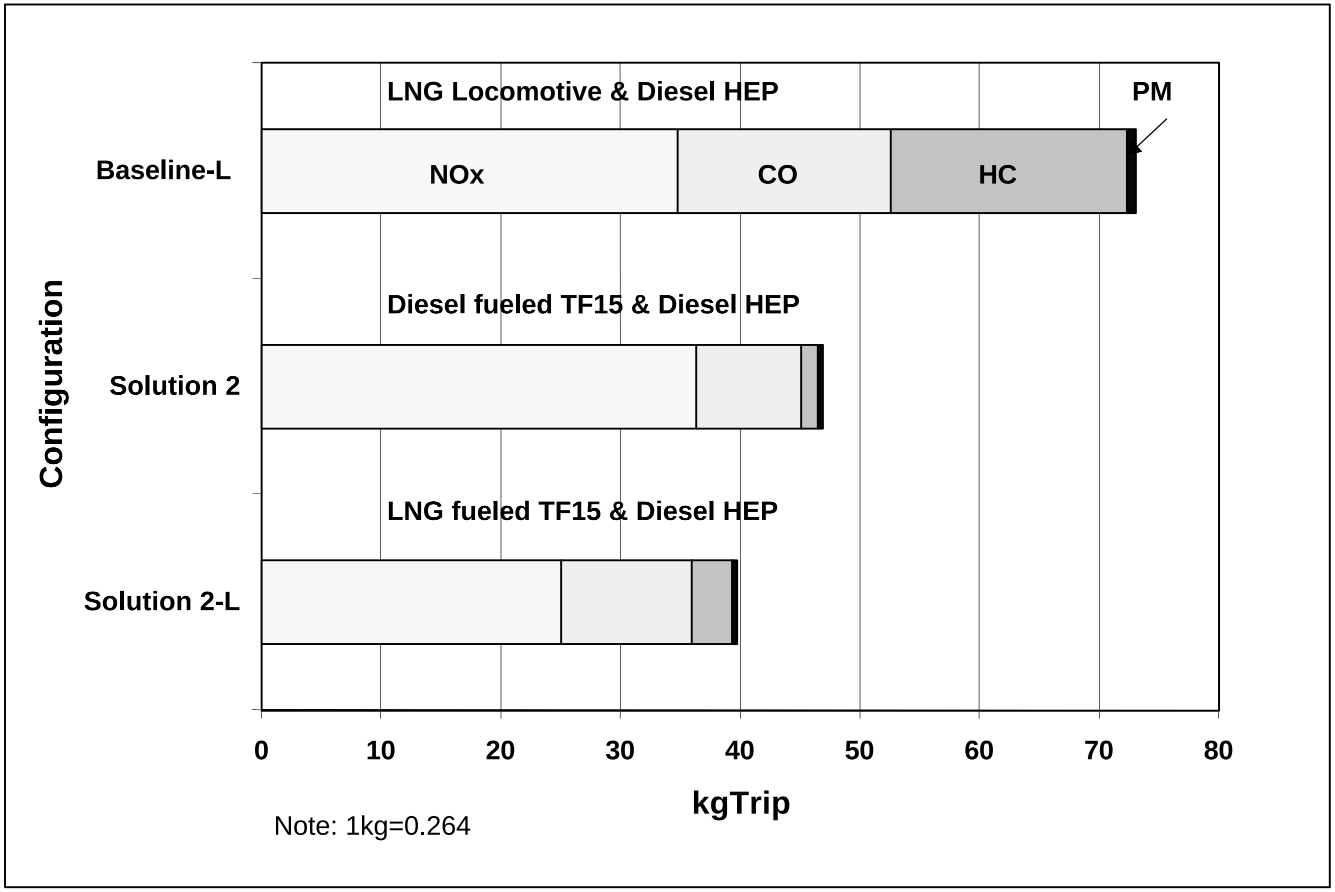


**Figure 9** LNG Emissions Comparison