990207

COMPARISONS OF BIOFUELS IN HIGH SPEED TURBINE LOCOMOTIVES: EMISSIONS, ENERGY USE AND COST

J.R. Pier
Technical Consultant
Allied International Corporation
22 Woodend Drive
Carlisle, Ontario
Canada L0R 1H2
905 690 1892
FAX 690 1893
E-Mail-jrpier@worldchat.com

Consultant to
Northeast Regional Biomass Energy Program

Rev “A”

ABSTRACT

This paper compares the performance of a 4000 HP (2984 kw) gas turbine powered passenger locomotive fueled with selected biofuels with that of the same locomotive fueled with diesel #2. The process of selecting the fuel from a detailed evaluation of thirteen readily available biofuels is explored and then a simulation of operation in a real high speed corridor is used to develop exhaust emission values in terms of tons (tonnes) per year for a complete service and then in terms of pounds (grams) per trip of primary smog producing pollutants. Energy use and costs per trip are developed from the same simulation. All of these values are compared with diesel #2 values developed in previous work. Biofuel use with respect to turbine maintenance costs are discussed.

The implications of carrying and delivering the fuel on a locomotive are also explored in terms of projected range with a given fuel tank size and minimum fuel tank size required to serve a typical corridor.

Key Words: Biofuel, Alternate Fuel, Gas Turbine, Locomotive

1.0 INTRODUCTION

The primary goal of this effort was to establish the practicality of using a biofuel in a railway application, such as the gas turbine presently operating in the RTLII Turboliner Train or a higher powered turbine locomotive, from the standpoint of general compatibility with the turbine, procurement and handling of the fuel, emissions based on an Empire Corridor or equivalent simulation and projected operating cost. For the purposes of this discussion, Empire Corridor refers to the line segment between New York City and Schenectady NY. It is anticipated that the data produced will have broad applicability to any gas turbine powered railway motive power.

This paper describes the evaluation of a number of biofuels, the methodology for narrowing the choice to one or more fuels for the simulation program and discusses the output of the simulation and its implications for initiating further studies.

2.0 FUEL SURVEY

The effort involved the survey, as a minimum, of five biofuels:

1. Rapeseed Ethyl Ester (REE)
2. Soy methyl Ester (SME)
3. Hydrogenated Soy Ethyl Ester (HySEE)
4. Pyrolysis Oils from Wood (PO)
5. Ethanol (ETOH)

Evaluation of each biofuel was to be based on:

- Availability
- Compatibility with the turbine fuel delivery system over a temperature range of -30°FDB to 115° FDB (-34°CDB to 46°CDB)

- Energy content
- Emissions
- Cost/gallon (liter) based on projected use.

2.1 **Availability**

To determine required available volume, annual fuel consumption for the Empire corridor service was calculated for each fuel. The average demand for all fuels except ETOH, which is readily available in any quantity, was about 300,000 gallons (1,135,500 liters)/year. A review of the sources for each fuel indicated that this was a reasonable economic quantity although a plant would have to be built for HySEE production. Use of biofuel/diesel blends obviously reduces demand proportionately. Based on this information, availability became a non-issue in subsequent evaluations.

2.2 **Compatibility with Fuel Delivery System**

Compatibility with turbine fuel delivery systems was determined to be primarily a function of fuel viscosity at 104°F (40°C) and, in the case of ETOH, material corrosion. Since diesel #2 fuel normally is heated for low temperature operation, heating of the biofuels was considered reasonable as long as no chemical change of the fuel was incurred (*1)*. Use of ETOH in the pure state or as a blend would probably require replacement of any white metal or aluminum in the system as well as some elastomerics *(2).* Consultation with the turbine builder resulted in a maximum dynamic viscosity limit of 12 centistokes as a criteria. All of the fuels except PO fell within this range. However, research into the characteristics of PO fuels revealed that blending with ETOH would reduce the viscosity to the desired range*(3)*. Blending of the other fuels with diesel #2 also had a favorable effect on both viscosity and cost. Insertion of the various blends into the program expanded the scope to 13 biofuels. Where complete viscosity data were not available, the desired values were estimated from trend lines.

2.3 **Energy Content**

Energy content was obtained from the following sources:

• Diesel #2	National Biodiesel Board *(4)*
• REE	"Transportation Matters" Vol. 2, Number 1, CONEG Policy Research Center, May 1996, pg. 3 *(5)*
• SME	National Biodiesel Board *(4)*
• HySEE	Pacific Northwest & Alaska Regional Biomass Energy Program, 1996 Yearbook *(7)*
• PO	Orenda Aerospace Corp. Report*(8)*
• ETOH	Fuemeto, "What Kind of Fuel Am I" *(9)*

2.4 **Emissions**

Emissions data were obtained from the following sources:

• Diesel #2	Textron Lycoming (ASE) Fax, H. Rubenstein-J. Pier, 4 Feb 93
• REE	Charles Peterson, Univ. of Idaho *(6)*
• SME	National Biodiesel Board *(4)*
• HySEE	Pacific Northwest & Alaska Regional Biomass Energy Program, 1996 Yearbook *(7)*
• PO	Orenda Aerospace Corp. Report *(8)*
• ETOH	Allied Signal Engines (TF40 gas turbine manufacturer)

The REE, SME and HySEE data were for small diesel engines. These were converted to 4000 HP (2984 kw) turbine data by parametric methods as follows:
Assumptions:
1) Emissions characteristics of truck diesel and the GE 12-7FDL locomotive engine are similar (Both are 4 stroke cycle engines)
2) Emission values in grams/BHP-hr for the 12-7FDL and TF40 gas turbine at 100% power are comparable
3) Ratio of TF40 emissions to the 12-7 FDL engine applied to small truck REE emissions will adjust these emissions to anticipated gas turbine values.

As an example, the 12-7FDL engine NOx emissions are 8.5 g/BHP-hr and the TF40 NOx emissions are 2.0 g/BHP-hr yielding a ratio of 2.0/8.35=0.235. The REE NOx emissions of 5.9 g/BHP-hr for the diesel truck are adjusted by multiplying 0.235 X 5.9=1.4 g/BHP-hr. This procedure is followed for each pollutant.

Actual test data are available for ethanol (ETOH).

The other fuel emissions data were for gas turbines. In lieu of actual test data, emissions for the fuel blends were assumed to be the sum of the proportionate values for each component.

2.5 **Cost**

Cost data were acquired from the following sources:

• Diesel #2	AAR Book of Railroad Facts (1997) for the 1996 year *(10)*
• REE	University of Idaho Rept. 302, Sept. 1996, pg. 31, *(6)*
• SME	Methodology of (6) used
• HySEE	Pacific Northwest & Alaska Regional Biomass Energy Program, 1996 Yearbook, pg. 30, *(7)*
• PO	National Renewable Energy Laboratory (NREL) Rept., 2/27/97 *(11)*
• ETOH	Nebraska Energy Board (NEB) Energy Office, Governors' Ethanol Coalition (GEC), Appendix "C" *(12)*

Cost data for blended fuels were calculated from the costs of the primary component and the blend component.

3.0 EVALUATION

The characteristics of the various fuels and blends were tabulated as shown in Tables 1a, 1b and 2. Since diesel #2 is the baseline for comparison, a ratio of each significant biofuel characteristic to diesel #2 was calculated and tabulated as well. Each fuel was then ranked for each characteristic with respect to its relationship to the baseline fuel. Some general observations on each fuel follow below:

3.1 REE Biofuel

REE fuel is made from Rapeseed (Canola) which is an easily cultivated grain. Its cost is governed by the cost of the basic feedstock, which in this case is about $0.13/lb. ($0.29/kg) *(6)*. At this level its cost per unit of energy in the pure state is almost 3 times that for diesel #2. At a 50% blend it's cost is only 1.7 times diesel #2. The total emissions for pure REE fuel are 75% of those for the baseline fuel and 78% for the 50 % blend. Since viscosities fall well within the guideline, cost and emissions become the determinant selection factors.

3.2 SME Biofuel

SME fuel is made from soybeans, another easily cultivated crop, in a process similar to that for REE except that it uses methanol instead of ethanol in the transesterification process. Feed stock cost at the time of this effort was $0.12/lb ($0.26/kg) yielding an equivalent energy cost for the pure fuel which is about the same as REE and this holds true for the blends as well *(5)*. The emissions for SME are also about the same as for REE as are viscosities *(13)*. Once again, cost and emissions govern the choice of fuel.

3.3 HySEE Biofuel

HySEE is a product of waste vegetable and animal fat oils used in making french fries and other deep-frying operations. This oil costs about $0.11/lb ($0.24/kg) compared to $0.30/lb ($0.66/kg) for new vegetable oil. Making biofuel from waste oil is still in the experimental stages but offers potential cost advantages at the expense of emissions which are higher than those for REE or SME but still lower than those for diesel #2. The only available HySEE emissions data were expressed in terms of grams/mile for a John Deere 4239T test engine*(7)*. Since there was no readily available method of converting these values to grams/HP-hr, a simple ratio of the presented HySEE to diesel values was used. There is slightly less confidence in these converted values than for those discussed above. Viscosities are within the guidelines.

3.4 PO Biofuel

Pyrolysis oils as referred to in this work are produced through flash pyrolisis of wood waste. The oil produced has a dynamic viscosity of 18 to 25 centistokes, similar to that for "bunker C" fuel oil. Viscosity can be reduced by heating just prior to injection but temperature can not exceed 194°F (90°C) or chemical breakdown will occur.*(11)* Viscosity can also be reduced by blending with alcohol. Specific data for a 90-10 blend were available in the literature *(8)* and a 70/30-blend value was deduced by means of trend analysis. The heating value of PO is only 59% of diesel #2 but its cost is quite low at $0.47/gallon ($0.12/liter) so the equivalent energy cost is only $0.80/gallon ($0.21/liter). The major concern with pyrolysis fuels is the levels of contaminants, i.e., alkali, ash, char and tar which may be carried over from the combustor. *(8)* This can be addressed with an external combustor in stationary turbines but presents a larger problem with aeroderivitive gas turbines such as being considered in this study. The combination of high viscosity, low heat content and low volatility requires the use of a separate starting and shutdown fuel which isn't desirable in a locomotive application. (This situation prevailed in the "bunker C"-fueled gas turbine locomotives on the Union Pacific RR in the 60's and contributed to the demise of these units. Dual fuel is not desirable in a locomotive application.) The alcohol-diluted fuel might be better in this respect but the contaminants problem would still exist, leading to reduced life. Experimental work on a stationary gas turbine is continuing in Canada but an application with the TF40 gas turbine in this project does not seem wise at this point.

3.5 ETOH Biofuel

ETOH is probably the best known of the biofuels, in fact approximately 50 million gallons (189 million liters) are devoted to transportation uses in the Northeast each year, most of it in fuel blends. *(12)* It can be produced from any vegetable feedstock such as grains. However to get the price down, it will probably be necessary to go to celluosic biomass (CB) such as agricultural residues, grasses, trees, waste paper and the biomass fraction of municipal waste. This could result in a cost of $0.60/gallon ($0.16/liter), according to DOE estimates, as opposed to the present market price of $1.25/gallon ($0.33/liter). *(12)* The heat content of ETOH, while higher than methanol, is still only 63% of diesel #2 leading to an equivalent energy cost which is three times higher. Emissions from ETOH, as provided by the turbine builder, Allied Signal Engines, at 48% of diesel #2 are the lowest of any of the fuels evaluated. Its clean burning characteristics extend turbine life, possibly by as much as 100% based on experience with natural gas which has similar characteristics). Its disadvantages, in addition to its cost, are low vapor pressure leading to rapid evaporation and its miscibility with water, both of which contribute to handling problems. It also burns with an invisible flame, which is good for the turbine but creates a safety hazard outside of it (9*)*. With cost and emissions being the primary selection criteria, a 50% reduction in ETOH cost would make it a major contender.

4.0 NARROWING THE CHOICE

To provide a rationale for narrowing the fuel choices based on cost and emissions, Table 3 was constructed showing the ranking of each fuel based on the sum of the cost and emissions rankings. Although HySEE ranked #2 by these methods it was set aside because of questionable production availability and lower confidence in the emissions values. This left REE 20, ETOH and REE 50 in that order. To further narrow the choice, each of these fuels was evaluated in a computerized train simulation program as described below:

5.0 SIMULATION

Since a well documented simulation was available from previous work. *(14)* it was proposed that this work be used to further refine the final choice of a fuel. Although this simulation was for the Boston-New York City Corridor rather than the Empire Corridor, it offered a valid comparison at an appreciable saving in time and money. The Northeast Regional Biomass Program (NRBP) therefore approved this approach.

5.1 The Model

The application for which most high-speed locomotives will be used in North America is anticipated to be corridor service between city pairs separated by 200 to 500 miles (322 to 804 km). The use of existing rights of way and establishment of frequent train departures dictates relatively short trains with high power to weight ratios and the ability to negotiate curves at high speed with minimum passenger discomfort. For the simulation model, the Boston-New York City Corridor was selected, even though it is in the process of being electrified, because it is typical and because it is a well established route for which validated simulations are available. The train is a locomotive-4 coach consist 408 feet (124 meters) long and weighing 292 tons (265 tonnes) at a 65% load factor. Gross power to weight ratio is 12.8:1 assuring good acceleration coming out of the many curves on the system and permitting top speeds over 125 mph (200 km/hr) on the few straight stretches of track. The locomotive traction power is provided by a modular, non-recuperated dual shaft 4000 HP (2984 kw) Allied Signal Engines TF-40 with cold-end drive. The coaches incorporate active tilt systems with aluminum bodies to maintain reasonable tare weights while meeting FRA strength requirements. The tilt feature permits operation at 9 inches (229 mm) of cant deficiency providing a significant improvement in average speeds. For purposes of determining annual emission values and maintenance costs, 14 trains per day in each direction operating 300 days per year are assumed.

The computer model generates instantaneous brake horsepower requirements for the simulated trip. Using energy input vs. shaft horsepower data for the TF40 Gas Turbine, the brake horsepower numbers are converted to BTU requirements for the total trip. These are in turn converted to brake horsepower hours/trip to determine total emissions. Total fuel consumption for each type of fuel is determined based on the heat content of the fuel to develop energy costs/trip.

5.2 Fuel Characteristics

The three biofuels to be evaluated are a blend of 20% rapeseed ethyl ester (REE 20) biofuel fuel and diesel #2, a 50% blend of REE biofuel and diesel #2 (REE 50) and ethanol (ETOH). The REE biofuels are assumed to be heated as required to match the viscosity of diesel #2 at 104° F (40° C) (Fig 1). Table 4 compares these fuels to the baseline Diesel #2 fuel in terms of energy content and unit cost (All of the costs are 1996 values). The various alternative fuels have advantages and disadvantages as described in 3.1 and 3.5 above. REE 20 is the closest match to Diesel #2 in terms of energy content but its cost/unit of energy is 57% higher. The viscosity of REE 20 is closest to that of diesel #2 and REE is benign with respect to materials normally used in gas turbines and their fuel delivery systems. This avoids costly development to accommodate the biofuel. REE 50 is similar to REE 20 but with slightly higher viscosity offset by lower emissions. The cost of the feedstock typically constitutes 70% of the final fuel cost making any potential cost improvement subject to improved efficiency on the farm as well as the vagaries of the commodies market.

Ethanol is usually made from grains stocks but can be made from any vegetable matter. While it will remain in the liquid state at normal temperatures, its vapor pressure is very low. Care must therefore be observed to avoid excessive evaporation losses. It is also highly miscible with water making it vulnerable to loss of heating value if exposed to moisture in any form. Ethanol is highly corrosive to many of the materials used in turbine fuel delivery systems making redesign necessary. Formaldehyde can be a product of ethanol combustion. If concentrations are high enough to cause concern, a catalytic converter may have to be installed. Other than meeting the requirements for corrosion resistance and moisture intrusion, fuel tanks for ethanol can be similar to those for diesel fuel. Ethanol availability responds to the market demand as does its price.

Figure 2 illustrates the equivalent range or distance, which can be traveled, for each of the fuels assuming identical 1800-gallon (6813 liter) fuel tanks such as are presently installed on many locomotives. The relationships are more significant than the actual values; a range of 700 miles (1125 km) representing one round trip with at 40% safety margin, might be quite adequate in corridor service. Figure 3 is the inverse of Figure 2, showing the required fuel tank capacity to provide such a range for each fuel. The Diesel #2 and REE tanks are smaller than the 1800-gallon (6813 liter) tanks usually installed on passenger locomotives and it probably is feasible to find space for the 2300-gallon (8706 liter) ethanol tank

5.3 General Simulation Results

Simulation runs for the New York City-Boston Corridor were made for each fuel at 59°F (15°C) and at sea level altitude. These values represent ISO conditions at which all turbines are rated as well as being typical of fall and spring conditions in this corridor. Journey times were 2 hours and 45 minutes. Maximum speed attained was 125 mph (200 km/hr) and average speed, including four intermediate stops, was 84 mph (135 km/hr). The locomotive operated between 89 and 100% of full power for 41.3% of the trip and 61% of the trip occurred at 50% power or more. An objective for efficient non-recuperated gas turbine operation is to run in the most fuel-efficient range as well as to minimize cycling from zero power to full power. While the operation could probably be improved in this respect with fine-tuning of the speed manipulations, it was considered to be representative for this corridor.

5.4 Emissions

All exhaust emissions vary with power level. As noted above, simulation runs were made for ambient temperatures of 59°F (15°C) and time at each power level corresponding to all eight throttle notch positions conventional for locomotives was noted. Emissions at each level were then calculated using the grams/bhp-hr values for each pollutant multiplied by the bhp-hrs. Idling values were obtained by using grams/minute values. The cumulative values were then used to produce the Figure 4 comparison. This chart shows the total of unburned hydrocarbons, carbon monoxide, nitrous oxide and sulfur dioxide emissions measured in tons per year based on the traffic density described above. It can be seen that ETOH produces 91 (51%) fewer tonnes, REE 50 66 tonnes (37%) REE 20, 44 (26%) fewer tons. Although not included in the chart, it might be noted that other studies *(13)* have shown diesel locomotives to produce over 1000 tons (907 tonnes) of pollutants per year and electric locomotives 800 tons (726 tonnes) per year in a similar service. The main purpose of the alternate fuels from an emissions standpoint is reduction of smog producing emissions. This is quite evident in the Figure 5 bar chart showing the annual reduction in NOx and SO_2. The ETOH NOx reduction at 17.8 tons (16.1 tonnes) is 53% below the diesel #2 value, the REE 20 blend is 47% lower and the REE 50 blend is 46% lower. Sulfur dioxide emission reductions, based on 0.28% sulfur in the diesel fuel portion of the blend, are 8.9 tons (7.6 tonnes) per year or 50% for the REE 50 fuel and 3.6 tons (3.3 tonnes) or 20% for the REE 20 fuel. Since ETOH contains no sulfur, its reduction is 100%.

5.5 Energy Use and Cost

The bar chart of Figure 6 shows gallons (liters) used and cost per trip for each fuel. The numbers reflect the heat content per unit volume of the various fuels as can be expected. The fuel costs used are 1996 values from recognized sources. More recent values, when available, may change the absolute values but are unlikely to change the relationships significantly.

5.6 Maintenance Costs

Aircraft derivative gas turbine maintenance requirements have traditionally been defined in terms of a fixed "time between overhaul" or TBO. This approach, which has also been used to some extent with diesel locomotives, is not particularly appropriate to ground transportation. An "on condition" maintenance program is now being offered for many such applications. Sophisticated electronic monitoring systems contribute to both the ease and economics of obtaining continuous records of turbine condition. Modular construction also contributes to efficient maintenance by providing for quick changeout of the lightweight and compact turbine section or sections encountering the most service connected degradation. Cold-end drive design makes the hot end of the turbine, which is subject to the most thermal stress, readily accessible for changeout.

In a typical locomotive installation, a diesel #2 fueled gas turbine engine will require very little periodic maintenance. Since its lubricating oil does not come in contact with the combustion process, oil consumption is negligible and fuel filters are sized for extended service without replacement. Maintenance costs between module replacements are therefore minimal. However, when condition monitoring indicates that component replacement is required, which will typically occur after 12,000 to 15,000 hours of operation depending on the severity of service, the turbine is removed and rebuilt to new condition. Assuming the worst case in terms of service time, cost of the overhaul will be about $0.65 per locomotive mile. *(14)* Turbine module removal and replacement can be accomplished in one shift in a running maintenance facility so that locomotive availability percentages in the high 90's can be anticipated.

While these maintenance cost numbers are very competitive with diesel electric locomotives and superior to North American experience with electric locomotives, stationary power plant experience with natural gas which has similar combustion characteristics to ETOH, shows that for the same duty cycle, overhaul periods will be at least twice as long. This will yield a maintenance cost per mile of $0.33 or less, well below any other power plant type. Maintenance costs for vegetable-based biofuels should be similar to those for diesel #2. *(14)*

5.0 DISCUSSION

On the basis of cost and emissions, the REE fuels fare best. Of this group, REE 50 has the better emissions performance and REE 20 has lower cost. In addition, REE 20 emissions are 26% below that of diesel #2. REE 20 and diesel #2 have essentially the same cost/liter (gallon) of fuel burned in this simulation. . The simulation results have more relative value rather than absolute value because the baseline emissions data are a product of a parametric conversion from small diesel engine data rather than being based on actual test data. The simulation’s primary goal was to assist in narrowing the choice to one or two fuels for test stand evaluation with the subject turbine and the results satisfy this purpose. It would be interesting to have actual test results to use in a simulation but it is unlikely that the relationship between the fuels would change appreciably. However, a simulation for a specific corridor using test emission data would help to quantify the environmental impact of a given fuel in that corridor and could be of significant interest to a given state with a non-attainment area problem.

Of the five fuels evaluated, the vegetable based fuels show the most immediate promise. HySEE appears to have the potential for lower costs and progress in its development should be closely monitored. Ethyl alcohol (ETOH) has potential if the Department of Energy cost projections are met. Its emissions performance is excellent and its corrosion problems can be handled. Pyrolysis oils from wood as presently formulated are not a good candidate for use in areo-derivitive gas turbines.

While the incremental improvement in emissions from a diesel #2 fueled gas turbine to a biofuel powered turbine is not as impressive as the 90% improvement achieved in the conversion from diesel engine power to gas turbine power, it should be noted that the biofuel powered gas turbine exhaust will contain less sulfur dioxide in proportion to the blend, a primary component of acid rain, and also will be almost 50% lower in nitrous oxides, a major component of smog.

6.0 CONCLUSIONS

Biofuels offer a renewable gas turbine locomotive fuel source to protect against petroleum fuel shortages while creating a market for agricultural products. Emissions reductions, particularly of smog inducing pollutants, offer significant improvement to the environment. While pyrolisis oils from wood may find an application in stationary gas turbines, problems with high ash and alkali precludes their use in aeroderiviative gas turbines such as those adaptable to locomotive use. Cost of vegetable biofuels is still a problem but higher volume production and more efficient farming methods can be expected to help in this area.

Acknowledgments

The author would like to acknowledge the assistance of Greg Ernst, LDK Engineering, Burlington, Ontario, Canada in conducting the simulations.

References

1. Jerome R. Pier, “Final Report to Northeast Regional Biofuel Program”, Contract NRBP- R2-1500, June 30, 1998, Coalition of Northeastern Governors, Policy Research Center, Inc., 400 North Capitol St, N.W., Washington, DC 20001

2 "Bring on the Alternative Fuels", Advance Materials & Processes, May. 1990. pp 40-41

3. James P. Diebold and Stephan Czernak, National Renewable Energy Laboratory, Golden, CO 80228, "Additives to Lower and Stabilize the Viscosity of Pyrolysis Oils During Storage", Energy & Fuels 1987, Vol 11, 1081-10911990, pp 25-29

4. National Biodiesel Board, P.O. Box 104898, Jefferson City, MO 65110-4898, "The Physical Characterization Of Biodiesel/Low Sulfur Diesel Fuel Blends" Final Report, 30 Dec 1995

5. “Transportation Matters” Vol. 2, Number 1, CONEG Policy Research Center, May 1996, pg. 3

6. Peterson, Professor; D.L. Reece, Research Engineer; University of Idaho, Dept. of Biological and Agricultural Engineering, "Development Of Rapeseed Biodiesel Of Use In High Speed Diesel Engines", For The United States Dept. of Energy, Contract Number 93BIO9233, Progress Report 302, September, 1996, pp 24-31, 54

7. "HySEE Bodiesel Development", Idaho Feature Project, 1996 Yearbook, Pacific Northwest and Alaska Regional Biomass Program, pp 30-31, published by US Department of Energy, Seattle Regional Support Office.

8. R.G. Andrews, D. Fuleki, S. Zukowski and P.C. Patnaik, Orenda Aerospace Corporation, 1420 Blair Place Rd., Gloucester, Ontario, K1J 9L8, "Results of Industrial Gas Turbine Tests Using a Biomass-Derived Fuel", (un-dated, probably 1997)

9. Michael Fumeto, "What Kind Of Fuel Am I?", The American Spectator, November 1990, pp 25-29

10. Association of American Railroads (AAR) Book of Railroad Facts-1997 Edition

11. A.C. Moses and H. Bernstein, "Impact Study Of The Use Of Biomass-Derived Fuels In Gas Turbines For Power Generation", NREL/TP-430-6085, January, 1994

12. Appendix C, "Alternative Fuels Options: Competing In The Marketplace", Governors'

Ethanol Coalition responses to questions posed by The Coalition Of Northeastern Governors, July 28, 1992. Available at ttp:rredc.nrel.gov/biomass/doe/rbep/alt_fuels _2/c.htm

13. Colorado Institute For Fuels And High Altitude Engine Research, "Emissions From Bidiesel Blends And Neat Biodiesl From A 1991 Model Series 60 Engine Operating At High Altitude" Final report to National Renewable Energy Laboratory, September 1994

14. Jerome R. Pier, Technical Consultant, Allied International Corp., "Alternative Fuel-Powered Gas Turbine Locomotive", Presented To The Transportation Research Board Annual Meeting, January 1994, Committee A2MO5. Paper available from Allied Signal Engines, P.O. box 5281, Phoenix, AZ 85072-2181 as publication #2953OLPAPK

TABLE 1a Properties of Biofuels Compared to Diesel #2 Fuel-Viscosity and Energy Content

Fuel	Blend % Biofuel	Specific Gravity	Viscosity Cst-40° C (104° F)	Viscosity Ratio	Btu/Gallon ‘000s (MJ/liter)	Equivalent Volume Ratio
D2	0	0.8399	2.90	1	137.7 (45.4)	1.00
REE	100	0.8760	6.11	2.11	126.9 (41.9)	1.09
REE	50	0.8620	4.06	1.40	132.3 (43.6)	1.04
REE	20	0.8535	3.20	1.10	135.5 (44.7)	1.02
SME	100	0.8855	4.30	1.48	119.3 (39.3)	1.15
SME	50	0.8708	3.39	1.17	128.6 (42.4)	1.07
SME	20	0.8665	2.99	1.03	132.9 (43.8)	1.04
HySEE	100	0.8720	5.78	1.99	133.8 (44.1)	1.03
HySEE	80	0.8620	4.32	1.49	134.7 (44.4).	1.02
HySEE	20	0.8670	3.49	1.20	136.9 (45.1)	1.01
PO	100	1.25	18.5	6.38	81.0 (26.1)	1.70
PO	90/10	1.20	9.30	3.21	82.0 (27.0)	1.69
PO	70/30	1.11	2.40	0.83	83.1 (27.4)	1.66
ETOH	100	0.7893	1.74	0.60	86.6 (28.6)	1.59

Notes:

1) All blends are with diesel #2 except for PO fuels which are with ETOH

TABLE 1b Properties of Biofuels Compared to Diesel #2 Fuel-Cost and Emissions

Fuel	Blend % Biofuel	Specific Gravity	Cost $/Gallon ($/Liter)	Equivalent Energy Cost-$	Euivalent Cost Ratio	Emissions Ratio
D2	0	0.8399	0.68 (0.18)	0.68	1.00	1.00
REE	100	0.8760	2.56 (0.68)	2.78 (0.73)	4.09	0.48
REE	50	0.8620	1.62 (0.43)	1.68 (0.44)	2.48	0.63
REE	20	0.8535	1.05 (0.28)	1.07 (0.28)	1.57	0.75
SME	100	0.8855	2.35 (0.62)	2.71 (0.72)	3.99	0.73
SME	50	0.8708	1.51(0.40	1.62 (0.43)	2.38	1.26
SME	20	0.8665	1.01(0.27)	1.05 (0.28)	1.54	1.16
HySEE	100	0.8720	2.17 (0.57)	2.23 (0.59)	3.28	0.59
HySEE	80	0.8620	1.87 (0.49)	1.91 (0.51)	2.82	0.79
HySEE	20	0.8670	0.98 (0.26)	1.44 (0.38)	1.44	0.92
PO	100	1.25	0.47 (0.12)	0.80 (0.21)	1.18	88.6
PO	90/10	1.20	0.49 (0.13)	0.83 (0.22)	1.37	79.8
PO	70/30	1.11	0.70 (0.19)	1.17 (0.31)	1.72	62.2
ETOH	100	0.7893	1.25 (0.33)	1.99 (0.53)	2.90	0.40

Notes:

1) All blends are with diesel #2 except for PO fuels which are with ETOH
2) For development of emissions ratios see Table 2

TABLE 2: Emissions Of Various Pollutants For Biofuels And Diesel #2 g/BHP-hr (g/kwhr)

Values Based On TF40 Gas Turbine Operating At 80% Power

Pollutant	D2	Hysee 100%	Hysee 50%	Hysee 20%	Ree 100%	Ree 50%	Ree 20 %	Po 100%	Po 90/10	Po 70/30	Etoh 100%
HC	0.02 (0.27)	0.01 (.013)	0.02 (0.27)	0.02 (0.27)	0.01 (0.13)	0.02 (0.27)	0.02 (0.27)	N/A	0.00	0.01 (0.13)	0.01 (0.13)
CO	0.28 (0.38)	0.15 (0.20)	0.22 (0.29)	0.25 (0.36)	1.08 (1.45)	0.68 (0.91)	0.44 (0.59)	N/A	0.05 (0.07)	0.16 (0.21)	0.20 (0.27)
NOx	1.90 (2.55)	1.62 (2.17)	1.76 (2.36)	1.84 (2.47)	1.42 (1.90)	1.66 (2.23)	1.80 (2.41)	1.34 (1.80)	1.30 (1.74)	1.21 (1.62)	1.00 (1.43)
SO2	0.84 (1.13)	0.00	0.42 (0.56)	0.67 (0.90)	0.00	0.42 (0.56)	0.67 (0.90)	0.00	0.00	0.00	0.00
PM	0.00	0.00	0.00	0.00	0.00	0.00	0.00	268.0(359.2)	241.0 (323.1)	187.6	0.00
TOTAL	3.04(4.08)	1.78 (2.39)	2.41 (3.23)	2.79 (3.74)	2.51 (3.36)	2.77 (3.71)	2.93 (3.92)	269.3 (361.0)	242.6	189.0 (253.4)	1.21 (1.62)
Emissions Ratio	1	0.59	0.79	0.92	0.83	0.91	0.97	88.60	79.79	62.16	0.40

NOTES:

1) Diesel #2 emissions are for TF40 dual shaft gas turbine at 80% power

2) Emissions Ratio is biofuel emission total/diesel #2 emission total

TABLE 3 Ranking of Biofuels Compared to Diesel #2 Based on Cost and Emissions

---

RANK	FUEL	BLEND-%BIO	RANK SUM	AVG RANK
	DIESEL #2	100%	1+1	1.0
1	REE	20	5+4	4.5
2	HySEE	20	11+3	7.0
3	ETOH	100	10+1	5.5
4	REE	50	8+4	6.0
5	SME	20	4+9	6.5
6	HySEE	100	11+3	7.0
7	PO	100	1+13	7.0
8	PO	90/10	2+12	7.0
9	REE	100	13+2	7.5
10	HySEE	80	9+7	8.0
11	SME	100	12+5	8.5
12	SME	50	12+5	8.5
13	PO	70/30	6+11	8.5

NOTE: All fuel blends are with diesel #2 except the Pyrolysis Oils (PO) which are with ethanol (ETOH).

TABLE 4 Comparison Of Energy Content And Cost Of Fuels Selected for Simulation

---

Fuel	Btu/Gallon (MJ/Liter)	Cost/Gallon (/Liter)-$	Cost/Mil Btu (/MJ)-$
DIESEL #2	137,704 (45.42)	$0.68 ($0.18)	$4.94 ($0.015)
REE 20	135,543 (44.70)	$1.05 ($0.28)	$7.74 ($0.023)
REE 50	132,302 (43.63)	$1.04 ($0.27)	$7.86 ($0.024)
ETOH	86,000 (28.36)	$1.25 ($0.33)	$14.53 ($0.044)

FIGURE 1
TEMPERATURE INCREASE TO MATCH DIESEL # 2 VISCOSITY AT
104 DEGREES F (40 DEGREES C)

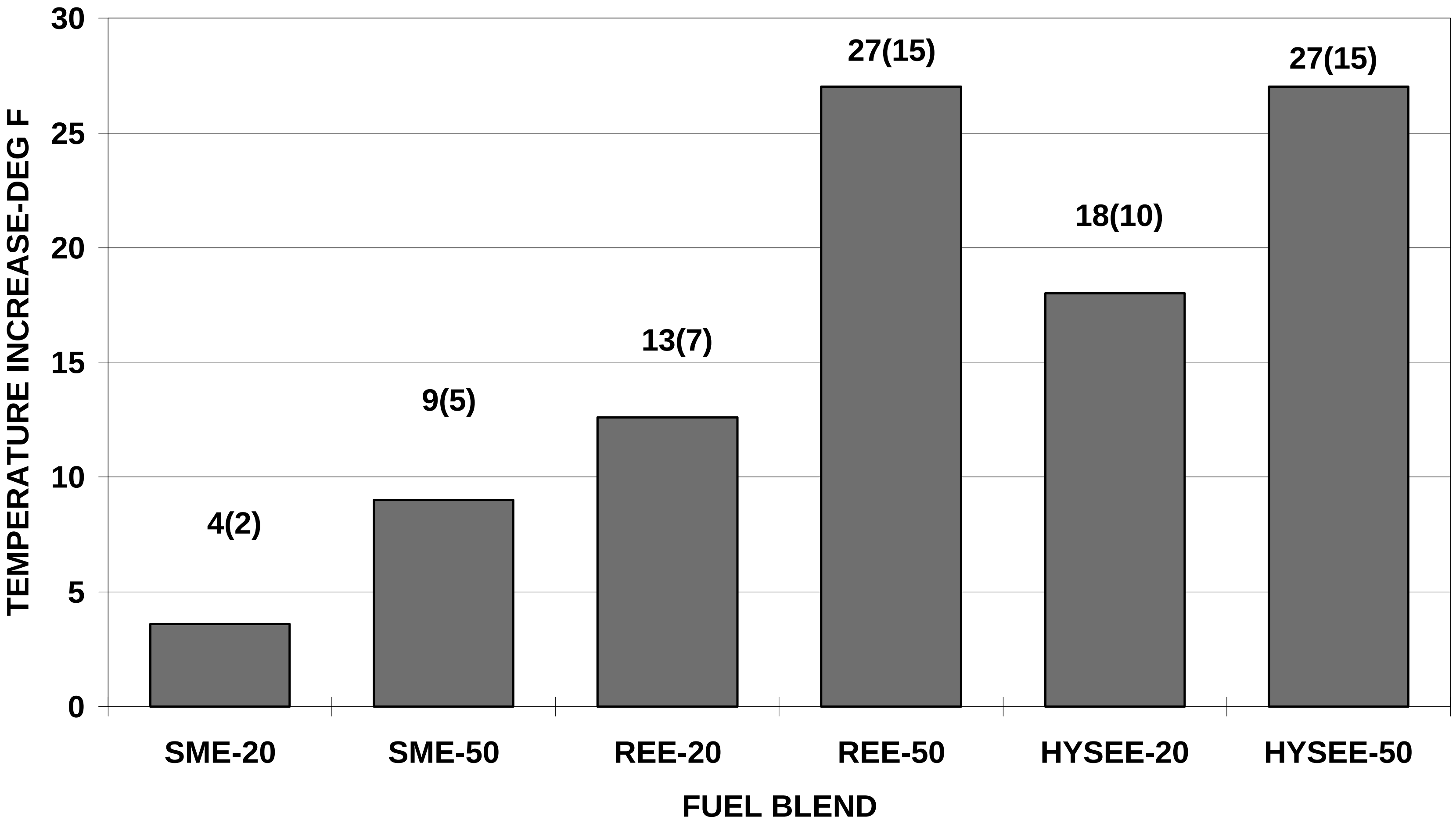


FIGURE 2

RANGE, MILES (KM)-1800 GALLON (6813 LITER) TANKS

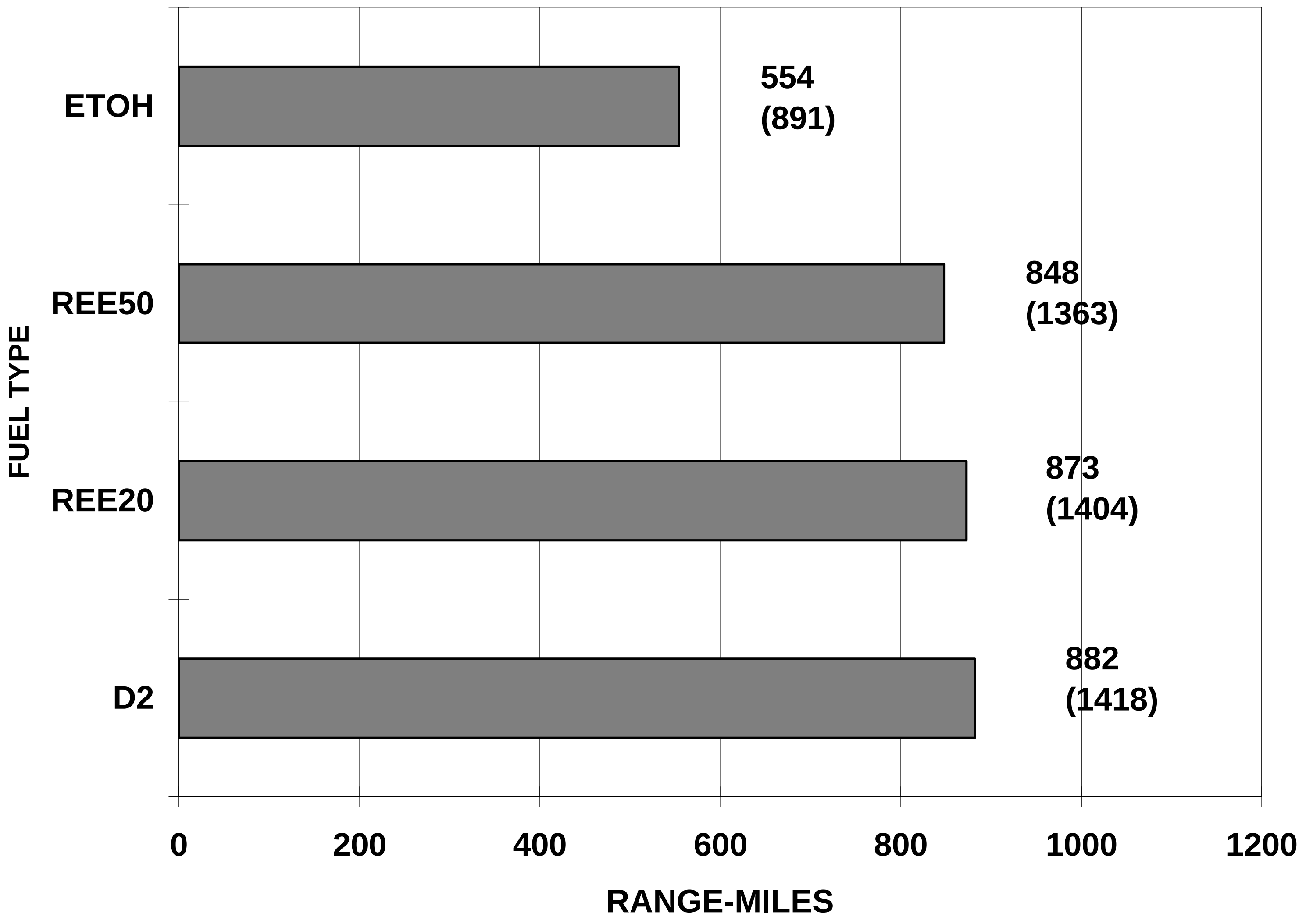


FIGURE 3
TANK SIZE, GALLONS (LITERS)-700 MILE (1125 KM) RANGE

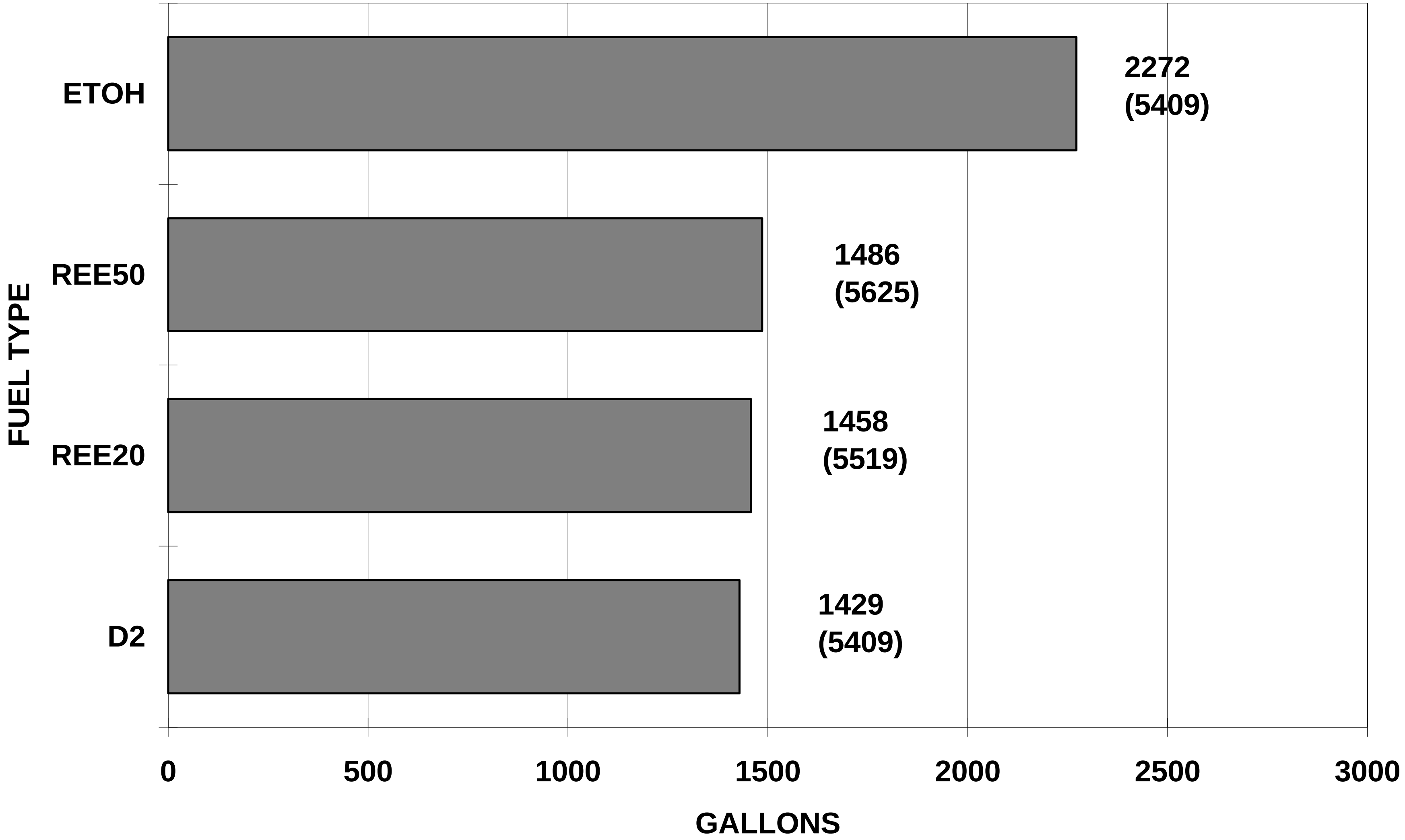


FIGURE 4
TOTAL ANNUAL EMISSIONS-TONS (TONNES)/YEAR

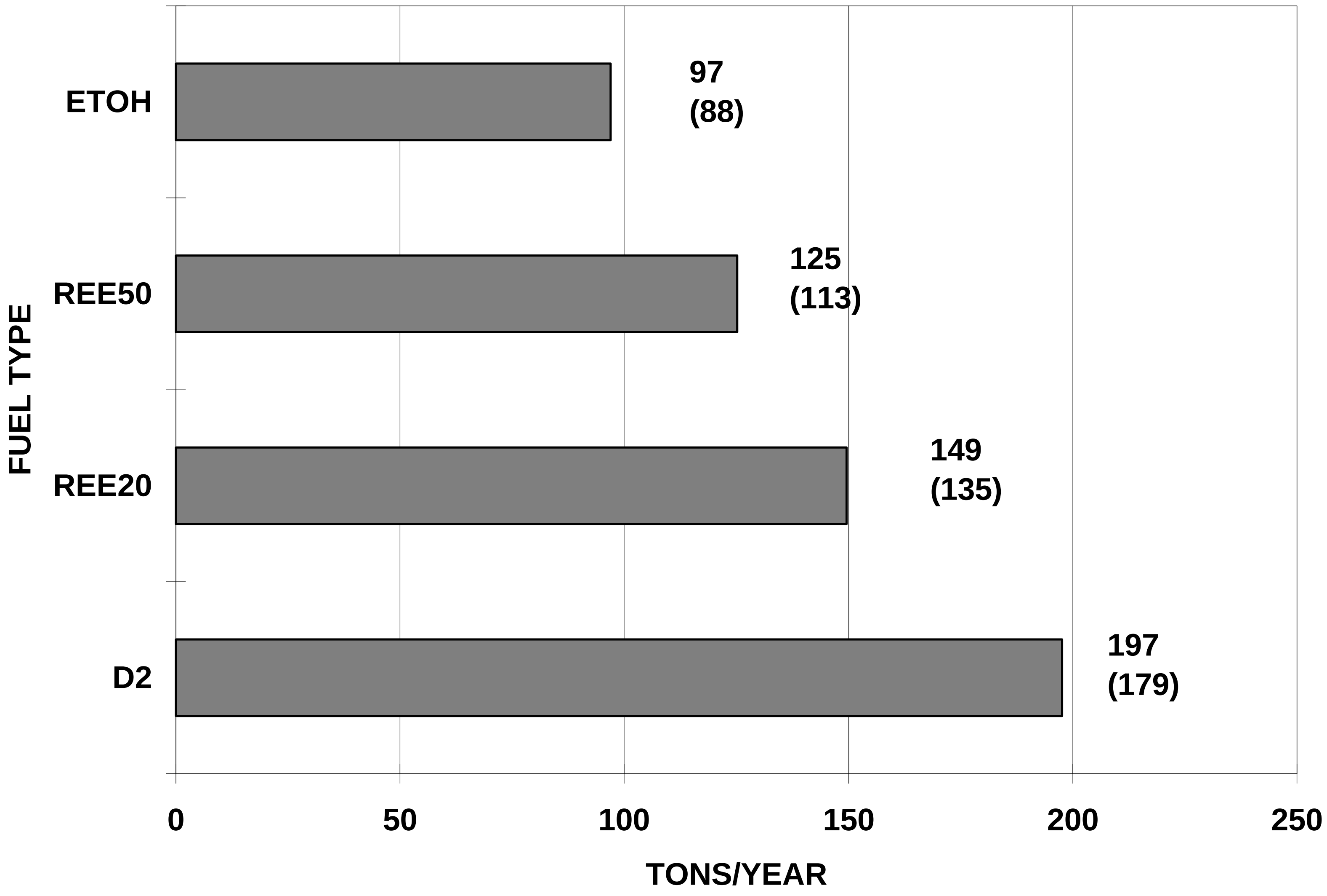


FIGURE 5
REDUCTION IN SMOG EMISSIONS TONS (TONNES)/YEAR

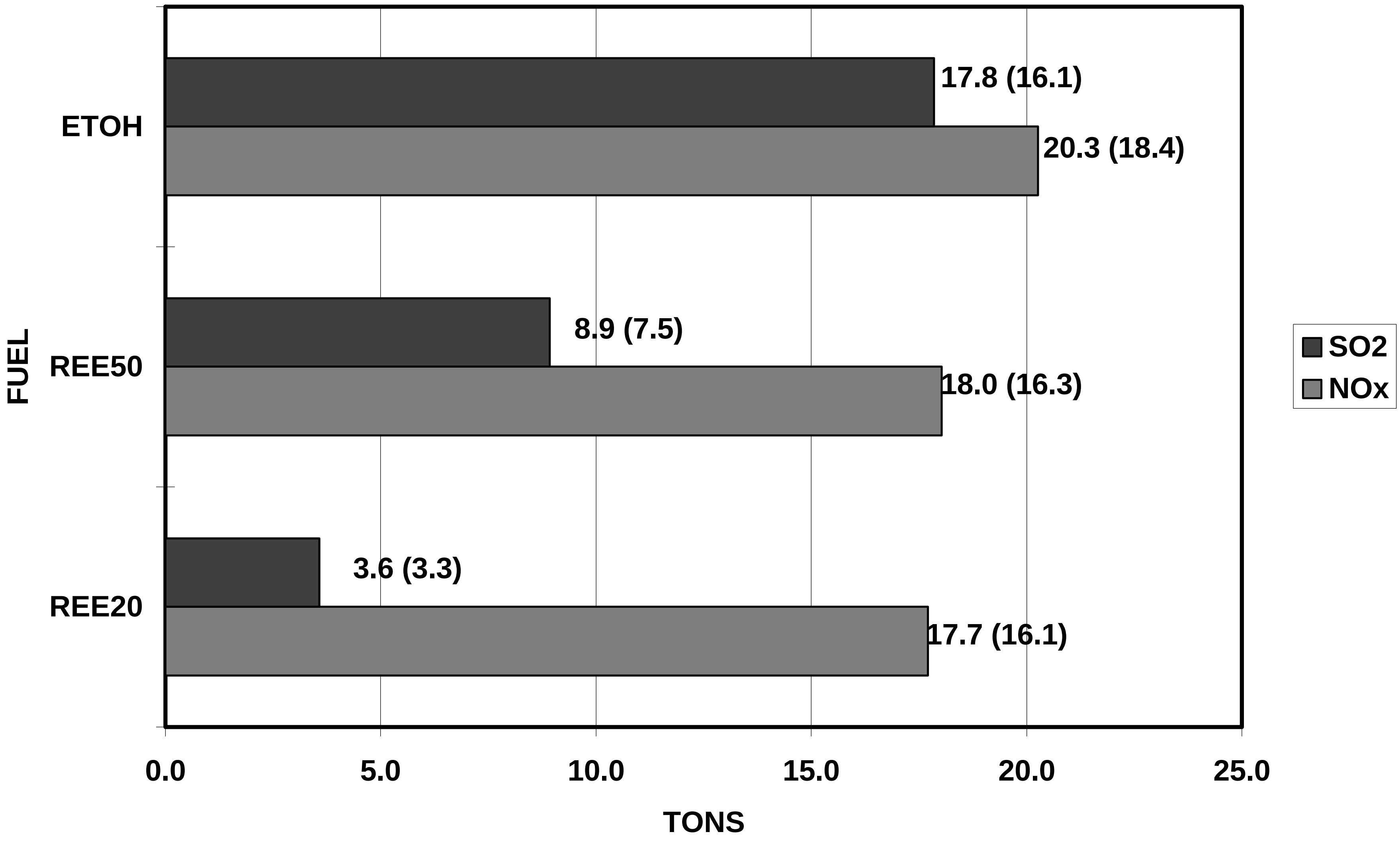
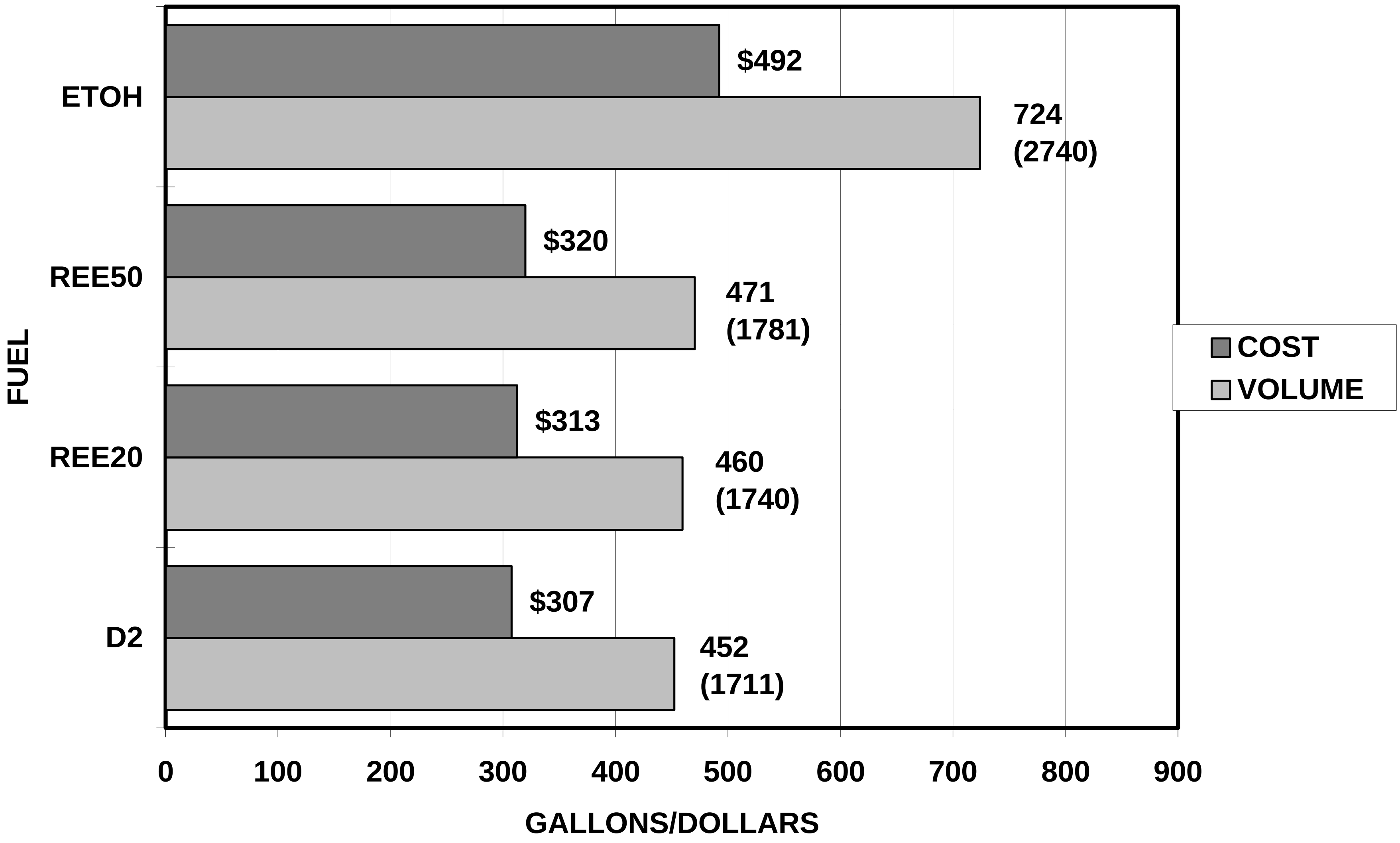


FIGURE 6
FUEL USE, GALLONS (LITERS) AND COST PER TRIP



List of Tables

List of Figures