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DIESEL ENGINE TECHNOLOGY UPDATE

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19. ABSTRACT (Continue on reverse if necessary and identify by block number)
This report reviews, assesses, and summarizes the research and development status and progress of advanced diesel engine/vehicle components technology. This report is a logical extension of a previous report, AFWAL-TR-80-2014, which identified vehicular diesel engine technology applicable to diesel powered electrical generator sets The previous report discussed variable area turbocharging, variable compression ratio piston, high-pressure fuel injection systems, turbocompounding, the adiabatic engine, and the Rankine bottoming cycle. This report adds discussion on alternative fuel, technology forecasting, engine cycle analysis, and cogneration.

While several of the previously reported technologies; i.e., variable compression ratio piston, have reached a level of maturity or disinterest; the advancement and cross fertilization of technologies have improved the thermal efficiency of the diesel engine to levels approaching 50 percent. It will be hard for other power sources and systems to exceed the thermal efficiency of the diesel engine and diesel cycle.

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FOREWORD

This report was submitted to the Aero Propulsion Laboratory, Aerospace Power Division with Mr. Jerrell Turner acting as the sponsor for the project. Andrew A. Kaupert, Lt. Col. USAFR, of the Detroit Detachment, ASD Reserves, ASD/XOR, Wright-Patterson AFB, Ohio, is technically responsible for this report which is the culmination of ASD project 83-021-DET.

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INTRODUCTION

The Aerospace Power Division of the Aero Propulsion Laboratory continues their efforts to improve the United States Air Force terrestrial energy power sources of the post-1985 era. As part of these efforts, the ASD Reserve Detroit Detachment has undertaken a series of diesel engine technology assessments to broaden the knowledge base concerning this type of technology. Previously, the Reserve detachment prepared a review of advanced diesel powered vehicular research and development programs which have potential application to stationary power sources. This effort is detailed in AFWAL-TR-80-2014. The time frame for that report was March to December 1979.

A follow-on project was undertaken to establish further definition of diesel engine technology with respect to the present USAF inventory, system requirements, comparison to other power generation devices, and utilization of a contractor developed methodology for technology prediction.

The objective of the present report is to update the technology transfer/development status of diesel engine advanced componentry described in AFWAL-TR-80-2014. The advancements noted in this report are verifiable in the open literature and contain no classified information. The opinions expressed in this report are the author's and constitute no endorsement by the Air Force or the author's employers for these components.

SECTION II

REVIEW OF TECHNICAL PROGRESS SINCE THE ISSUANCE OF AFWAL-TR-80-2014

1. Background

As with any technology assessment venture, the methodology for predicting the likely outcome of the technology must be described. The methodology followed is not dissimilar to the previous report, AFWAL-TR-80-2014. In that report, open literature was surveyed, discussions with principle investigators were held, and conclusions drawn following conservative historical projections. The assessment study results are then displayed using a referenced technology rating criteria. The hesitancy to review potential or revolutionary technology breakthroughs was the typical response from these investigators. Therefore, the use of more classical projections based on retrospective analysis must be employed. Technology assessments of system or component progress have been outlined in the literature regularly. More specifically, most technology achievements, as well as components and at time because of components, are exemplified by a learning curve (Figure 1).

Diesel engine componentry is no exception. Observations reveal that early learning experiences are marked by rapid progress, the rate decreasing with time. In many research and development programs, a second learning curve may be superimposed on the first. Figure 2 illustrates a learning curve relating to the thermal efficiency of internal combustion engines. When examined in detail, the curve in Figure 2 would undoubtedly be made up of overlapping

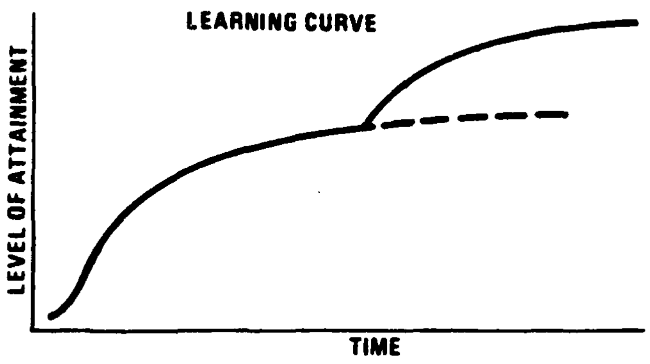


Figure 1. General shape of learning curves.
Note that progress levels off, but
breakthroughs can renew the curve

curves, each representing individual breakthroughs in understanding, technology, or improvements in componentry (Reference 1).

Other references bear out the existence of learning curves, especially the flat upper portion of the learning curve shown in Figure 3. This relatively modest rate of increase, be it in efficiency or another engine performance parameter, appears to the casual observer as little or no progress. Yet, this portion of the curve allows the observer to state with some confidence that a component technology has matured or conversely it has become a significant barrier to progress. See details in References 2, 3, 4, and 5. They develop the methodology for forecasting technology advancements.

Finally, we used a methodology of common reference to an accepted major component evaluation. In Reference 6, the evaluation of fuel cell component progress utilized a standard rating criteria. This criteria is illustrated in Table 1. The analysis of the diesel engine componentry progress in this report will be summarized later using the same rating criteria as described in Table 1.

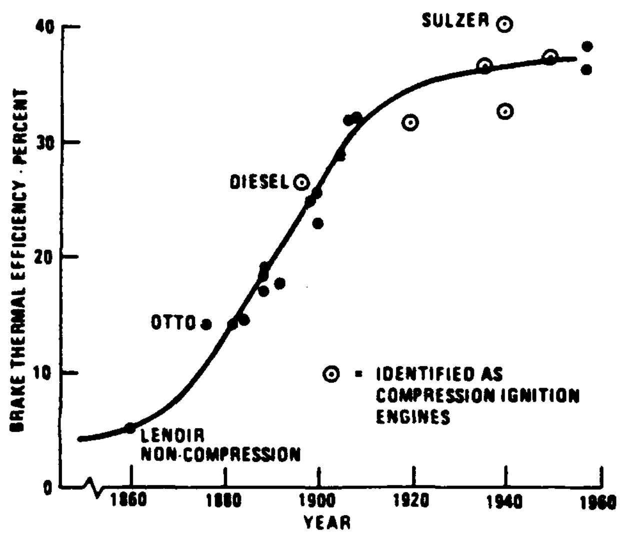


Figure 2. One hundred years of internal combustion improvement. Data mainly from large stationary engines

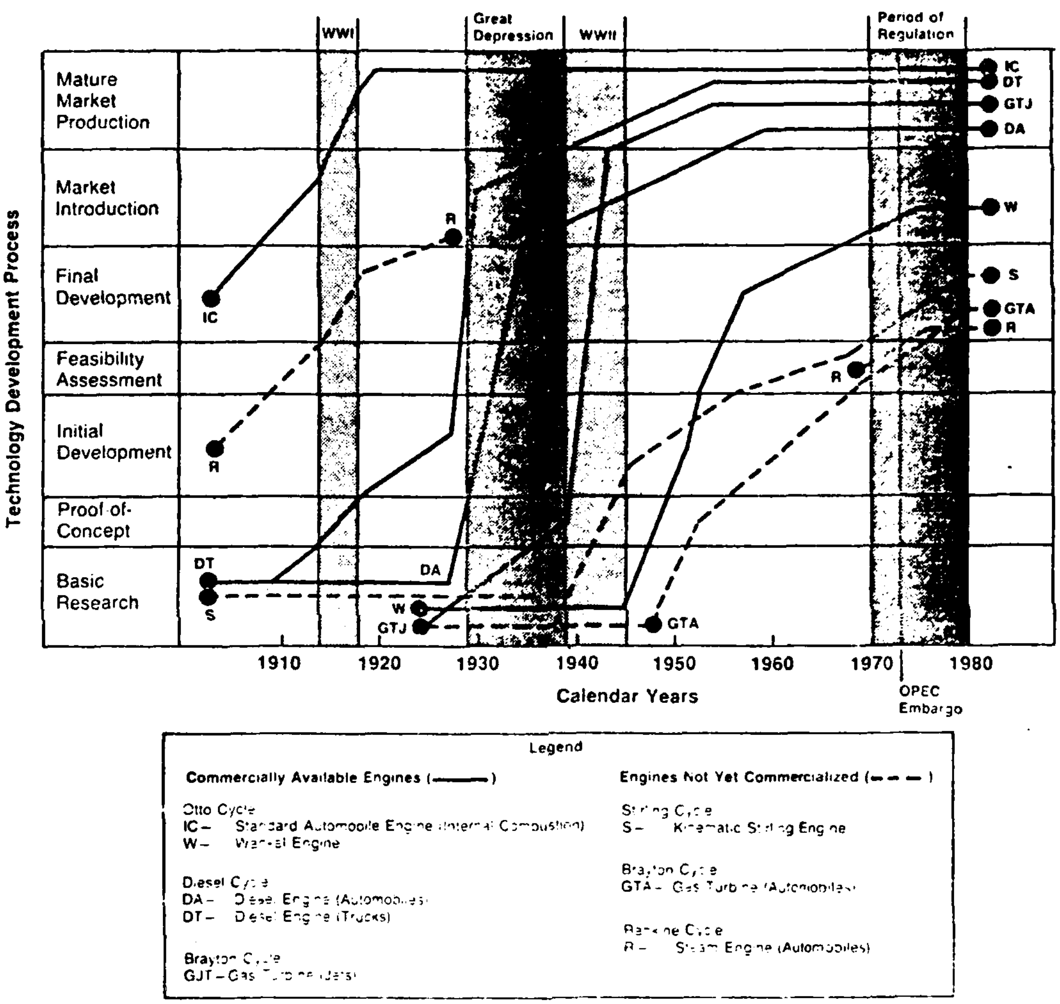


Figure 3. Historical Development of Automotive Engines

TABLE 1
TECHNOLOGY STATUS RATING CRITERIA

Technology Rating	Technology Status	Performance Data Base	Application or Development from Performance Data Base	Programs Requirements	R&D Program Characteristics Rationale	R&D Program Characteristics Probability
Established (A)	Firm selections can be made. Equipment is commercially available in form required.	Sufficient	None	Minimal, routine applications engineering.	Not Applicable	Not Applicable
Near Term (B)	A number of equipment candidates are identified. Candidates are commercial or near commercial.	Incomplete	Short extrapolations from existing data base are involved.	Confirmatory testing and minimal R&D.	Straight-forward	Virtually Certain
Developmental (C)	Equipment not previously designed, but engineering data base exists for design.	Incomplete; important gaps exist.	Large extrapolations from existing data required.	Considerable R&D is required.	A credible rationale exists. Alternative avenues are evident.	Good to excellent
Speculative (D)	Equipment not previously designed with major materials, design or manufacturing uncertainties.	Sparse or absent.	Highly speculative or not possible.	Extensive R&D is required.	Rationale is not clear, or requires a breakthrough or serendipity.	Fair to poor.

2. Diesel Engine Research and Development (R&D)

When the last diesel engine component technology assessment (AFWAL-TR-80-2014) was completed, the major thrust of diesel engine R&D was focused on improved performance and durability. This was demonstrated by systems such as Variable Compression Ratio pistons, Variable Area Turbochargers, and electronic fuel injection systems (UFIS), all developed to increase horsepower per unit weight. Durability was a major factor in components development with special interest in reducing Mean Time Between Failure (MTBF).

The principle sponsor of this development work was U.S. Army Tank Automotive Research and Development Command (TARADCOM), Warren, Michigan. Commercial interests in diesel engine development during this time period were concerned with achieving environmental and reduced fuel consumption goals. While several of the U.S. Army-developed systems could have had potential for solving the commercial goals, the commercial manufacturers were only interested in the prospects of the adiabatic engine's performance and electronic control of fuel injection. Of course, several commercial firms had cosponsored advanced research projects with the Army, mostly to improved power density. The commercial manufacturers never showed an interest in the Army multi-fuel engine capabilities, even in time of energy scarcity.

Since the last technology report, several external factors have influenced the diesel R&D picture. On the commercial side, fuel economy has been the principle thrust of the manufacturers. The world-wide recession, which started in the late 1970's and early 1980's, hit the commercial market the hardest. Even as the price of energy drops (at the time of this report oil approaches $15 bbl), the diesel commercial market has not revived as have gasoline-powered passenger vehicles. Interest in further R&D funding fell dramatically as sales of commercial power systems dropped. Added to this recession was the increased emphasis on environmental goals imposed by the U.S. Environmental Protection Agency. This was exhibited by further reduction in the oxides of nitrogen and exhaust particulate standards. (At the time of this report writing, proposed legislation has been introduced in Congress to codify these standards into the Clean Air Act.) The already taxed R&D funds was reemphasized to achieve these environmental goals, and efforts by the commercial manufacturers now center on achieving these goals.

While it is not clear that commercial engines will be available in the 1990's (the Engine Manufacturers Association has sued U.S. EPA over the newest diesel exhaust emissions standards), the U.S. Army has continued to modestly fund advanced diesel work. The Army has specific plans for advanced R&D work which includes the goals of: (1) low life-cycle cost, (2) increased power density, (3) improved performance, and (4) increased reliability (Reference 7). Much of this report centers on the applicability of the Army work to the USAF inventory of ground power generators.

While the Army advanced high-power output systems, other elements of the Army have concentrated on the below 1MW power generation systems. The U.S. Army Mobility Equipment Research and Development Command has done extensive work in reducing the weight, size, noise level, complexity, and number of generator sets in the DOD inventory (Reference 8). Their goal is to reduce the inventory shown in Table 2 by 30 percent and the number of makes and models involved from approximately 2000 to under 100. Also, all of the present gasoline powered generator sets are to be phased out. A good summary of the Army program can be found in References 8 and 9.

In summary, the Army program centers on advanced logistics, single fuel capability, lower signature (noise and radiation), improved reliability and surviveability, and increased commonality. Other than the advanced work involving Stirling engine technology, fuel cell and thermoelectric generators, the Army has yet to cross-fertilize the advanced technology work from TARADCOM into the future purchase of generator sets. This is the result of dealing with manufacturers who traditionally deal in the low-power output range and historically have incorporated advanced technology into the engine control many years after it has been proven in larger application. The R&D funds are not available to smaller manufacturers and they are not equipped to conduct fundamental research of advanced componentry. They can only find funds to copy previous successes.

Also, there appears to be a growing trend of less activity in basic research associated with the diesel combustion process. An exception to this basic research reduction is in the area of the effects of fuels and engine operating parameters on diesel particulate and oxides of nitrogen formation. The research community involved with this research has grown older and the available literature has become more scarce. There also appears to be less funds available for those fundamental programs previously reported as the emphasis switches to solving environmental goals or achieving fuel economy improvements.

TABLE 2

The DOD Standard Family of Mobile Generator Sets (Reference 9)

	Inventory						
	AF	Navy	MC	Army	Total		Prospects/
Size	Assets	Assets	Assets	Assets	Assets	D/G*	Changes
0.5	6	0	0	3,268	3,268	G	Phasing Out
1.5	746	0	0	38,887	39,633	G	No new buys
3.0	2,168	0	2,163	31,745	36,076	G	Being replaced by new mid std diesel set
5.0	934	109	0	26,496	27,539	G/D	Replacing gas sets with diesel
10.0	1,267	98	1,424	19,404	22,193	G/D	Replacing gas sets with diesel
15.0	397	244	0	3,655	4,296	D	Replaced by new diesel set
30.0	1,583	275	1,563	4,412	7,833	D	Same as 15 kW
60.0	6,173	318	620	5,455	12,566	D	Same as 15 kW
100.0	720	126	137	1,131	2,114	D	No changes
200.0	737	350	189	124	1,400	D	No changes
500.0	10	0	0	21	31	D	No changes
750.0	0	0	0	21	21	D	No changes
	14,741	1,520	6,096	134,619	156,976		

*D/G = Diesel/Gasoline Engines

3. Diesel Engine Components Discussed in AFWAL-TR-80-2014

The components discussed in this present report will follow the order of the previous report. Included here are variable area turbocharging, variable compression ratio piston, high-pressure fuel injection system, turbocompounding, adiabatic engine systems, and Rankine bottoming cycle. The previous report gives a brief description of these components/systems and a predictive overview of the R&D underway during the time period of that report.

a. Variable Area Turbocharging

Significant progress has been made with Variable Area Turbocharging (VAT) since early 1980. Several production units are in place and the U.S. Army has ceased funding the development of this component technology because the Army considers the concept an "off-the-shelf" or fully developed item (Reference 10). This concept will be used in future Main Battle Rank (MBT) projects which use diesel engines in the power range of 1500 horsepower and above.

More importantly, during 1981 several European investigators were convinced the VAT concept was a viable technology for improved engine response and lower fuel economy, principally for diesel-powered passenger vehicles (Reference 11). While limited performance data were presented, it was apparent the VAT concept held promise of major performance improvements.

Close on the heels of the 1981 data came an advanced concept of a bleed flow between the compressor and turbine sides of the turbocharger. Here again, this was Army-sponsored work in conjunction with their Very High Output (VHO) engine system concept. Horsepower was again the objective. The bleed flow concept apparently solved some or all of the transient "lug" problem, due to poor variable vane geometry response, that had plagued previous VAT turbochargers. Little performance data was presented (Reference 12). The finalization of this concept resulted in the Army's conclusion that VAT was a viable, mature concept.

The VAT concept is not without its detractors, however. In 1984, a prominent turbocharging authority (Reference 13) and another author (Reference 14) questioned the durability and cost viability of the VAT concept. While unconvinced about those parameters, both authors conceded that the improved fuel economy transient engine response were the likely outcome of the VAT concept. Again, the concept was described in terms of passenger automobiles.

Reference 15 was published in early 1983 with definitive data on VAT performance in a diesel generator set application. This reference contained the following quote. "Under contract to the U.S. Army, a six-cylinder, naturally-aspirated diesel was replaced with a four-cylinder diesel equipped with a VATN turbocharger to drive an Army 30-kw 400 Hz precision generator set. Transient tests (MIL-STD-705B) were conducted by the generator set manufacturer. The generator set surpassed all the associated compliance requirements. Estimates based on engine dynamometer tests indicate that the smaller turbocharged engine will reduce the fuel consumption 9 percent or more as compared to the current six-cylinder engine." The reference also described the durability and transient performance of the units. It is apparent that a VAT turbocharger could be produced and would give the promised performance with size and weight reductions as a bonus.

The first mass-produced variable-geometry turbocharger for a heavy truck application is described in Reference 16. Isuzu has incorporated the VAT concept along with variable swirl induction and electronic control of fuel to achieve their slated goals of lower fuel consumption, more horsepower per unit weight, and improved torque over a wider speed range. The VAT concept has arrived!

With the mass production potential being demonstrated by Isuzu, it appears that application of VAT to DOD diesel-powered generator sets could be accomplished. The VAT technology would be better suited for generator sets which are larger than 60 kw and/or have a moderate-to-severe transient duty cycle. This technology will provide rapid response during transient operation while simultaneously reducing the system signature (smoke). The VAT technology could be utilized to reduce diesel engine size, thereby reducing overall system size and fuel consumption.

For systems over 1MW, the VAT technology concept would best be combined with other concepts to be described later. The overall benefit would be a reduced system size and vastly decreased fuel economy consumption with a modest reduction in system signature.

Table 1 shows that the VAT concept can be rated as an established technology with application to DOD engine-generator sets limited only to the aggressiveness of either the DOD generator-set program manager or the manufacturers themselves.

b. Variable Ratio Piston

The Variable Ratio Piston (VCR) concept has not advanced since the last report. The VCR piston is designed to improve cold startability of diesel engine while providing fuel consumption benefits at less than full power levels. Both of these benefits, while interesting for high-power-output vehicular engines, may have little practicability for mobile generator sets. The complexity and yet to be proven durability of the VCR piston does not warrant further interest in this technology for generator sets. This is particularly relevant in a period of cheap fuel and generator systems that rarely operate at less than full load.

Confounding this analysis was the fact that there has been no new public information on the VCR piston technology since the last report. Contacts with the Army reveals there are no plans for VCR. Nor have funds been allocated for research or development of the technology (Reference 10). The VCR piston concept could be revived if the Army were to increase its efforts on diesel engines which have a horsepower greater than 1500. This event is unlikely because of the Army's apparent commitment to gas turbine technology in that horsepower range (Reference 7).

The VCR piston technology is rated as near term and should be considered only for diesel generator sets in the 1MW and above range. Close consideration should be given to this concept only if the size and weight constraints of stationary generator sets become very important.

c. High-Pressure Fuel Injection System

The last update report discussed an Army-funded diesel fuel injection concept called the Universal Fuel Injection System — UFIS. The principle thrust of the conceptual research was to achieve injection system flexibility and reduced exhaust emission. Since the last report, the UFIS system has undergone a name and manufacturer change from UFIS to EFIS -- electronic fuel injection system -- and from the American Boash to the United Technologies Corporation.

The new manufacturer also has retained the basic thrust for investigating this technology, i.e., the favorable NOx-particulate exhaust emission trade-off due to increased injection pressure (Reference 17). Because of this favorable trade-off, several other systems have been designed and developed which provide high-pressure injection coupled with improved injection timing and duration. Some of these systems will be briefly covered.

It appears that while there was little public discussion of high-pressure high-injection rate systems, considerable R&D was underway. The impetus for this work was the increased environmental goals of the U.S. Government and the rising cost of fossil fuels. In 1981, two technical papers emerged which, while coming to different directional recommendations for further research, foretold the direction of high-pressure fuel injection. The authors of Reference 18 concluded that the use of a piezoelectric source (the type used in the UFIS system) was impractical and bulky. They did conclude however that a system with flexible electronic timing and volume control combined on a solenoid/mechanical unit would be better suited for future engines. Of course, that conclusion was bolstered with data demonstrating both reduced exhaust emissions and fuel consumption. The second paper, Reference 19, reported that the concept of a solenoid-operated control system combined with a high-pressure fuel supply source (mechanical) and microprocessor control unit would be the potential answer to the quests for lower exhaust emissions and fuel consumption. Again, the data bore this conclusion out. From that time onward, the concept of high-pressure fuel injection with microprocessor (electronic) control was established. Piezoelectrics had passed from active consideration. The preliminary endurance tests showed over 1,000 hours of low wear rates and confidence that electronics could be viable in a diesel engine operating environment.

While the U.S. Army had abandoned support for a UFIS type fuel injection system (Reference 10), the Department of Energy continued a modest program of evaluation at the NASA Lewis Research Center (Reference 20). NASA also came to the same conclusion that an electronically controlled high-pressure fuel injection system was preferred to a UFIS type system. NASA plans to incorporate the improved non-piezoelectric system in a future diesel aircraft engine (Reference 21).

Work has continued by overseas investigators and fuel injection equipment manufacturers to refine and verify previous data (Reference 22). The results again showed the positive aspects of high-pressure electronically controlled fuel injection. Unfortunately, the size and weight of the units have not been reduced from the size and weight of UFIS type units.

By 1984, the potential for and necessity to reduce exhaust emission and fuel consumption spurred researchers to take the accepted principles of high-pressure fuel injection and attempt to reduce the systems to practice. Cost reduction was another prime factor, as fuel injection systems could cost up to 15 percent of total engine costs. One company, Ricardo Consulting Engineers, plc, approaching the generation of high-pressure for the fuel in two novel ways, hoped to reduce costs. One approach was to generate high fuel pressures using a system akin to the "water hammer" principle. The other principle was the use of a pressure intensifier to raise fuel pressures. Both systems achieved the same results as the previous discussed concepts, but at lower costs (Reference 23).

Meanwhile BKM, Inc., had claimed to reduce the cost of a high-pressure electronically controlled unit type injector by 27 percent over a comparable non-electronically controlled unit (Reference 24). Since that date, the General Motors Corporation, Detroit Diesel Allison Division, has announced it will be marketing an electronically controlled high-pressure unit fuel injector in the near future. A decrease in fuel consumption is the motivating factor for this pronouncement.

Therefore, we would have to rate the higher pressure electronically controlled fuel injection system as near-term technology. It could be applied and undoubtedly will be eventually applied to all of the DOD generator sets, across all power ranges. Initially, the low end of the power range, until more electronic controls are adapted commercially, will not receive this technology due to cost consideration.

The rapid advancement and survivability of electronics in the automotive environment, the advancement of diagnostic sensors and adaptive computer memories, plus the fuel and space saving attributable to this technology will ultimately see its incorporation into future generator sets.

d. Turbocompound Engine Systems

As reported in AFWAL-TR-80-2014, turbocompound engine systems are intimately associated with the adiabatic or low-heat-rejection diesel engine systems. Consequently, progress towards a separate application of a turbocompounded diesel engine has been confined to two projects demonstrated in the early 1980's. At that time, the Department of Energy was actively promoting any and all concepts for energy conservation and the U.S. Army was promising a high-horsepower, compact diesel engine. Since we learned the results of the program, discussed below, little data have been produced which confirm either the results of the program or potential application of turbocompounding. However, the U.S. Army has not disqualified turbocompounding technology from consideration in future programs, although, funding (exclusive of the adiabatic engine program) is nonexistent (References 10 and 25).

In 1982, the Cummins Engine Company reported the results of a DOE/Industry joint-funded program involving the comparison of a production NTC-400 diesel engine and a comparably sized turbocompounded engine in a vehicular application (Reference 26). A summary of the program revealed a fuel consumption improvement of 14.8 percent for the turbocompounded engine in comparison to the production engine. The turbocompounded engine, reported by Cummins, also achieved lower noise levels, improved driveability, improved gradeability, and moderately increased engine retardation (braking). The last three items are of no interest to a stationary power source application, although reduction of noise levels is extremely important.

A second turbocompound engine was placed in commercial service and accumulated 50,000 miles on a cross-country route without malfunction. Tank mileage revealed a 15.9 percent improvement over a production engine operating on the same route. Cummins concluded that the incremental fuel consumption improvement, strictly due to the turbocompounding alone, was estimated to 4.2 to 5.3 percent depending upon the terrain or mission load factor.

In 1983, Cummins reported the results of their Army-funded program to up-rate a 350-horsepower engine to 1000 horsepower for a military application (Reference 27). Within that report were data concerning, among other systems, a turbocompound engine operation. This report was significant in that it gave other researchers impetus to look at other horsepower improvement systems. The report also provided an expert's opinion on the viability of turbocompounding viz-a-vis' other turbocompounding systems. The critical data reviewed by Cummins are summarized in Table 3.

Cummins recommended that the VAT-Turbocompounded engine system be pursued. They achieved 1000 horsepower with this combination with a brake specific fuel consumption of 0.350 lbs/BHP-HR or about 40 percent thermal efficiency. Unfortunately, Cummins provided no data concerning fuel consumption improvement with the turbocompounding technology alone. A rating of near term must be given to the turbocompounding technology. This rating is a combination of impressive data and optimistic projections by researchers. However, it remains a fact that turbocompounding is still looking for an application. This application probably lies in some combination of VAT and the adiabatic engine system, undoubtedly in a high-horsepower military vehicle.

Turbocompounding, with an apparent 5 percent fuel consumption improvement, does not warrant further consideration for generator set application. While potentially a smaller engine-generator set package (more horsepower per unit volume) could be obtained, the added weight and system complexity are not offset by lower fuel consumption. Turbocompounding remains a technology that is best suited for integration with other technologies to provide near optimum performance in ground power equipment. Hence, turbocompounding should not be considered for Air Force application, in any power range, by itself.

e. Adiabatic Engine Systems

The adiabatic engine concept has been alternatively described as the most exciting, revolutionary technology advancement to the diesel engine, to a concept that has little merit in itself, but considerable merit in the technology spin-offs associated with the adiabatic concept. To say the least, the concept has been very thorough, provoking, and exciting! Work has progressed steadily since the time of the last report and considerable open literature data can be found to assess the progress of the concept.

There remains, however, very little information concerning the progress of the spin-off technology, i.e., ceramic parts and low friction surfaces. It does appears that in newer vehicular applications, some of these spin-off concepts have been incorporated into passenger car powertrains simply to achieve the

Table 3. Summary of Critical Data for Each of the Five Proposed Engine Systems (from Reference 27)

Criteria	Two Stage[1.]	VAT[2.]	VAT with Turbocompound[3.]	LCR/FLX[4.]	L.P. Comprex, H.P. Turbo[5.]
Compactness - volume ft^3	22.1	19.25	25.40 (axial PT) 21.24 (radial PT)	22.3	21.9
Weight, lbm	2965	2900	3175	2995	2975
Cost Increase % above VTA-903 Base	79	94	119	98	95
Mission Economy - Total Fuel Consumed During 16 Hr. Dat, lbm	921	919	857	1314	926
Rated BSFC, lbm/hp-hr	0.368	0.363	0.340	0.363	0.388
Response 0-30 mph Elapsed Time, Sec. (35 Ton Vehicle)	11.85	11.1	11.1	10.7	10.7
Reliability Maintenance Rating (1-10)	8	9	7	6	7
Potential for Improvement with Advanced Technology	6	7	9	6	6

Legend

1. A two-stage turbocharging system using two conventional low-pressure turbochargers and a single high-pressure turbocharger.

2. A single-stage advanced high-pressure ratio turbocharger with variable area turbine inlet (VAT) and variable compressor to meet range requirements.

3. A turbocompound system composed of an advanced high-pressure ratio turbocharger with variable geometry and a low-pressure power turbine geared to the engine crankshaft at a fixed gear ratio.

4. A low compression ratio flexible system (LCR-FLX) similar to the Hyperbar concept with a single-stage high-pressure ratio fixed geometry turbocharger wih an exhaust manifold burner.

5. A two-stage charging system using a Comprex low-pressure stage and a conventional high-pressure turbocharger stage.

fuel economy standards and perhaps achieve some durability demonstration with these parts in noncritical applications prior to full system applications. Specifically, references to the advent of ceramic valve train parts and low friction surfaces have been made in the news media for both foreign and domestically manufactured automobiles. However, the true advancements remain hidden due to the competitive nature of the automotive industry.

Early in 1981, the U.S. Army, in conjunction with Cummins, reported on the progress and goals of the Army-sponsored adiabatic turbocompound diesel engine. One goal was the use of no water or air cooling for the engine to enable the minimized heat transfer from the engine, thereby, increasing engine thermal efficiency. A schematic of the adiabatic turbocompound engine concept is shown in Figure 4. There is no cooling system! This present report was the natural follow on from the information discussed in Kamo and Bryzik's previous report (Reference 28).

Kamo and Bryzik reported the program objectives were:

BHP @ rated speed..................	500 hp
RPM @ rate speed...................	1900 RPM
Emission (NOx + HC)................	5 g/bhp-hr
BSFC...............................	0.28 lb/bhp-hr*
MTBF (Component)...................	250 hrs

* 50 percent thermal efficiency

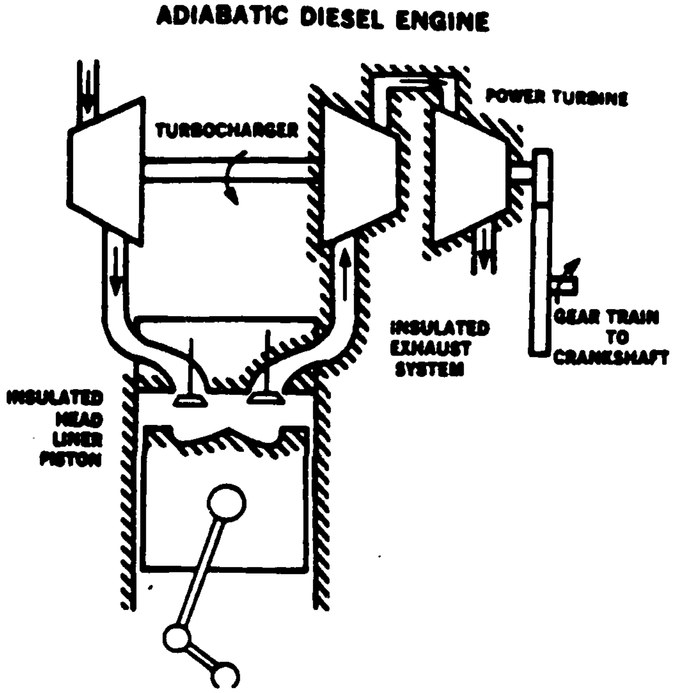


Figure 4. Adiabatic Turbocompound Engine Schematic

The basic adiabatic engine which was designed for testing in the laboratory is shown in Figure 5. The basic engine consists of the following components:

1. Insulated piston cap
2. Insulated "Hot Plate" for cylinder head
3. Insulated top liner "deck-spacer"
4. High-temperature lubrication package
5. Insulated exhaust ports
6. Other: exhaust manifold insulation, valves, injectors.

Kamo and Bryzik were candid enough to realize 250 hours of durability were not sufficient to "prove" a durable concept. The reliability and durability goal of a "real life" engine were set at: 10,000 to 15,000 overhaul life, 90 percent reliability on major engine components, service interval of 500 to 1000 hours, life of major components 5,000 to 7,000 hours, and warrantable features of 70 percent reliability through 100,000 miles or 2,000 hours. They were also candid in pointing out the then poor understanding of ceramics, high-temperature lubrication, and high-temperature operation of metals viz-a-vis' ceramics. Nonetheless, the Army embarked on the program hoping to demonstrate potential solutions to the aforementioned design/performance concerns. Additionally, the Army hoped to demonstrate a minimal fraction uncooled diesel engine design with 48 percent thermal efficiency in conjunction with turbocompounding and an unlubricated engine design with 55 percent thermal efficiency with significant exhaust energy still available for a bottoming cycle. The authors predicted that the goals set for the program could be achieved!

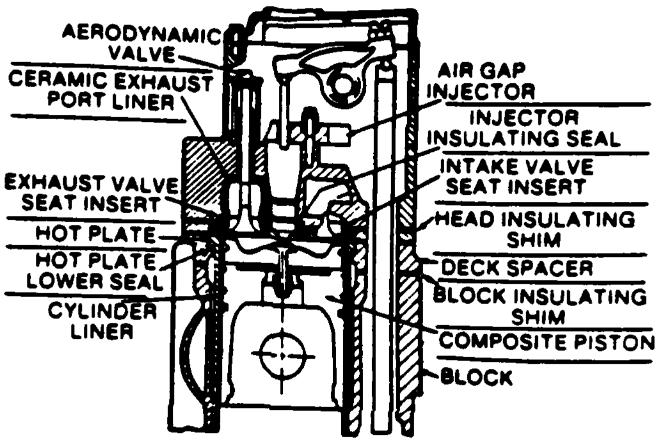


Figure 5. Cross section of Cummins basic adiabatic (insulated) diesel engine

In early 1982, an overall review of the adiabatic engine program at the U.S. Army was presented (Reference 29). Reference 29 developed the history and rationale of how the Army arrived at the adiabatic diesel as a prime candidate for propulsion units in the Army inventory. (See Figure 6.) Also reported, some of the rationale for why engine systems reported in AFWAL-TR-80-2014 were not developed as well as data concerning the costs of small production volume engine development program. Figure 7 displays the overall strategy for the Army adiabatic applications, while Figure 8 indicates the predicted production dates for the various adiabatic engine spin-off as well as predecessor engines. (Note that 0.25 bsfc is approximately 55 percent thermal efficiency.)

In late 1982, the Army reported on the progress of their adiabatic engine program (Reference 30). At that time, they had repeatedly demonstrated a 0.285 bsfc at 450 horsepower, over 500 hours of multicylinder engine operation and installation of an early engine version in a 5-ton truck while amassing 3000 miles without failure. This truck featured no conventional cooling system and with elimination of 361 individual parts, the size was reduced to 20 cubic feet and 338 pounds were eliminated. The Army continued to press on to its goals described previously. Significant interest by other Government agencies, industry, and academic sources were reported as the adiabatic concept and its problems received renewed impetus.

In 1983, more adiabatic engine program details were revealed with additional engine and vehicle hours being reported (Reference 31). The Army considered themselves on track with program goals.

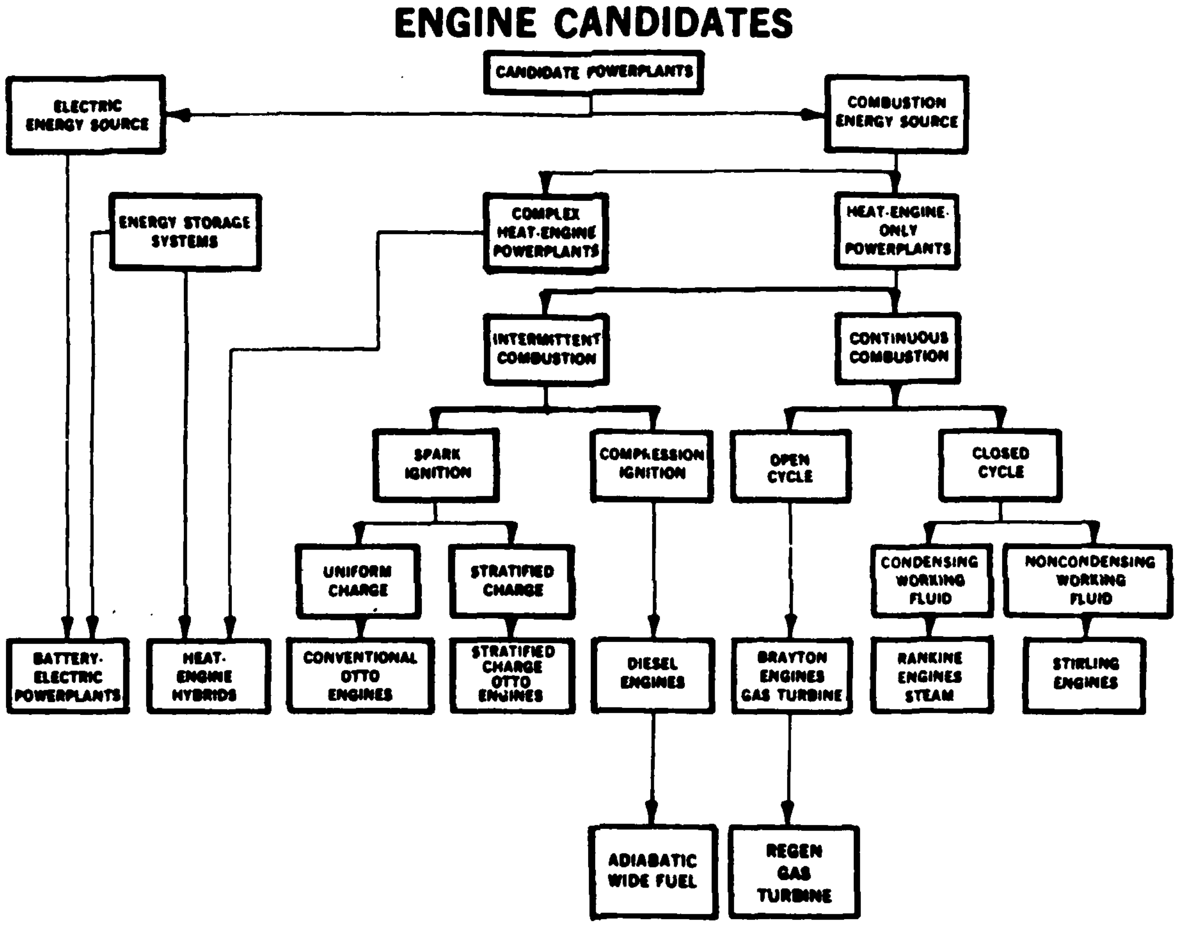


Figure 6. U.S. Army Engine Candidates

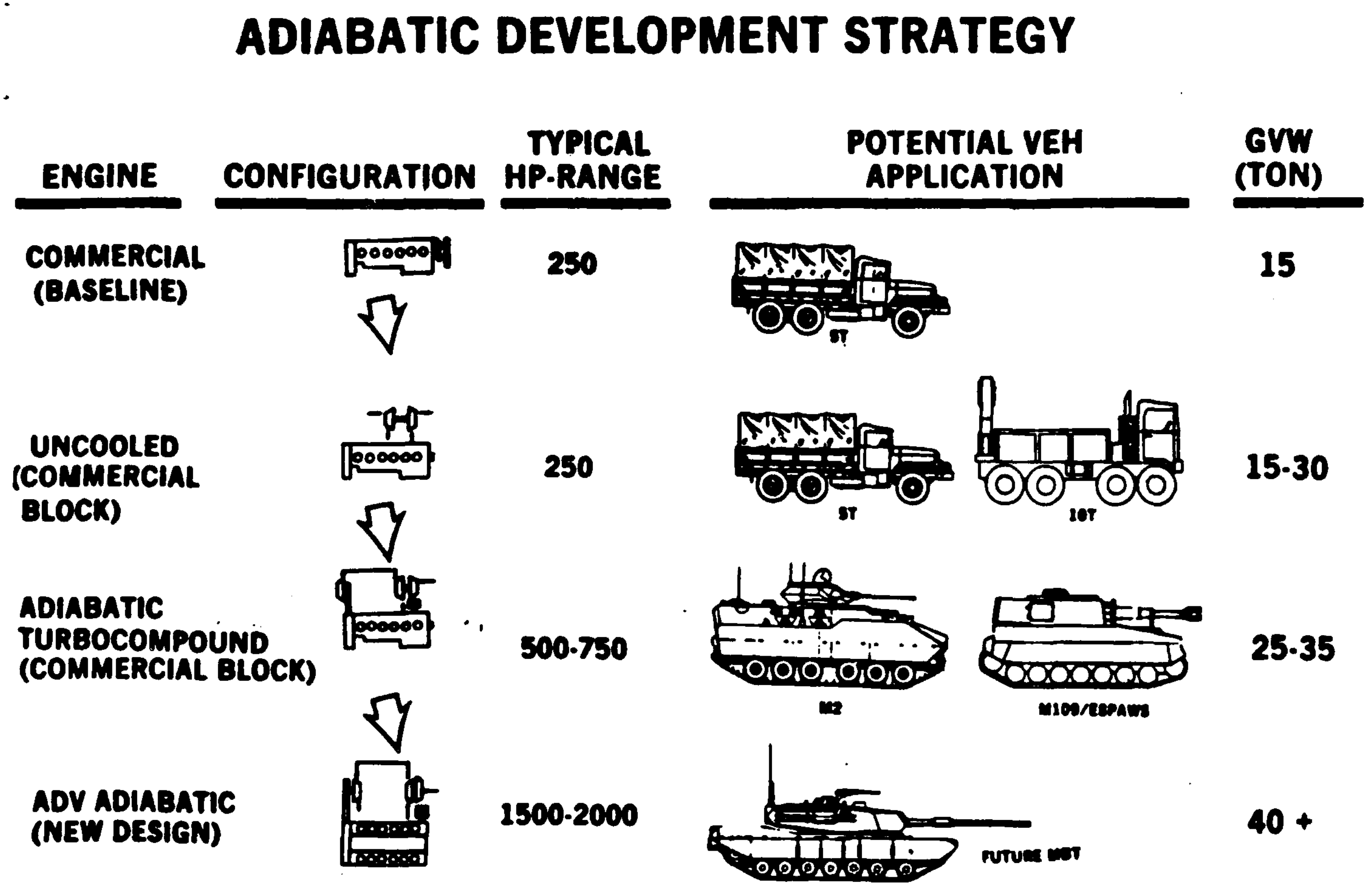


Figure 7. Adiabatic Development Strategy

PREDICTED PRODUCTION DATE ADIABATIC ENGINE SPIN-OFFS ENGINE PROGRAMS

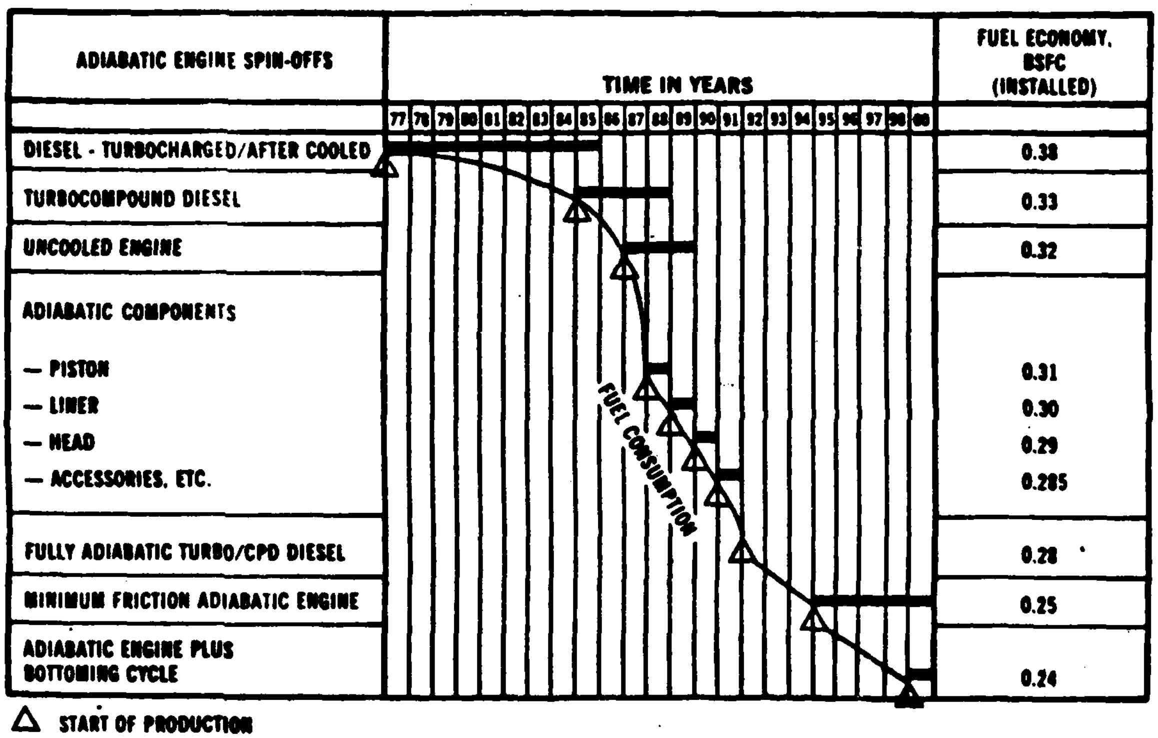


Figure 8. Predicted Production Date - Adiabatic Engine

At the same time, other researchers reported the findings of their companion studies. Ricardo came to the following conclusions. "Both the adiabatic engine and the insulated engine (note difference) are predicted to give substantial improvements in ISFC over the standard engine - 14 percent and 7.5 percent respectively. The superior ISFC of the adiabatic engine is the result of two major factors; first there is no heat loss during the combustion and expansion phases, and second the higher volumetric efficiency allows a lower back-pressure to be applied to the engine." Ricardo further concluded: "It is difficult to foresee materials being available which could enable a true adiabatic engine to be built, but an insulated engine should be feasible. (See Reference 31.) An observation from one of the foremost combustion research and engine development organizations caused a subtle but significant shift in emphasis by non-Army researchers and development groups to the insulated engine. The challenge was less ambitious and the pay-back (fuel economy) was more important.

In the 1984 report on the adiabatic engine, Kamo and Bryzik concluded that the adiabatic turbocompound engine had been demonstrated (Reference 32). They also outlined the ceramic research needed to fully develop the concept.

During the 1984 time period, other researchers started to reveal the results of their studies. Reference 33 indicated further research was necessary to understand the heat-transfer principles and exhaust emissions formulation fundamentals of the adiabatic engine. Reference 34 presented the results of a DOE/NASA sponsored analytical study to identify the essential features of a futuristic engine for cars. That study identified the research and development efforts needed to bring this concept to fruition and concluded that an aggressive 10-year program will result in production availability of these vehicles (78.7 mpg in a 3000-pound vehicle).

Also in this time period, two critical analysis were conducted on the low-heat rejection (LHR) (as the insulated engine is now named) diesel engine research. Reference 35 concluded that LHR would be feasible for passenger vehicles (part load operation) only when incorporated with turbocompounding. Reference 36 found similar conclusions, but also reported improved exhaust emissions were possible. The extent of engine insulation is not readily discernible between the two studies, therefore, the conclusions are not comparable. Further research was also suggested. Both of these papers are excellent summaries of the fundamentals of uncooled or adiabatic engines.

Finally, in early 1985, in spite of the Army assertion that the adiabatic engine had been demonstrated, it is evident from the data presented in Reference 37, much work remains on both engine materials development and the fundamental understanding of the adiabatic diesel engine operation. None of the work, however, requires major technology breakthrough for accomplishment.

Analysis of public information indicates that the adiabatic engine technology, as well as its many other forms, should be considered developmental technology. Even the most optimistic and enthusiastic support of the technology saw the technology maturing in the early to mid-1990's. Application of the technology to power generation equipment used by the Air Force will undoubtedly be sometime after the introduction of vehicular units. The concept can be applied to all diesel generator sets regardless of size, but introduction of certain aspects, i.e., ceramics and high-temperature lubricants, could be applied to the Air Force equipment before introduction of the full technology.

We must exercise caution when translating Army's technology progress to other applications. The Army is striving for high engine power and lower fuel consumption, irrespective of cost or price of fuel. Other researchers are motivated by lower fuel consumption, but obviously the price and type of available fuels drives interest in the concepts. Factored into this is the ever increasing environmental stringency imposed on the diesel engine in both its vehicular and stationary format. Again, interest lessens in the technology concept as projected exhaust emissions standards are lowered.

In spite of these constraints, the technology has created an atmosphere of research into diesel engine fundamentals that cannot but help improve an already superior thermal efficiency internal combustion engine. As progress is made on improving diesel engine efficiency, we see the same progress that was exhibited by the Otto cycle engine when pressed by fuel economy and exhaust emission standards. The only difference we see is that the diesel engine has the potential to approach 50+ percent thermal efficiency, whereas the Otto cycle has run its course of improvements.

f. Rankine Bottoming Cycle

Progress of this technology is best described in Reference 38 which stated "...and concluding the current contract activities...." Very little progress has been reported by either the government or its principle contractor, Thermo Electron, since 1983 when they reported that two 1,000-hour endurance tests were run with a 288 bhp, Class 8, long-haul truck with no apparent major technology difficulties. These tests also indicated a 12.5 percent improvement in fuel consumption. Further research was described in Reference 39.

The lack of funding for this technology has placed both research and development work on hold. For further consideration to be fully attractive, this technology requires working fluid improvements and the advent to high exhaust temperatures from a LHR or adiabatic engine. Because of these limitations, this technology will be considered in near term. The application of this technology is suited to only the larger diesel generator sets. As cogeneration becomes more acceptable and the other diesel engine technologies mature, an exotic toxic working fluid becomes less necessary.

g. Cogeneration

The worldwide energy crisis and general economic downturn of the early 1980's undoubtedly produced concerns, not only on reducing diesel engine fuel consumption, but also renewed interest in the other markets for diesel engines. One such obvious market was the cogeneration of hot water or steam by utilizing the waste energy from the engine cooling system and/or exhaust system. This recovery of waste energy is in addition to the return of electrical energy to the central utility grid.

At the same time, diesel engine performance was advancing with research on the low-friction engine and adiabatic or low-heat rejection engine. The recovery and utilization of waste energy for other forms of heat also became more attractive as the adiabatic technology advanced. The efforts in cogeneration appear to parallel both the diesel engine technology advancement and the worldwide concerns for energy conservation.

We became aware of marketable cogeneration systems as we reviewed literature from diesel marketing publications. The uses of the cogeneration concept are noval and innovative. The principle use is usually associated with either peak electrical load shaving or excess energy generation. Some of the publications include operational costs and/or other financial data.

An interesting power system, the automobile washing facilities shown in Figure 9, was reported in 1982 (Reference 40). The system contains jacket water heat recovery equipment for heating rinse water and reclaimed water. The engine also drives a blower which is located on an extended shaft on the generator. The blower recovers exhaust heat for the car drier air duct. This system paid for itself 2 years after installation.

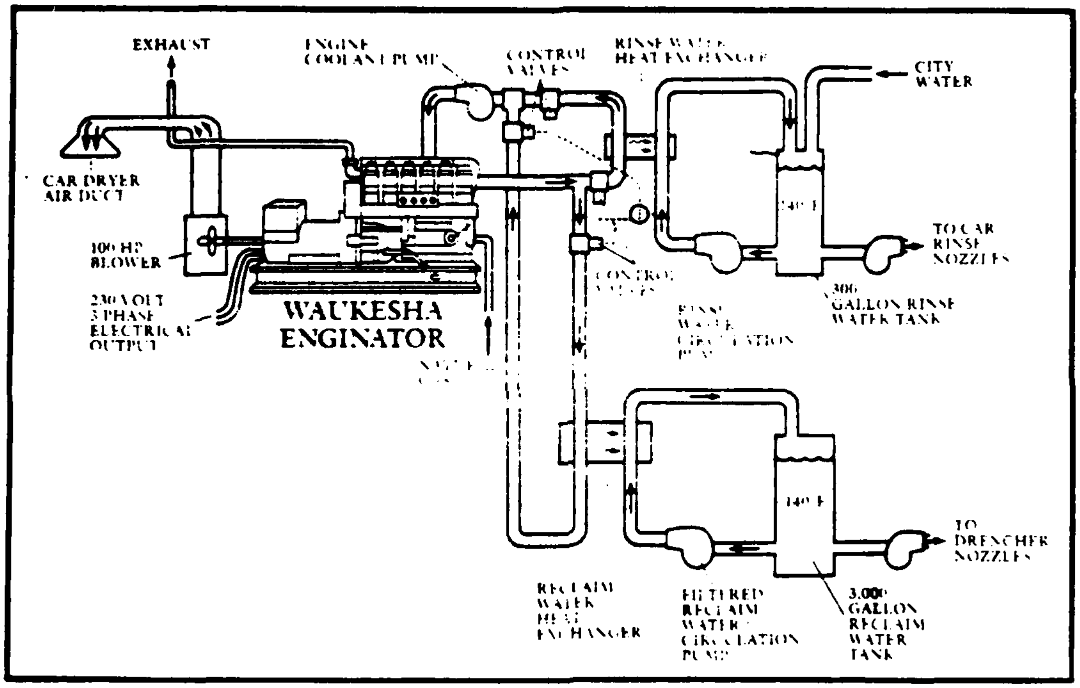
During the same time period, further details on cogeneration economics were published (Reference 41). A case study (Reference 41) unfortunately, uses natural gas as the fuel for the engine. Care must be exercised in the economic translation to diesel-fueled units. However, the cost methodology would be comparable once diesel operation, maintenance, and fuel costs are ascertained.

While references 40 and 41 centered upon systems in the 100- to 300- kW range, a larger system was described in Reference 42. Reference 42 describes a turn-key operation for diesel electricity and heating or cooling systems for large facilities (hotels, nursing homes, universities, etc.). These systems, used in the New York City area, consisted of a 2.4-MW steam turbine and eight 850-kW diesel generators. The diesel engines were equipped with waste energy recovery systems to augment both the steam turbine and electrical generation systems. The reported costs were $0.04 per kW/h for the steam turbine and $0.05 for the diesels *versus* $0.14-0.15 per kW/h for purchased electrical power. Reference 42 also revealed preliminary development work on cogeneration sets in the 30- to 40-kW range.

The existence of the marketable 60-kW cogeneration package, which also produces 440,000 btu/hr of hot water, driven by a 459 cubic inch natural gas fuel in a gasoline engine was discussed in May 1984 (Reference 43). The installed cost was projected to be $800/kW. The design details, life, maintenance intervals, and unit costs were detailed in Reference 44. The package specifications are given in Table 4 and the energy flow diagram in Figure 10.

Reference 45 provided a balanced historical overview of cogeneration technology and the Public Utility Regulatory and Policies Act of 1978. The paper also included several technology goals, plus a summary of one approach to cogeneration with an analysis of the feasibility of that approach. A summary of this report includes the following observations:

1. The generation of electricity by conventional methods is normally 30- to 40- percent fuel efficient. By utilizing a significant portion of the normally rejected heat of the process, the cycle fuel efficiency can be increased to 70 to 80 percent.



Schematic diagram showing the system for supplying power and heat in the car wash at Freeport, Ill. Both the engines at Freeport and Dixon, Ill. are Waukesha F1197G driving a 100 kW generator rated 230 volts, three-phase

Figure 9. Cogeneration Schematic

Table 4

TECOGEN Cogeneration Module

Specifications

INPUT:	760 cfh (6.0 Liters/sec) Natural Gas at 1020 Btu/scf (9.1 Kcal/Liter)
OUTPUT:	Electrical 60 kW 3 Phase Hz 208, 230 or 460 V Thermal 440,000 Btu/hr (30.8 Kcal/sec) Hot Water at 18 gpm (1.14 Liter/sec) 170°F (77°C) Input, 220°F (104°C) Outlet, typical
EFFICIENCY:	Electrical 26.4 percent of fuel HHV Combined Electrical and Thermal 83.1 percent of fuel HHV
DIMENSIONS:	82 in (208 cm) Long x 42 in (107 cm) Wide x 44 in (112 cm) High. Maximum width w/o Acoustic Enclosure 35 in (89 cm)
WEIGHT:	3000 lb (1360 Kilograms)
SOUND LEVEL:	70 dBA at 20 ft (6 meters)
CONTROLS:	Fully Automatic Microprocessor Controls for Unattended Operation (Includes Startup), Monitoring and Shutdown; Dynamic and Diagnostic Display)

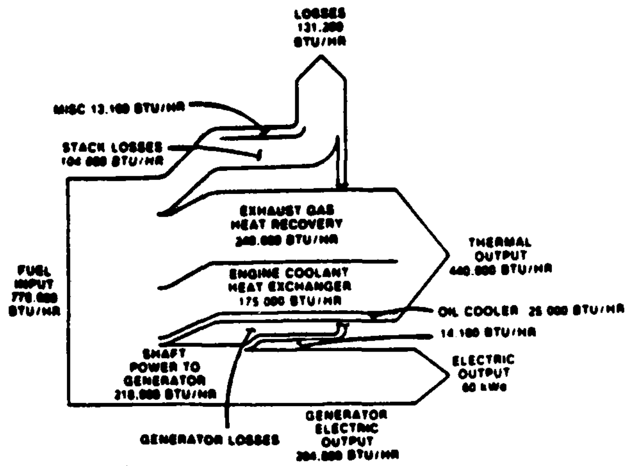


Figure 10. TECOGEN Energy Flow Diagram

2. Cogeneration can eliminate 3 to 4 percent of the power transmission losses of the total power generated.

3. Costs of installation are projected to be from $500 to $1,300 per kilowatt of capacity, depending on project size, complexity, and type. (The base units for the study was a 100-kW natural gas fired Caterpillar engine.)

4. A 430-kW cogeneration unit running on No. 2 Fuel Oil is targeted for a design peak thermal efficiency of 79.7 percent.

5. A study of over 50 potential cogeneration applications in the U.S. concludes that a suitable economic recovery rate does exist for small, packaged systems (where the average electrical cost is above 7 cents per kilowatt hour and the engine fuel cost is below 50 cents per million BTU). (Reference 45.)

A study by the Gas Research Institute (GRI) (Reference 46) is a follow-up to Reference 45. Table 5 indicates a potential market for cogeneration units. With market potential of this magnitude, the impetus for cogeneration R&D will continue with commensurate cost reductions. The GRI article concluded with a challenge to the cogeneration industry to develop packages by 1990 which will cost $700/kW for cogeneration units of 500 kW. GRI feels that this challenge will be met.

Cogeneration technology must be treated as an established technology. The cogeneration industry has emphasized that this technology must become cost competitive, versatile, and modular. Air Force application of the technology can range from 60 kW on up. Emphasis will be on standardized fuel (diesel) at remote sites. Natural gas will be used at CONUS locations where natural gas prices remain low. Further study of cogeneration technology potential is warranted.

h. Summary

There has been progress in certain technology areas and either abandonment or a slowing of the technology R&D in other areas. A brief summary, Table 6, recaps the assessment of technology progress since AFWAL-TR-80-2014.

Table 5

Potential Cogeneration Sites (From Reference 46)

Application	Number of Sales	Average Load (kWe)
Hospitals	7,100	300-800
Restaurants (18-24 hr.)	20,500	60-90
Supermarkets	29,550	240-300
Multi-family	54,000	50-400
Hotels/Motels	56,470	100-850
Shopping Centers	7,820	210-2200
Educational Facilities	13,000	500-2000
Large Office Buildings	24,000	200-800

Table 6

Synopsis of the R&D Progress of Selected Technologies

	Technology	Technology Rating	Potential Generator Set Application (kw)	R&D Effort
1.	Variable Area Turbocharger	A	60-1,000	Completed
2.	Variable Compression Ratio Piston	C	0-1,000 (possible) 1,000-3,000 (preferred)	Unfunded
3.	High-Pressure Fuel Injection Systems	B	All	Modest
4.	Turbocharging	B	250 up	Modest
5.	Adiabatic Engine	C	All	Large
6.	Ranking Bottoming Cycle	B	500 up	Unfunded-Modest
7.	Cogeneration	A	60 up	Modest-Large

SECTION III

Alternative Fuels Research

Alternative fuels research can best be described as a segmented attempt to discover the fundamental aspects of diesel combustion as first developed by the inventor of the diesel engine - Dr. Rudolph Diesel. The research of the early 1980's was focused upon the fuel economy and engine performance, including engine durability, when operated on alternative fuels. This research was ignited by the world energy crisis. Much of this early research included exhaust emission results, but these were included to round out the fuel performance data.

By mid-1984, the concerns for alternative fuels research, driven by a fuel crisis, had diminished. The research now focused on exhaust emissions. The proposed stringent NOx and particulate emissions from diesel engines had researchers turning to other fuels, principally those containing oxygen, to improve the engine's particulate emissions prospects. Reseach continues on alternative fuels for reducing diesel particulate emissions, but the evidence to date indicates that alternative fuels high in sulfur or nitrogen have little prospects of reducing diesel particulate matter. The sulfur is counted as particulate matter, and the high-nitrogen fuel exacerbates the NOx emissions problem. Increased control for reduction of NOx emission increases particulate emissions.

The prospects of alternative fuels used on an emergency basis was researched early and the reported results would indicate that most fuels will run acceptably in diesel engines without worry of engine damage. Environmental constraints and fuel consumption increases are ignored when run on an emergency basis.

Before embarking on a cursory review of the alternative fuels research, it would be beneficial to review the properties of automotive diesel fuel. The fuels used for diesel generator sets are not dissimilar, although broader in specification, and usually do not include as many additives. Reference 47 provides a primer on the then current (1979) diesel fuels. The specifications and quality have not changed appreciably although recent surveys would indicate the cetane number is falling in the U.S. market and the sulfur content is rising slightly. Additionally, proposed legislation would limit sulfur content (for particulate control) and this action would put extreme pressure on diesel fuel availability for the transportation sector with severe impact on the stationary engine segment of the marketplace. The effect of this proposed legislation on Air Force fuel quality is unknown.

Reference 47 gives a projection of diesel fuel support and demand from the 1979 timeframe. This projection is accurate today with the exception the Canadian fuel sulfur content is growing rapidly and is of concern to the Canadian Government. The Canadian sulfur content is approaching 1.5% on a mass basis.

The high water mark of alternative fuel research occurred in the early 1980's. Little has appeared in the open literature since 1983. The first rush of information occurred in the early 1980's when several research foundations provided excellent reviews of the potential for alternative fuels viz-a-vis' combustion cycle (Reference 49) as well as proposed research for the alternative fuel/engine interface (Reference 48). Attachment 5 also provides a summary of researchers conclusions on the government's role in future R&D as well as a strong endorsement of the diesel combustion cycle as being the optimum cycle for a broad range of fuels (Reference 48).

Reference 49 indicates the alternative fuels potential for combustion cycle engines and then the most commonly available fuel.

As evidenced by Table 7, the diesel engine appeared to have the least multifuel capability. However, both research firms concluded that the diesel engine provided the best promise for alternative fuel operation because the diesel engine was fully developed, but had not received the R&D attention the others had, i.e., it had more potential to be improved.

The lack of alternative fuel data on the other cycles indicate the engine community took the suggested research seriously and concentrated on alternative and emergency fuels for diesel engines. Research on alcohol fuels was done with the Otto cycle engine. That research is abundant and nearly complete.

Research results which have been reported are limited, and those listed below, while exotic, can be classified for emergency use only. The results also contain very limited data concerning the impact on reliability or durability of the engine. Again, the principle thrust was the characterization of exhaust emissions.

Table 7 (from Reference 49)

Suitability of Various Fuel/Engine Combinations for Road Vehicles

Fuel	Internal Combustion Engines: Spark Ignition	Internal Combustion Engines: Compression Ignition	Internal Combustion Engines: Stratified Charge	External Combustion Engine, e.g. Stirling, Gas Turbine
Gasoline	++++	++	++++	++++
Diesel Fuel	+	++++	++++	++++
Residual	+	++	++	++
Wide-Cut	+	++	++++	++++
LPG	+++	++	+++	+++
LNG	++	++	++	++
Alcohol	+++	++	+++	++++
Hydrogen	++	+	++	++

++++ = most suitable, + = unsuitable

The "Conference on Fleet Use of Unique Automotive Fuels," August 1981, reported that some of the emergency fuels included: (1) 10 to 15 percent used lubricating oil - filtered before use, (2) up to 25 percent used gasoline, (3) some used crude oils, (4) some used light residuals (<5 percent sulfur), (5) some used vegetable oils, and (6) some used alcohol. These should be used as true emergency fuels only. This will avoid catastrophic shut-down (Reference 50).

Reference 51 indicates that without recalibration of the rotary injection pump, the higher fuel densities and viscosities of peanut oil and sunflower oil caused fuel-flow and energy-delivery increases that yielded power and emissions increases. With the fuel flow adjusted to provide equal fuel energy input, engine power and thermal efficiency decreased slightly, while emissions increased slightly. They cautioned that the use of vegetable oil could have significant effects on engine reliability.

An October 1981 DOE report on synthetic fuel, alcohol emulsions, off-specification fuels, and methanol reemphasized the emergency nature of these types of fuels. The report also raised questions about the safety and handling aspects of those fuels and lack of engine wear data. DOE also recommended that a "handbook" on operation of diesel engines with ultimate fuels should be developed. (Reference 50 also alludes to a Southwest Research Institute (SwRI) "guidebook.") Further research was recommended (Reference 52).

In October of 1981, SwRI reported the results of their DOE-funded simulated coal-slurry fuel studies (Reference 53). SwRI concluded that the fundamental injection and atomization process was affected by these fuels, emissions and engine performance were slightly affected, and engine wear could be a problem if the slurry is poorly designed. They also concluded that coal slurries could be used if engine and fuel are properly designed. (Rudolph Diesel would have been pleased if there were to occur!)

In 1982, two reported emerged with a summary of the research to date on alternative fuels. The first report confirmed much of the theory and preliminary data concerning most alternative fuels which had similar properties to diesel fuel. However, the results were sufficiently confused because the report suggests a standardized test for alternative fuels. Wear data was limited or inconclusive. Further research was suggested (Reference 54).

The second report evaluated alcohol and ethanol blends in diesel engines. Four types of injection methods were evaluated because of the low cetane number of ethanol, hence, negating auto-ignition. The motivation for these tests was to allow agricultural interests to use excess grain products to make ethanol. The results were as expected: high exhaust emissions, increased complexity of fuel metering equipment, and a limit to alcohol substitutions due to combustion knock. The researchers reported no engine wear after 200 hours of operation (Reference 55).

Japanese researchers reported on a dual-fuel engine utilizing a methanol reformer to overcome the necessity for engine redesign and other exotic componentry for successful operation on alternative fuel. In spite of the increased hardware, they reported comparable energy output with lower smoke emissions and higher CO and HC emissions. They gave no durability data (Reference 56).

The compendium of papers, which included the above report, had the final report of the SwRI study on a coal solid derivation as a fuel. Major problems of engine redesign and further extensive research are necessary before coal or coal products (some liquids) can be a viable alternative fuel (Reference 57).

The results of operation on crude and processed shale oil were reported in early 1985. Three crude shale oils were chosen from six candidate shale oils to investigate their possible use as substitutes for No. 2 diesel fuel. Satisfactory hot-engine operation was achieved on the crudes using a fuel heating system. Regulated gaseous emissions changed little when the crudes are compared to diesel as fuels; but total particulates and soluble organics increased, and larger injector tip deposits and piston crown erosion were observed. After engine rebuild, two minimally processed shale oils were run without the fuel heating system, causing no engine problems. Most emissions were higher than No. 2 fuel using an 80 percent distillate of crude shale oil, but lower using a hydrotreated form of distillate (Reference 58).

As reported in Reference 59, the Air Force has an Alternative Aviation Fuels thrust which is characterizing the exhaust emissions and critical specification for fuels. The aim is to reduce specificity of fuels to allow a broader range of fuels as well as assess the environmental impact of present fuels.

In summary, it is evident that diesel engines will operate at various power-output states on several alternative fuels. This operation should be viewed as emergency use only with an increase of signature, namely, smoke and other pollutants. Long term operation on alternative fuels are to be avoided. Future operation on other fuels, exclusive of some broad-cut diesel fuel (i.e., similar to diesel fuel specifications now) will require major engine redesign including fuel management systems, piston shape, injection type (direct vs. indirect), structure, and fuel preparation componentry. It is not necessary for the Air Force to undertake such a venture since emergency operation is inherent in the present diesel engines in the inventory.

The previously reported technologies have not been assessed with respect to alternative fuels. Either the technology is simply not advanced enough to study alternative fuels, or the technology will be inherently compatible to alternative fuel, i.e., adiabatic engine. Research remains in these areas.

SECTION IV

A Look at the Future

As with Jonathon Swift's Gulliver, a sleeping giant has started to wake. Research into the diesel combustion process and engine fundamentals has intensified, primarily driven by the need to master the difficult challenges of exhaust emissions, but also to learn from and accumulate the lessons learned from spark-ignition engines as their improved thermal efficiencies approach unimproved diesel engine thermal efficiency. Further information must be gathered and more development must be undertaken, but the diesel engine potential is there. The rate of advancement remains cloudy as the market forces and fuel prices rise and fall. Unfortunately, the R&D impetus follows this cycle with the need to improve exhaust emissions the only constant factor in the R&D scenario.

The best assessment of future diesel technology trends appeared in late 1983 when the Society of Automotive Engineers published a summary of a NASA/DOE funded assessment program intended to identify potentially promising methods for advancing light-duty vehicle diesel engine technology. Table 8 is an extracted list of the reported technologies (Reference 60).

An analysis of this list shows technology/concepts which have been reviewed in some detail previously in this report. Other technologies are either speculative or have limited public information available. Reference 60 gives additional details for these other technologies.

Table 8

Diesel Engine Technology Options for Improvement

- Engine cycles and configurations
- Prechamber vs. direct injection
- Adiabatic
- Turbocompounding
- Miller cycle (Atkinson cycle)
- Spark assist
- Turbochargers
- Complex supercharger
- Positive displacement supercharger
- Ceramics
- Injection system
- Variable displacement
- Anti-friction bearings
- Gas lubricated piston/liner
- Oilless operation
- Preheat cycle
- Variable inlet and exhaust valve timing
- Higher air utilization

Since the time of the NASA/DOE report, two other glimpses into the future were given. The first was a compendium of Delphi-type predictions by diesel engine manufacturers and diesel engine component representatives upon the 50th anniversary of a diesel industry trade publication (Reference 61). The other article was similar to NASA/DOE study (Reference 62). The latter study predicted that the new generation of diesel engines would have: (1) low friction, (2) be a compact engine with lighter weight materials, (3) use composite materials and build-up rather than cast structures (taking advantage of CAD/CAM), (4) lower noise levels due to improved combustion systems, and (5) some electronic fuel injection systems. This article gave no time frame for when the developments would occur.

The former article, however, did have time frames and reference points throughout the article, and we have attempted to extract the most significant predictions below.

Generally, the leading diesel engines and designers around the world endorsed the list of technologies shown in Table 8. The common trend running through all of their comments and projections were: the diesel engine is on the brink of a tremendous new era of evolutionary improvements. There was also great optimism that the diesel engine will retain and improve its position as the most ubiquitous power source of modern times (Reference 61). Figures 11 thru 15 give the overall summary perspective of these experts as well as the status projection of the competitive power sources. We feel these projections are conservative.

The representatives of the medium- and slow-speed engine (e.g., large bore marine engines) endorsed future development of turbocharging concepts, improved lubricants, composite engine structures, electronic control of injection, turbocompounding, increased brake mean-effective pressures (smaller engine size), and improved materials.

The high-speed diesel engine community (e.g., truck engines, some generator sets) endorsed the Table 8 list, and included further emphasis on electronic control of injection as a necessity, adiabatic or LHR concepts, charge air-cooling a must, vastly improved turbocharging (for emission control and fuel consumption reduction), improved fuels and lubricants, and decreased engine friction through the use of ceramics and roller bearings. Figures 16 and 17 summarize these projections and obviously reflect the concerns for lower fuel consumption and exhaust emissions.

Component manufacturers predicted there would be component advancements via improved materials and electronics to meet the goals of the slow-, medium-, and high-speed diesel engine manufacturers in their attempts to improve the diesel engine.

Not all analysts were as bullish concerning diesel engine prospects. One analyst feels that in spite of the diesel engine's lower fuel consumption, its increased weight and poor air utilization will preclude its use in passenger vehicles. He projected that of all alternative power sources, a spark-ignited engine would be the main power source in the future (Reference 63).

A researcher from SwRI concluded that for state-of-the-art LHR engines, the improvements in fuel economy ranged from 0 to 15 percent from naturally-

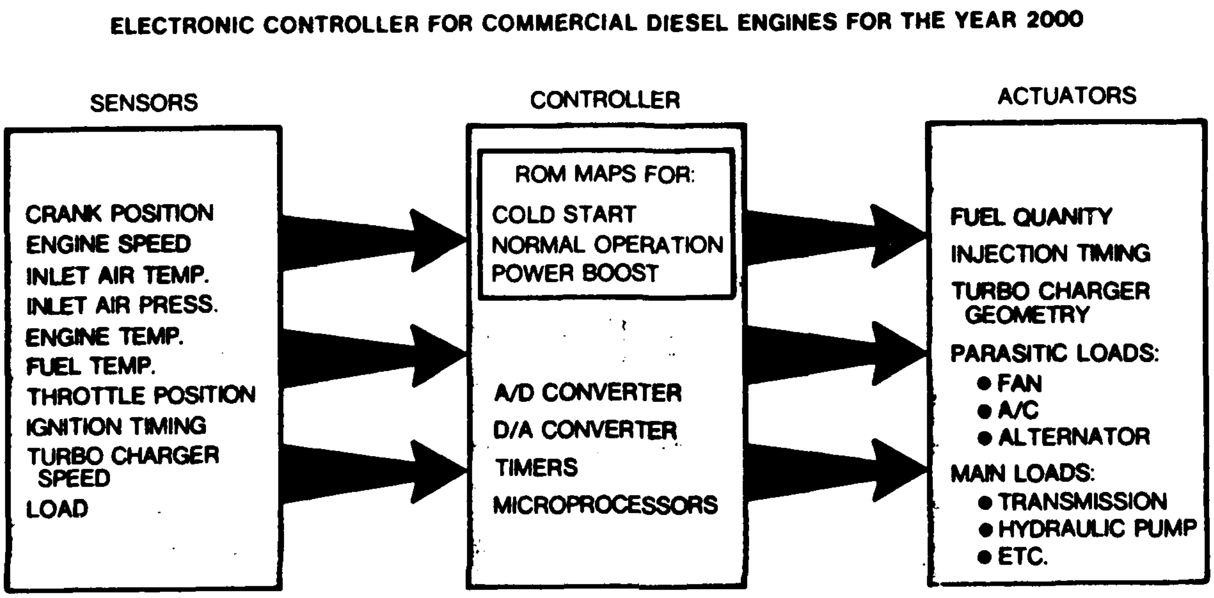


Figure 11. Electronic Controller for Commercial Diesel Engines for the Year 2000

ENGINE VERSION	EFFICIENCY (%)	BSFC (gms/kWh)	EARLIEST DATE OF INTRODUCTION
CURRENT TC & IC	37	230	NOW
IMPROVED BASIC ENGINE	42	190-200	1986-88
INSULATED	45	180-185	1988-92
TURBOCOMPOUNDED	50	165-170	1988-92
REDUCED FRICTION	55	150-160	1992-95
RANKINE BOTTOMING CYCLE ADDED	60	140-145	2000+

Figure 12. Diesel Engine Development Projection

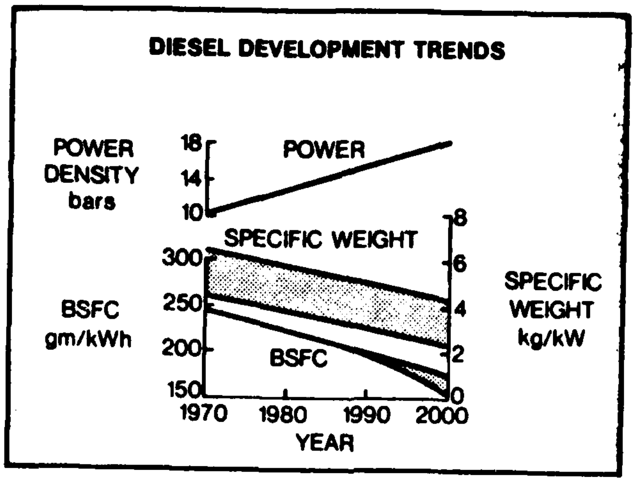


Figure 13. Diesel Development Trends, I

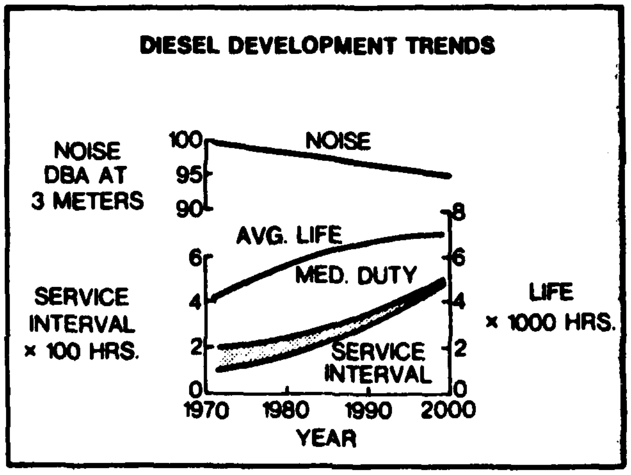


Figure 14. Diesel Development Trends, II

ENGINE TYPE	FUEL	THERMAL EFFICIENCY - % CURRENT	THERMAL EFFICIENCY - % POTENTIAL	SPECIFIC WEIGHT FACTOR	BULKINESS FACTOR m^3 FOR 100 kW UNIT	EARLIEST PRODUCTION
TURBOCHARGED & INTERCOOLED DIESEL	DIESEL, CURRENT QUALITY LEVEL	37	42	100	0.85	NOW
INSULATED TURBO-COMPOUNDED DIESEL	RED. QUAL. DIESEL OR WIDE CUT FUEL	45	56	105	0.85	1988
SPARK ASSISTED STRATIFIED CHARGE PISTON	MULTI	32	42	105	0.85	1985
SPARK ASSISTED STRATIFIED CHARGE ROTARY	MULTI	30	37	70	0.42	1990
GAS TURBINE						
METAL	MULTI	40	—	75	0.36	1990
CERAMIC	MULTI	—	56	70	0.36	1995
STIRLING						
METAL	MULTI	38	52	135	1.25	1995
CERAMIC	MULTI	—	—	135	1.25	2000+

Figure 15. Status of Alternative Engines

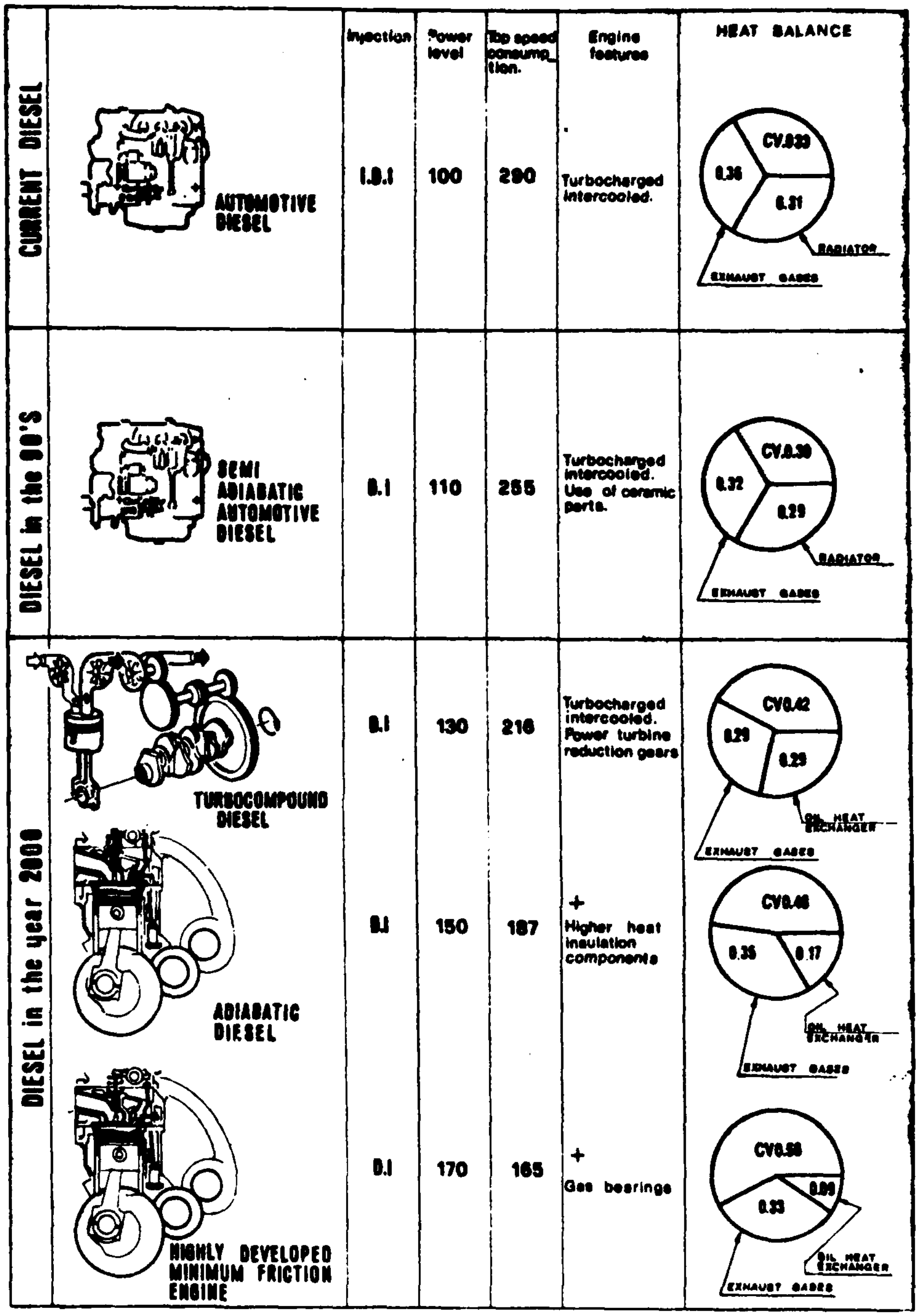
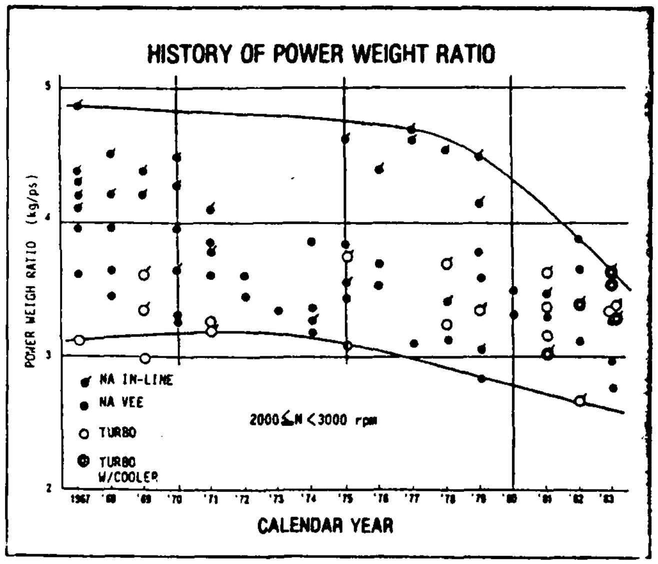


Figure 16. Technology Progress



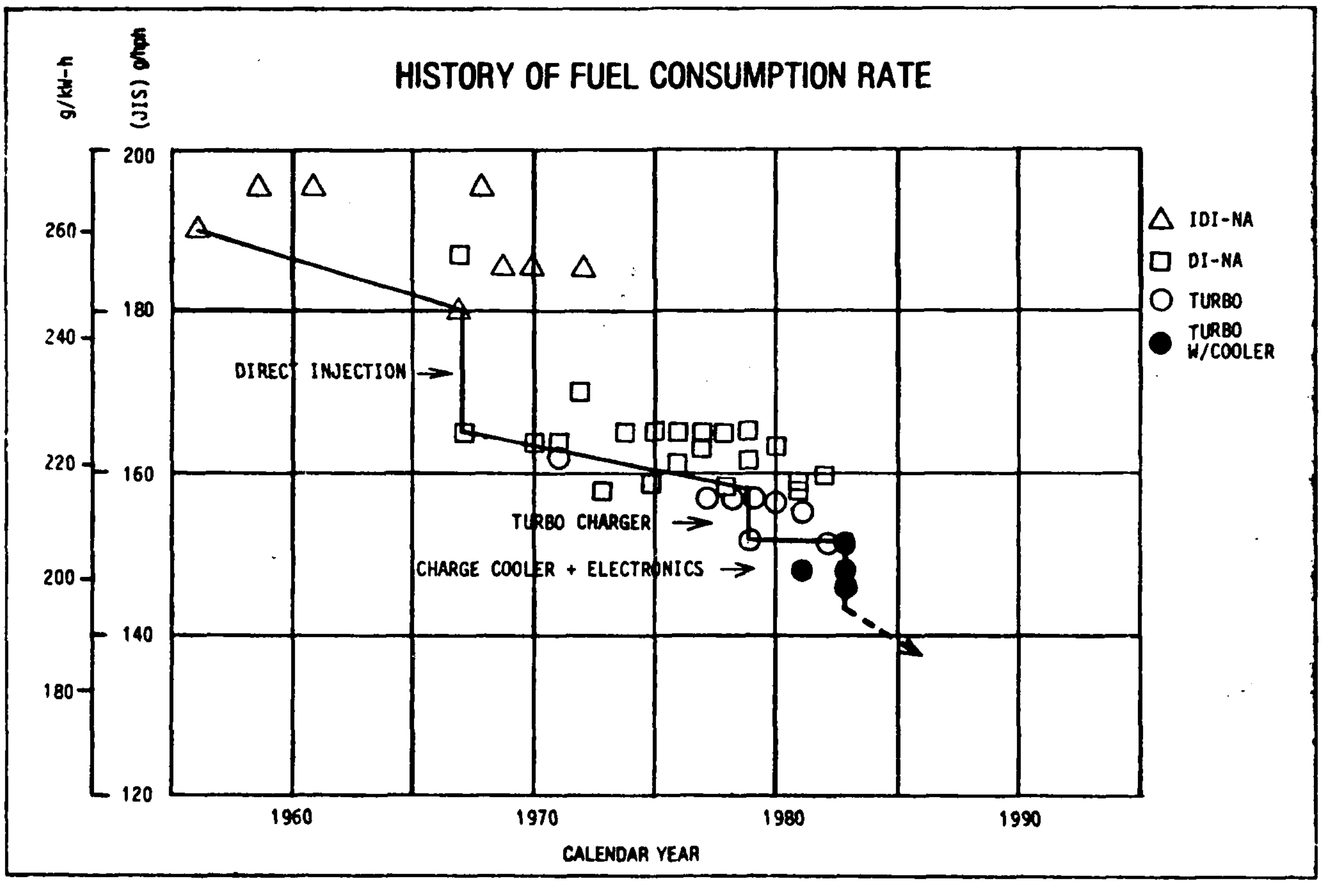


Figure 17. History of Fuel Consumption Rate

and Power to Weight Ratio

aspirated thru turbocharged to turbocompounded engines. LHR increased NOx emissions, reduced HC and CO emissions, offers benefits in noise reduction and smoke, and can operate on low cetane fuels. He concluded by saying that more research is needed to overcome the practical problems before LHR engines can be put into production (Reference 64).

Also, several researchers maintained that an examination of the thermodynamics of low-heat rejection engines may show that fuel consumption reduction is attributable to more piston work rather than excess thermal energy recovered from the exhaust stream or recovered by other means. This indicates that insulation of the diesel engine will be the major contributor to lower fuel consumption, and further research to achieve the true adiabatic engine may not be necessary (Reference 65).

Finally, the author briefly assembled open literature to review the various items of Table 8 that heretofore have not been mentioned.

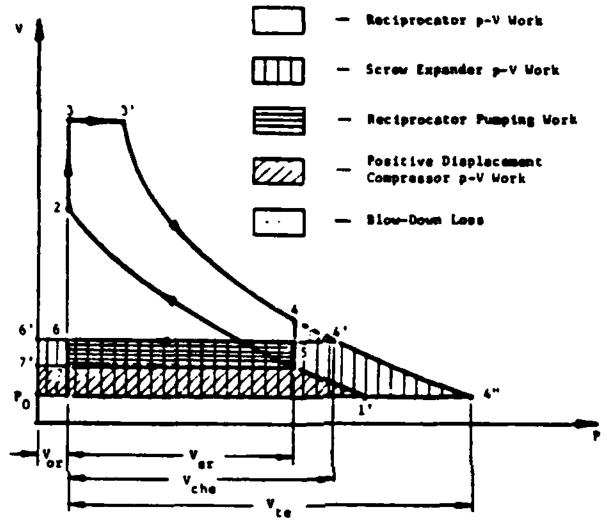
The Atkinson cycle was described in Reference 66 and the theoretical cycle is shown in Figure 18.

The Atkinson cycle, the screw-expander-compound system (the design to achieve Atkinson cycle operation), has the potential to perform better than turbocompounded baseline system by approximately 7 percent in terms of brake mean effective pressure and 5 percent of brake specific fuel consumption over a wide range of operating conditions. Unfortunately, the screw-expanded system needs major sealing, materials, and cost breakthroughs to be effective in the near term. Its progress should be monitored.

We plan to monitor the progress on methods of air induction and the various concepts for turbocharging or supercharging. All the proposed systems require advances in materials or the advent of electronic controls. Both the electronic control advances and the materials appear to be near-term problems. References 67 thru 70 contain further details regarding these systems.

Reference 71 developed a novel mechanism for variable crank-radius to connecting-rod-length engine for variable displacement. This concept of variable displacement has been researched before and as with this latest concept, it awaits the advent of better materials and engine structures before it can be accomplished.

A 1980 report indicated that thermal efficiencies approaching 75 percent could be achieved with an exhaust recycle or closed-cycle diesel engine. This Japanese concept allowed diesel engine operation under water to produce electrical energy in support of off-shore drill rigs. This concept is reminiscent of German U-boat operation (Reference 72).



ATKINSON CYCLE GENERATED BY DIESEL ENGINE AND SCREW EXPANDER AND COMPRESSOR

Figure 18. Atkinson Cycle Schematic

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