Technical Report

No. 13502

SPARK-IGNITED DIESEL ENGINE (U)
CONTRACT DAAE07-84-C-R047
and DAAE07-85-C-R054

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By

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Conventional diesel engines suffer from problems of excessive weight and size and excessively high rates of pressure rise and peak pressure because of the requirement of very high-compression ratios for the purpose of ignition. They also lack multi fuel capability. The use of electrical or other precise ignition means obviates the dependence on high compression for ignition and would allow the diesel engine to operate at the more efficient and practical compression ratio of 12 to 1. To accomplish this, an innovative ignition system with an unusually high rate of energy delivery was used in conjunction with a modified diesel engine. This new design was found to provide approximately equal efficiency under most operating conditions other than high load, and to provide instant cold start at the more desirable compression ratio of between 11 to 12 to 1. However, problems of spark plug fouling by the fuel spray made this approach impractical for this specific application. Approaches for handling the problem of plug fouling have been suggested in this report.
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1.0 INTRODUCTION

This final technical report, prepared by Combustion Electromagnetics Inc., CEI, for the U.S. Army Tank-Automotive Command (TACOM), under contract DAAE07-84-C-RO47 and DAAE07-85-C-R054, describes the prototype engine developed for achieving the objectives of this contract including the fuel injector and ignition system used, and the test results obtained. A Deutz FIL511D, single-cylinder, air-cooled, direct-injection diesel engine of 50 cubic-inch displacement was used as the base engine and was modified from the crankcase up into the prototype engine. The engine was tested both in its completed prototype form and in baseline form. The SuperFlow Computerized Engine Dynamometer and the Geneva APA 100 were used to conduct the tests and to collect all the required data.

2.0 OBJECTIVE

The primary goal of this work was to modify a high-power and high-energy ignition system developed by CEI (the "CEI Ignition") to be made suitable for Direct-Injection IC engines and to test it on a prototype engine of appropriate design, developed by CEI, by modifying an existing high-efficiency diesel engine. The engine would be modified to have a moderate compression ratio, no swirl, and moderate to high squish to help improve the air-fuel mixing and to speed up the burn. Cold start at the lower compression ratio would be achieved through use of the ignition. The expected results are a significant reduction in both the peak combustion pressures and in the rate of rise of pressure. This, in turn, was expected to provide a high engine efficiency, a low-heat transfer, and a multi fuel capability.

The single-cylinder prototype test engine would be designed to accommodate a central fuel injector and a dual (CEI) pulsed type discharge ignition for igniting the fuel spray and for coupling electrical energy to the flame front during the ignition and early combustion periods. The baseline and prototype engine would be dynamometer tested on a SuperFlow Computerized Engine Dynamometer Test Bed to assess both the benefits of the dual ignition system and the benefits of the engine design. The Geneva APA 100 would be used for in-cylinder measurements using a pressure transducer.
3.0 CONCLUSIONS

The new ignition and engine system was successful in meeting most of the contract objectives, but was unsuccessful in that the spark plug suffered from a persistent fouling problem due to contamination by the injected fuel. In addition, the combination of the required high spark breakdown voltage and the plug contamination made for an especially stressful environment for the ignition. This has led to the regrettable conclusion that, without further research to prove otherwise, high-power, high-energy ignition, i.e., CEI ignition, is not considered to be a practical approach at this time for controlling early-stage combustion in diesel engines. If there existed a demonstrated strong desire to pursue such an approach, then the research should include studies of fuel contamination of ceramics and possible ways to alleviate it, including the possible use of extended ceramic plugs and the possible development of a dual glow plug/spark plug.

4.0 RECOMMENDATIONS

4.1. Ignition/Engine Modifications

As stated in the "Conclusion" section, use of the CEI ignition in diesel engines is not recommended, unless work is successfully performed to develop ways to handle the combined problems of plug fouling and a very high ignition voltage requirement. However, a possible design will be presented which uses an unusually long insulator nose to minimize the plug-fouling problem, and a plug-tip location to provide a possible self-cleansing action by strong squish flow fields. Also, piston firing will be recommended to provide for the largest possible plug gap and elimination of the ground or "J" electrode.

4.2. Alternative Engines

CEI recommends taking a totally different approach in terms of engine type and design for meeting the objectives of a multi fuel direct injection engine with a high power to weight ratio; i.e., a lighter weight engine than the current diesel. Development of a low effective compression ratio two-stroke engine for this application is recommended as well as a low cost, low-pressure fuel injection system designed for early injection into a high-flow field which will promote mixing.
5.0. DISCUSSION

5.1. Background

There is a need to increase the diesel engine's capabilities for burning a variety of fuels and to reduce its weight and size. In addition, there is an advantage to reducing the engine heat transfer losses so that an air-cooling system, versus a water-cooling system, can be used. It is desired to accomplish these goals while maintaining or improving the engine efficiency, preferably while improving the engine's exhaust emission levels.

One way to achieve some of the desired goals is to better control the flame initiation process. This can be done in several ways, such as by using some electrical initiation means, e.g., a spark plug, or by using an electronically controlled fuel injection system. Electronic fuel injection still requires compression ignition as the ignition process, and therefore requires a very high compression ratio of 17:1 to 24:1, which is detrimental from the perspective of reducing engine size, weight, and heat transfer, and optimizing engine efficiency. An ignition system, on the other hand, is compatible with a lower compression ratio, including the compression ratio (CR) where best efficiency is achieved, i.e., 11 to 13 to 1 CR for the typical diesel engine. However, as was discovered in this work, the diesel-engine environment is particularly harsh for an ignition system from the perspective of plug fouling and high cylinder pressures.

However, it is clear that if the time of flame initiation can be specified as a function of engine RPM and load (as it is in a gasoline engine) and the engine can be operated at a moderate compression ratio, then the desired goals mentioned above can be met, and in addition, slightly higher engine efficiency can be achieved, as well as a substantially lower rate of rise of pressure, (one of the principal problems of the diesel engine).
5.2. **Fuel Injection System**

Considerable research was done on identifying suitable fuel injection nozzle characteristics for this contract. The results of this research were reported in Technical Report No. 5, which is included as part of Appendix A. The principal results related to spray pattern, including spray angle and spray traversal with time. The results indicate that a nozzle with 12 holes of approximately 0.006 inches diameter was suitable for achieving the objectives of good mixing and good utilization of the air. Such a design produced a spray which required 1.5 to 2.0 msecs to reach the spark plugs located one inch away, or approximately 20 crank angle degrees at a speed of approximately 2,000 RPM. A drawing and specification of the fuel injector tip is shown in Figure 5-1.

For the fuel pump, it was decided to use the pump that comes standard with the engine. Attempts to obtain special research type fuel injection systems from major manufacturers were unsuccessful. In fact, it was a disappointment that none of the major fuel injector manufacturers were interested in collaborating on this project. This resulted in some delays and reconsidering of approaches. In the end, as indicated in Figure 5-1, blank nozzle tips were obtained from United Technologies, Italy, and these were successfully laser drilled at a local facility. Testing with a hand-operated fuel injection pump indicated a suitable spray pattern, i.e., a circularly uniform spray pattern with good atomization. As is also indicated in Figure 5-1, the two holes located along the line joining the spark plugs were of a slightly larger diameter, i.e. 0.008" diameter, to insure that slightly more fuel mixture would be injected at the park plug sites.

Open chamber ignition of the fuel spray was not performed because of time limitations. Also, this had been investigated in the Phase I part of the contract, where it was shown that reliable ignition was achievable even at room temperature.
AMERICAN BOSCH
NON-HARDENED BLANK
ADB M/77-8718-1

Tip Wall Thickness
= 1.2 mm

- Drill a total of 12 holes on equal 30° spacing
- Drill 2, .200 mm holes in line with 1.5 mm fuel hole
- Drill 10, .150 mm holes in remaining locations

C.E.I.
8/03/89

1.85 mm alignment holes
2 places.

Figure 5-1. Fuel Injector Tip with Specifications
5.3. **Ignition System**

The ignition system used under this contract was developed by CEI which had an unusually high rate of energy delivery and the ability to deliver very rapid spark pulses in a single ignition and combustion duration.

Since the beginning of the contract, the CEI ignition went through a significant evolutionary process, to the point that when the engine tests were initiated, the ignition was near what is now deemed to be its final stage of development. One of the principal new features of the ignition was the development of a recharge circuit which delivered energy to the discharge capacitor between the very rapidly firing spark pulses of the pulse train, so that the amplitude of the spark pulses was maintained near the maximum level throughout the ignition firing period. A circuit drawing of the ignition is shown in Figure 5-2.

![Figure 5-2. Ignition System Circuit Drawing](image)

Two spark plugs were used in the engine, as is shown in Figure 5-3. They were placed symmetrically, one inch from the centrally located fuel injector. The objective was to initiate combustion at these two sites so that the burn time could be reduced (for a centrally located fuel injector). However, as will be discussed in Section 5.7 under "Alternatives", it is believed that most of the benefits of the ignition can be attained by the careful repositioning of both the fuel injector and the spark plug, with only one spark plug per cylinder being required. The use of one spark plug per cylinder is clearly advantageous in terms of simplicity and cost.
A typical (primary voltage) sequence of spark pulses ranges between about thirty pulses of approximately constant amplitude at low engine speeds to five pulses at high engine speeds. For the high engine speed condition, the time duration between pulses is approximately 0.25 msecs, resulting in the delivery of five ignition pulses within one millisecond. This is important given that the fuel spray velocity at the spark plug site is approximately 0.5 cm per msec, which would create five ignition sites over a length of 0.5 cm defined by the radius of the spark plug end. The first power converter that was developed for this contract work, designated as REDL3, was not used, as it was superseded by a more efficient and suitable system recently developed by CEI, shown in circuit form in Figure 5-2.

![Cross-section of Combustion Chamber](image)

**Figure 5-3. Cross-section of Combustion Chamber**

**Compression Ratio**: 12:1  
**Bore x Stroke**: 3.90" x 4.13"  
**Head Clearance**: 0.065"  
**Piston Bowl Volume**: 58 cc
5.4. **Engine Measurement Equipment**

Two pieces of equipment were purchased under this contract for the purpose of performing the engine testing: An engine dynamometer with computer data acquisition capability, the SuperFlow SF 901, and equipment for measuring the in-cylinder combustion processes, the Geneva APA 100.

The SuperFlow SF 901 is a complete engine dynamometer test stand which comes with a test stand for mounting the engine and a dial for varying the torque provided by the water brake. It is suitable for at least 500 horsepower. As part of the contract, a computer terminal was purchased which permitted communication with the main electronic test stand to perform calibrations and to develop averaging schemes as part of the data acquisition.

Standard with the SuperFlow is the ability to measure typical engine parameters such as RPM, torque, power, fuel flow, air flow, brake specific fuel consumption (BSFC), manifold pressure, water temperature, and oil temperature. A sample of the data is shown in Figure 5-4. Considerable work was performed to calibrate the system and to make it suitable for the diesel engine. For fuel measurements, a back-up weighing technique had to be implemented, since it was found that the pulsations created by the fuel pump produced errors in the measurements (by the fuel flow turbine). Furthermore, the higher viscosity of the diesel fuel affected the operation of the fuel flow meter.

A large air ballast was fabricated and installed to dampen the greater air fluctuations caused by the single-cylinder engine. The undamped pulsations gave a higher apparent air-flow reading.

The APA 100 required significant troubleshooting to get it to operate to specification. However, while this was an inconvenience, the manufacturer of the unit made himself totally available in helping eliminate problems in the system. In the end, the unit was found to operate sufficiently to allow appropriate pressure versus time curves to be obtained, and to permit proper averaging between cycles of the various key parameters, principally peak pressure and rate of rise of pressure. A typical output data curve is shown in Figure 5-5. The heat output data was suspect, and it was determined as not essential for the level of study that was being performed.
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Test: 2.00 Seconds/Data Point
Fuel Spec. Draw: 830 Air Sensor: 4.0
Vapor Pressure: .37 Barometric Pres.: 29.38 Ratio: 1.00 TO 1
Engine Type: 4-Cycle Diesel Engine displacement: 50.0 Stroke: 4.130
Indicated Data vs Crankangle

Engine: DEUTZ F1L 511
Cell: Superflow
Project: TACOM Baseline

No. Cylinders = 1
Bore = 100.00 mm
Stroke = 105.00 mm
Compr. Ratio = 17.00
Intake = 328.5, -120.5
Ign Timing = 984.0 Deg
Exhaust = 108.5, 392.5

Engine Speed = 1535.0 rpm
Engine Torque = 28.48 N-m

APA100: U.S. Army Tank Automotive Command

Title: de03ja.016

Figure 5-5. Typical APA 100 Pressure Data

DATA MARKERS:
Pmax = 80.9975
\theta = 5.00
dPmax = 5.6322
\theta = -5.00

Double-triangle is valve timing.
5.5. **Engine Design**

For the purposes of this contract work, a single-cylinder, air-cooled diesel engine was determined to be suitable. A study was conducted of readily available commercial single-cylinder engines. After careful evaluation, a Deutz F1L511D engine was selected, as this was a high-efficiency engine and therefore represented a suitably challenging baseline. The engine was of approximately 4 inch bore and stroke with an approximately 50 cubic-inch displacement. The more complete engine specifications are given below.

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<td>Bore/Stroke</td>
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<tr>
<td>Displacement</td>
<td>50 cubic inches (0.825 Liters)</td>
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<tr>
<td>CR</td>
<td>17:1</td>
</tr>
<tr>
<td>Maximum output</td>
<td>14 hp @ 3000 RPM</td>
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<tr>
<td>Maximum torque</td>
<td>27 ft.lbs @ 2000 RPM</td>
</tr>
<tr>
<td>Minimum idling speed</td>
<td>900 RPM</td>
</tr>
<tr>
<td>BSFC @ maximum torque</td>
<td>0.385 lbs/hp-hr</td>
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<tr>
<td>Engine weight</td>
<td>242 lbs (110 kg)</td>
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</tbody>
</table>

After some study, it was concluded that the best way to incorporate the new design was to completely replace the existing engine cylinder and cylinder head but to retain the engine's piston. The piston was modified by having the face appropriately machined to increase the bowl size for a compression ratio of approximately 12 to 1 (see Figure 5-3). A cast-iron cylinder and cylinder head were designed and fabricated to CEI specifications. With the exception of the rocker mounts, all parts were hand machined. The cylinder head was flat with vertical valves since the combustion chamber was contained entirely inside the piston. This also simplified machining of the parts.

For the combustion chamber located inside the piston, it was decided to use a high-squish combustion chamber similar to the existing one used in the engine in its baseline condition. The combustion chamber, which took the form of a bowl-in-piston, was designed such that the two spark plugs closely defined the outer edges of the bowl. The fuel injector was designed with a 150 degree included angle so that the fuel spray would move mainly against the air flow created by the squish to promote mixing of the air and fuel. This angle was also chosen so that injected fuel would reach the spark plug sites for ignition.
5.6. **Engine Testing and Results**

The engine was mounted on the SuperFlow computerized engine dynamometer for testing. Special mounts were made for the engine because of its high level of vibration. The mounts were made of four-inch square cross-section aluminum stock and were found to perform satisfactorily. In addition, the entire frame of the dynamometer was anchored to the floor by means of large blocks of wood spanning its width and shock-mounted to the floor through heavy duty machinery rubber mounts. These modifications were found to be sufficient to handle the engine. For pressure measurement, a water-cooled standard piezotronics pressure transducer was used, which was mounted in the cylinder head.

Initial tests were conducted to calibrate air flow and fuel flow. During these tests, it was discovered that the fuel-flow meter would not give reliable data because of pulsations in the fuel line and the high viscosity of the fuel, which was standard diesel fuel available at local gas stations. Therefore, a back-up weighing technique was devised so that when actual data was being taken, fuel consumption for a precise period of time was determined by the time measurement.

Measurements were made at four engine speeds: 1500, 2000, 2500, and 2800 RPM. For each engine speed three load settings were taken: 10 ft. lbs, 20 ft. lbs, and a maximum load which was typically 27 ft lbs. Measurements included printing of the complete data provided by the SuperFlow engine dynamometer computer (Figure 5-4), with the fuel flow being measured independently via the weighing technique. This permitted evaluation of BSFC, for each point. In addition, the APA 100 was operated at each point to provide peak pressure and maximum rate of rise of pressure at each point (see Figure 5-5 for sample data).

Summaries of the baseline data are shown for the three torque conditions in Figures 5-6, 5-7, 5-8. The same figures show the data that were taken later with the engine in its final redesigned form.
Figure 5-6, B.S.F.C. versus R.P.M. @ 10 ft. lbs. torque

Figure 5-7, B.S.F.C. versus R.P.M. @ 20 ft. lbs. torque
**Figure 5-8.** B.S.F.C. versus R.P.M. @ Full Torque.
At 10 foot lbs BSFC was approximately 0.6 lbs/hp-hr over the entire speed range of 1500 RPM to 2800 RPM. At 20 ft lbs, BSFC ranged from about 0.42 to 0.48 lbs/hp-hr, increasing approximately linearly with speed. At maximum load, BSFC was between 0.41 and 0.42, similar to the 20 ft lbs case, and was constant for speeds in excess of 2000 RPM, rising somewhat at the higher speeds to a maximum BSFC 0.44 lbs/hp-hr at 2800 RPM. The torque peaked at between 2000 and 2500 RPM at between 26 and 27 ft. lbs. The data from the SuperFlow and the APA 100 (for the baseline engine) are shown in Appendix B.

After completion of the baseline tests, the engine was disassembled down to the crankcase and the new piston and cylinder heads installed. A cross section of the combustion chamber, as defined by the piston and shown with respect to the centrally located fuel injector, is shown in Figure 5-3. The dimensions of the bowl in the piston were selected to give a compression ratio of approximately 12 to 1.

Initial attempts to operate the engine with a lower compression ratio of 10 to 1 and a lip at the perimeter of the cylinder bowl were unsuccessful with the engine producing insufficient power at the higher loads and the perimeter lip interfering with the fuel spray. Hence, the selection was made for a higher compression ratio of between 11 and 12 to 1, and a modified, simpler shaped bowl-in-piston combustion chamber, shown in Figure 5-3. As with the base engine, the water-cooled pressure transducer was used and installed in the cylinder head. One of CEI's latest prototype ignitions was used.

It was found that at room temperatures without the aid of the ignition, the engine would not start at the 12 to 1 compression ratio. With the aid of the ignition, with either one or two plugs, the engine would start immediately and operate until sufficiently warm, when the ignition could be either turned off or kept on. A run of data was taken at very light load during the starting and warm-up stage with the ignition consecutively turned on and off and the APA 100 in the data-acquiring mode to determine the differences in peak pressure. The results of this test are summarized in Figure 5-9, in terms of peak pressure versus time elapsed from engine start-up for the two cases with and without ignition assist. The actual data is given in Appendix C.
Figure 5-9. Peak pressure versus elapsed time from engine start-up.
As can be seen, the use of the ignition produced a substantially higher peak pressure for the first ten minutes of operation, which is desirable under the conditions of cold start, versus the conditions with the engine hot at high load where a lower peak pressure and lower rate of rise of pressure is desirable.

The engine was then run under the same conditions as the baseline at 10 and 20 ft. lbs and at full load at the four RPM conditions of 1500, 2000, 2500, and 2800 RPM. Once the engine was hot, selective data was taken with and without the ignition. The differences between the two cases were found to be small, while the differences with respect to the baseline engine were larger. Actual data of BSFC versus RPM are given for the modified engine in Figures 5-6, 5-7, 5-8, alongside the baseline data.

Plots of the maximum pressure and the maximum rate of rise of pressure for the three torque conditions are shown in Figures 5-10 through 5-15. The differences between the modified and baseline engine are remarkable, with the modified engine exhibiting, under practically all operating conditions, a peak pressure and peak rate-of-rise-of-pressure about one half that of the baseline engine. Given that the modified engine operated at comparable efficiency to the baseline engine, this data represents the achievement of one of the principle goals of this contract work. The actual data is given in Appendix D.
Figure 5-10. Peak Pressure versus R.P.M. @ 10 Fc-ft. torque
**Figure 5-11. Peak Pressure versus R.P.M.**

@ 20 Ft.-lbs Torque
Figure 5-12. Peak pressure versus R.P.M. @ Full Torque
Figure 5-13. Peak rate of rise of pressure versus R.P.M. @ 10 ft-lbs torque
Figure 5-14. Peak rate of rise of pressure versus R.P.M. @ 20 ft.-lbs. torque
Figure 5-15. Peak Rate of Rise of Pressure versus R.P.M. @ Full Torque.
5.7. **Conclusions and Alternatives**

From inspection of the data, one can draw several conclusions relating to the use of ignition in the modified engine relative to the baseline engine. The key conclusions are enumerated below:

1) The modified engine operates at similar efficiency and slightly lower peak output power as the baseline engine through the use of the ignition. This is an important result when one bears in mind that the engine compression ratio was a full 5 compression ratios lower, i.e. approximately 12 to 1 versus 17 to 1 compression ratio. This means that, in principle, one can have a significantly lighter engine (because of the reduced compression ratio), and significantly lower heat transfer to the walls. Furthermore, from an exhaust emission perspective, one would expect somewhat lower NOX emissions because of the lower peak pressures and temperatures at lower compression ratios.

2) This engine was operated without swirl and yet had approximately the same characteristics as the baseline engine. It can therefore be concluded that it would have significantly lower heat transfer losses because of the low swirl. This has a particular benefit of allowing the engine to operate with minimal air cooling, versus continuous forced air-cooling or water cooling, which is undesirable from the military application perspective.

3) At light loads, the efficiency of the modified engine was found to be significantly higher than the baseline engine. The reasons for this are not totally clear, since improved ignition probably should not have such a large effect. The differences may be attributed, in part, to the lighter air-cooling requirements of the engine under light-load conditions in its modified form, versus in the baseline form, where an approximately constant amount of forced air cooling was provided at all load conditions (for given engine speed).

The cooling air-blower, item 39, Figure 5-16, manufacturer's drawing of the engine, was removed and replaced by a small electric fan which was turned on when the engine had reached operating temperature. In addition, cooling was provided by the high temperature synthetic oil which was used in the engine, although no data was taken to evaluate this.
Discussions with a technical manufacturer's representative indicate that the cooling air blower (item 39) would absorb approximately 1/2 horsepower at an engine speed of 1500 RPM, which would account for approximately one half of the difference in efficiency found at the 10 ft lb, 1500 RPM (and 2000 RPM) case shown in Figure 5-6.

4) The modified engine exhibited approximately half the peak pressure and half the rate-of-rise-of-pressure under the conditions tested, excepting for the case of cold start where the modified engine in its spark-ignited form provided a higher peak pressure than without ignition, as is desired.

5) The modified engine provided instant cold start, as desired.

In the "Recommendations" section, Section 4.0, it was stated that should it be desirable to use the current approach of electrically igniting the spray in a diesel engine, then certain precautions should be taken, including taking into account the design recommendations enumerated below to optimize the chances of success. The principle concern, as already stated, is spark plug fouling by the fuel spray and the high pressure the ignition has to operate under.

In Figures 5-17 and 5-18, two approaches are shown which make use of the principles of ignition described in this report for the case of a conventional four-stroke diesel engine (Figure 5-17) and a two-stroke engine (Figure 5-18), which is recommended for this application. In both cases, certain design principles are followed, which are enumerated below:

1. The spark plugs should have extended insulators to reduce the chance of plug fouling due to the insulator becoming coated with fuel and/or carbon.

2. The spark plugs are preferably located near the region of high squish which aids the cleaning of the plug. However, as shown in these figures, the cleaning action would be restricted to principally one side of the plug.

3. The spark plug should be located far away from the fuel injector, approximately 1.5 inches in the cases shown here, for a combustion chamber with a bore size of approximately 4 inches. This has the following desirable characteristics:
a. The spray will have entrained significant air and become relatively homogeneous by the time it traverses the approximate 1.5 inch length to reach the spark plug site.

b. The spray velocity will have approached close to zero near the spark plug site, especially upon encountering the oppositely directed air squish created by the small piston-head near the spark plug.

4. The spark plugs should not have a ground, or "Jay" electrode, and should form the spark to appropriate protrusions on the piston. This permits the use of a larger spark gap under most operating conditions where ignition may occur 20 to 40 degrees BTDC. This is especially helpful at high engine speeds where a stronger ignition is provided through a larger gap provided by the earlier firing of the plug.

5. The sparking protrusions on the piston, which are preferably composed of erosion-resistant material such as tungsten-nickel-iron, will tend to run hotter than the other parts of the combustion chamber and, therefore, further aid in the ignition process by supplementing heat energy to the spark energy.

6. Finally, it should be appreciated that by placing the spark plug tip in a region where the squish fields and fuel spray collide will produce high microscale turbulence, which is helpful in producing strong flame initiation.

With respect to Figure 5-17, it should be understood that what is being proposed here is "a way" of implementing the above recommendations in a four stroke diesel engine design. There are numerous variations to this design, which depend in part on where one wants to locate the combustion chamber and the fuel injector.

Figure 5-18 depicts a cross scavenged two-stroke engine which is particularly well suited for using the design recommendations. The edge of the deflector section of the piston provides an edge suitable for firing the spark to, and for achieving a large spark gap.
Constructions Groups: General View

List of Construction Groups

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Figure 5-16. Manufacturer's Drawing of Deutz Test Engine
Figure 5-17. Alternative Spark Ignited Diesel

Figure 5-18. Alternative Spark Ignited Diesel (Two Stroke Engine)
APPENDIX A

FUEL INJECTION NOZZLE CHARACTERISTICS
Summary

The design of the fuel injector for the electrically ignited quiescent open chamber combustion process should meet, as closely as possible, several goals according to our current thinking.

The first goal is to mix the fuel and air using the energy in the fuel spray, since swirl and squish have been minimized to reduce heat transfer losses. To obtain this result it appears that the number of holes in the injector should be maximized since the Abramovitch jet mixing theory (to be briefly discussed later) indicates that there is no practical control of the cone angle of the spray for multi hole nozzles.

The second goal is to avoid liquid fuel impingement on the cylinder wall or ceramic insert since fuel impingement on the wall could lead to loss of fuel into the lubricating system. Thus the traversal time from the injector to the cylinder wall should be large enough for the fuel of the expected droplet size to completely vaporize. The quiescent non swirl combustion chamber design tends to minimize the travel time, since the fuel travels straight to the wall and not in a longer spiral path.

The third goal involves placing a combustible mixture at the ignitors at the proper time for ignition, preferably using the fuel injector cam and pump supplied with the engines. We currently think that not all of the fuel should be injected before ignition to minimize the rapid rate of pressure rise that could occur if a significant fraction of the mixture were to auto ignite (knock). For testing and evaluation purposes we would like to have the flexibility of having some combustible mixture arrive at the ignitor at say 30 degrees BTDC so that the effect of timing advance can be evaluated. Since our current fuel injection system is expected to start injection at 24 degrees BTDC, little time is available for fuel travel and mixing (relative to TDC). More advance may be desirable to provide more time for mixing and evaporation. If the combustion process works like a W.O.T. gasoline engine, less advance will be needed - probably about 15 degrees at 2,000 RPM, which would correspond to an injection timing of about 30 degrees BTDC.

With these initial goals established, we next attempted to learn about the state of the art in injector capabilities and analytical predictive techniques, by questioning local suppliers, manufacturers, two consultants, and reviewing recent SAE literature. We also measured some of the characteristics of the fuel injection system supplied with the single cylinder Deutz engine, such as the cam profile, full rack and partial rack injected volume, and line pressure vs speed and rack setting. With this data and a theoretical model we evaluated several design parameters and developed a "first" injector design.
Determination of Deutz Engine Fuel Injection System Parameters

The first project was to measure the cam follower-plunger lift profile. A gear driven auxiliary drive pulley was accurately marked in five degree increments and the plunger lift position was measured to the nearest .001 inch using a dial indicator. From these measurements we estimate that injection could in principle start as early as approximately 50 degrees BTDC and could end at 10 degrees ATDC. The manual indicates that the injection starts at 24 degrees BTDC. We still need to learn why this time is so retarded from the apparent potential starting point of 50 degrees BTDC and whether we can obtain some advance by modifying the pump.

The next tests were conducted by Boston Fuel Injection Company. They determined the peak line pressure and amount of fuel injected at each of four speeds and four rack settings. The delivery at the maximum rack setting was much less than the swept volume of the plunger minus the retraction volume, which was equal to about ten times the injected volume.

An estimate of the volume of fuel delivered per revolution for the standard engine was made using the rated power of 17.5 Hp and the BSFC of 0.41 lbs/hp-hr. This required a delivery of .040 cc/rev. assuming a fuel specific gravity of 0.9. This corresponded to a volume much closer to the measured volume than the swept volume.

Discussions with Deutz confirmed that the fuel injection system was designed to start injection at 24 degrees BTDC and to inject a maximum of 44 cc/1000 revolutions. This confirmation of engine based fuel delivery estimates leaves us currently without an understanding of how to optimally redesign the fuel system without further knowledge. For example the displacement rate of the injector plunger would deliver the maximum amount of fuel in 10 crankshaft degrees if no compliance existed in the piping and injector. We may set up a simple test fixture to suspend the fuel injector so it will spray an absorbent disc attached to the engine shaft to determine the duration of injection. This will improve our ability to design the nozzle hole size and pick the number of holes.

As a further attempt to understand the fuel injection process, we plotted the pressure vs delivery rate and found that the pressure varied linearly, not quadratically with speed, as would be predicted for normal orifice flow. Also the dynamic pressure computed for our smallest orifice, 12 hole design is only 862 psi for 2000 engine RPM, while line pressures over 4000 psi were measured using the standard, four hole (of unknown diameter) nozzle. Thus we will not attempt to determine the source of the line pressure during our current effort. Nor will we attempt to predict absolute values of injection timing or jet velocities, unless we are able to obtain additional information from Bosch or United Technologies.
Fuel Jet Model Assumptions

Based on the analytical results of the Rife jet velocity prediction equations, we are able to compare fuel injector designs of different hole size and number of holes. The analysis is based on the model that assumes that air is entrained into the jet in a manner which conserves linear momentum. Thus as the distance along the path from the nozzle hole increases, the jet velocity decreases since more mass (entrained air) is included in the jet. The result is that the diameter of the jet becomes a linear function of distance from the so called "pole" position, the position from which the jet appears to diverge (with infinite speed) and minimum (fuel) mass. The entrainment parameter is the sole determinant of the cone angle of the jet for a given fuel to compressed air density ratio! Neither changes in hole size nor fuel velocity have any effect on the predicted cone angle. They do have a small effect on the distance from the fuel injector to the pole position but over the range of interest in this project that distance is predicted to change by only a maximum of 0.1".

Predicted Results

Since we have no means to effect the entrainment factor for quiescent non swirl flow, our only means to improve the fuel distribution process appears to be to increase the number of holes in the fuel injector nozzle. For a given hole diameter, the predicted velocity is inversely proportional to the number of holes. If compressibility effects are important (not considered here) then a lower dependence on the number of holes would be expected.

Although the cone angle of the nozzle sprays is predicted to be invariant, the distance for a given loss of velocity ratio relative to the computed nozzle speed is directly proportional to the jet diameter. Thus smaller diameter jets slow down more rapidly than larger ones. This phenomenon led to an interesting result for the time for the jet to reach the ignitor location one inch from the center of the cylinder. For a design of 12 holes of 0.0035" diameter relative to a design of 6 holes of 0.007" diameter, we found that while the initial speed of the .0035" diameter hole jets was twice that for the larger hole nozzle, (four times the area but half the number of holes), the greater rate of decrease of velocity with distance for the smaller jets led to the predicted results that both jets arrive at the ignitor at practically the same time.

We can summarize results for time to distance predictions for dimensions similar to the cylinder radius by the following rules of thumb.

1. Time to distance is inversely proportional to the product of nozzle flow speed times hole diameter.
2. For a given plunger diameter and cam profile, time to distance is proportional to the number of holes of a given diameter or inversely proportional to diameter for a given number of holes.

Figure 1 shows the computed time vs. distance predictions for several hole sizes and number of holes which bound the range of expected designs. The time vs. distance calculations were made on the basis of the velocity between computed velocity intervals predicted by the Rife Equations being assumed to be the geometric mean of the two end point velocities. This is a reasonable approximation for the present purposes.
Our current research on drilling holes for the nozzle tips indicates that holes of 0.007 inch appear to be readily available. One vendor believes that 0.005 inch holes are possible by diamond drilling unhardened nozzle bodies. We have not yet determined if laser drilling or ultrasonic machining can produce smaller holes. Thus our present first designs are for 10 to 12 holes of 0.005" diameter if available, or 10 holes of .007" diameter. An analysis of the 12 hole, 0.005" hole diameter case is included (Figure 3) along with some other cases.

The travel times to the injector for the first part of the jet on the centerline for these nozzle designs are predicted to be on the order of 15 to 20 crankshaft degrees for the 2000 RPM condition we modelled. Thus the start of injection will need to be earlier than the present 24 degrees if we desire to start the ignition process at 20 to 30 degrees BTDC which is typical of normal spark ignition timing.

The time for other than the centerline of the jet to reach the one inch distance is even larger than the above calculated times. Thus we are considering ways to change the start of injection by about 20 to 25 degrees. We are considering obtaining another cam and mounting it onto the cam shaft at the appropriate timing.

The actual fuel injector we expect to use is one manufactured by United Technologies. It has a larger body than the pencil nozzle made by Stanadyne, but individual nozzle tips are available for it, and we expect to be able to get these tips machined to our specifications locally. We can accommodate the larger 17mm body within our current cylinder head design without significant compromise. Stanadyne was not willing to cooperate with us at this time because of too large a backlog.
Time, Milliseconds

to reach Radius on Jet C

FIG. 1

Crank shaft Degrees @ 2000 RPM

Supporting Data

17 April 1986

# Holes: Hole diameter, in
NOZZLE SCALING CALCULATIONS
17-Apr-86

ENGINE:
Bore: (in) 3.94
Stroke: (in) 4.13
Speed: (rpm) 2000
Comp. Ratio: 11
Disp. Vol.: 50.4
(in³)
Clearance: 5.04

PUMP:
Plunger: (mm) 7.5
Stroke: (mm) 7
Retract: (mm³) 35
Vol./Stroke: 274.3
Inj. Mass: (mg) 250.4

NOZZLE:
Hole Size: (in) 0.007
Number: 12
Coefficient: 0.6
Hole Area: 3.85E-05
Total: 4.62E-04

INJECTION PARAMETERS:
Specified in crankangle degrees (TDC = 0)
Start: (deg.) -50
End: (deg.) 10
Single Hole:
Rate: (mg/deg.) 0.35
Rate: (g/sec) 417
Rate: (g/sec) 5004
Velocity: (m/sec) 30.7
Nozzle:
Rate: (mg/deg.) 4.17
Rate: (g/sec) 5004

INLET:
Vol. Effic.: 0.95
Polytropic: 1.3
Inlet Press.: 14.7
Inlet Temp. (°F) 90
Density: 1.14E-03
Air at TDC:
TDC Press: 332
TDC Temp: 1129
Density Ratio: 11
TDC Density: 1.26E-02

COMBUSTION CHAMBER: Jet Mixing
Density Ratio: 72.7
Jet Vel.: 30.7
Radius: 0.0035
Entrain: (axial) 0.11

JET CALCULATION
Pole: 0.219
No Crossflow
Rel Vel, Vf/Vi: 0.9 0.7 0.6 0.5 0.4 0.3 0.2 0.1 0.05
Velocity m/sec: 28 21 18 15 12 9 6 3 2
Mass Ratio: 9 2.33 1.5 1 0.67 0.43 0.25 0.11 0.05
Air/Fuel: 0.111 0.429 0.667 1 1.493 2.326 4 9.091 20
Radius, inches: 0.01000 0.02300 0.03100 0.04200 0.05800 0.08300 0.13300 0.28300 0.58200
Mean Distance: 19.13 40.68 53.4 69.65 92.42 128.45 197.62 398.28 792.17
Distance, in.: 0.29000 0.36000 0.41000 0.46000 0.54000 0.67000 0.91000 1.61000 2.99000
Time msec: 0.251236 0.32456 0.38988 0.46717 0.618628 0.93636 1.76592 5.95671 20.2666
NOZZLE SCALING CALCULATIONS
17-Apr-86

ENGINE:
Bore: (in) 3.94
Stroke: (in) 4.13
Speed: (rpm) 2000
Comp. Ratio: 11
Clearance: 5.04

PUMP:
Plunger: (mm) 7.5
Stroke: (mm) 7
Retract: (mm³) 35

NOZZLE:
Hole Size: (in) 0.005
Number: 12
Coefficient: 0.6

INJECTION PARAMETERS:
Specified in crankangle degrees (TDC = 0)
Start: (deg.) -50
Duration: 60
End: (deg.) 10

Single Hole:
Rate: (mg/deg.) 0.35
Rate: (g/sec) 417
Velocity: (m/sec) 60.1

INLET:
Vol. Effic.: 0.95
Polytropic: 1.3
Inlet Press.: 14.7
Inlet Temp. (F) 90
Density: 1.14E-03

COMBUSTION CHAMBER: Jet Mixing
Density Ratio: 72.7
Jet Vel.: 60.1
Radius: 0.0025
Entrain: (axial) 0.11

JET CALCULATION
Pole: 0.156
No Crossflow
Rel Vel, Vf/Vi: 0.9 0.7 0.6 0.5 0.4 0.3 0.2 0.1 0.05
Velocity m/sec: 54 42 36 30 24 18 12 6 3
Mass Ratio: 9 2.33 1.5 1 0.67 0.43 0.25 0.11 0.05
Air/Fuel: 0.111 0.429 0.667 1 1.493 2.326 4 9.091 20
Radius, inches: 0.00700 0.01700 0.02200 0.03000 0.04100 0.05900 0.09500 0.20200 0.41600
Mean Distance: 19.13 40.68 83.68 95.65 128.45 217.62 498.28 792.17
Distance, in.: 0.20000 0.26000 0.29000 0.33000 0.39000 0.48000 0.65000 1.15000 2.14000
Time msec: 0.089172 0.12117 0.14076 0.17168 0.22842 0.33846 0.63226 2.12897 8.05594

Supporting Data, Tab. Ref. #5

RCM was 122
m/sec (JMR)

FIG. 3
NOZZLE SCALING CALCULATIONS
17-Apr-86

ENGINE:
Bore: (in) 3.94
Stroke: (in) 4.13
Speed: (rpm) 2000
Comp. Ratio: 11
Disp. Vol.: 50.4 (in³)
Clearance: 5.04

PUMP:
Plunger: (mm) 7.5
Stroke: (mm) 7
Retract: (mm³) 35
Vol./Stroke: 274.3
Inj. Mass: (mg) 250.4

NOZZLE:
Hole Size: (in) 0.0035
Number: 12
Hole Area: 9.62E-06
Coefficient: 0.6
Total: 1.15E-04

INJECTION PARAMETERS:
Specified in crankangle degrees (TDC = 0)
Start: (deg.) -50
Duration: 60
End: (deg.) 10

Single Hole:
Rate: (mg/deg.) 0.35
Rate: (g/sec) 417
Velocity: (m/sec) 122.6

INLET:
Vol. Effic.: 0.95
Polytropic: 1.3
Inlet Press.: 14.7
Inlet Temp. (F) 90
Density: 1.14E-03

COMBUSTION CHAMBER: Jet Mixing
Density Ratio: 72.7
Jet Vel.: 122.6
Radius: 0.00175
Entrain: (axial) 0.11

JET CALCULATION
Pole: 0.109
No Crossflow
Rel Vel, Vf/Vi: 0.9 0.7 0.6 0.5 0.4 0.3 0.2 0.1 0.05
Velocity m/sec: 110 86 74 61 49 37 25 12 6
Mass Ratio: 9 2.33 1.5 1 0.67 0.43 0.25 0.11 0.05
Air/Fuel: 0.111 0.429 0.667 1 1.493 2.326 4 9.091 20
Radius, inches: 0.00500 0.01200 0.01600 0.02100 0.02900 0.04200 0.06700 0.14200 0.29100
Mean Distance: 19.13 40.68 53.4 69.65 92.4 128.45 197.62 398.28 792.17
Distance, in.: 0.14000 0.18000 0.20000 0.23000 0.27000 0.33000 0.45000 0.81000 1.50000
Time msec: 0.030621 0.04106 0.04743 0.05877 0.077360 0.11315 0.21336 0.74129 2.80675

Supporting Data, Tech. Rpt. #5

FIG. 4
NOZZLE SCALING CALCULATIONS
17-Apr-86

ENGINE:
Bore: (in) 3.94
Stroke: (in) 4.13
Speed: (rpm) 2000
Comp. Ratio: 11
Clearance: 5.04

PUMP:
Plunger: (mm) 7.5
Stroke: (mm) 7
Retract: (mm$^3$) 35

NOZZLE:
Hole Size: (in) 0.0035
Number: 6
Coefficient: 0.6

INJECTION PARAMETERS:
Specified in crankangle degrees (TDC = 0)
Start: (deg.) -50
End: (deg.) 10

Single Hole:
Rate: (mg/deg.) 0.7
Rate: (g/sec) 835

Nozzle:
Rate: (mg/deg.) 4.17
Rate: (g/sec) 5010

Velocity: (m/sec) 245.6

INLET:
Vol. Effic.: 0.95
Polytropic: 1.3
Inlet Press.: 14.7
Inlet Temp. (F) 90
Density: 1.14E-03

COMBUSTION CHAMBER: Jet Mixing
Density Ratio: 72.7
Jet Vel.: 245.6
Radius: 0.00175
Entrain: (axial) 0.11

JET CALCULATION
Pole: 0.109

REL Vel, Vf/Vi: 0.9 0.7 0.6 0.5 0.4 0.3 0.2 0.1 0.05

Velocity m/sec: 221 172 147 123 98 74 49 25 12
Mass Ratio: 9 2.33 1.5 1 0.67 0.43 0.25 0.11 0.05
Air/Fuel: 0.111 0.429 0.667 1 1.493 2.326 4 9.091 20
Radius, inches: 0.00500 0.01200 0.01600 0.02100 0.02900 0.04200 0.06700 0.14200 0.29100
Mean Distance: 19.13 40.68 53.4 69.65 92.42 128.45 197.62 398.28 792.17
Distance, in.: 0.14000 0.18000 0.20000 0.23000 0.27000 0.33000 0.45000 0.81000 1.50000
Time msec: 0.015263 0.02047 0.02366 0.02933 0.038590 0.05648 0.10710 0.36836 1.38022

RCM was 122 m/sec (JMR)
NOZZLE SCALING CALCULATIONS
17-Apr-86

ENGINE:
Bore: (in) 3.94  Disp. Vol.: 50.4
Stroke: (in) 4.13
Speed: (rpm) 2000
Comp. Ratio: 11  Clearance: 5.04

PUMP:
Plunger: (mm) 7.5  Vol./Stroke: 274.3  0.913
Stroke: (mm) 7
g.VV
Retract: (mm3) 35  Inj. Mass: (mg) 250.4  Rohsenow & Choi

NOZZLE:
Hole Size: (in) 0.005  Hole Area: 1.96E-05
Number: 6  Total: 1.18E-04
Coefficient: 0.6

INJECTION PARAMETERS:
Specified in crankangle degrees (TDC = 0)
Start: (deg.) -50  Duration: 60
End: (deg.) 10

Nozzle:
Rate: (mg/deg.) 0.7  Rate: (mg/deg.) 4.17  
Rate: (g/sec) 835  Rate: (g/sec) 5010

Velocity: (m/sec) 120.3  
!RCM was 122 m/sec (JMR)

INLET:
Vol. Effic.: 0.95
Polytropic: 1.3
Inlet Press.: 14.7
Inlet Temp. (F) 90
Density: 1.14E-03

COMBUSTION CHAMBER: Jet Mixing
Density Ratio: 72.7
Jet Vel.: 120.3
Radius: 0.0025
Entrain: (axial) 0.11

JET CALCULATION
Pole: 0.156
No Crossflow
Rel Vel, Vf/Vi: 0.9  0.7  0.6  0.5  0.4  0.3  0.2  0.1  0.05
Velocity m/sec: 108  84  72  60  48  36  24  12  6
Mass Ratio: 9  2.33  1.5  1  0.67  0.43  0.25  0.11  0.05
Air/Fuel: 0.111  0.429  0.667  1  1.493  2.326  4  9.091  20
Radius, inches: 0.00700  0.01700  0.02200  0.03000  0.04100  0.05900  0.09500  0.20200  0.41600
Mean Distance: 19.13  40.68  53.4  69.65  92.4  128.45  197.62  398.28  792.17
Distance, in.: 0.20000  0.26000  0.29000  0.33000  0.39000  0.48000  0.65000  1.15000  2.14000
Time msec: 0.044567  0.06056  0.07036  0.08582  0.114222  0.16921  0.31611  1.06447  4.02795
NOZZLE SCALING CALCULATIONS
17-Apr-86

ENGINE:
Bore: (in) 3.94 Disp. Vol.: 50.4
Stroke: (in) 4.13 (in\(^3\))
Speed: (rpm) 2000
Comp. Ratio: 11
Clearance: 5.04

PUMP:
Plunger: (mm) 7.5 Vol./Stroke: 274.3 0.913
Stroke: (mm) 7
Retract: (mm\(^3\)) 35 Inj. Mass: (mg) 250.4 Rohsenow & Choi

NOZZLE:
Hole Size: (in) 0.007
Number: 6
Coefficient: 0.6
Hole Area: 3.85E-05
Total: 2.31E-04

INJECTION PARAMETERS:
Specified in crankangle degrees (TDC = 0)
Start: (deg.) -50 Duration: 60
End: (deg.) 10
Single Hole: Nozzle:
Rate: (mg/deg.) 0.7 Rate: (mg/deg.) 4.17
Rate: (g/sec) 835 Rate: (g/sec) 5010
Velocity: (m/sec) 61.4

INLET:
Vol. Effic.: 0.95
Polytropic: 1.3
Air at TDC:
Inlet Press.: 14.7 TDC Press: 332
Inlet Temp. (F) 90 TDC Temp: 1129
Density: 1.14E-03 Density Ratio: 11
TDC Density: 1.26E-02

COMBUSTION CHAMBER: Jet Mixing
Density Ratio: 72.7
Jet Vel.: 61.4
Radius: 0.0035
Entrain: (axial) 0.11

JET CALCULATION
Pole: 0.219
No Crossflow
Rel Vel, Vi/Vi:
Velocity m/sec: 55 43 37 31 25 18 12 6 3
Mass Ratio: 9 2.33 1.5 1 0.67 0.43 0.25 0.11 0.05
Air/Fuel: 0.111 0.429 0.667 1 1.493 2.326 4 9.091 20
Radius, inches: 0.01000 0.02300 0.03100 0.04200 0.05800 0.08300 0.13300 0.28300 0.58200
Mean Distance: 19.13 40.68 53.4 69.65 92.42 128.45 197.62 398.28 792.17
Distance, in.: 0.29000 0.36000 0.41000 0.46000 0.54000 0.67000 0.91000 1.61000 2.99000
Time msec: 0.126755 0.16331 0.19515 0.23265 0.305646 0.46130 0.87608 2.97147 11.2333
NOZZLE SCALING CALCULATIONS
17-Apr-86

ENGINE:
Bore: (in) 3.94
Stroke: (in) 4.13
Speed: (rpm) 2000
Comp. Ratio: 11
Disp. Vol.: 50.4 (in³)
Clearance: 5.04

PUMP:
Plunger: (mm) 7.5
Stroke: (mm) 7
Retract: (mm³) 35
Vol./Stroke: 274.3
Inj. Mass: (mg) 250.4

NOZZLE:
Hole Size: (in) 0.007
Number: 10
Hole Area: 3.85E-05
Total: 3.85E-04
Coefficient: 0.6

INJECTION PARAMETERS:
Specified in crankangle degrees (TDC = 0)
Start: (deg.) -50
End: (deg.) 10
Duration: 60

Single Hole:
Rate: (mg/deg.) 0.42
Rate: (g/sec) 501
Nozzle:
Rate: (mg/deg.) 4.17
Rate: (g/sec) 5010

Velocity: (m/sec) 36.8

INLET:
Vol. Effic.: 0.95
Polytropic: 1.3
Inlet Press.: 14.7
Inlet Temp. (F) 90
Density: 1.14E-03

INLET:
Air at TDC:
TDC Press: 332
TDC Temp: 1129
Density Ratio: 11
TDC Density: 1.26E-02

COMBUSTION CHAMBER:
Jet Mixing
Density Ratio: 72.7
Jet Vel.: 36.8
Radius: 0.0035
Entrain: (axial) 0.11

JET CALCULATION
Pole: 0.219
No Crossflow
Rel Vel, Vf/Vi: 0.9 0.7 0.6 0.5 0.4 0.3 0.2 0.1 0.05
Velocity m/sec: 33 26 22 18 15 11 7 4 2
Mass Ratio: 9 2.33 1.5 1 0.67 0.43 0.25 0.11 0.05
Air/Fuel: 0.111 0.429 0.667 1 1.493 2.326 4 9.091 20
Mean Distance: 19.13 40.68 53.4 69.65 92.42 128.45 197.62 398.28 792.17
Distance, in.: 0.29000 0.36000 0.41000 0.46000 0.54000 0.67000 0.91000 1.61000 2.99000
Time msec: 0.211373 0.27207 0.32517 0.38899 0.512658 0.76971 1.46442 4.82452 17.2172

FIG. 6

A-14
APPENDIX B

BASELINE ENGINE DATA
SUPERFLOW AND APA100 DATA
<table>
<thead>
<tr>
<th>DATE</th>
<th>TIME</th>
<th>RPM</th>
<th>TORQUE (lb-ft)</th>
<th>H.P.</th>
<th>FUEL (gph)</th>
<th>AIR (SCFM)</th>
<th>AIR (cfm)</th>
<th>A/F</th>
<th>BS.F.C (hr)</th>
<th>EXHAUST TEMP.</th>
</tr>
</thead>
<tbody>
<tr>
<td>12/23</td>
<td>11:01</td>
<td>1500</td>
<td>3.9</td>
<td>2.0</td>
<td>1.67</td>
<td>21.6</td>
<td>98.5</td>
<td>59.0</td>
<td>0.596</td>
<td>360°</td>
</tr>
<tr>
<td>12/22</td>
<td>15:05</td>
<td>2000</td>
<td>10.0</td>
<td>3.8</td>
<td>2.29</td>
<td>26.6</td>
<td>121.3</td>
<td>53.0</td>
<td>0.603</td>
<td>130°</td>
</tr>
<tr>
<td>12/21</td>
<td>15:34</td>
<td>2500</td>
<td>10.3</td>
<td>4.9</td>
<td>2.90</td>
<td>29.2</td>
<td>133.2</td>
<td>45.9</td>
<td>0.592</td>
<td>260°</td>
</tr>
<tr>
<td>12/20</td>
<td>15:57</td>
<td>2800</td>
<td>9.9</td>
<td>5.3</td>
<td>3.36</td>
<td>34.0</td>
<td>155.0</td>
<td>40.1</td>
<td>0.634</td>
<td>350°</td>
</tr>
<tr>
<td>11/22</td>
<td>14:49</td>
<td>1500</td>
<td>20.4</td>
<td>6.0</td>
<td>2.50</td>
<td>21.9</td>
<td>99.9</td>
<td>40.0</td>
<td>0.417</td>
<td>325°</td>
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<tr>
<td>11/21</td>
<td>10:40</td>
<td>2000</td>
<td>20.2</td>
<td>7.8</td>
<td>3.37</td>
<td>26.3</td>
<td>119.9</td>
<td>35.6</td>
<td>0.432</td>
<td>610°</td>
</tr>
<tr>
<td>12/21</td>
<td>16:20</td>
<td>2500</td>
<td>20.1</td>
<td>9.6</td>
<td>4.26</td>
<td>29.1</td>
<td>132.7</td>
<td>31.2</td>
<td>0.444</td>
<td>270°</td>
</tr>
<tr>
<td>11/21</td>
<td>15:15</td>
<td>2800</td>
<td>19.7</td>
<td>10.4</td>
<td>5.00</td>
<td>33.7</td>
<td>153.7</td>
<td>30.7</td>
<td>0.481</td>
<td>500°</td>
</tr>
<tr>
<td>12/20</td>
<td>9:57</td>
<td>1500</td>
<td>21.3</td>
<td>6.1</td>
<td>2.54</td>
<td>21.5</td>
<td>98.0</td>
<td>38.6</td>
<td>0.416</td>
<td>525°</td>
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<td>12/22</td>
<td>10:10</td>
<td>2000</td>
<td>26.5</td>
<td>10.0</td>
<td>4.15</td>
<td>26.1</td>
<td>119.0</td>
<td>28.7</td>
<td>0.415</td>
<td>700°</td>
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<tr>
<td>12/23</td>
<td>10:36</td>
<td>2500</td>
<td>26.3</td>
<td>12.6</td>
<td>5.30</td>
<td>28.9</td>
<td>131.8</td>
<td>24.9</td>
<td>0.421</td>
<td>850°</td>
</tr>
<tr>
<td>12/23</td>
<td>10:36</td>
<td>2800</td>
<td>26.0</td>
<td>13.9</td>
<td>6.11</td>
<td>33.6</td>
<td>153.2</td>
<td>25.1</td>
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J = 1.091 in 415.45 sec = 1.75 > 1.67 lbs
2nd Test in 415.55 sec = 1.60 > 1.67 lbs

B-4
Indicated Data vs Crankangle

Engine: DEUTZ F1L 511
Cell: Superflow
Project: TACOM Baseline

No. Cylinders = 1  Bore = 100.00 mm
Stroke = 105.00 mm
Compr. Ratio = 17.00  Intake = 328.5,-120.5
Ign Timing = 984.0 Deg  Exhaust = 108.5, 392.5

Engine Speed = 1512.0 rpm  Engine Torque= 13.56 N·m

APA100: U.S. Army Tank Automotive Command

Title: de09ja.010

DATA MARKERS:

Pmax = 79.9824
@ 3.00
dPmax = 6.6167
@ -4.00

Double-triangle is valve timing.
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<th>Speed (mph)</th>
<th>Torque (lb-ft)</th>
<th>Power (Hp)</th>
<th>FOB</th>
<th>AI</th>
<th>A/F</th>
<th>BSFC</th>
<th>BSAC</th>
<th>Man-P</th>
<th>Oil CAT</th>
<th>Fuel Oil Wet</th>
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Test: 2.00 Seconds/Data Point Fuel Spec. Grav.: .832
Air Sensor: 40
Vapor Pressure: .30
Barometric Pres.: 23.38
Ratio: 1.00 TO 1
Engine Type: 4-Cycle Diesel
Engine displacement: 50.0
Stroke: 4.130

\[
\text{1st } 70+ \text{ ft } \frac{71.10 - 70}{2.23} = 2.23 \text{ lb} \text{/HR}
\]

\[
\text{2nd } 70+ \text{ ft } \frac{67.89 - 70}{2.34} > 2.29 \text{ lb} \text{/HR}
\]
Indicated Data vs Crankangle

Engine : DEUTZ F1L 511
Cell : Superflow
Project : TACOM Baseline

No. Cylinders = 1  Bore = 100.00 mm
Stroke = 105.00 mm
Compr. Ratio = 17.00  Intake = 328.5, -120.5
Ign Timing = 984.0 Deg  Exhaust = 108.5, 392.5

Engine Speed = 2015.0 rpm  Engine Torque= 13.97 N-m

APA100: U.S. Army Tank Automotive Command

Title : de09ja.012

Crankangle Degrees

DATA MARKERS:

Pmax = 73.6342
@ 3.00
dPmax= 5.2802
@ -2.00

Double-triangle is valve timing.
**Test Number:** 25

**Date (M/D/Y):** 12/22/80 **Time (H:MiS):** 15:34:52 **Operator:** PULLHAMMER

**Engine description:** DEUTZ FIL511, STOCK

**Test description:** 2 sec. intervals: 2,500 RPM, 1/3 RATED TORQUE, FUEL #2

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<th>A/F</th>
<th>BSFC</th>
<th>BSNC</th>
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For 1st test in 54.50 sec = 2.91
For 2nd test in 54.80 sec = 2.90

B-8
Indicated Data vs Crankangle

Engine : DEUTZ F1L 511
Cell : Superflow
Project : TACOM Baseline

No. Cylinders = 1  Bore = 100.00 mm
Stroke = 105.00 mm
Compr. Ratio = 17.00  Intake = 328.5, -120.5
Ign Timing = 984.0 Deg  Exhaust = 108.5, 392.5

Engine Speed = 2480.0 rpm  Engine Torque= 13.97 N·m

APA100: U.S. Army Tank Automotive Command
Title : de03ja007

DATA MARKERS :
Pmax = 62.0278
@ 5.00
dPmax = 5.2560
@ 2.00

Double-triangle is valve timing.
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<th>Engine displacement: 10.32</th>
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**Notes:**
- 1 A con 1 in 47.62 sec = 3.33 > 3.30
- 2nd con 1 in 46.67 sec = 3.39 > 3.30

B-10
Indicated Data vs Crankangle

Engine: DEUTZ F1L 511
Cell: Superflow
Project: TACOM Baseline

No. Cylinders = 1
Bore = 100.00 mm
Stroke = 105.00 mm

Compr. Ratio = 17.00
Intake = 328.5, -120.5

Ign Timing = 984.0 Deg
Exhaust = 108.5, 392.5

Engine Speed = 2795.0 rpm
Engine Torque = 13.70 N-m

APA100: U.S. Army Tank Automotive Command

Title: de03ja.008

DATA MARKERS:

Pmax = 63.0768
@ 5.00

dPmax = 4.3756
@ 2.00

Double-triangle is valve timing.
Test Number: 22
Date (M/D/Y): 12/22/86 Time (H:M:S): 14:49:30 Operator: POUHANmER
Engine description: DEUTZ FIL511, STOCK
Test description: 2 sec. intervals, 1500 RPM, 2/3 RATED TORQUE, FUEL 72

Test: 2.00 Seconds/Data Point Fuel Spec. Grav.: .832 Air Sensor: 4.0
Vapor Pressure: 38 Barometric Press.: 29.38 Ratio: 1.00 TO 1
Engine type: 4-Cycle Diesel Engine displacement: 50.0 Stroke: 4.130

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<th>BSEC lb/hr</th>
<th>BSFC lb/hr</th>
<th>Men. P in</th>
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\[16^4 \times 715^3 \text{ in } (2.72 \text{ sec} = 2.51) \times \frac{9}{10} \text{ in } (6.00 \text{ sec} = 2.48) > 2.50 \% \text{ HR}\]

B-12
Indicated Data vs Crankangle

Engine : DEUTZ FIL 511
Cell : Superflow
Project : TACOM Baseline

No. Cylinders = 1  Bore = 100.00 mm
   Stroke = 105.00 mm
Compr. Ratio = 17.00  Intake = 328.5,-120.5
Ign Timing = 994.0 Deg  Exhaust = 108.5, 392.5

Engine Speed = 1550.0 rpm  Engine Torque= 27.25 N-m

APA100: U.S. Army Tank Automotive Command

Title : de03ja.009

DATA MARKERS :

Pmax = 82.7084  @ 5.00
 dPmax= 6.0615  @ -4.00

Double-triangle is valve timing.
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1st 20q in 116.52 sec = 3.41
2nd 20q in 176.66 sec = 3.33 > 3.37 1b5

B-14
Indicated Data vs Crankangle

Engine : DEUTZ F1L 511
Cell : Superflow
Project : TACOM Baseline

No. Cylinders = 1  Bore = 100.00 mm
Compr. Ratio = 17.00  Stroke = 105.00 mm
Ign Timing = 984.0 Deg  Intake = 328.5, -120.5
Exhaust = 108.5, 392.5

Engine Speed = 2025.0 rpm  Engine Torque = 27.52 N-m

APA100: U.S. Army Tank Automotive Command
Title : de03ja.015

```
DATA MARKERS :

Fmax = 81.4000
@ = 5.00
dFmax = 6.0999
@ = -3.00

Double-triangle is valve timing.
```
 Test Number: 24
Engine description: DEUTZ F6L511, STOCK
Test description: 2 sec. intervals, 2500 rpm, 1/2 water Torque, Fuel #2

Test: 2.00 Seconds/Data Point Fuel Spec. Grav.: .840 Air Sens: 4.0
Vapor Pressure: .37 Barometric Pres.: 29.30 Ratio: 1.00 TO 1
Engine Type: 4-Cycle Diesel Engine displacement: 20.0 Stroker: 4.130

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**WEIGHTED FUEL FLOW**

| 20.1 | 9.6 | 29.1 | 73 160 197 |

**1st 70 sec in 33.40 sec = 4.25 lbs HR**

**2nd 70 sec in 35.10 sec = 4.23 lbs HR**

B-16
Indicated Data vs Crankangle

Engine: DEUTZ F1L 511
Cell: Superflow
Project: TACOM Baseline

No. Cylinders = 1
Bore = 100.00 mm
Stroke = 105.00 mm

Compr. Ratio = 17.00
Intake = 328.5, -120.5

Ign Timing = 984.0 Deg
Exhaust = 108.5, 392.5

Engine Speed = 2490.0 rpm
Engine Torque = 26.98 N-m

Title: de03ja.011

DATA MARKERS:

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@ 4.00

dPmax = 6.2426
@ 1.00

Double-triangle is valve timing.
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**WEIGHED FUEL FLOW**

1st 30min in 48.29 sec = 14.93 > 5.00 lbs
2nd 30min in 46.96 sec = 5.07 > 5.00 lbs
Indicated Data vs Crankangle

Engine: DEUTZ F1L 511
Cell: Superflow
Project: TACOM Baseline

No. Cylinders = 1  Bore = 100.00 mm
Compr. Ratio = 17.00  Stroke = 105.00 mm
Ign. Timing = 984.0 Deg  Intake = 328.5,-120.5
Exhaust = 108.5, 392.5

Engine Speed = 2820.0 rpm  Engine Torque= 26.44 N-m

APA100: U.S. Army Tank Automotive Command

Title: de03ja.012

DATA MARKERS:

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@ 5.00

\( \text{d}P\text{max} = 4.8220 \)
@ 1.00

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1st 20g in 63.00sec = 2.52
2nd 20g in 61.93sec = 2.54

B-20
Indicated Data vs Crankangle

Engine : DEUTZ F1L 511
Cell : Superflow
Project : TACOM Baseline

No. Cylinders = 1
Bore = 100.00 mm
Stroke = 105.00 mm
Compr. Ratio = 17.00
Ign Timing = 984.0 Deg
Intake = 328.5,-120.5
Exhaust = 108.5, 392.5

Engine Speed = 1535.0 rpm
Engine Torque = 28.48 N-m

APA100: U.S. Army Tank Automotive Command

Title : de03ja.016R

DATA MARKERS :

\[
P_{\text{max}} = 80.9975 \\
\Theta = 5.00 \\
dP_{\text{max}} = 5.6322 \\
\Theta = -5.00
\]

Double-triangle is valve timing.
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Calculation: 2049 in 38.78 sec = 4.09
2nd 2049 in 39.79 sec = 4.15

B-22
Indicated Data vs Crankangle

Engine: DEUTZ F1L 511
Cell: Superflow
Project: TACOM Baseline

No. Cylinders = 1
Bore = 100.00 mm
Stroke = 105.00 mm

Compr. Ratio = 17.00
Intake = 328.5, -120.5
Exhaust = 108.5, 392.5

Ign Timing = 984.0 Deg
Exhaust = 108.5, 392.5

Engine Speed = 2015.0 rpm
Engine Torque = 34.44 N-m

APA100: U.S. Army Tank Automotive Command
Title: deo3ja.015

DATA MARKERS:

Pmax = 77.8286
θ = 6.00

dPmax = 5.4527
θ = -3.00

Double-triangle is valve timing.
Indicated Data vs Crankangle

Engine : DEUTZ F1L 511  
Cell : Superflow  
Project : TACOM Baseline

No. Cylinders = 1  
Bore = 100.00 mm  
Stroke = 105.00 mm

Compr. Ratio = 17.00  
Intake = 328.5,-120.5  
Exhaust = 108.5, 392.5

Ign Timing = 984.0 Deg  
Engine Speed = 2580.0 rpm  
Engine Torque = 34.58 N-m

APA100: U.S. Army Tank Automotive Command

Title : de03ja.014

DATA MARKERS:

Pmax = 67.4321  
@ = 8.00  
dPmax = 5.6135  
@ = 0.00

Double-triangle is valve timing.
COMBUSTION ELECTROMAGNETICS INC.
32 PRENTISS ROAD
Arlington, Massachusetts 02174
PHONE: (617) 641-0520

Test Number: 71
Engine description: DEUTZ F4L511 STOCK
Test description: 2 see intervals, 2500 RPM, MAX LOAD, Fuel 92

Test: 2.00 Seconds/Data Point Fuel Spec. Grav.: .832 Air Sensor: 4.0
Vapor Pressure: .37 Barometric Pres.: 29.38 Ratio: 1.00 TO 1
Engine Type: 4-Cycle Diesel Engine displacement: 50.0 Stroker: 4.130

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2nd Test 2091 min 21.00 sec = 5.12
3rd Test 2091 min 29.08 sec = 5.46

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Fuel Spec. Grav.: .832 Air Sensor: 4.0
Vapor Pressure: .37 Barometric Pres.: 29.38 Ratio: 1.00 To 1
Engine Type: 4-Cycle Diesel
Engine displacement: 50.0 Stroke: 4.130
Compressed Data vs Crankangle

Engine: DEUTZ F1L 511
Cell: Superflow
Project: TACOM Baseline

No. Cylinders = 1
Bore = 100.00 mm
Stroke = 105.00 mm
Compr. Ratio = 17.00
Intake = 328.5, -120.5
Exhaust = 108.5, 392.5

Ign. Timing = 984.0 Deg
Engine Speed = 2818.0 rpm
Engine Torque = 35.26 N-m

APA100: U.S. Army Tank Automotive Command
Title: de03ja.013

Data Markers:

Pmax = 69.0961

@ 4.00

dPmax = 5.5308

@ 0.00

Double-triangle is valve timing.
APPENDIX C

PEAK PRESSURE VERSUS ELAPSED TIME DATA
## Test Number:

**DE193A**

**Date (M/D/Y):** 1/19/90  **Time (H:M:S):** 12:13:17

**Operator:** cmw, cp, mm

**Engine description:** DEUTZ F3L511, CEI HEAD, CYLINDER, PISTON #2, 2, 2

**Test description:** CEI, SINGLE/DOUBLE PLUG, 26deg Inj.

### Test: Data Recorded Manually

**Fuel Spec. Grav.:** .831  **Air Sensor: 4.0**

**Vapor Pressure:** .35  **Barometric Pres.:** 30.43  **Ratio: 1.00 TO 1**

**Engine Type:** 4-Cycle Diesel  **Engine displacement:** 50.0  **Stroke:** 4.130

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C-3
**TACOM Engine Testing:**

**With Wildcat Ignition**

**Cold Start/Oil Temp 111°F**

**Average Engine speed:** 1500 RPM

**Average Torque:** 10 ft-lbs

**Due to CEI Ignition (15 pulses)**

**Timing:** 24° BTDC

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<td>12:30</td>
<td>1508</td>
<td>1505</td>
<td>9.9</td>
<td>9.8</td>
<td>92°F</td>
<td></td>
<td></td>
</tr>
<tr>
<td>ON</td>
<td>16:00</td>
<td>1504</td>
<td>1500</td>
<td>10.1</td>
<td>10.1</td>
<td>102°F</td>
<td>52.73</td>
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</tr>
</tbody>
</table>
Indicated Data vs Crankangle

Engine: DEUTZ F1L-511, CEI Ver 2.2
Cell: Superflow
Project: TACOM

No. Cylinders = 1  Bore = 100.00 mm
Compr. Ratio = 12.00  Stroke = 105.00 mm
Ign. Timing = -984.0 Deg  Intake = 328.5, 120.5
Exhaust = 108.5, 392.5

Engine Speed = ±500.0 rpm  Engine Torque = 0.00 N-m

AFR100: U.S. Army Tank Automotive Command

Title: DE19JA.010

Ign.
1:00
≈ 1420 RPM ??

Crankangle Degrees

DATA MARKERS:

Pmax = 29.5854
θ = 12.00 + 7°

\[
\begin{align*}
\frac{\text{d}P}{\text{d}\theta} & = 0.7234 \\
\theta & = 2.00 - 7°
\end{align*}
\]

Double-triangle is valve timing.
Indicated Data vs Crankangle

Engine: DEUTZ FIL-511, CEI Ver 2.2
Cell: Superflow
Project: TACOM

No. Cylinders = 1
Bore = 100.00 mm
Stroke = 105.00 mm

Compr. Ratio = 12.00
Intake = 328.5, -120.5
Exhaust = 108.5, 392.5

Ign Timing = -904.0 Deg

Engine Speed = 1500.0 rpm
Engine Torque = 0.00 N-m

APAI00: U.S. Army Tank Automotive Command

Title: DE19JA.011

![Graph showing cylinder pressure and crankangle degrees.]

DATA MARKERS:

\[ P_{\text{max}} = 26.0778 \]
\[ \theta = 7.00^\circ \]
\[ dP_{\text{max}} = 0.6609 \]
\[ \theta = 41.00^\circ \]

Double-triangle is valve timing.
Indicated Data vs Crankangle

Engine: DEUTZ F1L-511, CEI Ver 2.2
Cell: Superflow
Project: TACOM

No. Cylinders = 1  Bore = 100.00 mm
Compr. Ratio = 12.00  Stroke = 105.00 mm
Ign. Timing = -984.8-6eq  Intake = 328.5,-120.5
Exhaust = 108.5, 392.5

Engine Speed = 1500.0-rpm  Engine Torque = 0.00 N-m

Title: DE19JA.012-

DATA MARKERS:

Pmax = 29.3668
\theta = 12.60 +70
\delta P_{max} = 0.7494 
\theta = -11.00 -16^0

Double-triangle is valve timing.
Indicated Data vs Crankangle

Engine: DEUTZ Fil-511, CEI Ver 2.2
Cell: Superflow
Project: TACOM

No. Cylinders = 1  
Bore = 100.00 mm  
Stroke = 105.00 mm
Compr. Ratio = 12.00  
Intake = 328.5, -120.5  
Exhaust = 108.5, 392.5
Iqnt Timing = -904.6 Deg  
Exhaust Timing = 404.6, 392.5
Engine Speed = 1500.0 rpm  
Engine Torque = 0.00 N-m

APD100: U.S. Army Tank Automotive Command
Title: DE19JA.013

Crankangle Degrees

DATA MARKERS:

\[ P_{\max} = 26.2547 \]
\[ \theta \sim +2^\circ \]
\[ \frac{dP_{\max}}{d\theta} = 0.6609 \]
\[ \theta \sim -16^\circ \]

Double-triangle is valve timing.
Indicated Data vs Crankangle

Engine : DEUTZ F1L-511, CEI Ver 2.2
Cell : Superflow
Project : TACOM

No. Cylinders = 1  Bore = 100.00 mm
Compr. Ratio = 12.00  Stroke = 105.00 mm
Ign Timing = -97.0 Deg  Intake = 328.5-120.5
Exhaust = 108.5, 392.5

Engine Speed = 1500.0 rpm  Engine Torque = 0.00 N-m

APA100: U.S. Army Tank Automotive Command

Title : DE19JA.014

Crankangle Degrees

DATA MARKERS:

Pmax = 29.6166  @ -12.00  + 7°

Double-triangle is valve timing.
Indicated Data vs Crankangle

Engine: DEUTZ F1L-511, CEI Ver 2.2
Cell: Superflow
Project: TACOM

No. Cylinders = 1
Bore = 100.00 mm

Stroke = 105.00 mm

Compr. Ratio = 12.00
Intake = 328.5, -120.5

Ign Timing = 984.0-Deg
Exhaust = 108.5, 392.5

Engine Speed = 1500.0 rpm
Engine Torque = 0.00 N-m

APA100: U.S. Army Tank Automotive Command

Title: DE19JA.015

Graph showing Cyl. Press. (atm) vs Crankongle Degrees

DATA MARKERS:

\[ P_{\text{max}} = 26.5566 \]
\[ \theta = 2^\circ \]
\[ dP_{\text{max}} = 0.6661 \]
\[ \theta = -10^\circ \]

Double-triangle is valve timing.
Indicated Data vs Crankangle

Engine : DEUTZ FIL-511, CEI Ver 2.2
Cell : Superflow
Project : TACOM

No. Cylinders = 1
Bore = 100.00 mm
Stroke = 105.00 mm
Compr. Ratio = 12.00
Intake = 328.5,-120.5
Ign Timing = -984.0 Deg
Exhaust = 108.5, 392.5

Engine Speed = -1500.0 rpm
Engine Torque= 0.00 N-m

APA100: U.S. Army Tank Automotive Command
Title : DE19JA016

DATA MARKERS :

\[ P_{\text{max}} = 31.0988 \]
\[ @ \quad 11.06, \quad +9^\circ \]
\[ dP_{\text{max}} = 0.7182 \]
\[ @ \quad -6.06, \quad -8^\circ \]

Double-triangle is valve timing.
Indicated Data vs Crankangle

Engine: DEUTZ F1L-511, CEI Ver 2.2
Cell: Superflow
Project: TACOM

No. Cylinders = 1
Bore = 100.00 mm
Stroke = 105.00 mm

Compr. Ratio = 12.00
Intake = 328.5, -120.5
Exhaust = 108.5, 392.5

Engine Speed = 1500.0 rpm
Engine Torque = 0.00 N-m

APA100: U.S. Army Tank Automotive Command
Title: DE19JA.017

NO IGN
6:30
1419 RPM

Data Markers:

\[ P_{max} = 27.9888 \]
\[ \theta = 12.00 \] 90
\[ dP_{max} = 0.6870 \]
\[ \theta = -10.00 \] 13

Double-triangle is valve timing.
Indicated Data vs Crankangle

Engine: DEUTZ F1L-511, CEI Ver 2.2
Cell: Superflow
Project: TACOM

No. Cylinders = 1
Bore = 100.00 mm
Stroke = 105.00 mm

Compr. Ratio = 12.00
Intake = 328.5, -120.5
Exhaust = 108.5, 392.5

Ign Timing = 984.0 Deg

Engine Speed = 1500.0 rpm
Engine Torque = 0.00 N-m

APA100: U.S. Army Tank Automotive Command
Title: DE19JA.018

Crankangle Degrees

DATA MARKERS:
Fmax = 30.0496 @ -10.66° + 8°
DPMAX = 0.7307 @ -17.68° - 19°

Double-triangle is valve timing.
Indicated Data vs Crankangle

Engine: DEUTZ F1L-511, CEI Ver 2.2
Cell: Superflow
Project: TACOM

No. Cylinders = 1
Bore = 100.00 mm
Stroke = 105.00 mm

Compr. Ratio = 12.00
Intake = 328.5, -120.5
Ign Timing = 284.0 Deg
Exhaust = 108.5, 392.5

Engine Speed = 1500.0 rpm
Engine Torque = 0.00 N-m

APA100: U.S. Army Tank Automotive Command

Title: DE19JA.019

Crankangle Degrees

\[
\approx -3.88x + 4
\]

DATA MARKERS:

\[
\begin{align*}
\text{Pmax} &= 28.2136 \\
@ &= 12.00 \\
\text{dPmax} &= 0.7244 \\
@ &= 18.00
\end{align*}
\]

Double-triangle is valve timing.
APPENDIX D

MODIFIED ENGINE DATA
SUPERFLOW AND APA-100 DATA
Date: 1/17/90

Engine: Deutz FIL-511, CEI head, cylinder, piston

Test: Double Plugs, 20 deg adv, 26 deg inj

**Test DE17JA**

<table>
<thead>
<tr>
<th>Test</th>
<th>10</th>
<th>04</th>
<th>06</th>
<th>08</th>
</tr>
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<tbody>
<tr>
<td>RPM</td>
<td>1504</td>
<td>1998</td>
<td>2492</td>
<td>2807</td>
</tr>
<tr>
<td>TRD, ft-lb</td>
<td>10.3</td>
<td>9.8</td>
<td>10.0</td>
<td>9.8</td>
</tr>
<tr>
<td>COV</td>
<td>1.46%</td>
<td>0.84%</td>
<td>1.01%</td>
<td>0.60%</td>
</tr>
<tr>
<td>HP</td>
<td>3.0</td>
<td>3.7</td>
<td>4.7</td>
<td>5.2</td>
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<tr>
<td>Fuel, lb/hr</td>
<td>1.33</td>
<td>1.97</td>
<td>2.80</td>
<td>3.95</td>
</tr>
<tr>
<td>Air, scfm</td>
<td>17.2</td>
<td>24.8</td>
<td>27.4</td>
<td>27.4</td>
</tr>
<tr>
<td>A/F</td>
<td>59.0</td>
<td>57.3</td>
<td>44.7</td>
<td>31.6</td>
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<tr>
<td>BSFC</td>
<td>0.451</td>
<td>0.526</td>
<td>0.590</td>
<td>0.756</td>
</tr>
</tbody>
</table>

**ManP**

| CAT (F) | 66 | 62 | 64 | 66 |
| FuelT (F) | 53 | 49 | 53 | 54 |
| OilT (F) | 212 | 151 | 173 | 203 |
| Ext (F) | 392 | 330 | 477 | 643 |
| SAE TRQ | 9.8 | 9.2 | 9.2 | 9.0 |
| SAE HP | 2.8 | 3.5 | 4.3 | 4.8 |

**VolEff**

| 0.79 | 0.86 | 0.76 | 0.67 |
| 20 | 20 | 20 | 20 |

**Ignition**

| ON | ON | ON | ON |

**APA-100 data**

<p>| Pmax (atm) | 38.0 | 29.8 | 23.9 | 19.5 |
| @ (deg) | 1 | 7 | 13 | -4 |
| dPmax (atm) | 2.18 | 0.82 | 0.77 | 0.65 |
| @ (deg) | -5 | -16 | -16 | -26 |</p>
<table>
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<th></th>
<th></th>
<th></th>
<th></th>
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<td>1498</td>
<td>1997</td>
<td>2505</td>
<td>2797</td>
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<td>20.1</td>
<td>20.1</td>
<td>19.9</td>
<td>20.4</td>
</tr>
<tr>
<td>COV</td>
<td>1.75%</td>
<td>1.84%</td>
<td>0.91%</td>
<td>1.34%</td>
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<td>7.6</td>
<td>9.5</td>
<td>10.9</td>
</tr>
<tr>
<td>Fuel, lb/hr</td>
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<td>4.15</td>
<td>4.94</td>
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<td>19.7</td>
</tr>
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<td>34.9</td>
<td>29.0</td>
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<td>0.453</td>
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<td>64</td>
<td>63</td>
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<td>65</td>
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<tr>
<td>FuelT (F)</td>
<td>52</td>
<td>53</td>
<td>54</td>
<td>55</td>
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<td>OilT (F)</td>
<td>209</td>
<td>165</td>
<td>188</td>
<td>239</td>
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<td>Exit (F)</td>
<td>489</td>
<td>489</td>
<td>626</td>
<td>817</td>
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<td>18.8</td>
<td>19.2</td>
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<td>APA-100 data</td>
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<td>43.3</td>
<td>39.3</td>
<td>32.3</td>
<td>31.4</td>
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<tr>
<td>@ (deg)</td>
<td>3</td>
<td>6</td>
<td>7</td>
<td>5</td>
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<td>dPmax, atm</td>
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<td>-2</td>
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<td>2015</td>
<td>2524</td>
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<td>26.0</td>
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<td>COV (%)</td>
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<td>HP</td>
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<td>12.0</td>
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<td>20</td>
<td>20</td>
<td></td>
</tr>
<tr>
<td>Ignition</td>
<td>ON</td>
<td>ON</td>
<td>ON</td>
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<td>APA-100 data</td>
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<td>Pmax (atm)</td>
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<tr>
<td>@ (deg)</td>
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<td>9</td>
<td></td>
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<td>2.88</td>
<td>2.15</td>
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<tr>
<td>@ (deg)</td>
<td>-7</td>
<td>-6</td>
<td>-7</td>
<td></td>
</tr>
</tbody>
</table>
Indicated Data vs Crankangle

Engine : DEUTZ F1L-511, CEI Ver 2.2
Cell : Superflow
Project : TACOM

No. Cylinders = 1
Bore = 100.00 mm
Stroke = 105.00 mm

Compr. Ratio = 12.00
Intake = 328.5,-120.5

Ign Timing = 984.0 Deg
Exhaust = 108.5, 392.5

Engine Speed = 2800.0 rpm
Engine Torque= 0.00 N-m

APA100: U.S. Army Tank Automotive Command
Title : DE17JA.010

Crankangle Degrees

DATA MARKERS :

Pmax = 38.0059
@ 4.00

\( \frac{dP_{max}}{\theta} = 2.1806 \)
@ -2.00 - 50

Double-triangle is valve timing.

D-6
Indicated Data vs Crankangle

Engine: DEUTZ F1L-511, CEI Ver 2.2
Cell: Superflow
Project: TACOM

No. Cylinders = 1
Bore = 100.00 mm
Stroke = 105.00 mm
Compr. Ratio = 12.00
Ign Timing = 984.0 Deg
Intake = 328.5, -120.5
Exhaust = 108.5, 392.5

Engine Speed = 2000.0 rpm
Engine Torque = 0.00 N-m

APA100: U.S. Army Tank Automotive Command
Title: DE17JA.004

Crankangle Degrees

DATA MARKERS:

\[ \text{Fmax} = 29.7624 \]
\[ @ -9.00^\circ +7^\circ \]
\[ \text{dPmax} = 0.8171 \]
\[ @ -26.00^\circ -16^\circ \]

Double-triangle is valve timing.

1998 RPM
9.8 St.1bs
.526 BSFC
DOUBLE PLUG
Indicated Data vs Crankangle

Engine: DEUTZ F1L-511, CEI Ver 2.2
Cell: Superflow
Project: TACOM

No. Cylinders = 1
Bore = 100.00 mm
Stroke = 105.00 mm
Compr. Ratio = 12.00
Intake = 328.5, -120.5
Ign Timing = 984.0 Deg
Exhaust = 108.5, 392.5

Engine Speed = 2000.0 rpm
Engine Torque = 0.00 N-m

AFA100: U.S. Army Tank Automotive Command

Title: [DE17JA.006]

Crankangle Degrees

DATA MARKERS:

\[ P_{\text{max}} = 23.8607 \]
\[ @ \theta = 16.00^\circ \]
\[ dP_{\text{max}} = 0.7650 \]
\[ @ \theta = -19.00^\circ \]

Double-triangle is valve timing.
Indicated Data vs Crankangle

Engine: DEUTZ F1L-511, CEI Ver 2.2
Cell: Superflow
Project: TACOM

No. Cylinders = 1  Bore = 100.00 mm
    Stroke = 105.00 mm

Compr. Ratio = 12.00  Intake = 328.5, -120.5
Ign Timing = 984.0 Deg  Exhaust = 108.5, 392.5

Engine Speed = 2800.0 rpm  Engine Torque = 0.00 N-m

Title: DE17JA.0098

DATA MARKERS:

\[ P_{\text{max}} = 19.5204 \]
\[ \phi = -2.00\degree \]
\[ dP_{\text{max}} = 0.6453 \]
\[ \phi = -22.00\degree \]

Double-triangle is valve timing.
Indicated Data vs Crankangle

Engine : DEUTZ F1L-511, CEI Ver 2.2
Cell : Superflow
Project : TACOM

No. Cylinders = 1  Bore = 100.00 mm
Compr. Ratio = 12.00  Stroke = 105.00 mm
Ign Timing = 984.0 Deg  Intake = 328.5, -120.5
Exhaust = 108.5, 392.5

Engine Speed = 2000.0 rpm  Engine Torque = 0.00 N-m

APA100: U.S. Army Tank Automotive Command
Title: DE17JA.011

DATA MARKERS:
\[ P_{\text{max}} = 43.2622 \]
\[ @ 42.00^\circ \ 3^\circ \]
\[ d(P_{\text{max}}) = 2.8623 \]
\[ @ 4.00^\circ \ -5^\circ \]

Double-triangle is valve timing.
Indicated Data vs Crankangle

Engine : DEUTZ F1L-511, CEI Ver 2.2
Cell : Superflow
Project : TACOM

No. Cylinders = 1  Bore = 100.00 mm
Stroke = 105.00 mm
Compr. Ratio = 12.00  Intake = 328.5, -120.5
Ign Timing = 984.0 Deg  Exhaust = 108.5, 392.5

Engine Speed = 2000.0 rpm  Engine Torque = 0.00 N-m

APA100: U.S. Army Tank Automotive Command

Title : DE17JA.005

DATA MARKERS:

Pmax = 39.2653
@ 6.00
dPmax = 2.1546
@ 0.00

Double-triangle is valve timing.

D-11
Indicated Data vs Crankangle

Engine: DEUTZ F1L-511, CEI Ver 2.2
Cell: Superflow
Project: TACOM

No. Cylinders = 1  Bore = 100.00 mm
Compr. Ratio = 12.00  Stroke = 105.00 mm
Ign Timing = 984.0 Deg  Intake = 328.5, -120.5
Exhaust = 108.5, 392.5

Engine Speed = 2500.0 rpm  Engine Torque = 0.00 N-m

APA100: U.S. Army Tank Automotive Command
Title: DE17JA.007

DATA MARKERS:

\[ \begin{align*}
\text{Pmax} & = 32.3333 \\
\theta & = 17.66 \degree \\
\text{dPmax} & = 1.4572 \\
\theta & = 12.68 \degree
\end{align*} \]

Double-triangle is valve timing.
Indicated Data vs Crankangle

Engine: DEUTZ F1L-511, CEI Ver 2.2
Cell: Superflow
Project: TACOM

No. Cylinders = 1  Bore = 100.00 mm
Stroke = 105.00 mm

Compr. Ratio = 12.00  Intake = 328.5, -120.5
Ign. Timing = 984.0 Deg  Exhaust = 108.5, 392.5

Engine Speed = 2800.0 rpm  Engine Torque = 0.00 N-m

AFAL00: U.S. Army Tank Automotive Command

Title: [DE17JA.014]

Double-triangle is valve timing.

DATA MARKERS:

\[
P_{\text{max}} = 31.3757 \\
\theta_{\text{max}} = -11.88 \\
dP_{\text{max}} = 1.6602 \\
\theta_{\text{dP}} = 4.68 \\
\theta = -2^\circ
\]

2797 RPM
20.41 St. lbs
.4153 BSFC
1 PLUG
(ONE CUT OUT)
Indicated Data vs Crankangle

Engine: DEUTZ F1L-511, CEI Ver 2.2
Cell: Superflow
Project: TACOM

No. Cylinders = 1  Bore = 100.00 mm
Stroke = 105.00 mm
Compr. Ratio = 12.00  Intake = 328.5,-120.5
Ign Timing = 984.0 Deg Exhaust = 108.5, 392.5

Engine Speed = 1500.0 rpm  Engine Torque = 0.00 N-m

APA100: U.S. Army Tank Automotive Command

Title: "DE17JA.012"

Crankangle Degrees

DATA MARKERS:

Pmax = 47.4464
θ = 90°

dPmax = 3.4660
θ = 28° -7°

Double-triangle is valve timing.
Indicated Data vs Crankangle

Engine: DEUTZ F1L-511, CEI Ver 2.2
Cell: Superflow
Project: TACOM

No. Cylinders = 1
Bore = 100.00 mm
Stroke = 105.00 mm

Compr. Ratio = 12.00
Intake = 328.5, -120.5

Ign Timing = 984.0 Deg
Exhaust = 108.5, 392.5

Engine Speed = 2000.0 rpm
Engine Torque = 0.00 N-m

APAI00: U.S. Army Tank Automotive Command

Title

Crankangle Degrees

DATA MARKERS:

Pmax = 46.1141
@ -9.00 - 2°
dPmax = 2.8832
@ 1.00 - 6°

Double-triangle is valve timing.
Indicated Data vs Crankangle

Engine: DEUTZ F1L-511, CEI Ver 2.2
Cell: Superflow
Project: TACOM

No. Cylinders = 1
Bore = 100.00 mm
Stroke = 105.00 mm

Compr. Ratio = 12.00
Intake = 328.5,-120.5
Ign Timing = 984.0 Deg
Exhaust = 108.5, 392.5

Engine Speed = 2500.0 rpm
Engine Torque = 0.00 N-m

APA100: U.S. Army Tank Automotive Command

Title: DE29JA.015

Crankangle Degrees

DATA MARKERS:

\[
P_{\text{max}} = 43.6515 \\
\theta = 44.00 \text{ Deg} \\
dP_{\text{max}} = 2.1483 \\
\theta = 3.00 \text{ Deg}
\]

Double-triangle is valve timing.

\[\theta_{\text{BDC}} = 9^0\]

DUAL IGN
2524 RPM
26.0 sc. lbs (Max)
Tout = 207 °F
44.2 BSFC

D-16
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