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U.S. ARMY/CR91/A90-210

KEROSENE BASE FUELS IN SMALL GASOLINE ENGINES

Charles C. Failla, Project Engineer
Andrew A. Pouring, Principal Investigator

Sonex Research, Inc.

1991

United States Army

REPORT DOCUMENTATION PAGE

1. Report No.
U.S. ARMY/CR-91/ A90-210

2.

3. Recipient's Accession No.

4. Title and Subtitle
KEROSENE BASE FUELS IN SMALL GASOLINE ENGINES

5. Report Date
9 October 91

6.

7. Author(s)
Charles C. Failla; Andrew A. Pouring

8. Performing Organization Rept. No.
Sonex TR-91-10

9. Performing Organization Name and Address
Sonex Research, Inc.
23 Hudson Street
Annapolis, Maryland 21401

10. Project/Task/Work Unit No.

11. Contract(C) or Grant(G) No.
(C)DAAK 70-91-C-0025
(G)

12. Sponsoring Organization Name and Address
U.S. Army Troop Support Cmd.
Belvoir Cont. Operations Div.
Fort Belvoir, VA 22060-5606

13. Type of Report & Period Covered
Final
Contractor Report

14.

15. Supplementary Notes
Sonex Vendor ID: 00006232

16. Abstract (Limit: 200 words)

This document presents the results of an engineering study to demonstrate the technology for converting small gasoline spark-ignited engines, to burn kerosene type fuels to power small generators (0.5 to 3.0 kw). Commercially available (plus those in the developmental stage), reciprocating, two-stroke, four stroke and rotary engines were evaluated for their conversion potential. Unique combustion systems were identified and trade-off studies conducted on engine type , combustion systems, and modification required to burn kerosene type fuels, with special emphasis given to minimizing life cycle cost. Recommendations for the most feasible system are given.

17. Document Analysis a. Descriptors

Spark Ignited Engines
Kerosene Fuels
Generators

b. Identifiers/Open-Ended Terms

c. COSATI Field/Group

18. Availability Statement
National Technical Information Service, 5285 Port Royal Road, Springfield, VA 22161

19. Security Class (This Report)
Unclassified

20. Security Class (This Page)
Unclassified

21. No. of Pages
127

22. Price

(See ANSI-Z39.18) See Instructions on Reverse OPTIONAL FORM 272 (4-77)

☆ GPO : 1983 O - 381-526 (8393)

CONTENTS

1. Summary

An engineering study is presented to demonstrate the technology for converting small gasoline spark-ignited (SI) engines to burn kerosene type fuels to power small generators (0.5 to 3.0 Kw).

The contract objectives are as follows:

- To assess, analyze and evaluate the merits of:
  - a. engine types (2 & 4 stroke cycles, rotary)
  - b. combustion processes for conversion of small (0.5 to 3.0 Kw) SI gasoline engines to operate on kerosene fuels
- To devise and specify conversion modifications required for a suitable engine type and combustion system resulting from conclusions of a trade-off study considering all issues relevant to conversion of SI engines to operate on kerosene base fuels, emphasizing minimum life-cycle costs and identifying any development required.
- To submit a proposal for an SBIR Phase II effort, including the work, the schedule and the estimated costs of performing the work proposed.

All of the above contract objectives were attained and are documented here.

It is concluded that the best candidate engine for conversion is the Briggs & Stratton 4-stroke OHV engine, according to the results of the trade-off study.

The second best candidate engine for conversion is a Tecumseh 2-stroke engine.

No small rotary engine met the technical criteria.

It is recommended that the Sonex design for combustion chamber and piston rings be applied to the best candidate engine. Three options are given for the starting/combustion system:

A) Starting fluid
B) Fuel vaporization system
C) Direct injection

It is recommended that the U.S. Army evaluate all of the aspects of the above three options and specify the starting criteria for the Phase II effort.

Since Sonex has already demonstrated both 2 stroke and 4 stroke SCS systems with options A and B, the Phase II proposal submitted here is based on these options. If option C is specified, additional cost may be involved.

2. Introduction

2.1 Background

The U.S. Army has been attempting to improve safety and to reduce the logistics burden of fuels handling by embracing a "Single Fuel Forward" policy. At present, and for the near term, that fuel will be kerosene based, such as JP8 or DF2, but in the future could also include the lighter-end distillates down to JP4.

2.2 Purpose

The U.S. Army has large numbers of small engine-generators (0.5 to 3.0 Kw) that operate on gasoline. It is the purpose of this SBIR study to analyze and evaluate the merits of converting small gasoline engines to operate on kerosene based fuels.

2.3 Scope

Included in the scope of this study is a review of spark ignited engine types (two stroke, four stroke, and rotary) to assess, analyze and evaluate their merits for conversion to kerosene based fuels; also included is a review of combustion systems. The final results, conclusions, and recommendations for a specific design are based on a trade-off study of 12 factors, emphasizing minimum life-cycle costs.

2.4 Limits of Investigation

The trade-off study is limited to the following criteria for engines capable of powering generators in the range 0.5 to 3.0 Kw.:

- o Engine procurement cost
- o Engine modification cost
- o Engine power density
- o Engine life
- o Engine reliability
- o Maintenance costs
- o Operating noise levels
- o Fuel Consumption
- o Engine lubrication
- o Cold starting
- o Infrared signature
- o EMI/RFI

In arriving at the conclusions and recommendations of the trade-off study, special emphasis is given to minimizing the life cycle cost of the engine.

2.5 Development History

A 1988 study of the mobile electric power (MEP) requirements of the U.S. Army for the period 1990-2015 by the National Research Council (NRC) identified 133,000 MEP units now in use, with 75,000 units having a power rating of 3 Kw and below. The majority of these small units are ten or more years old. All these units are powered by spark-ignited engines fueled by gasoline.

The NRC study group searched for power sources capable of operating on "The Single Fuel on the Battlefield", adopted by the U.S. Army in 1986. This fuel is JP-8, generally regarded as a turbine fuel, seen in Table 1.

Kerosene fuel properties are not currently defined by U.S. military specifications, but can broadly be considered as all fuels above JP-4 through DF-A with the following characteristics (Goodger, 1975):

Property:	Temp. Range
Flash point	38 - 43 C
Distillation end point	280 - 300 C

Thus, in Table 1, JP-8 and DF-A would qualify as kerosene fuels. JP-4, with its distillation end point at 270 C is considered a wide-cut gasoline, not a kerosene. JP-5 (not shown in Table 1) has a flash point of 60 C, and distillation end point at 288 C and could be considered a borderline kerosene fuel. Replacement power sources for future mobile generating equipment must possess the capability to operate on distillate fuels in the boiling range of kerosene and higher.

The NRC study goes on to review the possibility of several classes of small engines of less than 10 Kw to meet this requirement:

- o Homogeneously charged SI engines
- o Stratified charge engines
- o Rotary engines
- o Diesel engines
- o Stirling engines
- o Gas turbines

The study immediately rules out the latter two types for use in low power ranges for a variety of reasons. The diesel engine is also ruled out in the low power range as not being commercially available, requiring development, and raising questions in terms of PMV (Power per unit mass per unit volume). The first three families of SI engines are specified in this contract and examined in detail in this study.

Table 1

Specifications Of Diesel And Turbine Fuels

Properties	VV-F-800C DF-A	 DF-2	MIL-T-5624-L JP-4	MIL-T 83133A JP-8
Flash Point, °C, min	38	52	NR[b]	38
Cloud Point, °C, max	-51	[a]	NR	NR
Pour Point, °C	Rpt	Rpt	NR	NR
Freezing Point, °C, max	NR	NR	-58	-50
Kinematic Viscosity at 40°C, cSt	1.1 to 2.4	1.9 to 4.1	NR	NR
Kinematic Viscosity at -20°C, cSt, max	NR	NR	Rpt	8.0
Distillation, °C				
10 percent recovered, max	NR	NR	Rpt	205
20 percent recovered, max	NR	NR	145	Rpt
50 percent recovered, max	Rpt	Rpt	190	Rpt
90 percent recovered, max	288	338	245	Rpt
End Point, max	300	370	270	300
Residue, vol percent, max	3	3	1.5	1.5
Sulfur, mass percent, max	0.25	0.50	0.4	0.3
Cu Corrosivity				
3 hrs at 50°C, max	3	3	NR	NR
2 hrs at 100°C, max	NR	NR	1B	1B
Ash, wt percent, max	0.01	0.01	NR	NR
Accelerated Stability, mg/100 mL, max	1.5	1.5	NR	NR
Neutralization Number, mg KOH/g, max	0.05	NR	0.015	0.015
Particulate Contamination, mg/L, max	10	10	1.0	1.0
Cetane Number, min	40	40	NR	NR

[a] Specified according to anticipated low ambient temperature at use location.

[b] NR = No requirements.

Rpt = Reported

SOURCE: Military Handbook Mobility Fuels User Handbook, MIL HDBK-114, 16 January 1984.

It is further concluded by the NRC that "The development of a homogeneously charged, spark ignited engine that burns JP-8 fuel in the 1.5 to 10 Kw range appears to be one approach for achieving low-signature, high-PMV engines at reasonable cost. This engine could use a low compression ratio (around 5:1) or new technology along with some charge stratification, such as the Sonex system".

The NRC conclusion is based on test results of a feasibility test conducted by Sonex under contract to the Onan Corporation to demonstrate that it is possible to cold start and stably operate a Sonex design, diesel fueled, 4-stroke, spark-ignited, carburetted, 5 Kw, motor generator set down to -14.4 C (6 F). Besides diesel fuel, JP5 was demonstrated successfully.

Before conversion, the engine was designed to be fueled with gasoline and the motor generator set was a normal commercial product available on the open market.

Since completion of the NRC study, Sonex has delivered to Grumman Electronic Systems several 2 stroke, high speed (6,300 RPM), spark-ignited, carburetted, diesel fueled, high-tech motor generator sets that start and run on diesel fuel under microprocessor control. These prototype units participated in competitive field trials of the U.S. Army TMAP (Tactical Multi Purpose Automated Platform) all-terrain robotic vehicle. While Grumman did win the competitive evaluation, further work on commercial development of this system by both Sonex and Grumman has been suspended until funding is available from the U.S. Army.

The principal features of the Sonex/Grumman program follow.

TMAP - SCS Engine Operational Highlights

- Diesel fueled two stroke
- Conventional spark ignited
- Carburetted
- Weight: 46lbs
- Continuous power output: 1700 watts
- Reliable low temperature starting on diesel fuel to 5 F (contract requirement, completed 25 cold starts with no failed starts)
- Excellent endurance (contract requirement: 60 hours at WOT at 6300 RPM)
- Power output of 3.1 Hp at 6300 RPM
- Fuel consumption similar to that of gasoline

2.6 Contract Objectives

The objectives of this study are:

1. To assess, analyze and evaluate the merits of:

   a) Engine types (2,4 stroke cycles, rotary)
   b) Combustion processes for conversion of small (0.5 to 3.0 Kw) SI gasoline engines to operate on kerosene fuels.

2. To devise and specify conversion modification required for a suitable engine type and combustion system resulting from conclusions of a trade-off study considering all issues relevant to conversion of SI engines to operate on kerosene base fuels, emphasizing minimum life cycle costs, and identifying any development required.

3. To submit a proposal for a SBIR Phase II effort, including the work, the schedule, and the estimated costs of doing the work proposed.

3 Survey of Applicable Engine Types

3.1 Computer Data Base Searches

Searches were conducted on fourteen information retrieval systems to identify possible engine types for this study. The most productive search resulted from the search of the SAE Global Mobility Data Base, for example: Borman, et al (1988), Ariga, et al (1988), Yamaoka (1976) and Zucchetto, et al (1989).

The objective of this search was to locate any new technologies in the development stage to evaluate their future potential. The energy cell and two stroke, SI, DI diesel (Ariga, 1988) are examples of this.

It becomes quite clear from reviewing the literature that active research in Spark Assisted Direct Injected (SADI) diesel combustion has increased in the past few years. It is also clear that all such systems reviewed by Enright, et al (1988) involve classical injection systems. The system most applicable to this study and selected for further evaluation here is that of Ariga (1988).

A small rotary engine that reached limited commercial use is quite well documented by Yamaoka, et al (1976) and is further evaluated here.

3.2 Survey of Manufacturers

In addition to the computer searches for applicable engine types still in development, manufacturers were contacted to determine if any new developments were near at hand. The SRC (1988) study cited Teledyne Continental Motors (Mobile, AL) as developing a small rotary engine, without injectors (about 2 or 3 Kw). However, when contacted, the vice president stated that all work on this project had been terminated.

Briggs & Stratton provided specifications on their latest four stroke cycle overhead valve engine as well as a pair of engines to evaluate. They also provided the latest specifications on their 3-hp two stroke cycle engine.

Honda of America was also contacted and provided specifications on their latest four stroke cycle overhead and side valve engines and generator sets.

Tecumseh Products was contacted and provided information on their two stroke engine.

Two stroke engine development appears confined to mainly chainsaw manufacturers who are the only major OEM's producing such engines in volume production (over one million). No innovative chainsaw or other two stroke technology was uncovered.

Very small two stroke, foreign made, model aircraft engines from about 1.5 hp down are commercially available but develop peak power at high rpm (approximately 10,000), cost several times more than slightly larger commercial two stroke engines and present difficulties in adapting starting systems.

One innovative 45 HP, two stroke engine concept under development to the U.S. Navy (but beyond the power range of this study) is worth noting. Under development in the Navy Firepump program is a SADI kerosene fuel engine. While no reports have yet been written on this development, Sonex has obtained some useful information on its electrical and direct fuel injection systems. Both the modified spark ignition system and direct injection system appear to be scalable to smaller sizes, and have allowed hand-pull starts at -29 C (-20 F) with no battery power. This innovation will be investigated further.

Representative commercially available engine types further evaluated in this study appear in Section 7.

4. Survey of Combustion Systems

4.1 Computer Data Base Searches

Searches were conducted for new combustion systems together with those for new engine types. Several references for one new combustion system for radical (or intermediate chemical species) initiated ignition were found in two and four stroke cycle engines. The earliest and most illuminating paper is on TS, or Toyota-Soken, combustion (Noguchi, et al 1979), which identified the "no spark" ignition process in a carburetted two stroke cycle engine. It was experimentally demonstrated by Noguchi that low compression ratio (less than 8:1) auto-ignition conformed to the process of radical initiated reaction identified in the 1930's by the famous Nobel physical chemist N.N. Semenov (1958). A closely related study by Allen, et al (1982) showed how a carburetted four stroke cycle engine could run on JP5, diesel fuel and gasoline with and without spark, once started with spark ignition. The engine used charge stratification and special piston designs to generate and conserve intermediate chemical species. This work, originally funded by the U.S. Office of Naval Research, was later expanded upon and is now being commercialized by Sonex Research, Inc. as the Sonex Combustion System (SCS).

Thring (1989) has the most recent contribution to radical ignition literature. His (and others) terminology for this process is Homogeneous Charge Compression Ignition (HCCI). He confirmed that controlled auto-ignition can be made to occur in a four stroke cycle engine with a standard piston by using large amounts of EGR (13% to 33%) and very high intake temperatures (greater than 370 C). In contrast, the work of Allen, et al (1982) used room temperature intake air and no EGR. Thring also found that HCCI occurs only at low load and low speed, but could duplicate DI diesel engine economy.

4.2 Survey of Manufacturers

One Japanese manufacturer found a method of practical application of TS combustion in a two stroke SI carburetted gasoline motor generator set. NICE, or the Nippon Clean Engine Research Institute Co., Ltd. produced a gasoline two stroke cycle 1.25 Kw, 3600 RPM engine with very stable combustion and emissions and fuel consumption comparable to a four stroke. The engine required a spark to start but ran in part of its load-speed map without a spark. The NICE engine used Active Thermo-Atmosphere Combustion (ATAC) as described by Onishi, et al (1979) which relies on residual active intermediate chemical species for ignition, just as the TS combustion. The engine is no longer in production.

As mentioned in Section 2, Sonex has modified a spark ignited two stroke cycle, carburetted engine to start and run on fuels ranging from JP4 to DF2 diesel for Grumman Electronic Systems' entry in the Army TMAP program. Commercial development of the 1.7 Kw motor generator set evaluated successfully under field test for the TMAP program has jointly been considered by Sonex and Grumman but will not be pursued until further funds are available from the U.S. Army.

Sonex, in the meantime, has investigated the feasibility of operating a small two stroke cycle carburetted engine on the combustion process defined as RI, or Radical Ignition. RI is related to TS combustion but is capable of running under all load-speed conditions. RI is defined more fully in Appendix A.

The preliminary tests of a simple RI, carburetted two stroke cycle design, requiring no EGR or heating of intake air, have shown that stable engine operation is feasible. Additional work will be required to determine benefits in power, fuel consumption, etc.

Table 2 summarizes combustion systems to be considered further in this study.

Table 2

Available SI Combustion Systems

Type	No. of Cycles	Sources
Homogeneous Carburetted	2	Briggs, Techumseh*
Homogeneous Carburetted	4	Briggs, Honda*
Homogeneous Carburetted	2	Husqvarna/SCS
Stratified Carburetted	4	Honda/SCS
Stratified Fuel Injected	2	AED (Navy Firepump)

* Plus others

5. System Modification Options Available to Burn Kerosene Type Fuels

In order to convert a spark ignited (SI) engine designed for gasoline operations to kerosene fuel, many engine components must be modified or replaced. These are listed below and followed by a detailed description of the major modifications required, depending on the option chosen for system modification, that is, whether conventional means are employed or newer evolving technology such as the Sonex Combustion System (SCS).

Breaking out the combustion system as a separate option did not prove feasible in this study as only homogeneous charge engines are commercially available. The stratified charge, spark assisted direct-injected (SADI) engine reported by Ariga (1988) apparently has not gone beyond the research stage. Insufficient information is available to consider it further in this report. However, another SADI system fueled by JP5 by AED for the Navy Firepump is evaluated further.

The SCS engines evaluated below can be either homogeneous charge or stratified charge depending on design requirements. Charge stratification is achieved by a unique manifold technique. Both 4-stroke and 2-stroke SCS engines have been demonstrated starting and running on diesel fuel. The 2-stroke version has successfully passed a one year field test in the TMAP program.

Each of the following engine components to be changed for kerosene type fuels are addressed below:

a. Combustion chamber geometry
b. Lubrication system
c. Ignition system
d. Fuel delivery system

5.1 Combustion chamber design

5.1.1 Conventional Approach

The combustion chamber volume must be increased in such a way as to decrease the compression ratio to a point where auto-ignition ceases to be a problem at rated power. This must be accomplished without significantly changing the squish and swirl patterns in the combustion chamber or creating stagnation areas that will cause hot spots due to loss of internal cooling.

The simplest solution to this problem is the use of multiple head gaskets to decrease the compression ratio (CR). This quick fix is limited in that it will only reduce the CR by 1 or 2 numbers before the probability of head gasket failure increases. The negative side of using additional head gaskets to decrease the compression ratio is that squish velocity will be reduced, which can affect the combustion process.

A second conventional method of reducing compression ratio is to remove material from the combustion chamber in the cylinder head. This method has the advantage of selectively adding combustion chamber volume and the disadvantage of changing design squish and swirl, which again can affect the combustion process. Low compression cylinder heads may be purchased new from the OEM or modified from original engine components. If these heads are modified (material removed from the stock head), then care must be taken to maintain the integrity and heat transfer characteristics of the metal.

A third conventional method would be to remove metal from the piston. Material may be shaved from flat areas on top of a piston like the candidate Honda design, thereby increasing combustion chamber volume but having the negatives of changing internal heat flows and perhaps weakening and/or over-heating the piston crown. If the piston has a bowl in the crown like the Briggs & Stratton QT-4, then the required material may be removed from the flat crown or bowl of the piston. This also will change the internal heat flows but should not weaken the piston substantially. For production, a new piston design could be required.

5.1.2 New Technology: The Sonex Combustion System

The ideal method of reducing compression ratio by increasing combustion chamber volume is one that theoretically will maintain the combustion chamber geometry. Until recently, this has been considered impossible and the use of one or a combination of the above methods was the only alternative. However, Sonex Research, Inc. of Annapolis, Maryland, has a new patented technique, using internal chambers in the piston that will reduce compression ratio without changing combustion chamber geometry. Also, depending on whether 2-stroke or 4-stroke technology is used, additional combustion benefits are derived as described in Appendix A.

5.2 Lubrication system

5.2.1 Conventional Approach

The 4-stroke cycle SI engine, unlike the 2-stroke, has a unique lubrication problem when operating on kerosene based fuels. This problem is called "crankcase oil dilution" and is caused by high boiling point fuels condensing on the cylinder wall and the combustion chamber.

When operating on gasoline, the fuel for the original engine design, the problems associated with oil dilution are minimal since gasoline has a relatively low boiling point at 1 atmosphere (215 F). Due to this low boiling point, gasoline will condense on the cylinder walls only when the walls are below this temperature, i.e., cold engine start-up. Any liquid gasoline on the cylinder walls during cold start may pass through the piston rings and mix with the oil in the crankcase. However, it is quickly vaporized and returned to the combustion chamber through the crankcase breather system, thus causing no problem.

Kerosene fuel on the other hand has a relatively high boiling point (approximately 492 F) and a significant amount of fuel will condense on the cylinder walls even under normal engine operating temperatures. This liquid kerosene will pass through the rings since conventional piston rings are designed to seal only under high pressure (the combustion stroke). The intake stroke, having insufficient pressure for ring sealing, will not prevent the liquid on the cylinder walls from passing and entering the crankcase. As the liquid accumulates it cannot boil off due to its high vaporization temperature and, therefore, continues to accumulate and dilute the crankcase oil.

This creates two major problems. One is that the diluted oil breaks down and causes bearing and cylinder wall failure due to loss of lubrication. The other is that crankcase liquid volume increases to a point above the normal level where reciprocating parts come into direct contact with liquid, causing excessive hydraulic/mechanical forces that will lead to material failure.

A second lubrication system problem became apparent when studying the 2-stroke engine for direct fuel injection conversion. In a conventional 2-stroke, the fuel/oil mix passes from the carburettor through the crankcase and into the combustion chamber, before igniting. The crankcase/cylinder walls and bearing surfaces receive their lubrication as the fuel/oil mix bathes them with a mist. If this path is shortcircuited, as it would be with direct fuel injection, an alternate crankcase lubrication system would be required. This system could be as simple as a crankcase mister or as complex as a direct oil spray onto the walls and bearings.

5.2.2 New Technology: The Sonex Combustion System

In the late 1980's, Sonex Research encountered this problem of crankcase lube oil dilution while operating a 4-stroke single cylinder air cooled Honda SI engine on kerosene fuel. To solve this problem Sonex developed a gapless ring and gapless ring expander that does not require high pressure for sealing. This ring, installed in the above 4-stroke engine and operating on kerosene fuel, completed endurance testing with no measurable crankcase oil dilution.

5.3 Ignition System

5.3.1 Conventional Approach

Two basic changes are required in the ignition system when converting from gasoline fuel to kerosene fuel operations. First is a retarding of the ignition timing of from 2 to 6 crank angle degrees from normal timing. This change in ignition timing is required since kerosene type fuels can have a much faster rate of heat release (ROHR) than gasoline fuels under abnormal conditions of ignition. This faster ROHR moves the peak pressure spike (P-Max) closer to and possibly before top dead center (TDC), resulting in an early and excessive impulse that will have a large negative work component. This premature pressure spike is commonly called "Spark Knock", "knock", or detonation. A 2 to 6 degree retard in ignition timing will correct this if the compression ratio is also lowered and can be accomplished by closing the point gap setting by .005" - .010" in a breaker point type ignition or by moving the timing trigger 2 to 6 degrees towards retard in an electronic ignition system.

The second ignition modification requirement is more difficult and expensive. A hotter, long duration spark is required for starting and low rpm operations when the engine is cold. The spark needs to be intense enough to vaporize the fuel droplets around the spark plug at cranking speeds and at low speed-load points where combustion temperatures are insufficient to maintain proper vaporization of the fuel. This system may not be available from the engine manufacturer, but it is relatively easy and inexpensive to purchase elsewhere.

Another possible ignition system requirement for kerosene fuel operation would be a spark plug heat range change. A hotter spark plug may be in order for start-up and low power operation where lack of fuel vaporization may wash or foul the spark plug electrode. On the other hand, a cooler tip plug maybe required for high power operations where excessive combustion temperatures may overheat the electrode, causing it to act like a glow plug and resulting in auto-ignition. Since each engine has its own requirement, a compromise spark plug may be required.

5.3.2 New Technology: The Sonex Combustion System

Experimental results are available for both 2 stroke and 4 stroke SCS engines operating on kerosene fuels demonstrating the ability of the SCS to operate with less or no knock, therefore, requiring less retard of ignition timing (and reduction of compression ratio) and greater power output. The SCS is also less sensitive to spark plug heat range.

5.4 Fuel Delivery System

Perhaps the biggest challenge in this type of conversion is the fuel delivery system. Modifications to this type of system can be as simple as replacing the carburetor fuel jet to allow for increased volume of kerosene required for kerosene fuel operations (1.02 times the volume of gasoline for the same heating value), or as complex and expensive as adding direct fuel injection into the combustion chamber.

The key here is starting aid specifications. If the specifications allow for starting on gasoline or a small amount of starting fluid, then only minor, inexpensive modifications to the fuel delivery system would be required. However, if the requirement specified only kerosene fuel for starting, then a carburetted fuel vaporization technique, such as the 2 and 4 stroke engines developed by Sonex Research would be satisfactory. This system uses a battery powered fuel vaporizer for starting and warmup and is switched off under normal operating conditions. If the specifications also prohibit the use of a battery and have a requirement for manual start, then the combination of direct fuel injection and hot spark is required. This type of system is being developed by AED for the Navy for use on its 45hp, 2-stroke, emergency Firepump engine.

Once the engine is started and is near operating temperature, fuel heating techniques can be used. Fuel heating is simply the use of engine exhaust heat to bring the kerosene based fuel closer to its vaporization temperature. This allows the fuel to vaporize faster in the combustion chamber resulting in smoother, more efficient engine performance. Fuel heating can be accomplished by using a hot engine surface, such as the exhaust pipe, to heat the fuel in the fuel line prior to its entering the fuel delivery system. Another method of heating the fuel is by using exhaust gas recirculation (EGR) to add heat to the incoming air at the fuel delivery system or combustion chamber. The problem with these methods is that they are not available when they are needed most, at engine start-up.

6. Engine/Generator Interface

Since generator power output is unspecified as to AC or DC voltage and hertz requirements in the present contract, both AC and DC generators will reviewed for merit and shortfalls in the proposed engine conversion. This section will cover:

- Engine - generator RPM requirements
- Engine - generator transmissions
- Inverters

6.1 Engine Generator RPM Requirements.

6.1.1 Alternating Current

Assuming a 1:1 engine to generator coupling ratio (generator turning the same speed as the engine), AC power has its limitations in that very few engine rpms are available to produce 60 hertz power. The choices are even further limited by the scope of this report to 1800 rpm or 3600 rpm for simple, inexpensive power generation.

Of the two speeds, 1800 is marginally acceptable for 4-stroke SI operations and totally unacceptable for 2-stroke and rotary engines due to engine efficiencies. On the other hand 3600 rpm fits nicely into the 4-stroke engine maximum efficiency region, but is marginally acceptable for the 2-stroke and rotary drives where preferred rpms are around 5000.

A second problem with AC power generation is the requirement for stable phase (low ripple) power. This can best be accomplished by having the drive engine operate at exactly the desired rpm with very little rpm fluctuation. Needless to say this is difficult and will require a sophisticated and somewhat expensive engine governor to accomplish this objective.

6.1.2 Direct Current

DC power generation is much cheaper and simpler to produce since there are no rpm restrictions put on the generator. With the phase requirement lifted, the candidate engine can be operated at or near an rpm providing maximum efficiency with no output voltage quality losses.

As noted in the NRC study speeds above 6000 rpm could be used with the advantage of more compact generators. This solution was used by Sonex in its Grumman TMAP program. Note that from the engine generator viewpoint, a requirement for DC power would be much preferred over AC power generation.

6.2 Engine/Generator Transmissions

The preferred solution to the rpm related AC power generation problem is to couple the engine to the generator through a transmission drive. A transmission will enable the engine to operate at design rpms while the generator can be geared down to its required rpm. A pulley and drive belt transmission is much preferred for this application over the geared and/or hydraulic transmissions for its simplicity, low cost, and light weight.

A major disadvantage to using transmission drives in motor generator sets is the reduction in generator efficiencies due to mechanical losses. However, the pulley/belt drive transmission has the least losses of the mechanical/hydraulic systems studied.

6.3 Inverters

An alternate method of operating an engine at optimum rpm and still having stable AC power is to generate DC power and run it through an inverter for clean phased AC. This method of power generation has the advantage of low ripple AC power and the disadvantage of low efficiencies and high cost and weight ratios. For example, a 2 Kw BALMAR inverter lists for $1,200 and weighs 39 pounds. This would approximately double the cost and weight of the motor generator set.

7. Trade-off Study/Life Cycle Costs

In order to determine which type engine, 2-stroke, 4-stroke, rotary, etc., is the best candidate for conversion from gasoline to kerosene fuel operation, a number of issues need be considered and a trade-off study performed. Of prime importance in this study are the issues relating to:

- Engine type
- Combustion process
- Modification required
- Engine procurement cost
- Engine modification cost
- Engine power density
- Engine life cycle
- Engine reliability
- Maintenance costs
- Operating noise levels
- Fuel consumption
- Engine lubrication
- Cold starting
- Infrared signature (IR)
- EMI/RFI

A two part matrix was developed for the evaluation and selection of the candidate engine. Part I, The Pre-evaluation Matrix, evaluates engines for their technical and commercial feasibility of conversion. Those engines judged to be both technically and commercially feasible continue on to Part II of the matrix, The Evaluation Criteria. The following is a detailed description of both parts of the matrix.

7.1 Pre-evaluation Matrix

7.1.1 Candidate Engine

The Pre-evaluation Matrix begins with the identity of the candidate engine (manufacturer, model number and rated horsepower).

Candidate Engine

Manufacturer
Model number
Rated horsepower

7.1.2 Engine Type

Next the matrix separates the candidate engines into specific types:

- The 2-stroke cycle, reciprocating engine having a high power density and a power stroke each crankshaft revolution.

- The 4-stroke cycle, reciprocating engine which is a heavier, more expensive engine have a power stroke every second crankshaft revolution.

- The rotary engine, having the intake, compression, power and exhaust events in a rotational 360 degree movement (versus reciprocating).

- Other - engines not falling into the above categories.

Engine Type

2-stroke reciprocating
4-stroke reciprocating
rotary
other

7.2 Combustion Process

The combustion process or type of burn is determined by the charge concentration in the combustion chamber. Here, the choices are:

- Homogeneous charge, in which the concentration of air fuel mix is uniform and burns rapidly and with high intensity.

- Stratified charge, in which the charge concentration is layered or non-uniform. Stratified charge combustion is slower and softer and is usually associated with lean burn engines or direct injected engines.

Combustion Process

Homogeneous Charge
Stratified Charge

7.3 Ignition Process

The ignition process is categorized by the method of triggering the combustion event. The choices are:

- Spark Ignited (SI) engine, where a magneto or battery powered ignition system is used to generate a spark that initiates combustion.
- Compression Ignition (CI), or diesel that uses the heat of compression to ignite air fuel mix.
- Radical Ignition (RI), that uses active radicals from the prior combustion event in combination with SI and/or CI to initiate reaction. The advantage of the RI process is that it reduces the energy threshold required for ignition, thereby producing a more dependable ignition and stable combustion.

Ignition Process

Spark Ignition
Compression Ignition
Radical Ignition

7.4 System Modifications

The heart of the Pre-evaluation Matrix is the section on System Modification options available to burn kerosene type fuel in existing SI engines. These modifications are divided into four categories:

- Combustion Chamber Geometry
- Lubrication System
- Ignition System
- Fuel Delivery System

Each of these four categories is addressed in detail in Section 5.

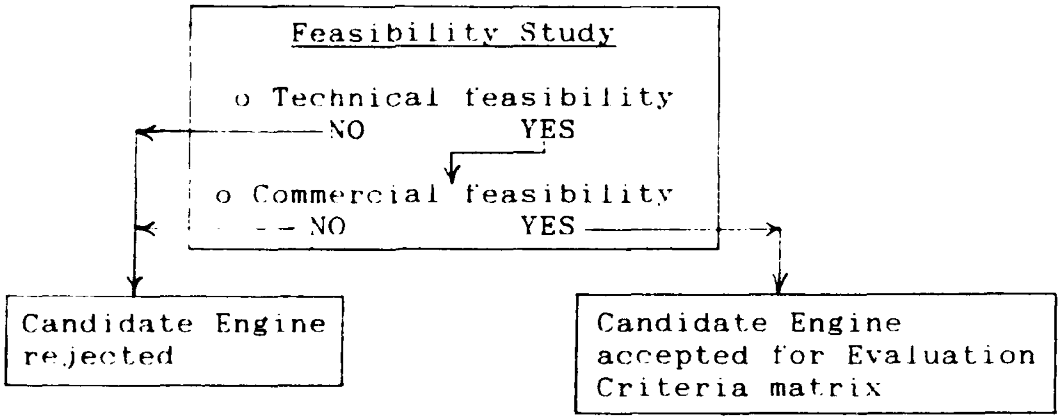
System Modifications

Combustion Chamber Geometry
Lubrication System
Ignition System
Fuel delivery System

7.5 Feasibility Study

The above criteria are used to determine if the engine modifications required are both technically and commercially feasible.

- o Technical Feasibility is defined as the capability of the off-the-shelf engine to undergo the modifications required to successfully convert it to kerosene fuel operation.
- o Commercial Feasibility at this point involves an approximation of the costs required for modification. This means that one looks at only the use of commercially available off-the-shelf components or simple fixes to complete the modifications required versus the requirement for expensive and time consuming fabrication of needed hardware. On this basis, detailed cost analysis is performed for the Evaluation Criteria matrix. Note that a candidate engine may be technically capable of undergoing modification, but at a cost that would prohibit it from ever being a commercial success. Candidate engines failing either or both the technical and commercial feasibility tests are immediately rejected and are not considered for further study. Engines that pass both tests continue to the second matrix, the Evaluation Criteria.



7.6 Evaluation Criteria Matrix

Once the subject engine successfully completes the Pre-Evaluation matrix it becomes a candidate for the second half of the study, the Evaluation Criteria matrix. This matrix uses cost as its primary consideration and engine performance as its secondary consideration. Costs are divided into two major categories: initial costs in dollars per kilowatt power produced

($/Kw) and operating costs in dollars per kilowatt hour ($/Kw-hr). Once these costs are calculated, life cycle costs can be evaluated.

7.7 Initial Cost ($/Kw)

Initial cost represents the sum of the costs required to prepare the engine for its mission and is expressed in dollars per kilowatt. Three components affect the initial cost:

- o Procurement costs
- o Modification costs
- o Engine life (spares)

7.7.1 Procurement cost

For purposes of this comparative study, the procurement cost is taken as the off-the-shelf list price of the unmodified engine with increases due to power limits factored in. Note that list price will be discounted when buying in volume, but this discount is not addressed in this study.

In order to state procurement cost in dollars per power output ($/Kw), several factors must be applied. First, one must find the power output of the engine at the rpm required for the generator-engine interface. This rpm and reasons for its selection will be discussed in the generator section of this report. Next, the rated power at the selected rpm will be corrected for the change in fuel and engine geometry. A 15% to 25% power loss is normal for this conversion using conventional technology due to reduced compression ratio and thermal loading requirements. A 25% power reduction correction factor will be used in this study, although for SCS systems this factor would be lower.

Finally, a correction factor for horsepower-in to kilowatts-out of the generator will be applied. This factor will assume the efficiencies of off-the-shelf, inexpensive generators and will not consider the state of the art high-tech generators because of their prohibitive costs. Accepted industry practice uses a factor of 2:1 (2hp in, to 1 Kw out), for this conversion.

7.7.2 Modification Cost

Modification cost ($/Kw), are divided into two basic categories. First, the actual cost of converting the engine to kerosene fuel operation; and second, the expense of the generator and its interface.

- Engine conversion costs. An approximate yet fairly accurate method of determining modification costs, including both the parts and labor to modify and install the part, is to break down each system into possible modifications required and estimate cost as a percentage of the unmodified engine's list price. The categories and sub-categories used are taken directly from the engine modification section of this report.

- Combustion Chamber Geometry.

	Modification	Percent cost
a.	Head gasket	10%
b.	OEM head/Machined head	20%
c.	Modification to piston	25%

- Lubrication System - Ring Modification

a.	2-stroke	0
b.	4-stroke	25%
c.	Rotary	0

- Ignition System

a.	Timing retard	10%
b.	Hot spark & plug	25%

- Fuel Delivery System

a.	Replace carburetor air/fuel jets	5%
b.	Electric fuel vaporizer system	25%
c.	Direct injection	100%

- Generator procurement. Generators will be of the off-the-shelf, inexpensive variety, differing primarily in size, due to the power output of the engine. It is estimated that a generator with a simple interface consisting of frame, coupling and minimal electronics will cost about the same as the list price of the engine. Therefore, a single generator procurement cost factor of 1:1 will be used.

a.	Generator cost	100%

Using this method, conversion costs can be as little as 125% for engines using starting fluids, to over 275% for manual start engines using kerosene fuel only systems. These percentages include the cost of the generator.

7.7.3 Engine Life

Expected engine life is included in this study for its influence on spare engines required in the inventory (additional $/Kw). Obtaining factual information on engine life is difficult due to variations in engine specifications, usage and environmental conditions, and can be accomplished best through field testing. However, the latest state of the art, small 4-stroke engines are designed for a 1500 hour engine life on design fuel with only a 20% failure rate. These engines are close tolerance engines with a premium price tag. A normal, high volume, inexpensive 4-stroke engine of the size proposed will have an average engine life of approximately 1000 hours and 2-stroke and rotary engines approximately 60% of that. These figures will change with engine size, operating rpm, brake mean effective pressure (BMEP) loading, lubrication and temperature, but the ratio of engine life between engine types should remain the same.

The effect of burning kerosene fuel in an engine designed for gasoline may also have an effect on engine life. However, if the converted engine is operating at the proper temperature with BMEP that is out of the knock region and with proper lubrication, there is no reason to believe that engine life will be adversely affected. One must remember that kerosene is a better lubricant than gasoline and that engine life depends on internal pressures and temperatures and on proper lubrication.

In summary, the purpose of this study is to select the best engine candidate for conversion based on minimum life-cycle costs and all of the factors of the trade-off study. Since engine spare requirements are yet to be determined, only normalized estimates of engine life can be used. Making the assumption that engine life will be unaffected by kerosene fuel operations and that both the 2-stroke and rotary engine life will be approximately 60% of the 4-stroke engine life, an additional initial cost factor of 67% [(10/6 - 1) x 100], will be placed on the procurement and modification cost (engine only) of these engines for spares.

7.8 Operating Cost ($/Kw-hr)

Operating cost effectively introduces time into the equation. Initial cost was expressed in $/Kw; now operating cost is expressed in $/Kw-hr, and is another way of saying it will cost this much money to operate a specified engine for a given amount of time. Subcategories of operating costs are:

- Maintenance
- Fuel
- Special fluids
- Special equipment

7.8.1 Maintenance expense

This is another expense that will require field testing to determine accurately. An approximation will be presented here.

Maintenance is divided into two categories, scheduled and unscheduled. Scheduled maintenance is performed at a specified time interval and is preventive in nature. Here, lubricants, filters, spark plugs, etc., are checked periodically in an attempt to prevent failure during operation. Unscheduled maintenance is that which is required to correct a malfunction that occurred unexpectedly. Of the two, scheduled maintenance expense can be accurately predicted and will normally run about 12.5% of the new engine procurement cost per 100 hours of operation. Unscheduled maintenance, on the other hand, can run from zero to full replacement cost and needs to be statistically determined during field testing. A best estimate of 12.5% of new engine cost per 100 hours will also be used for this expense, bringing total maintenance cost to 25% of the new engine procurement cost per 100 hours of operation.

7.8.2 Fuel

Fuel cost ($/Kw-hr) can be calculated from the candidate engine's Brake Specific Fuel Consumption (BSFC). Typical figures for various gasoline engine BSFC are in pounds fuel per horsepower hour (#/hp-hr) and are as follows:

- 4-stroke = .5 #/hp-hr
- 2-stroke = .65 #/hp-hr
- Rotary = .75 #/hp-hr

These figures are for gasoline fuel and will change slightly with kerosene, but once again it is the ratios that are important (i.e, a 4-stroke engine at equal power will consume approximately 77% (.5/.65) of the fuel of a 2 stroke and a rotary engine will consume 115% of that fuel).

In order to go from #/hp-hr kerosene to $/Kw-hr generator output the conversion factor of 2:1 (2 horsepower into the generator for each kilowatt of power out) must be applied. Therefore, for each Kw output of a 4-stroke motor-generator set operating at a BSFC of .5 #/hp-hr, one pound of fuel must be supplied. (.5 #/hp-hr) (2hp/Kw) = 1 #/Kw-hr.

Note that the density of gasoline and kerosene are within 10% of each other (6.18 #/gal gasoline, 6.83 #/gal kerosene), and the heating values of the two fuels are even closer. Therefore, the assumption will be made that operating fuel costs for kerosene will be approximately the same as gasoline assuming both fuels are equally priced.

In summary, assuming kerosene fuel priced at $1.50/gallon and the above BSFC:

- o 4-stroke engines will cost $0.22/Kw-hr
- o 2-stroke engines will cost $0.29/Kw-hr
- o Rotary engines will cost $0.33/Kw-hr

i.e., ($1.50/gal) (1gal/6.83#) (.5#/hp-hr) (2hp/Kw) = $0.22

7.8.3 Special Fluids

Special fluids are fluids other than kerosene fuel that are needed to operate the system. Examples of these fluids are :

- o Oil
- o Starting fluid
- o Coolant
- o Grease
- o Hydraulic/transmission fluid

Of the above fluids, the only ones that have a significant impact on this project are oil and starting fluid (starting fluid will be addressed later). The problem here is that on the battlefield, normal crankcase oil will be available for use with no great cost impact for small 4-stroke engines since 4-stroke engines are not very sensitive to oil type. However, conventional engines requiring fuel-oil mix such as the 2-stroke and rotary will have a problem using crankcase oil since crankcase oil has a high ash content that when burned will quickly foul spark plugs and carbon up combustion chambers. SCS engines have run with conventional lubricants, both 2 stroke and 4 stroke, with little or no fouling.

To prevent fouling in conventional engines, a special ashless oil or 2-stroke oil will be required if any appreciable 2-stroke or rotary engine life is to be realized. Since this oil will be used in small quantities (50:1 or 100:1 mix with kerosene is needed) and since this oil is not explosive under battlefield conditions, it may be possible to include it in the logistics plan.

In summary there should be no significant special fluids cost for the 4-stroke conversion, but a 2-stroke or rotary engine could require its own logistic support for ashless oil at an unknown but significant expense. An estimate of 0.05/Kw-hr will be used for the 2-stroke and rotary engines.

7.8.4 Special Equipment

Special equipment is addressed here because of the possible need for a battery for engine start-up. As already addressed in the system modifications section, certain options have a cost benefit but at the expense of requiring electrical power for vaporizing the fuel at start-up. This power, if required, can be scavenged from other mobile units in the field or it can be provided from a dedicated battery integrated into the motor generator set.

Unfortunately, all three engine types, 2-stroke, 4-stroke, and rotary, could require a battery to power fuel vaporizer systems, even for hand starting. This option results if either of two other options fail the selection criteria: the more expensive (and heavy) direct fuel injection with a hot spark system, or the less expensive but hazardous starting-fluid system. A best estimate for a starting battery to power vaporizer systems is $50, and it is expected to last the life of the engine.

7.9 Engine Performance

The final section of the Evaluation Criteria matrix, engine performance, deals with the ability of the candidate engine to perform its mission on the battlefield. Six topics were found to be pertinent and will be examined here. They are:

- Power density (Kw/#)
- Engine reliability (%)
- Cold start limits (F)
- Noise level (dB)
- IR signature
- EMI/RFI signature

7.9.1 Power Density (Kw/#)

Power density is an important factor in that it will be a measure of the weight a man will have to transport for a given amount of power output. Included in this weight are the basic engine, its modifications, the generator with interface, fuel & oil and any special equipment such as batteries. Three engine types will be considered, the 4-stroke being the heaviest basic engine, the 2-stroke being the lightest and the rotary falling somewhere in between.

Basic engine weight is defined as the dry weights of the engine without fuel or oil.

Modified engine weight is the basic engine weight plus the weight of the modifications. Here the significant modifications are the fuel vaporization system and/or the fuel injection system. It is estimated that a fuel vaporization system will weigh approximately one pound plus battery. A fuel injection system, with its rotary pump, pump drive, injector and connections will weigh approximately five pounds.

Fuel and oil will also add weight. Fuel (#/Kw-hr) will average approximately one pound per kilowatt-hour and crankcase oil, only of interest in the 4-stroke, will add approximately 2.5 pounds.

7.9.2 Generator and Interface

Since no specific generator has been identified in this contract, an approximation must be made for the weight of the generator and its interface. This approximation was made using the specifications of a production Honda motor generator set and will assume that the power generation system will equal the dry weight of the engine .

7.9.3 Special Equipment

Should a battery be required for starting, a small, high capacity battery weighing approximately five pounds would be recommended.

These weights will be totaled and put into matrix form.

7.9.4 Engine Reliability

Once started and operating on proper lubricants, there is no reason to believe that the candidate engine will have any better or worse reliability than the unmodified engine. Starting is the concern. Both of the existing kerosene fueled projects considered here, the Navy Firepump and the Grumman TMAP engine, have excellent starting capabilities. However, the Navy Firepump, using a manual start system, does not require a battery for starting as does the Grumman engine. Because of the manual start capabilities of the Navy engine, the hot spark-direct injection system is deemed to be the most reliable. This will be reflected in the Evaluation Criteria matrix.

7.9.5 Cold Start

Present cold start technology using direct injection or battery powered fuel vaporization has demonstrated reliable cold starting on kerosene fuel down to -20 F and 6 F, respectively. All three candidate engine types using one or both of these techniques will be able to cold start at these temperatures. Further analysis suggests that no engine type will have a major cold start advantage over another.

7.9.6 Noise Level (dB)

Since all three modified candidate engine types are operating as SI or RI engines and not CI, combustion noise associated with rapid burn rates (DQ/DO) should not differ significantly from gasoline fueled engines. Mechanical noise, that which is rpm related, should also be normal and possibly low because of the reduced rpm requirement associated with power generation.

In short, kerosene fueled SI/RI engine noise generation should be no greater than that of the gasoline powered SI engine. If a further dB reduction is required, existing muffler technology can meet most any specification.

7.9.7 IR Signature

There are two major sources of infrared emissions on an operation internal combustion engine. One is the heat of the engine metal surrounding the combustion chamber and the other is the exhaust system. Of these, the heat of the combustion chamber, even in air cooled engines, is the lesser problem. The exhaust system temperatures are the primary contributors to IR emissions. They can average several hundred degrees F above cylinder head temperatures and often the exhaust has to be diluted with cool air before exiting the muffler to reduce the temperature. The use of kerosene fuels vice design gasoline fuel may slightly elevate the IR exhaust signature since some unburned fuel (common in SI kerosene operations) may pass through the exhaust port and burn in the pipe.

When ranking the three candidate engine types for IR signature evaluation, engine thermal efficiency in the form of BSFC will be used. Here, excess fuel usage to produce a given amount of power will equate to excess waste heat. Therefore, the lowest untreated IR signature will result from the engine with the highest thermal efficiency (another way of saying the lowest BSFC). As stated earlier in the operating costs section, this ranking is the 4-stroke, 2-stroke and rotary engines. Using the 4-stroke engine as the norm, the 2-stroke engine has a 30% [(.5-.65)/.5 x 100] increase in signature over the 4-stroke engine and the rotary has a 50% increase.

7.9.8 EMI/RFI Signatures

Possible sources of Electrical Magnetic Interference and Radio Frequency Interference in an SI motor generator set are as follows:

- o Ignition system
- o Electric start system
- o Generator

Of these, only the ignition system may be required to undergo enough change to significantly alter the EMI/RFI signature when modifying the candidate engine to kerosene fuel operation. If the hot spark modification discussed earlier is used, a high intensity coil will be required. This will increase the electromagnetic field around the engine, increasing the EMI signature. In addition, a high intensity coil will generate a high energy spark at spark plug tip that will increase the RFI signature.

All three engine types may undergo an adverse EFI/RFI signature change if the "hot spark" modification is selected. Proper grounding and shielding of the ignition system can reduce these signatures. Alternatively, if RI is used once the engine is started, no electrical spark is required (See Appendix A), hence no RFI signature is emitted.

7.10 Candidate Engine Selection

7.10.1 4-Stroke Cycle Engine

A number of 4-stroke SI engines were examined for suitability of conversion to kerosene based fuel. These engines fit largely into two basic categories: the older side valve engine design and the newer, state-of-the-art, overhead valve (OHV) design. In addition, many sub-categories were found. For example:

- o Flat piston vs. bowl-in-piston design
- o Contact point ignition vs. fully electronic ignition
- o Air cooled vs. water cooled
- o Manual start vs. electric start
- o U.S. manufacturer vs. foreign

Two representative engines, one fitting each basic design, were selected for study:

- o Honda G100 K1, 2.2 hp, side valve engine
- o Briggs & Stratton OT-4, 3.8.hp, OHV engine

Four stroke engine characteristics

	Honda	Briggs & Stratton
Valve train	side valve	OHV
Piston design	flat	bowl-in-piston
Displacement (in)	4.63	9.18
Bore (in)	1.81	2.56
Stroke	1.81	1.78
Compression ratio	6.5:1	8.5:1
Horsepower (max)	2.2 @ 4200 rpm	3.8 @ 3600 rpm
Horsepower (max operating)	1.6 @ 3600 rpm	3.2 @ 3600 rpm
Weight dry (lbs.)	19.0	24.0

These engines, as was the case with most 4-strokes studied, successfully passed the Pre-evaluation Criteria matrix since they operated well within the speed/load range requirements and were simple and inexpensive in construction.

The engine analysis quickly led to three basic categories that greatly affected conversion cost. It was found that if fuel restrictions could be relaxed slightly to allow for the use of a very small amount of starting fluid at start-up, then the engine modification could be accomplished with a significant cost saving and at minimal added weight since the major engine modification expense is that of the starting system. This is referred to as "Option A - Starting Fluid".

A second option, one that strictly adheres to the use of kerosene fuel for starting, is one that requires battery power to vaporize the fuel at start-up. This option may or may not violate the engine conversion specifications since no restrictions on the use of a battery were given. This option is the second most expensive and complex, and is referred to as "Option B - Fuel Vaporizer and Battery".

The third option, referred to as "Option C - Direct Injection", adheres to the stringent requirements of kerosene fuel and no battery, and requires a very expensive direct fuel injection system along with other major modifications. This is the option selected by the U.S. Navy for use on its 45 hp Firepump JP5 fueled engine.

7.10.2 2-Stroke Cycle Engine

Most of the 2-stroke engines had great difficulty passing the technical requirements of the Pre-evaluation Criteria matrix. For example, the sturdy marine outboard motor power heads have satisfactory speed/load ranges, but failed technically because of their cooling requirements. Also, the high power density chainsaw type engines were able to meet the cooling demands, but failed technically because of their narrow power band and the difficulty in installing Option C in high rpm engines.

This left a few aircooled 2-stroke engines with an optimum mid-range power band from which to choose. Two representative engines, both being of the manual start, loop scavenged, and horizontal crankshaft design, were selected. These engines were not selected on the basis of their differing combustion chamber design as was the 4-stroke engine since work on this type of engine by Sonex and the Navy showed that loop scavenging was the design of choice; they were selected because each engine represents current technology from two of the largest 2-stroke engine manufacturers. The engines selected are as follows:

- Briggs & Stratton Model 62032-0529
- Tecumseh AH600 type 900384

Two Stroke Engine Characteristics

	Briggs & Stratton	Tecumseh
Scavenging	Loop	Loop
Piston design	Flat crown	Flat crown
Displacement (in)	6.21	6.00
Bore (in)	2.13	2.09
Stroke	1.75	1.75
Horsepower (max)	3.4 @ 3600 rpm	3.0 @ 4500 rpm
Horsepower (max operating)	2.3 @ 3600 rpm	2.4 @ 3600 rpm

Two stroke engine modification will be classified in the same three categories as the 4-stroke engines, Options A, B & C.

7.10.3 Rotary Engines

No rotary engine successfully passed the technical requirements of the Pre-evaluation Criteria matrix. Three basic reasons are cited for this failure:

1. Power generation requires high BMEP operation for extended periods of time. This type of operation in a simple rotary causes heat build-up in the main rotor, leading to engine failure.
2. Exhaust gas temperature (EGT) of a rotary engine is approximately 650 F higher than that of a reciprocating engine due to slower combustion. This high EGT will elevate muffler skin temperature and significantly increase the IR signature.

3. The study failed to locate any commercial rotary engines in the power range required or to identify any active small rotary engine development projects.

8. Data Format

8.1 Evaluation Matrix

Appendix B, "Evaluation Matrix Data Sheets", contains the results of 12 selected runs through the matrix. These 12 runs are grouped into four engine types:

- Honda 4-stroke cycle
- Briggs & Stratton 4-stroke cycle
- Tecumseh 2-stroke cycle
- Briggs & Stratton 2-stroke cycle

and three options per engine type:

- Option A - starting fluid
- Option B - fuel vaporizer and battery
- Option C - direct injection

The printout of the evaluation matrix consists of three pages of data, headed by a description of the candidate engine and followed by the modification option selected. The remainder of the matrix closely follows the format presented in Section 7.

8.2 Summary Table

Table 3 - "Summary Table" - lists pertinent information from the 12 runs of the evaluation matrix in table form. Two sets of numbers are presented for each run. The first is the dollar value for each category, i.e., Procurement cost for Honda, Option A is 450 ($/Kw). The second is the first number divided by the lowest number in the row (normalized), i.e., 450 ($/Kw) = 450/167 = 2.69, and is called the "normalized evaluation factor".

The bottom three lines also require explanation. The third line from the bottom is labeled "Weighted Normalized Evaluation Factor" (.5X final $/Kw and .5X lb/Kw). This is the normalized evaluation factor for total operating cost (OP) + Initial Costs and weight per unit power times a weighting factor. For this line the weighting factor is .5/.5 (.5 times power density in #/Kw and .5 times initial costs in $/Kw). Note that .5/.5 means that there is equal weighting. The next line uses a weighting factor of .6/.4. (60% cost and 40% power density), and the bottom line is more heavily weighted towards cost with the factors being .7 and .3.

Note that the lower the value of the weighted normalized evaluation factor, the better the candidate engine, i.e., On the last line the Briggs & Stratton 4-stroke cycle, Option A has the lowest evaluation factor (1.10).

Table 3

Summary Table

Table 3. SUMMARY TABLE

	HONDA FOUR STROKE-CYCLE						BRIGGS STRATTON FOUR STROKE-CYCLE						TECUMSEH TWO STROKE-CYCLE						BRIGGS STRATTON TWO STROKE-CYCLE					
OPTION >>>>>	A		B		C		A		B		C		A		B		C		A		B		C	
	VALUE	FACTOR	VALUE	FACTOR	VALUE	FACTOR	VALUE	FACTOR	VALUE	FACTOR	VALUE	FACTOR	VALUE	FACTOR	VALUE	FACTOR	VALUE	FACTOR	VALUE	FACTOR	VALUE	FACTOR	VALUE	FACTOR
PROCUREMENT COST ($/KW)	450	2.69	450	2.69	450	2.69	167	1.00	167	1.00	167	1.00	196	1.17	196	1.17	196	1.17	198	1.19	198	1.19	198	1.19
MODIFICATION COST ($/KW)	675	2.70	855	3.42	1733	6.93	250	1.00	317	1.27	642	2.57	274	1.10	323	1.29	705	2.82	277	1.11	326	1.30	712	2.85
ENGINE LIFE COST ($/KW)	675	2.70	855	3.42	1733	6.93	250	1.00	317	1.27	642	2.57	411	1.64	485	1.94	1057	4.23	415	1.66	489	1.96	1067	4.27
INITIAL COSTS ($/KW)	1800	2.70	2160	3.24	3915	5.87	667	1.00	800	1.20	1450	2.17	881	1.32	1004	1.51	1959	2.94	889	1.33	1013	1.52	1976	2.96
OPERATING COST ($/KW-HR)	1.4	2.19	1.43	2.23	1.35	2.11	0.69	1.08	0.68	1.06	0.64	1.00	0.88	1.38	0.92	1.44	0.92	1.44	0.88	1.38	0.93	1.45	0.83	1.30
TOTAL OP + INITIAL COSTS ($/KW)	3200	2.37	3593	2.66	5265	3.89	1353	1.00	1478	1.09	2087	1.54	1761	1.30	1924	1.42	2788	2.06	1774	1.31	1944	1.44	2810	2.08
POWER DENSITY (KW/LB)	0.014	0.56	0.012	0.48	0.013	0.52	0.019	0.76	0.017	0.68	0.018	0.72	0.025	1.00	0.021	0.84	0.022	0.88	0.022	0.88	0.019	0.76	0.02	0.80
WT PER UNIT POWER (LB/KW)	71.5	1.78	81.5	2.03	79.8	1.99	52.8	1.32	57.5	1.43	56.9	1.42	40.1	1.00	46.6	1.16	45.6	1.14	44.7	1.11	51.7	1.29	50.5	1.26
WEIGHTED NORMALIZED EVALUATION FACTOR (.5X FINAL $/KW AND .5X LB/KW)		2.07		2.34		2.94		1.16		1.26		1.48		1.15		1.29		1.60		1.21		1.36		1.67
WEIGHTED NORMALIZED EVALUATION FACTOR (.6X FINAL $/KW AND .4X LB/KW)		2.13		2.41		3.13		1.13		1.23		1.49		1.18		1.32		1.69		1.23		1.38		1.75
WEIGHTED NORMALIZED EVALUATION FACTOR (.7X FINAL $/KW AND .3X LB/KW)		2.19		2.47		3.32		1.10		1.19		1.51		1.21		1.34		1.78		1.25		1.39		1.83

8.3 Plots

Eight plots are required to graphically present the data in Table 3. Figure 1 is the plot of the normalized evaluation factor against engine type for the three options, A, B & C, using a .5/.5 weighted factor. Figures 2 & 3 are plots of the same information, only for .6/.4 and .7/.3 weighting factors. Figure 4 presents all three plots on one page.

Figure 5 is a plot of the normalized evaluation factor against engine type for the three weighted factors (.5/.5, .6/.4 & .7/.3), for a given Option (A). Figures 6 & 7 provide the same information for Options B & C. Figure 8 presents the last three plots on one page.

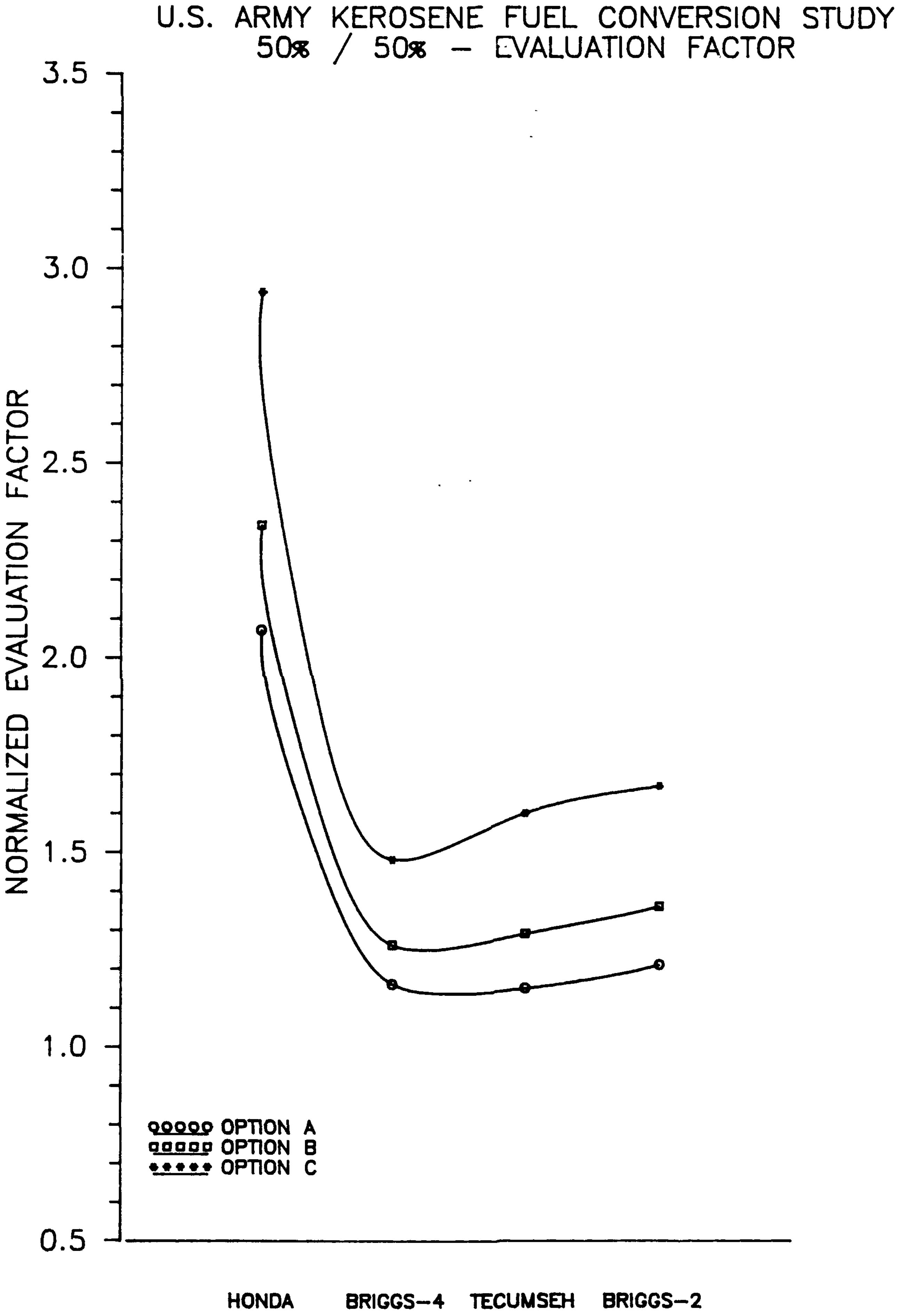

U.S. ARMY KEROSENE FUEL CONVERSION STUDY
50% / 50% – EVALUATION FACTOR

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Figure 1

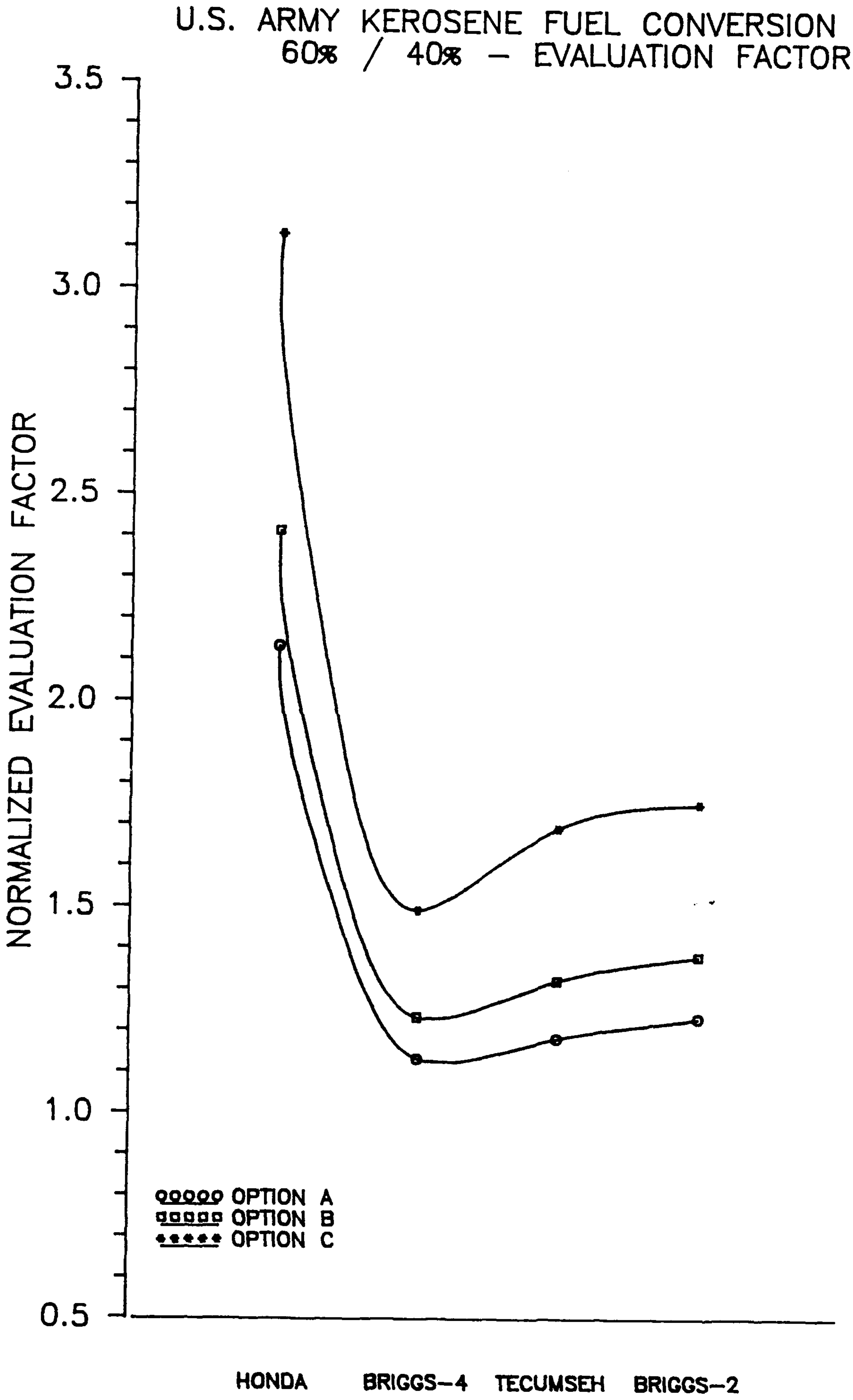

Figure 2

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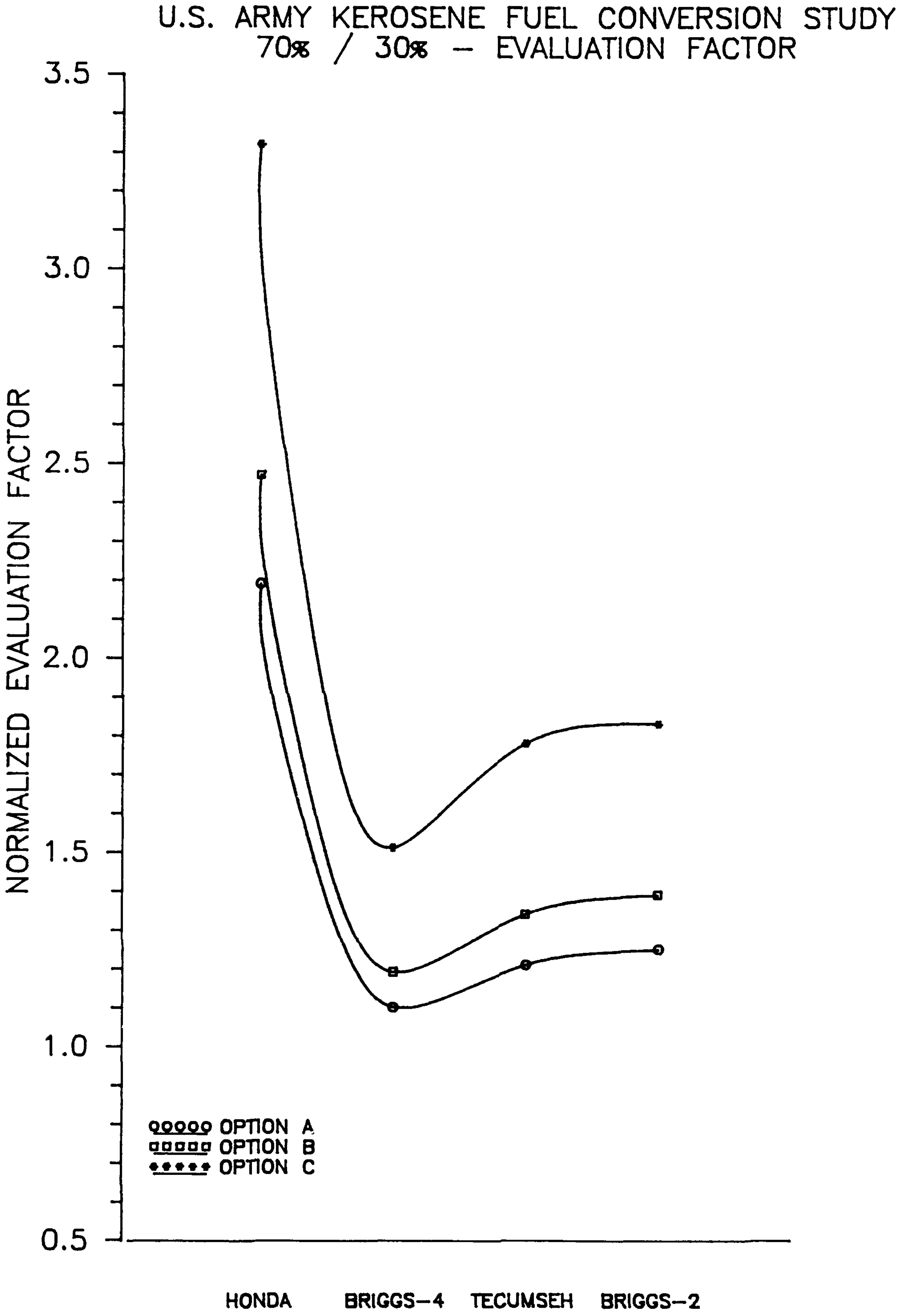

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Figure 3

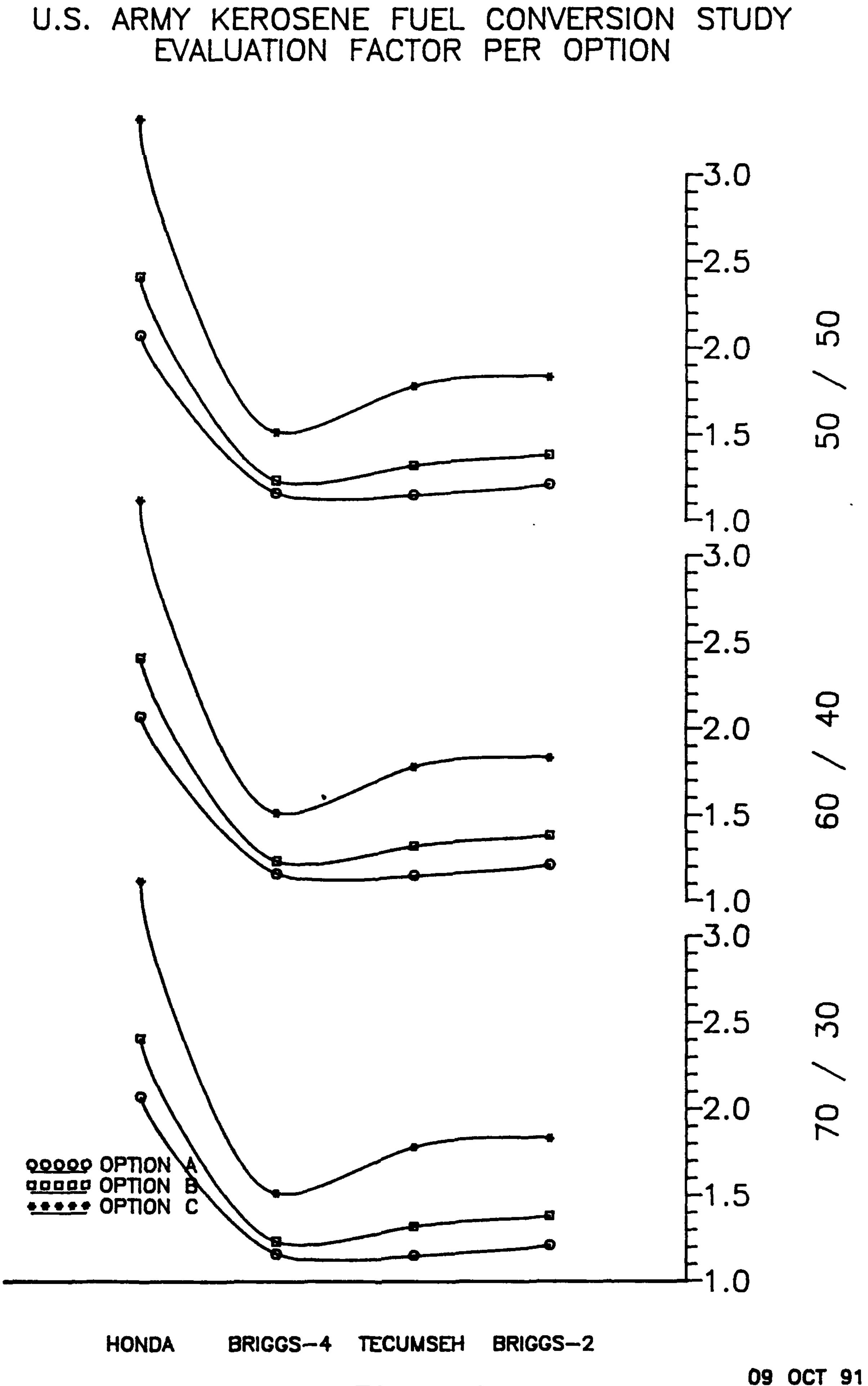
U.S. ARMY KEROSENE FUEL CONVERSION STUDY
EVALUATION FACTOR PER OPTION
3.0
2.5
2.0
1.5
1.0
50 / 50
3.0
2.5
2.0
1.5
1.0
60 / 40
3.0
2.5
2.0
1.5
1.0
70 / 30
OPTION A
OPTION B
OPTION C
HONDA
BRIGGS-4
TECUMSEH
BRIGGS-2
09 OCT 91

Figure 4

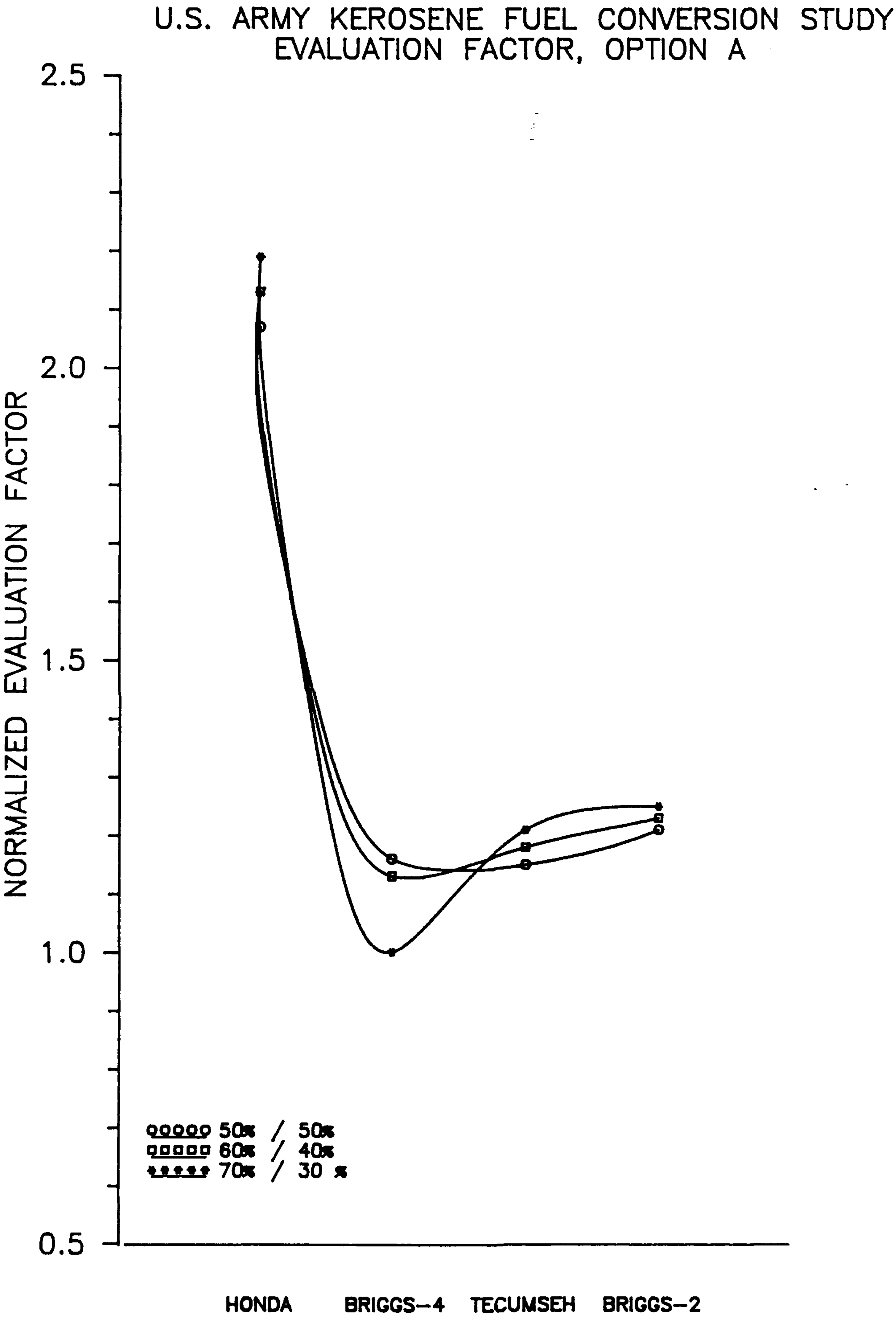

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Figure 5

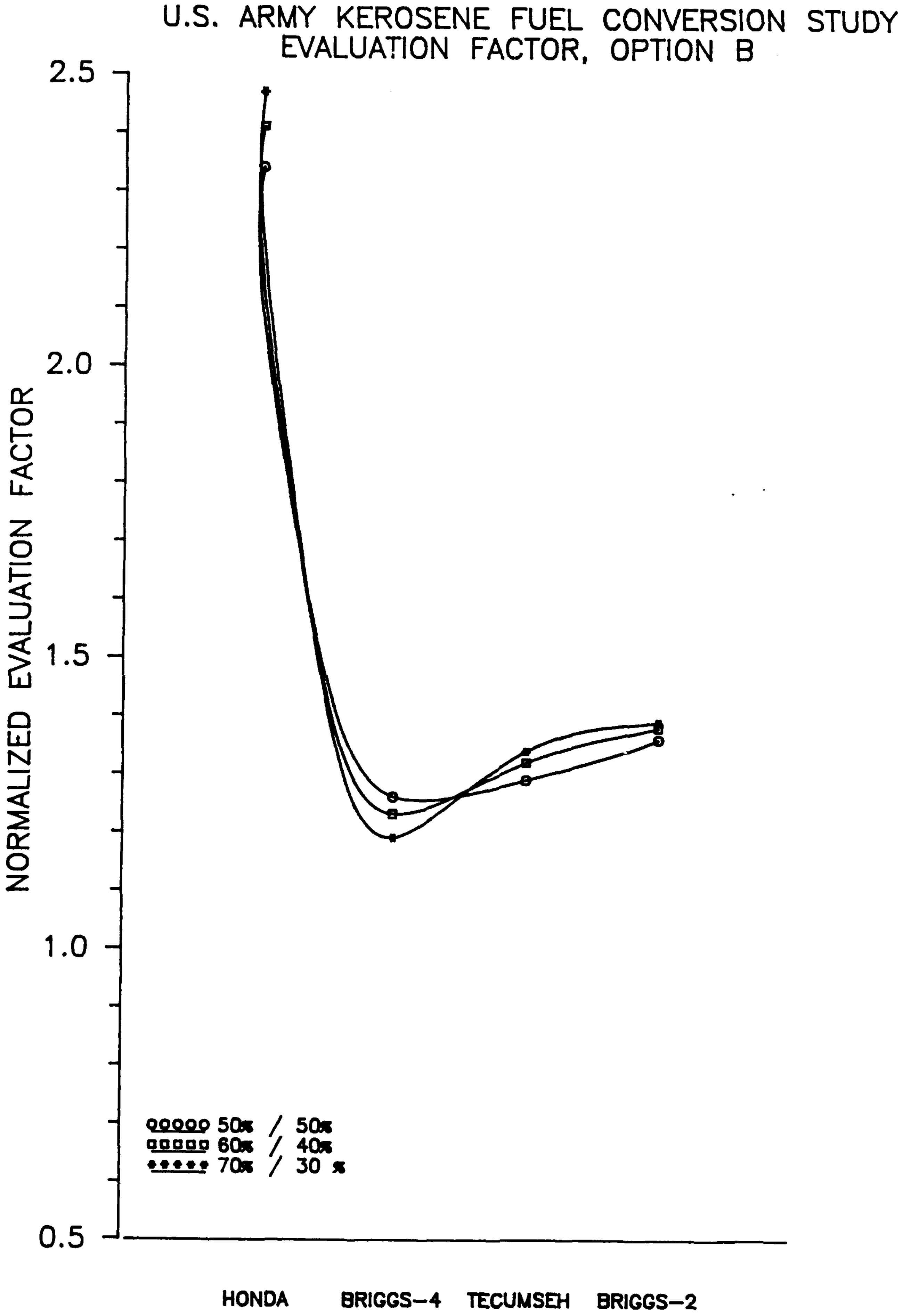

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Figure 6

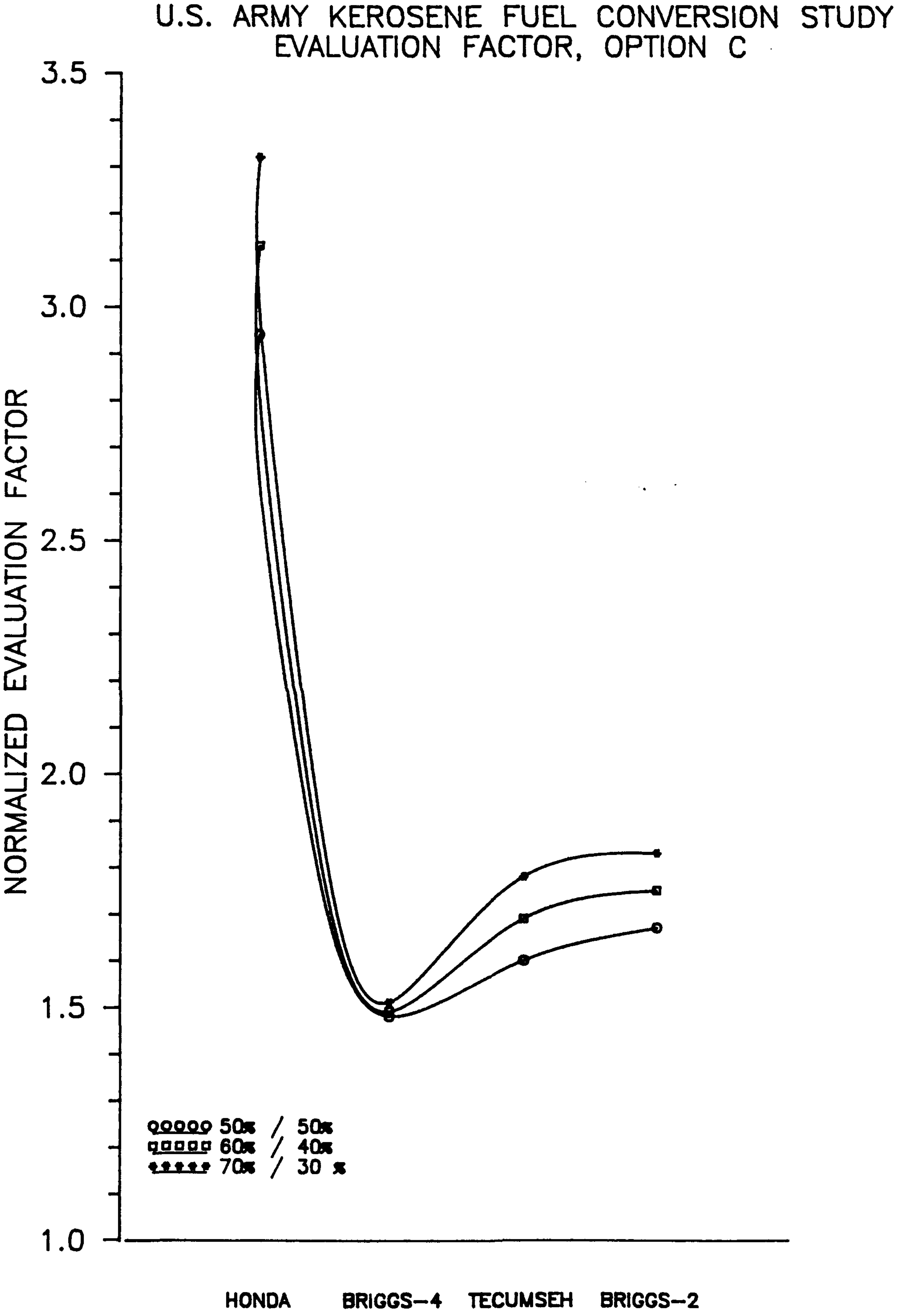

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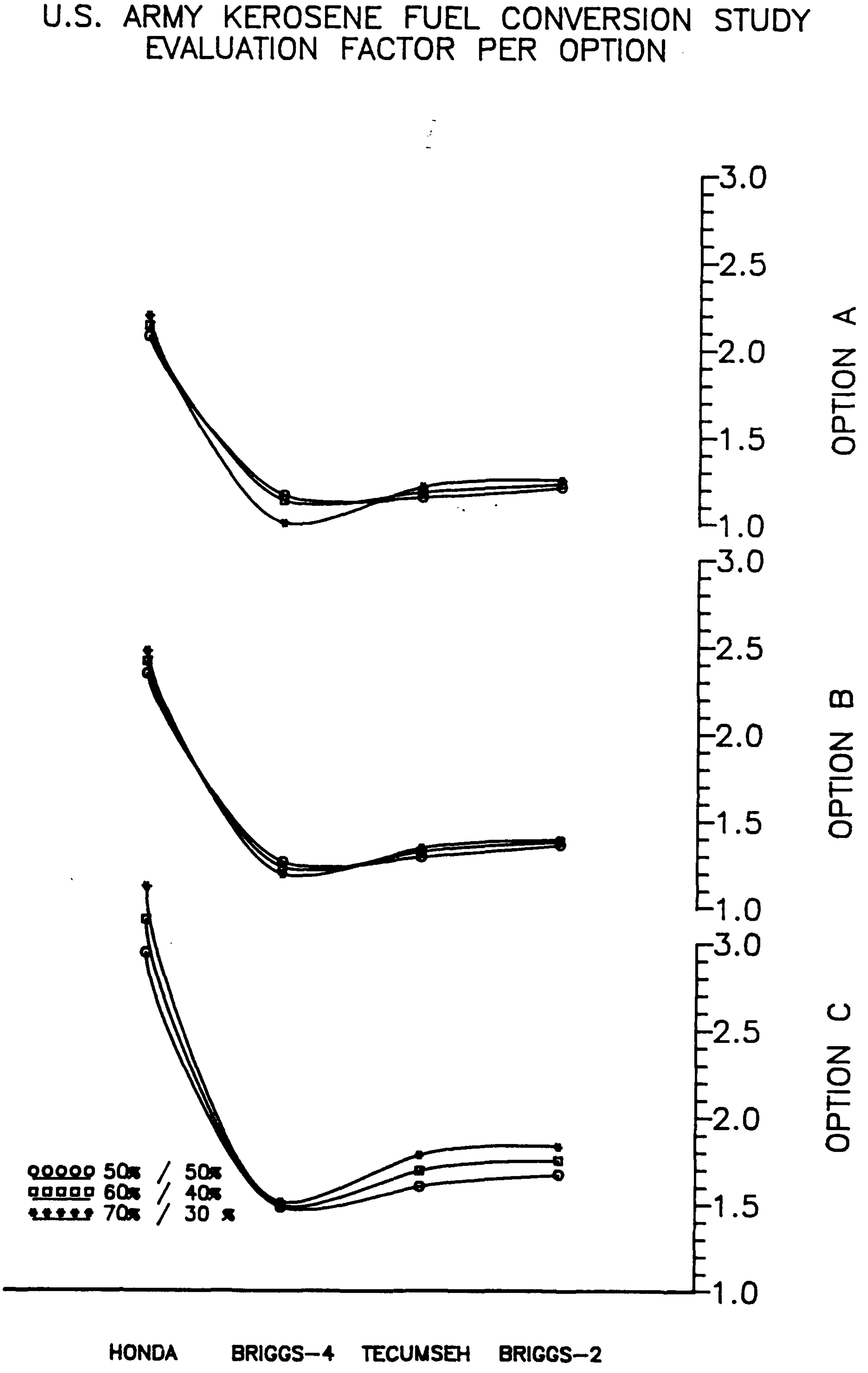
Figure 7



09 OCT 91

Figure 8

9. Conclusions

9.1 Best Candidate Engine

The best candidate engine is the Briggs & Stratton 4-stroke OHV engine. Of the four candidate engine types selected (the older side valve Honda, the newer OHV Briggs & Stratton, the Mid-Power band 2-stroke by Tecumseh and the equivalent 2-stroke by Briggs & Stratton), the Briggs & Stratton design was clearly superior. This becomes particularly apparent when viewing the plots in Figures 1 through 8. The engine with the lowest evaluation factors, and therefore the best candidate for modification, is the Briggs & Stratton 4-stroke OHV engine.

This engine type came out on top for all three Options (A, B & C) and improved its lead over the rest of the field as weighting factors favoring cost were applied. A good example of this can be found in the plots in Figures 5 through 8 where the three competing engine designs increase in normalized evaluation factor values as a cost weighted factor is applied (from .5/.5 to .7/.3), while the Briggs & Stratton design starts off low and goes lower yet as the weighted factor is applied. In the area of performance, the Briggs & Stratton, a 4-stroke, has the lowest BSFC, the longest engine life and the best signatures as well.

9.2 Second Best Candidate Engine

The second best candidate engine for conversion is the Tecumseh 2-stroke.

Since both candidate engines use the latest 2-stroke technology, they came out fairly equal in the competition, with the Tecumseh engine having a slight advantage over the Briggs & Stratton 2-stroke.

9.3 Third Best Candidate Engine

The technically older side valve Honda engine took a distant last place that put this technology out of the competition.

9.4 Other Engines

No rotary engine passed the Pre-evaluation matrix. Therefore, the rotary is not considered a candidate for modification.

10. Recommendations

10.1 SCS Technology

Much of the technology required for this conversion has already been developed and tested by Sonex Research, Inc. of Annapolis, Maryland. With this in mind, it is recommended that SCS technology be incorporated in:

- Piston design. The use of SCS technology in the bowl of the piston will maintain combustion chamber squish and swirl while reducing the compression ratio. Also, it is probable that with the use of SCS radical enhanced combustion, the expected 25% power drop inherent in conventional engine conversions of this type will be eliminated bringing, the generator output up from 1.2 Kw to approximately 1.5 Kw.

- Piston ring design. As stated earlier in Section 5, the 4-stroke engine has a problem with lube-oil dilution when operating on kerosene type fuels. SCS technology has already solved this problem through the use of a special gapless ring and gapless ring expander. The use of this technology would save additional time and development costs.

- Fuel vaporizer system (Option B only). Sonex has successfully demonstrated its fuel vaporizer system on a kerosene fueled, 4-stroke SI project funded by Onan Corporation, and on a 2-stroke project funded by Grumman Electronics Corporation. This technology successfully passed cold start and endurance testing and is recommended for use if Option B is selected.

10.2 Options.

It is recommended that the U.S. Army evaluate the three Options presented in this report for their merit on cost, operational requirements and existing technology, and that the Army specify the starting criteria for Phase II development.

10.3 Generator Output.

According to the Mobile Electric Power Asset Report dated 12 June 1991, the major category of motor generators in the .5 to 3 Kw range is the 1.5 Kw 60HZ AC generator. For this reason it is recommended that the initial engine modification use a 1.5 Kw 60HZ AC generator.

10.4 Alternative Starting System.

If a simple inexpensive starting system, requiring neither starting fluid nor battery power, were developed, it would allow for Option C performance at Option A prices. Sonex is currently designing a hand operated starting system using a primer pump and hot spark that will enable an engine to cold start on kerosene fuel without any starting aids or expensive direct fuel injection hardware. It is recommended that this development be included in the Phase II program.

11. Modifications Required for Recommended Engine

Once the candidate engine is selected a specific list of modifications can be presented. The required modifications for the selected engine are divided into four sections. The generator, having been discussed in Section 6, is not addressed here:

- Basic engine selection
- Option A
- Option B
- Option C

11.1 Basic Engine

The basic engine section covers the modifications common to most options. it is divided into three categories.

- Piston/combustion chamber
- Piston rings
- Carburetor fuel jets (Option A&B)

11.1.1 Piston/Combustion Chamber

The Briggs & Stratton 4-stroke engine has its combustion chamber divided between the cylinder head and piston bowl. This bowl-in piston geometry is ideal for the incorporation of SCS Mode 3 technology in the piston bowl.

An example of a Sonex Mode 3 (see Appendix A) SCS piston design used in a major European auto manufacturer's 4-stroke engine is enclosed as Figure 9. This piston drawing is shown for reference only. The Briggs & Stratton piston will have similar SCS technology but not the dimensions shown in the figure. Please note that the drawing is "sanitized" per the requirements of the Sonex client.

The prototype modified piston will consist of two parts: the piston base cut from the stock piston and the Sonex insert, cut from high strength aluminum. The Sonex insert contains the Sonex chambers which generate radicals for SCS combustion. The two parts of the piston will be attached mechanically (bolts) for the initial design and could be electron beam welded for the final product. The exact manufacturing technique is under investigation by Sonex piston licensee, AE Piston Products.

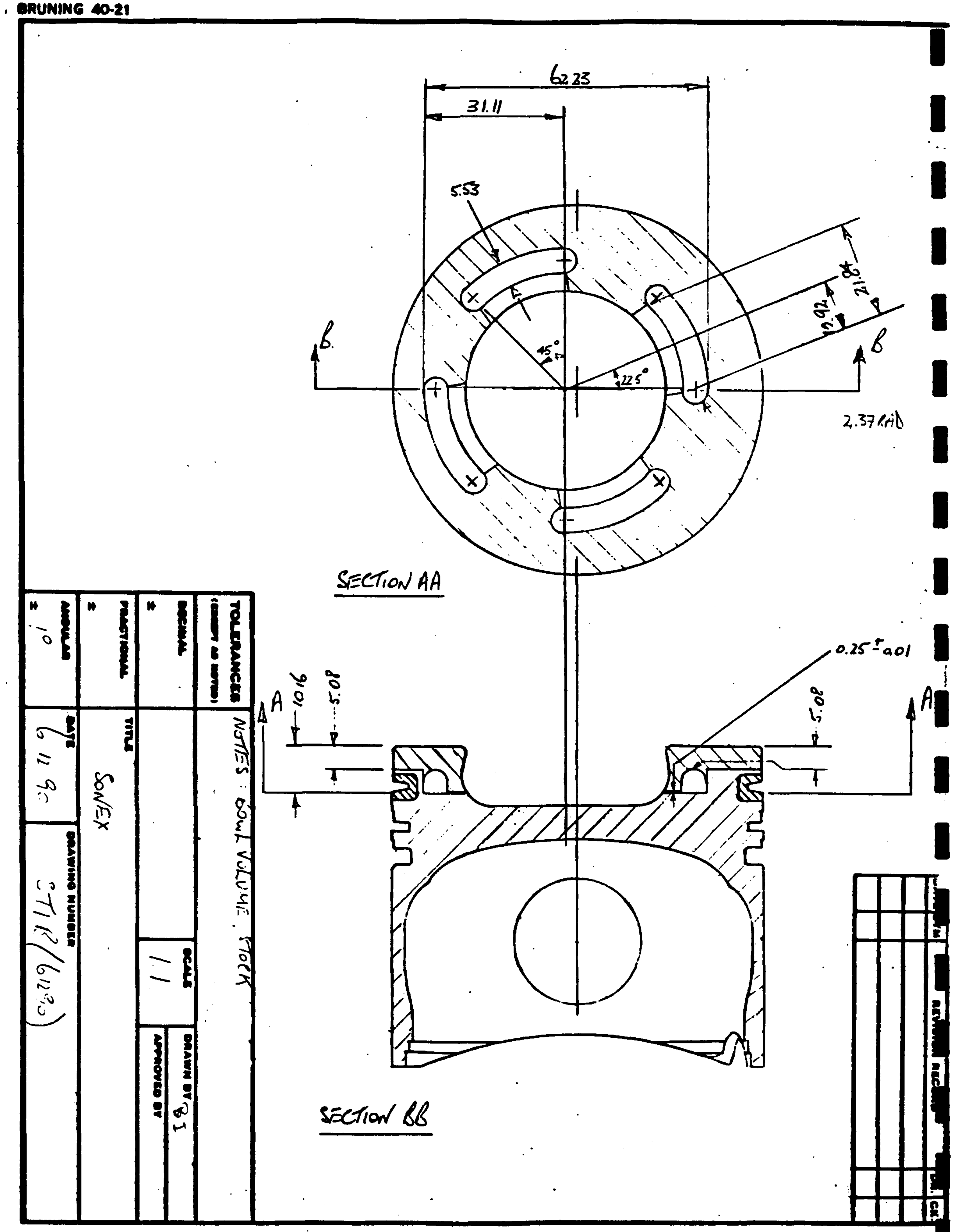

BRUNING 40-21
62.23
31.11
5.53
45°
22.5°
10.92
21.84
B
B
2.37 RAD
SECTION AA
0.25 ± 0.01
A
A
10.16
5.08
5.08
SECTION BB
TOLERANCES (EXCEPT AS NOTED)
DECIMAL ±
FRACTIONAL ±
ANGULAR ± 1°
NOTES: BOWL VOLUME, STOCK
TITLE SONEX
DATE 6 11 90
DRAWING NUMBER STIK/6120 (6120)
SCALE 1/1
DRAWN BY BI
APPROVED BY
REVISION RECORD
ITEM
DR.
CK.

Figure 9

11.1.2 Piston Rings

In order to prevent lube-oil dilution a special Sonex design top compression ring will be required. The remaining two rings, the second compression ring and the oil ring, will be stock. The special ring design was developed earlier.

11.1.3 Carburetor Fuel Jets

When changing from the design fuel (gasoline) to the required fuel (kerosene), a change in carburetor fuel jets, air jets and perc tube is required in order to operate at proper stoichiometry and to properly vaporize the fuel. This can be accomplished using conventional technology and, in most cases, off-the-shelf hardware. A brief test series will be required to optimize the carburetor for kerosene fuel operations.

11.2 Option A (Starting Fluid)

The only non-basic engine requirement for Option A operations is a starting fluid canister bracket and associated connections. It is envisioned that a canister containing a starting fluid can be stocked in the U.S. Army supply system as an expendable item much the same way as a spark plug might be stocked. As such, the canister would be fitted into a bracket support and connected to a tube, routing the fluid directly to the intake manifold of the engine.

11.3 Option B (Fluid Vaporizer)

The battery powered fuel vaporizer is used to vaporize a small portion of the kerosene fuel for easy starting. Once the engine is operating, the vaporizer system is turned off. The major system components are:

- o Vaporizer block
- o Glow plug assembly
- o Battery and control

11.3.1 Vaporizer Block

Figure 10 is a drawing of the vaporizer block used for the Grumman TMAP project. Its function is to provide for fuel metering and to house the glow plug assembly. It is located between the carburetor and intake manifold of the engine. A vaporizer block similar to the one shown is proposed for the Briggs & Stratton Option B modification.

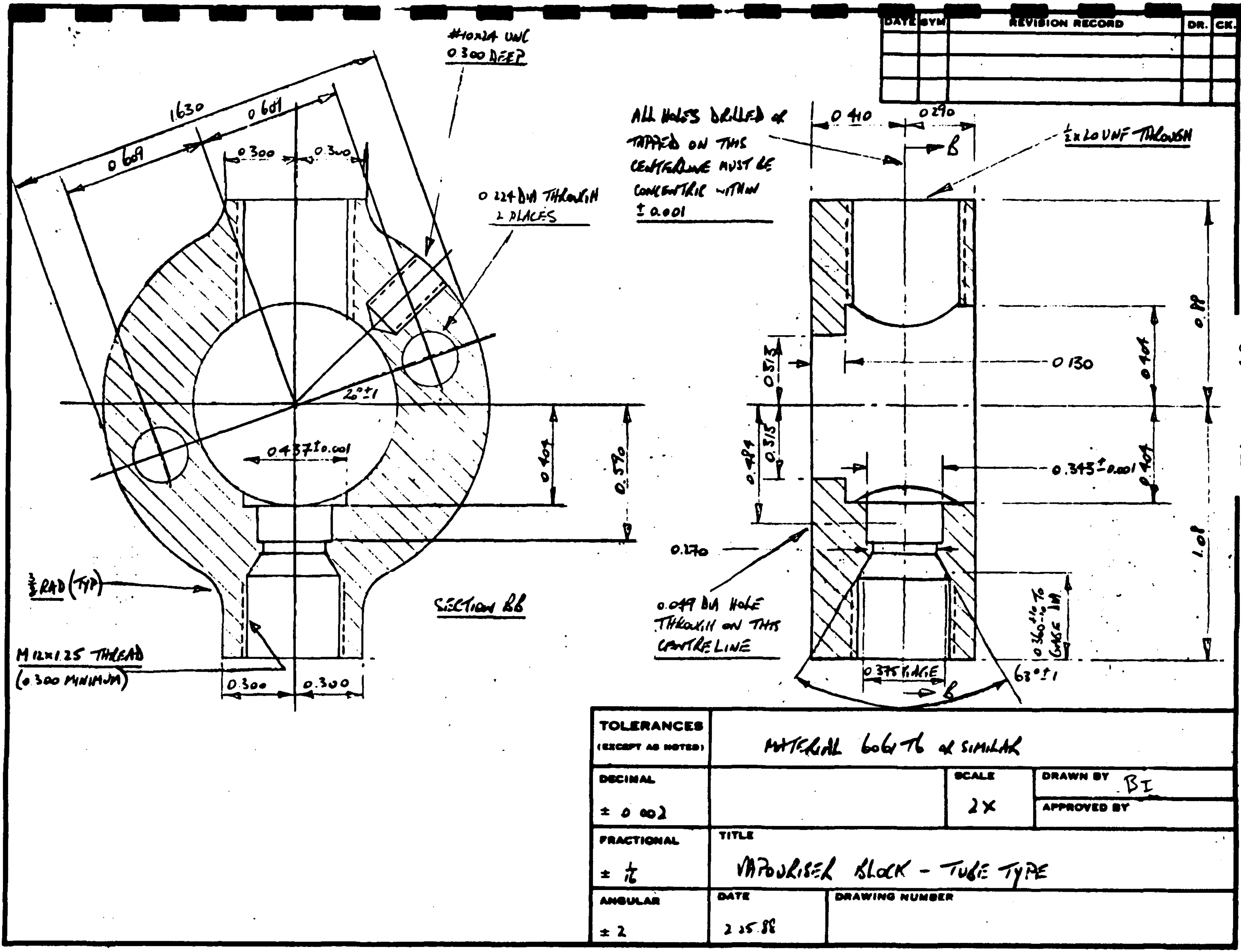

BRUNING 40-21
#10x24 UNC
0.300 DEEP
1.630
0.601
0.609
0.300
0.300
0.224 DIA THROUGH
2 PLACES
20°±1
0.437±0.001
0.404
0.590
3/8 RAD (TYP)
SECTION BB
M12x1.25 THREAD
(0.300 MINIMUM)
0.300
0.300
ALL HOLES DRILLED or TAPPED ON THIS CENTRELINE MUST BE CONCENTRIC WITHIN ± 0.001
0.410
0.290
B
1/2x20 UNF THROUGH
0.88
0.404
0.130
0.513
0.315
0.484
0.345±0.001
0.404
1.08
0.270
0.049 DIA HOLE THROUGH ON THIS CENTRELINE
0.360 +.010 -.0 TO GAGE DIA
0.375 GAGE
B
63°±1
DATE
SYM
REVISION RECORD
DR.
CK.
TOLERANCES
(EXCEPT AS NOTED)
MATERIAL 6061-T6 or SIMILAR
DECIMAL
± 0.002
SCALE
2X
DRAWN BY
BI
APPROVED BY
FRACTIONAL
± 1/16
TITLE
VAPOURISER BLOCK - TUBE TYPE
ANGULAR
± 2
DATE
2.25.88
DRAWING NUMBER

Figure 10

11.3.2 Glow Plug Assembly

The fuel vaporizer glow plug (Figure 11) is an off-the-shelf component requiring 12 VDC power to operate. Its function is to heat a small amount of kerosene fuel to its vaporization temperature thereby producing a fuel/air vapor ready for ignition. The glow plug assembly is a relatively long life component that fits into the base of the vaporizer block.

11.3.3 Battery and Control

A small 12 VDC rechargeable battery is required to power the glow plug assembly. It is controlled by a simple on/off switch. All battery and control components are off-the-shelf hardware.

11.4 Option C (Direct Injection)

Option C is the most expensive of the three options; however, its cold starting capability and excellent performance have been demonstrated in the Navy Firepump program. The components of this system are:

- o Fuel injection pump and injectors
- o Hot spark system

11.4.1 Fuel Injection Pump

If Option C is selected, a development program will be required to take an off-the-shelf direct injection system and convert it to the specifications of this engine. Several companies were found to sell fuel injection pumps, injectors and lines within the size and capacity constraints required. The Yanmar and Lister systems were the best candidates to supply components for this system.

11.4.2 Hot Spark System

A high intensity spark is required to ignite the partially vaporized fuel delivered by the Direct Injection System. For the past five years Sonex has been working closely with Nelson Specialties, Inc. of Woodbridge, Virginia, on specialty ignition components for various engine projects. Both Sonex and Nelson Specialties believe that the required Hot Spark System can be assembled from mostly off-the-shelf components with minimal additional expense.

T	W	E	H	A	B	I	J	V	P	Z	U	F/	L	G
														✓

DO NOT SCALE DRAWING

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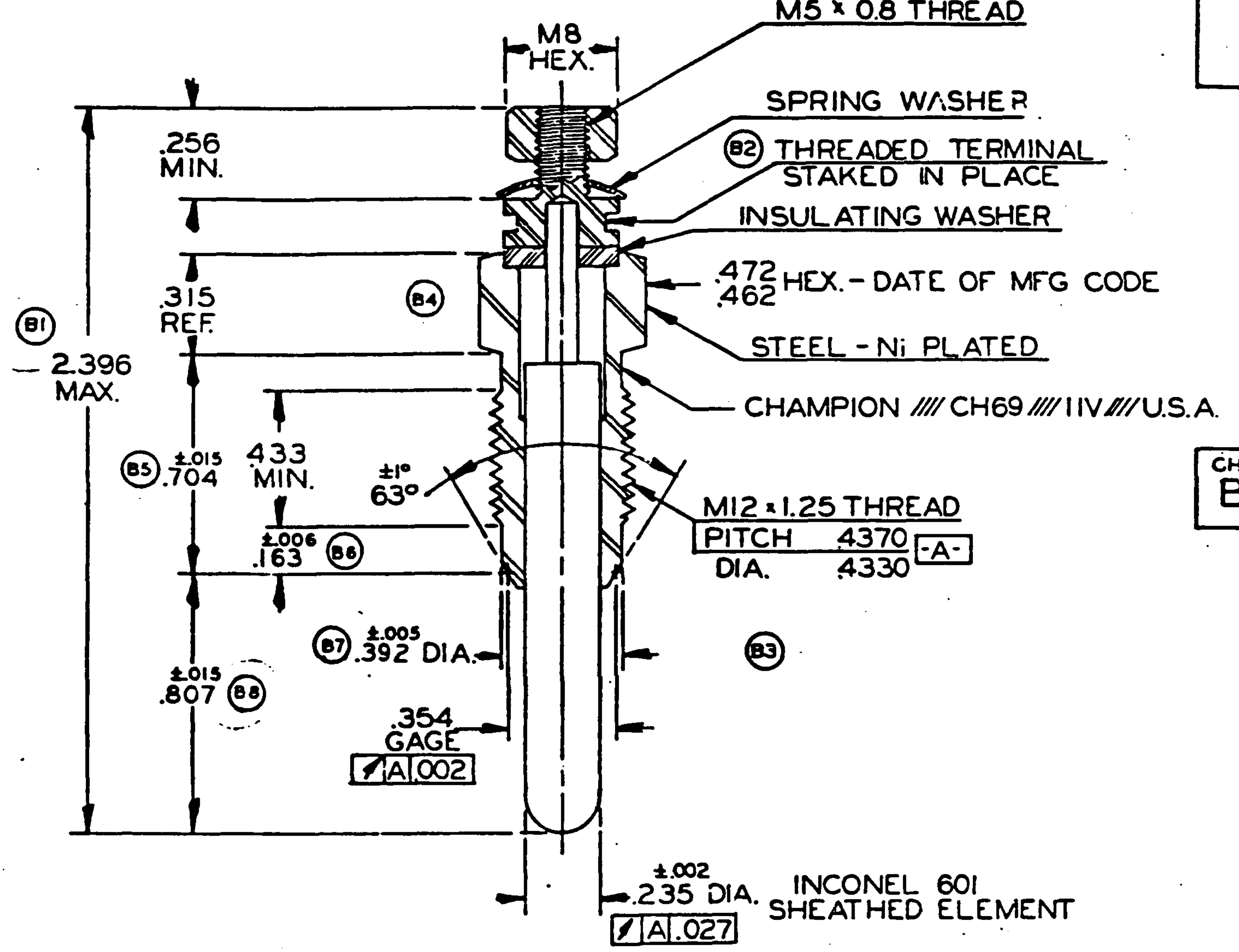
CHG. B



LET	REVISIONS	DATE	BY
B8	.822 .792	2-20-84	DLB
	.719 .689 B6 .169 .157 B7 .398 .390		
B4	INTERNAL CONFIG. REV.		
B3	BRAZE REM.	2-7-84	GK
B1	2.318 B2 TERM. REV.		

DRAWN	CHECKED	SCALE	DATE
GWK		2/1	5-12-82

CHAMPION SPARK PLUG COMPANY
TOLEDO, OHIO

NAME
GLOW PLUG
ASSEMBLY

MAT'L

TYPE NO.
CH69
(0030233)

3-30-84

Figure 11

12. Development Work Required

Three areas requiring further development are identified in the body of the report. They are listed here in their recommended order of importance.

12.1 Alternative Starting System (Identified in Section 10.4)

This system, if developed, will give the most return for the dollar. If this technology were available, it would eliminate the need for presenting Options A, B & C since unaided engine starting could easily be accomplished. The uniqueness of this technology places it in the high risk development category.

12.2 Hot Spark System (Identified in Section 11.4.2)

This system would be beneficial for any of the Options selected and would even increase the performance of an engine using the starting system identified in Section 12.1 above. It is, however, considered a requirement for the Option C conversion. This technology was proven on the Navy Firepump program and should be somewhat transferrable to this program. The Hot Spark System is considered a low risk development program.

12.3 Direct Fuel Injection System (Identified in Section 11.4.1)

This is the most costly of the three development programs and is only used for Option C. The development required for this program is low risk in that it requires identification and integration of existing hardware.

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CHEMICAL ACOUSTIC CHARGE CONDITIONING
FOR LOW EMISSION I.C. ENGINES

A.A. Pouring, D. Eng.
President and CEO
Sonex Research, Inc.
Annapolis, Maryland, USA

Oral presentation at: 1991 SAE Future Transportation Technology Conference, 6 August 1991 Portland, Oregon

Also: Vol I, First International Conference on Combustion Technologies for a Clean Environment, 3-6 September 1991, Vilamoura (Algarve) Portugal

CHEMICAL ACOUSTIC CHARGE CONDITIONING
FOR LOW EMISSION IC ENGINES

A.A.Pouring, President and CEO,
Sonex Research Inc.
Annapolis, Maryland, USA

ABSTRACT

The potential influence and limitations of classical fluid mechanics enhancement of combustion is reviewed briefly and compared with experimentally observed improvements in combustion efficiency produced by both acoustic and chemical (active radical) charge conditioning. Several designs which accomplish this charge conditioning are described and sample experimental results for unassisted CI of methanol fuel, CI-DI diesel fuel and SI gasoline fuel are given. The resulting benefits of low levels of undesirable emissions are given as well as evidence of a new generic engine design variable for in-cylinder control of ignition and combustion: chemical-acoustic charge conditioning.

KEY WORDS

Engines, Radical enhancement, Combustion, Emissions, Acoustic.

INTRODUCTION

Combustion in internal combustion (IC) engines can never be complete; at best, maximum combustion efficiency of 96.9% can be achieved Gerrish and Voss (1937), but, according to Table 1, only at an air fuel ratio (AFR) of 20:1 (lambda= 1.4). The favorable effect of operating at this AFR on emissions is clearly seen in Figure 1, Baumeister (1979); CO, HC emissions are at their lowest levels as well as brake specific fuel consumption (BSFC).

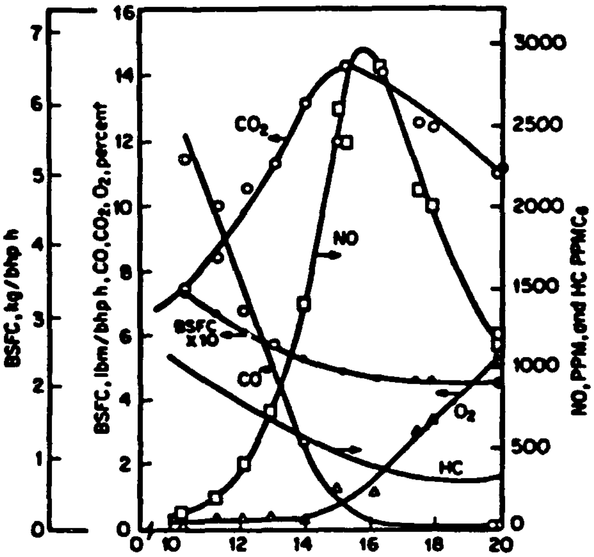

FIG. 1. Gasoline engine exhaust emissions and specific fuel consumption vs. air-fuel ratio.

Today's automotive gasoline fueled vehicles are calibrated to operate in the vicinity of an AFR = 14.7, or lambda = 1, to utilize with best efficiency the 3-way catalyst systems. Combustion efficiency, however, drops to near 92.5%. Fuel cost to the driver is roughly 10% higher than that possible at a lambda = 1.4, but the 3-way catalytic converter does bring the emissions into compliance with the ever tightening government regulations.

It is the objective of this paper to introduce the capability of Chemical Acoustic Combustion (CAC) to improve in-cylinder ignition and combustion reactions in IC engines (and therefore improve combustion efficiency) with benefits to emissions and fuel consumption.

Chemical Acoustic Combustion has been well documented for many years in combustion literature with an excellent review given by Oran and Gardner (1985). It is only in recent years that it has been introduced to IC engines by Pouring, et. al. (1986, 1988, 1990).

It will be demonstrated here that CAC in IC engines can easily do many things that conventional means cannot achieve at all or only with great mechanical difficulty. For example, CAC allows misfire-free *compression ignition* (CI) operation of direct-injection (DI) methanol at a compression ratio of 17:1 with no in-cylinder glow plug, spark plug or chemical ignition improvers. Conventional DI operation on methanol requires a compression ratio of 26:1 to achieve the same result, Hardenberg (1987).

LIMITATIONS OF CLASSICAL METHODS OF INCREASING COMBUSTION EFFICIENCY

According to Table I, combustion efficiency (CE, defined as the ratio of the energy liberated to that which could be liberated under ideal conditions) reaches a maximum at an AFR of 20:1 or a lambda = 1.4. Various in-cylinder techniques of fluid mechanics allow leaning out (lambda > 1) of a mixture through better mixing of air and fuel, but it is a combination of many engine variables that must be optimized for the engine to perform adequately at leaner mixtures.

In automotive applications, the question of emissions control for engine calibration above lambda = 1 is also a serious question, but at least one manufacturer has addressed this issue in a production vehicle: Toyota (Carina).

There are many reviews in the literature on the influence of fluid mechanics enhancement of the combustion zone for lean burn in SI engines. For example, Fansler and French (1987) treat the effects of swirl, squish and turbulence. Ford-Dunn, et.al. (1989) add the effect of tumble.

These four fluid mechanical effects are defined here as "classical methods".

<u>Squish</u>: The generation of in-cylinder, generally radial turbulence due to piston crown - cylinder head interaction near top dead center (TDC).

What effect does squish have on combustion?

- o Better mixing of air and fuel and the radial motion causes distortion of the flame front to accelerate burning.
- o But, the squish zone also hides a portion of the fuel-air charge, delaying combustion.
- o Combustion chambers with squish bands allow compact designs with low end gas temperatures (this helps avoid engine knock and detonation).

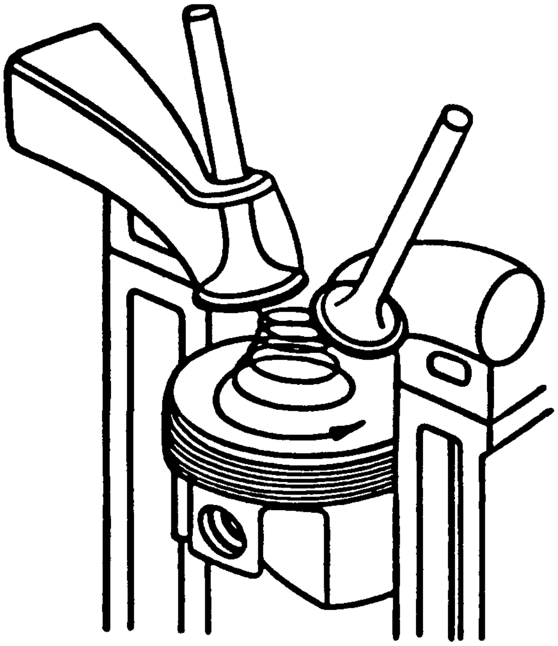

FIG. 2. In-cylinder air motion - swirl.

Air/Fuel	Percent by volume						H_2O/CO_2	H_2O/Fuel	Combustion eff., percent
	CO_2	O_2	CO	H_2	N_2	H_2O			
11	8.76	0.15	9.14	4.66	77.08	13.78	1.57	0.972	66.7
12	10.18	0.44	6.65	3.39	79.13	13.93	1.37	1.043	73.8
13	11.60	0.59	4.31	2.20	81.09	14.16	1.22	1.122	81.5
14	13.02	0.63	2.09	1.07	82.99	14.46	1.11	1.205	89.6
15	13.23	1.35	0.99	0.50	83.72	14.09	1.06	1.247	93.8
16	12.62	2.49	0.68	0.35	83.65	13.30	1.05	1.256	94.8
17	12.00	3.55	0.48	0.25	83.51	12.54	1.05	1.261	95.5
18	11.45	4.49	0.30	0.16	83.39	11.88	1.04	1.267	96.2
19	10.90	5.36	0.20	0.10	83.23	11.25	1.03	1.269	96.5
20	10.40	6.15	0.11	0.06	83.07	10.68	1.03	1.272	96.9
21	9.92	6.86	0.08	0.04	82.90	10.16	1.03	1.271	96.9
22	9.44	7.55	0.06	0.03	82.71	9.65	1.02	1.268	96.8
23	9.00	8.18	0.05	0.03	82.53	9.19	1.02	1.266	96.7
24	8.60	8.74	0.06	0.03	82.37	8.78	1.02	1.264	96.6

TABLE I. Variation of exhaust-gas constituents and combustion efficiency with air-fuel ratio.

- Squish is now out of favor with auto manufacturers due to unburned mixture and higher unburned hydrocarbons.

__Swirl__: Generated by a "snailshell" (or corkscrew) intake passage creating fluid motion parallel to cylinder walls during cylinder filling. A good example of such an inlet is taken from Ford-Dunn, et. al. (1989), in Figure 2.

What effect does swirl have on combustion?

- Swirl activates in-cylinder air motion which persists during compression. It increases local turbulence in the spark plug electrodes and allows ignition of leaner fuel-air charges. Swirl is particularly effective with SI stratified charges and is used extensively in modern diesels.

__Tumble__: Generated by skewing the flow in a near vertical intake port to favor one side of the intake valve, imparting a vertical roll or tumble. The outflow of a rotary valve also imparts tumble. Again, Ford-Dunn, et. al. (1989) give an excellent example, Figure 3.

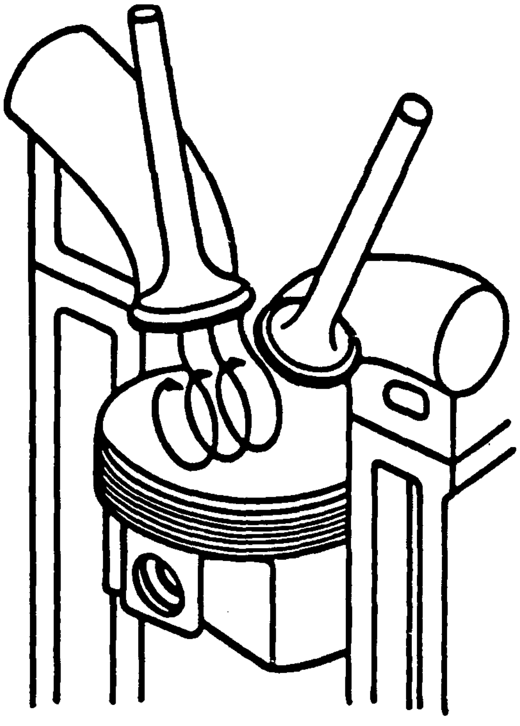

FIG. 3. In-cylinder air motion - tumble.

What effect does tumble have on combustion?

- The tumble effect is related to swirl in increasing turbulence and velocity at the spark plug electrodes allowing ignition of a leaner mixture.

- It should be noted that both tumble and swirl reduce the volumetric efficiency of normally aspirated engines at high output. Full power is therefore lower.

Conclusions with regard to classical fluid mechanics

- The benefits obtainable from air motion - swirl - tumble - turbulence are limited. Typical results are given by Ford-Dunn, et. al. (1989) in Figure 4, where the region influenced by swirl - tumble is shaded.

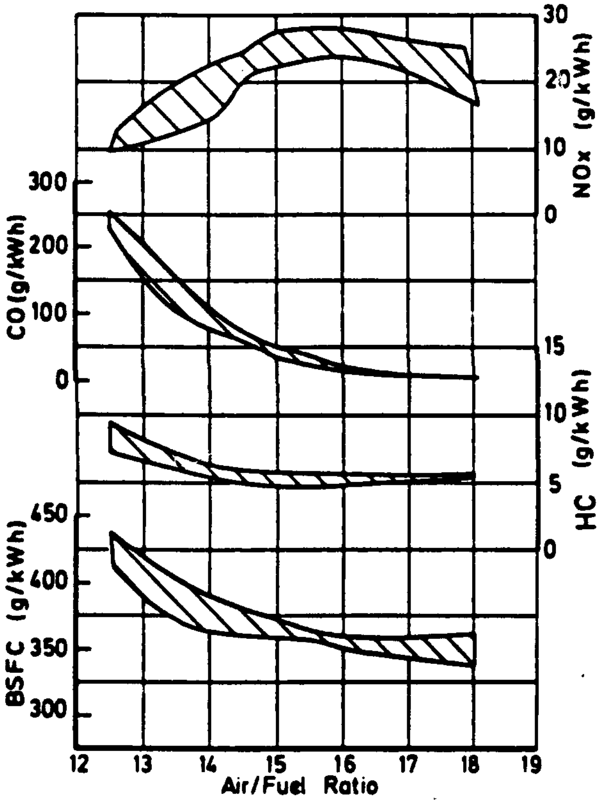

FIG. 4. Effects of swirl and tumble on exhaust emissions and specific fuel consumption at part-load; 3600 RPM, 3.5 bar BMEP.

- The maximum air-fuel ratio attained before the variation in IMEP (Indicated Mean Effective Pressure) exceeds 5% (generally accepted limit) is 18:1. The authors point out that this combustion improved by either swirl or tumble is "ignition limited" since the minimum in BSFC is not achieved before the IMEP variation exceeds 5%. This implies that additional ignition energy would be required to reach air-fuel ratios higher than 18:1.

To cite two other "classical methods of augmenting swirl to enable lean burn; the compression ratio can be increased, Quissch, et. al. (1988) or the fuel air charge can be stratified (Fansler and French, 1987). Development continues in both of these area to achieve stable combustion at high air-fuel ratios and hence high combustion efficiency.

For a lean burn to be useful in SI automotive applications, Vaughen and Hammerle (1987) point out that air-fuel ratios as lean as 22:1 are needed to control nitrogen oxide (NOx) emissions without the use of 3-way catalysts which are not effective at NOx control in lean burn exhaust. "Unfortunately, at 22:1 homogeneous charge combustion tends to misfire or burn very irregularly." Consequently, driveability is unacceptable.

The challenge to lean burn combustion and high combustion efficiency in IC engines is:

- How to lower the ignition energy required to maintain stable combustion.

IGNITION ENERGY

The challenge of lower ignition energy for leaner fuel-air mixtures has been met by the Sonex Combustion System (SCS). It was observed in early experiments by Allen, et. al. (1982) that certain piston designs in a CFR (Cooperative Fuel Research) engine were capable of not only creating sustained acoustic oscillations in the combustion chamber as in Figure 5, but also of changing the ignition characteristics of the mixture.

It was shown by Allen, et. al. (1982) that a transition can occur from spark-ignited combustion to "radical ignition" (RI) (with no spark) at relatively low compression ratios (order of 6:1) on gasoline, JP5, and diesel fuels when using a piston design similar to that in Figure 6.

RI is defined here as carburetted or non-carburetted, stratified charge, controlled auto-ignition at compression ratios less than those of classical compression ignition (CI).

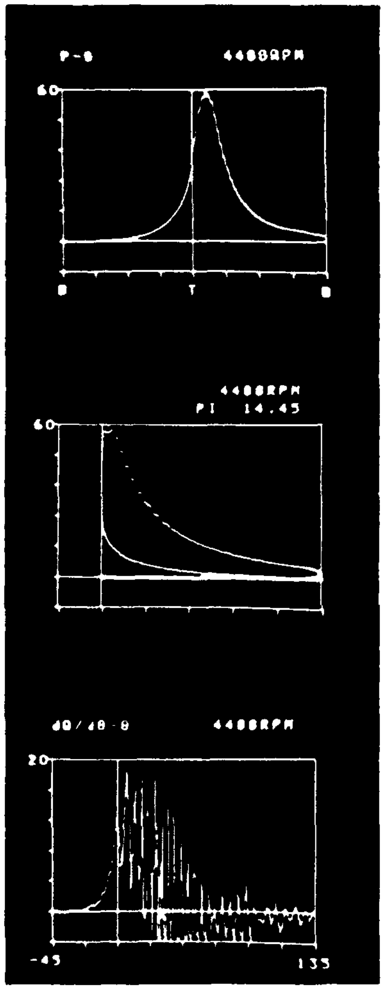

FIG. 5a. (Upper) SCS - Mode 1, pressure crank angle diagram.

5b. (Center) SCS - Mode 1, pressure displacement diagram.

5c. (Lower) SCS - Mode 1, rate of heat release diagram.

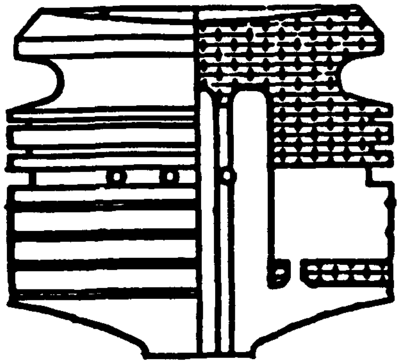

FIG. 6. SCS - Mode 1 piston design.

It was found in later experiments (unpublished) that the ignition energy required gradually approached zero, depending on the fuel used and air-fuel ratio at which RI occurred. With RI, zero ignition is required. RI occurs on leaning out the mixture from chemically correct or stoichiometric conditions, not by reducing the fueling by reducing fuel jet size or equivalent, but by providing additional secondary air in a controlled manner to the intake valve by a dual-plane intake manifold, Allen et. al. (1982). This lean-out procedure also creates an axially stratified charge (see later SI results).

Thus, by proper design, it is possible to take advantage of the <u>approach</u> to the operating condition of RI, with its decreasing ignition energy requirement, to operate ultra-lean-burn S.I. engines without actually getting to the RI condition.

RI has been observed experimentally for at least sixty years but the first documented experiments were published relatively recently, Onishi, et. al. (1979), Noguchi, et. al. (1979).

The work of the latter is particularly important because it identified the radical chemical species or intermediate reactive products leading to auto-ignition with gasoline fuels at low compression ratios (< 10:1). Combustion under these conditions is exceptionally stable with low emissions. The authors also showed that their results conformed with the Semenov Peninsula of Radical Initiated Reaction, Semenov (1958).

It will now be shown how the author and his colleagues have made use of these experimental observations to produce low-emission, lean-burn engine systems dependent on acoustic and/or chemical charge conditioning.

ACOUSTIC AND CHEMICAL INFLUENCES ON COMBUSTION

A series of piston designs has been patented by Pouring et. al. (1986, 1988, 1990) that allow control of ignition and combustion in IC engines by acoustic and/or chemical conditioning of the charge within the cylinder before, during and after the combustion event.

All SCS designs rely on a cavity of some kind in the combustion chamber; the cavity may be in the piston, in the cylinder head or exist temporarily between the piston and the cylinder head.

The three principal modes of inducing charge conditioning in IC engines by the piston designs shown in Figures 6, 7 and 8 are now reviewed briefly; for a full description see the patents referred to above.

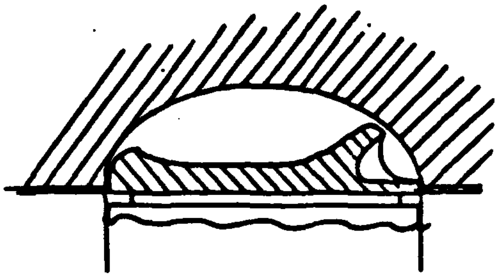

FIG. 7. SCS - Mode 2 piston design.

SCS Mode 1

Mode 1 relies on the priciple of acoustic resonance and the interaction induced in each of two chambers: the primary combustion chamber and the secondary resonance chamber generally located at the outer piston diameter. This approach allows a relatively simple mathematical description of the piston geometries following the Helmholtz resonator principle and mathematically ties the piston design process to control of engine knock. It also relates the chamber resonance to combustion chemistry allowing not only more complete combustion and lower emissions but also control of knock. An example of cylinder pressure behavior is given in Figure 5, together with the rate of heat release (ROHR) clearly showing the acoustic influence. More experimental results are given by Pouring et. al. (1986, 1987).

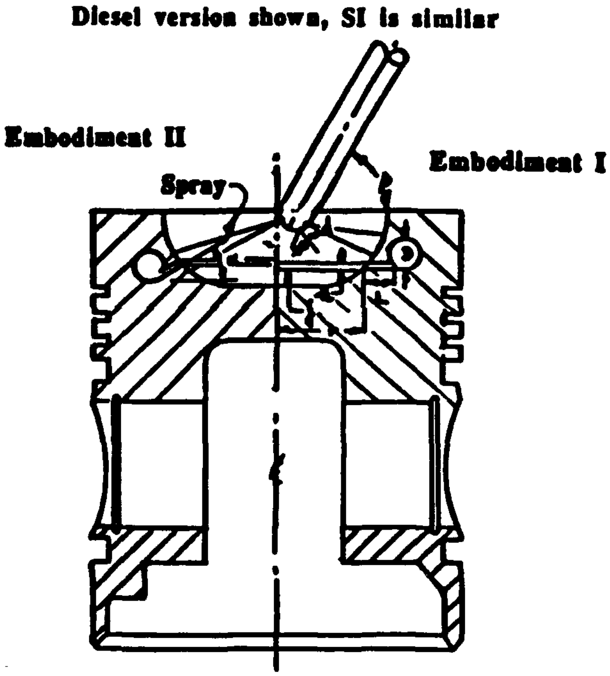

FIG. 8. SCS - Mode 3 piston design.

SCS Mode 2

The second approach to in-cylinder control of combustion relies on the interaction between the piston and cylinder head to create a temporary resonance chamber while the piston is near the TDC. Again, the Helmholtz resonator principle is followed allowing acoustic charge conditioning in high speed applications such as two-stroke engines. Experimental results for such a two-stroke engine design are given by Pouring et. al. (1987).

SCS Mode 3

The first two SCS modes are reviewed here rather briefly as references are available to gain further insight into these modes. Since no experimental results have yet been published on Mode 3, several examples are given here to show the great potential of this mode to reduce emissions and foster ultra-lean burn combustion.

It was found experimentally that the auto-ignition ability of the Mode 1 designs, Figure 6, could be transferred to Mode 3 by relocating the secondary SCS chamber to the piston bowl area as shown in Figure 8 and highly damping the oscillator. By proper attention to the principles of physical chemistry the SCS chambers can be designed to act as chemical reaction chambers and provide chemically active radical species to the intake event by fumigation from the cavities. The Mode 3 cavity is designed primarily to produce active chemical species or radicals during one engine cycle and conserve these species until the intake stroke of the next engine cycle. Thus, the new charge is preconditioned to react rapidly when fuel is injected.

DI Methanol Fuel (M100)

Mode 3 designs can therefore be used in direct injection engines to ignite low cetane fuels such as methanol at normal diesel compression ratios; to reduce particulates, NOx and CO from diesel fuel and to acheive ultra-lean combustion with gasoline fuels.

The first example of Mode 3 experimental results is for direct injection of methanol (M100), at a compression ratio of 17:1. No ignition improver, no spark plug and no in-cylinder glow plug was required. Starting was via a standard diesel flame glow plug in the intake manifold. Misfire-free operation was achieved in the entire engine map with no measurable smoke produced and reduced NOx. Since this work was conducted as a feasibility study for a client, no further details can be released at this time.

An example of combustion analyzer results for methanol is given in Figure 9, showing smooth stable ignition and a rapid ROHR at part load.

DI Diesel Fuel

The second example of Mode 3 experimental results is for direct injection of diesel fuel in a single cylinder conversion of a Perkins 4.236 engine, 98 mm bore and 127 mm stroke with compression ratio at 16:1. The engine was supercharged with a roots blower, an intercooler was used and an exhaust back pressure regulator was added to simulate a turbo. Testing was conducted with Phillips 66 D2 reference fuel.

Comparing SCS with the production baseline, for equal nozzle size (standard), and equal load, averaged over the range of conditions given below, the overall SCS reduction in Bosch Smoke Units (spot test) and nitric oxide, per cubic mm injected is:

Condition	Average improvement of SCS BSU/mm over baseline	Average improvement of NO/mm over baseline
1000 RPM, 1500 RPM 2000 RPM, 2500 RPM (Full to 75% load)	33%	21%
Idle	60%	38%

The average behavior of smoke and NO with respect to injection timing for the conditions reported above is shown in Figure 10.

The trade-off curves, with full load and idle shown in Figure 11, for Bosch Smoke - Nitric Oxide show simultaneous reduction of both smoke and nitric oxide for nearly all test conditions. This is unique to SCS technology. Nitric Oxide is significantly lower for the SCS engines for practically all load, speed and timing conditions, including idle.

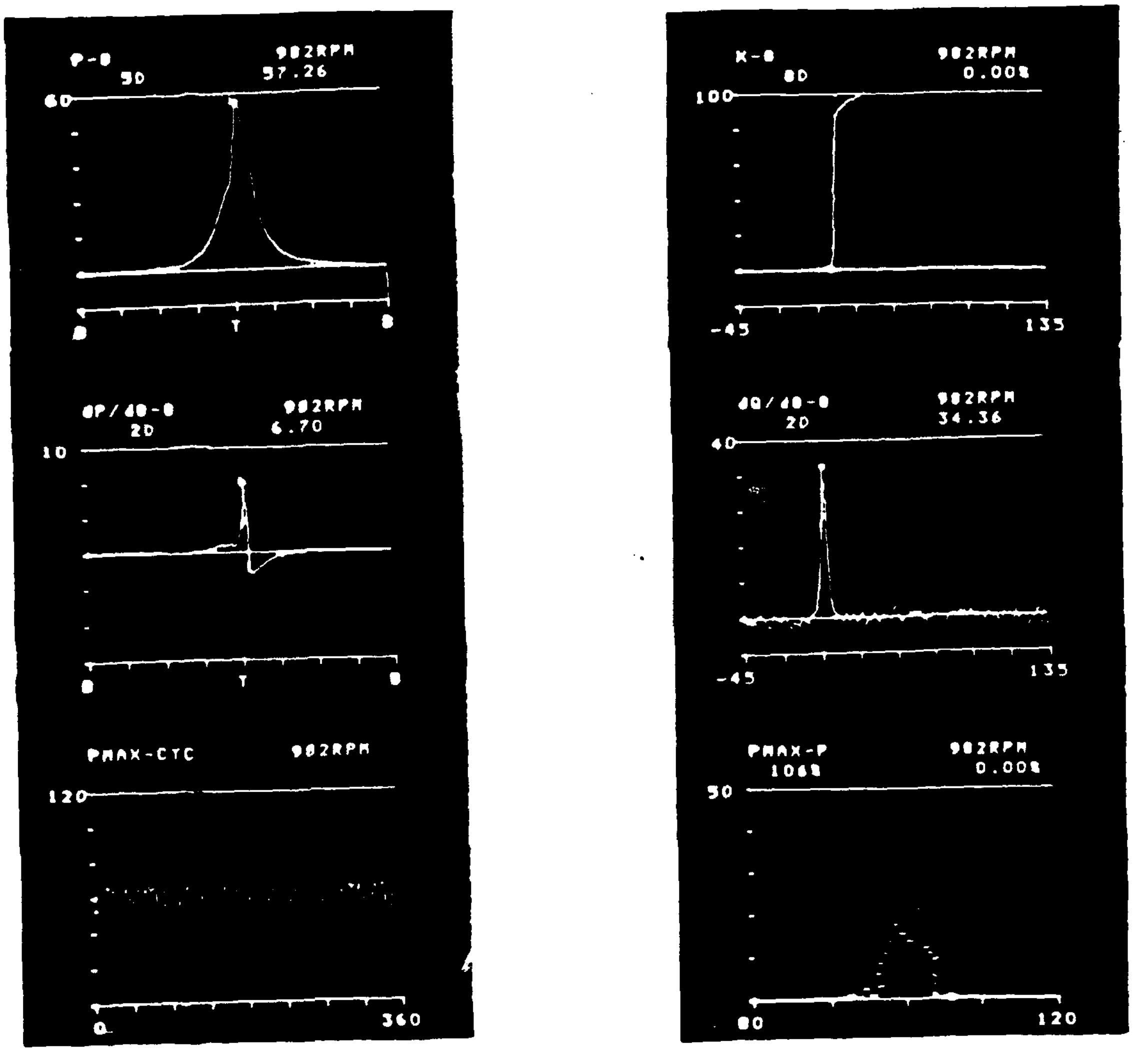

FIG. 9. DI Methanol 100 fuel,part load at 16 NM

a.(upper) Cylinder pressure

b.(middle) Rate of pressure rise

c.(lower) Variation of maximum cylinder pressure for 360 cycles

d.(upper) Heat release

e.(middle) Rate of heat release

f.(lower) Distribution of maximum cylinder pressure with respect to TDC

For comparable conditions, the specific fuel consumption is equal (within experimental error) at 1000 RPM, 1500 RPM, 2000 RPM and idle. At 2500 RPM (a very difficult test condition for this single cylinder engine) the SCS fuel consumption is approximately 4% higher. Carbon monoxide (on a per mm injected basis), when compared overall for all test conditions is reduced on the order of 30%. Unburned hydrocarbons were not recorded due to equipment failure, but based on the results from the same engine, normally aspirated, the boosted unburned hydrocarbons should be equivalent to the baseline.

SI Gasoline Fuel

The final example of Mode 3 experimental results is for ultra-lean combustion of spark-ignited carburetted gasoline fuel in a single cylinder engine. A single cylinder overhead valve engine was reconfigured so that a comparison could be made at nearly equal compression ratio

(8:1) with equal rod lengths, rod piston weights, etc. The SCS intake manifold was also modified so that normally aspirated secondary air could be admitted in a controlled manner. A spark-ignited piston design based on Mode 3, Figure 8, was used.

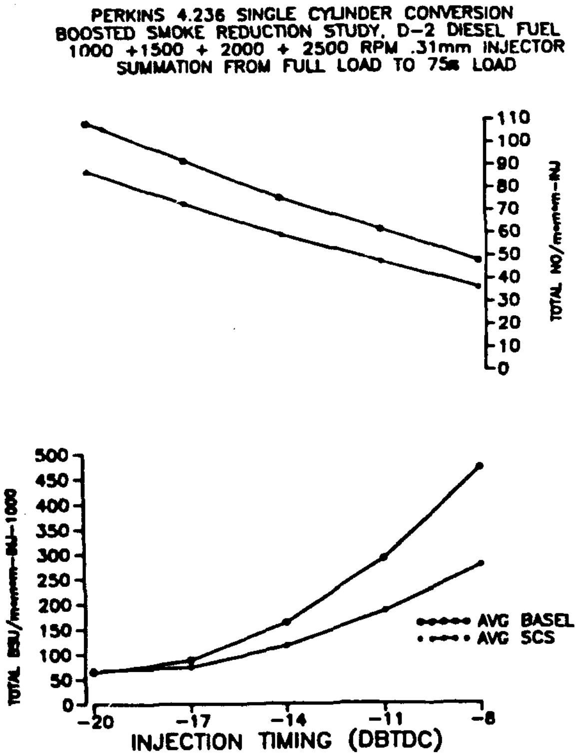

FIG. 10. DI diesel fuel, Bosch smoke-NO, injection timing.

Figure 12 shows typical performance of this engine design at part throttle, 1800 RPM and MBT spark.

First, with respect to torque, the baseline engine has the typical drop-off in torque as fuel flow is reduced through smaller jetting while the SCS leanout curve maintains torque at or slightly higher than at the start, then drops off after the minimum BSFC is reached at an air-fuel ratio of 22:1. The lean misfire limit (LML) is at 28:1.

This last point should be re-emphasised. There is a difference of 6 air-fuel ratios between the minimum in BSFC and LML. This factor alone would allow excellent driveability since engine calibration near the minimum in BSFC would not encounter misfire as is evident in the baseline engine where the minimum in BSFC is at an air-fuel ratio of 16:1 and the LML is at 16.5:1, the last point plotted.

It is seen that SCS CO and NO, the two parameters most indicative of a change in the character of combustion, are both displaced to higher air-fuel ratios than the baseline. This is because the SCS secondary air technique allows stratification of the charge in the cylinder with a richer charge at the spark plug, leaner at the piston face. The different behavior of the emissions between the SCS stratified charge and the homogeneous charge baseline is clearly seen.

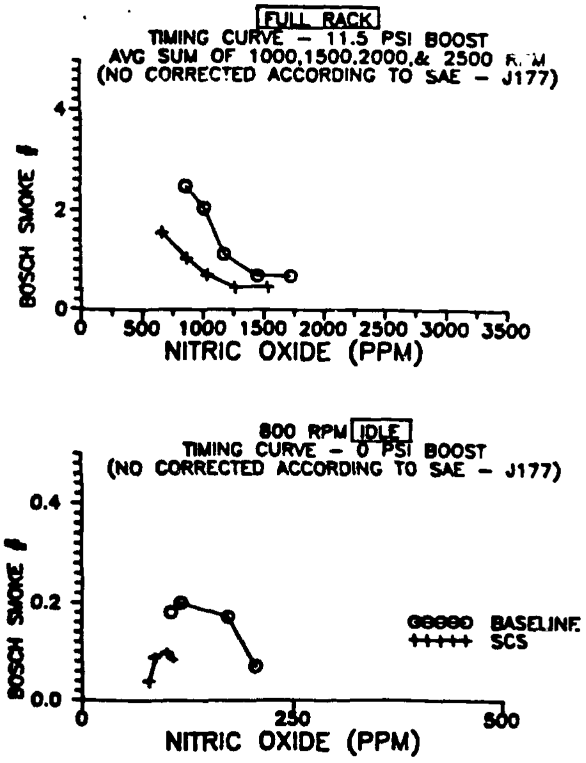

FIG. 11. DI diesel fuel, Bosch smoke-NO trade off curves.

The rise in unburned hydrocarbons beyond an air-fuel ratio of 18:1 may or may not be associated with the combustion process. Due to the fabrication technique of using a stock piston skirt and ring pack, the piston compression height had an unusually long crevice volume. It is expected that improved piston design in the future will correct this feature.

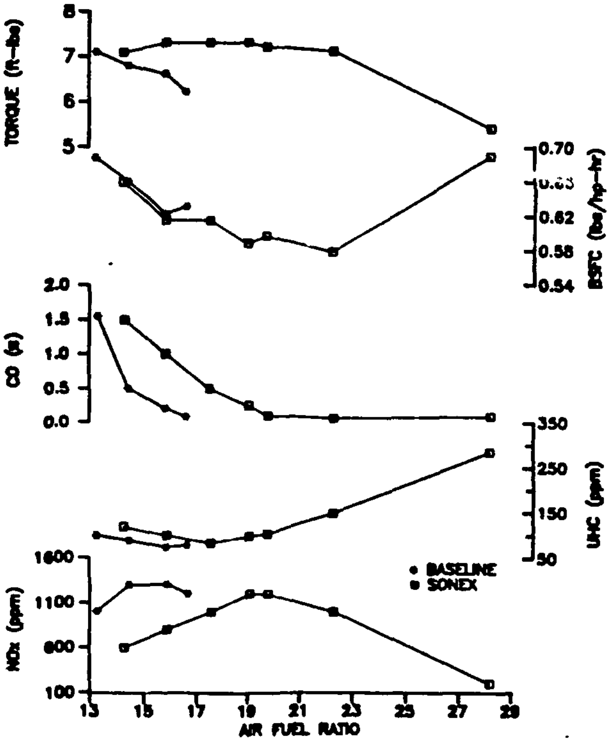

FIG. 12. SI gasoline fuel, part load lean-out curves.

Since the experimental results for SI combustion indicate the SCS process is not ignition limited, it appears that the ignition energy is lowered as postulated earlier. The wide margin between the minimum in BSFC and LML was seen throughout the engine map with this design.

It can be concluded that with the Mode 3 SCS, a practical lean burn system capable of running at the maximum theoretical combustion efficiency (air-fuel ratio = 20:1) has been achieved and should be transferred to automotive applications.

CONCLUSIONS

The experimental evidence for the latest SCS Mode 3 design for:

- SI gasoline engines indicates that lean burn at maximum combustion efficiency is possible, without encountering combustion instability.
- DI methanol engines indicates that CI is possible for even the lowest cetane, hard to ignite fuels, allowing the efficiency increase inherent with DI compression ratios.
- DI diesel engines, with simultaneous reduction of smoke (particulates) and NO, counters the classical trade-off of "lower smoke gives higher NO".

These results demonstrate that a new generic engine design variable (in addition to injection timing, compression ratio, swirl, etc.) is available for in-cylinder control of ignition and combustion in IC engines -- namely -- chemical-acoustic charge conditioning.

ACKNOWLEDGEMENT

The author thanks the entire Sonex staff for all the work which made this publication possible.

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Appendix B

Evaluation Matrix Data Sheets

```
                 EVALUATION MATRIX DATA SHEET

                 ENGINE DESCRIPTION
                 ------------------

 ENGINE MANUFACTURER:        HONDA
 ENGINE DESIGNATION:         G100 K1
 RATED POWER @ RPM:          1.6 @ 3600
 MAXIMUM POWER @ RPM:        2.2 @ 4200
 STROKES PER CYCLE:          FOUR (4)
 VALVE TRAIN:                SIDE VALVE
 PISTON DESIGN:              FLAT TOP
 DISPLACEMENT (CU IN):           4.63
 BORE (IN):                      1.81
 STROKE (IN):                    1.81
 COMPRESSION RATIO:            6.5:1
 DRY WEIGHT (LB):                  19



 OPTION:  A.   STARTING FLUID                      <<<
          B.   FUEL VAPORIZER AND BATTERY
          C.   DIRECT INJECTION

 A. INITIAL COST ($/KW)
          1. PROCUREMENT COST
            A. LIST PRICE:                   $  270.00
            B. HP @ 3600 RPM:                      1.6 HP
            C. HP USING KEROSENE:                 1.20 HP
            D. GENERATING CAPACITY:               0.60 KW
            E. PROCUREMENT COST ($/KW):      $  450.00 PER KW        $   450.00 PER KW
                                                                     -----------------
          2.  MODIFICATION COST ($/KW)
            A. COMBUSTION CHAMBER GEOMETRY
               HEAD GASKET  10%      <<<
               HEAD MODIFICATIONS  20%
               PISTON MODIFICATIONS  25%
                 PERCENTAGE:       10   COST: $   27.00

            B. PISTON RING MODIFICATION
               2 STROKE/CYCLE  0%
               4 STROKE/CYCLE  25%   <<<
               ROTARY  0%
                 PERCENTAGE:       25   COST: $   67.50

            C. IGNITION SYSTEM
               TIMING RETARD  10%    <<<
               HOT SPARK & PLUG  25%
                 PERCENTAGE:       10   COST: $   27.00

            D. FUEL DELIVERY SYSTEM
               CARBURETOR JETS  5%   <<<
               FUEL VAPORIZER  25%
               DIRECT INJECTION  200%
                 PERCENTAGE:        5   COST: $   13.50

          3.  GENERATOR COST                 $  270.00

              TOTAL MOD. COST:               $  405.00
              TOTAL MOD. COST PER KW:        $  675.00 PER KW        $   675.00 PER KW
```

Figure B-1

```
B.  ENGINE LIFE COST ($/KW)

         1.  PROCUREMENT COST ($/KW)        $  450.00 PER KW
         2.  MOD COST LESS GEN COST         $  225.00 PER KW
         3.  SPARE COST
              FOUR STROKE/CYCLE (100%)       <<<
              TWO STROKE/CYCLE & ROTARY (66.7%)
                PERCENTAGE:     100   COST: $  675.00 PER KW          $   675.00 PER KW
                                                                      -----------------

C.  TOTAL ENGINE PROCUREMENT.MODIFICATION. AND LIFE CYCLE COST:       $ 1.800.00 PER KW
                                                                      -----------------
D.  OPERATING COST  ($/KW-HR)

         1.  MAINTENANCE EXPENSE            $    1.13 PER KW-HR
         2.  FUEL EXPENSE
              4-STROKE @ $.22/KW-HR <<<
              ROTARY @ $.26/KW-HR
              2-STROKE @ $.29/KW-HR
                                            $    0.22 PER KW-HR
         3.  SPECIAL FLUIDS EXPENSE
              LOW ASH OIL-2 STROKE & ROTARY $    0.00 PER KW-HR
              STARTING FLUID                $    0.05 PER KW-HR
         4.  SPECIAL EQUIPMENT
              STARTING BATTERY OPTION ONLY
               4- STROKE (5%)
               2 STROKE & ROTARY (8.33%)
                PERCENTAGE:       0   COST: $    0.00 PER KW-HR

         5.  TOTAL OPERATING COST           $    1.40 PER KW-HR        $     1.40 PER KW-HR
                                                                      --------------------


E.  TOTAL PROCUREMENT AND OPERATING COST (ASSUMES 1000 HRS OPERATION) $ 3.199.50 PER KW
                                                                      =================
```

```
F.  ENGINE PERFORMANCE

        1.  WEIGHTS
             A. ENGINE                                19.0 LB
             B. GENERATOR                             19.0 LB
             C. FUEL VAPORIZER & BATTERY               0.0 LB
             D. FUEL INJECTION SYSTEM                  0.0 LB
             E. FUEL (4-HR MISSION)                    2.4 LB
             F. CRANKCASE OIL                          2.5 LB
             G. TOTAL WEIGHT                          42.9 LB
             H. POWER OUTPUT                           0.6 KW
             I. POWER DENSITY                        0.014 KW/LB
             J. WEIGHT PER UNIT POWER                 71.5 LB/KW
             K. VOLUME PER UNIT POWER                      CU FT/KW

        2.  STARTING RELIABILITY
             A. STARTING FLUID                         95% <<<
             B. BATTERY                                95%
             C. MANUAL                                 99%

        3.  COLD START LIMIT (ALL) . .                -20F

        4.  NOISE LEVEL
             A. ROTARY                                100%
             B. 4-STROKE                              110% <<<
             C. 2-STROKE                              120%

        5. IR SIGNATURE
             A. 4-STROKE                              100% <<<
             B. 2-STROKE                              130%
             C. ROTARY                                150%

        6.  EMI/RFI SIGNATURE
             A. STARTING FLUID                   NO CHANGE FROM GASOLINE
             B. FUEL VAPORIZER & BATTERY         NO CHANGE FROM GASOLINE
             C. DIRECT INJECTION                 SIGNIFICANT BUT UNSPECIFIED
                                                 INCREASE
```

```
                       EVALUATION MATRIX DATA SHEET

                       ENGINE DESCRIPTION
                       ------------------

ENGINE MANUFACTURER:       HONDA
ENGINE DESIGNATION:        G100 K1
RATED POWER @ RPM:         1.6 @ 3600
MAXIMUM POWER @ RPM:       2.2 @ 4200
STROKES PER CYCLE:         FOUR (4)
VALVE TRAIN:               SIDE VALVE
PISTON DESIGN:             FLAT TOP
DISPLACEMENT (CU IN):          4.63
BORE (IN):                     1.81
STROKE (IN):                   1.81
COMPRESSION RATIO:           6.5:1
DRY WEIGHT (LB):                 19



OPTION:  A.   STARTING FLUID
         B.   FUEL VAPORIZER AND BATTERY      <<<
         C.   DIRECT INJECTION

A. INITIAL COST ($/KW)
         1. PROCUREMENT COST
           A. LIST PRICE:                  $  270.00
           B. HP @ 3600 RPM:                     1.6 HP
           C. HP USING KEROSENE:                1.20 HP
           D. GENERATING CAPACITY:              0.60 KW
           E. PROCUREMENT COST ($/KW):     $  450.00 PER KW          $   450.00 PER KW
                                                                     -----------------
         2.  MODIFICATION COST ($/KW)
           A. COMBUSTION CHAMBER GEOMETRY
              HEAD GASKET  10%
              HEAD MODIFICATIONS  20%
              PISTON MODIFICATIONS  25%  <<<
                PERCENTAGE:      25   COST: $   67.50

           B. PISTON RING MODIFICATION
              2 STROKE/CYCLE  0%
              4 STROKE/CYCLE  25%   <<<
              ROTARY  0%
                PERCENTAGE:      25   COST: $   67.50

           C. IGNITION SYSTEM
              TIMING RETARD  10%    <<<
              HOT SPARK & PLUG  25%
                PERCENTAGE:      10   COST: $   27.00

           D. FUEL DELIVERY SYSTEM
              CARBURETOR JETS  5%   <<<
              FUEL VAPORIZER  25%   <<<
              DIRECT INJECTION  200%
                PERCENTAGE:      30   COST: $   81.00

         3.  GENERATOR COST                $  270.00

             TOTAL MOD. COST:              $  513.00
             TOTAL MOD. COST PER KW:       $  855.00 PER KW          $   855.00 PER KW
                                                                     -----------------
```

Figure B-2

```
B.  ENGINE LIFE COST ($/KW)

        1.  PROCUREMENT COST ($/KW)         $  450.00 PER KW
        2.  MOD COST LESS GEN COST          $  405.00 PER KW
        3.  SPARE COST
             FOUR STROKE/CYCLE (100%)          <<<
             TWO STROKE/CYCLE & ROTARY (66.7%)
               PERCENTAGE:     100   COST: $  855.00 PER KW          $   855.00 PER KW
                                                                     -----------------

C.  TOTAL ENGINE PROCUREMENT,MODIFICATION, AND LIFE CYCLE COST:      $ 2,160.00 PER KW
                                                                     -----------------
D.  OPERATING COST  ($/KW-HR)

        1.  MAINTENANCE EXPENSE             $    1.13 PER KW-HR
        2.  FUEL EXPENSE
             4-STROKE @ $.22/KW-HR <<<
             ROTARY @ $.26/KW-HR
             2-STROKE @ $.29/KW-HR
                                            $    0.22 PER KW-HR
        3.  SPECIAL FLUIDS EXPENSE
             LOW ASH OIL-2 STROKE & ROTARY  $    0.00 PER KW-HR
             STARTING FLUID                 $    0.00 PER KW-HR
        4.  SPECIAL EQUIPMENT
             STARTING BATTERY OPTION ONLY
              4- STROKE (5%)
              2 STROKE & ROTARY (8.33%)
               PERCENTAGE:       5   COST: $    0.08 PER KW-HR

        5.  TOTAL OPERATING COST            $    1.43 PER KW-HR          $     1.43 PER KW-HR
                                                                     --------------------

E.  TOTAL PROCUREMENT AND OPERATING COST (ASSUMES 1000 HRS OPERATION) $ 3,592.83 PER KW
                                                                     =================
```

F. ENGINE PERFORMANCE

1. WEIGHTS	
A. ENGINE	19.0 LB
B. GENERATOR	19.0 LB
C. FUEL VAPORIZER & BATTERY	6.0 LB
D. FUEL INJECTION SYSTEM	0.0 LB
E. FUEL (4-HR MISSION)	2.4 LB
F. CRANKCASE OIL	2.5 LB
G. TOTAL WEIGHT	48.9 LB
H. POWER OUTPUT	0.6 KW
I. POWER DENSITY	0.012 KW/LB
J. WEIGHT PER UNIT POWER	81.5 LB/KW
K. VOLUME PER UNIT POWER	CU FT/KW
2. STARTING RELIABILITY	
A. STARTING FLUID	95%
B. BATTERY	95% <<<
C. MANUAL	99%
3. COLD START LIMIT (ALL)	-20F
4. NOISE LEVEL	
A. ROTARY	100%
B. 4-STROKE	110% <<<
C. 2-STROKE	120%
5. IR SIGNATURE	
A. 4-STROKE	100% <<<
B. 2-STROKE	130%
C. ROTARY	150%
6. EMI/RFI SIGNATURE	
A. STARTING FLUID	NO CHANGE FROM GASOLINE
B. FUEL VAPORIZER & BATTERY	NO CHANGE FROM GASOLINE
C. DIRECT INJECTION	SIGNIFICANT BUT UNSPECIFIED INCREASE

```
                 EVALUATION MATRIX DATA SHEET

                 ENGINE DESCRIPTION
                 ------------------

ENGINE MANUFACTURER:          HONDA
ENGINE DESIGNATION:           G100 K1
RATED POWER @ RPM:            1.6 @ 3600
MAXIMUM POWER @ RPM:          2.2 @ 4200
STROKES PER CYCLE:            FOUR (4)
VALVE TRAIN:                  SIDE VALVE
PISTON DESIGN:                FLAT TOP
DISPLACEMENT (CU IN):            4.63
BORE (IN):                       1.81
STROKE (IN):                     1.81
COMPRESSION RATIO:              6.5:1
DRY WEIGHT (LB):                   19



OPTION:  A.  STARTING FLUID
         B.  FUEL VAPORIZER AND BATTERY
         C.  DIRECT INJECTION                   <<<

A. INITIAL COST ($/KW)
         1. PROCUREMENT COST
           A. LIST PRICE:                     $  270.00
           B. HP @ 3600 RPM:                        1.6 HP
           C. HP USING KEROSENE:                   1.20 HP
           D. GENERATING CAPACITY:                 0.60 KW
           E. PROCUREMENT COST ($/KW):        $  450.00 PER KW         $   450.00 PER KW
                                                                       -----------------
         2.  MODIFICATION COST ($/KW)
           A. COMBUSTION CHAMBER GEOMETRY
              HEAD GASKET  10%
              HEAD MODIFICATIONS  20%
              PISTON MODIFICATIONS  25%  <<<
                PERCENTAGE:       25    COST: $    67.50

           B. PISTON RING MODIFICATION
              2 STROKE/CYCLE  0%
              4 STROKE/CYCLE  25%   <<<
              ROTARY  0%
                PERCENTAGE:       25    COST: $    67.50

           C. IGNITION SYSTEM
              TIMING RETARD  10%    <<<
              HOT SPARK & PLUG  25% <<<
                PERCENTAGE:       35    COST: $    94.50

           D. FUEL DELIVERY SYSTEM
              CARBURETOR JETS  5%
              FUEL VAPORIZER  25%
              DIRECT INJECTION  200%<<<
                PERCENTAGE:      200    COST: $   540.00

        3.   GENERATOR COST                   $  270.00

             TOTAL MOD. COST:                 $1.039.50
             TOTAL MOD. COST PER KW:          $1.732.50 PER KW         $ 1.732.50 PER KW
                                                                       -----------------
```

Figure B-3

```
B.  ENGINE LIFE COST ($/KW)

         1.  PROCUREMENT COST ($/KW)        $  450.00 PER KW
         2.  MOD COST LESS GEN COST         $1.282.50 PER KW
         3.  SPARE COST
              FOUR STROKE/CYCLE (100%)       <<<
              TWO STROKE/CYCLE & ROTARY (66.7%)
                PERCENTAGE:     100   COST: $1.732.50 PER KW          $ 1.732.50 PER KW
                                                                      -----------------

C.  TOTAL ENGINE PROCUREMENT.MODIFICATION. AND LIFE CYCLE COST:       $ 3.915.00 PER KW
                                                                      -----------------
D.  OPERATING COST  ($/KW-HR)

         1.  MAINTENANCE EXPENSE            $     1.13 PER KW-HR
         2.  FUEL EXPENSE
              4-STROKE @ $.22/KW-HR <<<
              ROTARY @ $.26/KW-HR
              2-STROKE @ $.29/KW-HR
                                            $     0.22 PER KW-HR
         3.  SPECIAL FLUIDS EXPENSE
              LOW ASH OIL-2 STROKE & ROTARY $     0.00 PER KW-HR
              STARTING FLUID                $     0.00 PER KW-HR
         4.  SPECIAL EQUIPMENT
              STARTING BATTERY OPTION ONLY
               4- STROKE (5%)
               2 STROKE & ROTARY (8.33%)
                PERCENTAGE:       0   COST: $     0.00 PER KW-HR

         5.  TOTAL OPERATING COST           $     1.35 PER KW-HR          $      1.35 PER KW-HR
                                                                      --------------------

E.  TOTAL PROCUREMENT AND OPERATING COST (ASSUMES 1000 HRS OPERATION) $ 5.264.50 PER KW
                                                                      =================
```

F. ENGINE PERFORMANCE

1. WEIGHTS

A. ENGINE	19.0 LB
B. GENERATOR	19.0 LB
C. FUEL VAPORIZER & BATTERY	0.0 LB
D. FUEL INJECTION SYSTEM	5.0 LB
E. FUEL (4-HR MISSION)	2.4 LB
F. CRANKCASE OIL	2.5 LB
G. TOTAL WEIGHT	47.9 LB
H. POWER OUTPUT	0.6 KW
I. POWER DENSITY	0.013 KW/LB
J. WEIGHT PER UNIT POWER	79.8 LB/KW
K. VOLUME PER UNIT POWER	CU FT/KW

2. STARTING RELIABILITY

A. STARTING FLUID	95%
B. BATTERY	95%
C. MANUAL	99% <<<

3. COLD START LIMIT (ALL)	-20F

4. NOISE LEVEL

A. ROTARY	100%
B. 4-STROKE	110% <<<
C. 2-STROKE	120%

5. IR SIGNATURE

A. 4-STROKE	100% <<<
B. 2-STROKE	130%
C. ROTARY	150%

6. EMI/RFI SIGNATURE

A. STARTING FLUID	NO CHANGE FROM GASOLINE
B. FUEL VAPORIZER & BATTERY	NO CHANGE FROM GASOLINE
C. DIRECT INJECTION	SIGNIFICANT BUT UNSPECIFIED INCREASE

```
                    EVALUATION MATRIX DATA SHEET

                    ENGINE DESCRIPTION
                    ------------------

ENGINE MANUFACTURER:         BRIGGS & STRATTON
ENGINE DESIGNATION:          QT-4
RATED POWER @ RPM:           3.2 @ 3600
MAXIMUM POWER @ RPM:         3.8 @ 3600
STROKES PER CYCLE:           FOUR (4)
VALVE TRAIN:                 OVERHEAD
PISTON DESIGN:               BOWL-IN-PISTON
DISPLACEMENT (CU IN):            9.18
BORE (IN):                       2.56
STROKE (IN):                     1.78
COMPRESSION RATIO:              8.5:1
DRY WEIGHT (LB):                   28




OPTION:  A.   STARTING FLUID                    <<<
         B.   FUEL VAPORIZER AND BATTERY
         C.   DIRECT INJECTION

A. INITIAL COST ($/KW)
         1. PROCUREMENT COST
           A. LIST PRICE:                     $  200.00
           B. HP @ 3600 RPM:                        3.2 HP
           C. HP USING KEROSENE:                   2.40 HP
           D. GENERATING CAPACITY:                 1.20 KW
           E. PROCUREMENT COST ($/KW):        $  166.67 PER KW         $   166.67 PER KW
                                                                        -----------------
         2.  MODIFICATION COST ($/KW)
           A. COMBUSTION CHAMBER GEOMETRY
              HEAD GASKET  10%     <<<
              HEAD MODIFICATIONS  20%
              PISTON MODIFICATIONS  25%
                PERCENTAGE:       10    COST: $    20.00

           B. PISTON RING MODIFICATION
              2 STROKE/CYCLE  0%
              4 STROKE/CYCLE  25%   <<<
              ROTARY  0%
                PERCENTAGE:       25    COST: $    50.00

           C. IGNITION SYSTEM
              TIMING RETARD  10%    <<<
              HOT SPARK & PLUG  25%
                PERCENTAGE:       10    COST: $    20.00

           D. FUEL DELIVERY SYSTEM
              CARBURETOR JETS  5%   <<<
              FUEL VAPORIZER  25%
              DIRECT INJECTION  200%
                PERCENTAGE:        5    COST: $    10.00

         3.   GENERATOR COST                  $  200.00

              TOTAL MOD. COST:                $  300.00
              TOTAL MOD. COST PER KW:         $  250.00 PER KW         $   250.00 PER KW
                                                                        -----------------
```

Figure B-4

```
B.  ENGINE LIFE COST ($/KW)

         1.  PROCUREMENT COST ($/KW)        $  166.67 PER KW
         2.  MOD COST LESS GEN COST         $   83.33 PER KW
         3.  SPARE COST
              FOUR STROKE/CYCLE (100%)       <<<
              TWO STROKE/CYCLE & ROTARY (66.7%)
                PERCENTAGE:     100   COST: $  250.00 PER KW          $   250.00 PER KW
                                                                      -----------------

C.  TOTAL ENGINE PROCUREMENT.MODIFICATION. AND LIFE CYCLE COST:       $   666.67 PER KW
                                                                      -----------------
D.  OPERATING COST  ($/KW-HR)

         1.  MAINTENANCE EXPENSE            $     0.42 PER KW-HR
         2.  FUEL EXPENSE
              4-STROKE @ $.22/KW-HR <<<
              ROTARY @ $.26/KW-HR
              2-STROKE @ $.29/KW-HR
                                            $     0.22 PER KW-HR
         3.  SPECIAL FLUIDS EXPENSE
              LOW ASH OIL-2 STROKE & ROTARY $     0.00 PER KW-HR
              STARTING FLUID                $     0.05 PER KW-HR
         4.  SPECIAL EQUIPMENT
              STARTING BATTERY OPTION ONLY
               4- STROKE (5%)
               2 STROKE & ROTARY (8.33%)
                PERCENTAGE:       0   COST: $     0.00 PER KW-HR

         5.  TOTAL OPERATING COST           $     0.69 PER KW-HR          $     0.69 PER KW-HR
                                                                      --------------------


E.  TOTAL PROCUREMENT AND OPERATING COST (ASSUMES 1000 HRS OPERATION) $ 1.353.33 PER KW
                                                                      =================
```

F. ENGINE PERFORMANCE

1. WEIGHTS	
A. ENGINE	28.0 LB
B. GENERATOR	28.0 LB
C. FUEL VAPORIZER & BATTERY	0.0 LB
D. FUEL INJECTION SYSTEM	0.0 LB
E. FUEL (4-HR MISSION)	4.8 LB
F. CRANKCASE OIL	2.5 LB
G. TOTAL WEIGHT	63.3 LB
H. POWER OUTPUT	1.20 KW
I. POWER DENSITY	0.019 KW/LB
J. WEIGHT PER UNIT POWER	52.8 LB/KW
K. VOLUME PER UNIT POWER	CU FT/KW
2. STARTING RELIABILITY	
A. STARTING FLUID	95% <<<
B. BATTERY	95%
C. MANUAL	99%
3. COLD START LIMIT (ALL)	-20F
4. NOISE LEVEL	
A. ROTARY	100%
B. 4-STROKE	110% <<<
C. 2-STROKE	120%
5. IR SIGNATURE	
A. 4-STROKE	100% <<<
B. 2-STROKE	130%
C. ROTARY	150%
6. EMI/RFI SIGNATURE	
A. STARTING FLUID	NO CHANGE FROM GASOLINE
B. FUEL VAPORIZER & BATTERY	NO CHANGE FROM GASOLINE
C. DIRECT INJECTION	SIGNIFICANT BUT UNSPECIFIED INCREASE

```
                 EVALUATION MATRIX DATA SHEET

                 ENGINE DESCRIPTION
                 ------------------

ENGINE MANUFACTURER:          BRIGGS & STRATTON
ENGINE DESIGNATION:           QT-4
RATED POWER @ RPM:            3.2 @ 3600
MAXIMUM POWER @ RPM:          3.8 @ 3600
STROKES PER CYCLE:            FOUR (4)
VALVE TRAIN:                  OVERHEAD
PISTON DESIGN:                BOWL-IN-PISTON
DISPLACEMENT (CU IN):            9.18
BORE (IN):                       2.56
STROKE (IN):                     1.78
COMPRESSION RATIO:              8.5:1
DRY WEIGHT (LB):                  28



OPTION:  A.  STARTING FLUID
         B.  FUEL VAPORIZER AND BATTERY      <<<
         C.  DIRECT INJECTION

A. INITIAL COST ($/KW)
        1. PROCUREMENT COST
           A. LIST PRICE:                     $  200.00
           B. HP @ 3600 RPM:                       3.2 HP
           C. HP USING KEROSENE:                  2.40 HP
           D. GENERATING CAPACITY:                1.20 KW
           E. PROCUREMENT COST ($/KW):        $  166.67 PER KW          $   166.67 PER KW
                                                                        -----------------
        2.  MODIFICATION COST ($/KW)
           A. COMBUSTION CHAMBER GEOMETRY
              HEAD GASKET  10%
              HEAD MODIFICATIONS  20%
              PISTON MODIFICATIONS  25%  <<<
                PERCENTAGE:        25    COST: $    50.00

           B. PISTON RING MODIFICATION
              2 STROKE/CYCLE  0%
              4 STROKE/CYCLE  25%   <<<
              ROTARY  0%
                PERCENTAGE:        25    COST: $    50.00

           C. IGNITION SYSTEM
              TIMING RETARD  10%    <<<
              HOT SPARK & PLUG  25%
                PERCENTAGE:        10    COST: $    20.00

           D. FUEL DELIVERY SYSTEM
              CARBURETOR JETS  5%   <<<
              FUEL VAPORIZER  25%   <<<
              DIRECT INJECTION  200%
                PERCENTAGE:        30    COST: $    60.00

        3.  GENERATOR COST                    $  200.00

            TOTAL MOD. COST:                  $  380.00
            TOTAL MOD. COST PER KW:           $  316.67 PER KW          $   316.67 PER KW
                                                                        -----------------
```

Figure B-5

```
B.  ENGINE LIFE COST ($/KW)

        1.  PROCUREMENT COST ($/KW)          $  166.67 PER KW
        2.  MOD COST LESS GEN COST           $  150.00 PER KW
        3.  SPARE COST
             FOUR STROKE/CYCLE (100%)          <<<
             TWO STROKE/CYCLE & ROTARY (66.7%)
               PERCENTAGE:     100    COST: $  316.67 PER KW          $   316.67 PER KW
                                                                      -----------------

C.  TOTAL ENGINE PROCUREMENT,MODIFICATION, AND LIFE CYCLE COST:       $   800.00 PER KW
                                                                      -----------------

D.  OPERATING COST  ($/KW-HR)

        1.  MAINTENANCE EXPENSE              $    0.42 PER KW-HR
        2.  FUEL EXPENSE
             4-STROKE @ $.22/KW-HR <<<
             ROTARY @ $.26/KW-HR
             2-STROKE @ $.29/KW-HR
                                             $    0.22 PER KW-HR
        3.  SPECIAL FLUIDS EXPENSE
             LOW ASH OIL-2 STROKE & ROTARY $      0.00 PER KW-HR
             STARTING FLUID                  $    0.00 PER KW-HR
        4.  SPECIAL EQUIPMENT
             STARTING BATTERY OPTION ONLY
              4- STROKE (5%)
              2 STROKE & ROTARY (8.33%)
               PERCENTAGE:       5    COST: $     0.04 PER KW-HR

        5.  TOTAL OPERATING COST             $    0.68 PER KW-HR          $     0.68 PER KW-HR
                                                                      --------------------


E.  TOTAL PROCUREMENT AND OPERATING COST (ASSUMES 1000 HRS OPERATION) $ 1,478.33 PER KW
                                                                      ================
```

F. ENGINE PERFORMANCE

1. WEIGHTS

A. ENGINE	28.0 LB
B. GENERATOR	28.0 LB
C. FUEL VAPORIZER & BATTERY	6.0 LB
D. FUEL INJECTION SYSTEM	0.0 LB
E. FUEL (4-HR MISSION)	4.8 LB
F. CRANKCASE OIL	2.5 LB
G. TOTAL WEIGHT	69.3 LB
H. POWER OUTPUT	1.20 KW
I. POWER DENSITY	0.017 KW/LB
J. WEIGHT PER UNIT POWER	57.8 LB/KW
K. VOLUME PER UNIT POWER	CU FT/KW

2. STARTING RELIABILITY

A. STARTING FLUID	95%
B. BATTERY	95% <<<
C. MANUAL	99%

3. COLD START LIMIT (ALL) -20F

4. NOISE LEVEL

A. ROTARY	100%
B. 4-STROKE	110% <<<
C. 2-STROKE	120%

5. IR SIGNATURE

A. 4-STROKE	100% <<<
B. 2-STROKE	130%
C. ROTARY	150%

6. EMI/RFI SIGNATURE

A. STARTING FLUID	NO CHANGE FROM GASOLINE
B. FUEL VAPORIZER & BATTERY	NO CHANGE FROM GASOLINE
C. DIRECT INJECTION	SIGNIFICANT BUT UNSPECIFIED INCREASE

```
                   EVALUATION MATRIX DATA SHEET

                   ENGINE DESCRIPTION
                   ------------------

ENGINE MANUFACTURER:         BRIGGS & STRATTON
ENGINE DESIGNATION:          QT-4
RATED POWER @ RPM:           3.2 @ 3600
MAXIMUM POWER @ RPM:         3.8 @ 3600
STROKES PER CYCLE:           FOUR (4)
VALVE TRAIN:                 OVERHEAD
PISTON DESIGN:               BOWL-IN-PISTON
DISPLACEMENT (CU IN):            9.18
BORE (IN):                       2.56
STROKE (IN):                     1.78
COMPRESSION RATIO:             8.5:1
DRY WEIGHT (LB):                   28



OPTION:  A.   STARTING FLUID
         B.   FUEL VAPORIZER AND BATTERY
         C.   DIRECT INJECTION                 <<<

A. INITIAL COST ($/KW)
         1. PROCUREMENT COST
           A. LIST PRICE:                     $  200.00
           B. HP @ 3600 RPM:                        3.2 HP
           C. HP USING KEROSENE:                   2.40 HP
           D. GENERATING CAPACITY:                 1.20 KW
           E. PROCUREMENT COST ($/KW):        $  166.67 PER KW          $   166.67 PER KW
                                                                        -----------------
         2.  MODIFICATION COST ($/KW)
           A. COMBUSTION CHAMBER GEOMETRY
              HEAD GASKET  10%
              HEAD MODIFICATIONS  20%
              PISTON MODIFICATIONS  25%  <<<
                PERCENTAGE:      25   COST: $   50.00

           B. PISTON RING MODIFICATION
              2 STROKE/CYCLE  0%
              4 STROKE/CYCLE  25%   <<<
              ROTARY  0%
                PERCENTAGE:      25   COST: $   50.00

           C. IGNITION SYSTEM
              TIMING RETARD  10%    <<<
              HOT SPARK & PLUG  25% <<<
                PERCENTAGE:      35   COST: $   70.00

           D. FUEL DELIVERY SYSTEM
              CARBURETOR JETS  5%
              FUEL VAPORIZER  25%
              DIRECT INJECTION  200%<<<
                PERCENTAGE:     200   COST: $  400.00

         3.  GENERATOR COST                   $  200.00

             TOTAL MOD. COST:                 $  770.00
             TOTAL MOD. COST PER KW:          $  641.67 PER KW          $   641.67 PER KW
                                                                        -----------------
```

Figure B-6

```
B.  ENGINE LIFE COST ($/KW)

        1.  PROCUREMENT COST ($/KW)        $  166.67 PER KW
        2.  MOD COST LESS GEN COST         $  475.00 PER KW
        3.  SPARE COST
             FOUR STROKE/CYCLE (100%)        <<<
             TWO STROKE/CYCLE & ROTARY (66.7%)
               PERCENTAGE:     100   COST: $  641.67 PER KW          $   641.67 PER KW
                                                                     -----------------

C.  TOTAL ENGINE PROCUREMENT,MODIFICATION, AND LIFE CYCLE COST:      $ 1.450.00 PER KW
                                                                     -----------------
D.  OPERATING COST  ($/KW-HR)

        1.  MAINTENANCE EXPENSE            $     0.42 PER KW-HR
        2.  FUEL EXPENSE
             4-STROKE @ $.22/KW-HR <<<
             ROTARY @ $.26/KW-HR
             2-STROKE @ $.29/KW-HR
                                           $     0.22 PER KW-HR
        3.  SPECIAL FLUIDS EXPENSE
             LOW ASH OIL-2 STROKE & ROTARY $     0.00 PER KW-HR
             STARTING FLUID                $     0.00 PER KW-HR
        4.  SPECIAL EQUIPMENT
             STARTING BATTERY OPTION ONLY
              4- STROKE (5%)
              2 STROKE & ROTARY (8.33%)
               PERCENTAGE:       0   COST: $     0.00 PER KW-HR

        5.  TOTAL OPERATING COST           $     0.64 PER KW-HR      $      0.64 PER KW-HR
                                                                     --------------------

E.  TOTAL PROCUREMENT AND OPERATING COST (ASSUMES 1000 HRS OPERATION) $ 2.086.67 PER KW
                                                                      =================
```

F. ENGINE PERFORMANCE

1. WEIGHTS

A. ENGINE	28.0 LB
B. GENERATOR	28.0 LB
C. FUEL VAPORIZER & BATTERY	0.0 LB
D. FUEL INJECTION SYSTEM	5.0 LB
E. FUEL (4-HR MISSION)	4.8 LB
F. CRANKCASE OIL	2.5 LB
G. TOTAL WEIGHT	68.3 LB
H. POWER OUTPUT	1.20 KW
I. POWER DENSITY	0.018 KW/LB
J. WEIGHT PER UNIT POWER	56.9 LB/KW
K. VOLUME PER UNIT POWER	CU FT/KW

2. STARTING RELIABILITY

A. STARTING FLUID	95%
B. BATTERY	95%
C. MANUAL	99% <<<

3. COLD START LIMIT (ALL) -20F

4. NOISE LEVEL

A. ROTARY	100%
B. 4-STROKE	110% <<<
C. 2-STROKE	120%

5. IR SIGNATURE

A. 4-STROKE	100% <<<
B. 2-STROKE	130%
C. ROTARY	150%

6. EMI/RFI SIGNATURE

A. STARTING FLUID	NO CHANGE FROM GASOLINE
B. FUEL VAPORIZER & BATTERY	NO CHANGE FROM GASOLINE
C. DIRECT INJECTION	SIGNIFICANT BUT UNSPECIFIED INCREASE

```
                     EVALUATION MATRIX DATA SHEET

                     ENGINE DESCRIPTION
                     ------------------

ENGINE MANUFACTURER:         TECUMSEH
ENGINE DESIGNATION:          AH600 TYPE 900384
RATED POWER @ RPM:           2.45 @ 3600
MAXIMUM POWER @ RPM:         3 @ 4500
STROKES PER CYCLE:           TWO (2)
VALVE TRAIN:                 NONE
PISTON DESIGN:               FLAT TOP
DISPLACEMENT (CU IN):            6
BORE (IN):                       2.09
STROKE (IN):                     1.75
COMPRESSION RATIO:           NOT AVAIL.
DRY WEIGHT (LB):                16



OPTION:  A.   STARTING FLUID
         B.   FUEL VAPORIZER AND BATTERY
         C.   DIRECT INJECTION

A. INITIAL COST ($/KW)
         1. PROCUREMENT COST
           A. LIST PRICE:                    $  180.00
           B. HP @ 3600 RPM:                      2.45 HP
           C. HP USING KEROSENE:                  1.84 HP
           D. GENERATING CAPACITY:                0.92 KW
           E. PROCUREMENT COST ($/KW):       $  195.92 PER KW          $   195.92 PER KW
                                                                       -----------------
         2.  MODIFICATION COST ($/KW)
           A. COMBUSTION CHAMBER GEOMETRY
              HEAD GASKET  10%
              HEAD MODIFICATIONS  20%
              PISTON MODIFICATIONS  25%  <<<
                PERCENTAGE:      25   COST: $   45.00

           B. PISTON RING MODIFICATION
              2 STROKE/CYCLE  0%    <<<
              4 STROKE/CYCLE  25%
              ROTARY  0%
                PERCENTAGE:       0   COST: $    0.00

           C. IGNITION SYSTEM
              TIMING RETARD  10%    <<<
              HOT SPARK & PLUG  25%
                PERCENTAGE:      10   COST: $   18.00

           D. FUEL DELIVERY SYSTEM
              CARBURETOR JETS  5%   <<<
              FUEL VAPORIZER  25%
              DIRECT INJECTION  200%
                PERCENTAGE:       5   COST: $    9.00

        3.   GENERATOR COST                  $  180.00

             TOTAL MOD. COST:                $  252.00
             TOTAL MOD. COST PER KW:         $  274.29 PER KW          $   274.29 PER KW
                                                                       -----------------
```

Figure B-7

```
B.  ENGINE LIFE COST ($/KW)

         1.  PROCUREMENT COST ($/KW)          $  195.92 PER KW
         2.  MOD COST LESS GEN COST           $   78.37 PER KW
         3.  SPARE COST
              FOUR STROKE/CYCLE (100%)
              TWO STROKE/CYCLE & ROTARY (66.7%) <<<
                PERCENTAGE:    66.7   COST: $  411.22 PER KW           $   411.22 PER KW
                                                                       -----------------

C.  TOTAL ENGINE PROCUREMENT.MODIFICATION. AND LIFE CYCLE COST:        $   881.43 PER KW
                                                                       -----------------
D.  OPERATING COST  ($/KW-HR)

         1.  MAINTENANCE EXPENSE              $     0.49 PER KW-HR
         2.  FUEL EXPENSE
              4-STROKE @ $.22/KW-HR
              ROTARY @ $.26/KW-HR
              2-STROKE @ $.29/KW-HR <<<
                                              $     0.29 PER KW-HR
         3.  SPECIAL FLUIDS EXPENSE
              LOW ASH OIL-2 STROKE & ROTARY $     0.05 PER KW-HR
              STARTING FLUID                  $     0.05 PER KW-HR
         4.  SPECIAL EQUIPMENT
              STARTING BATTERY OPTION ONLY
               4- STROKE (5%)
               2 STROKE & ROTARY (8.33%)
                PERCENTAGE:       0   COST: $     0.00 PER KW-HR

         5.  TOTAL OPERATING COST             $     0.88 PER KW-HR         $     0.88 PER KW-HR
                                                                       --------------------


E.  TOTAL PROCUREMENT AND OPERATING COST (ASSUMES 1000 HRS OPERATION) $ 1.761.22 PER KW
                                                                       =================
```

F. ENGINE PERFORMANCE

1. WEIGHTS	
A. ENGINE	16.0 LB
B. GENERATOR	16.0 LB
C. FUEL VAPORIZER & BATTERY	0.0 LB
D. FUEL INJECTION SYSTEM	0.0 LB
E. FUEL (4-HR MISSION)	4.9 LB
F. CRANKCASE OIL	0 LB
G. TOTAL WEIGHT	36.9 LB
H. POWER OUTPUT	0.92 KW
I. POWER DENSITY	0.025 KW/LB
J. WEIGHT PER UNIT POWER	40.1 LB/KW
K. VOLUME PER UNIT POWER	CU FT/KW
2. STARTING RELIABILITY	
A. STARTING FLUID	95% <<<
B. BATTERY	95%
C. MANUAL	99%
3. COLD START LIMIT (ALL)	-20F
4. NOISE LEVEL	
A. ROTARY	100%
B. 4-STROKE	110%
C. 2-STROKE	120% <<<
5. IR SIGNATURE	
A. 4-STROKE	100%
B. 2-STROKE	120% <<<
C. ROTARY	130%
6. EMI/RFI SIGNATURE	
A. STARTING FLUID	NO CHANGE FROM GASOLINE
B. FUEL VAPORIZER & BATTERY	NO CHANGE FROM GASOLINE
C. DIRECT INJECTION	SIGNIFICANT BUT UNSPECIFIED INCREASE

```
                  EVALUATION MATRIX DATA SHEET

                  ENGINE DESCRIPTION
                  ------------------

ENGINE MANUFACTURER:       TECUMSEH
ENGINE DESIGNATION:        AH600 TYPE 900384
RATED POWER @ RPM:         2.45 @ 3600
MAXIMUM POWER @ RPM:       3 @ 4500
STROKES PER CYCLE:         TWO (2)
VALVE TRAIN:               NONE
PISTON DESIGN:             FLAT TOP
DISPLACEMENT (CU IN):             6
BORE (IN):                     2.09
STROKE (IN):                   1.75
COMPRESSION RATIO:         NOT AVAIL.
DRY WEIGHT (LB):                 16




OPTION:  A.  STARTING FLUID
         B.  FUEL VAPORIZER AND BATTERY     <<<
         C.  DIRECT INJECTION

A. INITIAL COST ($/KW)
         1. PROCUREMENT COST
           A. LIST PRICE:                 $  180.00
           B. HP @ 3600 RPM:                   2.45 HP
           C. HP USING KEROSENE:               1.84 HP
           D. GENERATING CAPACITY:             0.92 KW
           E. PROCUREMENT COST ($/KW):    $  195.92 PER KW          $   195.92 PER KW
                                                                    -----------------

         2.  MODIFICATION COST ($/KW)
           A. COMBUSTION CHAMBER GEOMETRY
              HEAD GASKET  10%
              HEAD MODIFICATIONS  20%
              PISTON MODIFICATIONS  25%  <<<
                PERCENTAGE:       25   COST: $   45.00

           B. PISTON RING MODIFICATION
              2 STROKE/CYCLE  0%    <<<
              4 STROKE/CYCLE  25%
              ROTARY  0%
                PERCENTAGE:        0   COST: $    0.00

           C. IGNITION SYSTEM
              TIMING RETARD  10%    <<<
              HOT SPARK & PLUG  25%
                PERCENTAGE:       10   COST: $   18.00

           D. FUEL DELIVERY SYSTEM
              CARBURETOR JETS  5%   <<<
              FUEL VAPORIZER  25%   <<<
              DIRECT INJECTION  200%
                PERCENTAGE:       30   COST: $   54.00

         3.  GENERATOR COST               $  180.00

             TOTAL MOD. COST:             $  297.00
             TOTAL MOD. COST PER KW:      $  323.27 PER KW          $   323.27 PER KW
                                                                    -----------------
```

Figure B-8

```
B.  ENGINE LIFE COST ($/KW)

        1.  PROCUREMENT COST ($/KW)          $  195.92 PER KW
        2.  MOD COST LESS GEN COST           $  127.35 PER KW
        3.  SPARE COST
             FOUR STROKE/CYCLE (100%)
             TWO STROKE/CYCLE & ROTARY (66.7%) <<
               PERCENTAGE:    66.7   COST: $  484.66 PER KW             $   484.66 PER KW
                                                                         ----------------
C.  TOTAL ENGINE PROCUREMENT,MODIFICATION, AND LIFE CYCLE COST:          $ 1.003.84 PER KW
                                                                         ----------------
D.  OPERATING COST  ($/KW-HR)

        1.  MAINTENANCE EXPENSE              $     0.49 PER KW-HR
        2.  FUEL EXPENSE
             4-STROKE @ $.22/KW-HR
             ROTARY @ $.26/KW-HR
             2-STROKE @ $.29/KW-HR <<
                                             $     0.29 PER KW-HR
        3.  SPECIAL FLUIDS EXPENSE
             LOW ASH OIL-2 STROKE & ROTARY   $     0.05 PER KW-HR
             STARTING FLUID                  $     0.00 PER KW-HR
        4.  SPECIAL EQUIPMENT
             STARTING BATTERY OPTION ONLY
              4- STROKE (5%)
              2 STROKE & ROTARY (8.33%)
               PERCENTAGE:    8.33   COST: $     0.09 PER KW-HR

        5.  TOTAL OPERATING COST             $     0.92 PER KW-HR         $     0.92 PER KW-HR
                                                                         --------------------

E.  TOTAL PROCUREMENT AND OPERATING COST (ASSUMES 1000 HRS OPERATION)  $ 1.924.30 PER KW
                                                                       ================
```

F. ENGINE PERFORMANCE

1. WEIGHTS

A. ENGINE	16.0 LB
B. GENERATOR	16.0 LB
C. FUEL VAPORIZER & BATTERY	6.0 LB
D. FUEL INJECTION SYSTEM	0.0 LB
E. FUEL (4-HR MISSION)	4.9 LB
F. CRANKCASE OIL	0 LB
G. TOTAL WEIGHT	42.9 LB
H. POWER OUTPUT	0.92 KW
I. POWER DENSITY	0.021 KW/LB
J. WEIGHT PER UNIT POWER	46.6 LB/KW
K. VOLUME PER UNIT POWER	CU FT/KW

2. STARTING RELIABILITY

A. STARTING FLUID	95%
B. BATTERY	95%
C. MANUAL	99%

3. COLD START LIMIT (ALL)	-20F

4. NOISE LEVEL

A. ROTARY	100%
B. 4-STROKE	110%
C. 2-STROKE	120% <<<

5. IR SIGNATURE

A. 4-STROKE	100%
B. 2-STROKE	130% <<<
C. ROTARY	150%

6. EMI/RFI SIGNATURE

A. STARTING FLUID	NO CHANGE FROM GASOLINE
B. FUEL VAPORIZER & BATTERY	NO CHANGE FROM GASOLINE
C. DIRECT INJECTION	SIGNIFICANT BUT UNSPECIFIED INCREASE

```
                    EVALUATION MATRIX DATA SHEET

                    ENGINE DESCRIPTION
                    ------------------

ENGINE MANUFACTURER:          TECUMSEH
ENGINE DESIGNATION:           AH600 TYPE 900384
RATED POWER @ RPM:            2.45 @ 3600
MAXIMUM POWER @ RPM:          3 @ 4500
STROKES PER CYCLE:            TWO (2)
VALVE TRAIN:                  NONE
PISTON DESIGN:                FLAT TOP
DISPLACEMENT (CU IN):              6
BORE (IN):                      2.09
STROKE (IN):                    1.75
COMPRESSION RATIO:            NOT AVAIL.
DRY WEIGHT (LB):                  16



OPTION:  A.  STARTING FLUID
         B.  FUEL VAPORIZER AND BATTERY
         C.  DIRECT INJECTION

A. INITIAL COST ($/KW)
         1. PROCUREMENT COST
           A. LIST PRICE:                      $  180.00
           B. HP @ 3600 RPM:                        2.45 HP
           C. HP USING KEROSENE:                    1.84 HP
           D. GENERATING CAPACITY:                  0.92 KW
           E. PROCUREMENT COST ($/KW):         $  195.92 PER KW          $   195.92 PER KW
                                                                         ----------------
         2.  MODIFICATION COST ($/KW)
           A. COMBUSTION CHAMBER GEOMETRY
              HEAD GASKET  10%
              HEAD MODIFICATIONS  20%
              PISTON MODIFICATIONS  25%  <<<
                PERCENTAGE:       25   COST: $    45.00

           B. PISTON RING MODIFICATION
              2 STROKE/CYCLE  0%     <<<
              4 STROKE/CYCLE  25%
              ROTARY  0%
                PERCENTAGE:        0   COST: $     0.00

           C. IGNITION SYSTEM
              TIMING RETARD  10%     <<<
              HOT SPARK & PLUG  25% <<<
                PERCENTAGE:       35   COST: $    63.00

           D. FUEL DELIVERY SYSTEM
              CARBURETOR JETS  5%
              FUEL VAPORIZER  25%
              DIRECT INJECTION  200%<<<
                PERCENTAGE:      200   COST: $   360.00

         3.  GENERATOR COST                    $  180.00

             TOTAL MOD. COST:                  $  648.00
             TOTAL MOD. COST PER KW:           $  705.31 PER KW          $   705.31 PER KW
                                                                         ----------------
```

Figure B-9

```
B.  ENGINE LIFE COST ($/KW)

         1.  PROCUREMENT COST ($/KW)        $  195.92 PER KW
         2.  MOD COST LESS GEN COST         $  509.39 PER KW
         3.  SPARE COST
              FOUR STROKE/CYCLE (100%)
              TWO STROKE/CYCLE & ROTARY (66.7%) ***
                PERCENTAGE:    66.7   COST: $1.057.43 PER KW          $ 1.057.43 PER KW
                                                                      -----------------

C.  TOTAL ENGINE PROCUREMENT.MODIFICATION. AND LIFE CYCLE COST:       $ 1.958.65 PER KW
                                                                      -----------------
D.  OPERATING COST  ($/KW-HR)

         1.  MAINTENANCE EXPENSE            $    0.49 PER KW-HR
         2.  FUEL EXPENSE
              4-STROKE @ $.22/KW-HR
              ROTARY @ $.26/KW-HR
              2-STROKE @ $.29/KW-HR ***
                                            $    0.29 PER KW-HR
         3.  SPECIAL FLUIDS EXPENSE
              LOW ASH OIL-2 STROKE & ROTARY $    0.05 PER KW-HR
              STARTING FLUID                $    0.00 PER KW-HR
         4.  SPECIAL EQUIPMENT
              STARTING BATTERY OPTION ONLY
               4- STROKE (5%)
               2 STROKE & ROTARY (8.33%)
                PERCENTAGE:       0   COST: $    0.00 PER KW-HR

         5.  TOTAL OPERATING COST           $    0.83 PER KW-HR       $     0.83 PER KW-HR
                                                                      --------------------

E.  TOTAL PROCUREMENT AND OPERATING COST (ASSUMES 1000 HRS OPERATION) $ 2.788.45 PER KW
                                                                      ================
```

F. ENGINE PERFORMANCE

1. WEIGHTS

A. ENGINE	16.0 LB
B. GENERATOR	16.0 LB
C. FUEL VAPORIZER & BATTERY	0.0 LB
D. FUEL INJECTION SYSTEM	5.0 LB
E. FUEL (4-HR MISSION)	4.9 LB
F. CRANKCASE OIL	0 LB
G. TOTAL WEIGHT	41.9 LB
H. POWER OUTPUT	0.92 KW
I. POWER DENSITY	0.022 KW/LB
J. WEIGHT PER UNIT POWER	45.6 LB/KW
K. VOLUME PER UNIT POWER	CU FT/KW

2. STARTING RELIABILITY

A. STARTING FLUID	95%
B. BATTERY	95%
C. MANUAL	99% <<<

3. COLD START LIMIT (ALL) -20F

4. NOISE LEVEL

A. ROTARY	100%
B. 4-STROKE	110%
C. 2-STROKE	120% <<<

5. IR SIGNATURE

A. 4-STROKE	100%
B. 2-STROKE	130% <<<
C. ROTARY	150%

6. EMI/RFI SIGNATURE

A. STARTING FLUID	NO CHANGE FROM GASOLINE
B. FUEL VAPORIZER & BATTERY	NO CHANGE FROM GASOLINE
C. DIRECT INJECTION	SIGNIFICANT BUT UNSPECIFIED INCREASE

```
                 EVALUATION MATRIX DATA SHEET

                 ENGINE DESCRIPTION
                 ------------------

ENGINE MANUFACTURER:        BRIGGS & STRATTON
ENGINE DESIGNATION:         MODEL 62032 TYPE 0529
RATED POWER @ RPM:          2.3 @ 3600
MAXIMUM POWER @ RPM:        3.4 @ 4200
STROKES PER CYCLE:          TWO (2)
VALVE TRAIN:                NONE
PISTON DESIGN:              FLAT TOP
DISPLACEMENT (CU IN):          6.21
BORE (IN):                     2.13
STROKE (IN):                   1.75
COMPRESSION RATIO:          NOT AVAIL.
DRY WEIGHT (LB):                 17



OPTION:  A.   STARTING FLUID                <<<
         B.   FUEL VAPORIZER AND BATTERY
         C.   DIRECT INJECTION

A. INITIAL COST ($/KW)
         1. PROCUREMENT COST
           A. LIST PRICE:                   $  170.50
           B. HP @ 3600 RPM:                      2.3 HP
           C. HP USING KEROSENE:                 1.73 HP
           D. GENERATING CAPACITY:               0.86 KW
           E. PROCUREMENT COST ($/KW):      $  197.68 PER KW          $   197.68 PER KW
                                                                      -----------------
         2.  MODIFICATION COST ($/KW)
           A. COMBUSTION CHAMBER GEOMETRY
              HEAD GASKET  10%
              HEAD MODIFICATIONS  20%
              PISTON MODIFICATIONS  25%  <<<
                PERCENTAGE:       25   COST: $   42.63

           B. PISTON RING MODIFICATION
              2 STROKE/CYCLE  0%    <<<
              4 STROKE/CYCLE  25%
              ROTARY  0%
                PERCENTAGE:        0   COST: $    0.00

           C. IGNITION SYSTEM
              TIMING RETARD  10%    <<<
              HOT SPARK & PLUG  25%
                PERCENTAGE:       10   COST: $   17.05

           D. FUEL DELIVERY SYSTEM
              CARBURETOR JETS  5%   <<<
              FUEL VAPORIZER  25%
              DIRECT INJECTION  200%
                PERCENTAGE:        5   COST: $    8.53

         3.  GENERATOR COST                 $  170.50

             TOTAL MOD. COST:               $  238.70
             TOTAL MOD. COST PER KW:        $  276.75 PER KW          $   276.75 PER KW
                                                                      -----------------
```

Figure B-10

```
B.  ENGINE LIFE COST ($/KW)

        1.  PROCUREMENT COST ($/KW)         $  197.68 PER KW
        2.  MOD COST LESS GEN COST          $   79.07 PER KW
        3.  SPARE COST
             FOUR STROKE/CYCLE (100%)
             TWO STROKE/CYCLE & ROTARY (66.7%) <<<
               PERCENTAGE:    66.7   COST: $  414.92 PER KW          $   414.92 PER KW
                                                                     -----------------

C.  TOTAL ENGINE PROCUREMENT.MODIFICATION. AND LIFE CYCLE COST:      $   889.36 PER KW
                                                                     -----------------
D.  OPERATING COST  ($/KW-HR)

        1.  MAINTENANCE EXPENSE             $    0.49 PER KW-HR
        2.  FUEL EXPENSE
             4-STROKE @ $.22/KW-HR
             ROTARY @ $.26/KW-HR
             2-STROKE @ $.29/KW-HR <<<
                                            $    0.29 PER KW-HR
        3.  SPECIAL FLUIDS EXPENSE
             LOW ASH OIL-2 STROKE & ROTARY $    0.05 PER KW-HR
             STARTING FLUID                 $    0.05 PER KW-HR
        4.  SPECIAL EQUIPMENT
             STARTING BATTERY OPTION ONLY
              4- STROKE (5%)
              2 STROKE & ROTARY (8.33%)
               PERCENTAGE:       0   COST: $    0.00 PER KW-HR

        5.  TOTAL OPERATING COST            $    0.88 PER KW-HR       $     0.88 PER KW-HR
                                                                     --------------------


E.  TOTAL PROCUREMENT AND OPERATING COST (ASSUMES 1000 HRS OPERATION) $ 1,773.56 PER KW
                                                                     ================
```

F. ENGINE PERFORMANCE

1. WEIGHTS	
A. ENGINE	17.0 LB
B. GENERATOR	17.0 LB
C. FUEL VAPORIZER & BATTERY	0.0 LB
D. FUEL INJECTION SYSTEM	0.0 LB
E. FUEL (4-HR MISSION)	4.6 LB
F. CRANKCASE OIL	0 LB
G. TOTAL WEIGHT	38.6 LB
H. POWER OUTPUT	0.86 KW
I. POWER DENSITY	0.022 KW/LB
J. WEIGHT PER UNIT POWER	44.7 LB/KW
K. VOLUME PER UNIT POWER	CU FT/KW
2. STARTING RELIABILITY	
A. STARTING FLUID	95% <<<
B. BATTERY	95%
C. MANUAL	99%
3. COLD START LIMIT (ALL)	-20F
4. NOISE LEVEL	
A. ROTARY	100%
B. 4-STROKE	110%
C. 2-STROKE	120% <<<
5. IR SIGNATURE	
A. 4-STROKE	100%
B. 2-STROKE	130% <<<
C. ROTARY	150%
6. EMI/RFI SIGNATURE	
A. STARTING FLUID	NO CHANGE FROM GASOLINE
B. FUEL VAPORIZER & BATTERY	NO CHANGE FROM GASOLINE
C. DIRECT INJECTION	SIGNIFICANT BUT UNSPECIFIED INCREASE

```
                  EVALUATION MATRIX DATA SHEET

                  ENGINE DESCRIPTION
                  ------------------

ENGINE MANUFACTURER:       BRIGGS & STRATTON
ENGINE DESIGNATION:        MODEL 62032 TYPE 0529
RATED POWER @ RPM:         2.3 @ 3600
MAXIMUM POWER @ RPM:       3.4 @ 4200
STROKES PER CYCLE:         TWO (2)
VALVE TRAIN:               NONE
PISTON DESIGN:             FLAT TOP
DISPLACEMENT (CU IN):          6.21
BORE (IN):                     2.13
STROKE (IN):                   1.75
COMPRESSION RATIO:         NOT AVAIL.
DRY WEIGHT (LB):                 17



OPTION:  A.  STARTING FLUID
         B.  FUEL VAPORIZER AND BATTERY      <<<
         C.  DIRECT INJECTION

A. INITIAL COST ($/KW)
         1. PROCUREMENT COST
           A. LIST PRICE:                  $  170.50
           B. HP @ 3600 RPM:                     2.3 HP
           C. HP USING KEROSENE:                1.73 HP
           D. GENERATING CAPACITY:              0.86 KW
           E. PROCUREMENT COST ($/KW):     $  197.68 PER KW           $   197.68 PER KW
                                                                      -----------------

         2.  MODIFICATION COST ($/KW)
           A. COMBUSTION CHAMBER GEOMETRY
              HEAD GASKET  10%
              HEAD MODIFICATIONS  20%
              PISTON MODIFICATIONS  25%  <<<
                PERCENTAGE:      25   COST: $   42.63

           B. PISTON RING MODIFICATION
              2 STROKE/CYCLE  0%    <<<
              4 STROKE/CYCLE  25%
              ROTARY  0%
                PERCENTAGE:       0   COST: $    0.00

           C. IGNITION SYSTEM
              TIMING RETARD  10%    <<<
              HOT SPARK & PLUG  25%
                PERCENTAGE:      10   COST: $   17.05

           D. FUEL DELIVERY SYSTEM
              CARBURETOR JETS  5%   <<<
              FUEL VAPORIZER  25%   <<<
              DIRECT INJECTION  200%
                PERCENTAGE:      30   COST: $   51.15

         3.  GENERATOR COST                $  170.50

             TOTAL MOD. COST:              $  281.33
             TOTAL MOD. COST PER KW:       $  326.17 PER KW           $   326.17 PER KW
                                                                      -----------------
```

Figure B-11

```
B.  ENGINE LIFE COST ($/KW)

         1.  PROCUREMENT COST ($/KW)        $  197.68 PER KW
         2.  MOD COST LESS GEN COST         $  128.49 PER KW
         3.  SPARE COST
              FOUR STROKE/CYCLE (100%)
              TWO STROKE/CYCLE & ROTARY (66.7%) <<<
                PERCENTAGE:    66.7   COST: $  489.02 PER KW          $   489.02 PER KW
                                                                      ----------------

C.  TOTAL ENGINE PROCUREMENT.MODIFICATION. AND LIFE CYCLE COST:       $ 1.012.87 PER KW
                                                                      ----------------
D.  OPERATING COST  ($/KW-HR)

         1.  MAINTENANCE EXPENSE            $    0.49 PER KW-HR
         2.  FUEL EXPENSE
              4-STROKE @ $.22/KW-HR
              ROTARY @ $.26/KW-HR
              2-STROKE @ $.29/KW-HR <<<
                                            $    0.29 PER KW-HR
         3.  SPECIAL FLUIDS EXPENSE
              LOW ASH OIL-2 STROKE & ROTARY $    0.05 PER KW-HR
              STARTING FLUID                $    0.00 PER KW-HR
         4.  SPECIAL EQUIPMENT
              STARTING BATTERY OPTION ONLY
               4- STROKE (5%)
               2 STROKE & ROTARY (8.33%)
                PERCENTAGE:    8.33   COST: $    0.10 PER KW-HR

         5.  TOTAL OPERATING COST           $    0.93 PER KW-HR       $     0.93 PER KW-HR
                                                                      --------------------

E.  TOTAL PROCUREMENT AND OPERATING COST (ASSUMES 1000 HRS OPERATION) $ 1.943.65 PER KW
                                                                      ================
```

F. ENGINE PERFORMANCE

1. WEIGHTS

A. ENGINE	17.0 LB
B. GENERATOR	17.0 LB
C. FUEL VAPORIZER & BATTERY	6.0 LB
D. FUEL INJECTION SYSTEM	0.0 LB
E. FUEL (4-HR MISSION)	4.6 LB
F. CRANKCASE OIL	0 LB
G. TOTAL WEIGHT	44.6 LB
H. POWER OUTPUT	0.86 KW
I. POWER DENSITY	0.019 KW/LB
J. WEIGHT PER UNIT POWER	51.7 LB/KW
K. VOLUME PER UNIT POWER	CU FT/KW

2. STARTING RELIABILITY

A. STARTING FLUID	95%
B. BATTERY	95% <<<
C. MANUAL	99%

3. COLD START LIMIT (ALL) -20F

4. NOISE LEVEL

A. ROTARY	100%
B. 4-STROKE	110%
C. 2-STROKE	120% <<<

5. IR SIGNATURE

A. 4-STROKE	100%
B. 2-STROKE	130% <<<
C. ROTARY	150%

6. EMI/RFI SIGNATURE

A. STARTING FLUID	NO CHANGE FROM GASOLINE
B. FUEL VAPORIZER & BATTERY	NO CHANGE FROM GASOLINE
C. DIRECT INJECTION	SIGNIFICANT BUT UNSPECIFIED INCREASE

```
                 EVALUATION MATRIX DATA SHEET

                 ENGINE DESCRIPTION
                 ------------------

ENGINE MANUFACTURER:       BRIGGS & STRATTON
ENGINE DESIGNATION:        MODEL 62032 TYPE 0529
RATED POWER @ RPM:         2.3 @ 3600
MAXIMUM POWER @ RPM:       3.4 @ 4200
STROKES PER CYCLE:         TWO (2)
VALVE TRAIN:               NONE
PISTON DESIGN:             FLAT TOP
DISPLACEMENT (CU IN):          6.21
BORE (IN):                     2.13
STROKE (IN):                   1.75
COMPRESSION RATIO:         NOT AVAIL.
DRY WEIGHT (LB):                 17




OPTION:  A.   STARTING FLUID
         B.   FUEL VAPORIZER AND BATTERY
         C.   DIRECT INJECTION                <<<

A. INITIAL COST ($/KW)
         1. PROCUREMENT COST
           A. LIST PRICE:                  $  170.50
           B. HP @ 3600 RPM:                     2.3 HP
           C. HP USING KEROSENE:                1.73 HP
           D. GENERATING CAPACITY:              0.86 KW
           E. PROCUREMENT COST ($/KW):     $  197.68 PER KW          $   197.68 PER KW
                                                                     -----------------
         2.  MODIFICATION COST ($/KW)
           A. COMBUSTION CHAMBER GEOMETRY
              HEAD GASKET  10%
              HEAD MODIFICATIONS  20%
              PISTON MODIFICATIONS  25%  <<<
                PERCENTAGE:       25   COST: $   42.63

           B. PISTON RING MODIFICATION
              2 STROKE/CYCLE  0%     <<<
              4 STROKE/CYCLE  25%
              ROTARY  0%
                PERCENTAGE:        0   COST: $    0.00

           C. IGNITION SYSTEM
              TIMING RETARD  10%     <<<
              HOT SPARK & PLUG  25% <<<
                PERCENTAGE:       35   COST: $   59.68

           D. FUEL DELIVERY SYSTEM
              CARBURETOR JETS  5%
              FUEL VAPORIZER  25%
              DIRECT INJECTION  200%<<<
                PERCENTAGE:      200   COST: $  341.00

         3.  GENERATOR COST                $  170.50

             TOTAL MOD. COST:              $  613.80
             TOTAL MOD. COST PER KW:       $  711.65 PER KW          $   711.65 PER KW
                                                                     -----------------
```

Figure B-12

```
B.  ENGINE LIFE COST ($/KW)

        1.  PROCUREMENT COST ($/KW)         $  197.68 PER KW
        2.  MOD COST LESS GEN COST          $  513.97 PER KW
        3.  SPARE COST
             FOUR STROKE/CYCLE (100%)
             TWO STROKE/CYCLE & ROTARY (66.7%) <<
               PERCENTAGE:    66.7   COST: $1.066.94 PER KW            $ 1.066.94 PER KW
                                                                       -----------------

C.  TOTAL ENGINE PROCUREMENT.MODIFICATION. AND LIFE CYCLE COST:        $ 1.976.28 PER KW
                                                                       -----------------
D.  OPERATING COST  ($/KW-HR)

        1.  MAINTENANCE EXPENSE             $     0.49 PER KW-HR
        2.  FUEL EXPENSE
             4-STROKE @ $.22/KW-HR
             ROTARY @ $.26/KW-HR
             2-STROKE @ $.29/KW-HR <<

                                            $     0.29 PER KW-HR
        3.  SPECIAL FLUIDS EXPENSE
             LOW ASH OIL-2 STROKE & ROTARY  $     0.05 PER KW-HR
             STARTING FLUID                 $     0.00 PER KW-HR
        4.  SPECIAL EQUIPMENT
             STARTING BATTERY OPTION ONLY
              4- STROKE (5%)
              2 STROKE & ROTARY (8.33%)
               PERCENTAGE:        0   COST: $     0.00 PER KW-HR

        5.  TOTAL OPERATING COST            $     0.83 PER KW-HR          $      0.83 PER KW-HR
                                                                        --------------------

E.  TOTAL PROCUREMENT AND OPERATING COST (ASSUMES 1000 HRS OPERATION) $ 2.810.48 PER KW
                                                                      =================
```

F. ENGINE PERFORMANCE

1. WEIGHTS

A. ENGINE	17.0 LB
B. GENERATOR	17.0 LB
C. FUEL VAPORIZER & BATTERY	0.0 LB
D. FUEL INJECTION SYSTEM	5.0 LB
E. FUEL (4-HR MISSION)	4.6 LB
F. CRANKCASE OIL	0 LB
G. TOTAL WEIGHT	43.6 LB
H. POWER OUTPUT	0.86 KW
I. POWER DENSITY	0.020 KW/LB
J. WEIGHT PER UNIT POWER	50.5 LB/KW
K. VOLUME PER UNIT POWER	CU FT/KW

2. STARTING RELIABILITY

A. STARTING FLUID	95%
B. BATTERY	95%
C. MANUAL	99% <<<

3. COLD START LIMIT (ALL) -20F

4. NOISE LEVEL

A. ROTARY	100%
B. 4-STROKE	110%
C. 2-STROKE	120% <<<

5. IR SIGNATURE

A. 4-STROKE	100%
B. 2-STROKE	130% <<<
C. ROTARY	150%

6. EMI/RFI SIGNATURE

A. STARTING FLUID	NO CHANGE FROM GASOLINE
B. FUEL VAPORIZER & BATTERY	NO CHANGE FROM GASOLINE
C. DIRECT INJECTION	SIGNIFICANT BUT UNSPECIFIED INCREASE

Appendix C

Small Business Innovation Research (SBIR) Program

Phase II Proposal

a.

APPENDIX A

U.S. DEPARTMENT OF DEFENSE

SMALL BUSINESS INNOVATION RESEARCH (SBIR) PROGRAM
PROPOSAL COVER SHEET

Failure to fill in all appropriate spaces may cause your proposal to be disqualified.

TOPIC NUMBER: A90-210

PROPOSAL TITLE: Kerosene Base Fuels in Small Gasoline Engines, Demonstration of

FIRM NAME: Sonex Research, Inc.

MAIL ADDRESS: 23 Hudson Street

CITY: Annapolis **STATE:** MD **ZIP:** 21401

PROPOSED COST: $487,500 **PHASE I OR II: PROPOSAL** II **PROPOSED DURATION: IN MONTHS** 13

BUSINESS CERTIFICATION:

	YES	NO
▶ Are you a small business as described in paragraph 2.2?	☒	☐
▶ Are you a minority or small disadvantaged business as defined in paragraph 2.3?	☐	☒
▶ Are you a woman-owned small business as described in paragraph 2.4?	☐	☒
▶ Will you permit the government to disclose the information on Appendix B, if your proposal does not result in an award, to any party that may be interested in contacting you for further information or possible investment?	☒	☐
▶ Has this proposal been submitted to other US government agency/agencies; or DoD components, or other SBIR Activity? If yes, list the name(s) of the agency, DoD component or other SBIR office in the spaces to the left below. If it has been submitted to another SBIR activity list the Topic Numbers in the spaces to the right below:	☐	☒

▶ Number of employees including all affiliates (average for preceding 12 months) 8

PROJECT MANAGER/PRINCIPAL INVESTIGATOR	CORPORATE OFFICIAL (BUSINESS)
NAME: Charles C. Failla	NAME: A. A. Pouring
TITLE: Project Engineer	TITLE: President
TELEPHONE: (301) 266-5591	TELEPHONE: (301) 266-5556

For any purpose other than to evaluate the proposal, this data except Appendix A and B shall not be disclosed outside the Government and shall not be duplicated, used or disclosed in whole or in part, provided that if a contract is awarded to this proposer as a result of or in connection with the submission of this data, the Government shall have the right to duplicate, use or disclose the data to the extent provided in the funding agreement. This restriction does not limit the Government's right to use information contained in the data if it is obtained from another source without restriction. The data subject to this restriction is contained on the pages of the proposal listed on the line below.

PROPRIETARY INFORMATION: None

DISCLOSURE PERMISSION STATEMENTS: All data on Appendix A are releasable. All data on Appendix B, of an awarded contract, are also releasable.

		Pouring	
SIGNATURE OF PRINCIPAL INVESTIGATOR	DATE	SIGNATURE OF CORPORATE BUSINESS OFFICIAL	DATE

Nothing on this page is classified or proprietary information/data.

b.

APPENDIX

U.S. DEPARTMENT OF DEFENSE

SMALL BUSINESS INNOVATION RESEARCH (SBIR) PROGRAM
PROJECT SUMMARY

TOPIC NUMBER: A90-210

PROPOSAL TITLE: **Kerosene Base Fuels in Small Gasoline Engines,**
Demonstration of

FIRM NAME: **Sonex Research, Inc.**

PHASE I or II PROPOSAL: II

Technical Abstract (Limit your abstract to 200 words with no classified or proprietary information/data.)

The objective of the project's Phase II effort is to demonstrate the technology for converting small, inexpensive, commercially available gasoline fueled engines to burn kerosene type fuels. This will lower the life cycle cost of generator sets and will enable a single fuel to be used on the battlefield.

The specific Phase II objective is to :

> Produce a prototype SI engine based on the recommendations of the Phase I study. The engine must start and run according to specifications to be agreed upon using kerosene based fuel and finally be coupled to a generator to demonstrate stable rated performance.

Anticipated Benefits/Potential Commercial Applications of the Research or Development

The proposed Phase II effort will provide an inexpensive lightweight 1.5Kw (approx.) motor-gensrator set that will burn kerosene basefuels and serve as a prototype for sets in the range 0.5 to 3.0Kw. Development of such engines will permit the Army to use a single fuel and will provide a much safer engine for commercial use.

List a maximum of 8 Key Words that describe the Project.

Engine	**Cost**
Genset	**Density**
Diesel	**Kerosene**
Weight	**Commercial**

C. Identification and Significance of the Problem

Sonex Research, Inc., in it's DOD - SBIR Proposal A90-210, Kerosene Base Fuels in Small Gasoline Engines, gave a situation review of the problems related to use of a single battle field fuel in motor generator sets and the importance of this issue relative to "ARMY 21".

Subsequently, Sonex completed Contract No. DAAK-70-91-C-0025, whose objectives were:

1. To assess, analyze and evaluate the merits of:
   - a. Engine types (2,4 stroke cycles, rotary)
   - b. Combustion process for conversion of small (0.5 to 3.0 Kw), SI, gasoline engines to operate on kerosene fuels.
2. To devise and specify conversion modification required for a suitable engine type and combustion system resulting from conclusions of a trade-off study considering all issues relevant to conversion of SI engines to operate on kerosene base fuels, emphasizing minimum life cycle costs, and identifying any development required.

This Phase II Proposal details the effort required to produce the prototype motor-generator set recommended in Phase I, including the work, the schedule and the estimated cost of doing the work proposed.

D. Phase II Technical Objectives

The objective of this phase is to produce a prototype SI engine based on the recommendation of the Phase I study. The engine must start and run according to specification to be agreed upon using kerosene base fuel and finally be coupled to a generator to demonstrate stable rated performance.

E. Phase II Work Plan

In order to achieve the aim of high power density (PMV) at lowest possible cost, commercially available components will be used to the maximum extent. When fabricating any new components required, the simplest approach will be used.

The general approach to be followed is outlined on the following page.

Task No.	Task
1.	Formulate performance specifications for the engine and generator (alternator).
2.	Receive approval of (1).
3.	Select appropriate engine, "generator".
4.	Design modification of all systems per Phase I recommendations.
5.	Fabricate necessary components.
6.	Assemble engine, conduct initial test and evaluation.
7.	Complete any modifications required/repeat (6).
8.	Complete performance test series as agreed upon.
9.	Repeat (7), (8) as required.
10.	Couple engine with "generator".
11.	Complete test series to be agreed upon, complete any modification required, retest.
12.	Prepare report, deliver prototype engine.

In keeping with the philosophy of maximum results at minimum cost, Sonex test and machine shop facilities will be used to the maximum extent. Some outside machining, plant visits to suppliers, etc. is envisioned, however, as well as acquiring some new test equipment.

Schedule

After receipt of contract, the weeks necessary to complete the various tasks of Phase II will be:

Task	No. of weeks	Cumulative No. of weeks
1	1	1
2	1	2
3	1	3
4	4	7
5	4	11
6	4	15
7	12	27
8	4	31
9	12	43
10	2	45
11	4	49
12	8	57

Final Product

The final product to be delivered will be a prototype motor generator set with an SI engine converted to run on kerosene base fuel, accompanied by a detailed report.

F. Related Work (as reported in Phase I proposal)

G. Relationship with Future Research and Development

Anticipated Results

For the first time the Army (and other service branches) will have kerosene fueled, small, lightweight engines capable of powering generators from 0.5 to 3.0 Kw. These engines will have maximum power density available at the lowest life-cycle cost available.

H. Potential Post Award Applications

Government Applications

It is possible that other small engine requirements for "Army 21", fueled by kerosene, can be satisfied by the engine designs resulting from this Phase II study.

Commercial Applications

Two original equipment manufacturers have expressed interest in developing commercial applications of the SCS engines discussed in Phase I. With the prototype proposed for the Phase II, a working demonstrator will be available for evaluation. Commercial development of such units would lower the cost of systems produced for the government.

I. Key Personnel

Individual Resumes

A contribution to this proposed Phase II project will be made by every member of the Sonex technical staff. Charles C. Failla will remain as Project Engineer.

Dr. Andrew A. Pouring has been a director, full-time employee and Chief Scientist of the Company since 1980, serving as its President from April 1980 through November 1983, and as Chief Executive Officer and President from May 1985 through the present. He served as a Professor of Aerospace Engineering at the United States Naval Academy from 1964 to 1983, and was Chairman of the Academy's Department of Aerospace Engineering from 1975 to 1978. He is the principal author of the Company's numerous patents and has contributed most of the patented improvements and extensions to the original discoveries. Since 1964, Dr. Pouring has been a part-time consultant to various companies through Trident Engineering Associates, Inc., a private scientific research and development firm. He is the author of numerous engineering reports, technical papers, and patents. Dr. Pouring is a member of various professional and scientific societies, including the American Society of Mechanical Engineers and the Society of Automotive Engineers, and has been organizer and chairman of many symposia for these societies. Dr. Pouring received his Bachelor's and Master's degrees in mechanical engineering from Rensselaer Polytechnic Institute. He received his Doctor of Engineering Degree and was a Post Doctoral Research Fellow at Yale University.

Mr. Charles C. Failla has been a Director and Vice President-Engineering since the incorporation of the Company. He is in direct charge of the day-to-day operations of the Company's laboratories and test cells and has made significant contributions to recent patents granted to the Company. From 1968 through 1974, Mr. Failla served as commander of a classified aircraft for the U.S. Navy. From 1975 to 1977 he was a Senior Project Engineer with Pacer Systems, Inc. Between 1977 and 1980, Mr. Failla was a mechanical engineering instructor at the U.S. Naval Academy. He received his BS and MS degrees in Aeronautical Engineering from the Naval Post Graduate School in Monterey, California.

Mr. Theodore P. Naydan has been Vice President - Operations since February 1985. He also served as the Company's Secretary, Treasurer and Chief Financial Officer from February 1985 through August 1991. From November 1984 until February 1985, Mr. Naydan was the Vice President for Operations and Engineering at DCTECH Research Center, Inc., a numerically controlled machine tool and CAD/CAM facility. From July 1981 to May 1984, he was the Vice President and General Manager of American Seamless Tubing, Inc., a subsidiary of the Copperweld Corporation. Between June 1968 and April 1981, Mr. Naydan was a commissioned U.S. Navy Officer serving in a variety of positions both on land and on the sea. He later taught at the Mechanical Engineering Department of the U.S. Naval Academy and served as consultant. Mr. Naydan received his BS from the U.S. Naval Academy and MS in Mechanical Engineering from the Naval Postgraduate School in Monterey, California.

Dr. Carlo Leto di Priolo has been the Vice President-International, Vice President - Research and Development and a Director of the Company since November 1983. In 1954 Dr. Leto di Priolo designed and built the first outboard engine which broke the 100 mile per hour barrier on the water. Dr. Leto di Priolo has been a consultant to various automotive companies, including Lancia, Ferrari and Fiat. Between 1953 and 1981, he also operated one of the largest outboard motor distribution companies in Europe, and between 1946 and 1982, he owned and operated Misal S.p.A., a major European tool company. He received his Mechanical Engineering Degree from Polytechnic Institute, Milan, Italy.

Mr. William P. McCowan, Junior Engineer

Technical experience: Twenty-three years of engine design and fabrication; co-designer of all Sonex 4-stroke products; twelve years of experience in engine instrumentation and testing.

Mr. Brad R. Bopp, Technician

Technical experience: Six years of engine development experience with emphasis on exhaust emissions, pollutants and alternate fuels; Expert in exhaust emission instrumentation selection, installation and repair.

Relevant Publications

Blair, G.P., Johnston, M.B.; Unsteady Flow Effects in Exhaust Systems of Naturally Aspirated, Crankcase Compression, Two Cycle Internal Combustion Engines, SAE 680594.

Blair, G.P., Johnston, M.B.; The Development of a High Performance Motorcycle Engine, I Mech. E. 1970.71 Volume 185 20/71.

Johnston, M.B.; Exhaust Port Shapes for Sound and Power, SAE 730815.

Pouring, A.A., Blaser, R.F., Keating, E.L., Rankin, B.H.; The Influence of Combustion with Pressure Exchange on the Performance of Heat Balanced I.C. Engines, SAE 770120.

Pouring, A.A., Failla, C.C., Rankin, B.H., Keating, E.L., Riddell, F.; Parametric Variations of Heat Balanced Engine, Fluid Mechanics of Combustion Systems Symposium, A.S.M.E., June 1981.

Allen, J., Pouring, A.A., Keating, E.L.; Heat Balanced I.C. Engine Transition Studies, AIAA-82-1116, AIAA/SAE/ASME 18th Joint Propulsion Conference, June 1982.

Pouring, A.A. and Rankin, B.H.; Time Dependent Analytical and Optical Studies of Heat Balanced Internal Combustion Engine Flow Fields, AIAA-82-1116, June 1982.

Keating, E.L., and Pouring, A.A.; Controlled Regenerative Dual Cycle Analysis, AIAA-85-1413, AIAA/SAE/ASME/ASEE 21st Joint Propulsion Conference, June 1985.

Pouring, A.A., Keating, E.L., Failla, C.C., Leto di Priolo, C; Evidence for Chemical-Acoustic Interaction in I.C. Engines, AIAA-86-0527, January 1986.

Pouring, A.A., Failla, C.C., Leto di Priolo, C., and Keating, E.L.; Octane Insensitivity of Supercharged I.C. Engines Using Chemical-Acoustic Charge Conditioning, ASME Automotive Engine Technology Symposium, 87-ICE-23, February 1987.

Pouring, A.A., and Slee, R.; A Review of Key Concepts of Resonant-Pulsed Combustion in I.C. Engines, 11th International Colloquium on Dynamics of Explosions and Reactive Systems, Warsaw, Poland, August, 1987.

Pouring, A.A., Failla, C.C., and Johnston, M.B.; Resonant Pulsed Combustion in Two Stoke I.C. Engines. Unmanned Systems, Summer 1987.

Pouring, A.A, Chemical Acoustic Charge Conditioning for Low Emission IC Engines, 1st International Conference on Combustion Technologies for a Clean Environment, Vol. I, Vilamoura (Algarve) Portugal, September 1991.

J. Facilities and Capital Equipment.

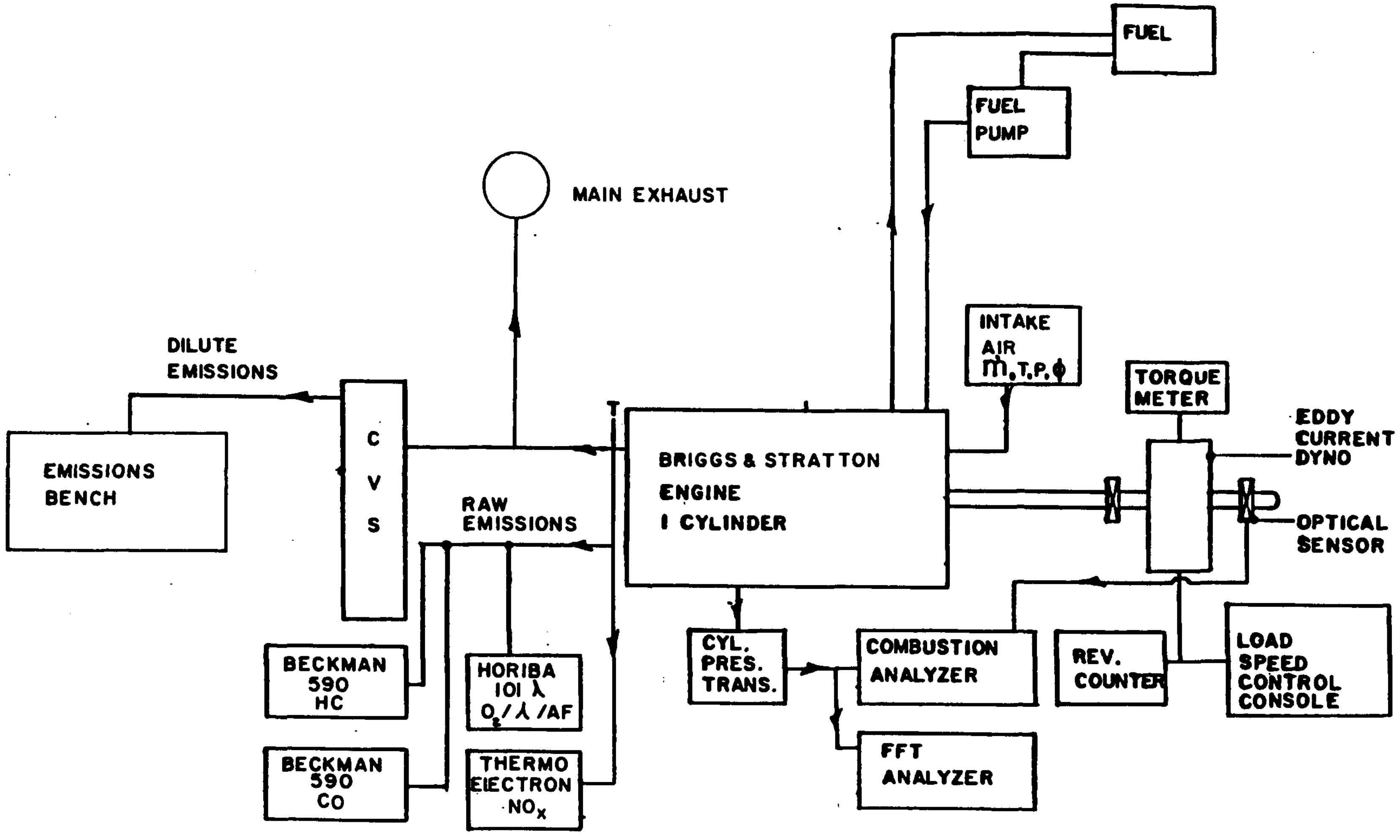
Sonex holds a long term lease on approximately 6000 square feet of office and laboratory space in its Annapolis facility. This lease runs through April 1994 and can be extended. The laboratory section has five large, modern test cells, each equipped with an engine dynamometer. One of these test cells is dedicated to this project.

A layout of experimental apparatus, all of which is either fully owned or controlled by Sonex, for this test cell is provided in Figure J.1. In addition to the test equipment, Sonex owns a machine shop with excellent machining and welding capabilities. This shop enables Sonex to fabricate components required to modify test engines to the Sonex designs.

The current Sonex Research test facilities meet all known federal, Maryland and local government laws and regulations pertaining to airborne emissions, waterborne effluents, external radiation levels, outdoor noise, solid and bulk waste disposal, and the handling and storage of toxic and hazardous materials.

K. Consultants

Dr. Mervyn B. Johnston was employed by the company from July 1986 to February 1991, as Project Engineer, Two-cycle engine development programs. From 1984 to 1986 he was Manager of Engineering Design at Chicago Pneumatic, a major U.S. air tool manufacturer. Prior to Chicago Pneumatic he was Director of Engineering for the Roper Corporation, a manufacturer of outdoor power equipment for both the consumer and commercial markets. From 1970 to 1977 he was Director of Research and Development at Homelite, a major U.S. chainsaw manufacturer. Dr. Johnston received both his Bachelors and Ph.D degrees from the Queen's University of Northern Ireland, with a specialty in the theoretical unsteady gas dynamics of particle flow in internal combustion engines.



LAYOUT OF EXPERIMENTAL APPARATUS

Figure J.1

APPENDIX C

U.S. Department of Defense
SMALL BUSINESS INNOVATION RESEARCH (SBIR) PROGRAM
PHASE II - FY1991
COST PROPOSAL

ITEM#

1. Name of offeror: Sonex Research, Inc.

2. Home office address: 23 Hudson Street
Annapolis, Maryland 21401

3. Research facility address: Same

4. Proposal title: Kerosene Base Fuels in Small Gasoline Engines, Demonstration of

5. Topic number: A90-210

6. Proposed cost: $487,500

7. Direct material cost: $10,000

8. Material overhead: 0

9. Direct labor:

Personnel	Estimated hours	Rate (rounded)	Amount
Principal Investigator	342	$60	$20,409
Program Manager	570	49	27,930
Project Engineer	912	49	44,688
Junior Engineer	1,368	33	45,076
Technician	1,368	17	23,324
Totals	4,560		$161,427

10. Labor Overhead:

Total direct labor hours 432

Direct labor overhead rate $21.24

Total $96,856

11. Special testing: Cold room facilities rental $26,250

APPENDIX C

ITEM#			
12.	Special equipment: Combustion Analyzer		$30,000
13.	Travel:		$7,500
14.	Consultants:		$13,200
15.	Other direct costs: Fuel, supplies, etc.		$9,500
16.	General and Administrative Expense:		
	Total direct labor	$161,427	
	G&A as a percentage of direct labor	67%	
	Total		$108,156
17.	Royalties:		0
18.	Fee or profit:		$24,611
19.	Total estimate cost and profit:		$487,500

20. Signature:

George E. Ponticas
Chief Financial Officer

Date

21. a. Has any executive agency of the United States Government performed any review of your accounts or records in connection with any other government prime contract or subcontract within the past twelve months? NO

b. Will you require the use of any government property in the performance of this proposal? NO

c. Do you require government contract financing to perform this proposed contract? NO

Progress payments are requested as follows:

$30,000 payable upon commencement for equipment purchase
$35,192 payable monthly thereafter for twelve months
$35,196 payable upon delivery of report

22. Type of contract proposed: Firm fixed price

KEROSENE BASE FUELS IN SMALL GASOLINE ENGINES

Report No. U.S. ARMY/CR91/A90-210

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