Energy Depot Concept

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Ammonia as an Engine Fuel

Walter Cornelius,
L. William Huellmantel, and Harry R. Mitchell
Research Laboratories, General Motors Corp.

THIS EVALUATION OF AMMONIA as an engine fuel was performed by the General Motors Research Laboratories in support of the energy depot concept proposed by the Allison Div. of the General Motors Corp. (1).* The objective of the energy depot concept is to free the Armed Forces from reliance on hydrocarbon fuels. One method is the production of a fuel from water and air. Of the potential fuels which might be produced, anhydrous ammonia (NH_3) was considered to offer the most advantages. The energy required to synthesize this fuel would be provided by a mobile nuclear reactor. The General Motors Research Laboratories undertook the task of evaluating anhydrous ammonia as a fuel for spark-ignited reciprocating engines.

The chemical equation below describes the combustion of a stoichiometric mixture of ammonia and air:

$$2\,NH_3 + 1.5\,(O_2 + 3.76\,N_2) \longrightarrow 3\,H_2O + 6.64\,N_2$$

Table 1 is a tabulation of those properties of ammonia and a typical commercial gasoline that have an effect on combustion.

As shown, the heating value of gasoline is 2.4 times that of ammonia. However, the stoichiometric air-fuel ratio for

Table 1 - Comparison of Properties of Anhydrous Ammonia and Gasoline

	Ammonia	Typical Gasoline
Chemical formula	NH_3	CH_x
Density, lb/gal	5.1	6.1
Boiling point (1 atm), F	-28	**
Freezing point, F	-108	-76
Vapor pressure (70 F), psia	128.8	**
Heat of vaporization (70 F), Btu/lb	508.6	116
Heat of combustion (Lower heat value -- gaseous), Btu/lb	8000	18,900
Stoichiometric air-fuel ratio	6.06	14.5
Stoichiometric heat release (weight), Btu/lb air	1320	1285
Stoichiometric heat release (Vol), Btu/ft^3 mixture	77.3	96.5
Octane rating -- Research Method (Min)	> 111	91

**Values not comparative with other data.

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*Numbers in parentheses designate References at end of paper.

ABSTRACT

Studies were conducted using spark-ignited reciprocating engines to evaluate ammonia as an alternate fuel for certain military applications. Conventional engines were found to perform poorly on ammonia. Several practical methods for improving engine performance while burning ammonia are described which include increased spark energy, increased compression ratio, engine supercharging, and hydrogen addition to the fuel. Dissociation of ammonia was investigated as a practical means for supplying hydrogen to an engine. The study indicates that satisfactory engine performance can be obtained while burning ammonia. Auxiliary equipment and controls necessary for vehicular use will require development.

ammonia is 6.06:1 as compared to a much leaner ratio of about 14.5:1 for gasoline. Based on equal volumes of stoichiometric air-fuel mixtures, the heat content of the ammonia-air mixture is about 80% of that of the gasoline-air mixture. Therefore, since a reciprocating engine is essentially a positive displacement device, the power produced with an ammonia-air mixture would not be expected to exceed about 80% of that produced with a mixture of gasoline and air, if the engine were normally aspirated in both cases. The high octane rating of ammonia is another important factor that must be taken into account when comparing performances of ammonia and gasoline in an engine. This permits higher compression ratios and supercharging to be used, which improve performance. Also, the heat of vaporization of ammonia is 4.4 times that of gasoline, and the engine consumes 2.4 times as much fuel by weight for equal power outputs because the heat of combustion of ammonia is lower. Therefore, ammonia fuel requires 10.3 times as much heat for vaporization as gasoline. This points out the need for a vaporizer when using gaseous ammonia as an engine fuel.

The use of ammonia as a fuel for internal combustion engines has been investigated in Europe. However, very limited information is available describing engine performance. The first practical use of ammonia as a fuel on a limited scale is believed to have been performed by Ammonia Casale Limited in 1935 (2). A second and more extensive application, the Gazamo Process, was tried on vehicles in Belgium during 1942 (3). In the Gazamo Process, the engine was supplied with a mixture of ammonia vapor and coal gas. Hydrogen that was present in the coal gas was used to promote the ignition of ammonia. Flow regulation and proportioning of the ammonia vapor and the coal gas were accomplished manually by the operator of the vehicle. This particular program was undertaken because of a shortage of petroleum fuel created by World War II and was terminated when this fuel shortage was relieved.

The experimental program undertaken at the General Motors Research Laboratories was to determine the feasibility of burning ammonia in a spark-ignited reciprocating engine. The major objectives were:

1. To evaluate the effects of various engine design and operational parameters on engine performance while burning ammonia.
2. To determine what minimum modifications to a conventional engine are required to provide engine performance on ammonia equivalent to that developed while using commercial gasoline.

Initial investigations were conducted on a single-cylinder test engine. These engine studies were of a basic nature and fulfilled the first major objective of the fuel evaluation program. In view of the encouraging results obtained on the single-cylinder engine, a conventional multicylinder automotive engine was procured and performance evaluations of the engine were begun. Only preliminary tests have been performed on the multicylinder engine. As a result, most of the experimental findings discussed in this paper are based on single-cylinder engine tests.

TEST EQUIPMENT AND PROCEDURE

Single-Cylinder Engine Installation - Fig. 1 shows the test cell installation of the single-cylinder engine. This overhead-valve engine has a displacement of 27 cu in., a bore of 3.375 in., a stroke of 3.018 in., and a nominal compression ratio of 9.4:1. The ignition system used initially was similar to conventional production equipment used on a 6 cyl automotive engine, with one exception: the standard high resistance carbon ignition cable was replaced with a conventional high tension cable. A standard AC spark plug of heat range type 44 was used. A fuel-air mixing chamber was substituted for the carburetor when ammonia was burned. It insured adequate mixing of the gaseous ammonia and air. A positive crankcase ventilation system was installed to safeguard against the possibility of a crankcase explosion. Engine airflow was measured by means of critical flow orifices; fuel flow was measured with a variable area flow meter.

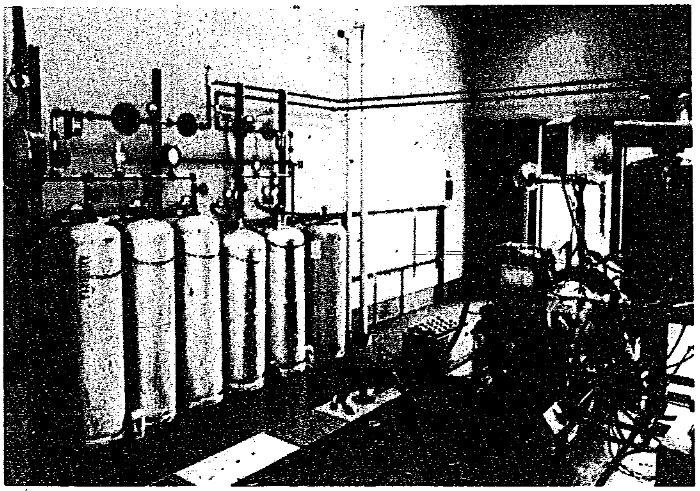

Fig. 1 - Test cell installation of single-cylinder engine and ammonia fuel supply system

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Compressed air from the air supply system of the test building was used when supercharging of the single-cylinder engine was investigated. The compressed air was flowed through electrical heating elements to simulate the rise in air temperature that would be incurred if an actual supercharger had been used.

Multicylinder Engine Installation - The test engine used was a 215 cu in. V-8 engine equipped with a turbosupercharger. Fig. 2 shows the engine installed on the test stand and equipped for operation on ammonia fuel. It is an aluminum engine with a nominal compression ratio of 10.25:1.

The turbosupercharger is powered by engine exhaust gas. The supercharge pressure was limited to 18 in. Hg gage.

The carburetor, which is normally mounted on the compressor inlet flange, was removed and replaced by an ammonia-air mixing chamber. The ammonia and air flows were each manually controlled and proportioned. As in the case of the single-cylinder engine installation, the flows were measured separately and the air and fuel were then introduced into the mixing chamber prior to admittance into the engine.

The standard engine ignition system was employed during preliminary engine tests. Ignition components similar to those used on the single-cylinder test engine were then substituted.

Fuel Systems - Gaseous ammonia was injected into the engine induction systems of both test engines. The fuel systems provided to accomplish this were similar in principle for the two engines but the system for the multicylinder engine was more complex. The fuel system for the single-cylinder engine was installed in the engine test cell and is shown in Fig. 1. Heat had to be provided to vaporize the ammonia in the multicylinder engine system, whereas sufficient heat was transmitted through the walls of the storage vessels in the single-cylinder engine system to cause vaporization.

Fig. 3 is a schematic of the ammonia fuel supply system for the multicylinder engine. Fig. 4 shows the fuel storage

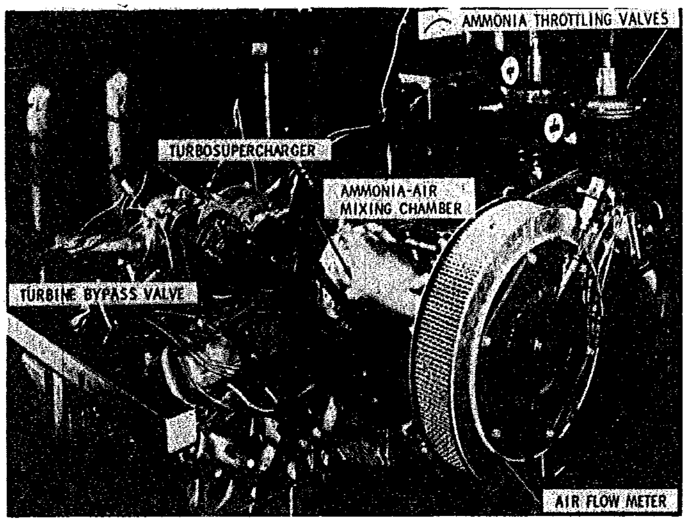

Fig. 2 - Test cell installation of multicylinder engine prepared for operation on ammonia fuel

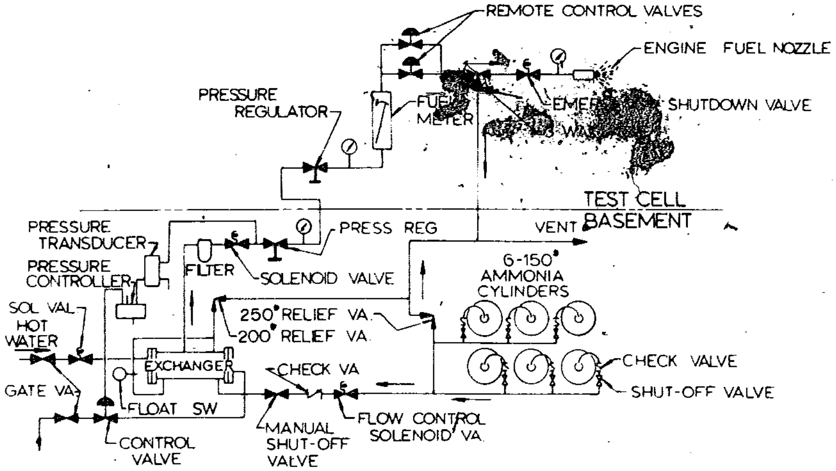

Fig. 3 - Schematic of ammonia fuel system for multicylinder engine

portion of the system that was located external to the engine test cell. Liquid ammonia was stored in six tanks each containing 150 lb of ammonia when full. During engine operation, the saturation pressure of ammonia (approximately 120 psig at room temperature) forced liquid ammonia into the heat exchanger where the ammonia was vaporized. Hot water was used to provide the heat required to vaporize the ammonia. The level of the liquid ammonia in the heat exchanger was controlled with a float switch which governed the operation of a solenoid valve located in the fuel line between the tanks and the heat exchanger. The flow of hot water through the heat exchanger was controlled automatically. From the heat exchanger, the gaseous ammonia flowed through two pressure regulators, to reduce its pressure, and through two variable area flow meters and manually controlled throttling valves. The gaseous ammonia was then admitted into the ammonia-air mixing chamber through four nozzles.

The addition of hydrogen to the ammonia was investigated only on the single-cylinder engine. For this investigation, gaseous hydrogen from high pressure bottles was added to the ammonia in the engine fuel-air mixing chamber. The hydrogen supply system used was similar to the ammonia supply system.

Exhaust Gas Sampling and Analysis Procedures - Chemical observations were employed, when feasible, to assist in the interpretation of performance measurements on the single-cylinder and multicylinder engines. To obtain chemical data, it was necessary to develop specialized gas sampling equipment and sampling techniques and to develop chemical and chromatographic instrumentation and analysis procedures. In several instances, calculating procedures had to be devised to reduce the experimental data.

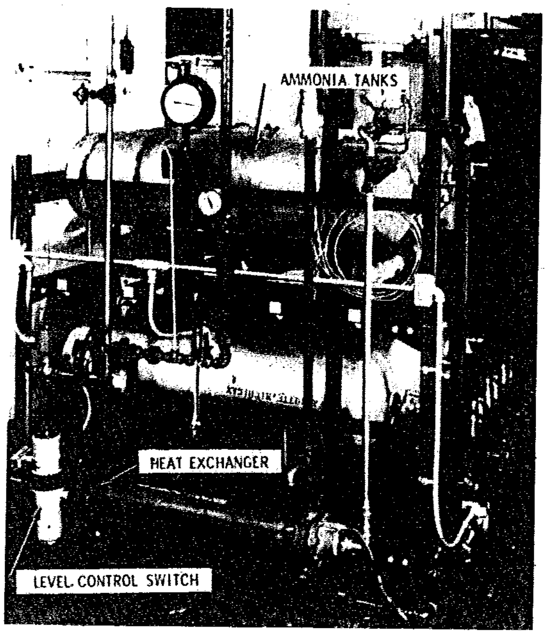

Fig. 4 - Ammonia fuel supply and control system for multicylinder engine

One important area of interest was the collection and analysis of gas samples from the exhaust manifold of the single-cylinder engine. Gas samples were collected in pre-evacuated bottles in such a manner that the concentrations of exhaust gas constituents approximated those in the actual engine exhaust gas stream.

Each gas sample was analyzed as required for ammonia, hydrogen, oxygen, and oxides of nitrogen. Standard spectrophotometric procedures were employed to determine the concentration values of ammonia and oxides of nitrogen. Oxygen concentrations were determined with an Orsat device. Gas chromatography was used to measure the concentration of hydrogen. The experimentally determined concentration values for the exhaust gas constituents were then expressed in suitable weight units and were substituted into appropriate reaction equations together with related engine fuel flow and airflow measurements.

Only three principle reactions were considered when characterizing the combustion process in mathematical terms. These reactions were: the simple oxidation of ammonia, the oxidation of hydrogen, and the dissociation of ammonia. The oxidation of ammonia to oxides of nitrogen was ignored since this reaction would have little effect on the calculated results.

An iterating procedure was employed to reconcile the reactant and product values in the reaction equations. This procedure naturally became more involved as the number of equations requiring simultaneous solution increased. In the case of the ammonia-hydrogen fuel mixtures investigated, it was assumed that all of the hydrogen that was inducted into the engine was burned. The unreacted oxygen remaining after the hydrogen-air reaction was satisfied was then applied to the combustion of ammonia. In general, satisfactory solutions of the combustion equations were realized after a relatively few trial calculations were made. Some typical reactant data and exhaust product data obtained from balancing these combustion equations are listed in Table 2.

Concentration values for the exhaust gas constituents have been used to determine:

1. The per cent of the ammonia inducted into the engine that actually burned.
2. The effect of engine operation on air pollution.

General Test Procedure - The single-cylinder engine was run on ammonia at both part-throttle and full-throttle settings over a wide engine speed range. Only full-throttle performance of the multicylinder engine was evaluated while burning ammonia. Normally-aspirated and supercharged modes of operation were investigated on both engines. At each engine operating condition investigated, performance data were obtained at the minimum spark advance for best torque (MBT spark advance) and the leanest air-fuel ratio for best torque (LBT air-fuel ratio).

When the single-cylinder engine was run on gasoline, performance data were obtained also at minimum spark advance and leanest air-fuel ratio settings for development of maximum power. However, multicylinder engine performance with gasoline was obtained with a standard production engine of a similar type.

All single-cylinder engine performance data were calculated on an indicated basis. When supercharged operation of the engine was evaluated, the performance data were corrected to account for the power required to compress the engine air with a 75% efficient compressor.

SINGLE-CYLINDER ENGINE STUDIES

Initial Operation on Ammonia - At the outset of the fuel evaluation program, serious doubt was raised as to whether an ammonia-air mixture could be ignited and combustion sustained in a spark-ignited internal combustion engine. The limited technical literature found on the subject of ammonia combustion was not encouraging. Therefore, it was heartening when ignition of ammonia was achieved in the single-cylinder engine, using a conventional automotive-type ignition system and a primary voltage of 12 v, and the engine could be run over a limited speed range and develop some useful work.

Fig. 5 presents indicated horsepower and thermal effi-

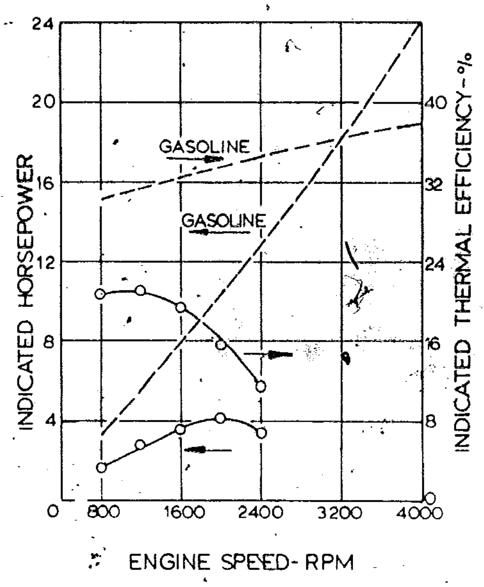

Fig. 5 - Performance of unmodified single-cylinder engine on ammonia and gasoline -- full-throttle normally aspirated operation, 9.4:1 compression ratio

Table 2 - Reactant and Exhaust Product Data

	Fuel Mixtures					
	1		2		3	
Reactants						
Ammonia, lb/hr	13.6		13.0		11.6	
Hydrogen, lb/hr	0.0		0.0		0.24	
Air, lb/hr	75.9		77.9		79.0	
A/F, % Theoretical air mixture	92.2		98.8		100.5	
Excess ammonia, lb/hr	1.07		0.15		0.0	
Combustion Data						
Ammonia burned, lb/hr	8.77		8.93		11.32	
Ammonia burned, % of inducted	64.5		68.6		97.5	
Exhaust Products - Experimental Data						
Ammonia in 1 pt sample bottle, mg	22.9		20.0		1.1	
Sample bottle pressure, in. Hg vac	3.7		2.6		3.5	
Hydrogen, % by vol	0.6		0.5		0.2	
Barometer, 29.25 in. Hg abs						
Exhaust Products - Calculated Data						
	lb/hr	ft^3/min	lb/hr	ft^3/min	lb/hr	ft^3/min
Ammonia	4.63	1.63	3.92	1.37	0.23	0.08
Hydrogen	0.03	0.10	0.03	0.09	0.01	0.03
Water	13.95	4.64	14.20	4.72	20.11	6.69
Oxygen	5.29	0.99	5.55	1.04	0.56	0.10
Nitrogen	65.51	14.00	67.17	14.38	69.93	14.92

ciency curves that were obtained at wide-open throttle while running the engine normally aspirated both on ammonia and on gasoline. An inspection of these plotted data shows that the engine performed poorly on ammonia. The maximum power developed at 2000 rpm was only 17.5% of the maximum power obtained at 4000 rpm while burning gasoline. Also, the maximum indicated thermal efficiency of the engine was 21% as compared to 38% when gasoline was used. Development of useful horsepower ceased when the engine speed was raised above 2400 rpm while burning ammonia.

The inability to burn ammonia effectively in the engine was judged to be the primary reason for the poor performance of the engine with this fuel. This observation was supported by chemical analyses of the engine exhaust gas that disclosed the presence of significantly large amounts of ammonia in the exhaust gas at full-throttle operating conditions. Therefore, considerable effort was devoted to obtaining representative engine exhaust gas samples and to developing a procedure for calculating from the exhaust data the per cent of inducted ammonia burned in the engine.

The following practical corrective actions were considered for improving the ignitability and combustion of ammonia in a spark-ignited engine:

1. Increase in spark energy.
2. Multiple ignition.
3. Increase in compression ratio.
4. Fuel additive for promoting the combustion of ammonia.

It was also realized that complete combustion of ammonia in a normally aspirated engine will not result in the development of as great a maximum engine power as that obtained while burning gasoline under similar engine operating conditions. The difference in energy content of equal volumes of stoichiometric gasoline-air and ammonia-air mixtures preclude this possibility. Supercharging the ammonia-fueled engine is a logical means for overcoming this power disparity. The relatively high octane rating of ammonia makes this a feasible approach.

All of these suggested corrective measures were subsequently evaluated on the single-cylinder engine with considerable success.

Effect of Ignition System Modifications - The first method that was investigated to improve the combustion of ammonia in the single-cylinder engine was the modification of the engine ignition system. The standard coil and 1.5 ohm primary circuit resistor were replaced with a high performance coil and a 1.0 ohm resistor to increase the spark energy. The primary voltage was increased from 12 to 13.6 v which approximates the voltage used in most current automotive engines.

Full-throttle engine tests were conducted to determine the effect of spark plug gap size on power output. It was found that engine performance was affected noticeably by variation in gap size, and that a gap of about 0.085 in. resulted in maximum power output.

The effect of these ignition system modifications on engine indicated power is shown in Fig. 6, together with indicated power data obtained while burning gasoline in the single-cylinder engine. Also shown in the figure are engine power data obtained while burning ammonia and using a dual ignition system. The maximum power of the engine was increased about 80% and useful power could be developed up to a speed of about 3200 rpm by replacing the standard ignition system with the single modified ignition system. A further gain of about 20% in power was realized when the dual modified ignition system was used.

Tests in which each of the two ignition systems were used separately disclosed that greater engine power was developed with the spark plug in the standard location than in the alternate location. Therefore, it is believed that further improvement in engine performance could have been realized by locating the second spark plug in a more favorable position.

Fig. 7 presents plots of the MBT spark advances and LBT air-fuel ratios established while operating on ammonia and using the single modified ignition system. Also plotted is the MBT spark advance curve for gasoline. As shown in the figure, the spark advances for ammonia are considerably greater than those for gasoline, indicating the relatively slow burning rate of ammonia.

The maximum power air-fuel ratio for ammonia varied from about 6.1:1 to 6.8:1. These air-fuel ratios are slightly leaner than the stoichiometric air-fuel ratio of 6.06:1 of an ammonia-air mixture.

Although the ignition system modifications resulted in a considerable improvement in engine performance, the power differential between gasoline and ammonia fuels was still greater than the theoretical difference. Chemical analyses of the engine exhaust gases indicated that an appreci-

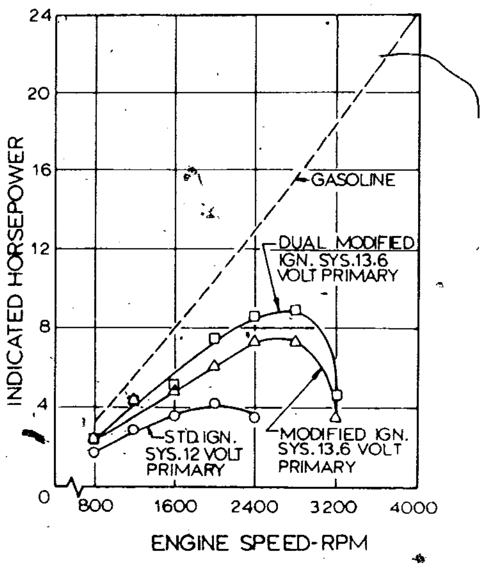

Fig. 6 - Increased power of single-cylinder engine through ignition system modifications -- ammonia fuel, full-throttle normally aspirated operation, 9.4:1 compression ratio

able amount of ammonia was still passing through the engine without burning.

Effect of Increased Compression Rat[illegible]o further improve the combustion of ammonia in the single-cylinder engine, compression ratios greater than 9.4:1 were investigated. Increases in engine compression ratio to 11.5:1, 15:1, and 18:1 were accomplished by substituting stepped-head pistons for the original flat-head piston.

Fig. 8 presents indicated horsepower curves for the various compression ratios tested and the power curve obtained while burning gasoline in the engine at the 9.4:1 compression ratio. These ammonia data and all subsequent full-throttle single-cylinder engine data discussed in this paper were obtained while using the single modified ignition system and a primary voltage of 13.6 v.

It will be noted in Fig. 8 that a sizable gain in engine power was obtained when the compression ratio was increased from 9.4:1 to 11.5:1. The maximum power was increased 59%. Further increases in compression ratio from 11.5:1 to 15:1 and to 18:1 had negligible effects on indicated power development at engine speeds below about 2400 rpm, but did result in increased engine power at higher speeds. The maximum power was increased 68% with the 15:1 compression ratio and 84% with the 18:1 compression ratio above that obtained with the 9.4:1 compression ratio. Maximum power occurred at 3200 rpm in the case of both of these higher compression ratios. However at speeds above 3200 rpm, engine power fell off rapidly.

In comparing the power curves for ammonia at these three higher compression ratios with the gasoline power curve, it can be seen that at speeds below about 2600 rpm the power produced with ammonia was about 80% of that obtained with gasoline. This is approximately the theoretical power ratio for the two fuels based on heating values and stoichiometric air-fuel ratios.

Fig. 9 illustrates the influence of engine compression ra-

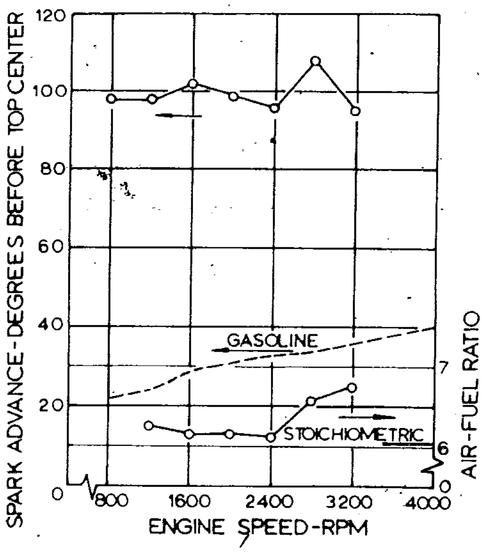

Fig. 7 - MBT spark advances and LBT air-fuel ratios for single-cylinder engine -- ammonia fuel, full throttle normally aspirated operation, modified ignition system, 9.4:1 compression ratio

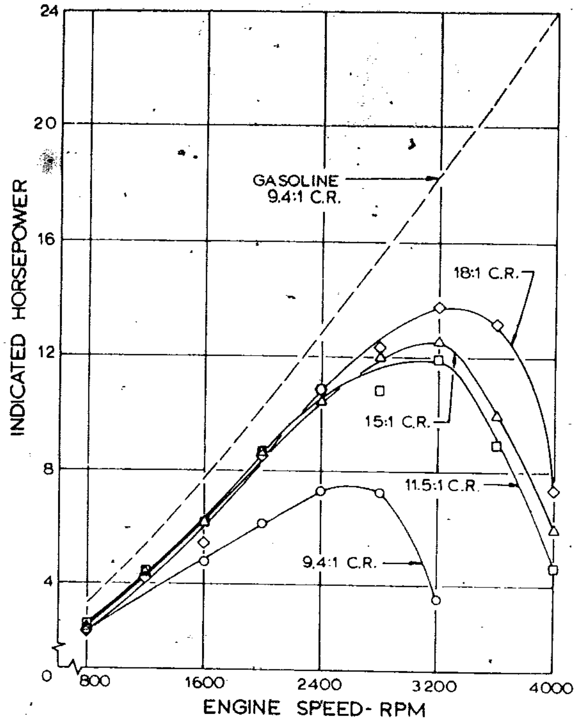

Fig. 8 - Improved performance of single-cylinder engine due to increased compression ratio -- ammonia fuel, full-throttle normally aspirated operation, modified ignition system

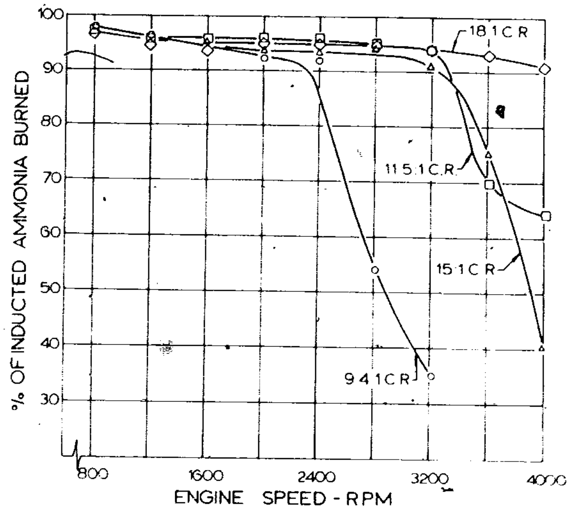

Fig. 9 - Improved combustion of ammonia in single-cylinder engine by increasing compression ratio -- full-throttle normally aspirated operation, modified ignition system

tio on the percentage of the inducted ammonia burned in the engine. The beneficial effect of increased compression ratio became measurable at an engine speed of 2000 rpm and became progressively more pronounced as the engine speed was increased further. These data emphasize the problem that is encountered when burning a fuel with a decidedly slower flame speed than that of a hydrocarbon fuel. In this case, the combustion of ammonia was promoted by increased cylinder pressure, temperature, and turbulence that accompanied an increase in compression ratio.

Piston shape may be partly responsible for the improvement in the combustion process realized by increased compression ratio. The greatest gain was made when the flat-head piston (9.4:1 compression ratio) was replaced with a stepped-head piston (11.5:1 compression ratio). The protrusion of the upper step of each stepped-head piston into the cylinder head probably caused an increase in gas turbulence in the combustion chamber and thus improved the combustion of ammonia. Further tests would have to be made to determine which factor, compression ratio or piston head shape, was more responsible for the improved engine performance. No attempt was made to develop a combustion chamber shape that would contribute to a more rapid burning of the ammonia.

Effect of Supercharging - To obtain a maximum power output with ammonia commensurate with that obtained with gasoline, supercharging of the single-cylinder engine was investigated. The increased charge density due to supercharging should overcome the theoretical power differential for the two fuels.

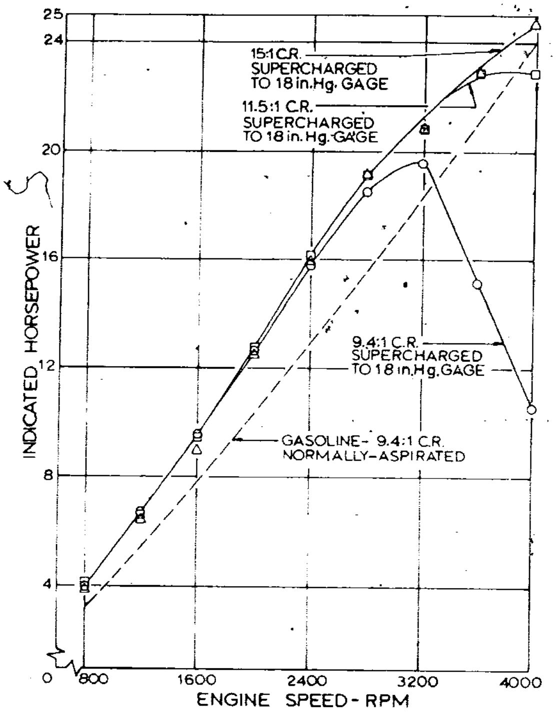

Fig. 10 - Increased performance of single-cylinder engine due to supercharging -- ammonia fuel, modified ignition system

The indicated horsepower data obtained while burning ammonia at supercharged engine conditions are shown in Fig. 10. Also shown again for the purpose of comparison is the indicated horsepower curve for the engine that was obtained while operating normally aspirated on gasoline at a compression ratio of 9.4:1. A supercharge pressure of 18 in. Hg gage was used. Failure of the 18:1 compression ratio piston due to insufficient diametrical clearance precluded testing of this piston at supercharged engine operating conditions.

The curves in Fig. 10 show that compression ratio had a negligible effect on supercharged engine performance at speeds below approximately 2400 rpm. However, at higher speeds, increasing the compression ratio resulted in a significant improvement in engine indicated power. These power gains at high engine speeds were the result of increased burning of the ammonia in the engine (Fig. 11).

Fig. 10 shows also that the engine power developed with ammonia over the entire engine speed range tested can be made to exceed that obtained while burning gasoline at a 9.4:1 compression ratio and normally aspirated engine operating conditions. This was accomplished by using the 15:1 compression ratio piston and a supercharge pressure of 18 in. Hg gage. The other compression ratios evaluated resulted in power outputs greater than those for gasoline over most of the speed range, but fell below those for gasoline at high speeds.

Part-Throttle Engine Considerations - Previously described engine tests indicate that a spark-ignited ammonia-fueled engine can be supercharged to provide full-throttle performance commensurate with that realized in current automotive gasoline engines. However, adequate full-throttle performance is but one of many requirements of a vehicular

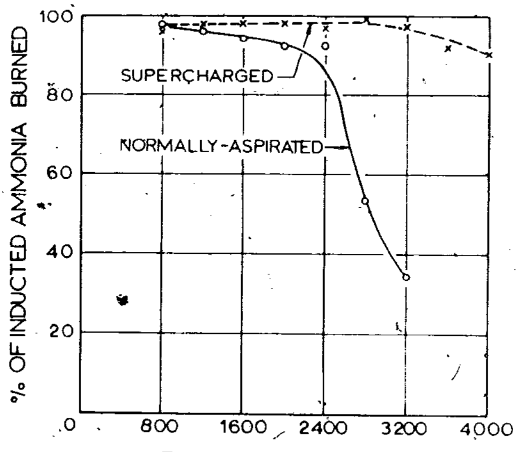

Fig. 11 - Improved combustion of ammonia in single-cylinder engine by supercharging -- modified ignition system, 9.4:1 compression ratio

engine. Satisfactory part-throttle performance cannot be overemphasized because a vehicular engine is operated most of the time at part loads. In the case of vehicle operation, the range, the amount of fuel required for acceptable range, and the operating cost of the vehicle are each dependent on the part load fuel economy of the engine.

Of all of the engine modifications evaluated on the single-cylinder engine, only compression ratio and ignition systems should have significant influences on part-throttle performance. For this reason, the effects of these two engine variables on part load efficiency of the single-cylinder ammonia-fueled engine were investigated.

Fig. 12 shows the effect of compression ratio and dual ignition on indicated thermal efficiency of the single-cylinder engine at various load settings. Typical data are presented that were obtained at an engine speed of 1600 rpm. For comparison purposes, part-throttle data for one cylinder of a multicylinder engine are included that were obtained during operation on gasoline. The displacement per cylinder of this engine is equal to that of the single-cylinder test engine. The road load requirement per cylinder of the multicylinder engine is indicated also on the figure.

It can be seen that for each compression ratio investigated, the indicated thermal efficiency of the single-cylinder engine diminished rapidly as engine load was reduced from full load to road load. At full throttle, the thermal efficiency approximated that of the multicylinder engine but was considerably less than that of the gasoline engine in the vicinity of road load. Only a slight improvement in single-cylinder engine efficiency was realized with dual ignition. As a result, it was felt that satisfactory part-throttle performance of a spark-ignited ammonia-fueled engine could not be realized by engine modifications.

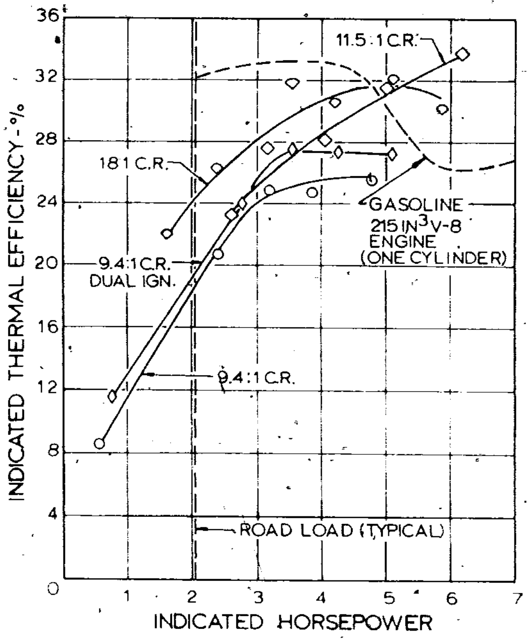

Fig. 12 - Minor improvements in part-throttle thermal efficiency of single-cylinder engine due to increased compression ratio and dual ignition -- ammonia fuel, modified ignition systems.

Hydrogen Enrichment of Ammonia - The possibility of enrichening the ammonia with hydrogen was considered as a means of improving the part-throttle performance of a spark-ignited ammonia-fueled engine. The use of hydrogen to promote the combustion of ammonia is a logical choice because it could be produced on the vehicle itself by decomposing some of the ammonia fuel in a catalytic dissociator. Hydrogen can be ignited readily and has a high flame speed.

The addition of a relatively small amount of hydrogen to the ammonia fuel was found to result in an appreciable improvement in the part-throttle performance of the single-cylinder test engine. A 2.5% by weight addition of hydrogen was found to result in the best performance at the speeds investigated. The effect of this amount of hydrogen enrichment on indicated thermal efficiency of the engine at part load is shown in Fig. 13 for an engine speed of 1600 rpm. As in Fig. 12, comparable multicylinder gasoline engine data are plotted.

It will be seen in Fig. 13 that hydrogen enrichment resulted in a sizable gain in indicated thermal efficiency of the single-cylinder engine over the entire load range investigated. The engine efficiency values obtained with the ammonia-hydrogen mixture were higher than those for gasoline over most of the load range. In view of these test results and supporting data at other engine speeds, it would

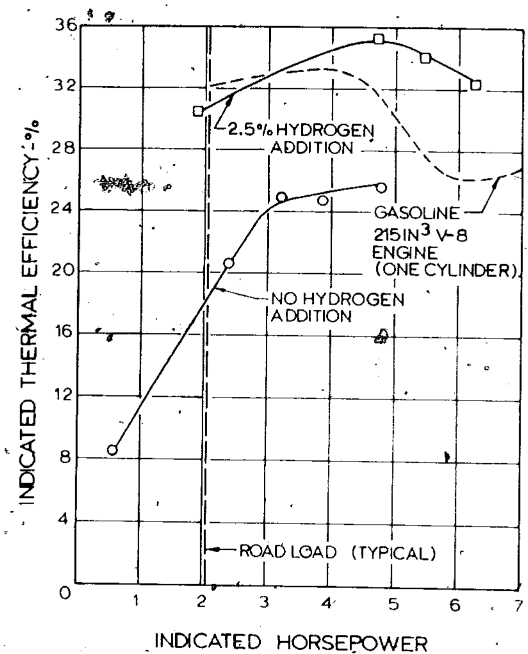

Fig. 13 - Improved part-throttle thermal efficiency of single-cylinder engine due to hydrogen addition to ammonia -- modified ignition system, 9.4:1 compression ratio

appear that hydrogen enrichment of ammonia offers a feasible scheme for obtaining satisfactory part-throttle performance of a spark-ignited ammonia-fueled engine. Further tests were performed on the single-cylinder engine to evaluate the influence of hydrogen addition to ammonia on full-throttle performance. Both normally aspirated and supercharged engine operations were investigated.

Fig. 14 illustrates the beneficial effect of hydrogen enrichment on engine indicated power at full-throttle normally aspirated operating conditions. It can be seen that only a very small amount of hydrogen addition is sufficient to cause a significant increase in engine power. Maximum engine power was approximately doubled when hydrogen equal to 2% by weight of the fuel mixture was added to the ammonia. Further gains of only a negligible amount were realized over an engine speed range of 800-3600 rpm when the concentration of hydrogen in the fuel mixture was increased to 3%. At 4000 rpm, a 3% hydrogen addition was more effective than a 2% addition. In general, it was found that the engine power began to decrease slightly as the percentage of hydrogen in the fuel mixture was increased above about 3%.

Fig. 15 illustrates the variant beneficial effect of hydrogen addition on indicated power of the supercharged engine. The illustrated data were obtained at each of three engine speeds by increasing the hydrogen concentration in the fuel mixture in small incremental steps until the engine power passed through a peak value. An engine supercharge pressure of 18 in. Hg gage was maintained at all times. Also included on the figure are maximum engine power data obtained while running the engine on ammonia only at the same supercharge pressure and while operating the engine on gasoline at normally aspirated conditions.

It will be seen in the figure that hydrogen addition had a slight detrimental effect on engine power development at the 2000 rpm investigated speed, but enhanced markedly engine power outputs at speeds of 3600 and 4000 rpm. Optimum concentrations of hydrogen of approximately 1.35% and 1.19% in the fuel mixture were established for engine speeds of 3600 and 4000 rpm respectively. Employing a hydrogen concentration of about 1.2% resulted in engine power development over the entire engine speed range investigated that was equal to or exceeded the engine power developed while burning gasoline in the engine under normally aspirated operating conditions.

Chemical analyses of engine gas samples collected during these tests revealed the role of hydrogen as a combustion promoter for ammonia. At most of the test conditions, the addition of hydrogen to ammonia was found to increase the percentage of inducted ammonia burned in the engine. The degree to which hydrogen enrichment abetted the combustion of ammonia tended to vary directly with the degree of ineffectual burning of the ammonia itself in the engine. Where combustion of ammonia was relatively poor (for example, during part-throttle, all normally aspirated full-

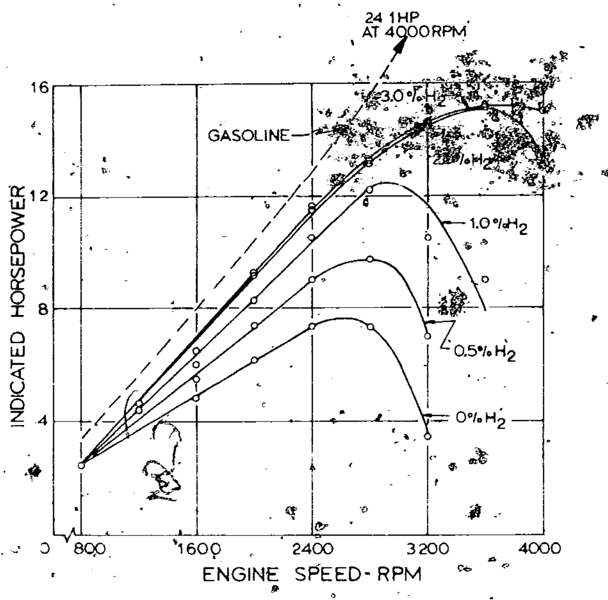

Fig. 14 - Improved performance of single-cylinder engine due to varying amounts of hydrogen addition to ammonia -- full-throttle normally-aspirated operation, 9.4:1 compression ratio

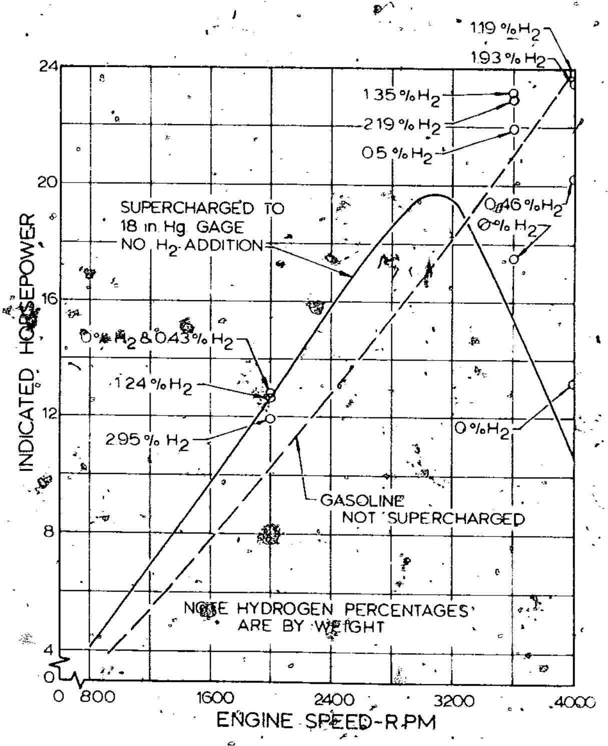

Fig. 15 - Varying improvements in performance of single-cylinder engine due to hydrogen addition to ammonia -- supercharged operation, modified ignition system; 9.4:1 compression ratio

throttle, and high-speed supercharged conditions), hydrogen addition to the ammonia was beneficial. On the other hand, supercharging the engine at low engine speeds provided optimum burning conditions for the ammonia, and hence, hydrogen addition was not needed.

The anomalous fact that engine power declined slightly at all full-throttle operating conditions investigated when hydrogen enrichment was increased past the optimum amount may be attributed to the widely different burning rates of the two fuels which necessitated a compromise MBT spark advance.

MULTICYLINDER ENGINE STUDIES

It was shown by the single-cylinder engine tests that with certain engine modifications and the addition of a small amount of hydrogen to the ammonia, satisfactory performance of a spark-ignited reciprocating engine could be expected. Therefore, it was decided to prove this more conclusively by operating a multicylinder engine on ammonia. The preliminary tests that were conducted verify the belief that a multicylinder engine could be developed that would produce power output while burning ammonia equivalent to that obtained while operating normally aspirated on gasoline.

Normally Aspirated Engine Operation - Fig. 16 presents two full-throttle brake horsepower curves that were obtained while burning ammonia in the multicylinder test engine at normally aspirated engine operating conditions. Curve A refers to data that were taken with the standard ignition system installed. Data for curve B were obtained after the ignition system had been modified. Also shown is a brake horsepower curve (C) for a similar engine of lower compression ratio (8.75:1 as compared to 10.25:1) that was obtained while operating the engine normally aspirated on gasoline. A comparison of the power outputs shows a degradation in maximum power of approximately 87% when switching from gasoline to ammonia fuel. When the modified ignition system was installed, the loss in engine power was reduced to 70%. It is realized that this comparison favors slightly the ammonia-fueled engine since it was run at maximum power spark advances whereas with gasoline the spark timing was retarded from the best power spark advances.

Two other types of ignition systems were tested in an attempt to improve engine performance while burning ammonia. These were a capacitor discharge system and a contact operated transistorized system. Also, several coil-resistor combinations were tested. Spark plug gap sizes were varied from 0.030 to 0.100 in. when testing the different systems. However, none of these ignition systems resulted in engine performance that exceeded that obtained while using the modified ignition system described previously. In fact, most of them resulted in inferior engine performance.

Supercharged Engine Operation - Fig. 17 presents engine

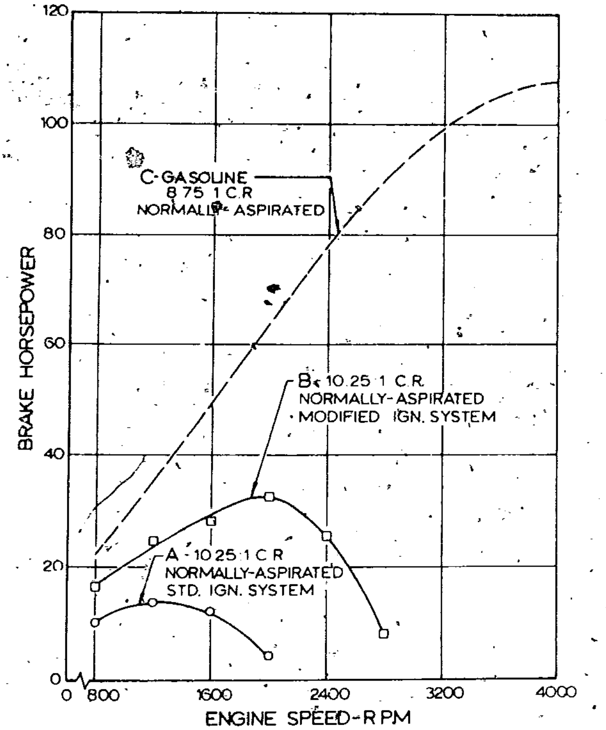

Fig. 16 - Performance of multicylinder engine on ammonia and gasoline -- full-throttle normally aspirated operation, standard and modified ignition systems

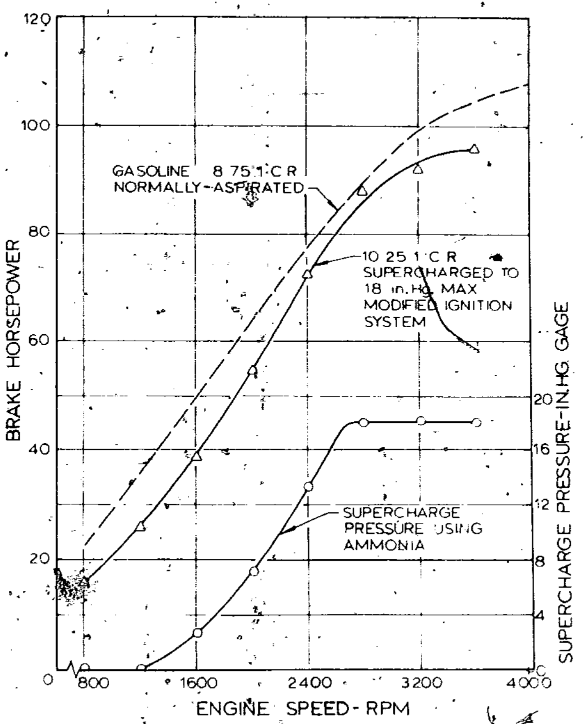

Fig. 17 - Improved performance of multicylinder engine due to supercharging -- ammonia fuel, modified ignition system

brake horsepower curves obtained during supercharged engine operation on ammonia and normally aspirated engine operation on gasoline. Also shown is the relationship between supercharge pressure and engine speed that was established while running the engine on ammonia fuel.

According to the supercharge pressure curve, supercharging was not evident until the engine exceeded 1200 rpm. Beginning at about 1200 rpm, the supercharge pressure began to increase rapidly with engine speed and reached the desired maximum pressure of 18 in. Hg gage at about 2800 rpm. Above 2800 rpm, the turbine bypass valve was opened to limit the supercharge pressure to 18 in. Hg gage.

The plotted data show that the engine power developed over the entire speed range when burning ammonia and using the turbosupercharger was less than that produced when burning gasoline in the normally aspirated engine. The maximum power realized with ammonia as the fuel was about 96 bhp at 3500 rpm. This maximum value is about 10% less than the maximum engine power obtained when using gasoline. Engine performance data were not obtained at an engine speed of 4000 rpm while burning ammonia due to difficulties encountered with the fuel supply system.

It should be noted that the two brake horsepower curves are in closest agreement at an engine speed of about 2800 rpm. At this speed, the desired supercharge pressure of 18 in. Hg gage was achieved while burning ammonia, and the beneficial effect of supercharging was a maximum. Below 2800 rpm, useful engine work derived from supercharging decreased progressively with speed and became practically nonexistent at engine speeds below 1200 rpm. The divergence of the two power curves above 2800 rpm is due probably to the progressive decrease with engine speed in the ability of the engine to burn ammonia efficiently.

Fig. 18 presents brake specific fuel consumption, brake thermal efficiency, and spark advance curves for the supercharged ammonia-fueled and normally aspirated gasoline-fueled multicylinder engines. Also shown is the air-fuel ratio curve for the supercharged ammonia engine operation. The curves obtained while burning ammonia in the engine extend only through an engine speed of 3200 rpm. Although corresponding engine power data were obtained at 3600 rpm, the fuel system failure that was mentioned previously precluded the recording of a full set of engine performance data.

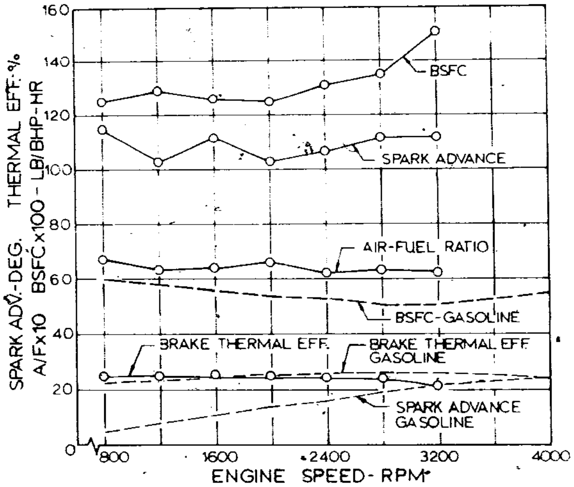

Fig. 18 - MBT spark advances, LBT air-fuel ratios and brake specific fuel consumptions for multicylinder engine -- ammonia fuel, supercharged operation, modified ignition system

As shown on Fig. 18, the two brake thermal efficiency curves agree closely over the engine speed range of 800-2800 rpm. However, at this higher speed the curve for ammonia began to fall off while that for gasoline remained about constant.

The brake specific fuel consumption of the engine while burning ammonia was about 2-1/2 times as great as that obtained with gasoline. The marked difference in heating values for the two fuels is primarily the cause of this large difference.

Spark advance requirements for the two fuels are also significantly different. The spark advance determined during operation on gasoline increased gradually from 5 deg btdc at 800 rpm to 24 deg btdc at 4000 rpm. A much greater MBT spark advance was employed while burning ammonia. It varied somewhat randomly between 103 btdc and 115 deg btdc over the engine speed range investigated.

The LBT air-fuel ratios established for operation on ammonia varied between 6.2:1 and 6.7:1 over the engine speed range. These air-fuel ratios are slightly leaner than the stoichiometric air-fuel ratio of 6.06:1 for ammonia and are much richer than the stoichiometric air-fuel ratio of about 14.5:1 for gasoline.

Again, samples of the exhaust gases were collected and the constituents analyzed. At one supercharged engine operating condition, it was determined that the per cent of inducted ammonia burned in the eight cylinders varied between 93 and 96.5%. An overall ammonia-burned value of 94.2% was determined from analyses of engine tailpipe gas samples.

GENERAL OBSERVATIONS

Engine Noise - No engine knock was detected during any of the tests described in this report. Although the octane number of ammonia is not known, these tests indicate that it is exceptionally high. However, during operation of the single-cylinder engine at a compression ratio of 18:1 at speeds of 2400 rpm and above, a rapping noise similar to that produced by heavily loaded diesel engines occurred when the spark advance was set for best power. This noise could be eliminated by retarding the spark slightly although this resulted in a slight power loss.

During normally-aspirated operation at the 18:1 compression ratio, several cylinder pressure-time traces were obtained to determine the cause of the rapping noise. Fig. 19 is a photograph of an oscillogram showing several such

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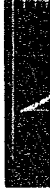

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traces. These pressure-time traces were obtained with the engine operating at 3600 rpm -- full throttle. The spark advance was set at 112 deg btc which was the MBT spark advance. The six upper traces were taken during consecutive engine firing cycles and the lowest trace is the motoring compression curve.

Peak pressure varied from cycle to cycle ranging from about 720-1700 psi, and the rate of pressure rise varied from about 25 to 100 psi/deg. This is considered to be high for the conventional spark ignition engine. It is felt that these large variations in peak pressure and rate of pressure rise were the cause of the rapping noise. Further evidence of this was obtained by observing that the rapping noise occurred in phase with the variations of peak cylinder pressure, that is, when several nearly equal peak pressure traces were followed by an extremely high peak pressure trace a rapping sound was heard.

This rapping noise was not present at the lower compression ratios. Oscilloscope traces obtained at the 15:1 compression ratio during both normally aspirated and supercharged engine operations showed less variations in peak cylinder pressure and rate of pressure rise from cycle to cycle.

Contribution to Air Pollution - The effect on air pollution must be weighed seriously when considering a vehicular application of the spark-ignited ammonia-fueled engine. Even a relatively small amount of ammonia in the engine exhaust is to be avoided because of its irritating odor and toxic effect.

Emission of ammonia from the single-cylinder test engine was minimized by burning an ammonia-hydrogen mixture required for optimum engine performance at the stoichiometric air-fuel ratio. A stoichiometric mixture of 98% ammonia and 2% hydrogen on a weight basis satisfied this requirement.

Ammonia concentrations in the single-cylinder engine exhaust were calculated to be about 81,000 ppm on dry basis (water formed by combustion excluded) at 3600 rpm and full-throttle. Adding 2% by weight of hydrogen to the ammonia and running at a similar engine operating condition reduced the concentration of ammonia in the engine exhaust approximately 94% to 5300 ppm. This significant decrease in ammonia emission was the result of a decided improvement in combustion efficiency when hydrogen was added to the ammonia. The per cent of inducted ammonia burned in the engine was increased from approximately 69 to 97.5%.

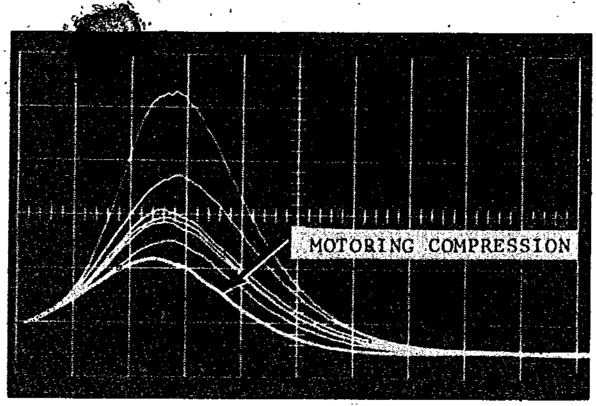

Fig. 19 - Cylinder pressure-time traces showing large variations of peak pressures and rates of pressure rise for six consecutive firing events in single-cylinder engine -- ammonia fuel, full-throttle normally aspirated operation, 18:1 compression ratio

These computed ammonia concentration values are appreciably greater than the tolerable limit established for the human body. However, when these quantities of ammonia are discharged from the engine tailpipe and mix with the ambient air, tolerable ammonia concentrations should result if sufficient ventilation is provided. This engine exhaust gas condition is similar to that which is experienced when carbon monoxide is emitted from the tailpipe of a gasoline engine.

Detectable amounts of hydrogen were emitted from the engine while burning rich air-fuel mixtures of both ammonia and ammonia-hydrogen fuels. Approximately seven times as much hydrogen was discharged while burning a 90% theoretical air mixture of ammonia and hydrogen as was discharged while burning a 92% theoretical air mixture of only ammonia.

While a considerable improvement in the combustion efficiency of the single-cylinder engine has been realized, still it is reasonable to expect that a measurable amount of ammonia will be emitted from any spark-ignited ammonia-fueled engine. If a decided reduction in ammonia emission from an engine should be required, it may have to be accomplished in the engine exhaust system. Dissociation of ammonia to hydrogen and nitrogen, absorption of ammonia, or chemical conversion of ammonia to innocuous constituents are various means that might be employed.

Exhaust gas samples were collected and were analyzed for concentrations of oxides of nitrogen during maximum power operation of the single-cylinder engine at several different engine speeds. It was found that the concentration of oxides of nitrogen increased with increasing indicated thermal efficiency of the engine and ranged from a concentration of about 200 ppm for a thermal efficiency of 15% to 1200 ppm for a thermal efficiency of 30%. If gasoline were to be burned in the engine at similar operating conditions, similar concentrations of oxides of nitrogen in the engine exhaust gas would be expected.

Engine Oil Analyses - During the course of this investigation, chemical analyses of the engine lubricating oil were made to determine if the use of ammonia as an engine fuel would have an adverse effect on the oil. Approximately 5 gal of commercial 20 weight oil were used to fill the lubricating systems of the single-cylinder and multicylinder test engines. This large quantity of oil was needed because the oil was circulated through a heat exchanger.

New oil was provided at the start of engine testing involving the use of ammonia as fuel. Samples of the oil were extracted at various times during the engine tests. The last sample from the single-cylinder engine was collected after approximately 75 hr of engine operation at diverse power and speed settings, while that from the multicylinder engine had 46 hr of similar operation. All of these oil samples together with a sample of the new oil, were chemically analyzed.

The chemical analyses disclosed that no noticeable deterioration of the oil had occurred. The total acid number of the oil remained approximately constant as did the amounts of barium, calcium, phosphorus, and zinc additives in the oil. No resins were found in any of the samples which indicated that no significant oxidation of the oil had taken place. The viscosity of the oil remained approximately constant.

Crankcase Gas Analyses - The possibility of an explosion occurring in the engine crankcase was considered seriously when the fuel evaluation study was instituted on the single-cylinder engine. It was reasoned that piston blowby would be greater when burning gaseous ammonia and hydrogen than when burning liquid hydrocarbon fuels. As a result, a positive crankcase ventilation system was installed on the engine.

Several engine runs were made with the specific purposes of measuring hydrogen and ammonia concentrations in the crankcase gas. Samples of the crankcase gas were collected while running the engine at a variety of supercharged and nonsupercharged conditions and while burning both ammonia and ammonia-hydrogen mixtures. No hydrogen or ammonia was detected in any of these crankcase gas samples.

DISSOCIATION OF AMMONIA

Single-cylinder engine tests have demonstrated the effectiveness of hydrogen enrichment of the ammonia fuel in the realization of acceptable part-throttle engine performance. It was found that 2.5% by weight of hydrogen was the minimum required amount. On the other hand, these same tests also disclosed that suitable maximum engine power might be developed without recourse to hydrogen enrichment of the ammonia.

At a first glance, it would seem reasonable to supply hydrogen and ammonia from separate fuel tanks. However, this would not only require the production, storage, and distribution of two fuels, but it would also introduce complications through the necessity for an additional fuel supply system on the vehicle. A most critical disadvantage involving the use of hydrogen is the cryogenic temperature required to maintain this fuel in the liquid state. Heavily insulated equipment in addition to specialized techniques would be required for its storage and handling. Losses in transfer and storage would be severe. Due to these unavoidable losses and the wide flammability limits of hydrogen, its use would be very hazardous.

The serious shortcomings of a separate vehicular hydrogen supply system would be eliminated if the desired amount of hydrogen could be either dissolved in the ammonia at the Energy Depot or produced by dissociating some of the ammonia. Studies have shown that sufficient hydrogen cannot be dissolved in liquid ammonia to provide the desired concentration (4). Therefore, the dissociation of ammonia was investigated.

The following simple chemical equation describes the ammonia dissociation process:

$$\underset{\text{(Ammonia)}}{2\,NH_3} \longrightarrow \underset{\text{(Hydrogen)}}{3\,H_2} + \underset{\text{(Nitrogen)}}{N_2}$$

To promote this decomposition process, a catalyst may be used (for example, nickel or iron) and heat must be supplied (5). In a vehicle, the engine exhaust gas provides a readily available source of free heat, but electrical energy provided by an engine-driven generator would also be a possible source of heat.

From a theoretical standpoint, a dissociator, heated by the engine exhaust gases, should fulfill all of the needs of an automotive ammonia-fueled engine. The temperature of the exhaust gas emerging from the cylinders of a conventional automotive engine is sufficiently high at all normal operating conditions to insure practically complete dissociation of the ammonia. Unfortunately from a practical standpoint, the dissociator cannot be located close to the cylinder exhaust ports and the reaction cannot be completed because the fuel would not remain in the hot zone long enough. Consequently, a catalyst must be employed to compensate for the short reaction time and for the inability to make use of maximum exhaust gas temperatures.

One of the points in favor of an ammonia dissociator is the fact that only a part of the ammonia supplied to the engine need be decomposed to provide the optimum concentration of hydrogen in the fuel mixture. The dissociation of about 13% by weight of the ammonia is required to provide the desired 2.5% by weight of hydrogen in the fuel mixture.

It was the original intent to undertake the development of a full-scale dissociator in several stages. The first stage was to be a basic study of the dissociation process -- to evaluate different techniques for promoting dissociation. This basic study was to be followed in succession by the construction of dissociators of increasing size for the single-cylinder and multicylinder test engines. Only the initial stage of the development program has been completed.

The basic ammonia dissociation study was conducted with miniature models using available laboratory equipment and procedures. A gas chromatograph was used to determine the degree of dissociation accomplished. The concentrations of both ammonia and nitrogen in the effluent from the dissociator were measured. The three different designs of ammonia dissociators evaluated in the laboratory are illustrated in Fig. 20. Cross-sectional views are presented, and the small size of these models can be appreciated by comparison with the scale. In each model, nickel in various forms was used as the catalyst. The desirable characteristics of nickel, as well as its established use in commercial ammonia dissociating devices, prompted the initial use of this material in the minatfure models.

Model A in the figure contained a bed of nickel catalyst (for example, powder or shot) that was heated by an electrical furnace to various selected temperatures. In the case of Model B, the tubes were constructed of Inconel or stainless steel, both of which contain nickel, and the temperature of the tubes was maintained at the desired temperature by an electrical furnace. Controlled electrical energy was supplied to the nichrome filament in Model C.

Figs. 21A-21C present some typical ammonia dissociation values that were obtained with these three models. In all cases, the ammonia flow rate was kept below 0.25 CFH. Temperatures ranged as high as 1000 F in Models A and B. Electrical energy to Model C was held below a maximum of about 20 w.

From comparisons of experimental data obtained with these models, it was concluded that the particle bed reactor containing nickel shot was the most effective one and the one best suited for engine application. Results obtained with the Inconel tube reactor were superior to those of the stainless steel reactor. The electrical power requirement of the filament type reactor was judged to be too high for immediate application to an engine. Actually, the filament reactor had been designed for quite a different purpose and it is conceivable that if a reactor of this type had been built specifically for this study, a more efficient device would have resulted.

A detailed analysis of the data from the particle bed reactor (nickel shot catalyst) yielded some important information of a practical nature. Catalysis appears to be a significant factor in the dissociation process at temperatures below 900 or 1000 F. At higher temperatures, the thermal effect appears to be the predominant one. A dissociator of a size reasonable for engine use was scaled up on paper from the microreactor data. Such a hypothetical dissociator should satisfy ammonia-fueled engine requirements in the high part-throttle and full-throttle operating ranges of a conventional automotive engine. Its effectual performance at engine idle and in the low part-throttle operating range is debatable due to the difficulty of providing exhaust gas at sufficiently high temperatures. A combination of the particle bed and electrically heated filament types of dissociator might satisfy these engine requirements if the currently high power requirement of the filament type reactor can be reduced. It must be emphasized that these observations are

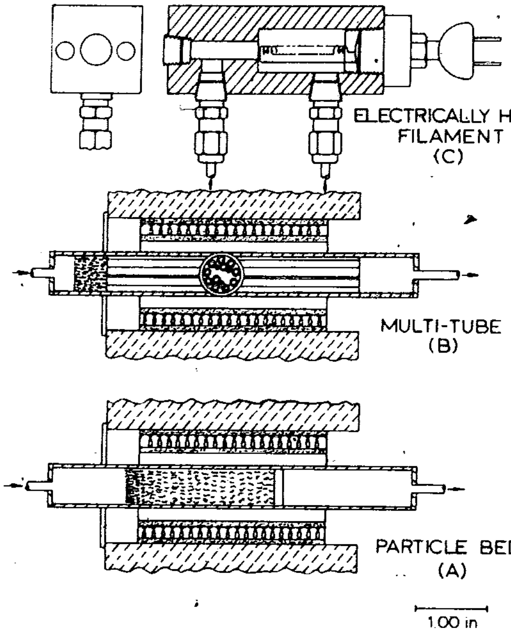

Fig. 20 - Experimental microreactors for studying dissociation of ammonia

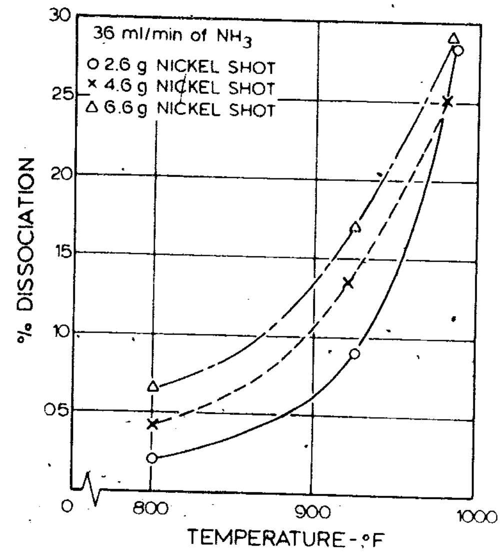

Fig. 21A - Typical ammonia dissociation data obtained with experimental microreactors -- Model A-particle bed

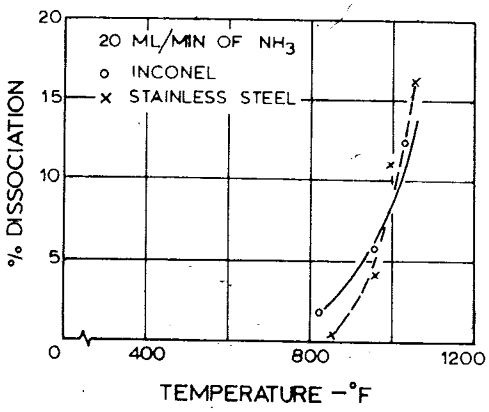

Fig. 21B - Typical ammonia dissociation data obtained with experimental microreactors -- Model B-multitube

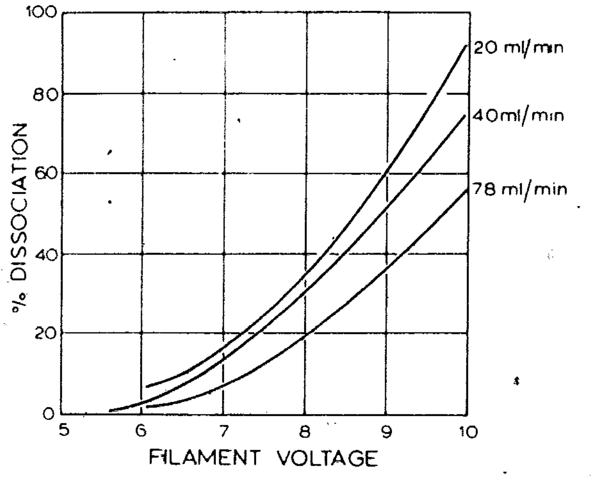

Fig. 21C - Typical ammonia dissociation data obtained with experimental microreactors -- Model C-electrically heated filament

based solely on laboratory evaluations of miniature models and hence. their direct application to full-scale designs and operating conditions must be considered speculative.

Complementary ammonia dissociation studies are being conducted at the Allison Div. on a much larger scale dissociator of the particle-bed type. This dissociator is sized for a single-cylinder engine and uses a promoted iron catalyst. Preliminary Allison test results corroborate, in general, the findings of this paper and indicate that a simple and reasonably sized dissociator of this type can be evolved for use on a multicylinder engine.

SUMMARY

The results of this study indicate that an ammonia-fueled spark-ignited reciprocating engine can be developed with performance equivalent to that obtained in current automotive gasoline engines. Desired maximum engine power may be developed by two different approaches. In one method, the addition of a supercharger to a conventional engine would suffice. The engine would have to be supercharged in excess of current automotive practices, which should be possible due to the high octane rating of ammonia. The other method would involve also the addition of a supercharger but only moderate supercharging of the engine, an increase in the compression ratio, and the addition of a small amount of hydrogen to the ammonia. The addition of a small amount of hydrogen to the ammonia is a requisite for suitable part-load engine performance.

Hydrogen, when added to ammonia in small quantities, was found to act as a combustion promoter in accelerating the burning of ammonia. Dissociation of a part of the ammonia fuel in the vehicle appears to be the most logical method for supplying the required hydrogen. A preliminary study indicates that a catalytic dissociator heated by the engine exhaust gas offers promise of fulfilling the needs of an ammonia-fueled engine.

The engine modifications involved when replacing gasoline with ammonia appear to be straightforward. Probably the greatest problem will concern the auxiliary equipment and controls. The development of an ammonia evaporator and fuel metering systems would possibly follow along the lines of similar LPG system developments. The dissociator would be a novel development but appears to be feasible according to preliminary Allison test results.

To drive equal distances in a vehicle, at least 2.8 times by volume and 2.35 times by weight as much ammonia as gasoline will be required. The fuel system in an ammonia-fueled vehicle will be bulkier than that in a conventionally fueled vehicle. However, it is believed that this will not be a serious handicap for the majority of military applications.

ACKNOWLEDGMENT

The authors wish to express their appreciation to W. A. Turunen for his direction and advice during this investigation and to R. L. Gatrell, of the Chemistry Dept., for developing special chromatographic equipment and techniques and conducting the ammonia dissociation experiments.

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Discussion of this paper appears on page 316.

DISCUSSION

Discussion of papers 650050 (p. 274), 650051 (p. [illegible]1), and 650052 (p. 300).

R. J. FLANNERY
American Oil Co.

THIS AUTHOR GENERALLY concurs with the remarks within the scope of the presentation. Several comments should be made.

The first relates to the choice between converted-internal-combustion and fuel-cell power units for vehicles. This choice might be influenced by the attractive possibility of a simple conversion kit allowing use of standard hydrocarbon-fueled engines. However, this convertability may not be unique to IC engines in view of other work directed toward fuel cell vehicles powered by steam reformed petroleum fuels. Such vehicles would be readily converted by changing to ammonia cracking.

The second relates to scope. While the application detailed in the paper, vehicles, is one of the most difficult, an army requires energy for various other purposes, ranging from cooking and lighting to communications power. Safe efficient burners for depot fuels will be needed. A variety of electric power supplies of capacity or type not possible to be provided by batteries in the isolated arena will also be needed. In many of these cases, the projected fuel cell, with suitable power processing auxiliaries, will probably be more efficient than corresponding converted engine generator sets.

The third relates to the direct ammonia fuel cell. In the paper, this approach was discarded for consideration at this time because of lagging technical advance. Yet this system holds a potential advantage which warrants at least continued attention to its possible development. This advantage is high efficiency on idle. The rate of the ammonia cracker cannot be changed rapidly, whereas the fuel consumption of the direct cell readily drops to a low level on idle. Important fuel savings can result. In addition, an ambient-temperature, direct ammonia cell would not require 25% of the ammonia's hydrogen to heat the ammonia cracker.

The fourth relates to the projection of the fuel cell performances. The projections presented do not seem too optimistic. But, for the benefit of those more casually acquainted with fuel cells, it should be noted that the comparison with present state of art should be made for power densities at the required operating efficiency, not at the maximum efficiency. Fig. A summarizes the power density data of Fig. 9 and 11 of the paper and shows the operating points selected in the design study. The voltage efficiency lines which have been superimposed on the curves reveal that the design points are all in the 60-70% range. The corresponding point on the 1963 state-of-art curve given is well below 100 wft^2.

Finally, in a truly isolated arena, some unexpected materials can become "fuels" in the sense that a supply of them can be used up. For example in the processes detailed, air purification and ion exchange water purification are required. Taking the KOH requirements for air purification given in the paper, some 30 tons/year of KOH would be required for the utilization in fuel cells of the yearly reactor output. Chemical needs for regeneration of the ion exchange bed would depend on available water and on undisclosed process details, but could be substantial and would apply whether engines or fuel cells were used. Use of thermally regenerable treatment chemicals would help alleviate a problem in this area.

E. B. RIFKIN
Ethyl Corp.

THIS PAPER IS an important contribution to the literature on combustion in reciprocating engines as well as a signif-

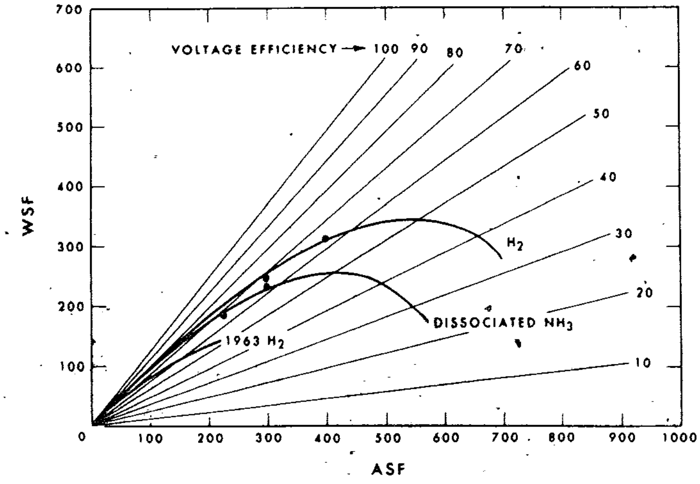

Fig. A - Power density data and operating points icant collection of data on the possible utility of ammonia in the energy depot concept.

The authors have clearly pointed out many of the important factors that must be considered if ammonia is to be viewed as a serious contender for use as a military fuel. From their data, it is obvious that, in contrast with gasoline, ammonia suffers from low heat of combustion, difficult ignitability, and low flame speed. However, these problems can be overcome to some extent by use of supercharging, high compression ratios, ignition system modifications, and partial dissociation of the fuel before induction.

As the authors' data show, ammonia-air mixtures are hard to ignite. Although minimum ignition energies are difficult to reproduce and to interpret precisely, some light on the problem is shown by the work of Buckley and Husa, in (1) who showed that the minimum ignition energy for an ammonia-air system was 680 millijoules in a condenser discharge. A comparable figure for n-heptane in air was 0.3 millijoules. This probably explains why the ignition system modifications described in the paper markedly increased power output.

Another serious limitation on ammonia-air combustion involves the flammable limits, or range of concentrations that will sustain a flame. In the case of hydrocarbons, these limits are very broad. Thus, n-heptane, for example, will burn under ambient conditions in air at any concentration between 1.1-6.7 Vols % (2). This gives wide latitude to the engine designer in his quest for maximum power under some conditions (rich mixtures) or maximum economy under other conditions (lean mixtures). Further, the stoichiometric concentration occurs at 2.3% n-heptane. This allows more than a factor of 2 in fuel concentration on either side of the stoichiometric composition.

The ammonia-air system is quite different. Here, the flammability limits are 15 and 28 Vol % ammonia (1), which in itself means that there is less than a twofold variation possible in ammonia concentration for a burnable mixture. The stoichiometric mixture occurs at 21.9%, with only a narrow latitude allowed on either side of this point. Thus, under ambient conditions, all flammable mixtures must be near stoichiometric. Undoubtedly, higher temperatures and pressures will somewhat broaden this range, so that a wider range of mixtures can be burned in an engine than indicated by these figures. An interpretation of some of the exhaust composition data in the authors' Table 2 can be based on this approach. Thus, fuel mixture 2, containing ammonia plus 98.8% of the theoretical air, still burns only 68.8% of the ammonia inducted. Recognizing that some mixture inhomogeneity probably exists in this system, we can theorize that the part of the charge in the center of the combustion chamber is well insulated from the walls, and thus probably burns completely because its temperature is high and its flammability limits fairly broad. However, the portion of the charge near the walls is cooler and has reduced flammability limits, so that quite likely a substantial portion of it is outside the combustible range and does not burn.

In addition to the flammability problem encountered in dry air, moist air would likely impose an additional penalty, since high humidity tends to substantially narrow the flammability limits in the ammonia-air system (3).

To overcome this flammability limit problem, the authors have used several techniques with substantial success. Supercharging and high compression ratios would both be expected to broaden flammability limits. The cracking of the ammonia prior to induction is another route, which is effective partially because of the very broad flammability limits of hydrogen (4-74 Vol %). Another possible route is available, which involves the use of limit-broadening additives in the fuel. Such an approach is not needed in the case of hydrocarbons, with their wide flammability limits, but could be very useful in ammonia combustion. Some indication that flammability limits can be broadened in this way is found in the work of Egerton and Powling (4), who showed that additive amounts of ethyl nitrate had a significant effect in raising the upper limit of flammability of several light hydrocarbons.

There is also a second reason for anticipating that additives may improve the combustion properties of ammonia-air mixtures. This is based on some evidence indicating that the ammonia molecule must dissociate (at least partially) into nitrogen and hydrogen before it will burn. As the authors point out, a catalyst is required to make this reaction proceed measurably at temperatures below 900 F. This opens the possibility for an additive to be introduced for the purpose of promoting such dissociation during compression. An ammonia-soluble metal compound, decomposing in the engine to produce a fine dispersion of solid metal or metal oxide, might be one possible approach. If effective, it could facilitate ignitability, broaden flammability limits, and increase flame speed. If this approach were successful technically, it might greatly add to the practicability of the military use of ammonia, since it would substantially reduce the need for major engine modifications.

In their work with hydrogen addition, the authors have shown how this approach is an attractive one for solution of some of the ammonia combustion problems. Their results may be somewhat optimistic in relation to practical approaches, since the cracking of ammonia would introduce nitrogen as well as hydrogen, and the increased dilution would operate to reduce some of the gains shown when hydrogen is added. From an energy standpoint, the cracking of ammonia prior to induction into the engine has the effect of increasing the available energy by nearly 13% on a weight basis. However, because the dissociation products occupy twice the volume of the ammonia, the energy would decrease on a volumetric basis by about 6%. Thus, an additional problem may be encountered in practice where it would be desired to maximize the mass of fuel and air inducted into the cylinder.

Some time ago, Messrs. Kerley, Felt, and Adams in Ethyl Corporation's Detroit Research Laboratories briefly examined the engine performance of ammonia in a single cylinder Waukesha engine with variable compression ratio

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and removable dome head. They maintained intake air temperature at 130 F, jacket temperature at 230 F, compression ratio at 8.5, and manifold pressure essentially atmospheric. Spark energy, supplied by the engine's Bendix CR 4-1 magneto, was about 80 millijoules. Even at the low speed of 600 rpm, they encountered poor combustion, as indicated by a brake thermal efficiency of 13.75%. This compares with a value of 22.2% for isooctane containing 3 ml TEL/gal under the same conditions. When two spark plugs were fired simultaneously, the value for ammonia increased to 18.5%. By the additional technique of increasing the compression ratio to 12.65, the brake thermal efficiency was raised to 21%. In general, their conclusions from this work support those of the authors.

Through their study, the authors have shown that there would be no incentive to use ammonia as a fuel in the civilian market as long as hydrocarbons are available.

Even in the military context, much further work needs to be done to clearly define the potentiality of the overall concept. The present work is an excellent beginning on the usefulness of ammonia in gasoline engines. Additional work needs to be done on diesel-cycle engines and on multifuel engines. These engines will encounter other problems, due to the probable low cetane number of ammonia and the difficulty of keeping a stratified charge within the flammability limits. Detailed consideration needs to be given to the economics of the entire concept, including not only the energy depot aspects, but also the complex task of modifying engines without rendering them so cumbersome as to be ineffective. Finally, the overall evaluation of the system in terms of competitive cost-effectiveness, in relation to present methods of wartime fuel supply, will probably be the factor that determines whether it ever becomes a reality.

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T. O. WAGNER
American Oil Co,

MESSRS. CORNELIUS, HUELLMANTEL AND MITCHELL have conducted a very sensible and logical program to explore the suitability of ammonia as an engine fuel. We commend them for their work.

During 1968, E. J. Domke and I at the American Oil Company Laboratories investigated the performance of ammonia in engines. The approach and scope of our work was much like that of the General Motors work except that we did not investigate the effects of dissociation of ammonia, and we extended our work to compression-ignition engines. We agree completely with the results the authors present. We would like to offer a few observations on the performance of compression-ignition engines operated on ammonia.

The Armed Forces inventory includes a high fraction of vehicles with compression-ignition engines and they, as well as spark-ignition, must be accommodated in the energy depot concept. We were able to operate a CFR cetane method engine on pure ammonia and ammonia with several additives. Ammonia (or ammonia plus additives) was injected in conventional fashion, although it was necessary to advance injection timing greatly and to use a plunger and bushing assembly in the injection pump larger in displacement than the one normally used in the cetane method engine. The engine was started on kerosene, and then switched to ammonia. The engine would not restart on pure ammonia at 35:1 compression ratio with normal coolant and inlet air temperatures. However, we were able to attain ignition and regular combustion by raising coolant temperature to 370 F and air temperature to 270 F. Power output at these conditions was slightly less than that obtained at normal conditions with kerosene. We did not analyze the exhaust, but it had a very strong odor of ammonia. Our investigation of additives was limited to only a few choices. Several were effective; they permitted ignition and regular combustion to be attained with somewhat lower compression ratio and coolant and air temperatures.

From these results and ideas they generated, we believe that with some engine modifications and with proper additive treatment, it may be possible to make compression-ignition engines operate satisfactorily on ammonia-based fuel. The alternate, of course, is to convert all compression-ignition engines to spark ignition. More work is necessary to determine which would be the best solution.

P. S. MYERS AND O. A. UYEHARA
University of Wisconsin

THE ENERGY DEPOT concept has been of considerable interest to the discussors. In 1962 the discussors and other coworkers presented a paper entitled "Portable Power From Nonportable Energy Sources." This paper was presented at the National SAE Powerplant meeting in Philadelphia and published in the 1963 SAE Transactions. The basic purpose of this paper was to see what solutions might be found to the problem of providing an energy supply suitable for portable power plants when our present petroleum supplies were exhausted. While this is a slightly different problem than the one under discussion today, there are many similarities and the conclusions are remarkably similar.

Inasmuch, as two different groups considering two different, but related, problems reached similar conclusions, it would appear that these conclusions were fundamental and should be emphasized. The first of these common conclusions is that, barring unexpected breakthroughs, chemical storage of energy is the only practical engineering technique. All other possible techniques are all too bulky, either because of high shielding requirements or because of the large bulk of the energy storage material and system.

The second common conclusion is that only materials available on a large scale, that is, water and air, can be considered for production of fuel because of the large quantities of material involved. The implication here is that hydrogen is going to be the basic means for storing the energy originally obtained, from nuclear or some other stationary power source.

The third common conclusion is that it will be necessary to store the fuel in the liquid form or its equivalent. Hydrogen can, of course, be combined with other compounds such as nitrogen to form easily liquifiable fuels. If this procedure is followed, one of the essential requirements is that the resulting fuel be stable both chemically and with respect to shock.

The fourth conclusion is that it was undesirable to manufacture a fuel containing oxygen inasmuch as oxygen is readily available in the air free of charge.

It is interesting to note that the papers by Mr. Rosenthal and Mr. Grimes, as well as our earlier paper, reached these common conclusions. It should be clear that these conclusions are applicable when considering portable power plants. Different conclusions might be reached when considering stationary power plants.

It is pointed out in the papers that the number of potential fuels containing hydrogen and other readily available compounds, are very limited. As the paper by Cornelius and co authors points out, the fuel finally chosen, ammonia, has certain combustion problems. These combustion problems seem to arise primarily because of the low energy content per cubic foot of mixture. In this respect the behavior of the ammonia-air mixture reminds one of the lean mixtures of conventional fuels which also have comparatively low heating values per cubic foot of mixture. Thus, it is very interesting to note, with the exception of turbulence, all of the steps taken to improve combustion performance of ammonia as an engine fuel increased the energy content per cubic foot of mixture at the time of spark, that is, increased compression ratio, turbocharging, and so forth.

The thought of improving combustion by enriching the ammonia-air mixture with hydrogen is intriguing and ingenious. We do have some questions, however, regarding the way in which this was accomplished, particularly, in view of the comments just made regarding the low heating value per cubic foot of the ammonia-air mixture. If we interpret properly the experiments conducted by Cornelius and his associates, the tests were run by adding hydrogen only to the ammonia-air mixture. The dissociation of ammonia, however, will produce both hydrogen and nitrogen. Is it proposed to separate the hydrogen and nitrogen, discarding the nitrogen and adding the hydrogen to the ammonia-air mixture? If not, should not the experiments have been run with the addition of both hydrogen and nitrogen to the ammonia-air mixture? Would the heating value of the mixture have been significantly less if hydrogen and nitrogen rather than just hydrogen had been added? Would it have not been just as easy, experimentally, to have added hydrogen and nitrogen in the proper proportions?

The discussors would also like to raise the question of whether or not the thermal inertia of the dissociator, which decomposes the ammonia to produce the hydrogen, would be a complicating factor in the design of the engine-dissociator system? For example, if the engine were operating at low load with consequent low dissociator temperatures and the throttle were suddenly opened, requiring increased quantities of ammonia to be dissociated, would the dissociator be able to supply these increased quantities?

It is also interesting to note in Fig. 14 of the Cornelius paper that 3% hydrogen addition does not produce any significant improvement over 2% except at the very highest speed of 4000 rpm. Can the authors give any explanation of this "leveling off" with increased hydrogen addition?

MORTON S. SILBERSTEIN
United Nuclear Corp.

THE PAPERS PRESENTED in this session on the Energy Depot concept deal primarily with the production fuel in the field and the utilization of this fuel to power army vehicles. In all of the concepts discussed, an inherent part of the energy depot is a mobile nuclear power plant which generates the electric power required as input for the fuel production process. I would like to offer some brief remarks about the nuclear power generating portion of the energy depot.

This power source is being developed under the Military Compact Reactor (MCR) program, for which Allison Division, General Motors Corporation is the prime contractor. United Nuclear Corporation, whom I represent, has the responsibility as subcontractor to Allison for design and development of the nuclear reactor portion of the MCR.

One of the accomplishments of this effort has been the design of an MCR unit for an electric output in the same 3000 kw range for which the Allison and Allis-Chalmers energy depot conceptual designs were evaluated.

To meet the size and weight requirements of mobility, the MCR is packaged in modules comparable to those described for the various energy depot fuel processing units. These packages are trailer or truck mounted for operation in the field, and are transportable overland on their trailers or alternatively by air or sea.

The nuclear reactor, surrounded by its biological shield, which must meet extreme low weight requirements compared with ordinary reactor shields, is the basic source of thermal energy. Its heat is transferred to a liquid metal coolant, which ultimately heats air in a heat exchanger. The heated air drives an open Brayton cycle gas turbine engine, which drives an alternator whose electric output is the power source for the fuel manufacturing units. Auxiliary electrical equipment and controls for the nuclear plant are housed in separate units connected to the reactor and engine by electric cabling.

The energy depot constitutes an extremely attractive and logical application for nuclear power. This is an example of where the demand for long time operation without additional fuel supplies is uniquely supplied by a nuclear energy source.

Mr. Rosenthal's paper pointed out the weight attractiveness of the energy depot in comparison with the continued supply of gasoline fuel, and the cost studies that have now been initiated. There are, of course, uses of the nuclear powered energy depot where independence from external supplies is an asset which cannot be measured in dollars, for instance, the holding of a key spot which would otherwise be lost. Nevertheless, it is of some interest to note, that although the cost of uranium fuel and its associated plant are generally considered to be high under military circumstances, the cost of delivered gasoline can also be surprisingly high.

A simplified analysis of several special wartime situations shows that the predominant cost of supplying a major defense position is often that of the replacement value of aircraft and ships lost in bringing in the supplies. On this basis, considering such instances as Tobruk and Malta in World War II (for which the necessary statistics are described by Winston Churchill in his books), delivered gasoline is found to cost \$50-\$80/gal. In different circumstances, then, gasoline may range in value from the \$.30 or so, per gal. available at the local filling station up to numbers hundreds of times as great under front line fighting conditions.

E. J. GAY
Consulting Engineer

THE MOBILE ENERGY depot modules present several logistical problems, which I think might be illustrated by Figs. B-N.

B. This is China on the old Burma-China Road between Kunming and Chungking. This section of the road is called the "Ladder." It has no guard rails and steep grades, with a 1/4 in of slime. When raining the Goer just wouldn't go! Only a 6 x 6 or 8 x 8 would do the job.

C. This is another view of the old Burma-China Road.

D. The photograph shows typical terrain between China and northeast India. We flew petroleum products over this area until the pipelines were built.

E. This is up front on the Ledo Road near Myitkyina; you needed snowshoes here.

F. The Ledo Road where a temporary wooden bridge with a load limit of 4 to 5 tons and a 4 in. pipeline on each side was built.

G. Two of the 4 in. pipelines - ahead of the finished road. These 4 in. coupled pipelines handled 1500 gal/hr/line. We shipped aviation gas - motor gasoline and diesel fuel via these lines. There was a pumping station every 8 miles. One of these lines could refuel seven of the old M-4 tanks/hr.

H. A portion of the Ledo Road that was near completion and included a Bailey bridge and mules!

I. The picture shows a finished portion of the Ledo Road. Grades in this area were as high as 14 to 16%. There was one short stretch at 25%.

J. This is a Korean river with a bridge out.

K. Korea - just back of the combat line. This dirt road with up to 12% grades was the only line of communication. A pipeline came within 15 miles of this road.

L. Typical Korean terrain.

M. This photograph was taken in Korea and shows fuel storage for the tent stoves. Kerosene was used. What do we do when we use ammonia?

N. Here are 6 in. pipelines and a pumping station in Korea. These 6 in. lines with a pumping station every 16.5 miles would handle 3300 gal/hr. They would refuel 10 new M-60 tanks per hour. The newer welded 6 in. and 8 in. pipelines operating at higher pressures will handle several times as much fuel.

There is every reason to believe that South Vietnam (and the territories north and west of South Vietnam) has equally difficult terrain. Certainly, my recent visit to Thailand would confirm this.

The problems I visualize can be summarized by the following comments:

Apparently, these Mobile Energy Depot modules weigh about 30,000 lb and a complete unit about 100,000 lb. It takes a plane nearly the size of the 707 to carry 30,000 pounds. There are not many military air strips in the area

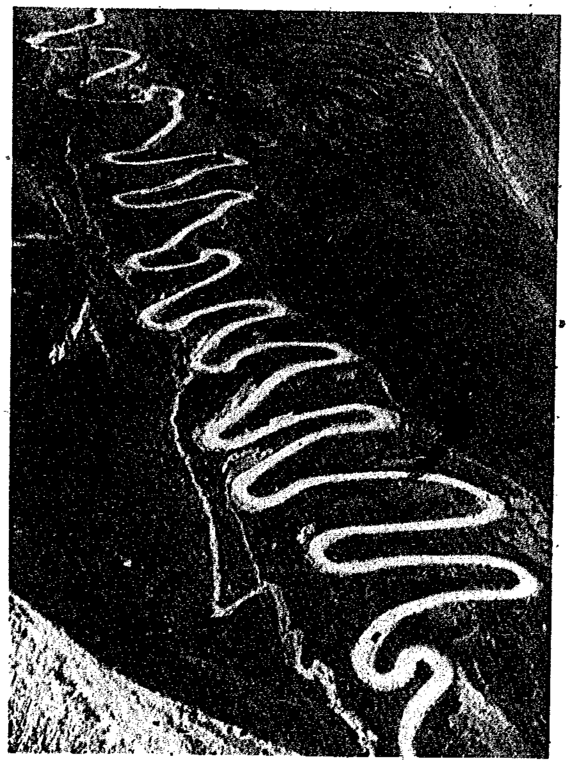

Fig. B. - Burma-China road