Energy Depot Concept

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Ammonia as an Engine Fuel

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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

*Numbers in parentheses designate References at end of paper.

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.

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.

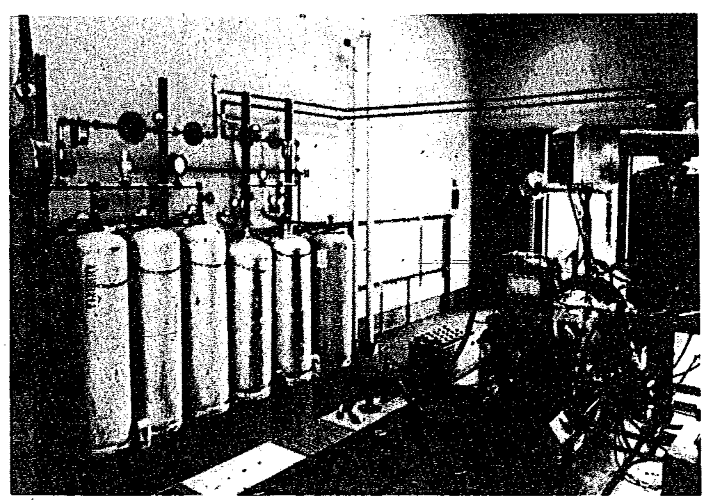

Fig. 1 - Test cell installation of single-cylinder engine and ammonia fuel supply system

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

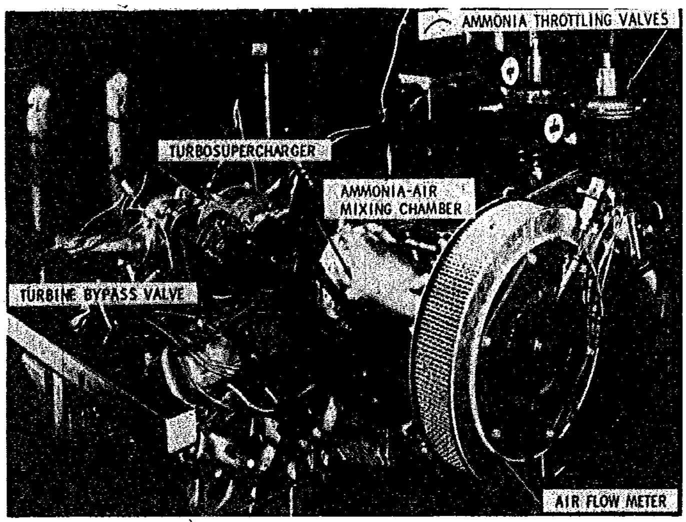

Fig. 2 - Test cell installation of multicylinder engine prepared for operation on ammonia fuel

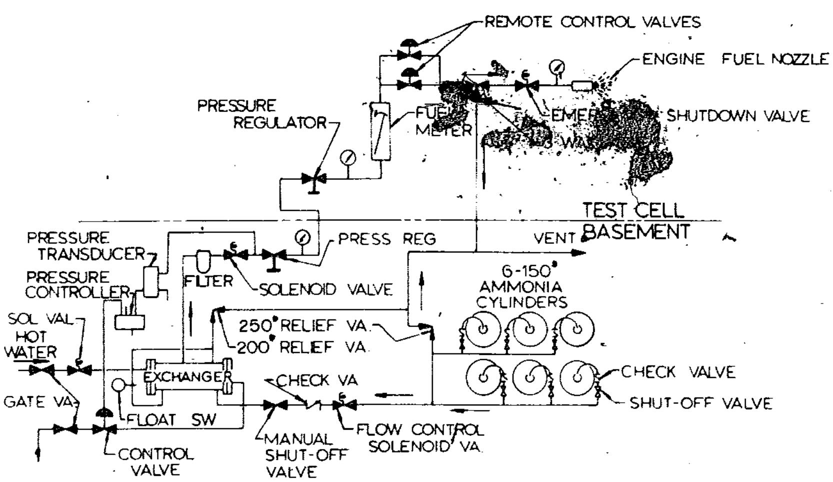

Fig. 3 - Schematic of ammonia fuel system for multicylinder engine

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.

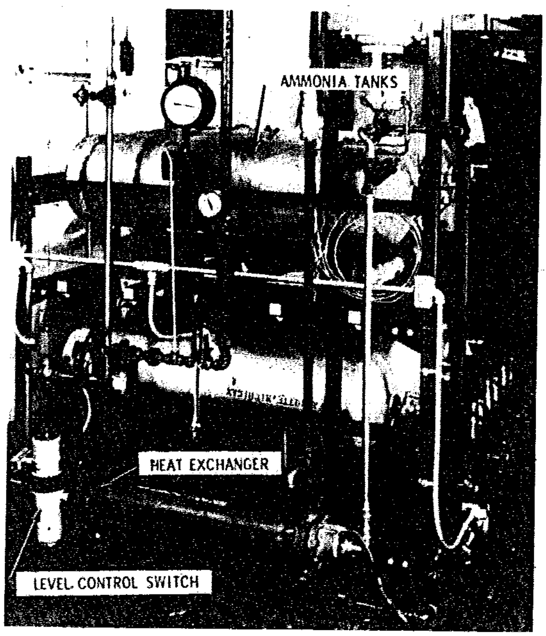

Fig. 4 - Ammonia fuel supply and control system for multicylinder engine

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-

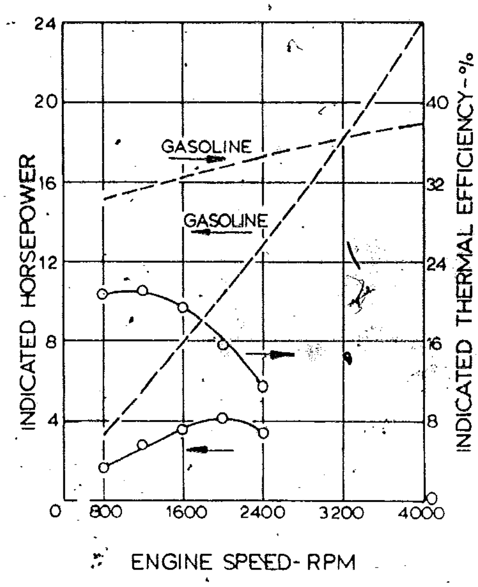

Fig. 5 - Performance of unmodified single-cylinder engine on ammonia and gasoline -- full-throttle normally aspirated operation, 9.4:1 compression ratio

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

	1		2		3	
	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 precludes 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-

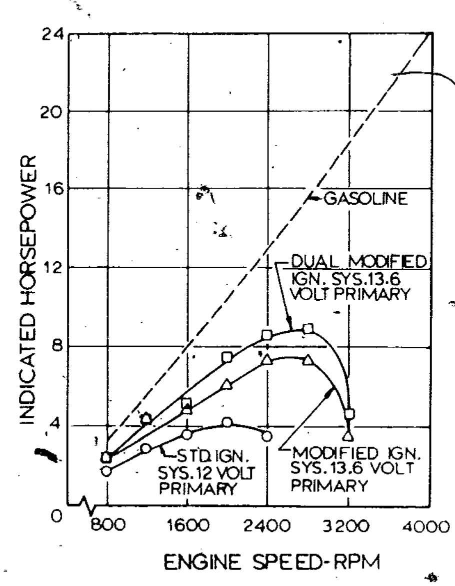

Fig. 6 - Increased power of single-cylinder engine through ignition system modifications -- ammonia fuel, full-throttle normally aspirated operation, 9.4:1 compression ratio

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

Effect of Increased Compression Ratio - To 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-

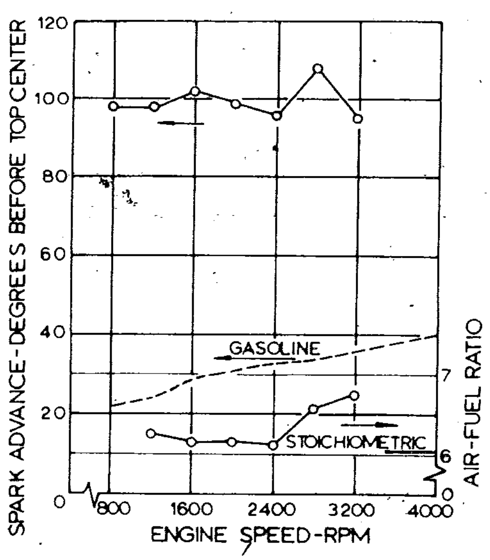

Fig. 7 - MBT spark advances and LBT air-fuel ratios for single-cylinder engine -- ammonia fuel, full throttle normally aspirated operation, modified ignition system, 9.4:1 compression ratio

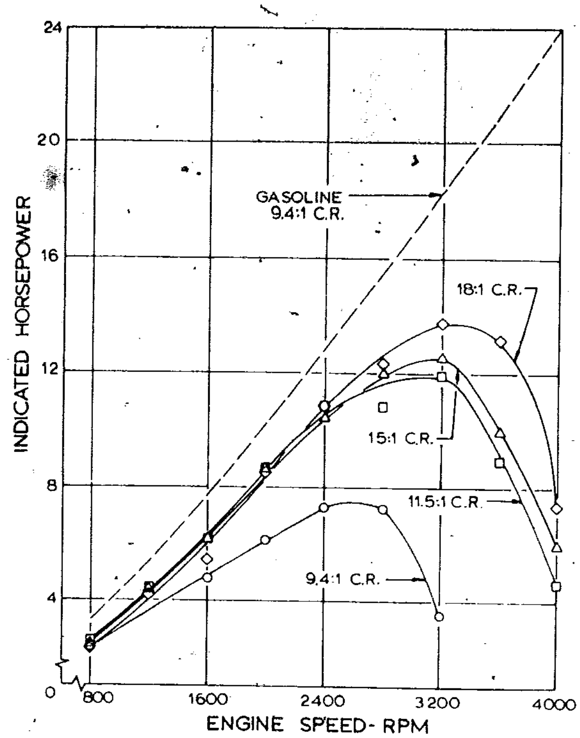

Fig. 8 - Improved performance of single-cylinder engine due to increased compression ratio -- ammonia fuel, full-throttle normally aspirated operation, modified ignition system

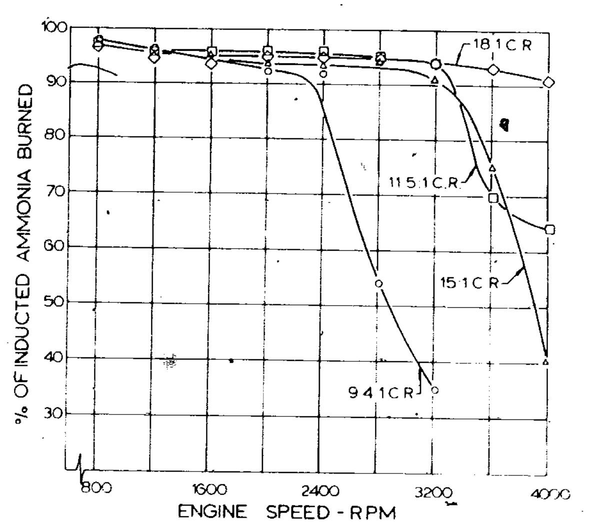

Fig. 9 - Improved combustion of ammonia in single-cylinder engine by increasing compression ratio -- full-throttle normally aspirated operation, modified ignition system

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.

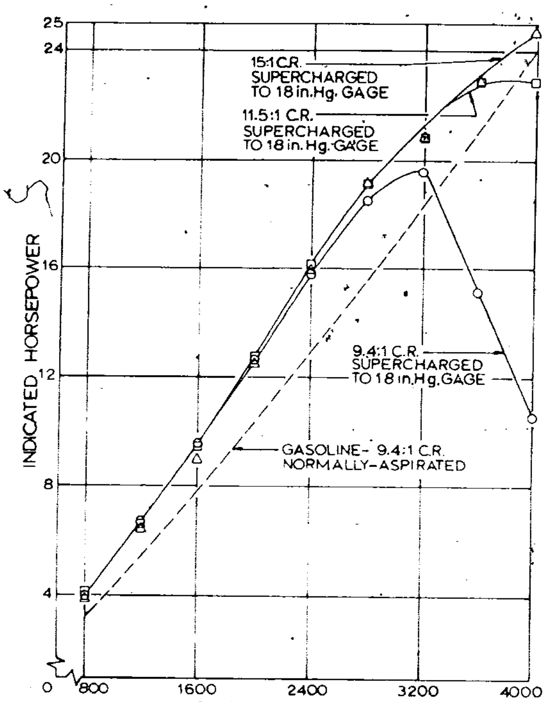

Fig. 10 - Increased performance of single-cylinder engine due to supercharging -- ammonia fuel, modified ignition system

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

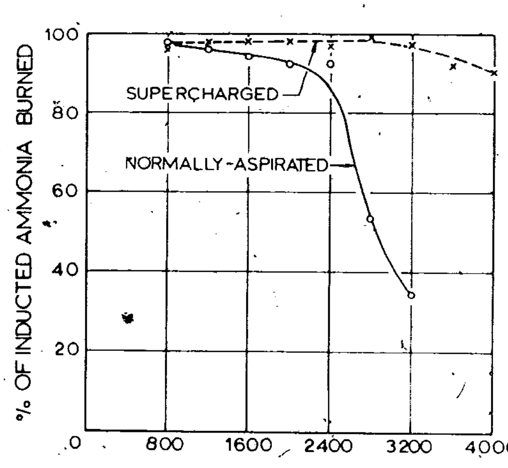

Fig. 11 - Improved combustion of ammonia in single-cylinder engine by supercharging -- modified ignition system, 9.4:1 compression ratio

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.

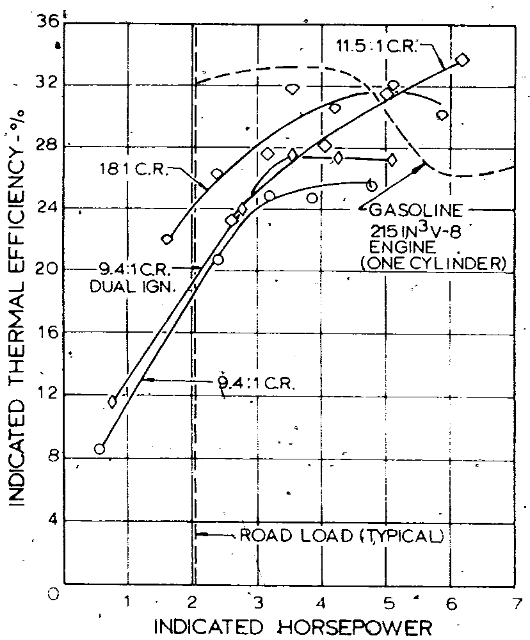

Fig. 12 - Minor improvements in part-throttle thermal efficiency of single-cylinder engine due to increased compression ratio and dual ignition -- ammonia fuel, modified ignition systems.

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

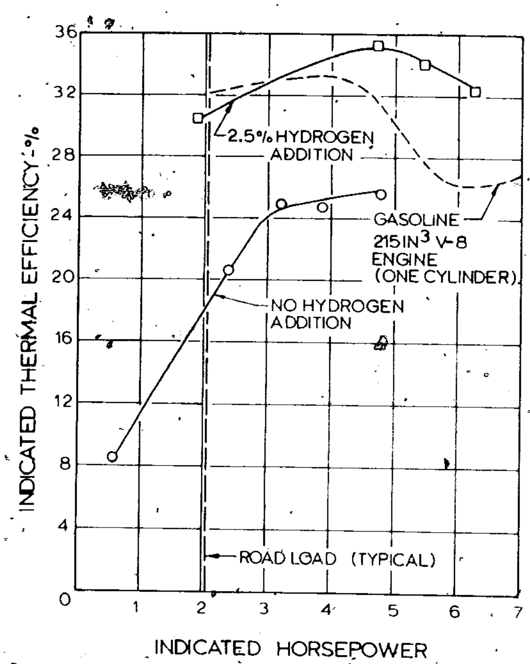

Fig. 13 - Improved part-throttle thermal efficiency of single-cylinder engine due to hydrogen addition to ammonia -- modified ignition system, 9.4:1 compression ratio

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, and normally aspirated full-

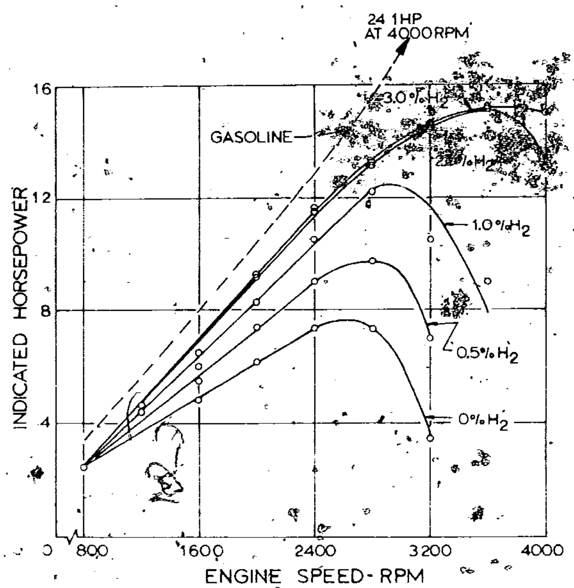

Fig. 14 - Improved performance of single-cylinder engine due to varying amounts of hydrogen addition to ammonia -- full-throttle normally-aspirated operation, 9.4:1 compression ratio

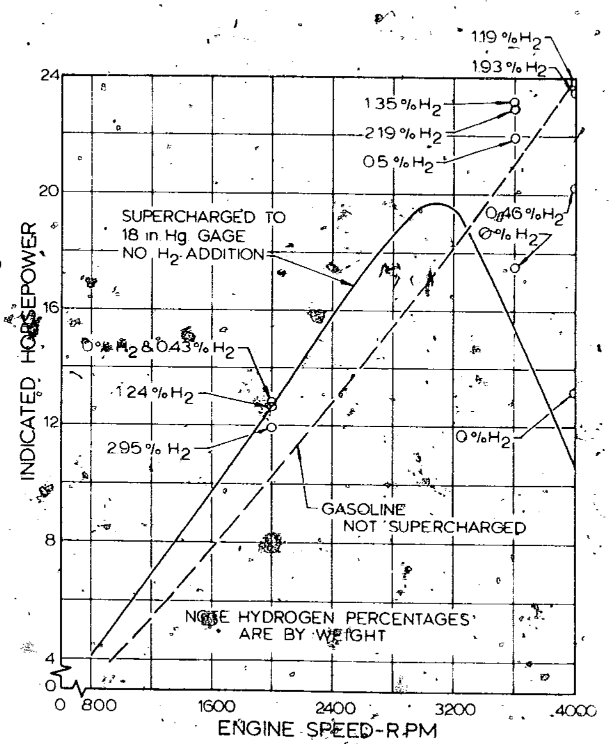

Fig. 15 - Varying improvements in performance of single-cylinder engine due to hydrogen addition to ammonia -- supercharged operation, modified ignition system; 9.4:1 compression ratio