Energy Depot Concept

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An Introduction to the Nuclear Powered Energy Depot Concept

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EVER SINCE THE FIRST internal combustion engine was installed in a military vehicle, military forces have become increasingly mechanized in the interests of enhanced mobility. The mule of the past has been replaced by mechanical beasts of burden. Similarly, the candle has given way to the electric light bulb, the campfire to the oil stove, and the carrier pigeon to the telephone and the telegraph. Mechanization has paid obvious dividends. It also has given the military forces a voracious appetite for petroleum fuels. Whereas the Army mule could forage for sustenance, trucks and tanks are dependent on fuel supply lines. Today, one of the major problems of military logistics is supply of petroleum products.

During World War II, petroleum products commanded roughly half the U.S. Army overseas shipping. In the Korean War, this proportion increased to about 70%. Today's fuel requirements account for approximately 70% of the entire supply load. While the problem of fuel supply extends to all the Military Services, it is especially significant in Army operations.

The vehicles and tools of the Army, essentially extensions of one man's capabilities, are characterized logistically by small, dispersed energy demands. The Army fuel requirement is the aggregate of a multitude of these small energy needs. As a result, the Army fuel supply system must extend from source to the location of the farthest individual soldier. In a theater of operations, the fuel supply system becomes a complex and vulnerable network that often restricts the very mobility it supports. Both quantity and distribution factors are involved.

With the nuclear powered energy depot concept, we propose to attack the petroleum supply problem in its entirety Nuclear reactor systems developed thus far are primarily electrical generators. Their fuel cores, weighing 850-900 lb, contain the energy equivalent of 90,000 barrels of diesel oil which weigh in excess of 26,000,000 lb. To the logistician, the utilization of a nuclear powerplant in place of a comparable diesel plant means a reduction in fuel transportation effort of 750 semi-trailer tank-trucks. It allows him to ship more than a year's fuel requirement along with other vital supplies in a single, standard cargo aircraft. It also may mean a reduction in manpower needs arising from shipping, storage, and operational functions.

As indicated earlier, petroleum products account for roughly 70% of all Army supply tonnage. Of this percentage, almost three quarters take the form of motor vehicle and aircraft fuel. Nuclear reactor systems at this time and for the forseeable future, will be too bulky to be considered as locomotive mechanisms for the relatively small military vehicles which operate on land. An alternative solution to the fuel supply problem is the manufacture of a chemical fuel near the point of intended use. The nuclear powered energy depot concept, a means of integrating the tremendous energy density available from reactors into the overall Army

ABSTRACT

Because of increased mechanization, petroleum supply has become one of the major problems of military logistics, especially in Army operations where small, dispersed energy demands often necessitate an extensive, vulnerable fuel supply complex. The nuclear powered energy depot, conceived as a potential solution to the problem, will utilize a nuclear reactor to produce a chemical fuel for vehicle and aircraft engines. The energy depot, logistically independent for a year, would operate with or near the consumer in the field and considerably broaden Army capabilities.

energy requirement, envisages the production of a chemical fuel from readily available materials such as air and water, by mobile units accompanying the forces in the field.

In effect, the energy depot will be a mobile fuel refinery and service station operating with or near the consumer. The technical approach involves consideration of three major subsystems: a mobile reactor as the primary source of energy, a fuel production complex which turns out a chemical fuel suitable for storage and transport to the user, and utilization devices applicable to a variety of operational needs such as vehicle and aircraft propulsion, heating, cooking, and local electricity generation. (Through the energy depot system, we hope initially to supplement petroleum supply; in the advanced stages, to eliminate the requirement for petroleum products, and achieve a greater freedom of maneuver for combat units; and consequently to achieve an eligibility for commitment of ground forces into areas and situations presently considered infeasible.)

Following in-house evaluation of the technical possibilities of an energy depot, the Army Nuclear Power Program undertook feasibility studies in the latter part of 1961. The contractors for these studies were the Allis-Chalmers Mfg. Co. and Allison Div. of General Motors Corp. Both studies followed the same ground rules concerning mobility requirements, raw materials availability (water, earth, and air), desired fuel characteristics and, hopefully, compatibility with existing and projected engines. Both studies, completed in May and June 1962, concluded that the concept was operationally feasible and that a logistic advantage would accrue. Representatives of the two firms will present papers covering their participation in the energy depot work.

The general conclusions of the two studies add up to three possible energy depot systems deriving primary energy from a reactor. The reactor produces thermal energy or electricity for process power or for the electrolysis of water. The resulting hydrogen is then liquefied for transport to the user or combined with nitrogen obtained by air fractionation in the synthesis of ammonia. These two fuels are then used in combustion engines or fuel cells to produce mechanical power. The revolutionary regenerative cell concept also offers possibilities although it is recognized that a long and expensive development program would be required to achieve a usable device. The regenerative cell operates similarly to a rechargable battery and would result in the elimination of the fuel production complex.

After considerable study and evaluation, it was decided that the initial energy depot work would be directed towards the production of ammonia for internal combustion vehicles. Phase two of the program, we feel, will probably be used with electric drive vehicles, powered with fuel cells, and regenerative cells considered a third phase.

Within the Army Nuclear Power Program we have attempted some rudimentary experimentation of our own on the utilization aspect of the project. At Ft. Belvoir, Va., enlisted personnel in our Nuclear Power Field Office modified a standard 1-1/2 hp Army engine to operate on ammonia. The success of this effort led them to attempt a more ambitious project, modification of a Chevrolet pick-up truck for ammonia-fueled operation. This second experiment, also successful in demonstrating the possibilities of ammonia as a fuel, has led us to hope that a conversion kit can be developed to permit inexpensive, easy modification of standard military vehicle engines to burn ammonia as a fuel.

The nuclear powered energy depot concept offers a potential breakthrough in reducing the logistic problem of military fuel supply. The capability for extended operation of reactors without continuous logistic support has been demonstrated. The utilization of this relatively independent energy source to produce vehicle fuel in a theater of operations will add a considerably broadened dimension to Army capabilities. Military units, equipped with Energy Depot system, may be capable of sustaining operations for periods up to a year without the need for providing fuel.

As a result of the development of the energy depot system, it is felt that the military forces in the field will have:

1. Greater capability to perform operational missions.
2. Greater freedom from logistic encumberance.
3. Greater economy of forces and resources in performing new capabilities.

Energy Depot - A Concept for Reducing the Military Supply Burden

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ONE OF THE MOST important factors in any combat operation is the ability to provide an adequate supply line. With ever increasing requirements for highly mechanized and highly mobile forces, fuel supply has become a critical consideration. Aside from the usual problems of logistics, maintenance of fuel supply in combat situations is further aggravated when rail and road transportation facilities are highly vulnerable or not available. Under these conditions, the maintenance of fuel supply can become very costly in terms of casualties to transportation personnel and equipment. This is particularly true when air supply must be used.

Modern armies can consume fuel at a voracious rate. Recent estimates indicate that even a small force of 1000 men can require several million pounds of fuel over a one year period. The same amount of energy could be produced by nuclear reactors weighing less than 1% of the equivalent fuel load. The weight advantage of nuclear energy supply can be directly translated into a reduction of transportation equipment and personnel. Furthermore, if the nuclear reactors could be used directly in the combat area, long and vulnerable supply lines between fuel manufacturing facilities and the combat zone could be eliminated.

Vehicle propulsion accounts for most of the fuel used in the Army. Consequently a number of studies were made to determine if nuclear reactors could be installed directly in military vehicles. These studies indicated that direct use of nuclear reactors was not practical for most vehicles. Therefore, an Army-sponsored program was initiated at Allison in July 1961 to determine if a method could be found for indirect use of nuclear energy as a source of vehicle propulsion power. The concept conceived for this purpose was termed the energy depot.

CONCEPT DEFINITION

In planning the initial study at Allison, the energy depot was visualized, as shown in Fig. 1, to consist of a nuclear powerplant and an associated energy conversion and storage system. The combined system would provide a means for fragmenting the available nuclear energy in a form suitable for vehicle propulsion. The overall system was to be capable of being packaged so that it could be transported by land, sea, or air. A nuclear powerplant suitable for the overall system was already under investigation in an AEC/Army program being conducted at Allison. Therefore, primary effort in the initial energy depot study was directed towards a definition of feasible processes for conversion, storage, and utilization of energy from the nuclear powerplant.

ABSTRACT

This paper reviews objectives, approach, and current status of energy depot studies conducted by the Allison Div. of General Motors.

An evolutionary concept is described for near term applications wherein nuclear energy, air, and water can be combined to produce a fuel for use in conventional vehicle engines. Fuel manufacture and engine operation studies are discussed. For longer term use, a revolutionary concept is described whereby a nuclear power source can be used to recharge an electric vehicle propulsion system. Both the evolutionary and revolutionary concepts are shown to provide important logistics advantages for military operations.

INVESTIGATION APPROACH

As shown in Fig. 2, a very broad approach was taken in the study of feasible processes for the energy depot. Consideration was given to storage of reactor output in its basic form of heat and radiation, as well as to the conversion of basic output for storage in the form of mechanical or chemical energy. Direct storage of reactor output would eliminate losses associated with the conversion of energy from one form to another. However, all methods for storage of heat and radiation were found to be too bulky for vehicle applications. Similarly, no reasonably compact method was found for storage of energy in mechanical form. Thus, it was concluded early in the study that nuclear energy would have to be converted and stored in chemical form in order to obtain a feasible system. It should be noted here that so-called electric storage batteries derive their energy from chemical reactions and were, therefore, considered in the chemical energy storage class.

The analysis of chemical energy storage systems was divided into two categories. One classification, called chemical manufacture, considered approaches in which fuels would be synthesized from locally available materials with a nuclear reactor as the power source for fuel manufacture. However, it was required that the fuel materials be universally available in substantial quantities in common earth, air, and water. For such systems, the reaction products from the energy utilization device would not be saved since the source of fuel materials was considered essentially limitless.

The second classification, called chemical regeneration, considered techniques that would permit complete freedom from local fuel material supply requirements. To achieve this, a given quantity of reactants would be taken into the field. After use in a power producing device, the products of reaction would be stored and subsequently regenerated to obtain the original reactants. Power for regeneration would be provided by an on-site nuclear powerplant.

Both thermochemical, or conventional combustion engines, and electrochemical devices were considered for energy utilization methods.

REGENERATIVE FUEL SYSTEMS

In the study of regenerative fuel systems, the use of combustion engines was considered impractical because of the difficulties associated with collection, compression, and/or liquefaction of the exhaust gases in order to reduce their storage volume prior to regeneration. Thus, primary effort in this area was directed toward fuel cells where the reaction products as well as the reactants could be obtained in liquid form for maximum compactness of storage.

After analyzing a large number of reactants, it was concluded that the liquid metals offered greatest promise as regenerative fuel materials because they offered potentially high power-to-weight ratios for fuel cell systems. Further, the liquid metals could be regenerated in liquid form rather than in gaseous form as with other reactants. The latter advantage eliminated the added complexity of liquefying or compressing the regenerated products for storage. It was also concluded that air would be desired as the oxidant since it was readily available and thus did not have to be stored. The most common electrolytes used for the electrochemical reaction of liquid metals with oxygen are aqueous solutions. Ordinarily, the liquid metals would react violently with the

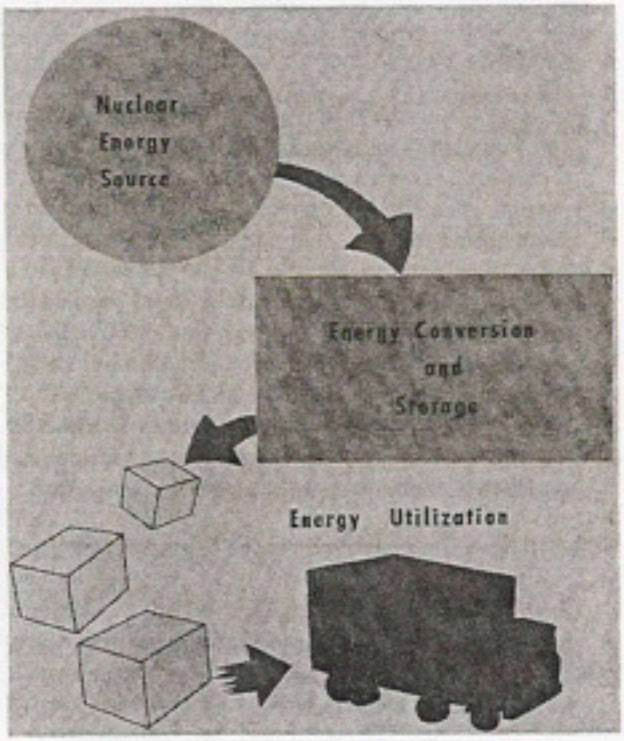

Fig. 1 - Energy Depot concept

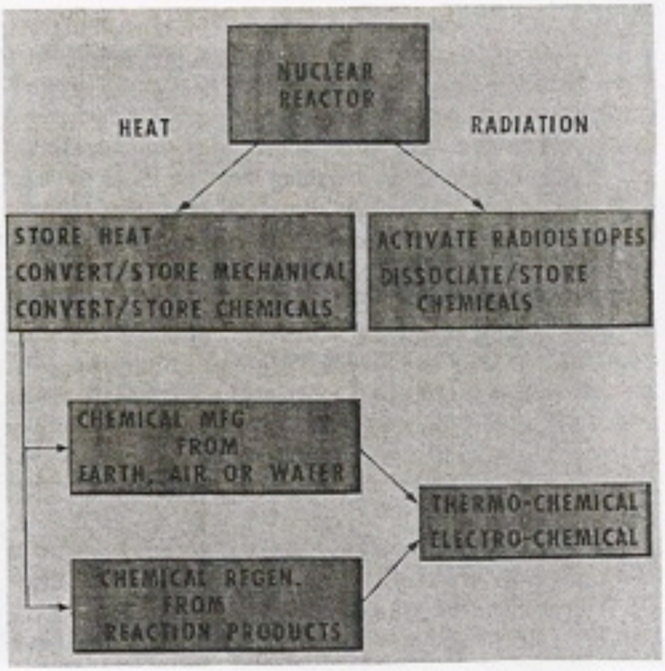

Fig. 2 - Approach

water in the electrolyte. To prevent this reaction, the liquid metals are combined with mercury in an amalgam before being fed to the reaction zone. The reaction product of the amalgam and air is an alkali hydroxide. This material could be returned to the depot and electrolytically regenerated to free the liquid metal for re-use. However, what was really desired was the ability to regenerate the fuel within the fuel cell in a manner similar to the recharging of a battery. This would eliminate the need for an electrolytic plant at the depot and the need to handle and store liquid metals.

The regenerative fuel cell system conceived for this study is shown in Fig. 3. Since it is a combination of two basic fuel cell types, it was termed the combined cell. In this system a fuel such as potassium would first be reacted with mercury. This reaction would produce electric power while forming an amalgam product. The amalgam would then be reacted with oxygen from air to form KOH. Mercury inventory would be minimized since it only serves to transfer K from one portion of the system to another. To recharge the system, the KOH would be pumped back into the amalgam cell and power would be supplied. This would electrolytically regenerate the K and return it to the amalgam. The oxygen would be liberated. The amalgam would then flow to the upper cell where it too would be electrolytically decomposed to return the K to the storage tank. Under an Army-sponsored program, laboratory studies were conducted at Allison to demonstrate the regenerative characteristics of this concept. On the basis of conceptual design studies, it was estimated that a powerplant of this type would be less than 1/10th the size and weight of an equivalent lead-acid battery. In contrast with a conventional battery, the range or operating time of this device is dependent only on its fuel storage capacity. Thus, it offered good potential as a power source for vehicles.

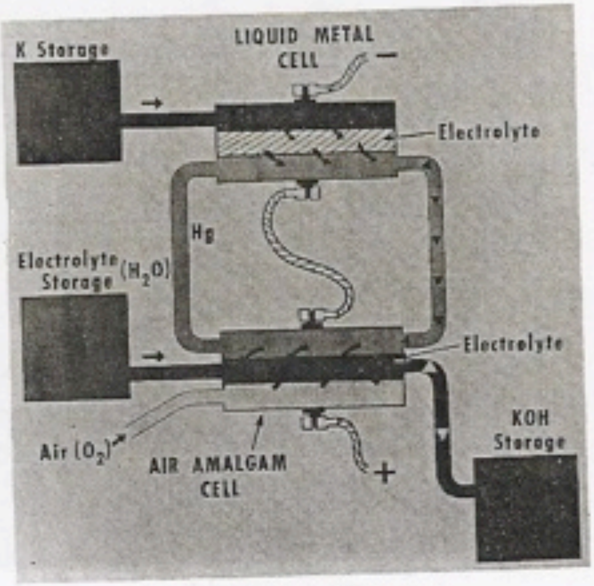

Fig. 3 - Combined cell schematic

A conceptual vehicle installation for the combined cell is shown in Fig. 4. Power from the cell would be fed to electric motors which would drive the wheels rather than the conventional engine and transmission system. The electrochemical processes used for both fuel regeneration and power production in this concept offer the highest efficiencies for conversion of chemical energy to other forms. This would provide a higher overall energy depot power conversion efficiency than any other system considered. Also in this concept, the energy depot proper would only consist of a nuclear powerplant which supplied electricity for recharging the batteries. This would improve Energy Depot mobility and would simplify energy depot operation. Or, in other terms, the combined cell approach would permit fewer depots for operation of a given number of vehicles.

As with other electrochemical devices, the combined cell is significantly larger and heavier than conventional engines of equivalent power output. As a result, its application would be limited to vehicles that can tolerate relatively low power-to-weight ratio propulsion systems. Therefore, consideration was also given to concepts which would utilize conventional engines in order to permit widest possible application of the energy depot concept.

MANUFACTURED FUEL SYSTEMS

In order to determine the feasibility for using conventional engines, first attention was directed to the characteristics and availability of potential fuel materials. Table 1 shows the distribution of elements in common earth, air, and water. An evaluation of materials available for fuel man-

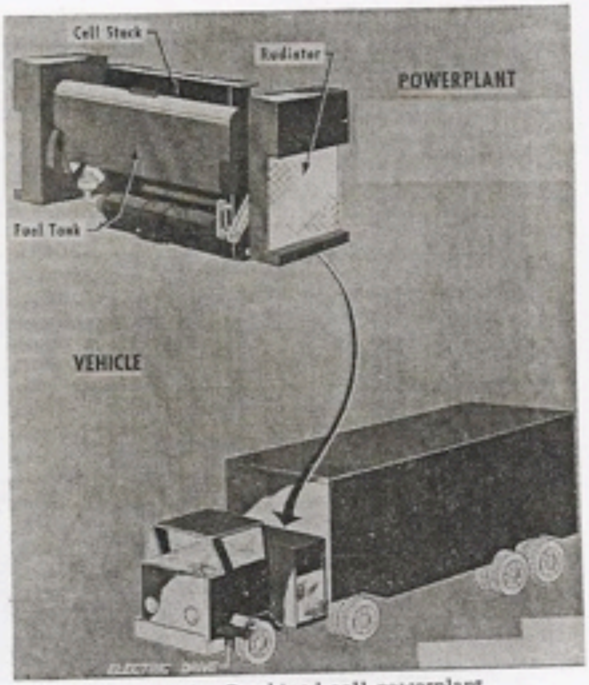

Fig. 4 - Combined cell powerplant

ufacture showed that common earth would not be a good source of supply. Silicon, a potential fuel material, can be found almost everywhere, but it is generally in oxidized forms that are difficult to break down. It would also be extremely difficult to use, because of its great affinity for oxygen.

Oxygen and nitrogen are readily available from air, but they are considered building blocks for fuels rather than fuels themselves.

Fortunately, hydrogen, an excellent fuel material, is readily available from water and was considered to be the key element in any field manufactured fuel.

Table 2 compares some potential energy depot fuels with gasoline. As shown, hydrogen obtained from water in gaseous form is not sufficiently dense to permit reasonable storage volume. In order to reduce volume, it was considered necessary to liquefy the hydrogen before it could be considered practical for vehicle propulsion. In addition, consideration was given to compounding the hydrogen with nitrogen and/or oxygen to increase its storage density. Of the many compounds investigated, the most promising was ammonia which could be prepared by combining hydrogen with nitrogen to form NH_3.

Thus the potential fuels were narrowed to liquid hydrogen and ammonia. In the final analysis, ammonia was selected in preference to liquid hydrogen as the recommended fuel for use in conventional engines. The selection was based on its ease of manufacture, ease of handling and storage, and greater safety in reciprocating engines.

After selection of a fuel, a conceptual design was prepared for an Energy Depot as shown in Fig. 5. This plant basically consists of a mobile ammonia manufacturing plant and an associated mobile nuclear powerplant. The conceptual design was based on a powerplant output of 3000 kwe. In the fuel manufacturing system, one module would be used to extract hydrogen from water by electrolysis. Another module would be used to obtain nitrogen from air by fractionation. The third module would combine the nitrogen and hydrogen under high pressure to produce anhydrous ammonia. The ammonia would be handled and stored in conventional, over-the-highway vehicles as used for com-

Table 1 - Chemical Fuels Source

			Per Cent
Earth			
Normal silicate rocks	- 95%	O_2	49.5
(includes sand)		Si	25.7
Shale	- 4%	Al	7.5
Sandstone Limestone	- 1%	Fe	4.7
		Mg	1.9
		Ca	3.4
		Na	2.6
		K	2.4
Dry Air			
Gases and vapor traces		N_2	78.0
		O_2	20.9
		A	0.9
		CO_2	0.03
		Inert	
Water			
Salt and fresh water, snow		H_2	11.1
Ice (atmospheric vapor)		O_2	88.9

Table 2 - Comparison of Fuels

Fuel	Heating Value Btu/lb	Specific Density lb/ft^3	Fuel Plus Container Btu/lb	Fuel Plus Container Btu/ft^3
Gasoline (ref.)	18,700	48.6	17,900	904,400
Hydrogen gas (70 F 2000 psia)	51,593	0.0065	2,220	32,800
Hydrogen liquid (-423 F 15 psia)	49,150	4.44	11,600	179,900
Ammonia liquid (70 F 125 psia)	7,492	42.6	7,340	247,400
Hydrazine liquid (70 F 15 psia)	6,723	62.8	6,450	409,500

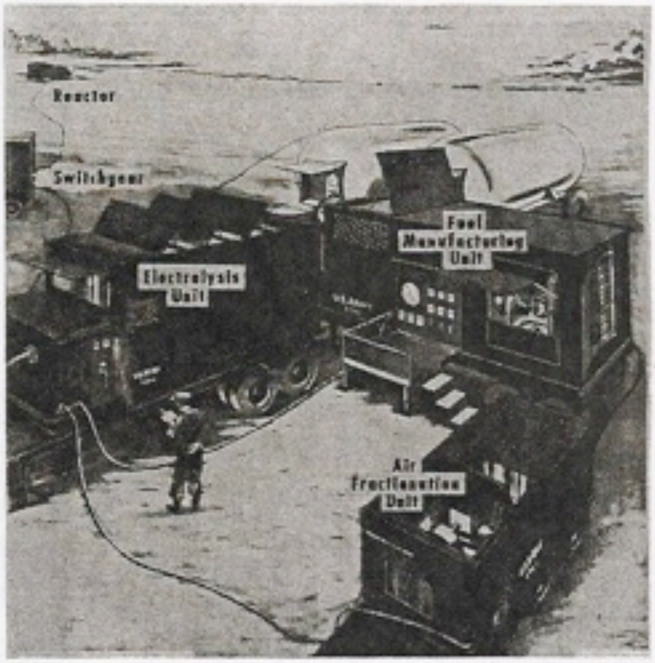

Fig. 5 - Energy Depot - mobile fuel manufacturing plant

mercial distribution of ammonia. This system could be moved by land, sea, or air to any battle zone and started up in a matter of hours.

The air fractionation and ammonia synthesis modules are based on current state-of-the-art equipment. However, the electrolysis unit is required to be an order of magnitude lighter than available commercial units. In order to achieve this objective, Allison has been developing a lightweight, compact unit under Army sponsorship.

The electrolysis unit will be comprised of a group of modules similar to the one shown in Fig. 6. Each module will contain a series of electrodes separated by plastic which also form the containment vessel when bolted together. An aqueous electrolyte will be fed into the unit. When power is supplied to the electrodes, the water in the electrolyte will be dissociated to form hydrogen and oxygen. The oxygen will be vented and the hydrogen will be fed to the ammonia synthesis unit. More than 150 electrodes were evaluated in order to determine the optimum composition for high efficiency and structural integrity. A laboratory prototype unit was fabricated and installed in the test rig shown in Fig. 7. Endurance and performance tests were conducted to evaluate power requirements, fluid flow characteristics, and mechanical design features. Results of the completed tests to date show that the proposed electrolysis unit will better the desired size and weight objectives for the energy depot system.

The next step in the investigation of the manufactured fuel approach was to determine the feasibility of using ammonia in conventional engines. Ammonia was known to have low flammability limits and high ignition energy re-

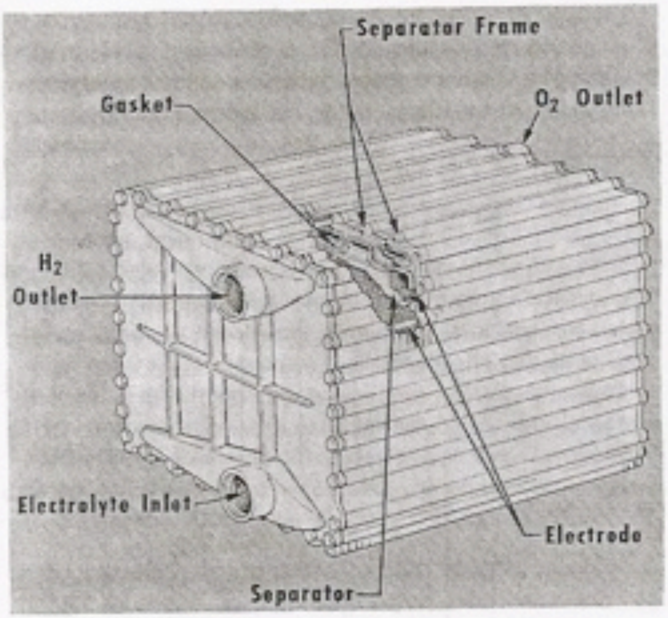

Fig. 6 - Electrolyzer module

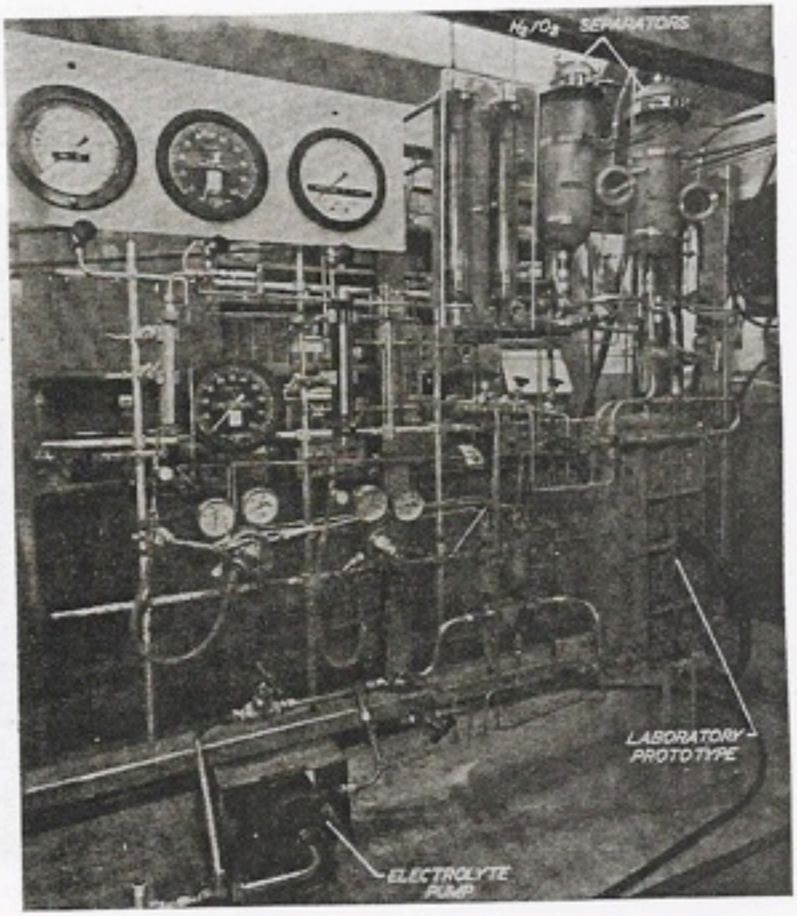

Fig. 7 - Multiple dynamic cell test rig

quirements. Although special engines might be developed to accommodate these characteristics, it was desired that modifications be held to a minimum so that existing engines could be operated on conventional fuel as well as ammonia. An extensive investigation was conducted to determine the feasibility of using ammonia in reciprocating engines. This program is described in an accompanying paper by the General Motors Research Laboratories.

At Allison, a comprehensive analytical and experimental effort was made to define the extent of modifications required for turbine engine operation. Combustion studies were conducted in the test rig shown schematically in Fig. 8. These tests evaluated both liquid and vapor injection of ammonia in a variety of injector and burner configurations. Some typical injectors are shown in Fig. 9. The results indicated that the poor flammability and ignition characteristics of ammonia could be improved by mixing it with hydrogen. The hydrogen would be provided by partially dissociating the ammonia before it is fed to the combustor. Fig. 10 compares the combustion test performance of pure

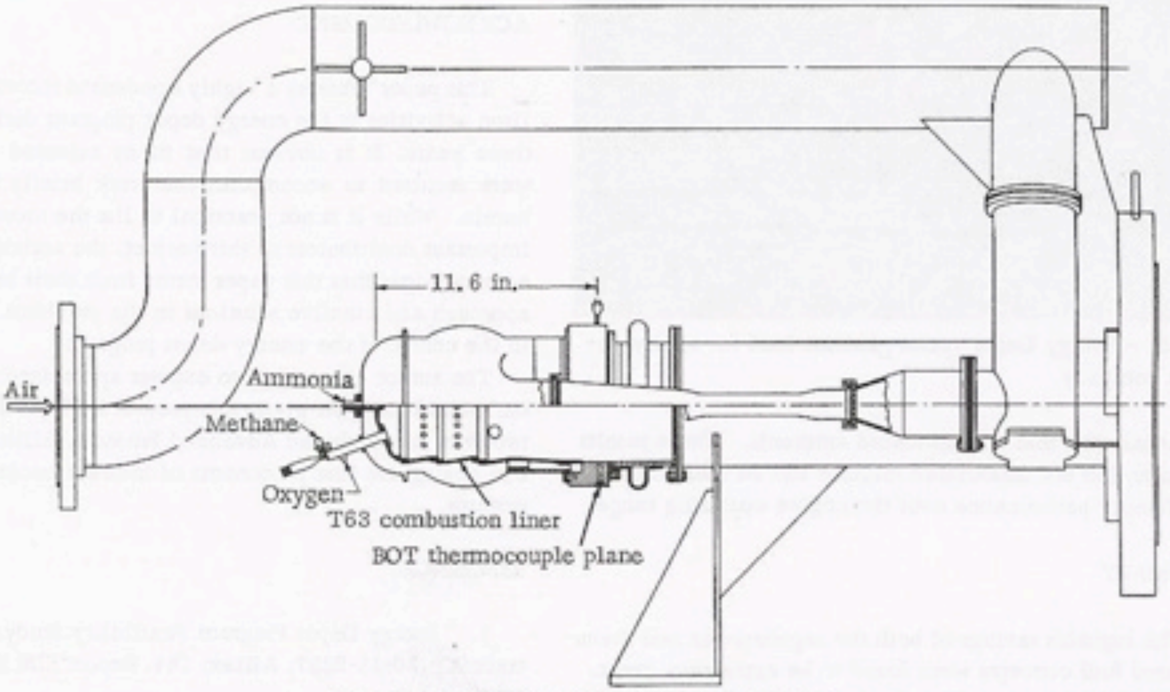

Fig. 8 - T63 combustion test rig schematic

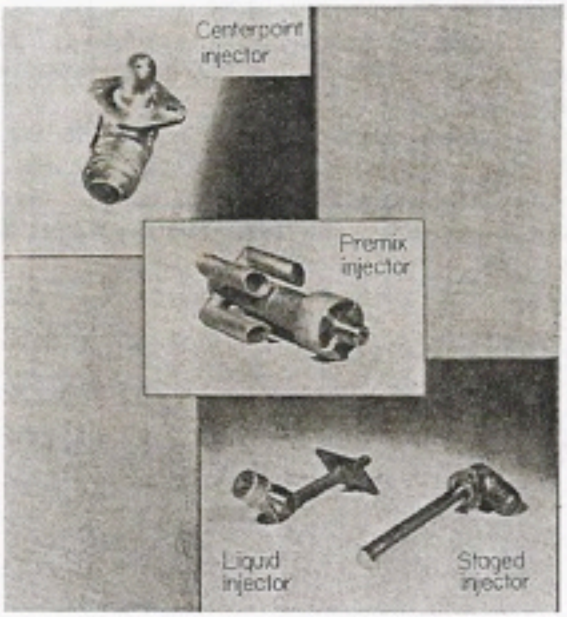

Fig. 9 - Ammonia injector designs

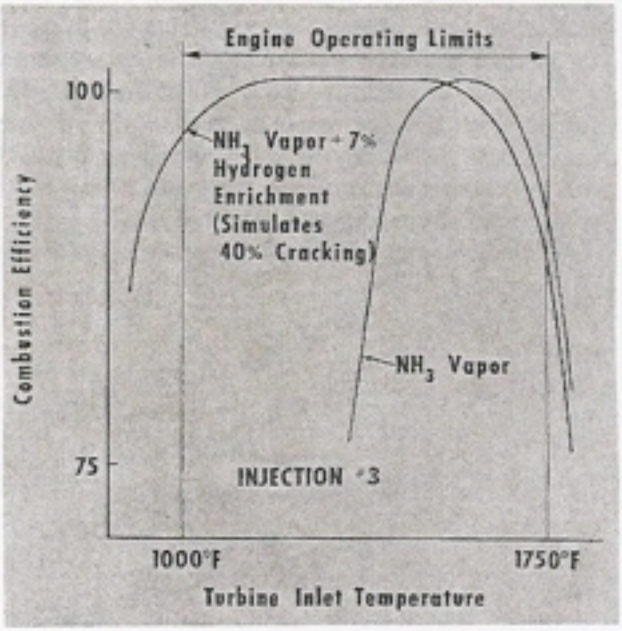

Fig. 10 - Hydrogen enrichment of ammonia vapor

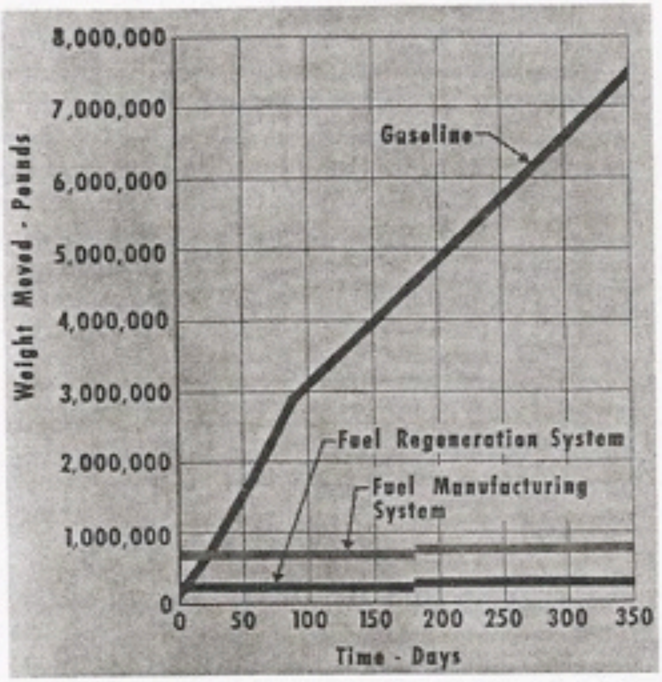

Fig. 11 - Energy Depot versus gasoline load for supply vehicle company

ammonia with that of dissociated ammonia. These results indicate that the dissociated mixture can be used to provide satisfactory performance over the engine operating range.

SUMMARY

The logistics savings of both the regenerative and manufactured fuel concepts were found to be extremely great. For example, Fig. 11 compares the weight of gasoline with the weight of equivalent energy depots that would be transported to a theater of operations to supply energy for a typical vehicle group over a one year period. With the regenerative fuel-combined cell concept, the cross-over point would occur in about five days. All of the fuel required after this period would weigh in excess of the equivalent energy depot. Similarly, with the ammonia manufactured fuel-combustion engine system the logistics load cross-over point occurs after about 30 days of operation.

The next step in the energy depot program is to determine its cost/effectiveness in competition with conventional fuel supplies. Preliminary studies have shown that the Energy Depot can improve the mobility of a combat group by removing its fuel supply constraint. Investigations are underway to determine the cost advantage of increased mobility versus the cost of procurement for the energy depot. If the energy depot proves as attractive from an economic standpoint as it does from a logistics standpoint, the usefulness of nuclear power for military applications will be greatly enhanced.

ACKNOWLEDGMENT

This paper presents a highly condensed summary of Allison activities in the energy depot program during the last three years. It is obvious that many talented specialists were required to accomplish the work briefly described herein. While it is not practical to list the more than 30 important contributors to this project, the author gratefully acknowledges that this paper stems from their broad-minded approach and creative solutions to the problems presented in the course of the energy depot program.

The author also wishes to express appreciation for the enthusiastic support given this project by T. F. Nagey, Director of Research and Advanced Projects, Allison Div., who was among the first proponents of indirect nuclear energy systems.

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Energy Depot Fuel Production and Utilization

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MODERN FIELD ARMIES today face an increasing fuel logistics problem. The major portion of the supplies brought to a theater of operations is fuel for vehicles, electric power generation, and heating. All studies point to an even greater increase in fuel consumption in the future.

Use of nuclear energy in the field is a potential solution to this problem. However, limitations of size and weight imposed by present nuclear technology prohibit the use of vehicles individually powered with nuclear energy. Therefore, the nuclear energy must be converted to energy forms that can be used to power individual vehicles.

In this concept, energy output of a mobile nuclear reactor would be processed to storable energy forms readily transportable to the energy consumers. This energy depot would be mobile and could accompany the field army in its operation. The concept would allow an extended operation of field units independent of outside fuel supplies. Field commanders would have greater freedom on operation, thus providing an opportunity to seize and maintain the initiative.

ENERGY DEPOT FEASIBILITY STUDY - A feasibility study of the energy depot concept was undertaken by Allis-Chalmers Manufacturing Co. with Air Products and Chemicals, Inc., as a subcontractor (1)* In this study every conceivable means to power vehicles indirectly with nuclear energy was considered. Numerous criteria or guidelines were used in evaluation and selection of attractive energy depot systems. Such systems have to be mobile, highly efficient, small in size and weight, and capable of operating essentially independent of supply. The energy depots must be road, air, and sea transportable. Thus, all equipment must be contained in modules, not exceeding 30,000 lb in weight and 8.5 × 8.5 × 24 ft in dimensions. Source of raw materials for the energy depot is limited to air and water. Earth as a raw material is eliminated because of variable composition. Maintenance materials are too minimal permitting extended operation free of outside supply. Energy forms should be storable to permit a supply buildup for use during movement of the energy depot. The conversion of nuclear energy to "power at the wheels" requires efficiency to minimize the depot's size and weight.

Using these criteria, analysis of potential energy depot systems leads to the general selection of systems which con-

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*Numbers in parentheses designate References at end of paper.

ABSTRACT

The Army's fuel logistics problem could be reduced or eliminated by use of nuclear energy in the field. In this concept, nuclear energy is converted to chemical fuels with locally available raw materials. Hydrogen can be produced by electrolysis of water with electricity from a nuclear reactor system. It can be converted to liquid hydrogen for ease of transportation. Alternately, liquid ammonia can be produced from the hydrogen and nitrogen extracted from air through liquefaction of air.

These fuels can be used most efficiently in fuel cell systems. The electric powered vehicles in these cases may have distinct military advantages. The fuels can be used to power modified combustion engines.

vert the nuclear energy to chemical fuels. These fuels can be stored, their energy transported in an easily divisible form, and they can be used for heating and to power vehicles.

Two broad chemical approaches can be employed in the energy depot concept; the open cycle and the closed cycle. In the open cycle process, the chemical fuel is synthesized from raw materials (air and water) at the depot site. The fuel is then transported to the user. There fuel is oxidized, energy is extracted, and oxidation products of the fuel are discharged to the atmosphere. In the closed cycle process, the oxidation products are retained at the user, returned to the depot, and reprocessed to fuel.

In the open cycle process, only the elements present in air and water are available to synthesize potential fuels and oxidants.

Consideration of the physical properties, the methods and efficiency of synthesis, the energy content, and the usage of compounds reduced the potential fuels to liquid hydrogen and the hydrogen carrier, liquid ammonia. Potential oxidants were reduced to air and liquid oxygen.

The liquid hydrogen synthesis process involves conversion of nuclear energy to electrical energy, electrolysis of water to hydrogen, followed by liquefaction of hydrogen. Ammonia is prepared by reaction of the hydrogen with nitrogen produced by liquefaction and fractional distillation of air. Both processes are basically techniques of densification of hydrogen for storage and transport.

Radiolytic decomposition of water and other chemonuclear synthesis processes were found to be of low efficiency, and the synthesis product purification process complicated fuel production. Direct thermal decomposition of water requires reaction temperatures too high for an attractive process. Indirect thermal decomposition of water using intermediate reaction steps with thermally regenerable chemicals does not appear to offer a highly efficient process for hydrogen production.

In the closed cycle processes, almost any chemical oxidation reduction process has potential as an energy carrier in the energy depot concept. Considerations of physical properties of compounds, energy content of fuels/oxidants, and efficiencies and methods of synthesis, and state-of-the-art of various powerplants rapidly reduce the list. Of all processes considered, only the sodium metal process and the methanol/caustic system survived for further analysis.

In the sodium process, sodium hydroxide solution at the depot is electrochemically converted to metallic sodium, water, and oxygen. Sodium and water are stored and transported to the using vehicle. They are used there to produce electric power for the vehicle drive. The sodium is converted to sodium amalgam in an electrochemical process producing electrical energy. Amalgam, water, and air are then supplied to a sodium amalgam/air fuel cell that produces more electrical energy for the vehicle drive. The sodium hydroxide solution product is returned to the depot for reprocessing. Alternately, the vehicle may return to the depot where electrical energy is fed into the electrochemical devices. This reverses the process above and produces sodium metal oxygen and water from the sodium hydroxide. This process is analogous to the recharging of secondary batteries. The sodium process is potentially very efficient, but in an early state of development (2-4). Operational and tactical characteristics of the system require further analysis before a system selection.

In the methanol/caustic system, sodium bicarbonate at the depot is reduced with hydrogen to methanol and sodium hydroxide. These are carried to the using vehicle. Methanol is used in a methanol/air fuel cell and to produce electrical energy for the vehicle drive. The oxidation products are returned to the depot as sodium bicarbonate solution. The total weight of the vehicle drive based upon the state-of-the-art of methanol cells eliminated this system in initial studies. Recent advances in methanol utilization efficiency may make this system attractive following further analysis.

Energy depot fuels need to be used with high efficiency to utilize the nuclear energy most effectively. The feasibility analysis showed that hydrogen and ammonia could be used most efficiently in fuel cells to produce power at the user.

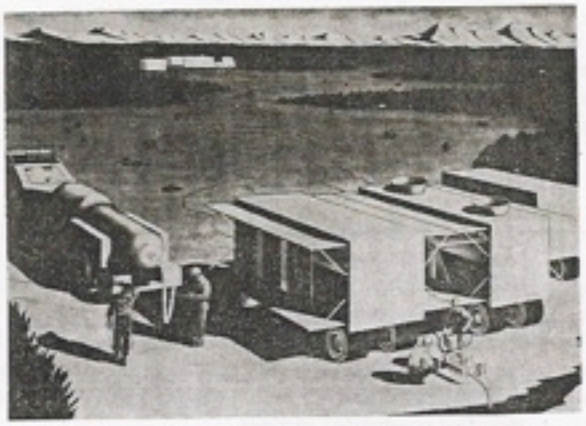

Fig. 1 - Artist concept of liquid hydrogen energy depot

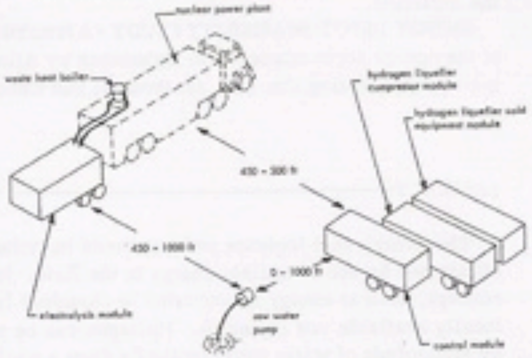

Fig. 2 - Arrangement for field operation

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ENERGY DEPOT FUEL PRODUCTION AND UTILIZATION CONCEPTUAL DESIGN - Allis-Chalmers with Air Products then undertook a conceptual design study of energy depot fuel production plants, and fuel cell powered vehicles using either liquid hydrogen or ammonia (5). The object of this study was to define more clearly the characteristics (weight, volume, processes, and performance) of the depots and vehicles designed for these two fuels. A fuel-cell-powered armored personnel carrier, based on the M113, was selected for the vehicular study.

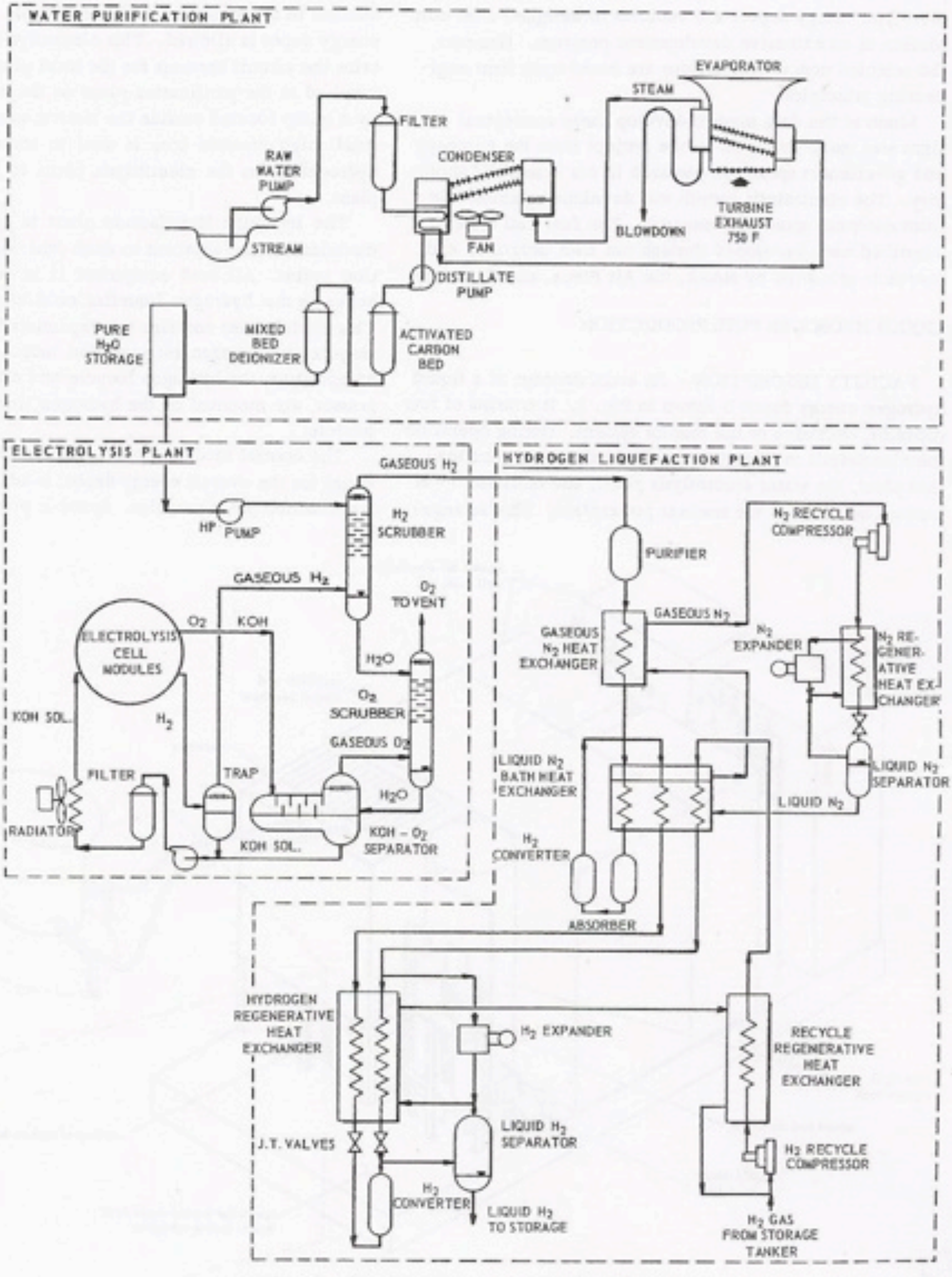

Fig. 3 - Liquid hydrogen process flow diagram

Other studies have shown the feasibility of mobile nuclear reactor electric power plants. For this analysis, a system capable of producing 3000 kw of electrical energy was assumed.

For purposes of this study, the conceptual designs were projected to the late 1960's state-of-the-art representing prototype energy depots and vehicles as designed after completion of an extensive development program. However, the selected conceptual designs are based upon firm engineering principles.

Much of the data used to develop these conceptual designs was made available to the project from the company and government sponsored research in our Research Laboratory. The electrolysis system was developed exclusively from company sponsored research. The fuel cell systems described were developed through our own programs and contracts sponsored by NASA, the Air Force, and the Army.

LIQUID HYDROGEN FUEL PRODUCTION

FACILITY DESCRIPTION - An artist concept of a liquid hydrogen energy depot is shown in Fig. 1. It consists of four modules, exclusive of the reactor system. During operation the electrolysis module -- containing the water purification plant, the water electrolysis plant, and rectifiers -- is located adjacent to the nuclear powerplant. This arrangement allows the water purification plant to use the waste thermal energy from the turbine exhaust (Fig. 2). However, the greater significance of this arrangement is that it requires only a short length of electrical cable to connect the turbine alternator to the electrolysis plant. Since this plant utilizes about 80% of the electrical power, a significant reduction in the weight of electrical cable needed by the energy depot is allowed. This electrolysis module also contains the circuit breakers for the total plant. Raw water is supplied to the purification plant on the electrolysis module by a pump located outside the reactor exclusion radius. A small high pressure hose is used to transport the gaseous hydrogen from the electrolysis plant to the liquefaction plant.

The hydrogen liquefaction plant is contained on two modules located adjacent to each other outside the exclusion radius. All cold equipment is in two insulated cold boxes on the hydrogen liquefier cold equipment module. This module also contains the expanders for the hydrogen recycle and nitrogen refrigeration loop. The two major compressors, the hydrogen recycle and nitrogen recycle compressor, are mounted on the hydrogen liquefier compressor module.

The control module, containing the centralized control panel for the overall energy depot, is adjacent to the two liquefaction plant modules. Space is provided on this mod-

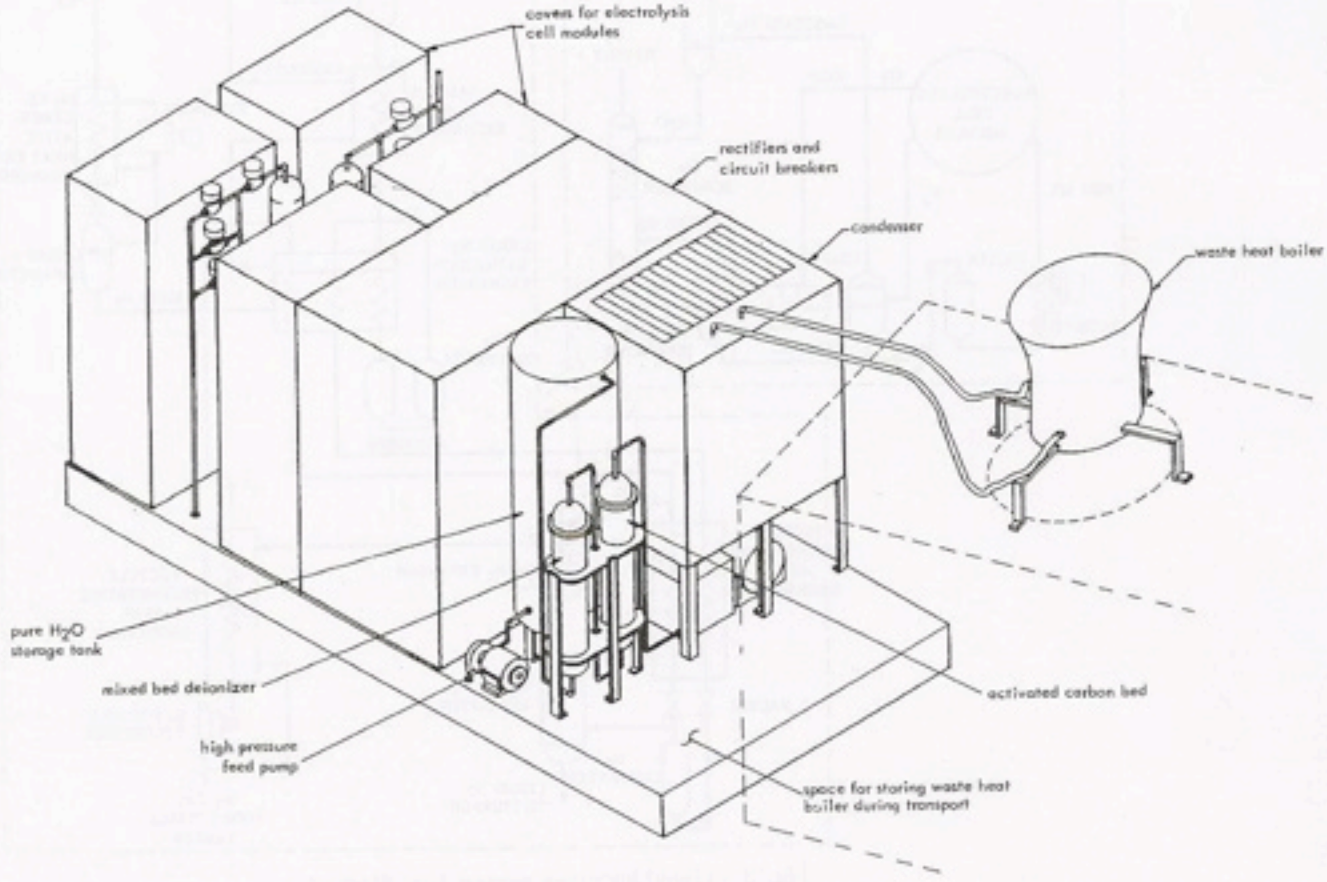

Fig. 4 - Electrolysis module

ule for depot maintenance operations, supplies, and for carrying the cables and hose during transit.

PROCESS DESCRIPTION - The process system flow diagram for the liquid hydrogen energy depot shown in Fig. 3 can be described in terms of the water purification plant, electrolysis plant, and hydrogen liquefaction plant.

Water Purification - A water purification plant is required to make the raw water suitable for use in the electrolysis plant. Contaminants in the water would remain in the electrolysis cells. The raw water (4-6 gpm) is heated in an atmospheric pressure boiler by the exhaust gas of the reactor gas turbine. One half to one third of the raw water is evaporated, and the remainder continually drained from the boiler to reduce scale formation on the heat-transfer surfaces.

Electrolysis Plant - In this study it was found desirable to operate the electrolysis cells above the pressures required for the feed stream of the hydrogen liquefaction plant. This eliminated the need for feed compressors for that system which resulted in a weight saving for the total fuel production plant. In addition, operation of the electrolysis plant at high pressure eliminates the inefficiencies of the mechanical and cycle losses of the hydrogen feed compressor and increases the product output. The theoretical increase in power, 1.36 kw hr/lb H_2, required for operating the electrolysis cells at 1840 psia, over that required for cells operating at atmospheric pressure was used for this design study. It is projected that the high pressure electrolysis process will require 19.86 kw hr/lb H_2 produced.

The electrolysis module is illustrated in Fig. 4. Electrolysis cell modules connected electrically in series parallel are assembled in multicell groups fitted into pressure tanks. These modules (Fig. 5) are arranged in four groups of six each. Each group has a rated input of 700 v.

Gas outlets from each electrolysis module are connected to one of the four collection manifolds, which conduct the fluids to the centrally located gas-electrolyte collection and separation equipment, serving all four circuits. Remotely

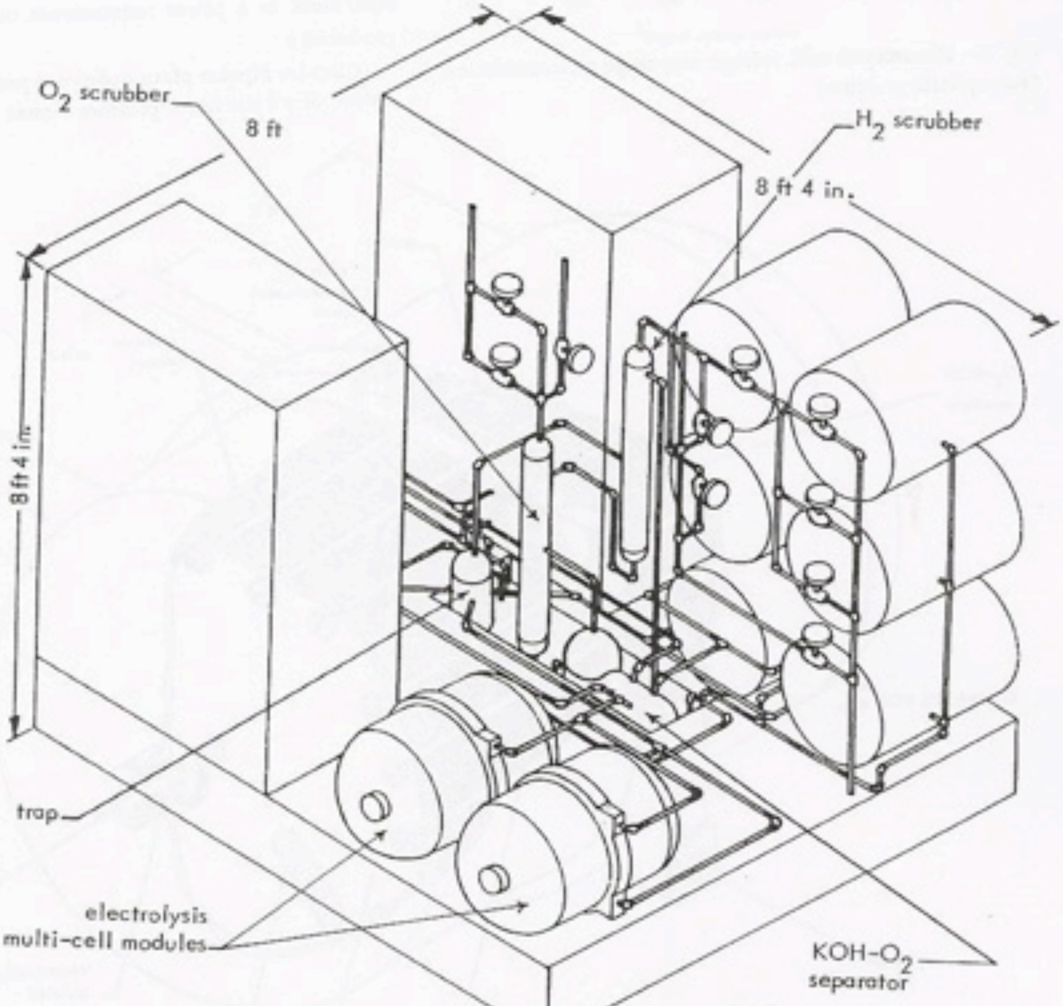

Fig. 5 - Electrolysis cell module stack

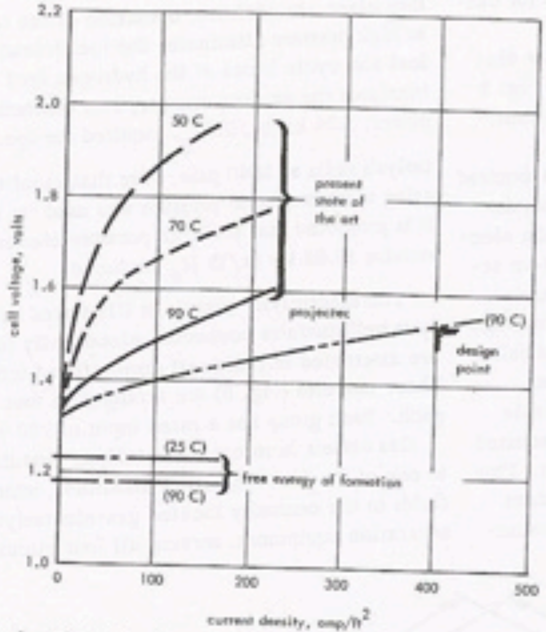

Fig. 6 - Electrolysis cell voltage amperage characteristics (atmospheric pressure)

operable valves provide for isolation of any of the four independent circuits. Pressure throughout the cycle is regulated by an arrangement of control valves at the outlets of the electrolysis plant.

Individual electrolysis cells are of the series bipolar design, similar to those used in Allis-Chalmers fuel cells. Major components of each cell consist of a hydrogen electrode, an oxygen electrode, an asbestos matrix electrolyte holder filled with KOH solution and an electrode holder or bipolar plate. Electrolyte is circulated through the oxygen evolution sides of the cells to provide make-up water, remove oxygen, and control the cell operating temperature.

Fig. 6 illustrates electrolysis cell voltage characteristics obtained by Allis-Chalmers with cells utilizing fuel cell bipolar plate construction. Extrapolation of today's state-of-the-art indicates that electrolysis cells can most probably be developed that operate at 1.535 v per cell and 400 amp/ft^2 current density at atmospheric pressure. (This is equivalent to a power requirement of 18.5 kw hr/lb H_2 produced.)

Circular bipolar plate geometry permits maximum utilization of a cylindrical pressure vessel (Fig. 7). The pro-

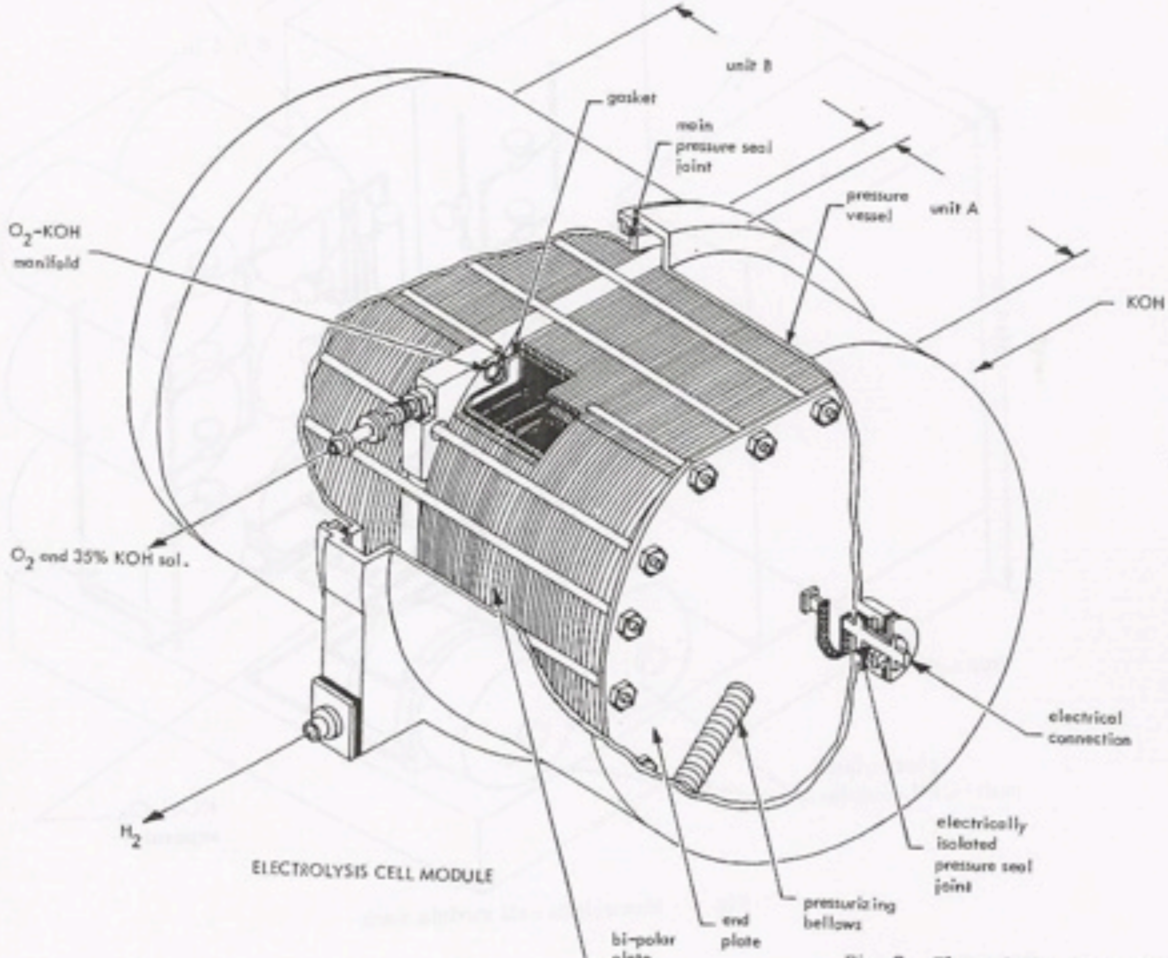

Fig. 7 - Electrolysis cell module

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X

posed design is based on the use of porous sintered metal electrodes. Catalysts are deposited on the electrodes to aid in the decomposition of water by lowering electrode potential.

In order to minimize internal resistance, the cell is designed with a thin KOH filled asbestos membrane. This membrane safely withstands the maximum pressure differentials allowed in the projected pressure control system. Each cell is sealed with O-rings. This seal separates the gas and electrolyte from the pressurizing liquid fill outside the cells. The pressure drop across these seals is negligible, since the liquid fill of the electrolysis module is held at a pressure only slightly less than that of the hydrogen gas. The pressure of the liquid exceeds the internal cell pressure only at shutdown and then only by the head of the liquid in the module.

The electrolysis cells are in pressure tanks (see Fig. 7), designed to take the pressure differential between the cell operating pressure and the atmosphere. Bellows pressurize the inside of the vessel (outside of the electrolysis cells) to the pressure level inside the cells with a nonelectrically conductive liquid. This design eliminates pressure differentials at each of the individual cell junctions.

Each electrolysis module contains two units (A and B in Fig. 7) of electrolysis cells operating electrically in parallel. Each unit contains 70 cells in series. The "pressure-seal" type of closure for the pressure vessel was selected over the more conventional bolted flange to reduce weight and overall diameter.

LIQUEFACTION PLANT - Hydrogen at about 1500 psi is delivered to the hydrogen liquefaction plant. A modified high pressure Claude liquefaction cycle (Fig. 3) was selected for the system because of its efficiency (6).

A hydrogen liquefier is a specialized combination of

Table 1 - Characteristics of the Energy Depots

Characteristics	Liquid Hydrogen	Liquid Ammonia
Fuel Production Efficiency*, %	68.0	67.1
Production Rate		
Fuel, lb/hr	114	710
Equivalent heat*, Btu/hr	6,960,000	6,870,000
Pure water, lb/hr	1050	1136
Hydrogen, lb/hr	117	126
Nitrogen, lb/hr	--	589
Power Requirements		
Water purification plant, kwe	7	8
Electrolysis plant;		
(a-c), kwe	8	9
(d-c), kwe	2320	2523
Liquefaction plant, kwe	525	--
Nitrogen generator plant, kwe	--	235
Ammonia synthesis plant, kwe	--	85
Transmission and distribution losses, kwe	45	40
Rectification losses, kwe	95	100
Total Electrical Power, kwe	3000	3000
Thermal energy to water purification plant, kwt	390	420
Electrolysis (d-c), kw/hr/lb H_2	19.86	19.93
Hydrogen liquefaction, kwhr/lb H_2	4.60	
Nitrogen generation, kwhr/lb N_2		0.40
Ammonia synthesis, kwhr/lb NH_3		0.12
Module Weights		
Electrolysis, lb	27,000	29,000
H_2 liquefaction, cold equipment, lb	28,000	--
H_2 liquefaction, compressors, lb	29,000	--
Control, lb	25,100	25,300
Ammonia	--	30,000
Totals	109,100	84,300
Module Dimensions		
Electrolysis, ft	22 x 8.5 x 8.5	24 x 8.5 x 8.5
H_2 liquefaction, cold equip., ft	24 x 8.5 x 8.5	--
H_2 liquefaction, compressors, ft	24 x 8.5 x 8.5	--
Control, ft	20 x 8.5 x 8.5	20 x 8.5 x 8.5
Ammonia, ft	--	24 x 8.5 x 8.5

*Based on higher heating values of fuels.

compressors, heat exchangers, expansion valves and engines, adsorbers, piping, and other standard types of process equipment. A transportable hydrogen liquefier could be built with present technology, but such a system would not meet the energy depot criteria. Commercial compressors, expanders, and heat exchangers would impose severe limitations on the characteristics of the plant. It is projected that lightweight, nonhydrocarbon lubricated double acting, reciprocating compressors operating at 850-1600 ft/min and 4000 rpm with an efficiency of 75% can be used. Advanced design, nonhydrocarbon lubricated, expanders with efficiencies of 90% would be used. These expanders would be operated at half speed during start up. Advanced concept high surface area heat exchangers will be incorporated in the liquefaction plant design. Anticipated power requirements for liquefying the high pressure stream of hydrogen are 4.6 kw hr/lb liquid H_2.

This liquid hydrogen fuel depot is expected to produce 114 lb of liquid hydrogen per hour from an electrical input of 3000 kw plus some thermal energy recovered from the reactor turbine exhaust heat. Characteristics of the liquid hydrogen fuel production plant are given in Table 1.

LIQUID AMMONIA FUEL PRODUCTION

FACILITY DESCRIPTION - The ammonia production unit is similar to the liquid hydrogen unit except here hydrogen is mixed with nitrogen and converted to ammonia for storage and handling. The ammonia energy depot occupies only three modules exclusive of the nuclear powerplant. Arrangement of the modules is similar to that for the liquid hydrogen depot shown in Fig. 2 with the exception that the two modules of the liquefaction plant are replaced by a single module adjacent to the control module. Both the nitrogen generator plant and the ammonia synthesis plant are mounted on this single module.

The projections for the size and weight of the electrolysis module in this system are based upon extrapolations of the weights and sizes developed under the liquid hydrogen energy depot design. Production of ammonia from hydrogen and air requires less input energy per pound of hydrogen than that needed for liquefaction of this hydrogen. The production rate for water purification and electrolysis plants are correspondingly about 8% larger than that for the liquid hydrogen plant. Because of the larger production rate, the size and weights of the water purification and electrolysis system are larger than in the liquid hydrogen system.

PROCESS DESCRIPTION - The process system flow diagram for the ammonia system is shown in Fig. 8. The process flow for the production of hydrogen is identical to that discussed before. The electrolysis plant is designed to operate at 2000 psi pressure. This permits hydrogen to be mixed directly with the nitrogen at this pressure in a stoichiometric ratio prior to the final stage of compression required by the ammonia snythesis process. Design of the electrolysis plant for operation at the 5000 psi required by the ammonia synthesis process was discarded as being excessively difficult for the resultant gains in the process. Operation of the electrolysis process at the 2000 psi delivery pressure requires a projected energy input of 19.93 kw hr/lb H_2 produced, or 1.43 kw hr/lb H_2 above operation requirements of the cells at atmospheric pressure.

NITROGEN GENERATION - Nitrogen for the production of the ammonia is provided by the liquefaction and fractional distillation of air (Fig. 8). An advanced design, four stage, 36,000 rpm, centrifugal air compressor was used in the design. Oversizing by 50% was used for fast start up and operation at extreme altitude conditions. A radial inflow turbine operating at 61,000 rpm and approximately 80% efficiency was used for the expansion engine. Main heat exchangers are envisioned to be of the aluminum plate-and-fin-type for maximum heat transfer capacity per unit of volume and weight. The distillation column will utilize either bubble-cap or sieve trays. It is estimated that an energy input of 0.4 kw hr will be needed to produce 99.993% N_2. The warm start up time of the plant would be about 12 hr.

AMMONIA SYNTHESIS - Ammonia is synthesized by the reaction of stoichiometric mixture of nitrogen and hydrogen over catalysts

$$3H_2 + N_2 \rightleftharpoons 2\text{-}NH_3$$

This equilibrium reaction for the formation of ammonia is favored by high pressure, low temperature, and low concentration of ammonia in the feed stream. The schematic for the synthesis cycle is shown in the lower portion of Fig. 8. The synthesis reaction is highly exothermic. It is envisioned that the chemical reactor will be cooled by water flowing through coils in the synthesis reactor. The superheated steam so formed is passed through a conventional-type steam turbine-generator to recover a portion of the heat of reaction as electrical energy.

A pivotal item in any ammonia plant is the synthesis catalyst. The energy, weight, and volume of the plant are largely determined by the ability of the catalyst to effect the synthesis reaction. Available catalysts are relatively crude materials which, though studied intensively, have not been appreciably improved. Cost of the available materials is so low that significant development programs have not been commercially justified. It is projected that an advanced synthesis catalyst can be developed which is more active than the best current materials.

Typical process conditions for commercial low pressure plants are 500 C and 300 atm. Under these conditions, the reactor effluent contains about 20% ammonia and represents a 75% approach to equilibrium. Characteristics of the energy depot plant have been estimated on the basis of a catalyst which produces 35% ammonia in the effluent stream (77% of equilibrium) at 400 C and at 350 atm. The flow rate of gases recycled back to the reactor is approximately equal to the feed gas rate; therefore, the conversion separation circuit operates with a gas flow rate approximately double the feed gas rate. It is anticipated that this combination of conditions will yield a substantial weight and volume savings for the overall plant. Compressors in the ammonia synthesis plant will be of the advanced type discussed before. It is estimated that an energy input of 0.12 kw hr/lb NH_3 will be needed for the ammonia synthesis plant.

The ammonia fuel depot is expected to produce 710 lb of anhydrous ammonia per hour from the 3000 kw output of the nuclear powerplant plus some thermal energy recovered

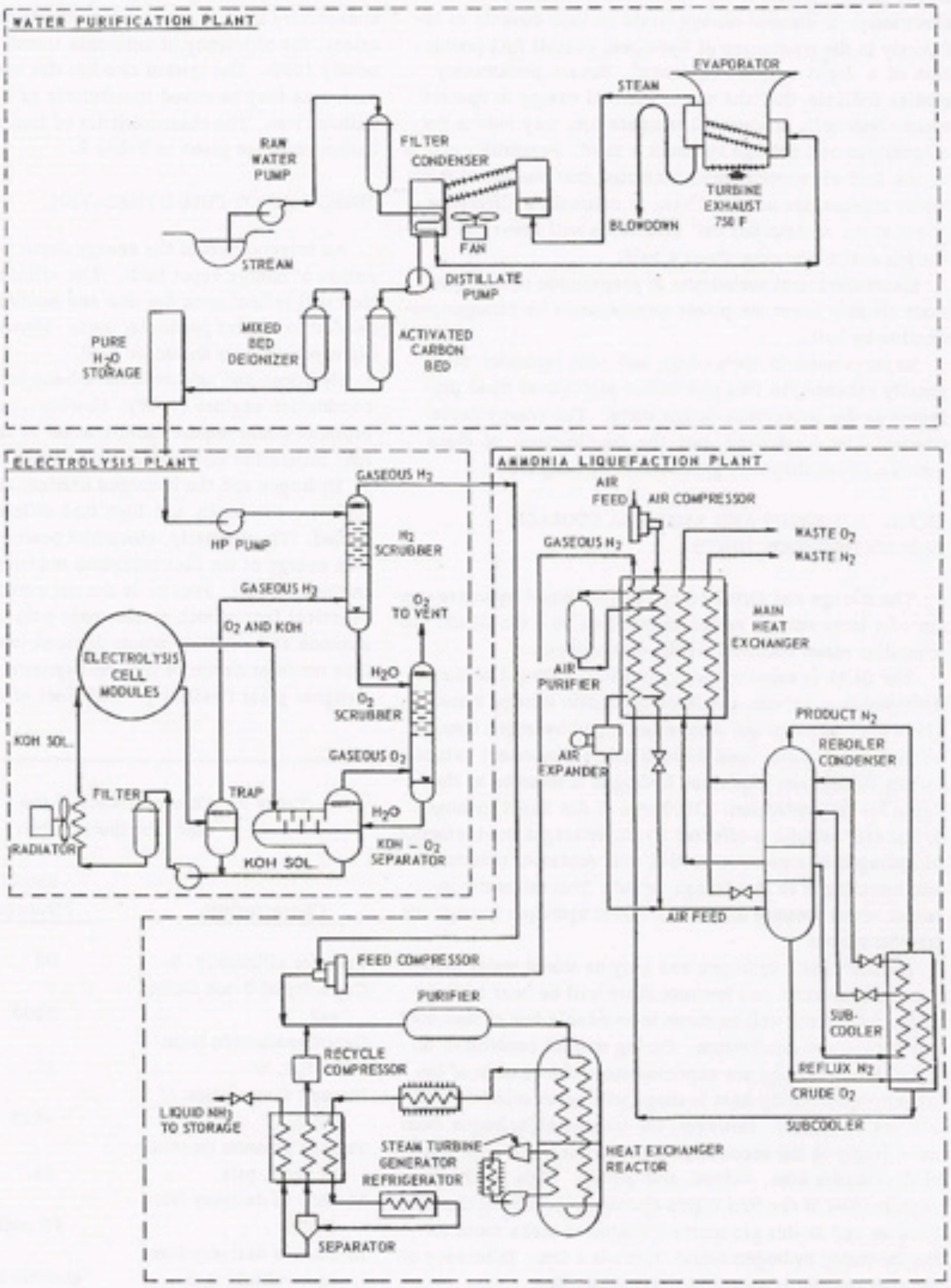

Fig. 8 - Liquid ammonia process flow diagram

from the reactor turbine exhaust heat. Characteristics of the liquid ammonia fuel production plant are given in Table 1.

FUEL PRODUCTION SYSTEM MODIFICATIONS - In the systems discussed, about 80% of the electric power is consumed in the production of hydrogen. The major inefficiency in the systems is the conversion of nuclear heat to electricity. If thermal energy could be used directly or indirectly in the production of hydrogen, overall fuel production of a depot may be increased. Recent preliminary studies indicate that the use of thermal energy to operate electrolysis cells at elevated temperatures may reduce the electrolysis cell voltage by about a third. Feasibility studies on the dual pH concept have indicated that the use of thermally regenerated acid and base to maintain a difference in pH at the electrolysis cell electrodes will lower the electrolysis cell voltage by about a half.

Electrochemical techniques of preparation of nitrogen from air may lower the power requirements for nitrogen production by half.

Improvements in technology and new processes may greatly enhance the fuel production yields over those projected in the conceptual design study. The energy depot concept does not depend upon the development of these techniques but they will greatly aid the program.

LIQUID-HYDROGEN AND AMMONIA STORAGE AND DISTRIBUTION UNITS

The storage and distribution units for liquid hydrogen consist of a large storage vessel mounted on an 8 ton GOER, and a smaller vessel mounted on the user vehicle.

The GOER is expected to carry about 3200 gal of liquid hydrogen in a vacuum insulated cryogenic storage vessel. The vessel receives and discharges liquid hydrogen through an insulated transfer hose through quick-disconnect valves. During filling, any vaporized hydrogen is returned to the depot for reliquefaction. Discharge of the liquid hydrogen to the user vehicle is effected by vaporizing a small amount of hydrogen in a pressure-raising coil (external radiator) and returning it to the storage vessel. This raises the internal vessel pressure and forces liquid hydrogen through the transfer system.

Because liquid hydrogen can only be stored under cryogenic temperature and because there will be heat leakage to the fuel, there will be some unavoidable loss of fuel during storage and distribution. During normal conditions, no losses during storage are expected since the amount of hydrogen vaporized by heat leakage will be so small that it will not be vented. However, the transfer of hydrogen from the primary to the secondary vessel requires the cool down of the transfer hose, valves, and piping. This results in vaporization of the first liquid hydrogen contacting the warm surfaces and as this gas must be vented to make room for the incoming hydrogen liquid, there is a loss. Efficiency of the fuel transfer is expected to be about 93%.

The ammonia storage and distribution units consist of a large reinforced plastic ammonia storage vessel m
on an 8 ton GOER, and a smaller vessel mounted on
vehicle. Both vessels store the liquid ammonia unde
sure at ambient temperature. A small pump is provi
move the liquid ammonia from the primary vessel to
user vehicle through a flexible base. The vessels are
vented except during emergency conditions. Because
unnecessary to vent gas in any of the filling or transfe
ations, the efficiency of ammonia transfer is expecte
nearly 100%. The system also has the advantage that
ammonia may be stored indefinitely in the pressurize
without loss. The characteristics of fuel storage and d
bution units are given in Table 2.

ENERGY DEPOT FUEL UTILIZATION

An integral part of the energy depot concept is the
zation of energy depot fuels. The efficiency of fuel u
tion will reflect upon the size and number of energy d
needed to support particular units. Ideally, the most e
cient powerplants should be used.

Hydrogen and ammonia have been used to power in
combustion engines (7-10). However, present vehicle
erplants would require modification to use these fuels.
fuel utilization efficiency could approach that of gasol

Hydrogen and the hydrogen carrier, ammonia, are id
fuels for fuel cells and high fuel efficiencies can be o
tained. Theoretically, electrical power equivalent to t
free energy of the fuel oxidation reaction can be produc
in the fuel cell. Fuel cells are not carnot cycle limited
Practical factors such as electrode polarization internal
sistance and auxiliary power demand lower the net outp
The modular nature of fuel cell systems allows the vehic
designer great flexibility. High fuel efficiency, silent o

Table 2 - Characteristics of the Fuel Storage and Distribution Unit

Characteristic	Liquid Hydrogen	Liquid Ammoni
Transfer efficiency, %	93	100
Capacity of 8-ton GOER, gal	3200	2900
Depot production hours to fill, hr	17	21
Storage temperature of fluid, F	-423	-30
Storage pressure (normal) of fluid, psia	14.7	153
Method of delivery from GOER	PR coil	pump
Method of delivery from user vehicle tank	electric heater	pump

ation, and design flexibility are obtainable with fuel cell powerplants and point toward a greater usage of fuel cells in future vehicles, and are a prime application in the energy depot systems.

Future fuel cell powered military vehicle must be entirely new power train. Present designs will probably not be retrofitted. However, in order to establish the feasibility of the application of fuel cell power to military vehicles, an armored personnel carrier (APC) based upon the M113 was selected for study. Two fuel cell powered vehicle drive systems were investigated for this vehicle: hydrogen/air and dissociated ammonia/air.* For comparison, the use of hydrogen, ammonia, and gasoline in the APC was also investigated.

FUEL CELL ASSEMBLIES

The fuel cell assemblies studied were hydrogen/air and dissociated ammonia/air. The hydrogen/air fuel cell assembly was the centerline design. All of the fuel cell systems consume hydrogen as the fuel and oxygen from air as the oxidant. Direct use of ammonia as a fuel in low temperature cells has not presently proved successful, and it must be dissociated into hydrogen and nitrogen for use. In the cases where the fuel and oxidant contain nitrogen, the nitrogen remains inactive and serves only to dilute the consumable gas. As a result, the projected performance of the hydrogen/air and the dissociated ammonia fuel cell are lower than hydrogen/oxygen systems.

Hydrogen consuming fuel cells can be classified as solid electrolyte, liquid electrolyte, or capillary-held electrolyte type. This study deals with the capillary membrane fuel cell long under development at Allis-Chalmers. Tests and analysis have proved that this type of fuel cell is feasible and well suited to use in a military vehicle. This fuel cell is an electrochemical converter that produces electrical energy, product water, and heat from a continuous supply of hydrogen and oxygen (air). The basic system has been described in detail in other reports (11-13).

HYDROGEN-AIR FUEL CELL ASSEMBLY - Early in the study it was necessary to designate a power output for the hydrogen/air fuel cell assembly which would approximately satisfy the power requirements for the vehicle drive unit on the APC. This was necessary to determine the weights, sizes and other characteristics of the fuel cell assembly and its components. A gross power output of 160 kw in continuous service was selected as the total power output of the fuel assembly. The auxiliaries for the fuel cell assembly require 12 kw of power. This assembly can produce 180 kw (net) in a 15 minute overload condition.

Hydrogen/air fuel cell assembly designs were projected to be achievable in the late 1960's on the basis of performance characteristics available in 1963. Actual assemblies developed may differ from those projected, but it is expected that with reasonable research and development, the size, weight, and performance goals are attainable. Fig. 9 shows the predicted performance related to results of tests performed on a fuel cell module built in an Allis-Chalmers development program. The prediction was also guided by results of research and development on hydrogen-oxygen assemblies for aerospace application.

A primary consideration in designing a vehicle power assembly is its weight. In applying fuel cells to a vehicle it is possible to project an operating design point so that the fuel cell assembly will be very efficient; that is, operate at low current density (amp/ft^2) and at high terminal voltage (see Fig. 9). The total electrode area for the cells is large and their weight is great. The amount of fuel consumed for a given mission would then be small. If the design point is chosen at a very high current density, then the voltage output of each cell is reduced, and the number of cells must be increased to obtain the desired output voltage. The weight of a module for a given power level decreases up to the point where the increased weight, resulting from the number of cells required, overcomes the weight saving because of the reduction in plate area. However, this occurs at a very high amp/ft^2 operating point for the projected performance curves. As this operating point increases for a given performance curve, efficiency falls. Consequently, the fuel consumption rate, and the water and heat to be removed all increase. These effects result in a system growth, requiring more fuel and larger capacity auxiliaries. If the performance curve, re-required power level, and mission time are known, it is possible to find a point of minimum assembly weight. Thus, the selection of the amp/ft^2 design point requires a balancing of the results of mathematical analysis with a knowledge and understanding of the nature of fuel cell development projected to the late 1960's. With all these factors in mind, the design point of 300 amp/ft^2 at 0.825 v was selected for continuous duty of the hydrogen/

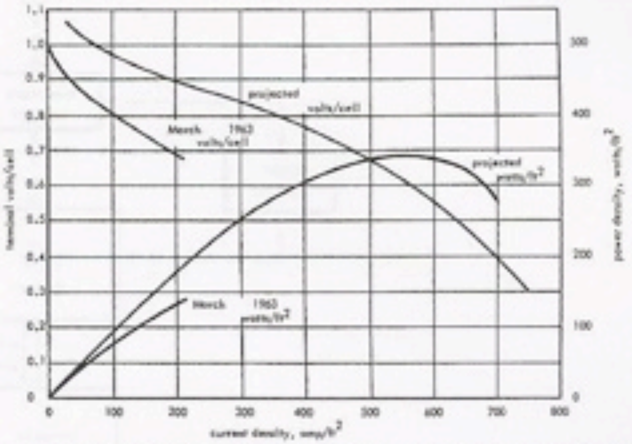

Fig. 9 - Projected performance curves for hydrogen/air fuel cells

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*The hydrogen/oxygen system for vehicles was analyzed and found to be very similar to the hydrogen/air system.

air fuel cell. A 15 minute overload point of 400 amp/ft^2 at 0.758 was used.

Process Equipment - Arrangement of the fuel cell process equipment is shown in Fig. 10. The fuel cells are arranged in modules consisting of 91 cells each. Sixteen modules make up the vehicle drive unit and are connected by common manifolds to the cooling circuit, the hydrogen and oxidant supplies, and the moisture removal condenser.

About 70% of the water is removed through the static moisture control system on the hydrogen side of the cell. The remaining 30% of the moisture is removed with the exhaust air. Moisture removal cavities of all cells are connected through a common manifold to the condenser. Pressure within this condenser is automatically maintained by the vacuum fan; thus, the migration of moisture stops at a particular concentration of electrolyte when the corresponding vapor pressure matches the pressure maintained in the condenser. Condensed moisture is returned to the air purifier to humidify the incoming air. An air purifier conditions the air entering the cells removing dust, carbon dioxide, and the like, and humidifying of air to a vapor pressure corresponding to minimum desired vapor pressure in the fuel cells.

The fuel cell modules are maintained at a constant tem-

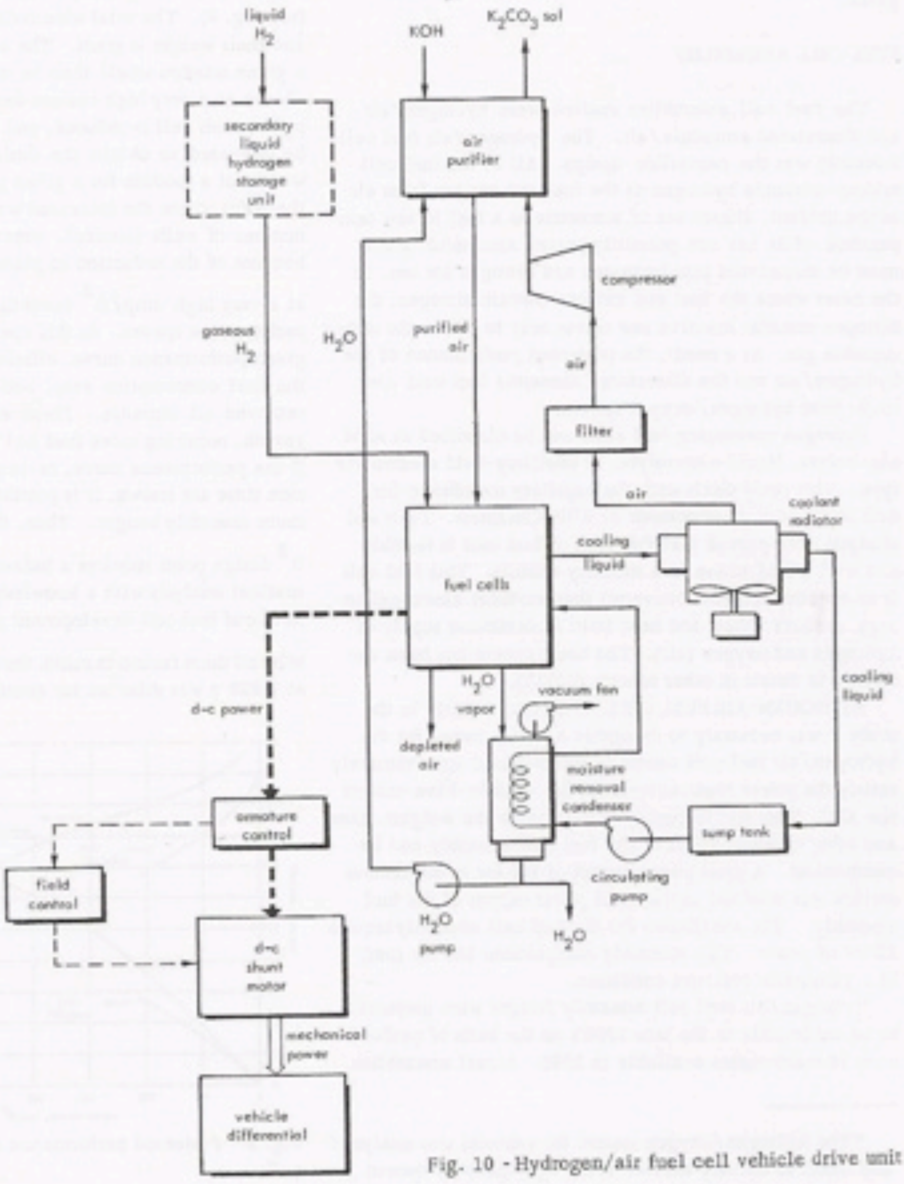

Fig. 10 - Hydrogen/air fuel cell vehicle drive unit

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perature of 180 F. Heat is dissipated both through moisture removal from the cells and through a cooling circuit. An electrically nonconductive, cooling liquid is circulated through the electrode holders in each fuel cell and the hot liquid is routed through a common header to the coolant radiator. The cooled liquid then goes to the sump tank and a circulating pump forces it through the moisture removal condenser and into the fuel cell modules to make a complete circuit.

The fuel cells are arranged in modules of 91 cells to give a module voltage of 75 v at the continuous load design point. Electrode area was selected to produce 10 kw of power per module. Current through each module is therefore 133 amp. Under overload conditions each module produces 178 amp at 69 v (12.3 kw).

The modules are arranged in four groups of four modules each. Each group of modules is connected in series to produce 300 v. The groups of modules are arranged so that modules 1-4 are in parallel with modules 5-8; modules 9-12 are parallel with modules 13-16. Switches enable those two parallel groups to provide an output voltage of 600 v and 266 amp when in series, or 300 v and 532 amp when in parallel.

The major design and operating characteristics for the hydrogen/air fuel cell assembly are summarized in Tables 3 and 4.

DISSOCIATED AMMONIA/AIR FUEL CELL ASSEMBLY - A gross power output of 160 kw in continuous service was selected as the total power output of the fuel cells for the dissociated ammonia fuel cell assembly study. This fuel cell assembly has a net power output of 147 kw in continuous service and 179 kw (net) in the 15 minute overload condition. The fuel cell assembly studied is 4% more powerful than required by the APC.

The dissociated ammonia fuel cell assembly differs from the hydrogen/air assembly in two major respects. The hydrogen fuel is diluted with nitrogen and a modification of the moisture removal process is required.

Table 3 - Hydrogen/Air Fuel Cell Assembly, Major Design

	Size and Weight
Module weight, lb	101
Module volume, ft^3	0.827
Number of modules	16
Assembly weight, lb*	3160
Assembly volume, ft^3*	45.9

*Includes 16 modules plus auxiliary equipment consisting of radiator, filter, air compressor, condenser, vacuum fan, circulating pump, water pump, plumbing and ducting controls, fluids, and air purifier.

The dissociated ammonia-air cell is not expected to reach the performance of the hydrogen/air cell because of the effect of nitrogen dilution on the hydrogen electrode.

The curve in Fig. 11 shows the performance estimated for this fuel cell projected to late 1960's. This projection assumes considerable development on both the fuel cell and the ammonia dissociator to minimize the amount of and effects of nondissociated ammonia. Rated current density was selected at 225 amp/ft^2 at 0.825 v per cell. Overload was selected at 300 amp/ft^2 at 0.758 v per cell.

AMMONIA DISSOCIATOR

An ammonia dissociator was conceptually designed to produce up to 20 lb of usable hydrogen per hour for the fuel

Table 4 - Hydrogen-Air Fuel-Cell Assembly Operating Characteristics

	Continuous Duty	15 min Overload
Gross power, kw	160	196
Auxiliary power, kw*	12	16
Net power, kw	148	180
Assembly voltage (parallel), v	300	276
Assembly voltage (series), v	600	552
Assembly amperage (parallel), amp	532	712
Assembly amperage (series), amp	266	356
Module power, kw	10.0	12.3
Module voltage, v	75	69
Module amperage, amp	133	178
Cell power, kw	0.110	0.135
Cell voltage, v	0.825	0.758
Cell amperage, amp	133	178
Cell current density, amp/ft^2	300	400
Operating temperature, F	180	--
Assembly weight/net power ratio lb/^{3}kw	21.4	17.6
Assembly volume/net power ratio ft^3/kw	0.310	0.255
Fuel consumption, lb H_2/net kwhr	0.108	0.118
Fuel consumption, lb H_2/hr	16.0	21.3
Purified air requirements, lb air/hr	790	1050
Air purification chemicals lb/hr	2.7	3.6

*Includes power for compressor, cooling fan, vacuum fan, circulating pump, water pump, and electrical control.

cell assembly. For this case, the ammonia dissociator produces 26.5 lb/hr of hydrogen in the form of 3:1 hydrogen-nitrogen mixture. This mixture is produced by catalytic thermal dissociation of ammonia at 1700 F and 50 psig pressure. Equipment required was estimated to weigh about 1025 lb and occupy about 12.5 ft^3. A schematic representation of the unit appears in Fig. 12.

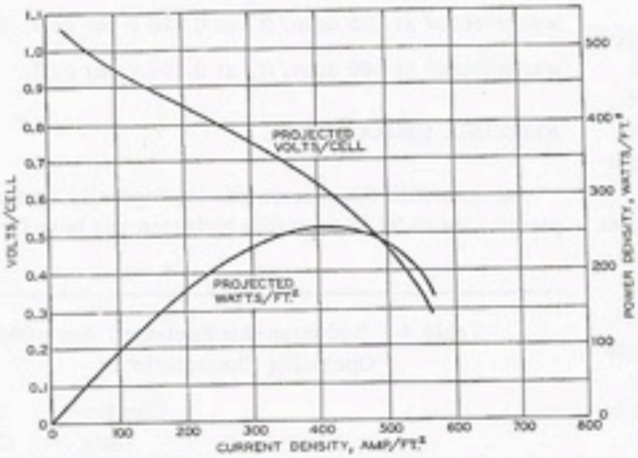

Fig. 11 - Projected performance curves for dissociated ammonia/air fuel cells

Theoretically, 113.3 lb/hr of dissociated ammonia is necessary to supply the fuel cell with 20 lb/hr of hydrogen. To make the process self-sustaining, about 6.5 lb/hr of hydrogen are burned in the reactor to supply the energy for the dissociation process. Included in this figure are possible radiation, diffusion losses, and so on. Therefore, a total of 150.1 lb/hr of ammonia is supplied to the reactor.

A palladium/silver foil hydrogen diffuser used after the dissociator could supply pure hydrogen to the fuel cells. This would allow the projection of hydrogen/air fuel cell system. The palladium/silver diffuser was disallowed because of its volume and because it requires the dissociator to be operated at high pressures.

PROCESS EQUIPMENT - Arrangement of the fuel cell process equipment is shown in Fig. 13. The arrangement is similar to that for the hydrogen/air fuel cell assembly with respect to the temperature control equipment and the supply of purified air to the oxygen electrode. The fuel supply equipment differs in that a hydrogen/nitrogen mixture from dissociated ammonia is fed to the fuel cell hydrogen electrodes. About 75% of the hydrogen in this mixture is used by the fuel cell to produce electrical power. The remaining hydrogen is burned to provide the heat for the dissociator.

Electrical arrangements for the dissociated ammonia/air

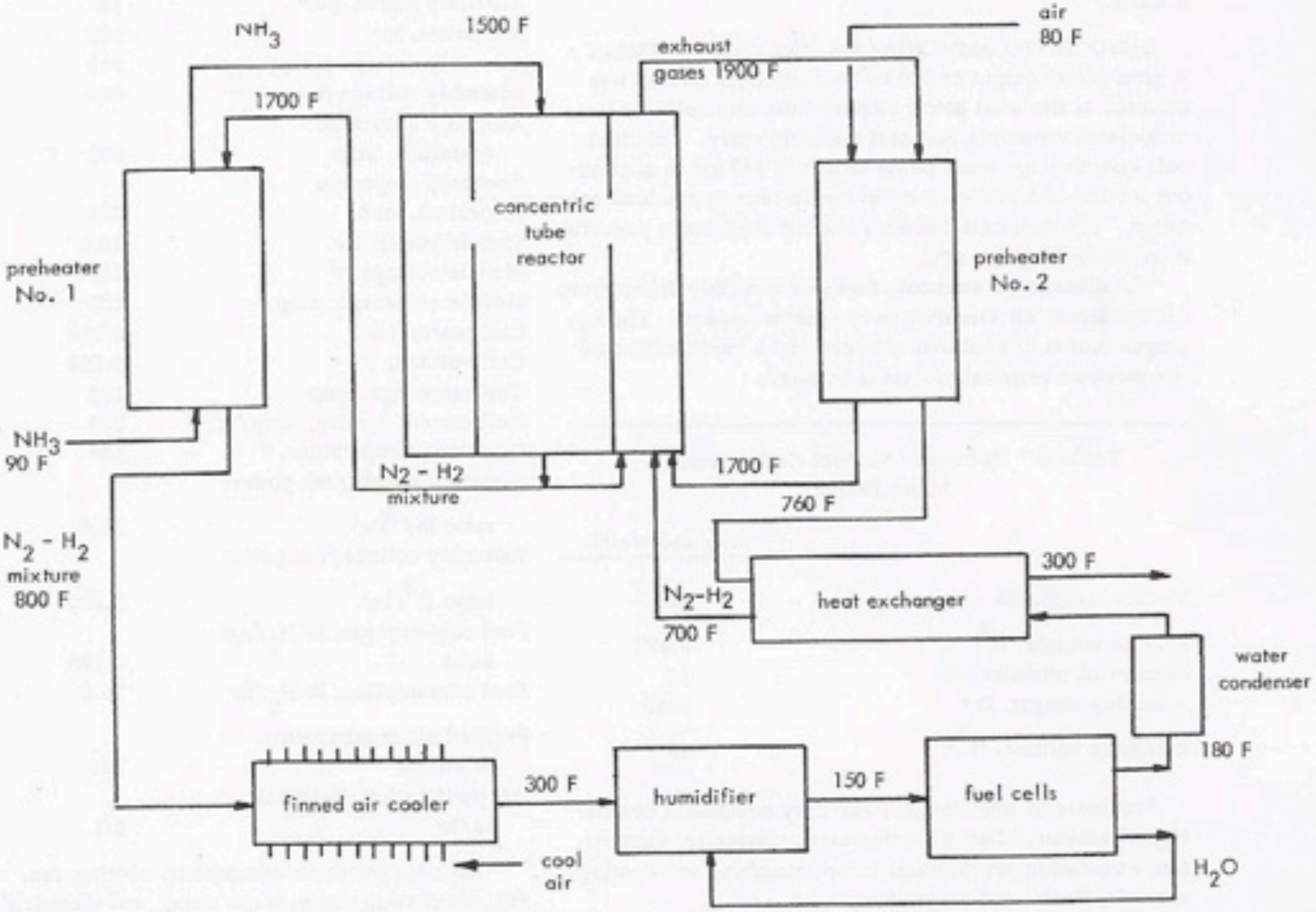

Fig. 12 - Ammonia dissociator process flow diagram

fuel cells are identical to that for the hydrogen/air cells. This system's auxiliaries consume about 1 kw more power.

The major design and operating characteristics for the dissociated ammonia fuel cell assembly are summarized in Tables 5 and 6.

ELECTRIC DRIVE ASSEMBLY

A detailed analysis was made of the electric drive assembly for the M113 (5). A d-c type motor was selected for the fuel cell powered vehicle. The advantages of the d-c drive assembly are:

1. It is more efficient since fuel cells produce direct current and there will be no losses due to conversion to alternate current.
2. The d-c drive assembly eliminates the need for a-c conversion equipment with its associated control.
3. A simple one-step switching of the fuel cell banks from series to parallel operation will change the output from low speed, high torque to high speed, low torque using full fuel cell output in both ranges.
4. The short time overload capability of the d-c motor is greatly superior to a-c motor.
5. Its ability to weaken its field and deliver constant horsepower with constant voltage and amperage input over a wide speed range (trading torque for speed) closely matcl normal traction requirements.

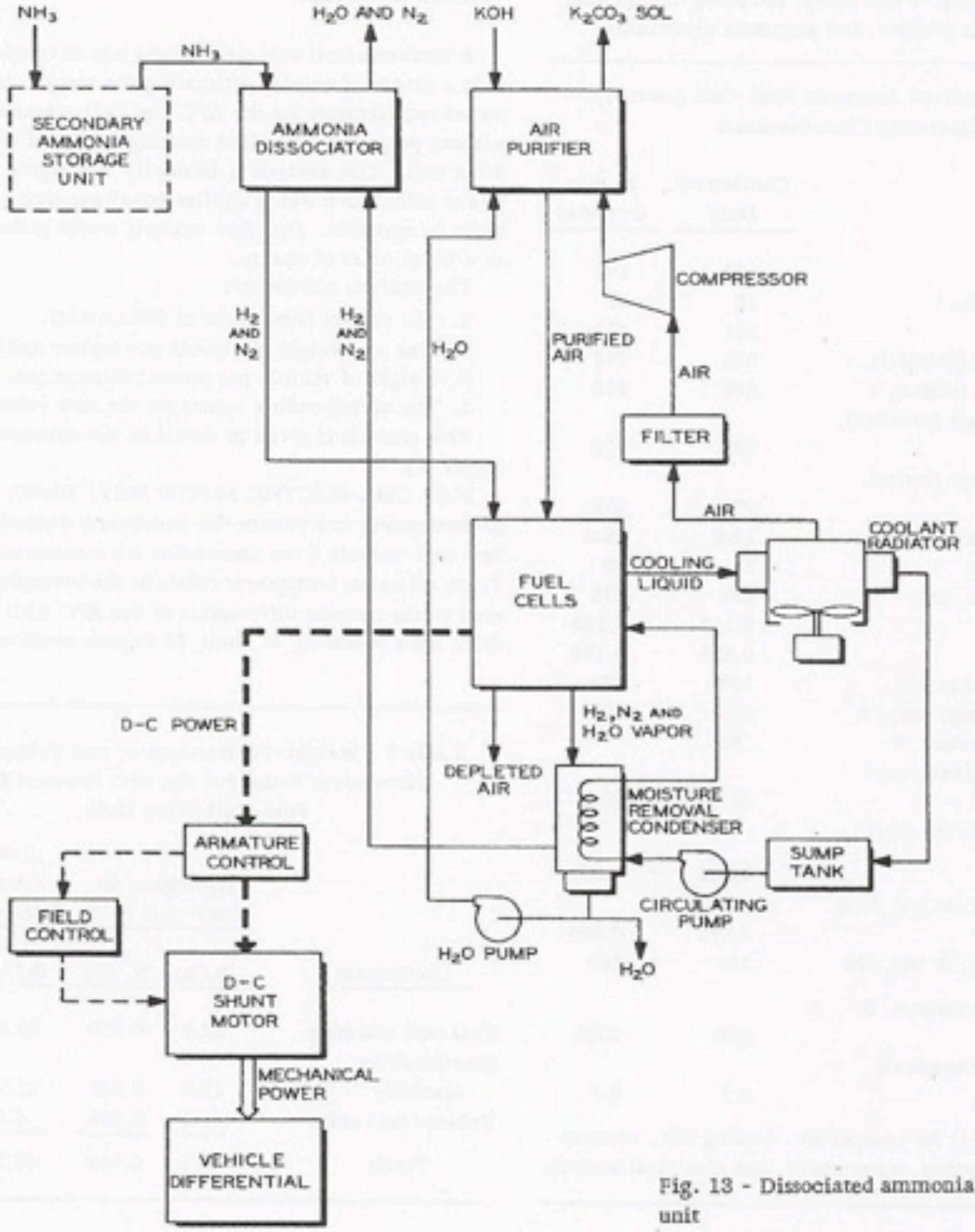

Fig. 13 - Dissociated ammonia/air fuel cell vehicle drive unit

Table 5 - Dissociated Ammonia Fuel-Cell Assembly, Major Design

	Size and Weight
Number of cells per module	91
Module weight, lb	134
Module volume, ft^3	1.09
Number of modules	16
Assembly weight, lb*	4800
Assembly volume, ft^3*	64.1

*Includes 16 modules plus auxiliary equipment consisting of radiator, filter, air compressor, condenser, vacuum fan, circulating pump, water pump, plumbing and ducting, controls, fluids, air purifier, and ammonia dissociator.

Table 6 - Dissociated Ammonia Fuel-Cell Assembly, Operating Characteristics

	Continuous Duty	15 min Overload
Gross power, kw	160	196
Auxiliary power, kw*	13	17
Net power, kw	147	179
Assembly voltage (parallel), v	300	276
Assembly voltage (series), v	600	552
Assembly amperage (parallel), amp	532	712
Assembly amperage (series), amp	266	356
Module power, kw	10.0	12.3
Module voltage, v	75	69
Module amperage, amp	133	178
Cell power, kw	0.110	0.135
Cell voltage, v	0.825	0.758
Cell amperage, amp	133	178
Cell current density, amp/ft^2	225	300
Operating temperature, F	180	--
Assembly weight/net power ratio lb/kw	32.7	26.8
Assembly volume/net power ratio/ft^3/kw	0.436	0.358
Fuel consumption, lb NH_3/net kwhr	0.816	0.894
Fuel consumption, lb NH_3/hr	120	160
Purified air requirements, lb air/hr	790	1050
Air purification chemicals lb/hr	2.7	3.6

*Includes power for compressor, cooling fan, vacuum fan, circulating pump, water pump, and electrical control.

Only disadvantages of the d-c drive assembly are that the motor is slightly larger and heavier than its a-c counterpart, and the d-c motor requires a commutator.

The design analysis indicated that a single shunt wound d-c motor was suitable for the drive of the APC based on M113. At low speeds up to 9 mph, the low voltage high current parallel circuit output of the fuel cells is applied to the armature of the shunt wound motor. This provides high torque to the motor eliminating the need for mechanical shifting. At higher speeds, the fuel cells are switched to the series circuit placing high voltage, low current source on the armature. Fine control in each range is provided by varying the field current which is excited from a constant voltage control.

VEHICLE ANALYSIS

A mathematical vehicle analysis was developed to provide a means of quickly estimating the weight, size, and power requirements for the APC fuel cell powered vehicle without preparing a detailed drafting layout of each vehicle drive unit. This analysis is basically a weight, volume, power calculation which applies equal averaging to all vehicle components. Detailed analysis would probably arrive at a lower order of change.

The analysis considered:

1. The present horsepower to differential.
2. Size and weight of present powerplant and fuel supply.
3. Weight of vehicle per present dimensions.
4. The corresponding values for the new vehicles.

This analysis is given in detail in the conceptual design report (5).

FUEL CELL-ELECTRIC MOTOR DRIVE UNITS - Weight-to-horsepower and volume-to-horsepower ratios for the three fuel cell-vehicle drive assemblies are summarized in Table 7. In all cases, horsepower refers to the horsepower delivered to the steering differential of the APC with the vehicle drive units operating at their 15 minute overload rating.

Table 7 - Weight-To-Horsepower and Volume-To-Horsepower Ratios For the APC Powered By a Fuel-Cell Drive Unit

	Hydrogen/Air Fuel-Cell Drive		Dissociated-Ammonia/Air Fuel-Cell Drive	
Component	lb/hp	ft^3/hp	lb/hp	ft^3/hp
Fuel cell assembly	16.4	0.259	25.0	0.364
Electric drive assembly	11.2	0.069	11.2	0.069
Vehicle fuel unit	1.5	0.314	4.5	0.163
Totals	29.1	0.642	40.7	0.596

Fuel cell assemblies contain all auxiliaries including the air purifier and ammonia dissociater where applicable. Values for the fuel cell assemblies assume that the electric drive assembly is 88% efficient. A 10% increase in the weight-to-horsepower ratio for mounting the fuel cell components, and a 20% increase in the volume-to-horsepower ratio were included as a packaging factor. The electric drive assembly includes the motor, cooling equipment, and controls.

Fuel rates for the respective fuel cell assemblies were determined by using the 15 minute overload rating adjusted to include the losses to the electric drive assembly. A 5.38 hr operating duration at full power was used to calculate the capacity of the fuel tank. The weights and volumes of the fuel containers were estimated from curves given in APCI-541101 with allowance for ullage, fill, and interconnecting lines, auxiliaries, and a packaging factor (14).

Table 8 - Characteristics of APC Powered By a Fuel-Cell Drive Assembly

Characteristics	Production Model M113 Gasoline	Fuel-Cell Powered Armored Personnel Carriers: Hydrogen/Air	Fuel-Cell Powered Armored Personnel Carriers: Dissociated Ammonia/Air
Combat weight to horsepower ratio, lb/hp	146	146	146
Range (full power duration), hr	5.38	5.38	5.38
Horsepower to differential, hp	157	182	203
Vehicle combat weight, lb	22,830	26,600	29,600
Fuel, lb	490	99	828
Fuel, gal	80	167	165
Fuel container and supply unit, lb	30	173	83
Fuel container and supply unit, ft^3	11	57	30
Powerplant, lb	1810	5020	7350
Powerplant, ft^3	50	60	88
Increase in hull weight, lb	--	830	890
Increase in hull volume, ft^3	--	56	60
Vehicle height, in.	72	79	80
Vehicle width, in.	106	106	106
Vehicle length, in.	192	192	192
Fuel rate, full power lb/hr	91.1	18.3	154
Air cleaning chemicals, lb	--	16.4	18.5

Values given in Table 7 were then used to calculate the characteristics of the respective armored personnel carriers assuming that these values remain constant over the range of power needed. The performance of these vehicles should be equal to the production M113. Since the components are designed at approximately the power required, this is considered a valid assumption. The result of the analysis is given in Table 8.

INTERNAL COMBUSTION ENGINE DRIVE UNITS - It is apparent that the change in fuel from petroleum to either liquid hydrogen or ammonia will also influence the design (or performance) of the APC when these fuels are consumed in an internal combustion engine. A brief analysis was made on the same basis as for the fuel cell powered vehicle.

Table 9 presents the weight-to-horsepower and volume-to-horsepower ratios for the internal combustion engine drive unit fueled by hydrogen or ammonia. In both cases the fuel efficiency of the engine was arbitrarily considered equal to that of the gasoline engine. The engine and its auxiliaries were arbitrarily assumed to be 10% heavier and larger than the gasoline engine. The results of this analysis for equal range vehicles are presented in Table 10. This table shows that the use of either liquid hydrogen or ammonia in the APC will require either a larger and heavier vehicle, or a compromise in the vehicle's range. In particular, the large liquid hydrogen tanks result in the largest vehicle studied; the roof is raised 11 in. and the hull is lengthened 5 in. In the case of the ammonia fueled internal combustion engine, the roof must be raised 5 in. to provide for the increased volume of the fuel. This vehicle is similar to the three fuel cell powered vehicles in outside appearance.

The fuel rates for the internal combustion engine powered vehicles are considerably greater than for the fuel cell powered vehicles. This is particularly true for the hydrogen fueled vehicles, 33.0 lb/hr versus 18.3 lb/hr, respectively. In the ammonia fueled vehicles, the fuel consumption rates are 154 lb/hr for the fuel cell powered vehicle versus 206 lb/hr for the internal combustion engine powered vehicle.

Table 9 - Summary of Weight-To-Horsepower and Volume-To-Horsepower Ratios for the APC Powered By an Internal Combustion Engine

Component	Gasoline lb/hr	Gasoline ft^3/hp	Hydrogen lb/hr	Hydrogen ft^3/hp	Ammonia lb/hr	Ammonia ft^3/hp
Engine and auxiliaries	11.6	0.319	12.8	0.351	12.8	0.351
Fuel Unit	3.3	0.069	2.9	0.607	7.3	0.264
Total	14.9	0.388	15.7	0.958	20.1	0.615

The efficiency advantage of the fuel cells over internal combustion engines is shown in Table 11. These values were computed from the vehicle analysis of the armored personnel carrier. In all cases they include the auxiliaries. The drive efficiency is defined as the horsepower-hours delivered to the vehicle differential divided by the equivalent energy of the fuel consumed using the higher heating values for each fuel.

Table 10 - Characteristics of APC Powered By Internal-Combustion Engine

	Fuel Consumed		
Characteristics	Gasoline*	Hydrogen	Ammonia
Combat weight-to-horsepower ratio, lb/hp	146	146	146
Range (full-power duration), hr	5.38	5.38	5.38
Horsepower to differential, hp	157	170	168
Vehicle combat weight, lb	22,830	24,800	24,500
Fuel, lb	490	178	1110
Fuel, gal	80	300	220
Fuel container and supply unit, lb	30	314	111
Fuel container and supply unit, ft^3	11	103	44
Powerplant, lb	1810	2180	2150
Powerplant, ft^3	50	60	59
Increase in hull weight, lb	--	1670	620
Increase in hull volume, ft^3	--	102	42
Vehicle height, in.	72	83	77
Vehicle width, in.	106	106	106
Vehicle length, in.	192	197	192
Fuel rate, full power, lb/hr	91.1	33.0	206

*Production model M113.

The energy depot systems are most easily compared by considering them as complete individual systems. Table 12 gives the number of horsepower-hours delivered to the vehicle transmission for each hour of depot operation, and the system efficiency.

SUMMARY

The fuel logistic problem can potentially be alleviated by using nuclear energy in the field. Feasibility studies indicate the technical possibility of converting nuclear energy, air, and water into the chemical fuels, liquid hydrogen and ammonia in the field. These fuels can be utilized to power internal combustion engines or more efficiently to power fuel cell electric drive systems. A conceptual design analysis of the fuel production portion of the energy depot system resulted in lightweight, compact, mobile units of high efficiency. The study of armored personnel carriers showed the suitability of fuel cell electric motor drive systems for military vehicles. The energy depot system should prove to be an exciting concept for the army of the future.

Continuing studies in the areas of hydrogen and ammonia production and their utilization in internal combustion engines and fuel cells should allow the early realization of the energy depot.

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Table 11 - Comparison of Drive Unit Efficiencies

	Efficiencies, Per Cent		
	Internal	Fuel Cell Drive Units	
Fuel and Oxidant	Combustion Engine	Continuous Duty	15 Minute Overload
Gasoline/air	21.5	--	--
Hydrogen/air	21.5	45.6	41.7
Ammonia/air	21.5	38.1	34.8

Table 12 - Comparison of Energy Delivered and System Efficiencies

	Horsepower-Hours Delivered To Transmission per Hour of Depot Operation			System Efficiency % Energy Delivered To Transmission / Electrical Energy Delivered To Depot		
	Internal	Fuel-Cell-Drive Unit		Internal	Fuel-Cell-Drive Unit	
	Combustion Engine	Continuous Duty	15 min. Overload	Combustion Engine	Continuous Duty	15 min. Overload
Liquid hydrogen	546	1158	1055	13.6	28.7	26.3
Ammonia	579	1026	937	14.4	25.5	23.3

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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

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	a
Freezing point, F	-108	-76
Vapor pressure (70 F), psia	128.8	a
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

[a] 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.

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*Numbers in parentheses designate References at end of paper.

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.

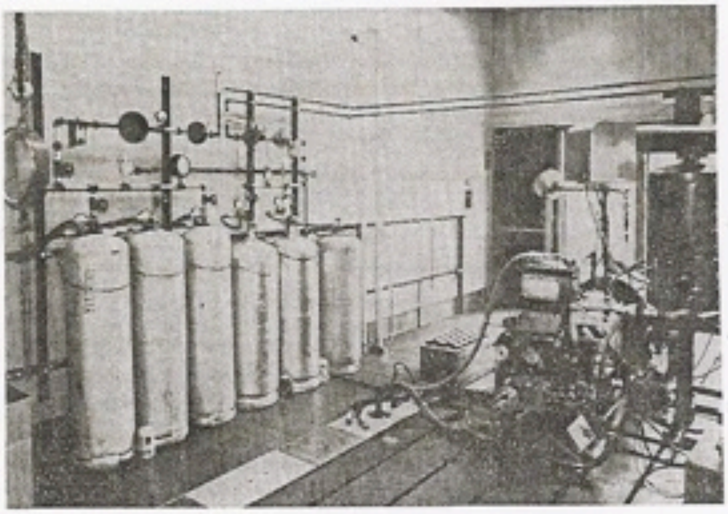

Fig. 1 - Test cell installation of single-cylinder engine and ammonia fuel supply system

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

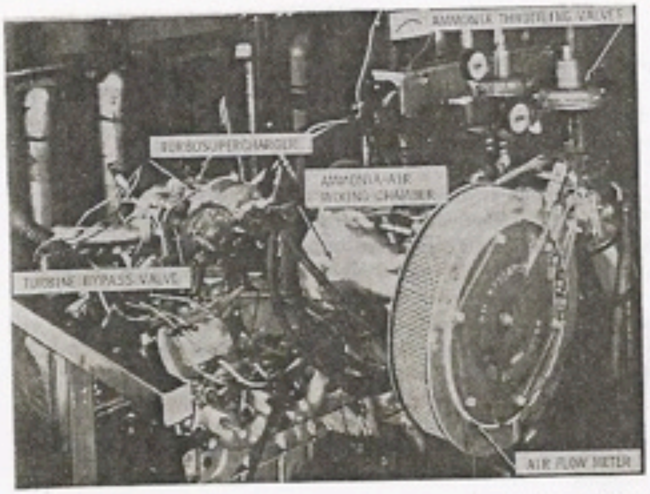

Fig. 2 - Test cell installation of multicylinder engine prepared for operation on ammonia fuel

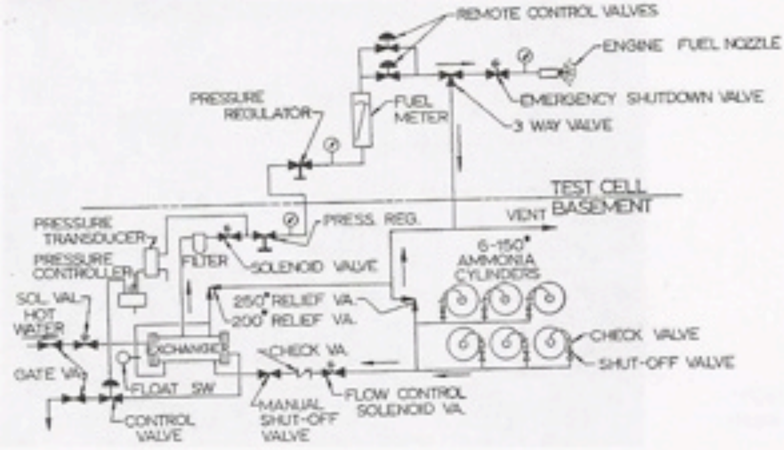

Fig. 3 - Schematic of ammonia fuel system for multicylinder engine

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.

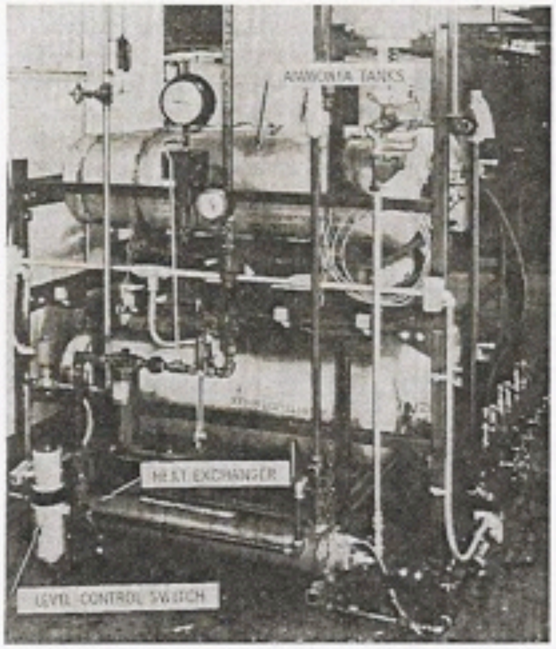

Fig. 4 - Ammonia fuel supply and control system for multicylinder engine

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, 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-

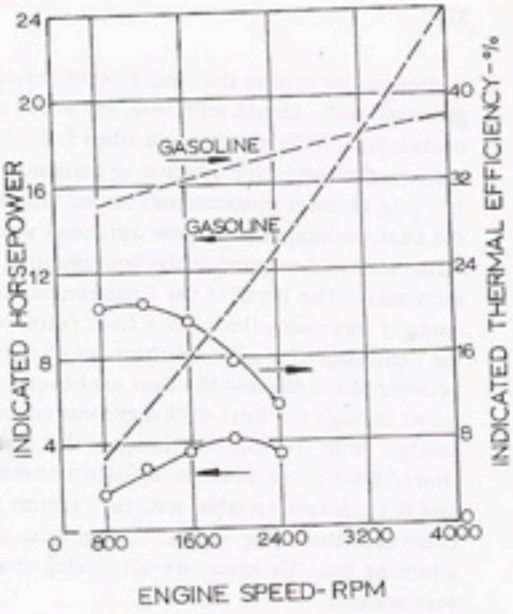

Fig. 5 - Performance of unmodified single-cylinder engine on ammonia and gasoline -- full-throttle normally aspirated operation, 9.4:1 compression ratio

Table 2 - Reactant and Exhaust Product Data

	Fuel Mixtures 1	Fuel Mixtures 2	Fuel Mixtures 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 lb/hr	1 ft^3/min	2 lb/hr	2 ft^3/min	3 lb/hr	3 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-

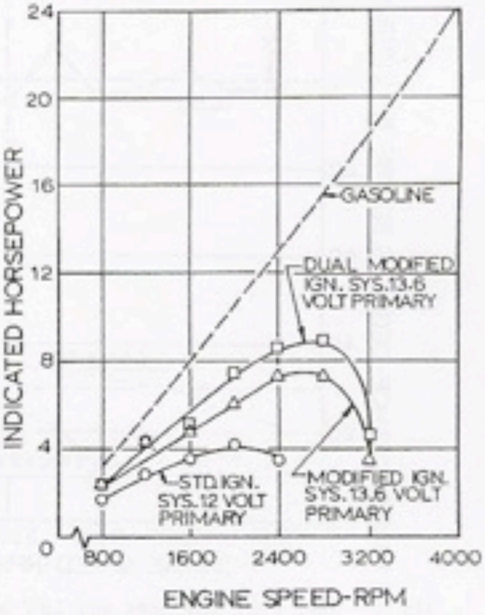

Fig. 6 - Increased power of single-cylinder engine through ignition system modifications -- ammonia fuel, full-throttle normally aspirated operation, 9.4:1 compression ratio

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

Effect of Increased Compression 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-

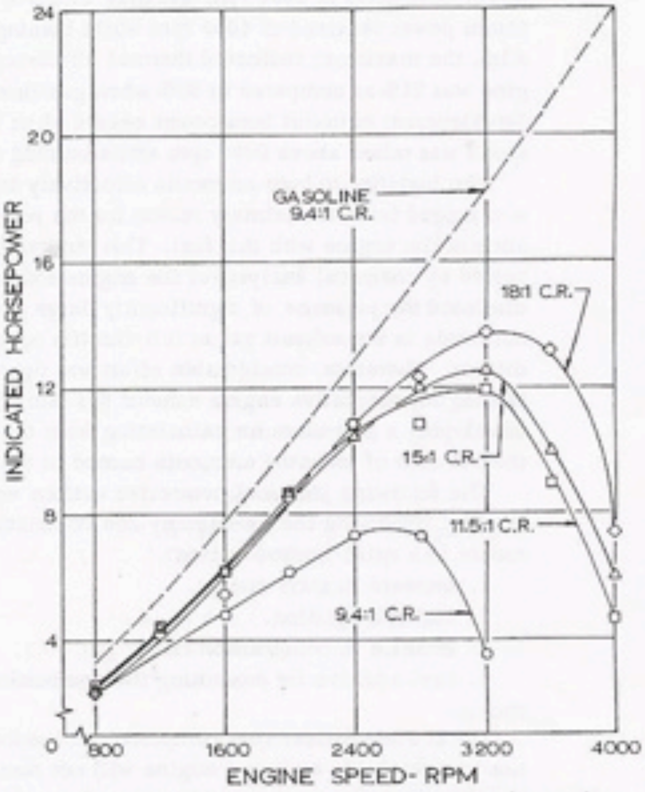

Fig. 8 - Improved performance of single-cylinder engine due to increased compression ratio -- ammonia fuel, full-throttle normally aspirated operation, modified ignition system

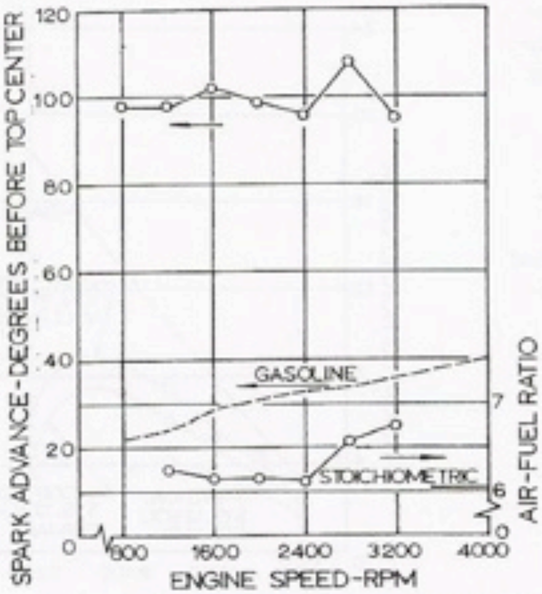

Fig. 7 - MBT spark advances and LBT air-fuel ratios for single-cylinder engine -- ammonia fuel, full throttle normally aspirated operation, modified ignition system, 9.4:1 compression ratio

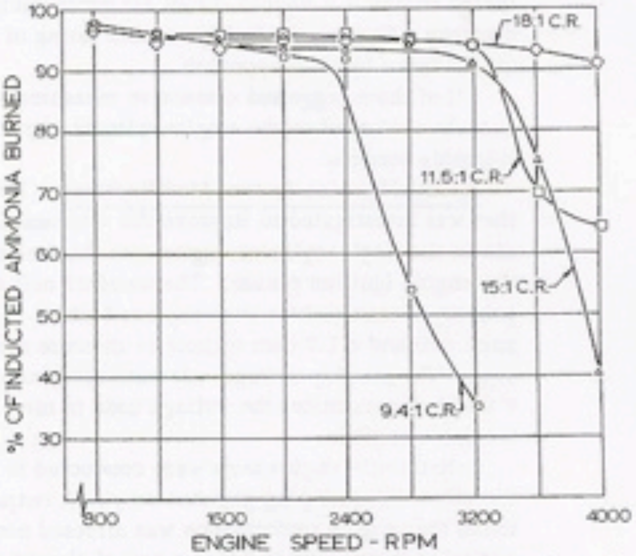

Fig. 9 - Improved combustion of ammonia in single-cylinder engine by increasing compression ratio -- full-throttle normally aspirated operation, modified ignition system

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.

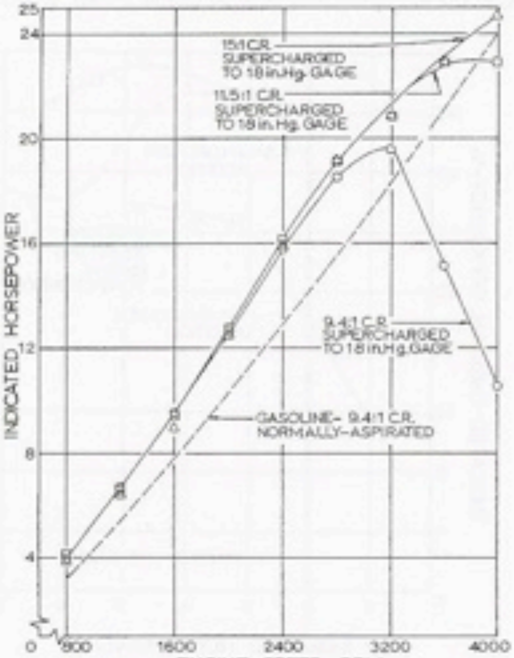

Fig. 10 - Increased performance of single-cylinder engine due to supercharging -- ammonia fuel, modified ignition system

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

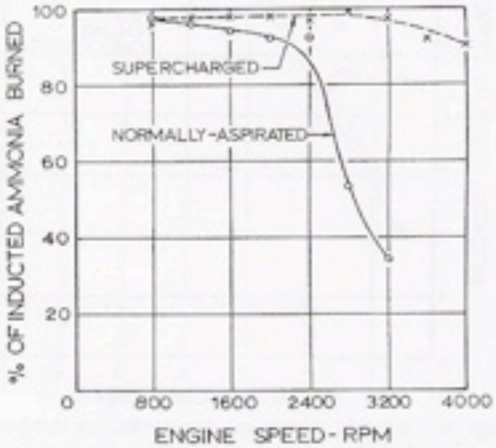

Fig. 11 - Improved combustion of ammonia in single-cylinder engine by supercharging -- modified ignition system, 9.4:1 compression ratio

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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 was 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.

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

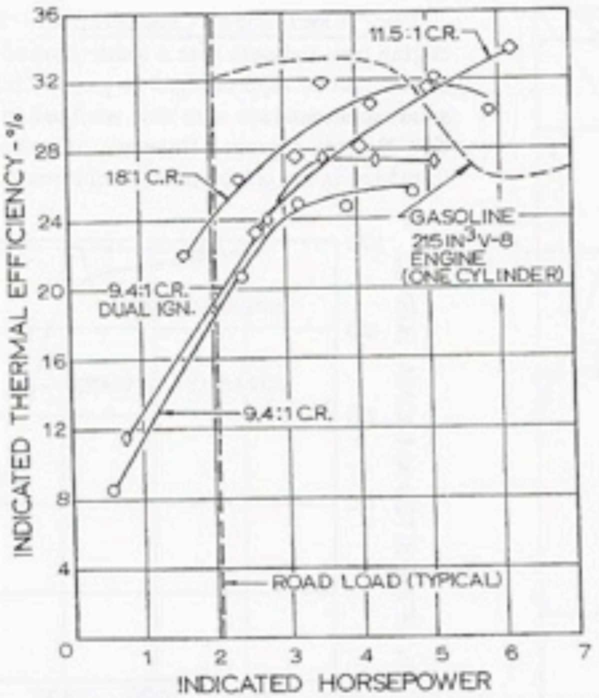

Fig. 12 - Minor improvements in part-throttle thermal efficiency of single-cylinder engine due to increased compression ratio and dual ignition -- ammonia fuel, modified ignition systems.

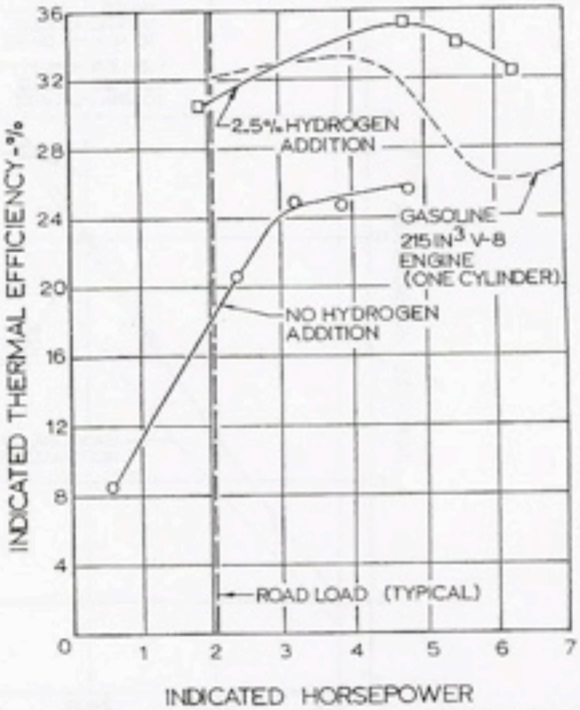

Fig. 13 - Improved part-throttle thermal efficiency of single-cylinder engine due to hydrogen addition to ammonia -- modified ignition system, 9.4:1 compression ratio

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 ha a slight detrimental effect on engine power development at the 2000 rpm investigated speed, but enhanced marked engine power outputs at speeds of 3600 and 4000 rpm. Optimum concentrations of hydrogen of approximately 1.3 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 engin power development over the entire engine speed range investigated that was equal to or exceeded the engine powe developed while burning gasoline in the engine under normally aspirated operating conditions.

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

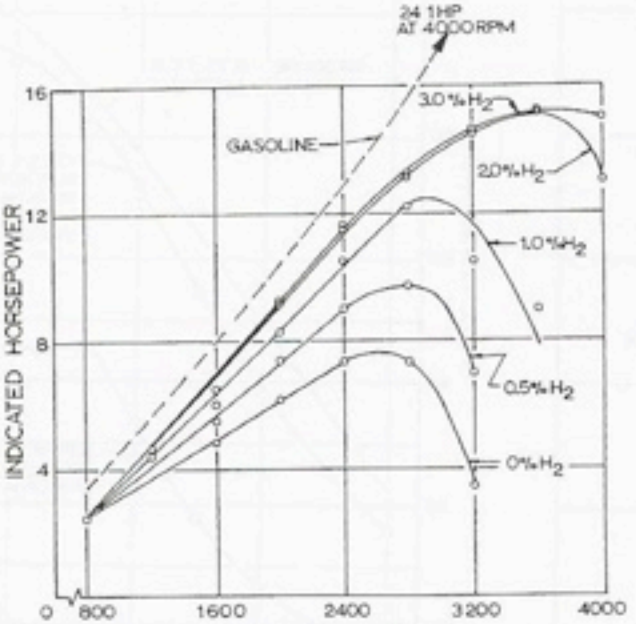

Fig. 14 - Improved performance of single-cylinder engine due to varying amounts of hydrogen addition to ammonia -- full-throttle normally-aspirated operation, 9.4:1 compression ratio

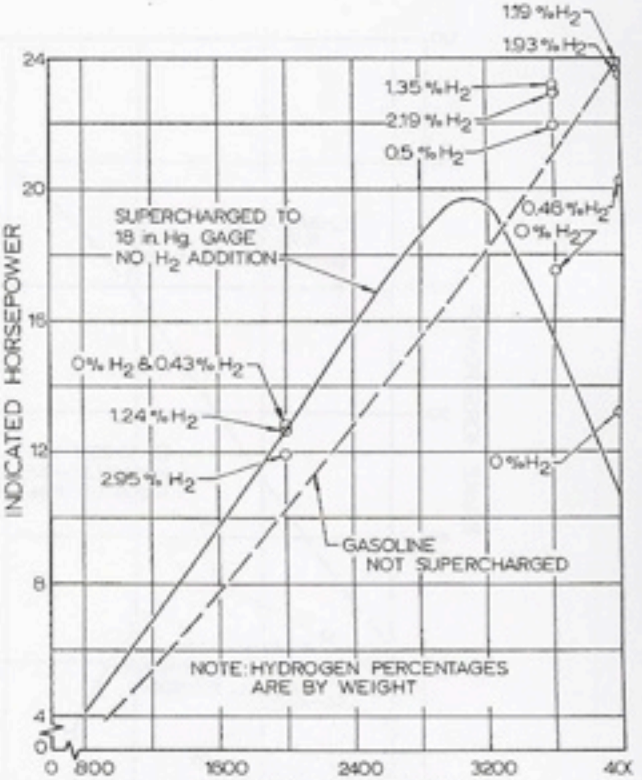

Fig. 15 - Varying improvements in performance of single-cylinder engine due to hydrogen addition to ammonia -- supercharged operation, modified ignition system, 9.4:1 compression ratio

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

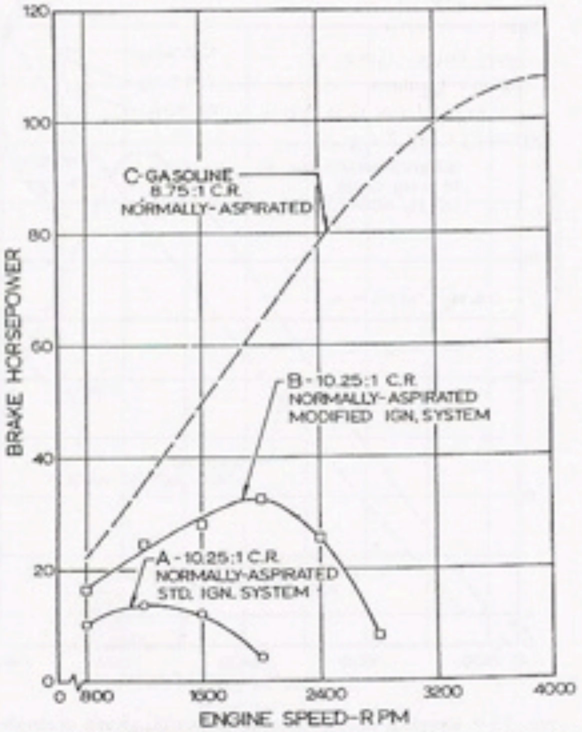

Fig. 16 - Performance of multicylinder engine on ammonia and gasoline -- full-throttle normally aspirated operation, standard and modified ignition systems

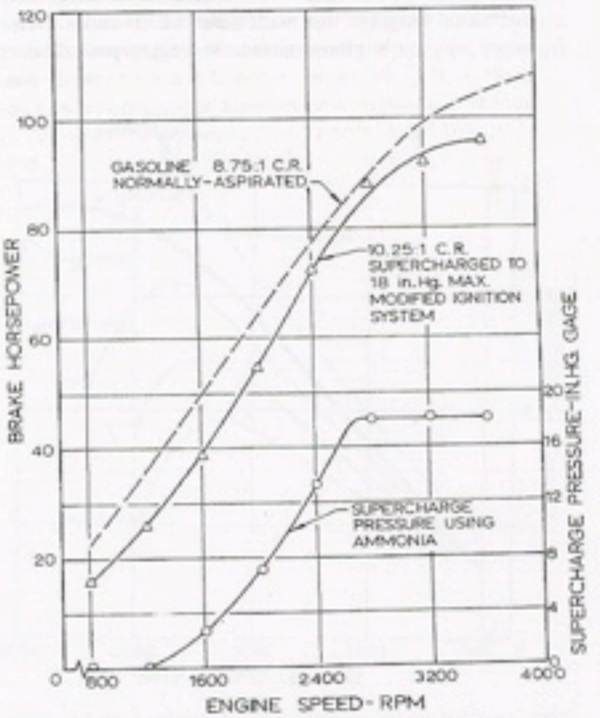

Fig. 17 - Improved performance of multicylinder engine due to supercharging -- ammonia fuel, modified ignition system

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.

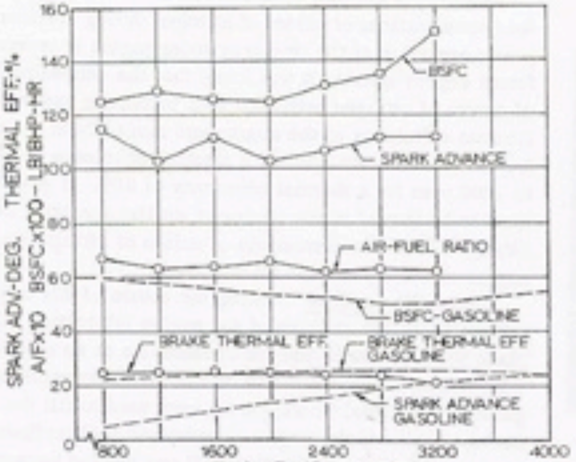

Fig. 18 - MBT spark advances, LBT air-fuel ratios and brake specific fuel consumptions for multicylinder engine -- ammonia fuel, supercharged operation, modified ignition system

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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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.

<u>Contribution to Air Pollution</u> - 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%.

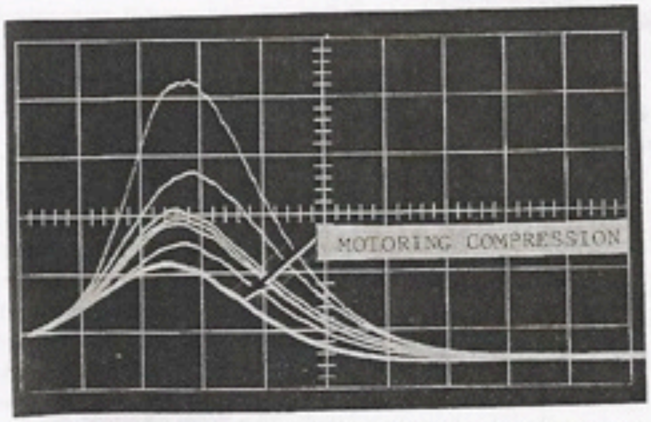

Fig. 19 - Cylinder pressure-time traces showing large variations of peak pressures and rates of pressure rise for six consecutive firing events in single-cylinder engine -- ammonia fuel, full-throttle normally aspirated operation, 18:1 compression ratio

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.

<u>Engine Oil Analyses</u> - 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 can not 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:

$$2\ NH_3 \longrightarrow 3\ H_2 + N_2$$

(Ammonia) (Hydrogen) (Nitrogen)

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 complete 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-cylinde and multicylinder test engines. Only the initial stage of the development program has been completed.

The basic ammonia dissociation study was conducted wit 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 characteristic of nickel, as well as its established use in commercial ammonia dissociating devices, prompted the initial use of this material in the minature 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

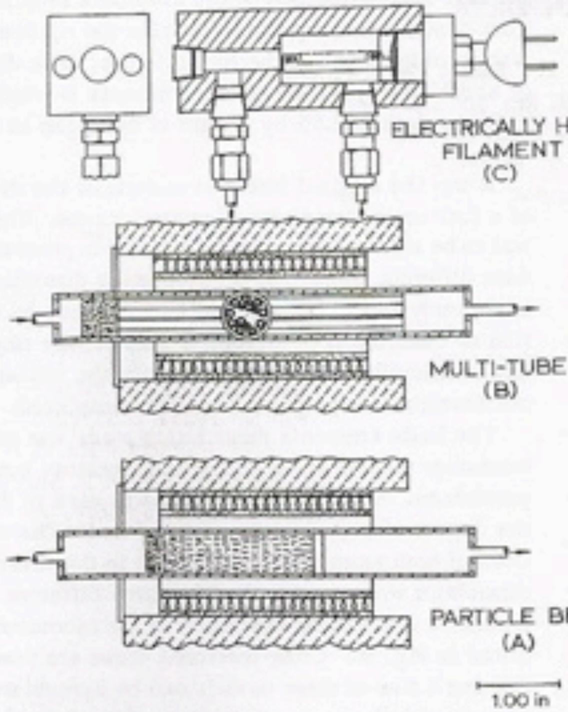

Fig. 20 - Experimental microreactors for studying dissociation of ammonia

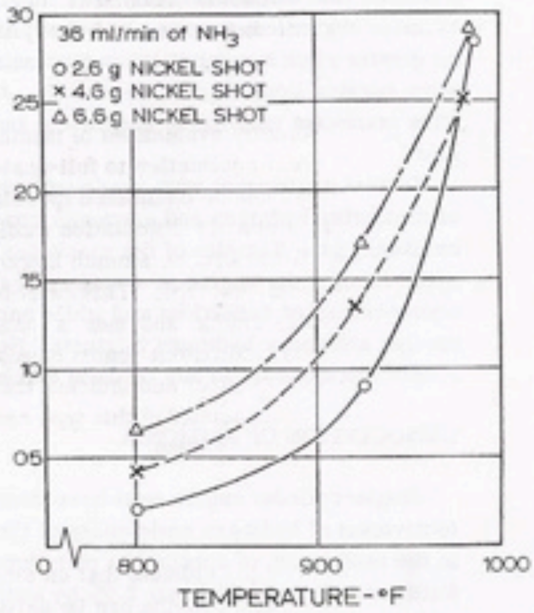

Fig. 21A - Typical ammonia dissociation data obtained with experimental microreactors -- Model A-particle bed

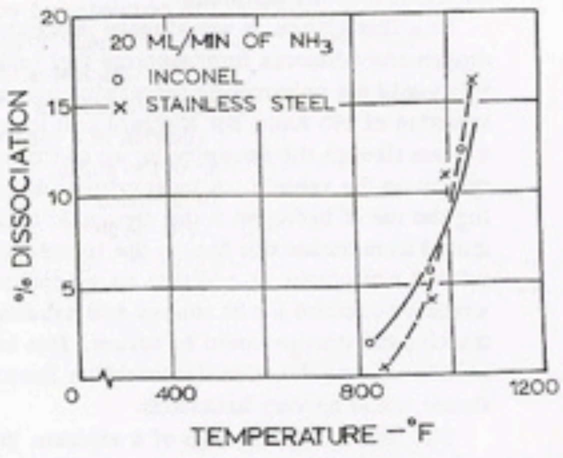

Fig. 21B - Typical ammonia dissociation data obtained with experimental microreactors -- Model B-multitube

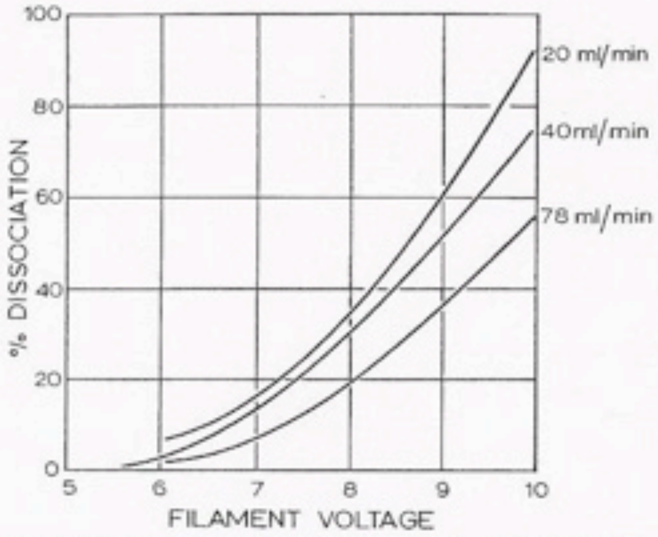

Fig. 21C - Typical ammonia dissociation data obtained with experimental microreactors -- Model C-electrically heated filament

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 time 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.

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