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(NYO 10422 - Vol. 1)

Volume I of II

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ACNP-62015A ✓

AEC Research and
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MOBILE ENERGY DEPOT FEASIBILITY STUDY - SUMMARY REPORT

13 July 1962

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Work performed under Contract AT(30-1)-2931
for the United States Atomic Energy Commission

**ALLIS-CHALMERS MANUFACTURING COMPANY
ATOMIC ENERGY DIVISION
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This document consists of 318 pages
Copy No. 14/ of 165 copies. Series A

NYO 10422
Volume I of II
C-83, Reactors - Critical Features of
Military Power Reactors
(M-3679, 26th Edition)

ACNP-62015A

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MOBILE ENERGY DEPOT
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Prepared under the direction of the
New York Operations Office
U. S. Atomic Energy Commission

SPECIAL REREVIEW FINAL DETERMINATION	Class:	4
	Reviewers	HFC 4
	Class.	4
	Date	12-15-81

Classification cancelled or changed by [signature] 12/15/81
by [signature] 3/14/63
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Work performed under Contract AT(30-1)-2931 for the
U. S. Atomic Energy Commission

prepared by

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ABSTRACT

Various methods of producing and using nuclear power for military land vehicles and other military equipment were investigated and evaluated. A nuclear-powered mobile energy depot (MED) would move with advancing armies and produce vehicle fuels from materials readily available in the field. This would make mechanized units independent of external fuel supplies for extended periods, and permit them to move quickly and easily to areas impossible for units that depend on the customary fuel supply lines.

Many possible MED systems were evaluated on the basis of energy sources, fuel manufacturing (by both conventional and chemonuclear processes), fuel storage and transportation, and fuel utilization in both present-day internal-combustion engines and power units of the future (i.e., fuel cells). The applications of more than a dozen MED systems to vehicular propulsion were studied.

Recommendations were made covering several preferred systems and areas for further study.

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FOREWORD

The increasing mechanization of modern armies, with the attendant increase in fuel requirements, has placed an increasing burden on military supply services. Owing to the special ability of nuclear fuel to provide a concentrated, long-lived source of power, largely independent of supply lines, military planners and strategists have long sought to make use of nuclear energy. For some applications requiring small amounts of power (up to a few kilowatts), radioisotopes may be used, but for power requirements measured in megawatts the only practical source of energy is the fission reactor.

Unfortunately, the shielding associated with a reactor would make the plant so large and heavy that the direct application of nuclear power to the majority of military vehicles would not be a practical possibility. In naval applications, where size and weight limitations do not apply and where cost is outweighed by other considerations, nuclear power plants have supplanted other forms of power in several cases.

The small power requirement of individual military land vehicles is also economically unfavorable for direct use of nuclear power reactors. The unit cost of a plant per installed kilowatt is inversely proportional to the size of the plant. Moreover, the operating cost per unit of energy produced is reduced as the load factor is increased. Thus, a few large plants in continuous operation are economically more favorable than many small power plants operating intermittently to meet the requirements of individual vehicles. For the latter use, there still seems to be no better system than chemically fueled power plants. However, the maintenance of a long, vulnerable fuel supply line to keep chemically fueled vehicles functioning requires a great expense and in time of war diverts military capacity that could be more usefully employed otherwise.

The concept of the mobile energy depot (MED) offers a possible solution to the problem of meeting these divergent requirements. In essence, the MED concept involves a compact nuclear power plant coupled to a fuel processing plant. The power reactor would be large enough to produce energy economically, but not too large and unwieldy to be transported readily. The fuel processing plant would also be of a size suitable for transportation by air or highway and would be capable of producing sufficient fuel to supply a considerable number of vehicles continuously. The feed materials for the fuel processing plant must be those commonly available anywhere in the world (i.e., air, earth, and water). The MED would move with advancing armies and create fuel for all army needs from materials readily available in the field. Tank, truck, and other mechanized units would be independent of an external fuel supply for many months, and could relocate quickly and easily to areas that would present prohibitive supply problems to conventional mechanized units.

Hence, the objective of the MED study was to investigate and evaluate various methods and systems by which power produced by one or more nuclear power sources can be used to manufacture fuel suitable to power military land vehicles and other military equipment.

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If this idea is fully developed, operations could be carried on in regions of the world and under conditions now beyond the capability of military units. Military operations would achieve a new flexibility and the ability of the military to function in the aftermath of nuclear warfare would be vastly enhanced.

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1. INTRODUCTION

In December, 1961, the U. S. Atomic Energy Commission awarded Contract AT(30-1)-2931 to the Allis-Chalmers Manufacturing Company for a Technical Feasibility Study of a Mobile Energy Depot. The objective of this study was to investigate and evaluate methods and systems by which nuclear energy can be stored in the form of chemical fuel, which can then be used in military land vehicles and other military equipment.

To achieve this objective, it was necessary to determine: (1) the characteristics of the nuclear energy source most suitable for an energy depot; (2) the most suitable chemical fuel system from the standpoints of field conversion, storage, and handling; and (3) the most promising engines and other devices for applying the stored energy to power vehicles and other equipment. In the performance of this study, it was necessary to limit the concepts investigated to those applicable to certain specific military vehicles and equipment.

The study was performed between December, 1961, and July, 1962, by Allis-Chalmers, as prime contractor, and Air Products and Chemicals, Inc., of Allentown, Pa., as sub-contractor.

The work was organized and carried out according to a Work Program (ACNP-62003, December 27, 1961 - revised January 11, 1962) prepared under the direction of the U.S. Atomic Energy Commission's New York Operations Office. The project schedule, Fig. 1, shows, in condensed form, how the work was organized into various tasks and the dates established for completion of these tasks. The requirement for personnel of different technical disciplines and wide experience with special types of equipment is evident from Fig. 1. Allis-Chalmers assembled a team of key personnel from its Atomic Energy, Research, Defense Products, and New Products Divisions, who were assisted by individuals from their own and other divisions as required. The synthesis of fuels, especially those produced by cryogenic processes (Subtask 4.2) and the transportation and storage of fuels (Subtask 4.3) were studied by personnel of the Research and Development Department of Air Products and Chemicals, Inc.

One of the first tasks performed consisted of compiling, editing, and issuing the Basic System Criteria, ACNP-62008. This document sets forth the ground rules on which this study is based and is presented, in condensed form, as Appendix A.

Figure 2 shows the functional relationships between the tasks shown on Fig. 1. Nearly all the tasks fell into three categories: energy sources, fuel manufacturing processes, and fuel utilization devices. These categories also form the basis for the arrangement of the body of this report.

Under Task 3.0 (Energy Sources), various methods of employing nuclear energy were considered for MED application. As indicated in Fig. 2, various types of both fusion and fission reactors were studied, as was the use of radioisotopes. This phase of the study also included consideration of various energy conversion techniques. By applying

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PROJECT SCHEDULE
FEASIBILITY STUDY OF A MOBILE ENERGY DEPOT SYSTEM
CONTRACT AT(30-1) 2931

TASK 3.0	TASK 4.0	TASK 5.0
1 Fusion Reactors	1 Selection of Most Likely Fuels & Fuel Requirements.	1 Review of Data and Reports
2 Isotopic Sources	2 Ranking of Fuels.	2 Calculations
3 Uncontrolled Reactions	3 Final Calculations for Fuel Systems	3 Preliminary Evaluation
4 Process Heat Reactors		
5 Power Reactors (GCR, BWR, PWR, etc)		
6. Thermoelectric Power		
7 Thermionic Power		
8 MHD		

FIGURE 1

FIG. 2
MOBILE ENERGY DEPOT
FEASIBILITY STUDY

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the basic criteria to each of these, the scheme best suited to the intended purpose was selected. Among the crucial requirements were maximum mobility and minimum size and weight of individual packages (modules). The state of development of each scheme was also considered. This phase of the study provided a solid basis for recommendations involving later phases of the MED development program.

Under Task 4.0 (Fuel Systems), the output of the energy conversion equipment was used as input to a chemical processing plant whose characteristics depend on the fuel under consideration. The fuels fall into two main categories: (1) those which can be created from air, earth, and water, and which are therefore expendable (nonregenerative systems); and (2) those which contain elements not present in air, earth, or water, and which therefore must be recaptured and recycled after use (regenerative systems). The energy requirements, size, and weight of each fuel manufacturing plant were determined for a fuel system required to support a representative number of combat vehicles. The weight, volume, and handling requirements for each fuel produced were also evaluated.

Under Task 5.0 (Fuel Utilization Devices), both internal- and external-combustion engines that might use the energy of the fuels produced by the MED were investigated. Both fuel cells and batteries were studied for use with electric drive systems. The application of these engines and the fuel storage requirements for vehicles of comparable range were reviewed. In general, it was found that fuels for the nonregenerative systems may be used either in modified internal- and external-combustion engines or in fuel cells, whereas the fuels for the regenerative systems can be used only in fuel cells and are not compatible with the combustion engines. Some fuel systems may be operated as either regenerative or nonregenerative, depending on whether it is necessary to conserve the materials entering into the reactions.

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2. SUMMARY

The over-all organization of this report corresponds to the following three-part division of work under the program:

- (1) Energy Sources (Task 3.0),
- (2) Fuel Systems (Task 4.0), and
- (3) Fuel Utilization (Task 5.0).

Each of these topics is discussed in detail in a major section of this report, and the discussion of each is summarized below. The work on which this report is based was reported in Allis-Chalmers monthly progress reports. 1,2,3,4

2.1 ENERGY SOURCES

Task 3.0, Energy Sources, drew heavily upon previous studies, principally those involving the Military Compact Reactor (MCR) concept.^{5,6} Because those studies covered the field very thoroughly, it was considered unnecessary to duplicate this effort. A careful study of the MCR reports indicates that their conclusions are well substantiated. At present there seems to be no reason to doubt that a liquid-metal--cooled reactor with a neutron spectrum well into the epithermal range would provide power in the multi-megawatt range without exceeding the size and weight limitations imposed by the mobility requirements. The MCR concept, with modifications, is well suited to the requirements of the MED. These modifications would include repackaging into a number of modules to increase mobility and adding a regenerator to increase power output and efficiency. Independently of the MED program, Allis-Chalmers has been studying some interesting advanced reactor concepts, but these studies are not yet sufficiently complete to form a basis for firm recommendations. Brief consideration was also given to the following energy sources, which were found unsatisfactory for a variety of reasons: nuclear explosives, which were found to be unproven as an energy source and in general not feasible for this application; fusion reactions, which have not been demonstrated in a practical device and which will require a long period of development; and radioisotopes, which were found to be impractical in view of the amount of power required from individual plants and in view of the total number of plants anticipated.

To complete the study of energy sources, it was deemed necessary to investigate direct energy-conversion techniques as well. Direct conversion of heat to electrical energy would, in theory, simplify plant arrangement and reduce plant size and weight, all of which are obvious advantages for portable power plants.

Many recent references in direct energy conversion were studied and it was found that the most significant work now under way is in the fields of thermoelectricity, thermionics, and magnetohydrodynamics. The consensus is that much more development is necessary

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for the efficiency, performance, and power output possible with any of these schemes to reach levels making them practical for the MED. The most practical way to convert heat to electricity in the amount required by the MED in a reasonably sized plant now or in the near future involves the use of a conventional turbogenerator. Because only limited time was available, it was not possible to optimize the plant characteristics other than in very broad terms. Minimum size and weight may be achieved by using 400 cps, or other, high frequency generators feeding suitable transformers and rectifiers to supply direct current to electrolytic cells for production of free hydrogen and oxygen from water. Direct chemical conversion by thermal energy rather than by electrical energy is possible, but direct thermal dissociation of water into hydrogen and oxygen with reasonable efficiency requires temperatures beyond the capability of existing heat-exchanger and cladding materials. Yields by radiolytic dissociation are too low to be competitive. The steam reforming of hydrocarbons and the reaction of steam with metals appear to be feasible methods of using thermal energy for the production of hydrogen, and should be investigated further.

Although this study is based on the use of a nuclear reactor as an energy source, there are circumstances that make it undesirable to be limited to a nuclear energy source. Fuel manufacturing systems using electrolytic cells are amenable to the use of electrical energy either from conventional electrical power systems or from nuclear power plants. Moreover, when coupled to the MCR, the complete MED may use either chemical or nuclear energy as the energy source. The MCR is designed to operate at full power with the reactor shut down by using chemical fuels in a combustion chamber that supplies the gas turbine. Fuel synthesizing plants using the reforming of hydrocarbons as a source of hydrogen may similarly be independent of a nuclear energy source. Existing commercial plants for the production of liquid hydrogen use the heat of combustion of a portion of the hydrocarbons as an energy source to bring about the reaction. Thus, the MED may be used in situations where chemical or electrical energy is plentiful and where economics, population density, or other factors are unfavorable for the use of nuclear energy. The MED might therefore use conventional power sources for checkout purposes within the continental United States (CONUS) and a nuclear reactor only when operating in remote areas. Most of the volume, weight, and cost of an MED is represented by the reactor complex. Every country in the world now has some kind of electric power distribution system, and experience indicates that, even in wartime, power supplies are rarely interrupted for more than a few days. A case can therefore be made for supplying more chemical processing plant components than can be serviced by the number of reactor plant components supplied, in the expectation that locally available conventional power would make up the difference. Complete MED plants, with their own reactors, would then be used only in very remote locations or where destruction has been total. This would reduce MED costs and operational complexity and simplify problems of plant location, protection of personnel from radiation, and availability of nuclear fuel.

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As a corollary to this, it should be noted that it would not be necessary to set up and operate a nuclear plant in order to check out the operation of the fuel synthesis plant. This could be done with any adequate conventional source of power.

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2.2 FUEL SYSTEMS

A major area of investigation listed in the Work Program⁷ is that of fuel systems (Task 4.0). This is the key portion of the MED investigation. Disregarding regenerative systems for the moment, the raw materials available (air, earth, and water)⁸ severely limit the fuels that can be considered. They must be compounds of hydrogen with nitrogen or of nitrogen and oxygen, or hydrogen by itself, because these are the principal elements in air and water. The use of elements from earth was investigated briefly, but it soon became apparent that the problems involved made the use of such materials unattractive. In any case, because hydrogen is a basic constituent of all nonregenerative fuel systems, the problem is one of producing sufficient hydrogen from available supplies of water and then converting the hydrogen into a form that can be shipped, stored, and used in present or future vehicle engines.

About 20 fuels were investigated. Some were eliminated because of their undesirable properties. More commonly, however, the synthesis plants required for some fuels were found to be large and complex compared with those for other fuels, with no attendant gain in energy content of the fuel. It was concluded that systems for the production either of liquid hydrogen or of anhydrous ammonia have the best potential. The choice between these two systems depends on a number of factors, of which some are technical and permit a prior evaluation, and others are intangible and cannot be evaluated fairly without considerable operating experience. Because such experience can be obtained only with equipment not yet in existence, the final selection of the better of the two systems is not possible at this time.

These two systems do, however, have some known characteristics that may be used to guide future programs. For example, hydrogen has a higher heating value per pound than any other known fuel, so that where minimum weight is a primary consideration, liquid hydrogen is the obvious choice. In the five-year projection discussed later, liquid hydrogen systems have a higher energy content per pound than gasoline, and could therefore be used for any type of vehicle, including helicopters and other support aircraft attached to a task force. On the other hand, because liquid hydrogen has a low density, hydrogen is at a disadvantage where low volume is important. Where chemical fuels are used with internal-combustion engines and the volume of fuel to be handled is not of great concern, there is little basis for choosing between liquid hydrogen and ammonia systems. For a given reactor power output, each system will support about the same number of tanks or trucks within the MED scheme.

The situation is quite different, however, for vehicles of the future, which may be expected to employ fuel cells. Within five years, fuel cells and electric drives will be developed to the point where they can be used in such vehicles as the M60 tank (Fig. 3). The potentially high efficiency of the fuel cell (60 per cent or more, compared with

FIG. 3. FUEL CELL POWERED TANK

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20 to 30 per cent for the internal-combustion engine) will permit either the use of smaller depots or the operation of more vehicles per depot. The ability to over-load electric drives for short periods and the lower power requirement for auxiliaries further improve the outlook for the fuel cell. Consequently, fuel cells and electric drives have been selected as the power source for the vehicles of the near future (Fig. 4). With these drives, the advantages of the hydrogen system over ammonia are more apparent. These considerations, despite the lack of present advantage for the hydrogen system with internal-combustion engines, would tend to tip the balance in favor of the hydrogen system.

Handling and transportation of liquid hydrogen should normally present no problem. This is principally a question of providing adequately insulated vessels and training personnel in handling techniques. In this respect, the situation is good now and is improving rapidly, owing to accelerated research programs now under way. Thousands of tons of liquid hydrogen are now being produced in plants scattered all over the country. It is predicted that by 1970 the production of cryogenic fluids will be a billion-dollar industry in the United States. The problem of applying this experience to a military environment under combat conditions can be solved only by practical experience.

Regenerative fuel systems were also investigated under Task 4.0. Regenerative systems are those that are practical only if the waste products are recycled and reconstituted into the original feed materials in a processing plant. Whereas nonregenerative systems can also be made to recycle their waste products (e.g., the hydrogen system can be made independent of water supply by returning the water from combination of hydrogen and oxygen in the fuel cells), the true regenerative systems (e.g., the sodium amalgam system), cannot be operated as open, once-through systems, because sodium is not commonly available in air, earth, or water. The adoption of such a system might be justified by the greater compactness in the operating vehicles, compared with nonregenerative systems. However, the regenerative systems are heavier, more complicated, and much more vulnerable. If the supply of sodium is interfered with, the entire mechanized unit stops functioning until the sodium is replaced. This seems to be a more serious threat to the continued operation of a fuel system than problems associated with cryogenic fluids.

Another possibility for improved logistics, although not contemplated in the Basic Criteria⁸ or the original Work Program,⁷ could be of considerable significance in connection with fuel cell power plants of the future. Because fuel cells have a much greater efficiency than internal-combustion engines, a given POL supply should do more work in the former than in the latter, assuming that the fuel is usable in both applications. However, hydrocarbon fuels normally used in internal-combustion engines cannot be used readily in present-day fuel cells, and it is impossible to predict the outcome of research programs along these lines. However, by catalytically cracking and steam-reforming hydrocarbon fuels, hydrogen can readily be produced and subsequently used in fuel cells. This process was studied briefly under Task 4.0 as discussed in Sec. 6 of this report. A large savings in the POL supply requirements for future military vehicles in forward areas seems to be quite possible.

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FIG. 4. FUEL CELL POWERED PERSONNEL CARRIER

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2.3 FUEL UTILIZATION

Because the study of fuels for the MED cannot be considered complete without consideration of ways of using the fuels, Task 5.0 was established for the study of fuel utilization.

Some of the results obtained in this part of the study have been anticipated in previous remarks on other aspects of the system. It was learned that a number of fuels which can be produced in the MED can be used in present-day internal- and external-combustion engines, with only relatively minor modifications to the engines. In particular, hydrogen, ammonia, hydrazine, and alcohol have been used successfully in this way. The use of hydrazine was soon eliminated because of the greater complexity of the fuel manufacturing plant without a corresponding gain in energy content. The use of alcohol requires either a supply of carbon or the recycling of waste products, which is difficult with internal-combustion engines. Because of the Basic Criteria, this system was ruled out. Both the hydrogen and the ammonia systems may be considered cryogenic, although much lower temperatures are required for liquid hydrogen than for ammonia. As mentioned previously, the plant size and power input required for supplying a given number of internal-combustion engine vehicles are about the same for hydrogen and ammonia systems.

Other factors, however, may eliminate ammonia. In confined spaces, such as tank hulls, the toxic and irritating characteristics of ammonia may present serious difficulties. Moreover, the odor of ammonia is detectable even in very dilute concentrations (17 ppm), which may make concealment more difficult. As pointed out previously, the vehicles of the future, using fuel cells, will require fewer modules for the MED chemical plant if the hydrogen system is used than if the ammonia system is used, owing to the nature of the processes involved. This is true even if ammonia is supplied to the vehicles and then cracked to hydrogen and nitrogen to supply hydrogen fuel cells, as described later.

Many variations are possible. For example, either the hydrogen or the ammonia system may be sized to operate using pure oxygen to give maximum power. The normal duty cycles for most military vehicles specify operation at less than full power for varying periods of time. During such periods, it may be possible to achieve the desired power output from the fuel cells by using air, or air enriched with oxygen, instead of oxygen alone. This will, of course, reduce the oxygen requirements, and thus alleviate the over-all space, weight, and power-input requirements. It should be mentioned that pure potable water is the end product of the combustion of hydrogen or ammonia dissociated in fuel cells. If necessary, this could be collected and used to supply task force personnel.

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3. CONCLUSIONS

This study concludes that it is entirely feasible to design and build an MED to produce chemical fuels from basic elements in air, earth, and water, using a nuclear energy source.

The detailed conclusions in this section are based on technical considerations and the experience of the personnel participating in this study. There are, of course, factors that could seriously affect these conclusions. However, until definitive engineering studies and designs of actual plants are complete and the plants themselves are operated, a more final judgment is impossible. For this reason, and to provide some margin of safety, it is considered desirable to maintain an adequate backup effort on several alternate concepts in addition to the preferred design. The general properties of the preferred MED systems and several alternates are given in Table 1.

3.1 H₂-AIR (O₂) SYSTEMS (PREFERRED)

The liquid hydrogen fuel system is considered to have the best possibilities for use in support of present day military vehicles as well as the fuel cell vehicles envisioned for the future (Figs. 5 and 6 are artist's renderings of the preferred system operating in the field). In this application, advantage would be taken of the duty cycle of the military vehicles (Sec. 7). The vehicle fuel cells would be sized to provide the required maximum output when operated on hydrogen and pure oxygen. However, when operating under cruising conditions at power levels below the maximum, air would be used instead of pure oxygen to the greatest possible extent. At power levels of up to 60 per cent of the maximum, the cells can be operated on air only, and at higher power levels, oxygen, in varying proportions, must be added. Because the duty cycle is about 50 per cent, a commensurate saving is possible in the quantity of oxygen supplied. A comparison of the hydrogen-oxygen system with and without air in Table 1 shows the extent of this saving.

Of more immediate concern is how to make the best use of the MED concept in connection with existing military vehicles. Obviously, a change to fuel cells and electric drives is not going to be made overnight. The interim period can, however, be used to good advantage in putting prototype MED units into operation in order to test them. Owing to the limitations in the Carnot-cycle efficiency of internal-combustion engines, a given quantity of fuel will supply fewer internal-combustion engines than fuel cell power plants. For the hydrogen system, about seven M60 tanks with internal-combustion engines will be supplied by the same quantity of fuel used in 22 tanks equipped with fuel cells.

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FIG. 5. KEY TO GENERAL OPERATING ARRANGEMENT - MOBILE ENERGY DEPOT

FIG. 6. GENERAL OPERATING ARRANGEMENT - MOBILE ENERGY DEPOT

TABLE 1

GENERAL PROPERTIES OF PREFERRED SYSTEMS
(CASE A: 22 TANKS)

	preferred systems				1st alternate: NH ₃ (cracked) H ₂ -O ₂ fuel cell***	2nd alternate: NaHg-H ₂ O-O ₂ fuel cell***
	H ₂ -air (O ₂) fuel cell*	H ₂ -air (O ₂) fuel cell	H ₂ -O ₂ fuel cell**	H ₂ -air fuel cell**		
over-all efficiency, % . . .	7.3	7.3	6.8	7.5	6.4	3.3
chemical system efficiency, %	31.3	31.3	29.0	32.2	27.6	14.2
POL crossover point, days . .	13.9	10.9	11.2	10.6	16.5	28
reactor energy input, Mwe. . .	5.51	5.51	5.95	5.35	7.79	12.13
weight of chemical plant, lb . .	53,500	53,500	53,500	53,500	150,000	123,000
no. of modules per plant . . .	2	2	2	2	6	5
weight of reactor, lb	281,800****	206,000	215,200	202,100	229,600****	447,200****
no. of reactor modules	8****	6	6	6	6****	12****
total no. of modules	10	8	8	8	12	17
weight of vehicle power plant, lb/tank	10,750	10,750	10,750	17,850	11,500	5257
volume of vehicle power plant, ft ³ /tank	110	110	110	183	115	58
weight of fuel per tank, lb (1-day supply)	135	135	135	135	1094	1655 (Na), 1802 (H ₂ O)
weight of O ₂ per tank, lb (1-day supply)	297	297	1090	0	1090	575
volume of fuel per tank, ft ³ (1-day supply)	31	31	31	31	21	27 (Na), 29 (H ₂ O)
volume of O ₂ per tank, ft ³ (1-day supply)	4.2	4.2	15	0	15	8

*Shown in artist's rendering - recommended first prototype.

**Represents simple modification of H₂-air (O₂) systems.

***The partial substitution of air for oxygen would be expected to afford changes in the system comparable to those achieved with the H₂ system.

****Using two reactors per MED.

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3.2 NH₃ SYSTEM USING CRACKED NH₃ TO SUPPLY AN H₂-O₂ FUEL CELL (1ST ALTERNATE)

As in the preferred systems, the chemical synthesis in the ammonia system starts with the production of hydrogen. However, instead of liquefying the hydrogen, the system combines nitrogen (produced by fractional distillation of liquid air) with the gaseous hydrogen as it comes from electrolysis units to form anhydrous ammonia. As indicated in Table 1, the power requirement for this process is only slightly higher than that for liquid hydrogen production. The plant size is, however, considerably greater: six modules compared with two modules and 150,000 lb compared with 53,500 lb. The volume and weight of the fuel cell power plant per vehicle are comparable with those of the hydrogen systems. The weight of reactants handled is considerably greater than for the hydrogen systems, owing to the added weight of the nitrogen. With respect to vehicle installation, the only difference between this system and the preferred systems is the addition of the ammonia cracking unit, because hydrogen is the fuel-cell fuel in all cases,

Because the duty cycle for the vehicles is the same for this system as for the hydrogen system, the same advantage would follow from the use of air-oxygen mixtures in place of pure oxygen. If air is used whenever possible while still maintaining the desired power output, the weight of reactants is reduced.

The essential differences between the ammonia and hydrogen systems are (1) in the nature of the cryogenic fuel handled between the MED and the vehicles, and (2) in a part of the MED itself. To produce ammonia, synthesizing modules are used instead of hydrogen-liquefaction modules; this triples the size and weight of the chemical plant. At the vehicles, it is necessary to supply catalytic crackers in order to extract hydrogen for use in the fuel cells, which are the same as in the preferred cases.

Ammonia may be burned in existing internal-combustion engines (with some modifications) by using a small percentage of an additive (e.g., hydrogen) to promote ignition and by modifying the fuel-feed system. Using the same amount of ammonia that would be adequate to supply 22 tanks equipped with fuel cells, only 11 tanks with internal-combustion engines could be supplied.

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3.3 NaHg SYSTEM (2ND ALTERNATE)

The sodium system (which is regenerative) requires twice as much reactor power as either the hydrogen or the ammonia system to supply the same number of vehicles (Table 1). Thus the over-all efficiency is only half of either the preferred or first alternate system. The size of the chemical processing plant is slightly less than for the ammonia system, but is still 2.5 times the size required for the hydrogen systems, whereas the total number of modules, including the reactor plant, is more than twice as great. The system is redeemed somewhat, however, by the smaller and lighter fuel cell system required per vehicle. As shown in Table 1, the size and weight are about half those of the hydrogen fuel cells used in the other systems. However, the volume and weight of reactants that must be handled are considerably greater.

In contrast with the hydrogen and ammonia systems, the fuel created in this system cannot be used in existing internal-combustion engines. Therefore, there can be no transition period during which the MED plants based on this system could be set up and operated with internal-combustion engine vehicles. It would be necessary to develop a new series of vehicle power plants while the MED plants are being developed. This would tend to increase the expense and duration of the development program, particularly because there is little current nonmilitary interest by others in such a system. In the case of the hydrogen and ammonia systems there are active current development programs, both private and government-sponsored, and the advances made in these programs would be reflected in the progress made on the MED fuel cell systems.

One of the most serious potential problems in connection with the sodium amalgam system is the vulnerability of the sodium and mercury supply lines, without which the vehicles will stop. With any of the other systems, vehicles will be able to operate as long as the plant is able to function and water and air are available.

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3.4 LONG-RANGE PROJECTIONS

The application of the MED discussed so far is rather narrow and restricted. Some of the more far-reaching implications of the MED concept should also be kept in mind. A new series of military vehicles based on the use of fuel cells and supported by MED's could entirely alter both strategic and tactical planning. For example, vehicles carrying a supply of oxygen as well as fuel can be made almost entirely independent of environment for limited periods. With watertight hulls, light armor, and flotation gear, the vehicles could be completely amphibious, operating on land and on or beneath rivers and lakes. The dangerous reliance on bridges for water crossings, with its attendant exposure and delays, would become a thing of the past. Instead, lakes and rivers would become ideal places of concealment for mechanical equipment. With a plentiful supply of oxygen and tightly sealed vehicles, crews could lie in wait for extended periods, as might be necessary in the event of all-out nuclear warfare. Sealed modules of the MED plant could be positioned beneath the surface of convenient lakes or rivers, and could use the surrounding water as raw material for the fuel product. Landing forces could be supported by MED plants placed in shallow water offshore by small submarine tugs. The plants could be operated from that position until the battle zone moved far enough inland to permit the plants to be brought ashore. In tropical regions, where dense jungle extends to the water's edge, rivers flowing to the sea could be used as highways to penetrate to the interior. When circumstances permit, reconnaissance and combat aircraft could be supported by the MED, which would increase the scope and range of action of the task force.

During the course of this study, many ideas have been advanced and suggestions made for study of many applications beyond the scope of this effort. A few of these ideas are listed below to indicate the range of possibilities for the MED.

(1) Refueling of support vessels in a naval task force. Some vessels in a task force may be nuclear powered and consequently be almost unlimited in range. Other vessels, such as destroyers, use fuel oil supplied by accompanying tankers, which must shuttle back and forth to supply ports. A nuclear-powered MED mounted on a ship capable of keeping up with a task force would be able to synthesize fuel from sea water (and air) and make the task force independent of external fuel supplies for extended periods. As mentioned previously, one large plant operating continuously is much more efficient than a number of smaller plants operating intermittently and, of course, the capital investment would probably be much less.

(2) Use of improved power plants in naval vessels. More compact and lighter power plants may be made possible by the use of liquid hydrogen and oxygen. For example, boilers could be reduced in size, or possibly eliminated entirely, by using combustion chambers for burning hydrogen with oxygen and then passing the resulting steam directly through turbines. Perhaps a small boiler could be used to supply steam

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for normal cruising power and a combustion chamber for direct production of steam from hydrogen and oxygen for maximum power. A study would have to be made to determine the optimum arrangement and also to determine whether a gas turbine might fit the situation better. The study could be extended to include the use of fuel cells and electric drives in a few applications.

(3) Use of synthesized fuels in aircraft. Some of the aircraft carried by a nuclear-powered aircraft carrier might be adapted to use fuel synthesized in an MED installed on the carrier and using excess reactor capacity. In the case of cargo aircraft supplying advanced bases, if such aircraft could be refueled at the advanced bases by fuel produced in an MED, the operating range of the aircraft and the amount of cargo carried could be increased.

(4) Use of synthesized fuels in missiles. Portable missile bases or bases in remote areas might fill some present or future need if it were possible to supply cryogenic fuel readily from locally available raw materials by using an MED.

In short, the combat and support potential of the MED concept is far more vast and the changes it would induce in combat techniques are far more profound than is evident from the application for which it is presently intended.

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4. RECOMMENDATIONS

It is recommended that work be continued on the preferred and alternate systems (1) to refine the concepts by optimizing variables and developing more complete data on each system, and (2) to prepare preliminary designs of each. In performing this work three objectives should be used as guidelines to define and schedule an orderly program:

- (1) A prototype MED must be in operation as soon as possible.
- (2) The program must provide for an orderly and rapid improvement of future MED's.
- (3) The program must encourage the application of the MED concept to all pertinent situations.

Table 2 outlines the principal items requiring design and development effort. This table shows that many of the development items are common to the liquid hydrogen and the anhydrous ammonia systems. Some of these items are already being developed in connection with other programs, so that it will be necessary only to follow these efforts and to try to influence their pace and direction. Other items will benefit indirectly from related programs, especially the rapidly advancing space program. Some items are applicable only to the MED program. These will require specific research and development programs if the listed objectives are to be realized.

A program of development resulting in a prototype MED system which has gone through an Engineering Testing Program is outlined below.

		<u>time required</u>
Phase I	feasibility study	0 (completed)
Phase II	conceptual design and optimization study	
	Part A projects immediately required	12 months
	Part B* projects not immediately required	6 months
	Part C** experimental fuel cell vehicle	12 months
Phase III	detailed design, fabrication, and testing of pilot plant	18 months
Phase IV	design and fabrication of prototype system	18 months
Phase V	engineering tests of prototype system	6 months

*May be concurrent with early effort in Phase III.

**Parts A and C may be concurrent.

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4.1 ENERGY SOURCES

The development of a suitable nuclear energy source is essential to the operation of the MED in regions where adequate electric power is not available. This study has shown that two methods of using nuclear energy to produce a chemical fuel are feasible: (1) the nuclear reactor may produce electrical energy, which is used in a fuel manufacturing process, or (2) the heat energy of a nuclear reactor may be used to produce fuel chemically.

4.1.1 Power Reactors

The development of a 14-Mwt MCR should be undertaken. This nuclear energy source may be generally as described in NDA 2143-16 ("Military Compact Reactor Program, Application Study - Mobile Power Units," United Nuclear Corporation and General Motors Corporation, August 15, 1961), with the following major modifications:

(1) Divide the large mobile power unit into modules whose size and weight are consistent with those of other components of the MED plant. The power unit should be operated with all modules in place on their transport vehicles. This will require the development of large, light, low-pressure air ducts for connecting the reactor and the power conversion modules.

(2) Increase the power output by adding a regenerator. This seems to be the simplest and most direct way of raising the MCR power level sufficiently to satisfy the input requirements of the chemical plant. This will require the development of a suitable rotary regenerator.

(3) Adopt 400-cps electrical generating equipment, and provide the necessary transformers and rectifiers to serve the electrolysis unit. This will require the development of a large 400-cps electrical generator.

An engineering design of a plant of the MCR type incorporating these features should be prepared.

It is also desirable to study an MCR specifically sized for the MED, incorporating the changes outlined above, and producing the desired output from one integrated plant rather than using two MCR's adapted from the NDA-GM studies. This study should determine the highest reactor thermal power that does not radically compromise the mobility of the reactor module. The development of this higher-powered MCR should also include a program for increasing the power density of these liquid-metal--cooled reactors in the future generations of this unit. The higher-powered reactors will significantly reduce the weight and number of modules of an MED.

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4.1.2 Process Reactors for Production of H₂

Attention should also be given to the direct utilization of reactor thermal energy for the production of hydrogen by the steam reforming of hydrocarbons. The optimum point for location of this plant in the POL supply chain must be determined and its capacity established. A reactor capable of supplying the process heat and electrical power required for the manufacture of liquid hydrogen by this route should be studied.

Other methods of using the thermal energy of the reactor directly should be investigated. The steam reforming of coal and natural gas may offer important logistic advantages in some situations. The reduction of steam by reaction with a metal may provide an efficient route to the production of hydrogen. If these or other processes appear promising after further study, the requirements for these nuclear reactors should be defined.

Development of processes for the direct dissociation of water by heat or radioactivity should also be encouraged. However, it is felt that no substantial amount of MED funds or effort should be used for this purpose, because many of the problems are basic, and other solutions, admittedly not as satisfactory, are available.

4.1.3 Direct-Conversion Devices

Great effort is being applied to the development of thermoelectricity, thermionics, and magnetohydrodynamics (MHD) by various firms and governmental agencies. Because these developments so far are still embryonic, personnel involved in developing the MED concept should not divert effort into these areas, although they should keep abreast of applicable developments.

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4.2 FUEL SYSTEMS

The fuel systems described elsewhere as being possible within five years do not exist today. Some components of the systems need more development than others to reach a practical stage. By judicious expenditure of funds and effort, it should be possible to balance the development of components in order to achieve the over-all goal in the proper time.

The development of compact hydrogen and ammonia plants requires considerable improvement, and reduction in size and weight, of some of the hardware involved. Some of this hardware is discussed below. Because it may take several years to accomplish these goals, a program should be started as soon as possible to design all the components of the compact synthesis plants.

The result of the development programs recommended in Secs. 4.2.1 through 4.2.5 will be a light, compact, efficient liquid-hydrogen--liquid-oxygen generator for use in an MED system.

It should be realized that much of the work outlined below is already under way. The solutions envisioned have been projected by practical people, well versed in the technology, and even solutions that fall short of the ultimate goal may provide a practical system.

4.2.1 Electrolytic Cells

The liquid hydrogen and anhydrous ammonia systems require the production of hydrogen by the electrolysis of water. Early in the study it was realized that commercial electrolytic cells would require many more modules of cells than would be feasible. The use of reversed fuel cells is a necessity for the complete elimination of POL and for a sufficiently compact MED. Although hydrogen-oxygen fuel cells have been operated in this manner in Allis-Chalmers' laboratories to demonstrate the principle, there is no commercial requirement for such light electrolysis units. Because they are basic to the MED fuel system, an electrolytic-cell development program should be instituted as soon as a decision is made to proceed with the development of the MED.

The size and weight of electrolytic cells will be reduced as a result of the studies undertaken to improve fuel cells. The studies will be concerned with (1) the development and application of improved and less expensive catalysts as electrode materials, (2) the design and construction of the electrodes and other components for operation at higher temperatures and higher current densities at the face of the cathode, and (3) the development and application of stronger and lighter structural materials for this use.

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4.2.2 Compressors

Centrifugal compressors have been envisioned for the liquefaction plants because they are lighter and more compact than reciprocating compression equipment. Presently, centrifugal compressors are relatively inefficient for the product flow rates required. However, the techniques by which centrifugal compressors can be made more efficient for lower flow rates are known today. A development program is required for (1) the development of stronger and lighter vane materials, (2) the accumulation of detailed knowledge of the properties of these materials so that the behavior of the vanes under stress can be accurately predicted, and (3) the development of improved bearing systems to be operated at very high speeds. The compressor efficiency will be increased as compressor speeds are increased and as the tolerances between parts are decreased.

4.2.3 Motors

The projected motor characteristics anticipate the development of (1) improved motor cooling techniques, possibly using cryogenics, (2) improved high-temperature winding insulations, (3) strong and light rotor assemblies, (4) improved bearing systems, and (5) improved commutation systems. These development programs are to be aimed at increasing the operating speed and efficiency and decreasing the size and weight of the drives.

4.2.4 Expansion Engines

The development of (1) stronger and lighter blade materials, (2) improved air-flow patterns and blade designs, and (3) improved gas-bearing systems will lead to very-high-speed expanders. Miniature working expanders operated at 250,000 rpm exist today.

4.2.5 Heat Exchangers

Heat exchangers with large surface areas per unit of weight will result from design and development programs directed toward the improvement of (1) fluid-flow patterns within the heat exchanger, (2) heat-transfer surface characteristics, and (3) heat-exchanger fabrication techniques.

4.2.6 Air Separation Devices

The size and weight of air separation devices can be reduced through an intensive research and development program. Horizontal separation equipment is presently being developed by Air Products for another classified project. The specific sizes and weights of such devices for use in the MED air plant have not been determined. However, there is every reason to expect that such devices can be designed for this application in five years and that they will be significantly smaller and lighter than conventional air distillation equipment. As the research progresses and the characteristics for the devices

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become more accurately defined, it will be possible to determine the best use of these devices for the MED application. For instance, it may become evident that one compact, highly developed device will replace the entire distillation column, or some combination of conventional distillation equipment and horizontal separators may prove to be most advantageous for this purpose.

4.2.7 Ammonia Compressor

The compressor for ammonia synthesis contributes significantly to the size and weight of the plant. Equipment to compress about 2000 lb/hr of mixed hydrogen-nitrogen gas from 1 to 950 atm will not be small and light, by any standard of transportability. The size and weight of the compressor can be decreased through the utilization of both rotary and reciprocating compressors, the development and application of stronger and lighter materials, the improvement of bearing systems, and the improvement of the product inter-coolers between compression stages.

If the ammonia-oxygen fuel system is selected for further development, the choice of air plant operating cycle (high-pressure or low-pressure) should be reviewed during the engineering design studies to determine which cycle gives the lowest over-all weight of synthesis plant (the high-pressure cycle was used in this report).

4.2.8 Storage and Transportation Vessels

The 4000-gal bulk-transport vessel and the vessels on the refueler for the hydrogen-oxygen MED system are projected to consist of reinforced-plastic inner and outer lines with an advanced insulation between them. High-strength plastics are now being developed for small, high-pressure, gas-storage vessels. Before these plastics can be used in the construction of large tanks, improved fabrication techniques must be developed. It is recommended that an intensive research and development program be initiated to select a high-strength plastic suitable for cryogenic-liquid storage, and to develop techniques for fabrication of large vessels from this material.

The fabrication and effective installation of present superinsulations is complicated. Also, these vacuum-type insulations are unable to support the compressive load of atmospheric pressure, and must therefore be surrounded by rigid walls. It is recommended that a program be carried out to develop simpler, more effective vacuum-type superinsulations that can be fabricated and installed on large vessels and that can support atmospheric pressure. The ability to support atmospheric load will be crucial in the design of light fuel-storage vessels for the Army vehicles. It is projected that with such capability, the rigid plastic outer liner of the vessel will be replaced by a thin flexible liner, such as Mylar. This lightweight design will be applicable for vessels placed within the protective armor of the vehicle or installed so that the outer liner cannot be contacted and damaged.

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It is anticipated that techniques can be developed that will allow the partial repair of these insulated vessels in the field. Such techniques may allow the crews of the transport vehicles to save and ultimately deliver some of the fuel remaining after the storage vessel has been punctured as a result of enemy action.

A program for the development of fabrication techniques for large foam-type vessels with a rigid inner liner is recommended as part of the ammonia-oxygen system.

4.2.9 Equipment for NaHg System

The development of the sodium systems for the MED would initially require research and development in the areas of (1) operation of a sodium amalgam fuel cell at high temperatures and with highly concentrated caustic electrolyte, (2) production of sodium amalgam by the reversal of a sodium amalgam fuel cell, (3) electrochemical production of sodium from sodium amalgam, and (4) design and construction of a small caustic concentrator operating with a low-grade heat source. The objective of these investigations would be the development of light, compact, and efficient units that could be integrated into the complete system. Many fundamental problems may arise, particularly in sodium and sodium amalgam production. These problems might require intensive investigations.

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4.3 FUEL UTILIZATION

Two programs should be carried on concurrently. Program 1 would require the procurement of components of fuel systems to adopt present internal-combustion engines in M60 tanks and other military vehicles to the use of hydrogen, ammonia, or both. Setups would be made on dynamometers to work out the proper settings for smooth power and torque curves over the operating-speed range. Extended road tests would then be made to obtain operating experience and to modify the systems as required for optimum performance. Program 1 would require one to two years.

Program 2 would require the development of fuel cell power plants. First, detailed engineering designs of experimental plants would be made, and the plants would be built and tested on stationary test beds. On the basis of these tests, prototype power plants for operating vehicles would be designed and built. During this three- or four-year period, development programs would be carried out on individual components so that at the end of five years it should be possible to equip a series of military vehicles with fuel cell power plants capable of operating in the expected conditions with normal maintenance and servicing.

Allis-Chalmers has devoted considerable effort to the development of a hydrogen-oxygen fuel cell and has thoroughly investigated several other systems that show promise as a possible power source for tractors and lift trucks. The most advanced system is the hydrogen-oxygen fuel cell. The ammonia cell at present has serious limitations. Much effort has recently been devoted to the application of the hydrogen-oxygen fuel cell to space vehicles. An official of one government agency said recently that the Allis-Chalmers cell is the only cell that will be in space within two years.

To meet the long-range objectives of the MED program, it would be desirable to make an early start on an engineering design program for a tank operated on the hydrogen-oxygen fuel cell. Two approaches should be considered: the installation of the fuel cells in tanks of current design, and the design of an entirely new tank expressly to accommodate the cells.

It is understood that a comprehensive study of electric drives for military vehicles is going on now, sponsored by the Ordnance Tank-Automotive Command. This study will be completed and the final report published in October, 1962. It is hoped that this report will be useful as a guide for further studies and development programs devoted to fuel cell motive power.

The development of a suitable ammonia cracking unit for use on a vehicle should also be undertaken. This unit would crack ammonia to produce hydrogen for use in the hydrogen-oxygen fuel cell and for use as an ignition promoter when forming ammonia directly in an internal-combustion engine.

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The scope of work under each program is outlined below:

Program 1

- (1) Procure experimental equipment to adapt present internal-combustion engines in military vehicles to the use of hydrogen, ammonia, or both.
- (2) Run dynamometer tests on engines thus equipped and adjust until performance is satisfactory.
- (3) Equip some vehicles with prototype fuel systems and road test until satisfactory.
- (4) Procure sufficient approved systems for extended field service.

Program 2

- (1) Design an integrated experimental power plant, including hydrogen fuel cells, electric motor drive, controls, etc.
- (2) Set up and test on test bed, using different components, such as electric motors and controls to achieve best performance.
- (3) Design and build prototype power plants to fit military vehicles.
- (4) Calibrate these power plants on test stand and install in vehicles for extended tests on test track.
- (5) Design and build final units for extended field trials.

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5. ENERGY SOURCES

Energy sources were studied to determine the characteristics required for application to the MED. This section sets forth the principal characteristics and design criteria of a nuclear reactor concept for immediate development as the MED energy source, describes known problem areas, and defines the research and development effort required to realize this power source.

This section also discusses fusion reactors (Sec. 5.2), radioisotopic power sources (Sec. 5.3), thermoelectric and thermionic energy conversion systems (Secs. 5.1.3.1 and 5.1.3.2), MHD systems (Sec. 5.1.3.3), and thermal and radiolytic process reactors (Sec. 5.1.2) as possible future energy sources for MED. The state of development of each is evaluated, and their applications to the MED are discussed. Table 3 gives the conclusions reached during this portion of the study.

TABLE 3

STUDY OF ENERGY SOURCES FOR THE MOBILE ENERGY DEPOT

<u>ENERGY SOURCE</u>	<u>CONCLUSIONS</u>
FUSION	Not available presently. When developed (≥ 20 years) it may not be applicable because of size.
RADIOISOTOPES	Not practical. The quantity of energy available is not adequate to influence future POL requirements.
<u>DIRECT CONVERSION REACTORS</u>	
Thermoelectric	Not promising. The weight to power ratio is too high and the efficiency too low.
Thermionic	Not available presently. The technology is too young to evaluate application in the distant future.
MHD	Not promising presently. The technology is too young to evaluate application in the distant future.
<u>PROCESS REACTORS TO PRODUCE H₂</u>	
Thermal Dissociation of Water	Not technically practical. A nuclear reactor cannot operate at the required temperatures.
Radiolytic Dissociation of Water	Not technically practical. The reactor requires an impossible amount of shielding and the purification of H ₂ -O ₂ is problematical.
Steam Reforming of Petroleum	Should develop as means of alleviating POL logistic requirements. Has excellent short-range and long-range potential.
<u>POWER REACTORS</u>	
Liquid Metal Cooled	Should develop as the energy source for the mobile energy depot. Has excellent short-range and long-range potential.

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5.1 FISSION

5.1.1 Power Reactors

5.1.1.1 Selection of Military Compact Reactor (MCR) Concept. The selection of a nuclear power reactor for a mobile power plant has received considerable attention over the last five years. The most complete and applicable study of this problem was performed by the United Nuclear Corporation and General Motors Corporation under the Military Compact Reactor (MCR) Program for the U. S. Atomic Energy Commission. This well-documented study^{1,2,3,4} defined an epithermal reactor cooled by liquid metal (potassium) and coupled to an open-cycle air turbine. Allis-Chalmers is in basic agreement with the conclusions of that study and others^{5,6,7} that a mobile compact reactor should be liquid-cooled, and either epithermal or fast. Fast or epithermal reactors cooled by liquid metal have also been selected^{7,8} for space applications, where their high power densities are a definite advantage.

The MCR program selected potassium-39 as the preferred reactor coolant. However, mercury⁵, lithium⁶, and sodium⁷ have also been proposed as liquid-metal coolants. Mercury, because of its high vapor pressure and poor compatibility at temperatures of 1200-1600 F⁹ is not suitable for a high-efficiency power conversion system. Lithium is recognized as an outstanding reactor coolant, and recently the AEC requested that the Pratt and Whitney Aircraft Division of the United Aircraft Corporation undertake development of the SNAP-50 reactor, a lithium-cooled advanced compact nuclear power reactor for space applications¹⁰. However, high-temperature lithium can only be contained in the refractory metals⁹. The development effort required to achieve a satisfactory lithium container would render unlikely the development of MED in the next 4 to 7 years. The choice of potassium-39 over NaK and sodium as a coolant is based primarily on its lower activation and rapid decay of radioactivity following reactor shutdown. From a technological point of view, Allis-Chalmers is in agreement with the selection of potassium-39 as the reactor coolant.

The work performed under the MCR program leading to the selection of the open-cycle air-turbine power conversion system is adequate and reasonable. An open-cycle air turbine permits a system of minimum weight, high efficiency, and maximum simplicity.

A repetition in their document of the data developed under the MCR program is unnecessary and is beyond the scope of this study. The data and conclusions developed under the MCR program are directly applicable to the selection of a nuclear power reactor for use with the MED and can be used to advantage.

Although changes in the specific designs put forth under that program may be desirable to better integrate the mobile power unit with the MED, the over-all reactor concept selected under the MCR program should be developed for use with the MED. Changes

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to the large mobile power unit described under the MCR program⁴ are recommended in Sec. 5.1.1.2. Changes that were considered and rejected are also discussed there.

5.1.1.2 Changes to the MCR. The large mobile power unit developed under the MCR program is in many respects an ideal energy source for the MED. It is compact, has a high power-to-weight ratio, and is designed for land, sea, and air mobility.⁴ It deviates from the MED requirements in only three important characteristics:

- (1) The power plant mounted as a single unit on the XM-524 military trailer weighs over three times as much as other modules of the MED.
- (2) The power output of the MCR is only 2610 kwe, which is not adequate to meet the power requirements of the fuel manufacturing plant designed to support 22 tanks or 87 trucks powered by hydrogen-air (oxygen) fuel cells. This plant requires 5510 kwe, based on a 16-hr plant day.
- (3) The power from the MCR is supplied at 60 cps a-c and 4160/2400 v. The fuel manufacturing plant requires about 63 per cent of its power as low-voltage d-c current and the remainder as 400-cps high-voltage a-c current.

The fuel manufacturing plant is separated into modules which can be transported on most highways and roads throughout the world. If the power plant of the MCR is mounted as a single unit on the XM-524 military trailer, this load will require special routes to conform to bridge and highway weight limits in moving from site to site. It is therefore recommended that the power reactor be road transported as four separate modules or trailer loads: the reactor module (consisting of the assembled MCR reactor and shield packages), the power conversion module, the electrical equipment module, and the control module. All modules except the reactor module will be transportable on the M-172A1 semi-trailer. It is possible that improvements in the shielding and mechanical design may lower the weight of the reactor module to the 50,000-lb capacity of this semi-trailer. Detailed design of the MCR should provide for rapid connection of the four modules without off loading from their transport vehicles.

The power output of the MCR must be increased if it is to be adequate for the above fuel manufacturing plant. If a regenerator is added to the MCR, the power output is increased from 2610 kwe to approximately 3430 kwe. Two MCR's modified in this way will supply the power for an MED supporting the representative tank unit plus a small amount of power for service use around the depot area. These two reactors are each 14-Mwt units. Consideration should also be given to raising the thermal power of the reactor. It is estimated that a single 23.7-Mwt reactor using a regenerative cycle will supply the power for an MED supporting the representative tank unit if no power is furnished for services.

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The electrical power requirements for the fuel manufacturing plant are special. The requirements for a large exclusion radius for the reactor and a large percentage of the power as low-voltage direct current make it desirable to change the electrical generating equipment on the MCR. It is recommended that the generators on the MCR be changed from 60 cps to 400 cps units. This will permit substantial reductions in the weights of the generators, the transformers required to make low-voltage current, and the motors used throughout the liquefaction plant. The conversion to low-voltage current and its subsequent rectification will require considerably more electrical equipment than that presently supplied with the MCR.

During this study three other changes to the MCR were investigated. A change in the shielding was studied and found to be impractical. A change in the power conversion equipment was studied and found to result in a reduction in over-all cycle efficiency; this change is not recommended. The effect of increasing the reactor outlet temperature was studied to understand how this would affect the performance of future reactors. This may improve the performance of future reactors slightly, but the development of reactors of higher temperature will be costly and time consuming. For the present, the outlet temperature of the MCR should remain at 1500 F.⁴

5.1.1.2.1 Division into Modules. The large mobile power unit of the MCR program is presently designed to be transported over roads on two trailers. Except for the operating control unit, the entire power plant is carried on the XM-524 military trailer. The weight of equipment on this trailer is 103,740 lb. The control unit weighs 2000 lb and is carried on a one-ton trailer.⁴ However, the MED has been designed so that no module exceeds 30,000 lb. Each module is separated and transported from one site to another as an independent unit. Separation for movement and reassembly at the new site requires breaking and making electrical and pipe connections between the modules of the fuel manufacturing plant. These operations are not expected to impose any prohibitive delay on relocation of the MED.

It should be noted that the nuclear power plant package described above weighs about 3-1/2 times the permissible weight for an MED module. This far exceeds the gross weight of vehicle and load permitted by the Department of Defense¹¹ or any of the States.¹² Thus, the nuclear power plant package will have to be moved from site to site over special routes to conform to bridge and highway weight limits. The fuel manufacturing plant, on the other hand, may be transported freely on most highways and roads throughout the world. It is therefore recommended that the nuclear power plant be separated into four modules for road transport. All of these modules except for the reactor and its shielding will be transportable on the M-172A1 semi-trailer, whose capacity is 50,000 lb when towed by the M-123 truck tractor. If the future shielding studies are successful in reducing the shielding weight by 10,000 lb,⁴ or if future design studies result in a total weight reduction in the reactor module of about 10,000 lb, then the reactor and shielding module will also be transportable on the M-172A1 semi-trailer.

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With minor design modifications, the large mobile power unit may be separated into the following four modules without significantly extending the time required to move the MED from one site to another:

- (1) The reactor module, consisting of the assembled MCR and shield packages. The burner sections on the reactor package should be moved to the power conversion module so that the plant may be operated on petroleum independent of the reactor package.
- (2) The power conversion module, consisting of air turbine, alternator, regenerator, and burner sections.
- (3) The electrical cabinet module, consisting of master control cabinet, circuit breaker cabinets, transformers, and rectifier cabinets.
- (4) The control-unit module, consisting of reactor controls, fuel manufacturing plant controls, connecting cables, spare parts, and tools.

The connections between modules will remain as given for the large mobile power unit of the MCR program⁴ except for the following changes:

The shield package and the reactor package will remain assembled except during air transport.

The four air ducts to and from the liquid-metal--air radiators may be combined into one inlet and one outlet duct.

The turbines driving the primary coolant pumps should use air directly from the liquid-metal--air radiator. This will eliminate two piping connections between the reactor and power-conversion modules.

No fuel line is required between the reactor and power-conversion modules if the combustion sections and fuel tank are both on the conversion module.

The electrical cable connecting the electrical cabinet module to the liquefaction plant, a part of the load, will remain. In addition a large bus bar will be required between this module and the electrolysis cells. This will require that the electrical cabinet module and the electrolysis cells be located together.

Since the electrical equipment module will be located at the fuel manufacturing plant, this module must be connected to the power conversion module by a load cable, an exciter cable, and an instrumentation and control cable. All these cables should be about 100 ft long to cover the required reactor exclusion radius.

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The control unit module will require a control and instrument cable to the liquefaction plant and to the electrical equipment module.

Of the above connections, only the large air ducts present any problems in quick breaking or reconnection of the power conversion system. Primarily this is a problem of making the connections sufficiently flexible so that the ducts may be joined without requiring a prohibitively accurate alignment of the vehicles. There are several possible methods for achieving this flexibility. Among these are the flexible metal hoses, flexible bellows sections, and combinations of slip joints and ball joints. This connection might be made as follows: A ball joint positioned vertically on each of the two modules to be connected would permit alignment of the flange faces when the two modules were at slightly different elevations or were not level. The connecting pipe would consist of an inverted U pipe equipped in the middle of the U with a longitudinal slip joint to accommodate variations in the distance separating the modules. This slip joint would require turnbuckles with which to adjust the length of the connecting pipe. The connecting pipe would be joined to the top of the ball joints by quick-disconnect flanges using a yoke clamp. Although ball joints and slip joints of the required size and rating are not currently available, they require a minimum development effort. The yoke clamps have been developed for hinged closures in applicable sizes and ratings.

If a regenerative cycle is used for the power conversion system, the pressures in these connecting lines will be less than 50 psig. If a simple cycle is used the pressures will be less than 100 psig. Table 4 shows the number of modules and their weights for an MCR modified for application to the MED. The second item is the power plant shown in the artist's rendering of the MED in operation (Fig. 5). If a single reactor is used to furnish power to the fuel manufacturing plant, the number of modules making up the power plant is reduced to six.

5.1.1.2.2 Shielding Changes. It is desirable to minimize the weight of the reactor module as it is transported from one site to another. For this reason removable shielding in liquid form was proposed as a substitute for the outer neutron shield of the reactor. This shielding could be pumped into a tank transporter for movement from site to site while the reactor is shut down. The reactor would not be operated unless this shielding were returned to its shielding tank surrounding the outer lead shielding blanket. The shielding tank would remain in place and intact during moves to minimize the time required to prepare the plant for travel. The difficulties that this concept entails, and by reason of which it is not recommended, are discussed below.

During this study, shielding materials were surveyed to determine which are liquid at reasonable operating and handling temperature. Shielding liquids must have a low density to avoid a prohibitive increase in weight. The materials which appeared promising are listed in Table 5. The weights of these materials necessary to give an equivalent amount of shielding were estimated from their respective densities and macroscopic neutron removal cross sections.

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TABLE 4

WEIGHTS OF MCR MODIFIED FOR THE MOBILE ENERGY DEPOT APPLICATION

	<u>weight, lb</u>
<u>14 Mwt MCR - simple cycle - 2.48 Mwe to fuel manufacturing plant*</u>	
reactor and shielding module	62,000
power conversion module	25,600
electrical equipment module	27,000
control unit module	<u>12,900</u>
total	127,500
<u>14 Mwt MCR - regenerative cycle - 3.26 Mwe to fuel manufacturing plant**</u>	
reactor and shielding module	61,400
power conversion module	35,300
electrical equipment module	29,300
control unit module	<u>14,900</u>
total	140,900
<u>23.7 Mwt MCR - regenerative cycle - 5.51 Mwe to fuel manufacturing plant***</u>	
reactor and shielding module	79,500
power conversion module #1	30,400
power conversion module #2	30,400
electrical equipment module	16,100
transformer and rectifier module	27,200
control unit module	<u>22,400</u>
total	206,000

*Two furnish only 90% of power required by fuel manufacturing plant.

**Two furnish all power required by fuel manufacturing plant plus 1000 kwe for service loads.

***One furnishes all power required by fuel manufacturing plant.

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TABLE 5

SURVEY OF LIQUID SHIELDING FOR OUTER NEUTRON SHIELD*

<u>material</u>	<u>density, g/cm³</u>	<u>Σ_{r_f} cm⁻¹</u>	<u>equivalent shielding weight, lb</u>
(CH ₂) _x	0.876	0.107	12,670
C ₃₀ H ₆₂	0.952	0.109	13,500
NH ₃	0.771	0.111	10,750
C ₈ H ₁₈	0.739	0.095	12,030
LiH	0.78	0.118	10,220**
(CH ₂) _n	0.92	0.111	12,810
(CH ₃) ₃ NBH ₃	0.758	0.104	11,280
LiBH ₄ · 2NH ₃	0.666	0.102	10,100
LiBH ₄	0.66	0.109	9,370
Be(BH ₄) ₂	0.604	0.104	8,980
H ₂ O	1.00	0.100	15,460
LiNO ₃ · 3NH ₃	0.70***	0.0606	17,900

*Based on information in Ref. 13.

**Base case, total weight of LiH in outer neutron shield.⁴

***Estimated.

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Table 5 shows that none of the liquids investigated has a macroscopic neutron removal cross section greater than that of LiH. All of the liquid shields would therefore require a larger tank surrounding the reactor than the existing structures. Since the presently designed MCR structures exceed the basic size criteria, the use of a liquid can only compromise the module dimensions further.

Only three of the liquids considered give a lighter outer neutron shield than does lithium hydride: namely, lithium borohydride in ammonia ($\text{LiBH}_4 \cdot 2\text{NH}_3$), lithium borohydride alone, and beryllium borohydride ($\text{Be}(\text{BH}_4)_2$), and only the last two are significantly lighter. The lithium borohydride is disqualified by its excessive decomposition rate and rapid hydrolyzation by water. The beryllium borohydride is impractical because of its difficult chemical preparation. Therefore, a liquid outer neutron shield will not save shielding weight but will probably add to the total reactor weight.

It might be possible to design a detachable outer shielding tank that would include a portion of the lead gamma shielding. However, this appears to result in an excessively complex tank structure when all of the required passages are provided. It was therefore considered necessary that the reactor module carry all of the gamma shielding as a fixed structure. The shielding module for the MCR carries 9400 lb for this purpose. The reactor module must also carry the tank and support structures. As a result, the minimum weight of the reactor module is about 50,100 lb, or about 10,830 lb heavier than the MCR air transport module as presently designed. This additional weight will restrict its transport to the C-133.¹¹

On the other hand, if the MCR shielding is not modified, the total assembled weight of the reactor and shield modules is 60,320 lb,⁴ or twice the allowable weight set forth in the basic criteria. This will cause any reasonable tractor-trailer combination to exceed nearly every highway load limit established by State law throughout the United States.¹² Nevertheless, this load is less than many items of military equipment and is not unrealistic in terms of military highway construction. Further, if the shield development program leads to a weight reduction of 10,000 lb (a 5,000- to 10,000-lb reduction was predicted⁴), the assembled reactor and shielding module would weigh only slightly over 50,000 lb. This combined module could then be carried on the M172A1 low-bed semi-trailer, when towed by the 10-ton M123 tractor truck.

In conclusion, the use of a liquid outer neutron shield in lieu of the lithium hydride currently used in the MCR does not significantly improve the highway mobility of the reactor module, but does seriously limit its air mobility. This change is therefore not recommended for the present design of the MCR. Should future requirements demand a larger reactor, consideration should be given to removing the shield tank and part of the gamma shielding during air transport. This tank and shielding would remain in place during highway transportation. For the larger reactor, the ability to remove and replace part of the shielding may improve its highway mobility significantly.

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5.1.1.2.3 Increasing the Output of the MCR. Previous studies have described in detail the large mobile power unit based upon the MCR concept.⁴ This mobile power unit produces 2610 kwe of 60-cps alternating current. If used as the energy source for the MED, the electrical generating equipment should be changed to a 400-cps system for reasons explained later in the report. However, the amount of power produced remains approximately 2610 kwe. Before this 400-cps current can be used by the fuel manufacturing plant, a part of it must be converted to low-voltage direct current. The remainder will be routed to several compressors, pumps, and other liquefaction plant equipment. A 5 per cent loss is estimated between generator outlet terminals and fuel manufacturing plant input terminals. Thus, this MCR will provide only about 2480 kwe to the fuel manufacturing plant.

The fuel manufacturing plant designed to support the representative tank unit of 22 tanks requires 5.51 Mwe for 16 hr per day, or approximately 88,100 kwhr/16-hr day. (When strategic conditions permit, the plant will be operated on a 24-hr day.) Since the MCR will deliver only about 2.48 Mwe to the fuel manufacturing plant, more than two MCR's will be needed to produce the required power.

Even if two MCR's are used as the energy source for the MED, their power output should be raised to fully satisfy the power requirement of the fuel manufacturing plant. Several methods of doing this were investigated. Changing the gas turbine to a steam turbine system was found to reduce the net power output. The addition of a rotary regenerator to the gas turbine system was found to increase the net power output by about 30 per cent. This change would permit two regenerative-cycle MCR's to satisfy the power requirements of the fuel manufacturing plant and to furnish a small amount of power for service use if they are operated for 16 hr per day. Higher reactor operating temperatures were also studied and were not found to be warranted. The increase in reactor power necessary to supply the MED from one reactor was investigated. A single 23.7-Mwt reactor coupled to a regenerative Brayton cycle was found to be adequate.

5.1.1.2.3.1 The Rankine vs. Brayton Cycle. In theory the Rankine cycle is more efficient than the Brayton cycle, because of its lower pumping power requirements. This suggested that the efficiency of the power system might be improved by substituting a steam Rankine cycle for the open Brayton or gas-turbine cycle now used in the MCR. Although the total system would weigh more than the present MCR, the weight of the reactor and its shielding would not be increased. If the reactor and power system are transported as two separate modules, a weight increase on the lighter module might not be important. The strict limitation on relocation time for the MED requires that both the liquid-metal and steam systems remain intact and closed during transport. For this reason, an intermediate loop was placed between the two systems to circulate air (see Fig. 7). This loop requires no purging or evacuation when the modules are rejoined after transport. If time between moves permits, nitrogen may be used instead of air to lessen the hazards associated with a leaking liquid-metal heat exchanger. Since the loop should be pressurized for maximum performance, the use of nitrogen rather than air at this time might be desirable.

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FIG. 7. STEAM RANKINE CYCLE WITH INTERMEDIATE LOOP

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The cycle shown in Fig. 7 was investigated for a range of conditions using the following assumptions:

- (1) The reactor is potassium-cooled with an exit temperature of 1500 F.²
- (2) The condenser sink temperature is 250 F.²
- (3) The effectiveness of heat exchanger 1 is 0.80 on the air side.

It was found that the ratio of reactor power to unit volume of air flow in the intermediate loop (L/W_a) must fall between 0.15 and 0.25 for a practical system. If this value is less than 0.15, the temperature of the air entering heat exchanger 1 is so high that an undesirably large air mass must be circulated to remove the heat of the reactor. This temperature exceeds 774 F at values for L/W_a of less than 0.15. The value of L/W_a can only exceed 0.25 if the effectiveness of heat exchanger 2 exceeds 0.95 on the air side. In view of the above limitations, a practical operating value of L/W_a will be in the neighborhood of 0.20.

Figure 8 shows the over-all plant efficiency for various values of L/W_a from 0.15 to 0.25. The steam enters the turbine at 1200 F and 2400 psia. Three curves for varying ratios of loop pressure drop to highest loop pressure are given. All of these curves show the over-all plant efficiency to be less than 25 per cent.

Figure 9 shows the over-all plant efficiency for various steam pressures from 1800 psia to 3000 psia. The loop operates under a L/W_a ratio of 0.20 and the ratio of the pressure-drop to the loop pressure is assumed to be 0.05. Three curves for varying steam-turbine inlet temperature are given. Only the curve for 1400 F exceeds 25 per cent over-all efficiency. This temperature is not achievable with a practical heat exchanger. Other conditions throughout the range were examined and in all practical cases the cycle efficiency was found to be less than 25 per cent. It is therefore concluded that the steam turbine with an intermediate loop will not permit an over-all cycle efficiency greater than 25 per cent. It will be shown later that a regenerative Brayton cycle can result in a cycle efficiency of up to 28 per cent when coupled to a reactor operating with a 1500-F coolant-outlet temperature.

The Rankine cycle with intermediate loop does not offer any advantage over the Brayton cycle under the limitations imposed by the mobility requirements for the reactor. The investigated change is therefore not recommended.

5.1.1.2.3.2 Addition of a Regenerator. Since the reactor and its shielding constitute the heaviest indivisible component of the MED, any means of increasing the plant power output without increasing the weight and size of the reactor should be considered. One way to achieve this is to change the cycle from a simple to a regenerative open Brayton

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FIG. 8. OVER-ALL PLANT EFFICIENCY FOR GIVEN STEAM DATA

$T_3 = 1200 \text{ F}$

$P_3 = 2400 \text{ psia}$

FIG. 9. OVER-ALL PLANT EFFICIENCY FOR GIVEN AIR LOOP DATA

$$\begin{aligned} L/W_A &= 0.20 \\ \Delta p/p_o &= 0.05 \\ E_i &= 0.80 \end{aligned}$$

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cycle, in which part of the heat normally thrown away in the hot turbine exhaust would be returned and used to preheat the air entering the liquid metal radiators. The more effective this regenerative heat exchanger, the more efficient the cycle. Two basic types of heat exchangers are used for this purpose: the stationary heat exchanger and the rotary heat exchanger. The stationary exchanger, or recuperator, is heavier and larger than an equivalent rotary regenerator. Generally the stationary exchanger is designed for an effectiveness of 60 to 80 per cent.¹⁴ Rotary regenerators, however, are capable of higher effectiveness (85 to 92 per cent in relatively small sizes).^{15, 16} The major problem with rotary regenerators has been the development of seals with low leakage rates and long lives. Many gas turbine companies have and are working on the rotary regenerator. However, neither rotary regenerators nor stationary recuperators of the sizes required are catalogue items.¹⁷ Procurement of a suitable regenerator for the MED power plant will require development effort, and primary attention should be given to the development of a rotary regenerator.

Figure 10² shows the Brayton cycle efficiencies for the simple cycle, the regenerative cycle, the regenerative cycle with intercooling, and the regenerative cycle with intercooling and reheat. At the temperature available from the reactor (1392 F)⁴ there is a considerable gain in efficiency between the simple and regenerative cycles. There is almost no incentive to add intercooling to the regenerative cycle, and the addition of both intercooling and reheat adds only about one third of the gain resultant from adding a regenerator to the simple cycle.

The addition of a regenerator alone adds significantly to the output of the power unit. It is estimated that the net output from the large MCR would increase by 30 per cent from 2.61 Mwe to about 3.43 Mwe with the addition of a rotary regenerator that was 87 per cent effective. This increase in power would permit the 14-Mwt reactor to produce slightly over half the power required by an MED supporting the representative 22-tank unit. A drum-type rotary regenerator for the 14-Mwt MCR is estimated to weigh 7600 lb. The drum is about 6-1/2 ft in diameter and 6 ft long. Its housing is approximately 7 ft long, 8-1/2 ft wide, and 8-1/2 ft high, including a small exhaust duct.

The above cycle change would increase the weight of the total plant by slightly more than the weight of the regenerator. However, the effect of this change on the total weight of the reactor module would be insignificant; the radiators would be slightly heavier to provide more heat transfer surface and to handle the increased flow of air required by the regenerative cycle. Although the increased weight to the power conversion module will cause it to exceed the 30,000-lb limit for an air transportable module, the alternator may be removed and shipped separately if air transport is limited to the C-130 aircraft. In any event, the slight additional weight will not cause any significant reduction in highway mobility of the module, since in either case it will be well below the capacity of the M172A1 semi-trailer.

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FIG. 10. COMPARISON OF BRAYTON CYCLE EFFICIENCIES

From NDA 2143-5
Volume 1, Fig. 5.38

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5.1.1.2.3.3 Raising the Reactor Temperature. Another means of increasing the power output from the reactor without increasing its size and weight directly is to raise the temperature of the coolant leaving the reactor to permit the gas turbine to be operated with hotter gases. Figure 10 shows the effect on the cycle efficiency of raising the turbine inlet temperature. According to Fig. 10, the power unit for a simple Brayton cycle might operate with a cycle efficiency of about 22.3 per cent at a turbine inlet temperature of 1392 F. Losses and power to auxiliaries reduce this to about 18.6 per cent over-all efficiency for the MCR.⁴ If the turbine inlet temperature is raised 200 F to 1592 F the cycle efficiency becomes about 25.8 per cent. Assuming a proportional loss, the over-all cycle efficiency is 21.5 per cent and the power produced is increased from 2.61 Mwe to about 3.0 Mwe for the higher temperature reactor. Thus raising the turbine inlet temperature to 1592 F results in a 15 per cent increase in the power output for a simple Brayton cycle.

At a power output of 3.0 Mwe, two high-temperature MCR's will produce sufficient power to supply the mobile energy depot supporting the representative 22-tank unit operating on a hydrogen-air (oxygen) fuel cell system. This also allows for losses to the transformer and rectifier units and a small service load.

Raising the operating temperature of the reactor from 1500 F to 1700 F (which corresponds to the 200-F increase in turbine inlet temperature) is not simple. The reactor outlet temperature for the MCR was chosen "sufficiently high to provide a good over-all cycle efficiency from the power conversion system, at the same time permitting the development of a reactor design which is compatible with current materials and component technology."⁴ Operating temperatures near 1700 F would entail serious problems of material compatibility in the primary system. It would also require major revisions in the structural materials throughout the system, since austenitic stainless steels are not satisfactory for structural strength at temperatures above 1500-1600 F. Moreover, the fuel element design may require extensive revision to contain the additional fission gases released at the higher temperature.

It is therefore recommended that the operating temperature for the first-generation power reactor for the MED be limited to 1500 F. As the technology of high-temperature liquid-metal reactors advances, the reactor operating temperatures may be raised accordingly.

5.1.1.2.3.4 Increasing the Reactor Thermal Power. If a single MED is to support the representative unit of 22 tanks, the fuel manufacturing plant requires an electrical energy input much greater than the output of the present MCR. Increasing the reactor operating temperature and adding a regenerator to the power system will increase the electrical output of the MCR, but not enough so that a single 14-Mwt reactor will satisfy the representative MED. Two or more MCR's may be used with each MED. However, with regard to capital costs, it is highly desirable to increase the power of the MCR so that one reactor would be adequate. The number of operating personnel will also be reduced if a

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single reactor is used as the power source. It is estimated that a single 23.7-Mwt MCR coupled to a regenerative Brayton-cycle power system will produce enough electrical power to satisfy the requirements of an MED supporting the representative unit of 22 tanks operating on the hydrogen-air (oxygen) fuel cell system. If the power system uses a simple Brayton cycle, the reactor power must be about 31.1 Mwt to produce the required electrical power.

The large mobile power unit (MPU) version of the MCR is designed for overland transport as an assembled and operable unit on a standard military trailer, the Hyster (XM-524), with only its control unit carried separately (for example, on an M-14 trailer).⁴ The weight of the equipment on the trailer is 103,740 lb. It was pointed out earlier that the MCR could achieve considerable highway mobility if the unit is divided into two or more modules. If this is done, the reactor and its shielding is the heaviest indivisible mass that must be transported, and weigh 60,320 lb (future studies should reduce this by 5000 to 10,000 lb). When compared with other items of heavy military equipment, for example, the tanks it will support, this is a significantly lighter highway load. The problem of balancing highway mobility of the reactor with MED capacity should be carefully studied. After this upper limit on weight and size is established for highway transportation, the reactor should be studied for disassembly into packages that are transportable by air.

A preliminary study was made of the effect of increasing the power of MCR. Figure 10 shows the total weight of the assembled reactor and shield module versus the reactor thermal power. The following assumptions were used in calculating the values with which Fig. 10 was plotted:

- (1) the volume of the core is increased to maintain a uniform average power density;
- (2) neutron and gamma leakage from the core are proportional to reactor power;
- (3) shielding consists of uniform shells whose weight could be estimated from change in shell radii and the thicknesses of lead and lithium hydride required to give equal shielding; no allowance was made for increased coolant activity;
- (4) the weight of the primary cooling system and heat exchangers is proportional to reactor power; and
- (5) no consideration was given to control of the larger core.

Figure 11 shows that separation into modules would permit doubling the reactor thermal power without increasing the highway weight over that of the existing MCR design.

Figure 11 also shows the diameter of the basic shielding sphere for the MCR. It is assumed that the outside dimensions are controlled by the clean shielding, i.e., that the coolant

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FIG. 11. TOTAL WEIGHT AND OUTSIDE DIAMETER REACTOR + SHIELD MODULE
Scale up of 14 Mwt MCR Design, Based on Equal Power Density,
Simple Cycle, No Quick Disconnects

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lines are routed so that the shielding of passages does not increase the width of the package. The shielding-diameter curve shows that the width will be greater than the permissible 96 in. for truck transportation, but less than the 120 in. permitted for tracked vehicles.¹¹ The width will be satisfactory for rail transportation both within the U. S. and overseas. Whether the higher-powered MCR can be designed within the height requirements for overseas truck and rail transportation can be determined only through a design study.

The major component in increased reactor weight for increased power is the increase in core size (and hence weight). This causes a corresponding outward movement of the shielding. Because the shielding weight is proportional to the cube of the mean radius, any increase in the core size causes a rapid increase in the shielding weight. However, if the 12.5-in.-diameter and 12.5-in.-high core of the MCR could be operated at 23.7 Mwt, the required additional shielding would cause an increase of only about 11,200 lb. The 23.7-Mwt reactor and shielding module would then weigh about 71,500 lb and the basic shielding sphere would be only about 105.3 in. in diameter. If the development of liquid-metal--cooled reactors includes an increase in permissible power densities similar to that of the water-cooled reactors, a significant increase in the thermal power of mobile reactors will be possible.

5.1.1.2.4 Providing Electrical Power to the Fuel Manufacturing Plant. If a nuclear reactor is to serve as an energy source for the MED, it must furnish energy in the form required by the fuel manufacturing plant. In nearly all the energy systems studied, a major part of the energy is consumed in an electrolytic cell. This requires low-voltage, high-amperage direct current. Additional power is required to operate pumps, compressors, and other fuel-handling equipment. This power could be either alternating or direct current; alternating current is generally preferred. For example, the electrical power requirement for an energy depot capable of supporting a unit of 22 tanks using the hydrogen-air (oxygen) fuel cell system is:

<u>power, Mwe</u>	<u>use</u>	<u>preferred form</u>
3.49	electrolytic cells and water purification	low-voltage direct current
2.025	liquefaction plant	high-voltage 400-cps alternating current
total power 5.51		

The 400-cps alternating current is preferred for the liquefaction plant, to take advantage of the small, light motors of this frequency developed for other military applications.

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It is desirable in both the MCR and the ML-1 Army mobile reactors to use an exclusion area around the reactor, to reduce the weight of shielding required to protect operating personnel.^{4, 18} The exclusion radius for the MCR is 450 ft, and the power unit is designed to be operated from this distance. From an operational standpoint, however, it is necessary to have access to the fuel manufacturing plant. The handling of the fuel and the operation and maintenance of the electrolytic cells and liquefaction equipment are all much simpler when direct access to the fuel manufacturing plant is permitted. The separation of the reactor power plant and the fuel manufacturing plant is also desirable from the standpoints of concealment and damage control. For these reasons, the two portions of the MED are designed to be separated by the minimum exclusion radius of the reactor.

Because two types of power are required, the generation of power by two machines rated in the proper ratio was considered. The low-voltage direct current would be produced by a unipole generator, and the 400-cps alternating current would be produced by a high-speed alternator.

A unipole generator provides low-voltage (less than 100 v) direct current at a specific weight of approximately 4 lb/kw. The rotor speeds of this machine are considerably lower than those of a 400-cps alternator. Consequently, either two separate power turbines must be used or a gear box provided.

This system requires the transmission of low-voltage, and consequently high-amperage, power for at least the exclusion radius of the reactor. Table 6 gives the weight of copper or aluminum bus bars required to carry this current for three power-reactor sizes. The 23.7-Mwt reactor would furnish adequate power to operate a fuel depot supporting the assumed tank unit. The weights of the bus bars show clearly that the transmission of the low-voltage direct current consumed by the electrolytic cells over the 450-ft exclusion radius is impractical.

TABLE 6
WEIGHT OF BUS BARS CONNECTING GENERATOR AND ELECTROLYTIC CELLS

reactor	power, * Mw	estimated weight, lb**	
		copper***	aluminum****
14-Mwt MCR, simple cycle	1.57	30,500	26,300
14-Mwt MCR, regenerative cycle	2.07	40,200	34,600
23.7-Mwt MCR, regenerative cycle	3.49	67,600	58,300

*At 100 v d-c.

**Length: 500 ft.

***At 1000 amp/in.².

****At 350 amp/in.².

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By comparison, the weights of the electrical cables required to carry all the power produced by the above three reactors at 4160-v, 400-cps current are only about 4800, 6400, and 10,700 lb, respectively. On the basis of these figures, it was concluded that the generators must produce alternating current at a reasonably high voltage. Two frequencies of current were considered. Figure 12 shows the specific weights of 400-cps generators vs. their rotating speeds. In general, the specific weight of these machines is extremely sensitive to speed; i.e., if other factors are equal, the higher-speed machines are much lighter than the slower machines. Allis-Chalmers estimated that a 12,000-rpm 4-pole generator might be developed with a specific weight of about 2 lb/kw. The minimum voltage for this machine would be about 4000 v. A specific weight of 3 lb/kw has consequently been selected as a reasonable basis for estimating weights of these generators throughout this report. (In the power ranges required 400-cps generators are not standard items. The only 400-cps generators built to date have capacities much lower than required. Although the development of the required sizes involves primarily an extension of known techniques, a design and test program must be carried out before these units can be accepted as components of the MED.)

Figure 13 shows the specific weights of 60-cps generators. These are much heavier than the high-speed 400-cps generators. Conventional units can be expected to weigh approximately 9 lb/kw. Allis-Chalmers has recently studied a design for a light-weight 6000-kw generator with a total weight of 24,000 lb. This involved aluminum parts and high-temperature windings, and the resulting 4 lb/kw is considered the minimum for this type of machine. A specific weight of 6 lb/kw has consequently been selected as a reasonable basis for estimating the weights of 60-cps generators throughout this report.

Approximately 63 per cent of the electrical energy produced by the nuclear power plant must be converted to low-voltage direct current for use by the electrolytic cells. The voltage required depends on the number of electrolytic cells in series. A voltage of 100 to 300 v is desirable. Figure 14 shows the weight of the transformers needed to convert 4160 v a-c to 100 and 300 v for both 60-cps and 400-cps power. Each 400-cps transformer weighs approximately 60 per cent as much as the corresponding 60-cps transformer. Thus, it is also desirable from the standpoint of transformer weight to use 400-cps current. Figure 15 shows the weight of the silicon rectifiers necessary to convert alternating to direct current. The weight of these rectifiers is controlled primarily by current; consequently the 300-v rectifiers weigh only about one third as much as the 100-v rectifiers. Thus, the 300-v system requires both a lighter transformer and a lighter rectifier than the 100-v system.

Table 7 compares the combined weight of the generator, transformer, rectifier, and cable for the two voltages, the two frequencies, and the three reactor combinations. This table clearly shows that the 300-v, 400-cps system is the lightest for all three reactor combinations. This system is therefore recommended for use with the MED.

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FIG. 12. SPECIFIC WEIGHT OF 400-cps GENERATORS

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FIG. 13.

SPECIFIC WEIGHT OF 60-cps GENERATORS

POWER, Mw

+ Data from NDA-2143-5
Vol. 1, Table 5.17
o A-C Study

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FIG. 14. APPROXIMATE WEIGHT OF RECTIFIER TRANSFORMERS (input: 4160 v)

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FIG. 15. APPROXIMATE WEIGHT OF SILICON RECTIFIERS

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TABLE 7

WEIGHTS OF 400-cps AND 60-cps ELECTRICAL SYSTEMS

		estimated weight of equipment, lb			
		300-v output		100-v output	
		400 cps	60 cps	400 cps	60 cps
14-Mwe MCR, simple cycle					
generator	2.62	7,900	15,700	7,900	15,700
cable	2.62	4,800	3,900	4,800	3,900
transformer	1.57	9,000	14,800	13,300	22,400
rectifier	1.57	5,200	5,200	15,500	15,500
total		26,900	39,600	41,500	57,500
14-Mwt MCR, regenerative cycle					
generator	3.44	10,300	20,700	10,300	20,700
cable	3.44	6,400	5,200	6,400	5,200
transformer	2.07	10,400	17,100	15,400	25,800
rectifier	2.07	6,200	6,200	18,700	18,700
total		33,300	49,200	50,800	70,400
23.7-Mwt MCR, regenerative cycle					
generator	5.82	17,500	35,000	17,500	35,000
cable	5.82	10,700	8,700	10,700	8,700
transformer	3.49	14,300	23,700	21,300	35,500
rectifier	3.49	9,400	9,400	28,300	28,300
total		51,900	76,800	77,800	107,500

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5.1.2 Process Reactors

The direct production of fuel in a reactor is the most direct theoretical energy conversion system and therefore should offer a high total system efficiency. Two processes are available to produce fuel directly: thermal dissociation of a chemical compound in an endothermic reaction, and radiolysis of a chemical compound by the kinetic energy of fission fragments. If either system is to be practical, the dissociated chemicals must recombine in a highly exothermic reaction within the utilization device and they must satisfy the many other physical requirements of a fuel. Hydrogen was recognized as a possible fuel at the beginning of the study. The problems associated with designing a reactor that could dissociate water either thermally or radiolytically were investigated; both reactors were found technically impractical.

The use of a nuclear reactor to produce high temperatures for the steam reforming of petroleum to form hydrogen appears both rewarding and technically practical. Basically, this system uses nuclear power to convert conventional fuels into more efficient fuels. It is shown in Sec. 6.2.2 that the use of a nuclear reactor for this purpose will significantly reduce POL requirements for existing vehicles. The use of a nuclear reactor for the reforming of petroleum will result in very great reductions in POL requirements if the vehicles are powered by fuel cells. The use of this combined process and power reactor for steam reforming of petroleum and for producing power for the liquefaction process therefore appears to have an important future in the MED concept.

5.1.2.1 Thermal Dissociation of H₂O. As the study progressed it became increasingly evident that hydrogen was one of the more promising fuels. For this reason, the thermal dissociation of water was investigated as a means of obtaining hydrogen with a minimum of input energy.

Water, or steam, is formed by either of two chemical reactions:²⁰

Both reactions are reversible. The energies of the reactions are given for absolute zero. If the reactions move to the right, steam is formed in an exothermic reaction. If they move to the left, steam is dissociated into hydrogen, oxygen, and hydroxyl ions in endothermic reactions. The state of a stoichiometric mixture of hydrogen and oxygen may be determined for a given temperature from the equilibrium constant, K_p , for each reaction. The equilibrium constant is defined as:

$$K_p = \frac{(P_{\text{H}_2\text{O}})}{(P_{\text{H}_2})(P_{\text{O}_2})^{1/2}} \quad (3)$$

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for reaction (1) and

$$K_p = \frac{(P_{H_2O})}{(P_{OH})(P_{H_2})^{1/2}} \quad (4)$$

for reaction (2). The partial pressures, P_{H_2O} , P_{H_2} , P_{O_2} , etc., are expressed in atmospheres.

In equations (3) and (4), a high K_p would indicate that the mixture is predominantly steam, and a low K_p that the mixture has largely dissociated. Figure 16²⁰ shows the value of $\log_{10} K_p$ vs. $1/T$ for the two chemical equations. It is evident from these curves that very high temperatures are required to achieve a low K_p . For example, a temperature of about 4300 F is required for $K_p = 100$, or $\log_{10} K_p = 2$. Therefore, even at this temperature, only a small fraction of the hydrogen would exist as free molecules. A temperature of about 7000 F is required before $K_p = 1$, or $\log_{10} K_p = 0$. It is apparent that temperatures greater than 5000 F are required if there is to be any useful percentage of free hydrogen.

One of the principal limitations on the operating temperature of the nuclear reactor is the melting temperature of the fuel. The temperature of the coolant (in this case steam) must be considerably lower than the maximum fuel temperature, for the satisfactory transfer of heat from fuel to coolant. Table 8 lists the melting temperatures of various reactor fuel materials. Only three have melting temperatures of 5000 F or higher; urania (UO_2) melts at 5000 F, and the two thorium-uranium (ThO_2-UO_2) mixtures melt at 5880 F. All three have poor heat transfer coefficients. Consequently, it is impossible to design reasonable fuel assemblies that will permit attainment of the required coolant temperatures. The thermal dissociation of water using a nuclear reactor as a heat source therefore does not appear practical.

5.1.2.2 Radiolysis of H_2O . Radiolysis is, in theory, a means of separating water into hydrogen and oxygen. This direct separation by the energy source would obviate the large amount of electrical equipment associated with electrolysis. However, if this process is to be practical, a significant portion of the energy released in the fission reaction must be used for radiolysis. This is possible only if the reaction uses the kinetic energy of the fission fragments for the dissociation. This represents about 84 per cent of the energy released.²² For these fission fragments to dissipate their energy in the water, the uranium fuel must be in solution, in the form of very small particles, or in the form of thin ribbons. The optimum reactor designed for this radiolysis should therefore be similar to an aqueous homogeneous reactor.

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FIG. 16.

THERMAL DISSOCIATION OF WATER.

Ref: "Combustion, Flames and Explosions of Gases," B. Lewis and G. von Elbe, Academic Press, Inc., 1951.

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TABLE 8
MELTING TEMPERATURES OF REACTOR FUELS²¹

<u>fuel material</u>	<u>melting temperature, °F</u>
unalloyed uranium:	
U	2070
alpha-uranium alloys:	
U-2 Zr	2060
U-1.5 Mo	2066
gamma-uranium alloys:	
U-10 Mo	2280
dilute uranium alloys:	
Zr-7 U	3250
Zr-22 U	3100
Al-16 U	1185
Al-25 U	1185
Al-35 U	1166
thorium alloys:	
Th-5 U	2000
Th-10 U	2000
Th-10 U - 1.5 Mo	~2000
Th-10 U - 0.1 Be	~2000
plutonium alloys:	
Al-2 Pu	1202
Al-10 Pu	1202
metallic dispersions:	
SS-25 UO ₂	2550 to 2600
SS-30 UO ₂	2550 to 2600
SS-28 UN	2550 to 2600
compounds:	
UO ₂	5000
UC	4440
U ₂ C ₃	3180
UC ₂	4580
PuC	3000
ThO ₂ - 6.5 UO ₂	5880
ThO ₂ - 10 UO ₂	5880
PuO ₂	2240 to 2280

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The yields expected from this reactor and the efficiency of this method of energy conversion are discussed elsewhere. From the standpoint of reactor design, this system is not promising for the MED for two reasons: (1) the core and highly radioactive gas-separation loop will be large and correspondingly difficult to shield; and (2) the methods of rapidly evolving large quantities of hydrogen-oxygen and decontaminating it sufficiently to permit safe handling as a fuel are uncertain.

The homogeneous reactors are reported to have been run at power densities of 25 to 35 kw/liter. Higher powers are deemed possible but have never been attempted. However, autoclave tests were made at powers up to 100 kw/liter. The greatest difficulty encountered was in cooling the core vessel walls to prevent hot spots from burning holes through the metal. Good circulation of the core solution is imperative. Because the liquid-metal--cooled core of the MCR has an average power density of about 557 kw/liter,⁴ it is apparent that, unless radiolysis is much more efficient than electrolysis, the core for the aqueous homogeneous reactor will be very large. The core solution will also have to be cooled, either by passing it through a heat exchanger, which must also be shielded, or by placing cooling coils within the core tank, which will tend to make the core larger. The separation of the large quantity of hydrogen-oxygen mixture required as fuel for the MED will require circulation of the core solution through a gas separator, which must also be shielded. The gases removed will contain radioactive fission gases, and must therefore be further decontaminated within shielding. For these reasons, the shielding required by this type of process reactor precludes its use in any mobile application.

The separation from the core solution of the large quantities of hydrogen and oxygen produced and their subsequent decontamination are major problems. Decontamination during hydrogen liquefaction may be possible. However, very high orders of decontamination are required, and liquefaction may be unsuitable owing to the partial pressures of the gases and the low quantities of krypton and xenon permissible in the product fuel. Certainly, this activity will complicate the liquefaction process.

In view of the above problems, using a reactor for radiolysis of water as the means of producing fuel for the MED is not considered practical. The problems of making this reactor mobile appear insurmountable.

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5.1.3 Direct Conversion

5.1.3.1 Thermoelectric Conversion. The performance of any thermoelectric conversion device depends upon three properties of the materials making up the device: (1) the Seebeck coefficient, which is a measure of the voltage developed for a given temperature difference between the hot and cold junctions; (2) the thermal conductivity, which determines how easily heat flows from the hot to the cold junction, thus reducing the temperature difference and the voltage produced; and (3) the electrical conductivity of the junction materials, which determines the internal resistance losses to the device itself.²³

These properties are combined into a "figure of merit" for each of the conductors making up the thermoelectric conversion device as follows:

$$Z = \frac{S^2}{\rho \cdot K}$$

where

Z = figure of merit

S = Seebeck coefficient

ρ = electrical resistivity

K = thermal conductivity

The higher the value of Z, the better is the material for thermoelectric use. It can be shown that the efficiency of the thermoelectric conversion device is a function of this value of Z and of the well known Carnot efficiency. As Z increases, the device approaches the Carnot efficiency. It is therefore desirable to use materials with high values of S and relatively low values of ρ and K.

An investigation of the properties of materials leads to the use of semiconductors to obtain the desired characteristics. Some semiconductor materials have Seebeck coefficients up to 1000 $\mu\text{V}/^\circ\text{K}$, compared with metals used in conventional thermocouples, which have coefficients up to 80 $\mu\text{V}/^\circ\text{K}$. Semiconductors are also generally poor conductors of heat, especially when compared with these metals. Unfortunately, most semiconductors have a high resistivity to electrical current, which has led to the "doping" of semiconductor materials for thermoelectric applications.²⁴

Although the figure of merit, Z, is the major parameter determining efficiency of operation, several auxiliary properties of the materials used determine the limitations of the device in a practical design. These properties include the material melting point, vapor pressure, coefficient of thermal expansion, carrier concentration, carrier mobility, location of energy gap (intrinsic or extrinsic material), mechanical strength, and insensitivity to radiation.

A combination of effects dictates the use of many thermocouples in a practical device. The output of each device may be only about 0.2 v and therefore many units must be employed in series to obtain useful voltages. A second factor is thermocouple length. It can be shown that there is a maximum length if maximum power density is to be obtained, because the power density decreases with the square of the device length.

In a megawatt-range generator (e.g., a nuclear reactor), very many thermocouples are required to attain reasonable power densities and usable output voltages. This considerably complicates the generator design owing to the large number of insulators and electrical leads required.

Most devices built to date are of low power, the largest single reported generator produces 2.5 kw.

Westinghouse has constructed a 5-kw generator²⁵ composed of two 2.5-kw modules in parallel. Each module consists of 25 groups of 85 thermocouples each and generates an output voltage of 220 v d-c. Each module has an efficiency of 4.5 per cent (6 per cent thermocouple efficiency), with an over-all generator efficiency of 2.25 per cent. The generator has a weight-to-power ratio of 500 lb/kw; the weight includes the thermocouples, burner and heat-transfer structure, but not the fuel.

The Westinghouse TAP-100²⁵ generator built for the Air Force weighs 47 lb, and has delivered 102.5 w at an efficiency of 3.7 per cent with a weight-to-power of 460 lb/kw.

Another Westinghouse device²⁵ delivers 500 w at 28 v d-c and weighs 35 lb, for a 70-lb/kw ratio.

RCA has developed a sandwich device²⁶ with an efficiency of 12 per cent.

The SNAP devices built by the Martin Company use thermoelectric elements manufactured either by Minnesota Mining and Manufacturing Company or by Martin, and a radioisotopic source of heat, and have very high weight-to-power ratios.

Table 9 summarizes the characteristics of these devices.

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TABLE 9
CHARACTERISTICS OF THERMOELECTRIC DEVICES

investigator	power, w	efficiency, %	weight/power ratio, lb/kw	operating temperatures, °C	
				hot junction	cold junction
Westinghouse	5000 (2x2500)	2.25 (over-all)	500	550	100
Westinghouse TAP-100	102.5	3.7 (over-all)	460	582	154
Westinghouse* . . .	500	-	70	-	-
RCA	-	12	-	550	20
Martin SNAP-327,28	5.3	5.5 (over-all)	1,000	593	204
Martin SNAP-3B24.	3.4	6.8 (over-all)	1,100	482	78
Martin SNAP-7A29	10	4.7 (over-all)	12,000 (with fuel)	482	10

*Under development September, 1960.

Considerable effort is being directed toward the development of new thermoelectric materials, with the ultimate goals of higher figures of merit, higher operating temperature, and lower costs.

The materials being investigated are too numerous to list here, but some typical ones^{23,26} are: the sesquisulfides of lanthanum, cerium, and praseodymium; the phthalocyanine class or organic semiconductors; liquid cuprous sulfide; chalcogenides; chalcopyrites; and bismuthides, selenides, arsenides, antimonides, oxides, and silicides of many elements.

Investigators in the field of thermoelectric materials²⁶ include: Westinghouse; General Electric; RCA; Chrysler Corporation; Merck, Sharp and Dohme; General Mills; General Atomics; General Ceramics; National Lead Company; Transition Electronic Corporation; Electro-Optical Systems; Bell Telephone Laboratories; Knolls Atomic Power Laboratory; Battelle Memorial Institute; Ohio State University Research Foundation; and Stanford Research Laboratory.

The present cost of thermoelectric materials is about \$200 to \$1500 per pound for high-purity crystalline forms. Current thermoelectric generators in volume would cost over

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\$1000/kw today. It is estimated that by 1970 the cost of materials could be reduced to \$25 per pound, and \$10 to \$15 per pound might be possible by 1975 if new, more abundant compounds are developed for thermoelectric use.

If, applied to the MED, the heat source for the thermoelectric converters would be a nuclear reactor for in-core use, considerable research-and-development effort would be required with respect to radiation damage, effective material bonding at the hot and cold junctions in a nuclear environment, and non uniform heat generation within the reactor. Preliminary tests by Westinghouse³⁰ and G.E.²⁶ indicate that radiation effects causing degradation of the semiconductor material may not be permanent and can be partially annealed out.

In-core applications may be desirable from the standpoint of utilization of low coolant temperature with the resulting elimination of high-pressure piping systems. In-core use also obviates large external heat exchangers. However, this reduction in weight of external components must be compared with the increase in the weight of shielding required around the reactor, whose size increases because of the introduction of thermoelectric elements within the reactor core. Before in-core use can be seriously considered, materials with higher operating temperatures and low neutron cross sections must be developed. The lead telluride thermocouples now widely used are limited to a maximum temperature of about 1000 F.

Nuclear thermoelectric systems with the thermoelectric devices outside the core have also been proposed.³¹ This removes the nuclear requirements from the materials used in the thermoelectric device and greatly simplifies the reactor design. These external thermoelectric-generator--heat exchanger combinations have to be large, if they are to provide the surface area necessary to accommodate the high number of thermoelectric couples required for power generation in the megawatt range.

It is estimated that by 1970 thermoelectric couples will be developed to operate between 1500 and 1800 C³² with a projected over-all efficiency of 20 per cent. Assuming that a decrease by a factor of 5 in weight-to-power ratio accompanies the increased efficiency, a ratio of, at best, 16 lb/kw could be attained.

The most serious limitation is the weight-to-power ratio, which is too high for a portable megawatt-range reactor system. For this reason, thermoelectric conversion does not appear to be practical for the application under study, unless it is incorporated as an efficiency-raising device, a bottoming device, to supplement a conventional turbine generator. A second possibility would be a design that would thermally cascade thermoelectric and thermionic devices. Here also, the high weight-to-power ratio will penalize the system. It is therefore concluded that thermoelectric conversion is not promising for any mobile power station where weight is important.

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5.1.3.2 Thermionic Conversion. Thermionic conversion devices use the emission of electrons from a hot surface to convert heat energy directly into usable electric power. When sufficient heat is applied to certain cathode materials, such as tungsten, electrons are emitted. These electrons can then be collected upon a cooler anode. The potential difference established between the electrodes may be used to supply a current to a power-consuming load.

The major effort to date in the development of thermionic converters has been concentrated on those filled with metallic vapor. Most of these devices have used cesium vapor in the interelectrode space to provide positive ions to reduce the negative space charge effects; it can be shown that each positive cesium ion will allow the passage of approximately 490 electrons.

Development of both low and high-pressure diodes is under way. The low-pressure diodes use dispenser cathodes, such as Philips Type B (tungsten impregnated with barium) or thoriated tungsten. This type of diode relies upon the condensation of cesium vapor on the anode surface to reduce its work function. The low-pressure diodes have interelectrode spacing of about 5 to 20 mils. Cesium pressures are about 0.001 to 0.01 mm Hg. The cesium vapor pressure is controlled by varying the temperature of a cesium reservoir.

The high-pressure converters use cesiated cathodes and fill pressures of about 0.001 to 0.01 mm Hg. The higher cesium pressure enhances the cathode work function, but increases the losses due to electron collision with the plasma and heat conduction across the plasma gap. High pressures also lead to degradation of the converter owing to increased cesium corrosion.

Most cesium diodes depend upon contact (resonance) ionization of the cesium at the emitter surface. Under certain conditions, volume ionization related to current flow has been observed to be much greater than contact ionization, thus significantly reducing the plasma resistivity and interelectrode spacing requirements. This effect has been called the "ball-of-fire", "arc," or "ultra-low-voltage arc" mode of operation, and appears quite promising for low-temperature converters. Devices have been fabricated with 100-mil interelectrode spaces.³³

Several investigators have developed converters using a ZrC:UC (an alloy of zirconium carbide and uranium carbide) cathode which would use the heat directly from uranium fission within a nuclear reactor to generate electricity. Los Alamos^{23,34} and General Atomics³⁵ have demonstrated the in-core use of this type of converter. The problems associated with a bare fissionable cathode are related mainly to fission-product contamination of the electrode surfaces, leading to changes in work functions and to fission-gas contamination of the cesium plasma.

Ushakov³⁶ has suggested that the required cesium vapor could be generated by the fission process because there is a large yield of cesium among the fission products.

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General Motors is investigating³³ a converter filled with inert gas and using a uranium-bearing cathode and a low-work-function anode. This device would use fission fragments to ionize the gas and reduce the space charge effect. This investigation has suggested that the high gamma-radiation intensity might also be employed as an effective ionizing agent.

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The efficiency of any of the converters mentioned in this section is determined by the ratio of electric power delivered to the load to the total heat input. The efficiency of a thermionic diode can be expressed as:

$$\eta = \frac{JV}{q_e + q_r + q_c + q_p + q_i}$$

where J = net current density, amp/cm²

V = load voltage, v

q_e = electron cooling of cathode, w/cm²

q_r = radiative cooling of cathode, w/cm²

q_c = conductive cooling of cathode through electrical leads, w/cm²

q_p = conductive cooling across plasma, w/cm²

q_i = heat losses in plasma, w/cm²

An examination of the various heat losses that affect efficiency leads to the following conclusions:

(1) Back emission of electrons from the anode should be minimized. Because the emission current density decreases approximately by a factor of 10 for each 200-K decrease in temperature, devices should be designed to operate with the greatest practical temperature difference between cathode and anode.

(2) The space charge effect should be minimized to reduce the required cathode and anode voltages, thereby permitting a lower heat input for a given power output.

(3) Radiation from the cathode should be reduced, possibly by internal radiation shields.

(4) The lengths of leads for electrical connections and cathode supports should be optimized to obtain minimum conductive heat transfer.

(5) Plasma density should be optimized to obtain maximum cancellation of the space charge while maintaining low thermal conductive and ohmic heat losses.

The major problems associated with plasma diodes are as follows:

(1) Cesium is highly corrosive at high temperatures and moderate pressures and thus severely limits converter life. Materials capable of long life in such an environment will have to be developed.

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(2) The evaporation rates of cathode materials must be reduced if long life is to be obtained.

(3) The effects of intense radiation upon insulators and electrode materials must be investigated if nuclear applications are considered.

(4) The long-life behavior of converter materials at high temperatures must be investigated further.

(5) The effects of the internal magnetic field generated at high current densities must be reduced further if high efficiencies are to be obtained.

(6) Anode work functions should be reduced. This will require extensive investigation of new materials.

(7) Devices must be developed to operate at lower temperatures while producing power at a high rate.

(8) A method of generating a-c power directly and efficiently must be found if central station use is to be considered.

In spite of the present problems, thermionic converters appear very promising. In the few years since the initial steps were taken to develop thermionic conversion devices, great progress has been made in the understanding of the various modes of operation.

The principal investigators include: Aerojet General Nucleonics; American Telephone and Telegraph; Atomics International; Babcock & Wilcox; Bendix; Boeing; Electro-Optical Systems; Ford Instrument Co.; General Atomics; General Electric; General Motors; Hughes; Marquardt; Martin; RCA; Republic Aviation; Thermo Electron; Thiokol; Westinghouse; Argonne National Laboratory; Brookhaven National Laboratory; Los Alamos Scientific Laboratory; Knolls Atomic Power Laboratory; Massachusetts Institute of Technology; Battelle Memorial Institute; and the National Aeronautics and Space Administration.

Table 10 lists materials typical of those being investigated.

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TABLE 10

MATERIALS UNDER INVESTIGATION FOR USE IN THERMIONIC DEVICES

<u>cathodes</u>	<u>anodes</u>	<u>insulators</u>
tungsten	nickel with barium	aluminum oxide
thoriated tungsten	silver oxide	zirconium oxide
Philips Type B tungsten	oxygenated tungsten	beryllium oxide
molybdenum	stainless steel	sapphire
cesiated refractory metals	copper	
zirconium-uranium carbide	molybdenum	
thorium carbide	tantalum	
tantalum	columbium	
rhodium		
metallic borides		

Table II summarizes the characteristics of several experimental thermionic converters.

TABLE 11

CHARACTERISTICS OF EXPERIMENTAL THERMIONIC DEVICES

<u>investigator</u>	<u>total power, w</u>	<u>power density, w/cm²</u>	<u>efficiency, %</u>	<u>weight/power ratio, lb/kw</u>	<u>cathode temperature, °C</u>
Hatsopoulos ³⁷	3.2	-	5	25	-
Los Alamos ^{34, 38}	30	20	10	-	2000
RCA-Thiokol ^{32, 39}	270	-	8	12.5	2200
General Atomic ⁴⁰	90	21	10	-	1925
RCA	-	> 2	11	7	1350
RCA	-	3.5*	13	1	1400
RCA	-	5.5*	17	-	1500
RCA	-	12.5*	23	-	1650
Thermo Electron ²³	200	-	13	50 (over-all)	-
Thermo Electron ²³	-	12	15	-	-
General Electric ²³	-	7.5	15	-	-
Ford Instrument ³³	-	5	15	-	1200
Atomics International ⁴¹	-	8	16	-	1650
Atomics International ⁴¹	-	13*	20.5*	-	1700
Atomics International ⁴¹	-	17*	21*	-	1800
SNAP-IIIc(TECO)	3.5	-	5.9	-	1125

*Extrapolated

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In the MED, thermionic converters would be employed with a nuclear reactor as a source of heat. Both the in-core and out-of-core uses of thermionic converters appear promising.

The converters considered for in-core use would be cesium diodes constructed for assembly with the fuel either as a sandwich plate or as coaxial tubes. The use of fuel such as ZrC: UC as the converter cathode appears to be impractical from the standpoint of testing before assembly with fuel. A second serious limitation with an unclad fuel cathode is the detrimental effect of the fission products that are released into and contaminate the cesium plasma.

The thermionic converter is particularly suited to in-core use because the high temperature of the fuel can be used directly with a consequently lower reactor coolant temperature. The lower coolant temperature allows the use of a lighter, lower-pressure system.

The principal disadvantage of in-core use lies in the additional complexity of the fuel elements and core structure, which creates formidable fabrication problems. In addition, the output of a serial array of converters is limited by the device operating at the lowest cathode temperature. This limitation poses the serious problem of providing extremely flat neutron flux and temperature distributions within the core.

The detrimental effects of the intense radiation within the core on converter life require considerable investigation. Much research-and-development effort in the field of high-temperature, low-neutron--cross-section materials is required.

The increase in size of a reactor using in-core devices and the consequent weight increase due to shielding requirements might be great enough to eliminate this method of power generation in a mobile nuclear plant, particularly for the presently attainable power densities.

The alternative method, using an out-of-core heat exchanger with integral tubular thermionic converters, increases the required system temperature and the pressure rating, thus increasing the weight. The heat exchangers must also be large to provide the required surface area for the large number of converters necessary for large-scale power generation.

Thermionic conversion is suited to the MED in that there are no moving parts, and therefore only minimum maintenance and no noise. Although the present weight-to-power ratios of such devices are about 10 to 50 lb/kw, it has been estimated that, in five to eight years, ratios of about 1 lb/kw, an efficiency of 25 per cent or greater, and reasonably low operating temperatures will be attained.

Converter lifetimes of 5000 to 10,000 hr are presently attainable and an increase is to be expected as new devices are developed. It is estimated that large-scale production will cost about \$2/w by 1967, and \$0.50/w is foreseeable.

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It must be recognized that thermionic conversion devices have not been assembled into the series and parallel arrangements necessary for producing power in the megawatt range. Although development is moving very rapidly, thermionic converters are still only laboratory devices. Until units of significant power output are built and operated for prolonged periods, it will be difficult to appraise the application of thermionics to the MED; they cannot yet be considered for such an application.

5.1.3.3 Magnetohydrodynamic (MHD) Systems. Magnetohydrodynamics is the study of the motion of an electrically conducting fluid in the presence of a magnetic field. Its application to power generation is expected to permit the use of a much higher temperature than can be employed in steam-turbine generating systems with the best materials known today or envisioned for the foreseeable future.

In the MHD generator, a stream of partly ionized gas is arranged to flow at high velocity between the poles of a magnet, so that an electromotive force is generated at right angles to the direction of fluid flow and to the direction of the magnetic field. Collecting electrodes suitably placed at opposite sides of the fluid stream are connected to conductors, which transmit the electric current to an external circuit.

The basic advantage of MHD systems is that electric power is generated in an upper range of cycle temperatures starting at approximately 5000 F. Engineering studies of complete power systems have indicated that the thermal efficiency of large stationary power units may be improved by approximately 30 per cent over the efficiencies of present conventional steam plants burning fossil fuels.

Combustion at 5000 F and above has been effectively accomplished in short-life-cycle laboratory facilities. The development has not yet progressed to the stage where reliable service at these temperatures can be expected over long periods.

Combustion must take place at a pressure of at least 100 psi in order to provide potential energy whereby the necessary gas velocity will be established in the generating channel. The high initial pressure adds to the design problems of the combustion system.

The oxidizing air must be compressed to combustion pressure and then preheated to approximately 3800 F, which requires an advanced heat-exchanger development that has not yet been demonstrated to be acceptably reliable.

A good method of air preheat for large stationary units has been proposed, but the system presently envisioned would be far too bulky for light mobile plants or the MED. The essential preheat component will require extensive research and development.

An alternate method for securing high combustion temperature would use air substantially enriched in oxygen. This would introduce cycle complications and problems related to oxygen supply in the MED.

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Appendix G, "Feasibility Study of 300 Mwe - MHD Power Plant," by R. C. Allen illustrates the application of MHD to large power systems. This paper indicates the nature of the complex system necessary to achieve the high efficiency possible with the MHD cycle. It is not envisioned that systems requiring the many components illustrated would be practical in a mobile plant or MED, in which components must be easily and quickly transportable.

The MHD generator will have a cycle-fluid discharge temperature of about 3500 to 4100 F, at which point the ionization will have dropped to a level that reduces the conductivity to such a low value that MHD cannot be further employed.

The regenerative heating of the heat-transfer medium for preheating the high-pressure combustion air will reduce the exhaust gas temperature to approximately 1700 F. High thermal efficiency cannot be achieved unless the heat energy in this exhaust gas from the MHD regenerator can be effectively used in a second-phase energy conversion cycle.

It is therefore necessary to employ an elastic fluid power unit, preferably a steam turbine, to drop the exhaust gas temperature to the normal heat rejection level of conventional cycles. This second power cycle is a further disadvantage for application in a mobile power unit or MED.

Allis-Chalmers has conducted substantial laboratory research on MHD generators with respect to the following:

- (1) the conductivity of various combustion gases;
- (2) the effects of small amounts of alkali metals introduced as seed material to increase conductivity;
- (3) electrode design, internal cooling, etc.;
- (4) the Hall effect in multiple-electrode systems;
- (5) methods of computing thermodynamic properties, which take into account all major chemical elements in the fuel and oxidizer, the effect of seed material, and the inclusion of appropriate corrections for the dissociation of compounds in the gaseous mixture; and
- (6) the development of metal alloys and refractories for the high-temperature channel.

MHD is presently believed to promise very significant efficiency increases in large-scale plants for the generation of electric power. Allis-Chalmers forecasts that it will

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be at least ten years before there is an authoritative evaluation of the merits of this cycle with respect to power generation costs.

The system does not yet appear to have merit with respect to application in military vehicles for propulsion or for a small MED.

Some applications, however, may be of great interest, such as the arrangement of the MHD generating element in the discharge stream of a rocket engine. High electrical outputs can be generated during the burning time of the rocket propellant. Although this application is outside the immediate intent of the present MED study, future requirements of the MED may indicate the desirability of a study of this specific application.

It is not presently recommended that the MHD concept be proposed as an alternate source of basic power for the MED.

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5.2 FUSION

The mean binding energy per nuclear particle is less for the lighter and heavier elements than for the elements of intermediate weight. It is therefore theoretically possible to release nuclear energy by the fission of the heavier elements or by the fusion of the lighter elements. The fission process is well established as a source of useful power, and is proposed as the energy source for the MED. The release of useful amounts of power from fusion has not yet been demonstrated, so this discussion is presented merely in the interest of completeness.

The fusion process, like the fission process, is of interest because potentially it is the source of tremendous amounts of energy from a small amount of fuel. The fuel will be the heavier isotopes of hydrogen: deuterium and tritium. A gram of deuterium could yield up to about 8×10^{10} calories.⁴² If 1 g of deuterium could be separated from 8 gal of water, 1 gal of water would produce energy equivalent to that of over 300 gal of gasoline. If the fuel is supplied to the fusion device as deuterium and tritium, then the logistic supply problem becomes insignificant in comparison with its equivalent POL requirements, i.e., 1 g of deuterium vs. 300 gal of gasoline.

For a further discussion of the fusion process, see Appendix F.

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5.2.1 Status of Fusion Devices

For the present, thermonuclear reactions do not represent an available energy source. All present experimental machines consume much more energy than they produce in any thermonuclear reaction. For a pulsed reactor to produce more energy than is supplied, the product of the particle density and the containment time must exceed 10^{14} atoms-sec/cm³ for the deuterium-tritium reaction; at the same time the mean ion energy must be greater than about 5 kev (about 100 kev in magnetic-mirror systems). Performance improvements by a factor of 10^3 to 10^4 are necessary in existing experimental devices.

The recent International Atomic Energy Agency plasma-physics conference, held at Salzburg, Austria, September 4-9, 1961, brought forth no new ideas for confining hot plasmas. However, the results of much experimental and theoretical work were reported. It is now universally recognized that the stability of the plasma in a magnetic field is the key question to be answered and the emphasis of experimental work has consequently shifted more and more in the last few years to those configurations which in theory appear to be most stable.

5.2.1.1 Magnetic-Mirror Machines. The magnetic-mirror machines have recently been the subject of great interest as a result of developments with cryogenic coils and the apparent feasibility of making superconducting coils that will supply strong d-c magnetic fields with small power expenditures. If the flute instability (instability that is parallel to the magnetic-field lines) can be eliminated, the magnetic-mirror machine may be the first power producing reactor. Flute instability is still a problem, both theoretically and actually. Nevertheless, experiments in both the U.S. and Russia have shown that this machine is more stable than theory indicates.

5.2.1.2 Cusped-Geometry Machines. Originally, cusped-geometry machines were not considered promising because of the large particle losses inherent with the cusps. However, the cusped-geometry machines have received renewed interest lately because other machines have failed to solve the problem of plasma instability. The large losses through the cusps may be acceptable if these machines can eliminate plasma instability. Experiments are now necessary to confirm the theoretical stability of the cusped-geometry machines and measure the particle loss rate through the cusps.

5.2.1.3 Pinch Machines. The major difficulty with the pinch machine is its plasma instability. Theoretically, this instability could be avoided by the hard-core pinch machines, but experiments have shown that even these machines are unstable.

5.2.1.4 Stellarator. The most advanced stellarator is the Model C Stellarator at Princeton, which started operating in the summer of 1961. So far it has been operated only with ohmic heating and without the additional helical windings theoretically necessary for hydromagnetic stability. Eventually, both magnetic pumping and ion cyclotron resonance will be tried to raise the plasma temperature. It is still too early to assess the role that the C Stellarator will play in the development of useful fusion power.⁴³

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5.2.2 Harnessing Thermonuclear Energy

5.2.2.1 Form of Energy Produced. In order to evaluate the approaches to the harnessing of thermonuclear energy, it is necessary to indicate the energy carried off by each particle during a fusion reaction. The equations for the reactions may be written as follows:

As can be seen, a large part of the energy released, especially from the most favorable deuterium-tritium reaction, will be carried off by the neutrons or uncharged particles. In all the forms of controlled thermonuclear reactors presently envisioned, the neutrons will escape from the reacting system and deposit their energy elsewhere. They do this because they are not influenced by the magnetic containment fields. Conversely, these neutrons cannot be used to generate electricity directly. Only the energy of the charged particles may be retained in the system and used to sustain the thermonuclear reaction.

5.2.2.2 Proposed Methods. Until a controlled thermonuclear reaction can be made to produce more energy than is consumed by the machine in establishing the conditions leading to the reaction, there can be no real demonstration of the methods proposed for harnessing this energy. Nevertheless, several devices are known in theory to convert this energy into a usable form.

If a reactor is operated in pulses, direct conversion of part of the thermonuclear energy into electrical power is theoretically feasible. In this machine, a quantity of fuel is injected into the reaction chamber, where it is compressed and heated rapidly to permit the thermonuclear reaction to take place. The expansion of the charged particles produced by the reaction in a magnetic field then produces electrical energy. In this type

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of machine, it is desirable to use primarily deuterium as the fuel to release a more favorable percentage of energy to the charged particles.

The energy of the neutrons may also be converted to heat energy by surrounding the thermonuclear reaction chamber with a material that will slow down these high-energy particles. This may manifest itself in direct heating of the surrounding media or capture of the neutron with subsequent release of gamma or beta energy. These last forms of energy may also be absorbed in the media to appear finally as heat energy. It is obvious, however, that, if direct absorption of neutrons is the method of conversion, the surrounding media must be quite thick. Otherwise, so many of the neutrons and gamma photons will escape that the efficiency of the system will be poor.

The neutrons may be used to convert the large supplies of uranium-238 and thorium-232 into the fissionable isotopes plutonium-239 and uranium-233. In this case, the thermonuclear reactor would replace the breeder reactor as a means of supplying fission reactors with a plentiful source of fuel. The thermonuclear reactor thus might generate limited amounts of power, but its prime function would be the production of fissionable material.

A further application of the neutrons thus produced is to capture the slow neutrons in lithium-6, thus producing tritium for addition to the deuterium to be used as the thermonuclear fuel. This deuterium-tritium fuel will permit operation of the thermonuclear device at a lower temperature than the deuterium-deuterium fuel. On the other hand, the deuterium-tritium fuel also releases a greater proportion of the total thermonuclear energy as neutrons. Whether the final system is more efficient than a reactor based on the deuterium-deuterium reaction will depend to a great extent on the design of the thermonuclear system. Several forms of lithium have been proposed as the blanket material. One of the earliest was molten lithium. This proved to be impractical because it introduces a severe corrosion problem, and because prohibitively large energy is required for pumping a molten conductor perpendicular to a strong magnetic field. The lithium-fluoride--beryllium-fluoride ($\text{LiF}-\text{BeF}_2$) system has been studied, but the high melting point of lithium-fluoride is a major disadvantage. Lithium compounds containing hydrogen may cause significant problems in the separation of tritium produced from the hydrogen carried by the compound. Among the compounds holding promise for this application, the nitrate and nitrite of lithium have many desirable characteristics. Their melting temperatures are reasonable, their absorption cross sections are acceptable, and they are thermally stable up to the desired operating temperatures.⁴⁴

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5.2.3 Application to the MED

It has been shown that no thermonuclear experiments have been able to create and sustain the proper conditions for a useful thermonuclear reaction to take place. The instability of the plasma in the confining magnetic field has proved to be a most difficult problem. This and the maintenance of a very pure plasma, to prevent radiation losses, appear to be the two major barriers to the development of thermonuclear reactors. It is difficult to predict when satisfactory solutions will be found to these problems. One can only estimate on the basis of recent efforts and their results. The problems of stability and plasma purity have been reasonably well defined since the Second Geneva Conference in 1958. These problems, especially the stability problem, have received prime attention over the last three and one half years and, although significant progress has been made, there is still much to do. Furthermore, it is becoming evident that large machines may be required to achieve the necessary plasma temperatures and confinement times. If large machines are required, the longer lead time and larger capital investment will reduce the number of experiments performed over any given period. A possible alternative to the use of large machines lies in the application of superconductivity to the field coils. If cryogenic superconducting coils are developed, they could make possible the very-high-density magnetic fields required to operate the smaller machines. However, these superconducting coils also require time for development. For these reasons, it is predicted that at least five years will pass before even isolated laboratory machines achieve a net energy output in a thermonuclear reaction. It is not unreasonable to expect that 20 years or more may be required to achieve any significant output in a thermonuclear reaction. This, of course, is a pessimistic estimate.

Concerning the development of useful thermonuclear power plants, one must make some guesses based on experience. The first self-sustaining fission chain reaction was achieved in December, 1942. In 1955, the USS Nautilus became operable. Thus 13 years were required to achieve a useful military power plant. It may be argued that there was a considerable period during the 13 years when no real effort was made toward the harnessing of controlled fission energy, and therefore the cases are not comparable. On the other hand, the conversion of heat energy to electrical energy was a proven system long before the fission reactor was developed. The conversion of fusion energy into electrical energy has no such proven power conversion path. The temperatures and other requirements make the conventional system impossible, and preclude final development except with the actual machines. Therefore, it is estimated that useful thermonuclear power plants will not be achieved until at least 10 years after laboratory machines have established the best approaches to the problem. Because this may require more than 10 years, the advent of thermonuclear power is not close.

If the most optimistic estimates for achievement of a net energy reaction, the development of a thermonuclear device, and the development of the energy conversion system are considered, the earliest possible useful military prototype is at least 20 years away,

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and 30 years is a more reasonable estimate. If the fusion program encounters new and unforeseeable difficulties, the development of thermonuclear power plants may easily be delayed until after the year 2000. Because this time schedule is incompatible with the development of the MED, fusion cannot be considered as a reasonable power source for this application.

If it is found that only large machines can create and sustain the conditions necessary for a thermonuclear reaction, fusion energy will become even less applicable to the MED. One method of converting the thermonuclear energy into useful energy is to use this machine as a breeder or fission-fuel producer. If this is seen to be the best approach to the harnessing of fusion energy, fusion reactors will probably be big central stations that make fuel for the many fission reactors supplying power. Under these conditions, the power source for the MED will be fission energy rather than fusion energy.

In summary, the development time required before fusion energy can become available in a form useful to the MED is much too great to consider fusion for this application, and there is a good chance that the thermonuclear reactors that are developed will have characteristics making them unsuitable for the MED.

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5.3 RADIOISOTOPES

Radioisotopes were considered as a possible energy source for the MED. Radioisotopes may be produced in four ways:

- (1) an underground nuclear explosion produces radioisotopes, which are mined from the explosion cavity;
- (2) a large central reactor in the United States produces radioisotopes, which are packaged and shipped to the utilization device or vehicle in the field;
- (3) a large central reactor in the United States produces radioisotopes, which are packaged and sent to an MED that makes chemical energy in the field; and
- (4) a mobile reactor makes radioisotopes in the field to keep utilization devices supplied.

Several factors eliminate the underground nuclear explosion as a source of radioisotopes:

- (1) The nuclear explosion must be detonated at a great depth to ensure containment of the radioactivity.
- (2) Both burial of the explosive device and recovery of the end products require extensive mining equipment.
- (3) The recovery of the radioisotopes is particularly difficult because of the high activity of the mined material.
- (4) Separation of the radioisotopes from the mined material also requires extensive equipment. This equipment requirement and the delay imposed by the mining operation preclude an underground nuclear explosion at the point of use.
- (5) The use of a production area within the continental United States requires shipping the radioisotopes to the point of use. Because the fission products created by a nuclear explosion are predominantly short-lived, the energy of the explosion must be correspondingly increased to compensate for handling delays. Ultimately, the energy delivered to the user becomes only a minute fraction of the energy released in the explosion.

It was therefore concluded that underground nuclear explosions can never be a source of sufficient radioisotopes to reduce the POL requirements of a field army.

The production of radioisotopes within a reactor was examined for two cases: the energy available from all fission products produced during a relatively short period of reactor operation, and the energy available from selected isotopes after a long period of reactor operation.

In the first case, it was assumed that the production reactor was operated for 1000 hr and that all fission products were then separated and shipped to the utilization device. Because the separation, packaging, and shipment of the fission products will take time, and because the radioisotopes must furnish energy to the utilization device over a period long enough to make the system reasonable, the energy available from all of the fission products was determined for periods of six, 12, and 18 months after removal from the reactor. Table 12 shows energy available from all fission products per megawatt of production-reactor thermal power.

TABLE 12
ENERGY AVAILABLE FROM ALL FISSION PRODUCTS

form of energy release	watts released per megawatt of reactor thermal power*		
	6 months**	12 months**	18 months**
β	46	20	12
γ	<u>39</u>	<u>6</u>	<u>2</u>
total	85	26	14

*Reactor operated 1000 hr.

**Time after removal from the reactor.

Because a significant portion of the energy appears as gamma energy, these radioisotopes would require extensive shielding during transportation and handling. Furthermore, it is difficult to envision a small, light engine that can convert this gamma energy into useful mechanical or electrical power. The fission products serving as fuel for this engine must be shielded and the gamma energy must be absorbed in some medium to bring about its conversion. Both of these requirements dictate a heavy machine to convert fission product power to a usable form of energy.

In addition to the problems associated with the design of an engine operating on the energy emitted by fission products, the production of sufficient quantities of fission products to alleviate the POL logistic problem is unlikely. For example, 22 tanks have a combined power demand of approximately 15,400 hp or 11,500 kw. 135,000 Mw of reactor thermal power are required to provide the 11,500 kw of energy available to the tanks six months after the fission products are removed from the reactor. This assumes

that the vehicle engine is 100 per cent efficient in converting the beta and gamma energy into a useful form. If these same fission products must furnish the required energy 12 months after removal from the reactor, the source power must be about 450,000 Mw.

The isotopes cerium-144 (Ce-144), promethium-147 (Pm-147), strontium-90 (Sr-90), cesium-137 (Cs-137), and their daughters were studied in the fission products requiring long reactor operating periods. These four isotopes are considered the most important fission product isotopes for the production of power.⁴⁵ A reactor operating period of 10^8 sec (3.17 years) was assumed. The decay energy released by these four isotopes and their daughter elements was computed using the methods and data of Perkins and King.^{46,47} Table 13 gives the watts released per megawatt of reactor thermal power for the three periods selected as reasonable to ship and use these isotopes in the vehicle.

TABLE 13

ENERGY AVAILABLE FROM FOUR MAJOR FISSION-PRODUCT ISOTOPES

isotope	form of energy release	watts released per megawatt of reactor thermal power*		
		6 months**	12 months**	18 months**
Ce-144	β γ	16 3	10 2	7 1
Pr-144***	β γ	209 6	134 4	86 2
Pm-147	β	4	3	3
Sr-90	β	7	4	4
Y-90***	β	20	19	19
Cs-137	β	4	4	4
Ba-137m***	β γ	1 12	1 12	1 12
totals		282	193	139

*Reactor operated 3.17 years.

**Time after removal from reactor.

***Daughter.

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This table shows that cerium-144 gives more energy than the other three isotopes combined. Nevertheless, the energy available from all four is relatively small. The 22 tanks require a source reactor thermal power of 41,000 Mw and 60,000 Mw to make 11,500 kw available to the tanks six and 12 months, respectively, after the isotopes are removed from the reactor. Since the energy conversion is not 100 per cent efficient at the tanks, the source reactor thermal power must be much larger. Assuming a 10-per cent conversion efficiency, a generous efficiency because the rate of radioactive decay cannot be controlled, the source reactor thermal power must be 410,000 Mw and 600,000 Mw to make 11,500 kw available to the tanks after six and 12 months, respectively.

The electrical generating capacity of the United States was forecast for 1961 at 187,000 Mw.⁴⁸ Because most of this is produced in fossil-fueled steam turbine plants, it is estimated that the boiler capacity of these plants is 750,000 to 1,000,000 Mwt. Thus, if the entire United States electrical output were generated by nuclear power stations, all these plants would make enough of the four selected isotopes to supply only about two units of 22 tanks each. It is therefore concluded that fission products cannot significantly reduce the POL requirements for the Army's overseas forces.

Three reactor-produced radioisotopes are of interest. These are polonium-210 (Po-210), plutonium-238 (Pu-238), and cerium-242 (Cm-242). These are all alpha emitters, and have specific powers high enough to be usable, as shown in Table 14.

TABLE 14

TYPICAL RADIOISOTOPIC HEAT SOURCES^{49,50}

nuclide	mode of decay	half-life	fuel form	density, g/cm ³	thermal power w/cm ³	specific weight kg/kw
Po-210	α	138 days	Po	9.3	1320	0.0075
Cm-242	α	162 days	Cm ₂ O ₃	11.8	1169	0.010
Pu-238	α	86.4 years	PuC	12.5	6.9	1.8
Ce-144	β	285 days	CeO ₂	6.4	12.5	0.51
Pm-147	β	2.6 years	Pm ₂ O ₃	6.6	1.1	6.0
Cs-137	β	33 years	CsCl	3.9	1.27	3.1
Sr-90	β	28 years	SrTiO ₃	4.8	0.54	8.9

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These radioisotopes are produced through the capture of neutrons. A single neutron used in a fission reaction will produce about 200 Mev and about 2.5 more neutrons. If the neutrons are used to produce these radioisotopes, the amounts of energy available from the decay of each are 5.3 Mev for polonium-210, 5.5 Mev for plutonium-238, and 6.1 Mev for curium-242.⁵¹ Thus, the use of neutrons to produce a radioisotopic fuel is uneconomically from the standpoint of neutron utilization. It is therefore apparent that these radioisotopes will not be used where large amounts of power are required and where a nuclear reactor can be used directly.

It was concluded that radioisotopes hold little or no promise as an energy source for the MED. The amounts of energy available from fission products and the poor neutron economy of the reactor-produced radioisotopes make them unsuited to an application where the energy requirements are measured in megawatts.

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6. FUEL SYSTEMS

6.1 SURVEY OF FUELS AND OXIDIZERS

The basic premise of the MED concept is the conversion of nuclear energy into usable mobile energy forms. Only a small quantity of materials can be supplied to the depot system from external sources. Only air, water, and earth are available at the depot site to produce chemical compounds. Thus, the fuels and oxidizers must be drawn from those materials (a) which can be synthesized from the elements in air, water, and commonly available earth or (b) which can be used in a closed-loop regenerative system.

6.1.1 Compounds Made From Air and H₂O

The materials available from air are oxygen, nitrogen, inert gases, and very small amounts of carbon monoxide and carbon dioxide. Hydrogen and oxygen are available from water. The possible permutations and combinations of these elements for use as fuels or oxidizers are listed below.

molecular formula	name	molecular formula	name
H ₂	hydrogen	NH ₄ NO ₃	ammonium nitrate
O ₂	oxygen	NH ₄ NO ₂	ammonium nitrite
H ₂ O ₂	hydrogen peroxide	NH ₄ N ₃	ammonium azide
O ₃	ozone	N ₂ H ₅ NO ₃	hydrazine nitrate
NH ₃	ammonia	N ₂ H ₅ NO ₂	hydrazine nitrite
N ₂ H ₄	hydrazine	N ₂ H ₅ N ₃	hydrazine azide
NH ₂ OH	hydroxylamine	NH ₂ OH · HNO ₃	hydroxylamine: nitrate
HNO ₃	nitric acid	NH ₂ OH · HNO ₂	hydroxylamine: nitrite
HNO ₂	nitrous acid	NH ₂ OH · HN ₃	hydroxylamine: azide
HN ₃	hydrazoic acid	N _x O _y	nitrogen oxides

These compounds, in fuel-oxidizer combinations, were considered as possible energy sources to power field vehicles with various engines and fuel cells. Some were eliminated in the first survey on the basis of physical and chemical properties and the energetics of synthesis.

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H₂

Hydrogen is the most obvious fuel, and is readily obtained by the electrolysis of water. Because it has a very high energy content and is so simple to synthesize, the use of hydrogen as a fuel will be considered in great detail.

O₂

Oxygen is a very good oxidizer and is generally safe. It can be produced simply with a fairly low energy input either by water electrolysis or by separation from liquid air.

H₂O₂

Hydrogen peroxide is a powerful oxidizer and is relatively stable when contained in vessels constructed of such materials as aluminum or polyethylene or if traces of stabilizers (such as salts containing tin or silicates) are added. Without such precautions, the exothermic decomposition tends to proceed spontaneously and explosively. Hydrogen peroxide and its aqueous solutions have extensive military and commercial applications. The synthesis of hydrogen peroxide by the hydroquinone process is relatively complex, and considerable energy is needed for the electrolytic process. For the MED concept, liquid oxygen has many advantages over hydrogen peroxide as an oxidizer; the hydrogen peroxide system will therefore be only briefly considered in the MED program.

O₃

Ozone is highly energetic. It can be synthesized from air and thus would be an excellent fuel in the MED. The depot unit could be used anywhere on earth with this fuel. The synthesis, although simple, requires relatively large amounts of energy. Moreover, the compound is sensitive to dissociation (there are, however, new methods of handling it) and no engines have yet been developed that could use it as a fuel. Ozone is not extensively considered in this study but a thorough evaluation of the potentialities of ozone should be considered.

NH₃

Ammonia has been used as a fuel in fuel cells and in internal combustion engines. It is commercially stored as a liquid. The processes for synthesizing ammonia are well known and reasonably simple. The synthesis is exothermic and requires only nominal energy.

N₂H₄

Hydrazine is very active and can be readily used as a fuel (it has been used as a fuel

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in fuel cells, engines, and rockets). The synthesis by classical or chemical means is quite complex and the energy inputs are high. Chemonuclear synthesis of hydrazine from ammonia appears interesting for the MED.

NH₂OH

Hydroxylamine synthesis generally involves ammonia as an intermediate product or a byproduct, and its utilization would be about the same as that of ammonia. Hydroxylamine offers no apparent advantages over ammonia and will therefore not be considered further.

HNO₃

Nitric acid is a strong oxidizer. The synthesis practices commonly used are (1) oxidation of ammonia to nitrogen oxides and subsequent reaction with water and oxygen and (2) direct reaction of nitrogen and oxygen to nitrogen oxides and subsequent reaction with water. In the first process, the reaction requires the production of ammonia, and the ammonia could just as easily be oxidized in field vehicles. In the second, the fixation of nitrogen is a highly endothermic process which would require large amounts of electrical or thermal energy. No advantage is seen for nitric acid over oxygen as an oxidizer.

HNO₂

Nitrous acid is unstable, and converts rapidly to nitric acid in the presence of oxygen. It would therefore be difficult to use nitrous acid in the MED.

HN₃

The technical difficulties which would be encountered in the synthesis and storage of hydrazoic acid cannot be justified on the basis of its energy content and difficulty of field use.

NH₄NO₃, NH₄NO₂, and NH₄N₃

It is technically possible to synthesize the ammonium salts of nitric, nitrous, and hydrazoic acids. The production of the salts would first require the synthesis of the acids discussed above. No significant advantage is seen for these fuel-oxidizer combinations in salt form, over ammonia and air-oxygen, to power field vehicles.

Ammonium nitrate and other ammonium salts might have great interest for the MED as explosives. The field unit could, in broad concept, become independent of POL and ammunition.

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6.1.2 Compounds Synthesized in a Closed-Loop System

In the MED concept, it is possible to synthesize fuel and oxidizer at the depot, transport them to the field vehicle, and combine them in the vehicle, extracting energy and forming oxidation products. These products can be collected and returned to the reactor depot for reprocessing to fuel and oxidizer. This is a closed-loop system. The system using air and water is an open-loop system in which the oxidation products are returned to the depot site by natural processes.

The closed-loop system allows the consideration of many fuel and oxidizer combinations. Elimination can be made on the basis of weight, volume of various components, technical difficulties in synthesis, transportation, and utilization, and physical, chemical, and toxicological properties. Many systems were surveyed, and more detailed consideration was given the following systems: carbon fuels such as methanol, formic acid, and formates, with oxygen as oxidizer; alkali metals with oxygen; and lithium and hydrogen to form lithium hydride.

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6.1.3 Selection of Fuels and Oxidizers for Further Study

The use of such materials as iodine, chlorine, bromine, fluorine, sulfur oxides, etc., as oxidizers was considered. The difficulties of manufacture, handling, corrosion, and toxicity of these compounds overcame their possible advantages as oxidizers, and oxygen was chosen.

Some physical and chemical properties of the possible fuels and oxidizers remaining after the screening are presented in Table 15 (see Appendix B for additional properties).

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TABLE 15

PROPERTIES OF FUELS AND OXIDIZERS

name and molecular formula	molecular weight	melting point, °C	boiling point, °C	density, lb/ft ³	heat of combustion, Btu/lb*	Btu/ft ³ *	kwhr/lb*	kwhr/ft ³ *
hydrogen H ₂ (gas)	2.016	-259	-253	0.00561 at 0 C and 1 atm	61,060 (51,630)	342.6 (289.6)	17.89 (15.13)	0.100 (0.0849)
hydrogen H ₂ (liquid)	2.016	-259	-253	4.37 at -252 C	61,060 (51,630)	266,830 (225,620)	17.89 (15.13)	78.18 (66.10)
ammonia NH ₃ (gas)	17.03	- 77.7	- 33.3	0.0481 at 0 C and 1 atm	9,665 (8,000)	464.9 (384.6)	2.83 (2.34)	0.136 (0.113)
ammonia NH ₃ (liquid)	17.03	- 77.7	- 33.3	50.99 at -79 C	9,665 (8,000)	492,820 (408,665)	2.83 (2.34)	144.4 (119.9)
hydrazine N ₂ H ₄ (liquid)	32.05	1.4	113.5	63.1 at 25 C	6,982 (5,800)	440,560 (365,900)	2.04 (1.70)	129.1 (107.2)
methanol CH ₃ OH (liquid)	32.04	- 97.8	64.6	49.42 at 25 C	9,730 (8,550)	480,850 (422,540)	2.85 (2.51)	140.9 (123.8)
formic acid HCOOH (liquid)	46.03	8.40	100.7	76.45 at 25 C	2,520 (2,110)	192,650 (161,300)	0.738 (0.618)	56.4 (47.3)
sodium Na (solid)	22.99	97.5	880	60.5 at 20 C	5,750	347,875	1.68	101.9
gasoline (liquid)	-	-	-	46.1 at 25 C	20,000 (18,000)	922,000 (829,800)	5.86 (5.27)	270.1 (243.2)
oxygen O ₂ (gas)	32.00	-218	-183	0.0892 at 0 C and 1 atm	-	-	-	-
oxygen O ₂ (liquid)	32.00	-218	-183	71.2 at -184 C	-	-	-	-

*The high heat of combustion values are indicated first; the combustion products include liquid water at 25 C. The lower heat of combustion values are indicated in parentheses; the combustion products include water vapor at 25 C.

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6.2 MANUFACTURING PROCESSES

6.2.1 Conventional Processes

During the course of the study, fuel synthesis plants for several of the more promising fuels were examined from the standpoint of weight, size, and power requirements. These plants were sized to supply the fuel requirements for 20 fuel-cell-powered tanks. The methods for determining the fuel requirements are described in Sec. 7. The plant sizes were based on a five-year projection of technology. Because approximately four to five years would be needed to design, build, and test the MCR, only the projected fuel-plant data are included in this report.

Plant projections have been made for hydrogen and production by electrolysis and steam reforming of hydrocarbons, for liquefaction of hydrogen and oxygen, for the production of ammonia, and for the production of sodium. Data for hydrazine and methanol are also included, but these projections are less complete because early comparisons indicated that these fuels would be less desirable.

6.2.1.1 H₂-O₂ System

6.2.1.1.1 H₂O Electrolysis. Hydrogen will be produced by the electrolysis of water. Before it is passed to the electrolytic cells, raw water from the supply will be purified in a small still. A regenerative purifier will be used to conserve energy. The incoming water stream will be heated as it condenses the product stream. A water purifier¹ operating on this principle consumes about 50 Btu/lb of water purified. The raw MED feed-water may contain much mud or other foreign matter. The energy for purification has been conservatively estimated at 100 Btu/lb of water purified. A purifier to handle 1674 lb of water/hr is expected to require 0.05 Mwe, to weigh about 1000 lb, and to occupy a space of about 100 ft³. This purifier will produce water from which the electrolytic cells can separate 186 lb of hydrogen/hr. A smaller one can be used if the pure product water from the user's fuel cells is returned to the synthesis depot.

The recommended electrolytic cell is a hydrogen-oxygen fuel cell modified to operate in reverse. Such atmospheric-pressure cells have been operated in the laboratory by Allis-Chalmers. Commercial electrolytic cells were considered but were rejected in favor of the reversed fuel cell. Present commercial electrolytic cells contain noncatalytic electrodes, whereas fuel cells contain catalysts on the electrodes, which increase the energy conversion per unit electrode surface. Present commercial electrolytic cells of the high-pressure type produced by the Lurgi Company were sized for the MED. The production of 186 lb of hydrogen per hour would require 21 modules with an envelope size of 8 x 8.5 by 10 ft, and weighing 30,000 lb each. About 9 Mwe would be required with Lurgi cells. Commercial cells are not generally designed as

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small, light units for mobile applications. On the other hand, the desire for light and small units has influenced fuel-cell designs throughout their development. For these reasons, hydrogen-oxygen fuel cells, modified to operate in reverse, are recommended for the electrolysis of water for this application.

The Allis-Chalmers hydrogen-oxygen fuel cell, modified for operation as an electrolytic cell, is reported to have the following present and projected characteristics:

	<u>present</u>	<u>5-yr projection</u>
$\frac{\text{lb of cell system}}{\text{lb H}_2 \text{ produced/hr}}$	325	140
$\frac{\text{ft}^3 \text{ of cell system}}{\text{lb H}_2 \text{ produced/hr}}$	5.36	1.634
$\frac{\text{kw consumed}}{\text{lb H}_2 \text{ produced/hr}}$	20.17	18.5

On the basis of the projected values, the electrolytic cell system to produce the required 186 lb/hr of hydrogen and 1488 lb/hr of oxygen will weigh about 26,000 lb and occupy about 304 ft³. About 3.44 Mwe will be supplied to the cells during operation. The cell system includes the basic electrolytic cells and auxiliary piping and wiring. The envelope volume of the unit will be about 1000 ft³.

6.2.1.1.2 H₂ and O₂ Liquefaction. For MED applications in which large amounts of hydrogen are to be stored and transported to the user, the hydrogen will be liquefied to increase its density. Figure 17 is a schematic of the liquefaction process. The Claude liquefaction cycle has been selected for this application because it is relatively simple and requires relatively low energy for operation. The cycle is shown in Fig. 18.

The energy of a perfectly insulated Claude hydrogen liquefaction cycle operating at a pressure of 60 atm with hydrogen precooling to 65 K was calculated to be 5.9 kwhr/lb of hydrogen². This may be calculated from the data in Fig. 19. This value includes the energy of the liquid-nitrogen precooler, a hydrogen compressor that is 65-per cent efficient, an expander that is 80-per cent efficient, and the energy associated with ortho-parahydrogen conversion. These efficiencies are representative of existing equipment. Two important contributions to the liquefaction energy are not included: (1) the pressure drops caused by fluid flow through the heat exchangers and piping will result in an increase in the size of the compressor to pump the same amount of fluid; and (2) the heat leaking into the liquid hydrogen will cause some boil-off, resulting in a lower net production of liquid hydrogen. These two factors cannot be accurately evaluated until

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FIG. 17. SCHEMATIC OF HYDROGEN-OXYGEN LIQUEFACTION PLANT

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FIG. 18. CLAUDE LIQUEFACTION CYCLE

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the engineering design of the plant is complete. For the present calculations, it is estimated that, as a result of heat-leak and fluid-friction losses, the cycle calculated above will be operated at an efficiency of about 60 per cent. That is, it is estimated that the energy of hydrogen liquefaction in this plant will be about 10 kwhr/lb of hydrogen. The power for hydrogen liquefaction will be about 1.86 Mwe.

Chelton² assumed that liquid nitrogen was used to precool the hydrogen. Nitrogen is generally available at hydrogen production facilities because an air separation plant is employed to generate the oxygen consumed in the recovery of hydrogen from hydrocarbons. An air separation plant will not be associated with the MED liquefaction plant and it will be more convenient to use liquid air as the precoolant than liquid nitrogen.

The oxygen and the hydrogen will be delivered from the electrolytic cell at about 10 psig. Cells have been operated in the contractor's laboratory at pressures up to 15 psig. At this high a pressure, an oxygen compressor will not be required. The oxygen will be liquefied in the heat exchanger employed for hydrogen precooling. Cooling is supplied in this heat exchanger by the cold-return hydrogen stream and by liquid air. On the basis of data from operating air plants, it is assumed that oxygen can be liquefied by heat exchange with liquid air for about 0.4 kwhr/lb of liquid oxygen. This value is accepted as representative in the present design. The power required to liquefy the oxygen is estimated at 0.6 Mwe.

Hydrogen and oxygen boiloff in liquid storage vessels at the depot may be returned to the liquefaction plant for reprocessing. The vapors may also be used to supplement the fuel supply for heating, cooking, and power applications in the vicinity of the depot. As explained in Sec. 6.3, these procedures will maintain a very low fuel "loss" rate due to vaporization of the cryogenic liquids.

A 450-hp reciprocating compressor powered by a 400-cps motor, would be used today for compressing the hydrogen. This compressor and drive would weigh about 50,000 lb and occupy about 2200 ft³. It is expected that in five years a centrifugal compressor will be available for this purpose. The compressor and its cooler will weigh about 6000 lb. The 400-cps motor will weigh about 500 lb. The combination will occupy a space about 4 ft wide, 7 ft long, and 3 ft high.

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The compressor for the liquid-air plant must compress 48,950 lb/hr of air from 17 to 87 psia. A two-stage radial centrifugal 2000-hp compressor is envisioned for this service. It is anticipated that in five years the compressor, cooler, and drive will weigh about 9000 lb and occupy a space 4 ft wide, 10 ft long, and 4 ft high. The reciprocating compressor and its 400-cps motor that would be used today would weigh about 30,000 lb and occupy about 960 ft³.

It is anticipated that in five years the hydrogen expander will be a high-speed, air-bearing, radial-flow device similar in design to machines presently manufactured by Air Products. They will weigh about 200 lb and will occupy about 8 ft³. The expander in the liquid-air cycle will also be of the radial type, will weigh about 200 lb, and will occupy about 25 ft³. Presently, these two expanders would be of the reciprocating type and weigh 15,000 and 3500 lb and occupy 360 and 120 ft³, respectively.

The over-all heat-transfer coefficient of present gas-to-gas heat exchangers in this service is about 100 Btu/(hr)(ft²)(°F). It is expected that development programs now underway at Air Products will result, in five years, in heat exchangers with over-all heat-transfer coefficients of 500 Btu/(hr)(ft²)(°F).

On this basis, the combination heat exchanger, A-B in Fig. 17, will contain about 375 ft² of heat-transfer area. Such an exchanger, with the projected surface, plate, and fin design, and of aluminum construction, will occupy about 12 ft³ and weigh about 500 lb. Exchanger M, the liquid-air precooler, will be of copper and of the shell-and-tube type, and will contain 140 ft² of heat-transfer area. It will occupy about 3 ft³ and weigh about 900 lb. The remaining heat exchangers will occupy only a few cubic feet and will not seriously affect the layout of the plant. Exchangers A-B and M, if constructed today for the same function, would weigh 550 and 6000 lb and occupy 13 and 40 ft³, respectively.

The master controls to operate the synthesis plant will fit into a control panel 5 ft wide, 2 ft deep, and 4 ft high. It is estimated that this assembly will weigh 1000 lb.

6.2.1.1.3 Module Arrangement. Based on the above five-year projections of the characteristics of process equipment, the liquid hydrogen-oxygen plant, exclusive of the power supply, will consist of the following modules:

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TABLE 16

TRANSPORTABLE LIQUID H₂-O₂ PLANT*

<u>function</u>	<u>number</u>	<u>size, ft (L x W x H)</u>	<u>weight, lb</u>	<u>power required, Mwe</u>
water electrolysis	1	25 x 8.5 x 5	29,000	3.44
water purification	-	--	1,000	0.05
compressors, drives, storage, controls, and liquefaction equipment	1	30 x 8.5 x 8.5	23,500	2.46
Totals	2	3230 ft ³	53,500	5.95

* This plant will produce 2970 lb of liquid hydrogen and 23,760 lb of liquid oxygen in 16 hr of operation.

Figure 20 is a preliminary layout of the electrolysis module (the interconnecting piping is not shown). An arrangement of units of cells into a bank is represented at the right in the figure. This arrangement of the units and banks allows for the auxiliary piping and for the replacement of defective cell units. There is sufficient space on this module for the storage of the interconnecting pipes and wiring. The weight of this module includes 3000 lb for aluminum structure.

Figure 21 is a block layout of the liquefaction module. The compressors, intercoolers, and motors will be spaced down the center of the module. To facilitate repairs, nothing will be placed beside or above this equipment. The cold box will contain all the heat exchangers, expanders, and product sumps. The control panel and the control room will occupy the end section of the module. The weight given above for this module includes about 5000 lb for structure.

6.2.1.1.4 Long-Range Projection of Equipment Capabilities. It is assumed here that advances in the technology of electrolytic cells, compressors, motors, expanders, and heat exchangers to be achieved between five and 15 years from now will be due to extensions or expansions of the development programs undertaken to achieve the five-year goals. There are three approaches by which these advances can be utilized:

- (1) equipment smaller and lighter than the 1967-model equipment may be designed to produce the required amounts of fuel and oxidizer with the same energy input;

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FIG. 20. BLOCK SCHEMATIC OF A WATER ELECTROLYSIS MODULE

FIG. 21. BLOCK SCHEMATIC OF A HYDROGEN-OXYGEN LIQUEFACTION MODULE

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(2) equipment of 1967-model size and weight may produce greater quantities of fuel and oxidizer with proportionally large input; or

(3) equipment of 1967-model size and weight may produce 1967-model quantities of fuel and oxidizer with a lower energy input.

Since each section of the 1967 plant will fit into one module, the first approach seems to offer the fewest benefits. Careful consideration should be given to the second and third approaches, or a combination thereof.

6.2.1.1.5 Plant Operating Characteristics. The startup and shutdown of the synthesis plant have been considered. The plant will be started and stopped by pushbutton and will operate automatically and without attention once started. Thus, few trained personnel will be required to operate the plant. The necessary instrumentation and control technology are already in use.

The plant will be started from either of two conditions: warm and cold. In the warm condition, all liquefaction equipment and insulation have been warmed to near ambient temperature since the last operation. It is anticipated that liquid air will appear about 2 hr after the plant is started up and that liquid oxygen will be produced within 4 hr of startup. Liquid hydrogen will appear about 1 hr later. These times may be shortened significantly if partially full product-storage modules are present. Some of the stored product may be employed to assist in cooling the equipment and insulation during startup. It is estimated that, with such priming, the system will yield liquid oxygen within 1 hr of startup and liquid hydrogen about 1/2 hr later.

Cold startup will be necessary after a brief power outage or if the entire plant has been down for several hours for routine repairs. Liquid product remaining in portions of the system will help to keep the equipment cool. It is estimated that liquid oxygen will be produced within about 15 min and liquid hydrogen within about 30 min of a cold startup. These estimates are based on operating experience with liquid oxygen and hydrogen plants.

The plant will be designed to be shut down quickly and safely by either of two commands: the operator may push the "stop" button, or the plant will stop automatically when the power supply is interrupted. Plant operation will stop when the compressors have been stopped.

6.2.1.1.6 Reforming of Hydrocarbons.

6.2.1.1.6.1 Method. The purpose of the Mobile Energy Depot is to significantly reduce the POL requirements for military vehicles operating in the field. This objective would be achieved if more effective use were made of the fuel currently supplied, i.e., if more

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vehicles could be operated on the same quantity of POL. One system proposed to accomplish this is to reform hydrocarbons to hydrogen, which could then be consumed in a hydrogen-oxygen fuel cell. The high efficiency of the fuel cell and the use of an electric drive would decrease the fuel requirements.

A number of commercial methods are available to produce hydrogen from hydrocarbons. The first of these is the steam reforming of naphtha into hydrogen and carbon monoxide. This system will be discussed in some detail below. A second process is the partial oxidation of hydrocarbons to carbon monoxide, hydrogen, and heat; the carbon monoxide is then reacted with steam ("shift reaction") to produce hydrogen and carbon dioxide. A third process for producing hydrogen was recently announced by Universal Oil Products³. The "Hypro" process is a single-step catalytic conversion of hydrocarbons to hydrogen and carbon. The pyrolysis of the hydrocarbon results in carbon deposition on the catalyst. It is removed periodically by burning with air in the Hypro unit (reaction 2). Carbon suspended in the product gas is removed by a cyclone separator. The heat inputs in the second and third are similar. Hydrogen is produced according to the following reaction ($C_{12}H_{26}$, dodecane, is used as a representative hydrocarbon):

$$\frac{25 H_2}{C_{12}H_{26}} = \frac{50}{170} \times 100 \text{ lb} = 29.4 \text{ lb } H_2 / 100 \text{ lb } C_{12}H_{26}$$

This quantity of hydrogen is significantly less than can be produced by steam reforming (reactor heating) as shown in reaction (4). This is evident in that part of the reactant is used to provide system cracking heat. According to M. W. Kellogg Co.⁴, partial oxidation is somewhat more difficult, primarily owing to gas-flow control and gas separation requirements. All these processes require the use of a shift converter to convert carbon monoxide to carbon dioxide (reaction 3). The reaction, however, is exothermic and self-sustaining after the operating temperature is reached. It is further shown that the partial oxidation system is no more efficient than simple steam reforming. Sufficient data are not yet available on the "Hypro" process to analyze the system completely.

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If no additional heat were required for (1), it can be shown by calculations similar to those below that the use of "Hypro" hydrogen, in the projected hydrogen-oxygen fuel cell, would produce 1.2 times the performance as naphtha burned directly in an internal-combustion engine. Since the power requirements for oxygen production have not been taken into account, it is believed that this improvement in use of POL is too small to merit further consideration.

Hydrocarbons, such as dodecane, can be steam reformed according to the following reaction. The hydrocarbon chosen as representative of this fuel is dodecane.

$$\frac{37 \text{H}_2}{\text{C}_{12}\text{H}_{26}} = \frac{74}{170} \times 100 \text{ lb} = 43.5 \text{ lb H}_2 / 100 \text{ lb C}_{12}\text{H}_{26}$$

In actual practice, 41.5 lb of H_2 can be obtained from 100 lb of naphtha⁴. The remaining analysis of the production of hydrogen from hydrocarbons depends on the source of heat for the reformer, hydrogen liquefaction, and air separation plant. Two sources of power will be considered: (1) direct oxidation of hydrocarbons, and (2) nuclear reactor.

6.2.1.1.6.2 Heat Sources.

6.2.1.1.6.2.1 Oxidation of Hydrocarbons. If hydrocarbon oxidation is used to supply the heat for the reformer, it can be shown⁴ that one part hydrocarbon must be burned for one part hydrocarbon reformed. This represents a thermal efficiency of approximately 65 per cent, a value routinely obtained in commercial practice. An efficiency of approximately 85 per cent would have to be obtained if one part hydrocarbon were to be burned to reform two parts hydrocarbon. Furthermore, some fuel would have to be consumed to provide power for liquefaction of the hydrogen. If a hydrogen-oxygen fuel cell were used, one part hydrogen would be consumed to liquefy one part hydrogen.

As mentioned above, 41.5 lb of hydrogen are produced by steam reforming 100 lb of naphtha. However, the total quantity of hydrocarbon consumed is 200 lb (100 lb reformed and 100 lb burned). Thus, 41.5 lb of hydrogen are actually produced from 200 lb of naphtha. But half the hydrogen is then consumed to produce electric power for liquefaction, so that only 20.8 lb of liquid hydrogen to be used in field vehicles are produced from 200 lb of hydrocarbon.

The actual heating value of a hydrocarbon fuel in an internal-combustion engine is approximately 0.35 times that of hydrogen (per unit weight)*. Thus, the use in an internal-combustion engine of the 20.8 lb of hydrogen obtained from 200 lb of hydrocarbon would produce the same performance as 59 lb of naphtha (20.8/0.35).

*This figure is based on the relative heats of combustion of gasoline (18,000 Btu/lb) and hydrogen (51,600 Btu/lb).

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The daily POL requirement per tank is 1095 lb or 383 lb of hydrogen (1095×0.35). The projected hydrogen-oxygen fuel cell requires 135 lb of hydrogen per day per tank, or 35.2 per cent of the hydrogen used in an internal-combustion engine. Thus the use of 20.8 lb of hydrogen in the cell would produce the same performance as $59/0.35 = 167$ lb of hydrocarbon in an internal-combustion engine.

Thus, because chemical energy would be required to heat the reformer and liquefy hydrogen, the direct reforming of hydrocarbons does not significantly reduce the POL requirement. Note that if the reformer efficiency were increased so that the heat produced by burning one part hydrocarbon were sufficient to reform two parts hydrocarbon, the use of the hydrogen (from 150 lb of hydrocarbon) in the projected fuel cell would produce the same performance as 167 lb of hydrocarbon, i.e., an increase in POL capability by a factor of 1.11.

Similarly, with current reformer efficiency and a nuclear reactor to provide power for hydrogen liquefaction and the air separation plant, the POL capability would increase by a factor of 1.67. In other words, a given quantity of POL would operate 1.67 times as many vehicles. The projected hydrogen-oxygen fuel cell would be used as the vehicle power plant.

6.2.1.1.6.2.2 Nuclear Reactor. A further reduction in POL can be achieved if a nuclear reactor is used as the sole source of power. The process heat would be obtained directly from the primary cooling loop of the reactor. Some electric power would also be obtained from the reactor to operate the hydrogen liquefaction plant and the air separation plant. The primary advantage of steam reforming is the large quantity of hydrogen obtained per unit weight of fuel, as shown in reaction (4).

Because the nuclear reactor is supplying heat for reforming, 41.5 lb of hydrogen will be produced from 100 lb of hydrocarbon. The reactor will also supply the electric power for the liquefaction plant, so hydrogen will not be lost in this step. As mentioned above, the actual heating value of hydrocarbon fuel in an internal-combustion engine is approximately 0.35 that of hydrogen (per unit weight). Thus, the use in an internal-combustion engine of the 41.5 lb of hydrogen obtained from 100 lb of hydrocarbon would produce the same performance as $41.5/0.35 = 119$ lb of hydrocarbon, representing an increase in POL capability by a factor of 1.19. That is, a given quantity of POL would operate 1.19 times as many vehicles. It has also been shown that the present hydrogen-oxygen fuel cell power plant requires 35.2 per cent of the hydrogen required by the internal-combustion engine. Thus, the use of the 41.5 lb of hydrogen obtained from 100 lb of hydrocarbon would produce the same performance as 340 lb ($119/0.35$) of hydrocarbon, representing an increase in POL capability by a factor of 3.4. These data are summarized in the following table.

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TABLE 17

INCREASE IN POL CAPABILITY BY REFORMING OF HYDROCARBONS

<u>item</u>	<u>factor</u>
reforming heat from hydrocarbons plus fuel cells for liquefaction	0.85*
reforming heat from hydrocarbons plus nuclear reactor for liquefaction	1.70*
entire process power from nuclear reactor	3.40*
entire process power from nuclear reactor	1.26**

* Based on H₂ requirements for projected fuel cell power plant.

** Use of present I.C. engine, operating on H₂.

6.2.1.1.6.3 Plant Design With Nuclear Heat Source: The size and power requirements for the reformer are estimated from a design published by the M. W. Kellogg Co.⁴. The weights and volumes of the individual components are based on commercially available items. Thus a projected (five-year) plant would probably be somewhat smaller and lighter. Taking this factor into account, a plant 70 per cent as large as the one described seems reasonable.

Because steam reforming is endothermic, heat must be continually supplied to the system. This is accomplished in the conventional plant by burning fuel oil. In this system, the heat would be supplied directly from the primary cooling loop of the reactor. The quantity of heat required is discussed below.

The plant was originally designed to produce 2000 scfh (11.3 lb/hr) of hydrogen. Exclusive of storage facilities, hydrogen compressor, and skid structure, and with a palladium-diffuser purifier, the 2000-scfh plant would weigh 11,700 lb. This includes the 70-per cent factor mentioned above. The storage facilities, skid structure, and hydrogen compressor are considered in other parts of the over-all system. This plant would produce 181 lb of hydrogen in a 16-hr day. To be compatible with the MED module, the plant was scaled up linearly to a weight of 27,000 lb. Such a reforming unit would produce 418 lb of hydrogen in a 16-hr day.

Each module represents a complete reforming unit. However, such a configuration is generally inefficient for a chemical plant. This is particularly important because reactor heat will be used to supply power to the reformer. The engineering of this portion of the plant would be simplified if the reforming furnaces were combined as sole occupants of a module. Because the reforming furnace is the heaviest component of the reforming plant, such an arrangement could represent a significant reduction in system weight. The combined units should obviously weigh less than the sum of the individual units.

Some account should also be taken of the extra piping needed for the use of the reactor heat. In lieu of a more complete design study, it is assumed that this increase in weight will correspond to the decrease in weight obtained by combining the reformer furnaces.

The reactor power requirements were estimated from the heating value of the naphtha used to heat the reformer described in the Kellogg report. This figure was obtained as follows: The 2000-scfh (11.3-lb/hr) plant consumes 29.5 lb of naphtha/hr as fuel, i.e., 610,500 Btu/hr (80-per cent combustion efficiency). In 16 hr, $16 \times 610,500$ or 9.77×10^6 Btu are supplied. Because the reactor heating and hydrocarbon heating efficiencies are assumed to be the same (80 per cent), the reactor would have to supply the same amount of heat. (The actual reactor heating efficiency should be much greater than 80 per cent.) Because 1 Btu equals 2.93×10^{-4} kwhr, 2863 kwhr of heat can produce 181 lb of hydrogen. Thus, the reformer requires 2863 kwhr/181 lb of hydrogen or 15.8 kwhr/lb.

The specifications of the reformer plant are summarized below.

weight of H ₂ produced per day	2970 lb
weight of hydrocarbon reformed per day	7160 lb
weight of plant	190,000 lb
volume of plant	10,500 ft ³
power	2.86 Mwt

For the nuclear reactor to serve as a heat source for this process, the nuclear coolant outlet temperature must be approximately 2000 F. This allows for the thermal gradients necessary to operate the reforming equipment. At present, the helium-cooled reactors appear to offer the greatest promise of achieving this temperature. There has been considerable effort to develop nuclear process-heat reactors aimed with higher coolant temperatures. The Ultra High Temperature Reactor Experiment (UHTREX) has as its experimental goals a maximum helium outlet temperature of 2400 F and a thermal output of 3 Mw⁵. The Bureau of Mines has also worked toward developing a high-temperature process-heat reactor, and has successfully operated a helium-loop experiment at 2500 F for 1000 hr⁶. Therefore, a helium-cooled process-heat reactor operating with a coolant outlet temperature of about 2000 F appears feasible with a reasonable amount of development effort.

The steam reforming of petroleum using nuclear energy as a process heat and power source promises a very worthwhile reduction in the POL requirements of future overseas armies. Its development and application in the immediate future appears feasible.

The steam reforming of petroleum should, however, be studied in greater detail. This study should include the determination of the optimum location of the plant in the POL supply chain, the determination of the most useful plant capacity, a preliminary design

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of a complete nuclear plant for the steam reforming of petroleum and the subsequent liquefaction of hydrogen, the determination of the research-and-development effort required to design a reactor capable of supplying the process heat and power needed by the plant, and an outline of the requirements, costs, and time to develop such a plant.

6.2.1.1.7 Thermal Production of H₂ Through Reaction of H₂O with Oxides. Hydrogen can be produced by reaction of steam with certain oxides. In the reaction, the oxides are further oxidized. These oxidized products can then be thermally decomposed to oxygen and the original oxide.

The sequence of reactions can be illustrated as follows:

Two types of systems are considered below: solid oxides and gaseous oxides. Metals can also undergo a reaction similar to reaction (1); they will be discussed later.

The basic principles of these types of processes for hydrogen production appear interesting. It may be found that the thermal energy of the reactor may be used more efficiently in these processes than in electricity production and subsequent electrolysis. These processes should be considered in greater detail.

6.2.1.1.7.1 Solid Oxides. The steam-iron commercial process for hydrogen production uses in half of the cycle a reaction similar to reaction (1). The temperature needed, however, to decompose the iron oxide is probably higher than could be practically obtained in the MED concept.

A simple solid-metal-oxide system for continuous production of hydrogen could consist of two chambers containing metal oxides. Through one heated chamber steam would be passed over the lower oxide form and hydrogen would be produced according to reaction (1). At the same time, the higher oxide form, in the second chamber, would be heated to a high temperature to decompose the oxide according to reaction (2). At an appropriate time, through a switching mechanism, steam would be passed into the second chamber and heat would be applied to the first chamber. The reactions would cycle between the two chambers to produce hydrogen continuously.

Auxiliary equipment would be needed for pumps, heat exchangers, and switching devices. The reaction chambers could be fluidized bed reactors, rotating kilns, or packed columns.

The choice of the metal oxide would be a function of at least the dimensional stability of the solid oxide particles and the decomposition temperature of the oxide. If the crystal structures of the higher and lower forms of the oxide are markedly different, the cycling process will cause considerable spalling and fragmentizing of the particles. Eventually this would prevent the free passage of gases through the bed of oxides. The decomposition temperature of the oxide will affect the choice of construction materials.

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A solid-oxide system as described has not been constructed. For sizing purposes, a copper oxide system is assumed. The reactions would probably be:

and

The net reaction is

The oxidation reaction would produce, at 100-per cent yield, 1 lb of hydrogen for every 70 lb of cuprous oxide. However, probably only the outer fourth or less, of the oxide particle would be active in the process. Thus, 280 lb of cuprous oxide would be needed for 1 lb of hydrogen. Assuming a 1/2-hr cycle time and a production of 186 lb/hr, 26,000 lb of oxide would be needed in each reactor. If a bulk density of 2 is assumed for the oxide bed, the volume would be about 200 ft³. The associated auxiliaries and framing controls would probably weigh in the range of 10,000 lb per reactor. The total weight of the system would be about 62,000 lb.

Several assumptions have been made to arrive at this weight, but it can be assumed that a system producing 3000 lb of hydrogen per 16-hr day would occupy two to five modules.

6.2.1.1.7.2 Gaseous Oxides. Gaseous-oxide systems could also be used. The reactions considered in this case can be illustrated as follows:

with a net reaction, again, of

In a simple design, a water-gas-shift reactor could be used for reaction (6). The carbon dioxide from reaction (6) could be passed into a hot chamber or the reactor to produce reaction (7). After separation of carbon monoxide from oxygen, the carbon monoxide could be passed to the water-gas-shift reactor.

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6.2.1.2 Modified H₂-O₂ System (NH₃ Formed from H₂ and Cracked at Point of Use).
It is possible to ship the hydrogen in the form of ammonia and then catalytically dissociate the ammonia at the point of use into hydrogen and nitrogen. The user's fuel cell would operate on hydrogen and oxygen.

Ideally, 1053 lb/hr of ammonia, containing 186 lb/hr of hydrogen, must be produced by the plant. This production rate will not be sufficient to support the 22 tanks, however. First, the Claude cycle for the synthesis of ammonia will convert about 95 per cent of the reactants into product. Second, not all the ammonia at the using vehicle can be dissociated into nitrogen and hydrogen (a catalyst chamber 2 in. in diameter and 5 ft long will dissociate an estimated 90 per cent of the ammonia), and the fuel cell will be supplied with mixtures of hydrogen, nitrogen, and ammonia. Third, for the dissociation rate to be high and for the chemical equilibrium to be high in the direction of decomposition, the reaction must be carried out at 700 F or above. The decomposition reaction is endothermic and energy must be added to keep the reaction going. This heat may be supplied by burning hydrogen and oxygen or air. It is estimated that 75 per cent of the hydrogen formed from ammonia will be delivered to the fuel cell, while the remaining 25 per cent will be burned to maintain the decomposition reaction. Instead of 186 lb/hr, 248 lb/hr of hydrogen must be produced. This is almost as high as the 321 lb/hr required if the ammonia is used directly in the fuel cell.

There will be some savings in reactor power through this approach. The size and weight of the synthesis equipment will not change drastically. However, more equipment will be carried by the user for the ammonia cracking reaction. This approach uses ammonia as a hydrogen carrier, thus eliminating the need for liquefying hydrogen. Furthermore, the hydrogen-oxygen fuel cell has been much more fully developed than the ammonia cell, which presently has some serious limitations.

The dissociated ammonia approach would require the production of 22,300 lb of ammonia and 23,760 lb of oxygen per 16-hr day. The plant characteristics obtained by factoring the plant which produces 27,700 lb of ammonia per day are given in Table 18.

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TABLE 18

TRANSPORTABLE LIQUID NH₃-O₂ PLANT*

<u>module function</u>	<u>number of modules</u>	<u>module weight, lb</u>	<u>module size, ft (LxWxH)</u>	<u>power required, Mwe</u>
water purification and electrolysis	2	50,000	25 x 8.5 x 5	4.84
air compressor, heat exchanger, and deoxo unit	1	15,000	15 x 8.5 x 5	0.78
air separator	1	30,000	30 x 8.5 x 8.5	-
N ₂ -H ₂ compressor	1	30,000	30 x 8.5 x 8.5	0.625
NH ₃ synthesis	1	25,000	30 x 8.5 x 8.5	0.0**
		150,000		6.24

*This plant is a factored reduction of the 27,700-lb/day plant. A more detailed engineering analysis would be made of the individual units to obtain more precise characteristics.

**Because the reaction is exothermic, no heat must be added to keep the reactants at the proper temperature once the plant is in operation.

6.2.1.3 NH₃ System. This section discusses a transportable plant to synthesize ammonia from air and water. The process equipment described here is that projected to exist in five years. The plant has been sized for the production of 27,700 lb of liquid ammonia and 39,100 lb of oxygen during 16 hr of operation. Products generated during the remainder of the day will be placed in reserve storage. The production of the above amounts of fuel and oxidizer in 16 hr is projected to be sufficient to supply 22 Army tanks powered by the ammonia-oxygen fuel cells expected to exist in five years.

Hydrogen will be supplied by the electrolysis of water, nitrogen will be separated from the air, and ammonia will be synthesized from water and air as starting materials in a process represented in Fig. 22.

Figure 23 is a process flow sheet for the Claude synthesis of ammonia. In this process, the gaseous hydrogen and nitrogen streams are mixed, compressed to 950 atm, and passed, at a temperature of 500 C and at a space velocity of about 100,000 liters/liter of catalyst/hr, through a bank of Claude reactors and auxiliary collection units. This equipment converts about 95 per cent of the inlet gases to anhydrous ammonia.⁷

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FIG. 22. SCHEMATIC OF AN AMMONIA PROCESS

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FIG. 23. CLAUDE PROCESS FOR AMMONIA SYNTHESIS

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The Claude process is representative of other ammonia synthesis processes. It has the advantages of an anhydrous liquid product, relatively high conversion efficiency, and relatively compact equipment.

After a preliminary evaluation of this plant, it was evident that the size and weight of the ammonia synthesis equipment will be about three times as great as that projected for the hydrogen-oxygen plant, discussed and the power required will be about 30 per cent greater than the power for the hydrogen-oxygen plant when each plant is sized to supply fuel cell powered tanks. The reverse is true if the two fuels are used for heating and cooking instead of for electrical power from a fuel cell.

For these reasons, the ammonia plant has not been considered in as great detail as has the hydrogen plant. The estimates of equipment size and weight are sufficiently accurate that the nature of the ammonia-oxygen fuel system can be ascertained.

6.2.1.3.1 Electrolysis of H_2O . Commercially, the Claude process converts about 85 per cent of the reactants into product. The remaining 15 per cent is vented, thus removing accumulated argon (from the liquid nitrogen) and methane (from the hydrogen feed). However, because in the MED system the hydrogen is of high purity, produced from the electrolysis of water, rather than from water gas or coke-oven gas, the quantity of gas bled off can be reduced to 5 per cent. To produce 27,700 lb of ammonia, 321 lb/hr of hydrogen must be produced in 16 hr by the electrolysis plant as feed for the Claude process.

The water purification unit previously discussed is recommended for use here. The two water purifiers to process the 2890 lb/hr of water will weigh about 1000 lb each. About 0.08 Mwe will be consumed for water purification.

Based on the projections of electrolytic-cell characteristics, the cells will weigh 45,000 lb and will occupy a volume of 525 ft³. About 5.94 Mwe will be consumed to produce the hydrogen. The oxygen generated by the electrolytic cells will be vented.

Each of two electrolysis modules will contain electrolytic cells weighing 22,500 lb, a water purifier weighing about 1000 lb, and about 3000 lb of aluminum structure. The total module weight will therefore be about 26,500 lb.

6.2.1.3.2 Air Separation. Nitrogen will be generated by air separation. Very high purity nitrogen must be supplied to the synthesis reactors, because the major impurity in the nitrogen, oxygen, would react with hydrogen to form water, which would poison the conversion catalyst. Therefore, the air separation plant will be designed to produce nitrogen that is 99.0 to 99.9 per cent pure. This gas stream will be mixed with the

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hydrogen stream from the electrolytic cells and the mixed gases will be passed through a Deoxo unit in which the small amount of oxygen present as an impurity will be catalytically combined with hydrogen. The product gases from this unit should contain only a few parts per million of oxygen.

Not all the nitrogen that enters the air plant can be recovered as high purity product. This air column will be designed to recover about 19 per cent of the nitrogen, which is consistent with data from operating air plants. The unrecovered, impure nitrogen will be vented. On the basis of the above recovery value, 1500 lb/hr of high-purity gaseous nitrogen and 2400 lb/hr of high purity liquid oxygen will be generated. That is, the air plant will produce simultaneously the required amounts of nitrogen and liquid oxygen. For the purpose of calculating the power requirements, the plant is to be considered a 29.3-ton/day liquid oxygen plant. On the basis of the energy requirement for oxygen production stated in Sec. 6.2.1.1.2, the power required to operate the air separator will be about 0.98 Mwe.

Both high-pressure (2000-psia) and low-pressure (90- to 100-psia) cycles are commonly used in liquid oxygen plants. For high-pressure systems, 0.4 kwhr/lb of liquid oxygen (Sec. 6.2.1.1.2) is a representative energy. The energy of a low-pressure cycle is about twice as high, according to L. S. Gaumer, Jr., Manager, Process Design, Air Products and Chemicals, Inc. Although the compressor and main heat exchanger will be smaller and lighter for the high-pressure system, the equipment walls will be thicker. Equipment weights will not be different enough to give either cycle a decided advantage. The low-pressure cycle is less complex, but requires larger and heavier power-generation equipment. For the purpose of the present calculations, a high-pressure cycle has been selected for the air plant. It is anticipated that the over-all weight of an MED system based on ammonia and oxygen will be the lowest as a result of this choice. If the ammonia-oxygen-fuel system is selected for further development, this choice of cycle should be reviewed during the engineering design studies.

The low-pressure section of the separation column will contain about 50 trays to obtain the specified nitrogen purity. For the flow rates involved in this plant, the trays will be 3 to 4 in. apart. With the product sump at the bottom and a vapor-liquid disengagement space at the top, the low-pressure column will be about 20 to 25 ft high and about 4 ft in diameter. The high-pressure and condenser-reboiler sections of the column will each be about 8 ft high and about 4 ft in diameter.

Normally, the high-pressure, condenser-reboiler, and low-pressure sections will be stacked in one column, in this case, 35 to 40 ft high and 4 ft in diameter. These dimensions are not compatible with the size of a basic module for the MED system. There are at least three solutions to this problem.

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(1) The high-pressure and condenser-reboiler sections can be separated, as a unit, from the column and be placed beside the low-pressure column. The two columns would be transported horizontally on a module about 25 to 30 ft long and weighing about 30,000 lb. At the selected depot site, a special crane would lift the entire cold box containing the columns and set it in a vertical position. The flat-bed truck used to haul this module could be specially designed to up-end the cold box by techniques employed with mobile missile launchers.

(2) The low-pressure column can be split into three sections and the high-pressure column and the condenser reboiler separated from each other. These column segments will be less than 8-1/2 ft high and can be placed on a standard module. The module will not need to be up-ended for operation at the depot. Control of such a sectioned column is more difficult than that of a standard column. Additional pumps and control equipment will be required to deliver the liquid products from one section of the column to another.

(3) Miniaturized air distillation equipment, presently being developed by Air Products for another classified project, may have application for MED. Although the size and weight of such equipment to serve MED was not established during the present study, there is no doubt that application of the advanced techniques will allow size and weight reductions of the air plant.

A choice between these three solutions can be made at the appropriate stage of the air-plant design program.

The compressor for the air plant will compress about 10,400 lb/hr of air from atmospheric pressure to about 2500 psia. A combination of axial and centrifugal equipment is envisioned for this application. The compressor and its 400-cps, 1300-hp drive are expected to weigh 10,000 lb and to occupy a space 4 ft wide, 3 ft high, and 10 ft long.

The main heat exchanger of the air plant will be of the shell-and-tube type, will occupy about 3 ft³, and will weigh approximately 1000 lb.

Presently, a 30-ton/day oxygen plant would weigh about 350,000 lb and occupy about 15,000 ft³.

6.2.1.3.3 NH₃ Synthesis. The product hydrogen and nitrogen streams will be passed through a Deoxo unit, which will catalytically combine any remaining oxygen with hydrogen. This unit will occupy about 10 ft³ and weigh about 1000 lb.

After passing through the Deoxo unit, 1820 lb/hr of the stoichiometric high purity mixture of hydrogen and nitrogen will be compressed to 950 atm with a 1050-hp reciprocating

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compressor. * A specific piece of machinery was not sized for this task. It is anticipated that the compressor will be a combination of the reciprocal and centrifugal types, and that, with its cooler and drive, it will completely fill one module. Today, the reciprocating compressor and its associated cooler and drive would weigh about 100,000 lb and occupy 4400 ft³.

*A 120-ton/day ammonia plant is quoted to consume 0.72 kwhr/lb of ammonia.⁸ Of this, 0.5 kwhr/lb has been estimated for the compression of the reactants. However, the commercial plant converted 85 per cent of the reactants into products, and the plant considered for the MED will convert about 95 per cent. Thus, the appropriate energy for compression will be about 0.45 kwhr/lb of product ammonia. This agrees with the compressor rating calculated independently on the basis of gas flow rates and system pressures.

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The catalytic converters will weigh an estimated 20,000 lb.* Perhaps by the development of strong, light structural materials, the weight could be reduced to 15,000 lb. The converters, condensers, product sumps, and associated equipment are expected to fit on one module weighing 25,000 lb, including structure.

The cold vent gas from the air plant will be used to liquefy ammonia in the product vent line (Fig. 23). The synthesis reaction is exothermic and no heat need be added to maintain the reactant temperature once the plant is in operation. About 0.79 Mwe will be required for the hydrogen-nitrogen compressor.

The product ammonia will be delivered as a liquid at atmospheric pressure.

6.2.1.3.4 Module Analysis. On the basis of the above values, the approximate size and weight of the total ammonia-oxygen generation plant have been estimated. The organization of the components into modules is presented in the following table, for a plant that will produce 1933 lb/hr of liquid ammonia and 2440 lb/hr of liquid oxygen.

TABLE 19
TRANSPORTABLE LIQUID NH₃-O₂ PLANT

function	number	weight, lb	size, ft (L x W x H)	power required, Mwe
water purification and electrolysis	2	26,500 (each)	25 x 8.5 x 5 (each)	0.08 (purification) 5.94 (electrolysis)
air compressor, heat exchanger, and Deoxo unit	1	15,000	15 x 8.5 x 5	0.98
air separator	1	30,000	30 x 8.5 x 8.5	-
N ₂ -H ₂ compressor	1	30,000	30 x 8.5 x 8.5	0.79
NH ₃ synthesis	<u>1</u>	<u>25,000</u>	<u>30 x 8.5 x 8.5</u>	<u>-</u>
totals	6	153,000	1320 ft ² of floor space	7.79

*This value is based on information found in the report by Curtis, where it is shown that the converters for the Haber process, for equal production rates, will weigh about 140,000 lb.⁹

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6.2.1.4 Na Systems.

6.2.1.4.1 Manufacture of Na, H₂O, and O₂ from Na OH. Classically, sodium metal was prepared from sodium hydroxide. Present commercial methods, however, use sodium chloride as the prime raw material. The techniques of preparing sodium from sodium hydroxide are rather ancient. Modern technology would have to be applied to permit sodium manufacture from sodium hydroxide.

6.2.1.4.1.1 Na Synthesis by Electrolysis of Fused Na OH. The classical method of preparation of metallic sodium from sodium hydroxide by electrolysis is the Castner Process.^{10,11,12} Sodium is formed at the cathode by this reaction:

The anode reaction is:

A secondary reaction occurs at the cathode when water diffuses through the electrolyte bath (fused sodium hydroxide) and reacts with the sodium as follows:

The over-all reaction is:

Because in the classical Castner cell water reacts with half of the sodium produced, the sodium yield can never be greater than 50 per cent of theoretical, and other reactions in the cell may lower the yield even more. Metallic sodium is soluble in fused sodium hydroxide. The solubility data in the literature may be open to question, because sodium will react with sodium hydroxide to form sodium hydride and sodium monoxide.¹³

The reported solubility data are 25.3 g of sodium per 100 g of sodium hydroxide at 480 C, and 10.1 g of sodium per 100 g of sodium hydroxide at 600 C.¹¹ Sodium may diffuse to the anode and react with oxygen to form sodium peroxide (sodium dioxide), which may react with more sodium to form sodium monoxide.

The commercial Castner cell consists of a cylindrical iron container or pot surrounded by insulation and a means of supplying external heat. The cathode rod (iron, copper, or nickel) enters through the bottom of the pot. A cylindrical sodium collector is supported directly above the cathode. Below the collector a cylinder of iron wire gauze surrounds

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the upper portion of the cathode and serves as a diaphragm. The gauze cylinder in turn is surrounded by an iron or nickel anode. Some sodium particles pass through the diaphragm screen to the anode, where they react with oxygen. If a very fine mesh screen is used, it will hinder the passage of sodium particles but act as a bipolar electrode. A compromise in mesh size must be chosen to optimize conditions. Nonconductive screens have been proposed but do not appear practical. If an aqueous solution or slurry of sodium hydroxide is returned to the reactor, energy input is required to separate the sodium hydroxide from the water. Evaporation or freeze-drying techniques could be used. A 50-per cent sodium hydroxide solution will deposit sodium hydroxide dihydrate when cooled to 12 C. These crystals would have to be heated to give anhydrous sodium hydroxide. The sodium hydroxide is premelted before it is added to the cell. The most favorable operating temperature for the cell is 320 to 330 C. In commercial operation, an external source of heat is needed to maintain temperature in small cells, but heat of reaction and infrared heating may make external heating unnecessary in large cells. However, the operating temperature of the cell should not be much above the melting point (318 C for pure and 300 C for impure sodium hydroxide), or excessive diffusion will occur, thus reducing sodium production as discussed above. Operation at 25 C above the melting point, for example, will cause the rate of recombination of sodium to equal the rate of decomposition of the sodium hydroxide, and the production will be zero. For operation at 5 C above melting point, the yield approaches the theoretical. At lower temperatures, however, the output per unit is quite low. Temperature control is therefore critical.

The Castner cell process has not had the benefits of modern technology. Since the 1930's, almost all sodium has been made from sodium chloride as a raw material. It may be possible to improve the Castner cell to reduce the parasitic consumption of sodium and increase the efficiency. If a suitable diaphragm could be found, the migration of sodium and water through the fused salt electrolyte could be prevented. This diaphragm would have to transmit sodium or hydroxyl ions or both and not transmit neutral sodium and water. Materials of this type that would be compatible with fused sodium hydroxide have not been found in the literature.

It may also be possible to use a molten salt bridge to separate the anode and cathode reactions. The possibility of removal of the water from the electrode reaction as soon as it is formed could be studied.

Commercial Castner cells are about 18 in. in diameter and 24 in. high, and hold about 250 lb of molten sodium hydroxide. The sodium hydroxide used must be pure and dry; metallic sodium is usually added to ensure dryness. The cells are usually connected in series. The voltage per cell is 4.5 to 5.0 v. A 1250-amp cell holding 150 lb of sodium hydroxide produces an average of 0.92 lb/hr of sodium. The current efficiency averages about 36 per cent over long periods. If the decomposition potential of sodium hydroxide is taken to be 2.25 v at 330 to 340 C, the energy efficiency is less than 18 per cent.

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The production of 1 lb of sodium ideally would require 528.5-amp-hr. The back reaction in the Castner cell (reaction 4) is less than 50 per cent efficient. Thus, at least 1057 amp-hr would be required. The working cell has a 36-per cent current efficiency, thus requiring 1468 amp-hr. At 4.5 to 5.0 v per cell, 6.6 to 7.34 kwhr are needed to produce 1 lb of sodium.

The Castner Process produced 0.0434 lb of hydrogen and 0.7 lb of oxygen during the production of 1 lb of sodium (reaction 4). The hydrogen could be combined with half of the oxygen in a fuel cell to produce supplemental power. Approximately 0.4 kwhr or 1360 Btu of power would be produced from this quantity of hydrogen. The heat capacity of sodium hydroxide is 4.18 joules/g/°C; and the heat of fusion is 167.0 joules. The conversion of solid sodium hydroxide at 25 C to fused salt would require about 1300 to 1400 Btu/lb of sodium hydroxide. On the basis of sodium metal production, heat in the region of 2200 to 2500 Btu would be needed to melt sodium hydroxide to produce 1 lb of sodium. This is almost twice the energy produced in the hydrogen-oxygen fuel cell.

6.2.1.4.1.2 Castner Cell Synthesis Plant. The production of sodium by the Castner process (from fused sodium hydroxide) in the MED concept would require a new design. The classical cell would be much too bulky and heavy. The design of a new, compact, lightweight cell would require considerable engineering study. The commercial Castner cell, which produces sodium at 1 lb/hr weighs about 350 lb and has a volume of about 3.5 ft³. Extra weight and volume are required for insulation. We will assume that a cell could be designed and built that would have a volume of 2 ft³, weigh 200 lb, and produce 1 lb/hr. More efficient design and construction would reduce the power requirements. The internal resistance could be lowered, for example, by closer spacing of the electrodes. The Castner cell presently needs about 7 kwhr/lb of sodium. We will assume that the future cell will use about 6 kwhr/lb of sodium.

The chemical plant producing sodium from fused sodium hydroxide would consist of evaporators (or concentrators), Castner cells, sodium casting or loading units, and a hydrogen-oxygen fuel cell or hydrogen burners and liquid oxygen plants.

This plant could process the product received from the sodium amalgam-oxygen fuel cells and the physical amalgamation system. The incoming raw material would consist of a 71-per cent sodium hydroxide solid or slurry. The 22 tanks would produce 86,660 lb of the 71-per cent sodium hydroxide solution slurry. The daily production would have to be 36,410 lb of sodium, 39,644 lb of water, and 12,650 lb of oxygen. The hourly production (for a 16-hr day) would be 2275 lb of sodium, 2477 lb of water, and 790 lb of oxygen.

The sodium hydroxide received would be heated and concentrated to a molten sodium hydroxide liquid (with a melting point of 318 C).

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The water removed from the sodium hydroxide solution in the concentrator would be condensed and shipped to the field vehicles. The molten sodium hydroxide would be transferred to Castner cells and electrolyzed to sodium, hydrogen, and oxygen.

The molten sodium would go to a casting plant or be transferred to liquid-sodium transfer tanks. The hydrogen would either be used in a fuel cell to produce power for electrolysis or be burned to supply heat for evaporation. In either case, the water product would be collected. The oxygen would be liquefied for fuel cell use in field vehicles.

Some of the module characteristics of a sodium plant are listed below (for a sodium production rate of 2275 lb/hr).

TABLE 20

CASTNER ELECTROLYTIC CELL CHEMICAL PLANT SYSTEM

<u>function</u>	<u>number</u>	<u>volume, ft³</u>	<u>weight, lb</u>	<u>power, Mwe</u>
evaporator, concentrator, and condenser	1	2,000	25,000	1.5
Castner cells	18	22,750	540,000	15.92
liquefaction of oxygen . .	<u>1</u>	<u>2,000</u>	<u>20,000</u>	<u>0.32</u>
	20	26,750	585,000	17.74

6.2.1.4.2 Na Synthesis from NaOH via NaHg. Sodium could be prepared through an amalgam intermediate.¹⁴ The electrolysis of aqueous sodium hydroxide with a mercury cathode and an oxygen evolution anode produces sodium amalgam and oxygen according to this reaction:

The reaction would be somewhat similar to the commercial electrolysis of aqueous sodium chloride:

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These cells generally operate with a current yield efficiency of 90 to 95 per cent and a voltage energy efficiency of 50 per cent. The decomposition voltage of hydroxyl ion is much greater than that of chloride ion. The voltage energy efficiency would probably be about 40 per cent. The required energy per pound of sodium is estimated at 3.5 to 4.0 kwhr.

The amalgam produced would contain a very low percentage of sodium. When the sodium concentration of an amalgam builds up to more than 0.2 to 0.3 per cent, the current yield efficiency drops rapidly. The usual practice is to produce a 0.2-per cent amalgam. The freeze precipitation of a sodium-mercury compound from the amalgam as a means of separating sodium does not appear feasible. Examination of the phase diagram of the sodium-mercury system (Fig. 24) indicates that the solid phase has the same composition as the liquid phase at 0.2 to 0.6 per cent sodium.¹¹ Sodium could be produced from this amalgam by distillation or electrolysis.

6.2.1.4.2.1 Distillation Separation of Na from NaHg. The distillation process on a 0.2-per cent amalgam require the evaporation of 500 lb of mercury to obtain 1 lb of sodium.¹⁵ A single-stage distillation of 500 lb of pure mercury would require over 65,000 Btu, or 13.2 kwhr. The evaporation of mercury from an amalgam of increasing sodium content would require more energy (i.e., breaking up of compounds, increase in viscosity, etc.). Multiple-stage distillation might lower the energy by 30 per cent, giving approximately 9.3 kwhr/lb of sodium. The removal of the last few per cent of mercury from the sodium would be very difficult. Sodium containing 0.5 to 1 per cent mercury makes the metal hard and unsuitable for most uses. Mercury content can be lowered by passing the liquid sodium over metallic calcium at 380 C. This reduces the mercury content to 0.01 per cent. The purification process uses about 0.6 lb of calcium per 100 lb of sodium. The calcium-mercury formed can be thermally decomposed.

6.2.1.4.2.2 Electrolytic Separation of Na from NaHg. An electrolytic process for obtaining sodium from amalgam has been developed in Germany.¹⁵ The amalgam (0.2 per cent) from the electrolysis of a saline solution is preheated to 230 to 250 C and added to the electrolytic cell. In the cell, rotating steel disks dip into the amalgam and carry a film of it into a pool of molten electrolyte floating on top of the amalgam. The electrolyte is 53 per cent sodium hydroxide, 28 per cent sodium bromide, and 19 per cent sodium iodide. This eutectic melts at 230 C. Spaced between the rotating steel disks are stationary nickel plates. When current is passed, sodium transfers from the amalgam through the electrolyte and is deposited on the nickel electrodes. It then floats to the top of the molten electrolyte. The sodium contains 0.5 to 1 per cent mercury. This can be removed by the process discussed above. The German process required 1.25 kwhr/lb of sodium separated from the amalgam. The total system of electrolysis of sodium hydroxide to amalgam and amalgam to sodium would require about 5.0 to 5.25 kwhr/lb of sodium, based on commercial data. This is a lower power consumption than electrolysis of fused sodium hydroxide, but it is an untried system.

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FIG. 24. THE SODIUM - MERCURY PHASE DIAGRAM

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The oxygen produced in the electrolysis could be recovered, liquefied, and carried to the field vehicles.

Some of the module characteristics for a system of sodium separation from sodium hydroxide via sodium amalgam are listed below, for a plant producing sodium at the rate of 2275 lb/hr.

TABLE 21

Na SEPARATION FROM NaOH VIA NaHg

<u>function</u>	<u>number</u>	<u>volume, ft³</u>	<u>weight, lb</u>	<u>power, Mwe</u>
electrolysis of NaOH to NaHg . . .	2	2000	45,000	7.96
NaOH solution concentrator	-	-	-	1.0
NaHg to Na (concentration cells) . .	2	4000	58,000	2.85
liquefaction of oxygen	<u>1</u>	<u>2000</u>	<u>20,000</u>	<u>0.32</u>
	5	8000	123,000	12.13

6.2.1.4.2.3 NaHg Production from Aqueous NaOH. No commercial cells are made to produce sodium amalgam from sodium hydroxide solution. It is assumed that the sodium amalgam fuel cell can be run in reverse to produce sodium amalgam, oxygen, and water. Modifications of electrodes and other equipment might be necessary.

In the electrolysis, the sodium hydroxide solution in the cell would become more dilute. Removal of water from the sodium hydroxide solution would return the electrolyte to proper operating conditions and produce water. The reverse sodium amalgam-oxygen cell would produce 7 lb of sodium in the form of 0.2 to 0.4 per cent sodium amalgam per hour, would weigh 90 lb, and would occupy 1 ft³. An input of 3.5 kwhr would be needed per pound of sodium in the form of amalgam.

The oxygen produced in the electrolysis of sodium hydroxide solution could be recovered, liquefied, and carried to the field vehicles.

6.2.1.4.2.4 Metallic Na Production from NaHg. The sodium amalgam could be processed to sodium in a reverse of the sodium concentration cell. The commercial cell of

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this type requires an input of 1.25 kwhr/lb of sodium. The reverse sodium concentration cell that would produce 17 lb of sodium per hour would weigh 290 lb and have a volume of 1 ft³. The reverse sodium concentration cell that would produce 1 lb of sodium per hour from sodium amalgam would weigh 17.06 lb and have a volume of 0.0588 ft³.

6.2.1.5 Manufacture of Other Fuels.

6.2.1.5.1 N₂H₄ Synthesis. As illustrated in Fig. 25, hydrazine hydrate may be made from urea, sodium hydroxide, and sodium hypochlorite by this reaction:

Urea will be synthesized from ammonia and carbon dioxide. The sodium hydroxide, sodium hypochlorite, and carbon dioxide will be regenerated in closed-loop cycles from the byproducts of the hydrazine synthesis. The regeneration steps add a great deal of complexity and energy consumption to the over-all process, but are necessary. Without byproduct reprocessing, piles of salts will accumulate near the depot, and sodium hydroxide and carbon will have to be supplied continuously to the depot.

In addition to the energy associated with the synthesis of ammonia, 0.31 kwhr/lb of hydrazine will be consumed to synthesize urea from carbon dioxide and ammonia,¹⁶ and 4.12 kwhr/lb of hydrazine will be required to operate a chlorine-sodium hydroxide electrolytic cell involved in regenerating sodium hypochlorite from the byproduct sodium chloride.¹² The thermal energy required to decompose limestone during the recovery of carbon dioxide and sodium hydroxide from the byproduct sodium carbonate will be about 750 Btu/lb of calcium carbonate above 500 C. About 0.7 kwhr/lb of hydrazine has been added to cover uncertainties in these energy estimates. The energy required to synthesize 1 lb of hydrazine and its associated liquid oxygen is estimated to be about 10 kwhr. This estimate is considered low, because chemical conversion efficiencies of 100 per cent have been assumed here for several steps, including the final synthesis.

It was determined under Subtask 5.0 (Sec. 1) that in five years about 1343 lb/hr would have to be synthesized to supply the fuel needs of 22 fuel cell powered tanks. At least 13.4 Mwe will be supplied to operate this plant. About 1 Mwt at or above 500 C will be required to decompose the calcium carbonate. These power estimates are felt to be lower limits.

6.2.1.5.2 CH₃OH Synthesis. Methanol can be synthesized from carbon monoxide and hydrogen with raw water and potassium carbonate as basic raw materials. The hydrogen will be produced by the electrolysis of water. The oxygen from the electrolytic cells will be liquefied by a liquid-air refrigerator. The carbon monoxide will be recovered

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Fig. 25. SCHEMATIC OF PROCESS FOR HYDRAZINE PRODUCTION

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from potassium carbonate, a byproduct of the fuel cell reaction, in a closed-loop calcium cycle. Potassium hydroxide, one of the products of this closed loop, will be transported with the methanol to the user's fuel cells.

Figure 26 is a schematic representation of a methanol synthesis plant. Carbon dioxide is reduced with hydrogen to carbon monoxide, which is then reacted with hydrogen to form methanol. The synthesis will take place at about 350 C and about 300 atm.

The process is complex because of the basic MED criterion that raw materials should be obtained locally whenever possible. The most dependable local source of carbon in this situation will be the potassium carbonate from the fuel cell. Animal or vegetable matter or earth will be used as carbon sources for makeup when these materials are available. Alternatively, small amounts of petroleum fuel may be supplied to the depot for this purpose.

The generation of carbon monoxide and potassium hydroxide from potassium carbonate is accomplished in a closed-loop calcium cycle. This cycle was chosen because the decomposition temperature of potassium carbonate, under vacuum, is above 900 C (1650 F). Calcium carbonate, however, may be decomposed at a lower temperature, as is indicated in Fig. 27,¹⁷ which illustrates that the decomposition temperature is related to the pressure. The decomposition of calcium carbonate requires about 750 Btu/lb of calcium carbonate at a temperature greater than 500 C (930 F). This process heat will be obtained either from the nuclear reactor or from the combustion of hydrogen and oxygen from the electrolytic cell.

Based on Allis-Chalmers' five-year projection of the methanol-oxygen fuel cell, 22,700 lb of methanol, 34,000 lb of liquid oxygen, and 79,500 lb of potassium hydroxide must be produced during 16 hr of plant operation to support 22 Army tanks. The synthesis reaction, by which about 95 per cent of the reactants are converted into product,¹⁸ must be supplied with hydrogen at 187 lb/hr. The reduction step, in which about 90 per cent of the carbon dioxide is reduced,¹⁶ will require hydrogen at 104 lb/hr. The total hydrogen requirements will therefore be 291 lb/hr.

The efficiency of the carbon recovery operation, which includes the reduction and the methanol synthesis reactions, is about 85 per cent by the above figures. Carbon dioxide must be supplied at 293 lb/hr from a source other than the potassium carbonate. This amount of carbon dioxide can be obtained by treating earth at about 27 ft³/hr. About 0.5 kwhr/lb of methanol produced will be expended in compressing the carbon monoxide and hydrogen before feeding into the synthesis reactor.¹⁹

On the basis of these production rates, the power required to produce methanol and liquid oxygen from raw water and potassium carbonate is 8.03 Mwe and about 0.98 Mwt at or above 930 F. The electrical energy required to produce 1 lb of methanol and its associated liquid oxygen is 5.66 kwhr/lb of methanol produced.

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FIG. 26. SCHEMATIC OF PROCESS FOR CH_3OH PRODUCTION

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FIG. 27. DECOMPOSITION PRESSURE OF CaCO₃

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6.2.2 Chemonuclear Manufacturing Process

Considerations of the MED concept in terms of fuel requirements for a selected group of nonregenerative systems based on air and water have indicated the desirability of direct synthesis. The results of the initial phase of this study²⁰ showed that any fuel synthesis requiring more than one chemical conversion step placed a large power demand on the reactor. The increase in the number of modules required for an increase in the number of process steps was also apparent. In direct synthesis, the goal, prime materials are converted into power fuels, with the elimination of electrolysis equipment and of electrical generating and chemical processing equipment wherever possible. Chemonuclear synthesis was examined with this goal in mind.

6.2.2.1 Introduction. The energy produced in a nuclear reactor can be used in the form of heat or radiation energy. In the former case, the nuclear energy is permitted to degrade to thermal energy in fuel rods and then removed through a heat-transfer medium for use in electrical power generation or, if desired, in chemical processing. Fission products and beta activity are contained in the fuel elements and their energy converted to heat, and the neutron and gamma flux is eliminated from the site of heat utilization by shielding. Over-all efficiency of conversion of thermal to electrical energy varies from 30 per cent for a large, permanent installation such as the Pathfinder reactor²¹ to an estimated 18 per cent for a smaller, compact mobile unit such as the MCR²².

For direct utilization of the radiant energy, the reactor design must permit intimate interaction between the chemical substrate and the reactor fuel, to maximize dissipation of the fission-fragment energy in the substrate. Approximately 168 Mev of the 200 Mev resulting from the fission of a uranium atom appear as fragment recoil energy²³. Because 84 per cent (168/200) of the total energy of fission is contained in the fission fragments, maximum utilization of their energy in a radiation reaction is potentially an efficient method of using reactor energy.

After absorption in the chemical substrate, the efficiency of the chemical reaction is determined by the efficiency of the radiant event leading to the desired primary reaction and the relative rates of the competing secondary reactions involving the radicals and ions primarily produced. The observed product yield, G , defined as the number of product molecules produced per 100 ev absorbed in the chemical system, varies with the type of radiation used. For a closed-cycle system involving an energy-producing reaction in a converter using a chemical fuel and a regeneration or the processing (endothermic) reaction carried out in a nuclear reactor, the percentage of fission energy, E , which finally is available to the surroundings as chemical energy in the fuel may be given by

$$E = \frac{G \Delta H \times}{23}$$

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where $G = G$ value, ΔH = heat of the endothermic reaction in kcal/mole, and x = fraction of the fission energy released in the chemical system by the fission recoils and other nuclear radiations. It is seen that intimate contact between reactor fuel and the chemical system is necessary to maximize x . Fission recoil decomposition of water leads to the production of hydrogen with a G value of 1.8. With ΔH for the reaction equal to 68 kcal/mole, an efficiency, E , of 4.5 per cent, is obtained for the production of hydrogen in an aqueous homogeneous reactor where x is approximately 0.84. It is seen that a significant increase in G value is required to improve the over-all energy efficiency.²⁴

A disadvantage of the chemonuclear reaction that appears to be intrinsic is the radioactive contamination of the chemical system. The highly radioactive fission fragments after thermalization remain in the reactant-product mixture. Even if the products are gaseous, as is the case for hydrogen and oxygen produced from water, the gases are contaminated with the gaseous fission products, xenon, krypton, and iodine.

6.2.2.2. Chemonuclear Reactors. Two reactor systems suitable for chemonuclear synthesis have been studied experimentally. In one system, fuel in the form of enriched-uranium--glass fibers or enriched uranium dioxide powder permits both reactor criticality and the intimate contact with the chemical reactant necessary for efficient radiation energy transfer. The system was first demonstrated by Hardeck and Dondes²⁵ of Rensselaer Polytechnic Institute, and has since been studied by Steinberg, Powell, and Green²⁶ of Brookhaven National Laboratory and by Cusack, Miller, and Yockey²³ of Aerojet-General Nucleonics. The latter workers have calculated an efficiency of 95 per cent for the deposition of fission fragment energy in liquid ammonia for a suspended fuel particle size of one micron.²³ The losses expected are due to self-absorption in the solid fuel filaments or powders and to system geometry. This system is in an early state of development.

Another reactor system which has potential for chemonuclear synthesis is the homogeneous reactor. Although much research-and-development effort has been expended on this system, the major effort has been directed toward the production of electrical power via the conventional steam turbine cycle. In this reactor system, the nuclear fuel is dissolved in the medium to be reacted chemically. An aqueous homogeneous reactor used for chemical synthesis would be a direct source of hydrogen and oxygen.

6.2.2.3 Evaluation of the Homogeneous Reactor for Direct Synthesis of H_2 and O_2 from H_2O . Because of the amount of research and development on the aqueous homogeneous reactor, a rather detailed examination of this system for chemonuclear synthesis of hydrogen and oxygen is possible. Its relative efficiency for chemical reaction can be seen by comparing its gas yield with those of heterogeneous reactors:

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<u>reactor</u>	<u>power level, Mwt</u>	<u>H₂-gas yield, liters/Mwhr</u>
EBWR ²⁷	20	54
BORAX IV ²⁸	2	160
HRT ²⁹	5 to 10	13,300*

*This yield corresponds to a G value of 1.8 for H₂ production.

Problems of direct interest were the gas yield, methods of venting and decontaminating the product gases from the core solution, handling and separating the large volumes of hydrogen and oxygen, core size, corrosion (which has been a serious difficulty for the HRT), and the approximate over-all size with shielding.

The Oak Ridge National Laboratory was visited to discuss the adaptability of the homogeneous reactor to the MED application. The visit was arranged with Dr. John Swartout, Deputy Director of the Laboratory, and there were discussions with the scientists and engineers in charge of the various phases of the HRT program. Some of the conclusions are discussed below.

(1) Gas Yield: No significant increase in gas yield over a G_{H₂} of 1.8 is to be expected.²⁹ It is felt that this statement is overly conservative and that studies designed to increase rather than decrease gas yield might produce an improvement of 50 to 100 per cent. This opinion is not shared, however, by the ORNL personnel, including Dr. John Boyle, water-radiation chemist.

(2) Corrosion: Corrosion should present no problem over the range of possible core temperatures. The use of a Zircaloy core maintained at 200 C should keep corrosion down to 1 to 2 mills/yr. Elimination of the large breeder blanket required for economic reasons for the HRT would make direct wall cooling possible and the maintenance of core temperatures relatively easy.

(3) Reactor Wattage: HRT experiments were carried out at 25 to 35 kw/liter of core solution; 35 kw/liter corresponds to 1 ft³/Mwt for reactor plus auxiliaries. Autoclave tests have been carried out at power densities up to 100 kw/liter, and 200 kw/liter was felt to be feasible, indicating possible corresponding increases in reactor compactness. Hot spots at these high power densities can be avoided by using Zircaloy, maintaining good circulation of core solution to prevent salt deposition, and keeping the core walls 15 to 20 C below the core solution temperature.

(4) Reactor Control: Reactor control should present no problem with rapid circulation of core solution and rapid venting of product gases.

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(5) Solid Precipitation: At the temperatures considered, uranium concentration can be kept within the limits prescribed by the need to prevent solid precipitation.

(6) Product Handling: Rate of gas evolution at steady state is large. Rapid venting of gas and removal of extremely small amounts of highly radioactive xenon and krypton from large volumes of a hydrogen-oxygen gas mixture are required. It is felt that this can be done by selective condensation using a baffled, externally cooled exchanger to remove radioactive gases that have higher boiling points than hydrogen and oxygen, then condensing the relatively large amounts of oxygen, and finally liquefying the hydrogen. Traces of oxygen can be removed from the hydrogen by a catalytic recombiner before liquefaction. Gaseous mixture would be produced at approximately 32,000 liters/min by an 81-Mwt reactor, the size required for Case A application. The rapid handling of such volumes of initially radioactive gas continuously would be difficult.

(7) Shielding: The shielding requirements for close access upon shutdown and the reactor size needed to produce the required fuel suggest, to the ORNL people, a size that would preclude mobility. As indicated in para. (3), at a power density of 35 kw/liter, the reactor and auxiliaries will occupy 1 ft³/Mwt. Thus, an 81-Mwt reactor would have a minimum basic volume of 81 ft³.

To summarize, the chief technical difficulties associated with the production of hydrogen and oxygen by chemonuclear synthesis do not lie primarily in the area of reactor-core corrosion or gas yield, but in the areas of handling large quantities of a gas mixture, achieving adequate shielding, removal, decontamination, and separation. In addition, reactor size based on the relatively low gas yield and the shielding requirements would appear to preclude mobility. Thus, the present evaluation would not select chemonuclear synthesis for hydrogen and oxygen production.

6.2.2.4 Chemonuclear Reactor Power Requirements. Evaluation of the chemonuclear reactor systems under consideration on the basis of weight or volume is difficult because of the lack of experimental engineering data. The experiments already carried out^{23,25,26} have been research studies designed to demonstrate reaction feasibility and to obtain yield and conversion data. For this reason, a comparative evaluation can be made only on the basis of reactor thermal power required for chemonuclear synthesis. For purposes of comparison, thermal power requirements were calculated for synthesis of ammonia and hydrogen with the more conventional mobile compact reactor, using the electrolysis and Claude process synthesis routes. Fuel requirements were determined by the needs of the corresponding fuel cell power systems for Case A application. The basis of the fuel requirements for each system has been developed in Sec. 7 of this report. Synthesis power data for the various conventional process steps are listed and referenced in an addendum to Table 24.

In determining power requirements for chemonuclear synthesis of fuels for the ammonia-oxygen, hydrazine-oxygen, and hydrogen-oxygen systems, it was assumed that the reactor

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will produce heat for electric power production via conventional turbine as well as initiate chemical reaction by fission recoil radiolysis. In this connection, an estimate of the efficiency of conversion of thermal to electrical energy for a chemonuclear reactor is also difficult because of the lack of experimental engineering data. It can be assumed, however, that for thermoneutral or exothermic reactions, such as the synthesis of ammonia from nitrogen and hydrogen, the energy of the fission products will ultimately be available as heat energy. The efficiency of heat utilization to produce electric power will depend on reactor design and temperature of operation. Reactor temperature, in turn, may be determined by the chemical reaction being carried out. For the initiation of an endothermic reaction, such as the conversion of hydrazine from ammonia, however, a significant amount of the fission recoil energy will appear as chemical energy in the energetic product, hydrazine. In such a case it might be advantageous to produce at least some of the electrical power required for chemical processing with a more conventional mobile compact heterogeneous reactor.

6.2.2.5 NH₃ Synthesis. Reactor power for ammonia synthesis was calculated assuming 168 Mev/fission and 3.1×10^{10} fissions/sec/w of thermal power. In the absence of experimental fission recoil data, the G_{NH_3} was assumed to be 2 for conversion of a 1-to-3 mixture of nitrogen and hydrogen at a gas pressure of 500 atm and a temperature of 250 C. Because of the latitude possible in the G value, no corrections were made for efficiency of energy deposition or geometry. A synthesis power figure of 83 Mwt was determined (Table 22).

In addition, 8.05 Mwe are required for separation of the required amounts of nitrogen and hydrogen from air and water. Subject only to an ultimate chemonuclear reactor design, and data on the efficiency of removing thermal energy for simultaneous electric power production, it is expected that the heat required for the electric power can be obtained with no increase in reactor power over that required for synthesis.

6.2.2.6 N₂H₄ Synthesis. Results of Aerojet-General Nucleonics research²³ indicate a hydrazine yield of 666 lb/Mwt/16-hr day and an average $G_{N_2H_4}$ of 2. The data were obtained with agitated slurries of enriched uranium dioxide suspended in liquid ammonia contained in a stainless-steel capsule and placed in the neutron field of the 5-w AGN-201 M reactor. The above yield was also determined independently using the calculation described in the preceding section, assuming a $G_{N_2H_4}$ of 2, after applying the 95-per cent fission fragment energy deposition efficiency reported by Aerojet-General. With these data, a reactor power of 32.4 Mwt was calculated for synthesis of the hydrazine required for Case A application (Table 22). In addition, 6.62 Mwe are required for processing.

6.2.2.7 Hydrogen Synthesis. ORNL data on HRT²⁹ were used to calculate a hydrogen yield of 36.7 lb/Mwt/16-hr day. A homogeneous reactor power of 81 Mwt is determined for synthesis of the requisite amount of hydrogen (Table 22). In addition, 2.36

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Mwe (12 Mwt) are required for process power. In this case there should be no difficulty in obtaining the electric power as byproduct energy from a reactor rated at the synthesis level.

6.2.2.8 Evaluation of Chemonuclear Process. The chemonuclear reactor data are presented in Table 22. For comparison, on a reactor-power basis, data for the hydrogen-oxygen, ammonia-oxygen, and methanol-oxygen fuel cell power systems were developed and are presented in Table 23. Table 24 presents similar data for the internal combustion of hydrogen and ammonia using conventional chemical synthetic routes and powered with MCR units. All power systems were calculated for Case A application. For the purpose of the comparison, a straight 20-per cent efficiency of conversion of thermal to electrical power was assumed for determining total MCR thermal power. However, as indicated in Sec. 5, the use of a regenerative cycle is expected to increase MCR efficiency from 17.7 per cent²² to 23 per cent.

6.2.2.8.1 Comparisons on the Basis of Reactor Power. From Table 22, it can be seen that 33 to 65 Mwt of chemonuclear reactor power are required for the hydrazine-oxygen fuel cell system,* and 83 Mwt for the ammonia-oxygen fuel cell system; 81 Mwt are required for the hydrogen-oxygen fuel cell. Electric power requirements are very low, 2.36 Mwe for the homogeneous reactor system, reflecting a power advantage of the direct chemonuclear synthetic route.

It is seen in Table 24 that, on the basis of weight of material transported from reactor to tank, the internal-combustion engine operating on hydrogen is most efficient. This observation confirms the fact that on an energy-to-weight basis, hydrogen is the most efficient chemical fuel known. On the basis of reactor power, however, the relatively large amount of hydrogen required for internal-combustion leads to the rather high reactor power demand of 72 Mwt. Table 24 also shows that ammonia as an internal-combustion engine fuel requires a sizable reactor power demand, 73 Mwt. In addition, the 54,500-lb requirement for Case A application, reflecting the low Btu value of ammonia, leaves much to be desired from the viewpoint of fuel transportation.

Synthesis of ammonia by the conventional Claude process with MCR power is seen to require considerably less reactor power than that calculated for chemonuclear synthesis, (39 Mwt vs. 83 Mwt). Similar comparison of the data of Tables 22 and 23 shows that reactor power requirement for hydrogen production in the homogeneous reactor is 81 Mwt compared with 30 Mwt by conventional electrolysis.

In terms of reactor power required, the conventional electrolytic synthesis of hydrogen and oxygen powered by the MCR is seen to be the most efficient system (Table 22). The

*Based on the limiting case, in which no heating value is obtained from the chemonuclear reactor and an MCR is required for all the processing power.

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value for total electrical power of less than 6 Mwe (Table 23), approaches the capability of two MCR units, especially if they are equipped with regenerators to increase cycle efficiency and electrical output (Sec. 5). With the information developed in Sec. 7 of this report, a Case A depot can be derived consisting of two MCR plants, one module of electrolytic cells, and one liquefaction module.

The possibility of a hydrogen-air fuel cell system that would eliminate the need to produce and transport 24,000 lb of oxygen is also of considerable interest. A hydrogen-air fuel cell has approximately 60 per cent of the output of the hydrogen-oxygen cell. With this system, total fuel transportation can be limited to approximately 3000 lb of hydrogen/22 tanks/8-hr day.

6.2.2.8.2 Comparison on the Basis of the Processing Plant Size. Table 25 lists plant weight, volume, process power, and reactor power required for the production of hydrogen, ammonia, and methanol by conventional synthesis with MCR power and for homogeneous reactor synthesis of hydrogen. The corresponding fuel cell power systems for Case A application are the basis of the fuel requirements. It is seen that no advantage is obtained with respect to weight or volume by direct synthesis of hydrogen and oxygen in the reactor over the presently proposed electrolysis route. It should be noted, however, that the electrolysis units have been especially designed in this study (Sec. 6.2.1.1) to minimize weight and volume for mobility.

6.2.2.9 Chemonuclear Synthesis of O₃. Ozone is a potential vehicle monopropellant that could be synthesized directly in a chemonuclear reactor. This chemonuclear formation of ozone has been discussed in the literature³⁰ and what follows is based on that report. Oxygen is fed into a nuclear reactor loaded with particles of urania (UO₂) or urania glass fiber and converted to ozone by the radiation. The nuclide collision process produces an avalanche of free oxygen radicals, which react to form ozone, because the chance of two oxygen radicals meeting each other is negligible. A small fraction, conservatively estimated at 20 per cent, of the nuclide collision energy is lost in thermal agitation. It can also be shown that for fission fragments, an average of 34 per cent of the energy is lost by nuclide collision and 66 per cent by electron friction. There is also some loss of fission-fragment energy due to self-absorption in the urania particles or fibers. This amounts to about 5 to 10 per cent of the total fission-fragment energy for 1- to 5-micron particles. However, besides fission fragments, the fission process produces beta, gamma, and neutron radiation which carries approximately 13 per cent of the fission energy and which will deposit approximately 80 per cent of this in the oxygen, mostly through electron interactions. Thus, the over-all G value due to all processes is approximately 8.56.

For comparison purposes the G value previously noted for the chemonuclear synthesis of hydrazine was 2.0. Thus, the formation of ozone is a more efficient process. This high G value reflects the fact that any radiation decomposition of ozone produces the

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starting material for ozone synthesis, i.e., oxygen. The radiation decomposition of hydrazine produces nitrogen and hydrogen. The starting material for the synthesis, however, is ammonia.

The safe handling of gaseous ozone, under pressure, has been studied and reported by workers at Temple University¹⁰. Because there is, in general, a characteristic surface-to-volume ratio above which a flame does not propagate, it has been found possible to safely store gaseous ozone in cylinders containing hollow, inert spheres. The presence of the spheres reduced the available volume of the cylinders by only 10 per cent. Attempted spark ignition of ozone stored in this manner was unsuccessful, demonstrating the effectiveness of such a storage system.

The decomposition of ozone into $3/2 O_2$ evolves 34.4 kcal/mole or 1300 Btu/lb, while the formation of water from hydrogen and oxygen evolves 5800 Btu/lb of reactants. This ozone decomposition could be accomplished in an internal-combustion engine with a spark ignition or in a gas turbine over a catalytic surface. The possibility of an ozone-oxygen fuel cell has also been suggested.¹ This cell would operate according to the following equations:

This cell would have the additional advantage of not having a water-balance problem. The actual construction of such a device has not been reported.

The principal advantage in the use of ozone as a monopropellant is that the starting material, oxygen, is universally available. Thus, for example, such a synthesis plant could function quite well in a desert area. Such a plant is not presently available and considerable research and development in many areas, e.g., synthesis, separation, storage, and utilization, would be necessary before an operational system could be considered. Nevertheless, this fuel cycle has an inherent simplicity that should not be overlooked for future applications.

6.2.2.10 Summary. The application of chemonuclear reactors to the MED concept has been reviewed. Chemonuclear reactors are in an early state of development, and their power requirements are seen to exceed those of systems based on the more conventional MCR using conventional chemical processing techniques (83 compared with 39 Mwt and 81 compared with 30 Mwt for the ammonia and hydrogen fuel cell power systems, respectively).

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It is felt, however, that on the long term basis (a 20-yr projection), the inherent compactness and potential efficiency of nuclear energy for chemical conversion will render chemonuclear systems of continuing interest to both MED and mobile military systems. An example is the hydrazine system. The conventional Raschig process unit for hydrazine synthesis would be impractical for a mobile unit, especially when added to a Claude process unit for ammonia and the MCR reactor for power. The chemonuclear system considered on the basis of reactor power alone is not unreasonably large. In addition, the possibility of such a depot serving a dual function of providing a source of mobile electric power via the hydrazine-oxygen fuel cell system and of high-energy propellant-oxidizer system, hydrazine-oxygen provides added justification for continuing interest in chemonuclear conversion systems.

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TABLE 22

CHEMONUCLEAR REACTOR POWER REQUIREMENTS FOR SELECTED FUEL CELL POWER SYSTEMS
(Case A - 22 tanks rated at 420 hp net, electric drive, operating on 8-hr/day basis with 50% use factor)

fuel system	synthesis route		material requirements, lb	power requirements		fuel cell thermal* efficiency, %	reactor power, Mwt
				Mwe ***	Mwt		
NH ₃ -O ₂ fuel cell	N ₂	liquefaction of air	25,420	0.78		62.8	
	H ₂	electrolysis of H ₂ O	5,467	6.32			
	O ₂	electrolysis of H ₂ O	43,689				
	O ₂ (liquid)	liquefaction	43,689	0.95			
	NH ₃	chemonuclear synthesis	30,981		82.6		
	Total			8.05	82.6		83
N ₂ H ₄ -O ₂ fuel cell	N ₂	liquefaction of air	18,800	0.59		76	
	H ₂	electrolysis of H ₂ O	3,500	4.06			
	O ₂ (liquid)	liquefaction of air	21,000	0.54			
	NH ₃	Claude process	45,600	1.43			
	N ₂ H ₄	chemonuclear synthesis	21,500		32.4		
	Total			6.62	32.4		33 to 65**
H ₂ -O ₂ fuel cell	(fission recoil decomposition of H ₂ O in homogeneous reactor)				81.2	73.4	
	O ₂ (liquid)	separation and liquefaction	23,760	0.51			
	H ₂ (liquid)	separation and liquefaction	2,970	1.85			
	Total			2.36	81.2		81

*The heat of combustion for this calculation is the "lower" heating value.

**Maximum reactor power if chemonuclear reactor produced only N₂H₄ and MCR were used for electric process power, operating at 20% efficiency.

***See Addendum Table 24.

TABLE 23

MOBILE REACTOR POWER REQUIREMENTS FOR SELECTED FUEL CELL POWER SYSTEMS

(Case A - 22 tanks rated at 420 hp net, electric drive, operating on 8-hr/day basis with 50% use factor)

fuel system	synthesis route		material requirements, lb	power requirements		fuel cell thermal* efficiency, %	reactor power, Mwt **
				Mwe **	Mwt		
H ₂ -O ₂ fuel cell	H ₂	electrolysis of H ₂ O	2,970	3.49		73.4	30
	O ₂	electrolysis of H ₂ O	23,760				
	H ₂ (liquid)	liquefaction	2,970	1.86			
	O ₂ (liquid)	liquefaction	23,760	0.60			
	Total			5.95			
NH ₃ -O ₂ fuel cell	N ₂	liquefaction of air	24,000			62.8	39
	H ₂	electrolysis of H ₂ O	5,140	6.02			
	O ₂ (liquid)	liquefaction of air	39,100	0.98			
	NH ₃	Claude process	27,700	0.79			
	Total			7.79			
CH ₃ OH-O ₂ fuel cell	H ₂	electrolysis of H ₂ O	4,680	5.49		49	40.4 + 0.98
	O ₂	electrolysis of H ₂ O	34,000				
	O ₂ (liquid)	liquefaction	34,000	0.84			
	CO ₂	reduction	31,100	1.07			
	KOH	recovery	79,500		0.98		
	CH ₃ OH	reduction of CO	22,700	0.68			
	Total			8.08	0.98		

*See Appendix I for discussion of efficiencies. The heat of combustion for this calculation is the "lower" heating value.

**See Addendum Table 24

TABLE 24

MOBILE REACTOR POWER REQUIREMENTS FOR SELECTED INTERNAL-COMBUSTION POWER SYSTEMS

(Case A - 22 tanks rated at 700 hp gross, operating on 8-hr/day basis with 50% use factor)

fuel system	synthesis route		material requirements lb	power requirements Mwe	engine thermal efficiency %	reactor power, Mwt
H ₂ -air	H ₂	electrolysis of H ₂ O	8,000	9.4	30 (est.)	72
	H ₂ (liquid)	liquefaction	8,000	5.0		
	Total			14.4		
NH ₃ -air	N ₂	liquefaction of air	44,900	1.7	30 (est.)	73
	H ₂	electrolysis of H ₂ O	9,620	11.3		
	NH ₃	Claude process	54,500	1.7		
Total				14.7		

Addendum (factors used in calculations):

purification and electrolysis of water: 18.5 kwhr/lb of H₂
 liquefaction of nitrogen (air): 0.5 kwhr/lb of N₂
 liquefaction of oxygen (air): 0.4 kwhr/lb of O₂
 liquefaction of hydrogen: 10 kwhr/lb of H₂
 electric power - Claude process: 0.72 kwhr/lb of NH₃
 conversion efficiency, reactor thermal
 output to electric power: 20 per cent²²
 power requirements based on a
 16 hr plant day

TABLE 25

FUEL PROCESSING PLANT CHARACTERISTICS

(16-hr/day basis)

(Case A - 22 tanks rated at 420 hp net, electric drive, operating on 8-hr/day basis with 50% use factor)

fuel system	process		plant weight, lb	plant volume, ft ³	power requirements		total reactor power, Mwt*
					Mwe	Mwt	
H ₂ -O ₂ fuel cell	electrolysis of H ₂ O		30,000	1060	3.49		
	liquefaction of H ₂ + O ₂		23,500	2170	2.46		
	Total		53,500	3230	5.95		30
H ₂ -O ₂ fuel cell	(fission recoil decomposition of H ₂ O)		--	--		81.2	
	O ₂	separation and liquefaction	30,000	2200			
	H ₂	separation and liquefaction	23,500	2170	2.36		
	Total		53,500	4370	2.36	81.2	81
NH ₃ -O ₂ fuel cell	H ₂	electrolysis of H ₂ O	53,000	2120	6.02		
	N ₂	liquefaction	45,000	2810			
	O ₂	liquefaction			0.98		
	N ₂ -H ₂	compressor	30,000	2160	0.79		
	NH ₃	Claude process	25,000	2160	--		
	Total		153,000	9250	7.79		39
CH ₃ OH-O ₂ fuel cell	H ₂	electrolysis	43,900	1890	5.49		
	O ₂	liquefaction	15,000	635	0.84		
	CH ₃ OH	synthesis	114,700	6720	1.75	0.98	
	Total		173,600	9245	8.08	0.98	40

*Based on 20% efficiency in conversion of thermal to electric power, except for homogeneous reactor, where chemonuclear synthesis power is the major power requirement.

6.2.3 Comparison of Fuel Systems from a Viewpoint of Fuel Synthesis

Table 26 compares the weight of synthesis equipment and the power required for the fuel synthesis plants.

TABLE 26

COMPARISON OF FUEL SYNTHESIS PLANTS* TO SERVICE 22 FUEL
CELL POWERED TANKS
(five-year projection)

<u>fuel system</u>	<u>number of modules</u>	<u>plant weight, lb</u>	<u>synthesis power</u>
H ₂ -O ₂ (electrolysis)	2	53,500	5.95 Mwe
H ₂ -O ₂ (steam reforming)	8	213,500	2.86 Mwt 2.46 Mwe
NH ₃ -O ₂	6	153,000	7.79 Mwe
N ₂ H ₄ -O ₂	-	-	13.4 Mwe** + 1 Mwt**
CH ₃ -OH-O ₂	-	-	8.03 Mwe + 0.98 Mwt
Na-O ₂			
Castner process	20	585,000	17.7 Mwe
Na from NaHg	5	123,000	12.1 Mwe

*The power source is not included.

**These values approximate the lower limits of the power.

Enough fuel and oxidizer will be produced in each plant to support 22 Army tanks powered by fuel cells anticipated in five years. The results of the fuel synthesis study are summarized below.

A two-module liquid-hydrogen--liquid-oxygen generation plant, weighing about 53,000 lb, and a source of 5.95 Mwe are envisioned for the fuel supply for 22 Army tanks powered by the advanced hydrogen-oxygen fuel cells anticipated in five years. The basic raw material is water. Because of the lightness and compactness of the plant, the engineering simplicity of the processes, and the low power required for fuel synthesis, this fuel system is outstandingly superior to the other fuel systems considered for complete elimination of petroleum requirements.

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The ammonia-oxygen plant, for example, would be three times as heavy, not including the greater weight of the power source, which must supply about 30 per cent more power. The processes carried out in the ammonia plant would be more complex. Water and air would be the starting raw materials.

The hydrazine-oxygen fuel system would involve a very complex synthesis process requiring large amounts of energy. A series of intricate chemical reactions must be carried out to recover, from the byproducts of the synthesis, process materials that are not available locally. The synthesis path to hydrazine involves the production of ammonia. Because of the added process complexity and the increased equipment weight and volume required to synthesize hydrazine from ammonia, hydrazine does not appear to promise a net advantage over ammonia as a fuel for this application.

The methanol fuel system does not appear promising because carbon, one of the basic raw materials, will be difficult to supply. Earth, and animal and vegetable matter can be used as a carbon source, but will not be readily available in many areas of the world in which the MED system might be operated. Petroleum fuels can be flown in to provide the carbon supply. The most accessible local source of carbon (and the recommended source) is the carbonate byproduct of the fuel cell reaction. This would be stored in the using vehicle, transported back to the synthesis depot, and chemically processed to recover carbon dioxide, a feed material for the synthesis of methanol. Either sodium hydroxide or potassium hydroxide must be manufactured in the synthesis plant, transported to the user, and stored by the user with the fuel and oxidizer. More different materials, in large amounts, must be produced, stored at the depot, transported to the user, stored by the user, and transported back to the depot than for any of the other fuel systems. Damage to the synthesis plant, bulk storage or transportation vessels, or using vehicle, which results in the loss of methanol, the hydroxide, or carbonate, will interrupt the closed carbon cycle, and cause a decrease in the capacity of the entire MED.

The sodium fuel systems require the cycling of sodium or its compounds through the system. Sodium is produced at the depot from the sodium hydroxide returned from the field operations. Two systems are available for synthesis of sodium. The Castner process requires a chemical plant of 20 modules weighing 585,000 lb and 17.74 Mwe to produce sodium for 22 tanks. The sodium-via-sodium amalgam process requires a chemical plant of 5 modules weighing 123,000 lb and 12.1 Mwe. The plants are relatively heavy and require large energy inputs. The system is dependent on the complete recovery and utilization of the sodium. Any spillage or loss will interrupt the closed loop and decrease the capacity of the MED.

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6.3 FUEL STORAGE AND TRANSPORTATION

The objective of this phase of the study was the determination of the equipment and facilities required to store, transport, and deliver selected fuel materials to a user safely, economically, and efficiently.

6.3.1 Material Characterization

Lists of fuels and oxidizers considered in this study are presented in Sec. 6.1. The most feasible of these are liquid hydrogen and liquid ammonia as fuels and liquid oxygen and air as oxidizers. The handling of these materials will be considered in more detail. The battery-operated vehicles and sodium-amalgam fuel cell system are considered special cases and are discussed elsewhere in this report.

The following materials were considered early in the study and then eliminated from the list of promising fuels and oxidizers for the MED: diborane, formic acid, hydrazine, hydrogen peroxide, nitric oxide, nitrogen dioxide, nitrogen tetroxide, nitrous oxide, sodium borohydride, and UDMH (unsymmetrical dimethylhydrazine). The eliminations were based on preliminary evaluations of physical and chemical properties, energy and equipment required for synthesis, and energy to be regained at the using vehicle.

Most of the eliminated materials are highly toxic. If these materials were employed in the MED, material toxicity would be an important factor in design and operation. The necessary safety precautions for handling these chemicals are well understood and these materials are presently being handled safely in routine, well-controlled operations.^{31,32} However, the MED does not represent a routine, well-controlled operation. As a result of enemy action, toxic and dangerous materials might be released uncontrollably. Equipment and surroundings would then become untenable for some time.

Anhydrous ammonia is considered toxic. In spite of this, it survived the preliminary screening because it is an excellent fuel, the energy required for synthesis was considered to be relatively low, and it can be easily stored and handled as a liquid.

Hydrogen, oxygen, and enriched air are not toxic. The only harmful effect of a high concentration of hydrogen is unconsciousness due to anoxia (the exclusion of oxygen). All three materials are slightly dangerous as cryogenic liquids because of their low temperatures. However, the high evaporation rates of cryogenic liquids tend to reduce the hazard to personnel of extensive contact of the liquids with the skin.

As would be expected, most of the fuels and oxidizers reported present moderate or severe explosion and fire hazards.

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6.3.2 Preliminary Survey of Tankage

The weights of present bulk-liquid trailers have been ascertained and are listed below. The carriage for the storage vessels is estimated at 5500 lb.

TABLE 27
BULK-LIQUID TRANSPORT TRAILERS

service	vessel material*	capacity, gal	trailer weight, lb	weight/volume, lb/gal**	
				vessel	vessel and 5500-lb carriage
O ₂ ***	aluminum	5,600	16,000	1.9	2.9
O ₂	steel	5,600	20,800	2.7	3.7
H ₂ ***	aluminum	12,000	32,000	2.2	2.7
H ₂	steel	12,000	44,500	3.3	3.7
H ₂	aluminum	7,000	29,000	3.4	4.1
H ₂ ***	steel	7,000	40,000	4.9	5.7
noncryogenics	aluminum	12,000	17,000	1.0	1.4
noncryogenics	steel	12,000	24,700	1.6	2.1

* All but the last two entries are constructed with double walls and vacuum-powder insulation. The last two have single walls and are not insulated.

** The weight/volume ratio is the empty weight of the vessel or trailer divided by the volume of the storage container.

*** Presently in service; the dimensions of the other trailers have been estimated on the basis of those in service.

Table 28 presents the ratio of vessel weight to contents weight for each material considered in this study. Based on the information above, 1.9 and 2.7 lb/gal for insulated vessels constructed with aluminum and steel, respectively, have been used in these calculations. For noninsulated vessels, the aluminum and steel shell weights of 1.0 and 1.6 lb/gal, respectively, were employed. For the storage of ammonia it is assumed that 2 in. of foam insulation (density: 2 lb/ft³) are added to a noncryogenic vessel. The weight of the insulation does not significantly increase the over-all vessel weight; 1.0 and 1.6 lb/gal for aluminum and steel vessels, respectively, have been assumed for present liquid ammonia storage vessels. The density of each material to be stored is given in the table. Except for sodium borohydride, which is a powder, each material will be handled as a liquid. The justification for this decision is presented in Sec. 6.3.4. Potassium hydroxide and potassium carbonate are included in the table, because they will be stored and transported as part of the methanol-oxygen fuel system (Sec. 6.3.4).

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TABLE 28

PRESENT AND PROJECTED BULK-STORAGE WEIGHT AND VOLUME RATIOS FOR VARIOUS MATERIALS

material	density, lb/gal	storage temperature	vessel weight ⁽²⁾ contents weight, lb/lb			gross vessel volume ⁽²⁾ capacity volume, gal/gal	
			present ⁽³⁾			present	
			steel	aluminum	projected ⁽⁴⁾	aluminum	projected ⁽⁴⁾
anhydrous ammonia	6.8 at -110 F	- 28 F ⁽¹⁾	0.28	0.18	0.047	1.55	1.16
diborane	3.7 at -170 F	-124 F ⁽¹⁾	0.73	0.51	--	1.55	--
enriched air	8.3 to 9.5 at -316 to -297 F	-300 F (avg) ⁽¹⁾	0.30 (avg)	0.21 (avg)	--	1.55	--
formic acid	10.0	ambient	0.16	0.10	--	1.01	--
hydrazine	8.4	ambient	0.19	0.12	--	1.01	--
hydrogen	0.595 at -423 F	-423 F ⁽¹⁾	4.5	3.2	1.2	1.55	1.11
hydrogen peroxide	12.1	ambient	0.13	0.083	--	--	--
methanol	6.6	ambient	0.24	0.15	0.035	1.01	1.01
nitric oxide	10.6 at -238 F ⁽³⁾	-241 F ⁽¹⁾	0.25	0.18	--	--	--
nitrogen dioxide	12.1	ambient	0.13	0.83	--	--	--
nitrogen tetroxide	12.1	ambient	0.13	0.83	--	--	--
nitrous oxide	10.2 at -128 F	-127 F ⁽¹⁾	0.26	0.19	--	--	--
potassium hydroxide ⁽⁵⁾	10.5	ambient	0.15	0.095	0.022	1.01	1.01
potassium carbonate ⁽⁶⁾	12.3	ambient	0.14	0.081	0.019	1.01	1.01
sodium borohydride (powder)	67.4 lb/ft ³	ambient	0.18	0.11	--	--	--
UDMH	6.6	ambient	0.24	0.15	--	--	--
oxygen	9.57 at -297 F	-297 F ⁽¹⁾	0.28	0.20	0.075	1.55	1.11
gasoline	6.0	ambient	0.27	0.17	--	1.01	--

(1) The normal boiling point; insulated vessel assumed.

(2) Estimated for a 4000-gal vessel, approximately 23 ft long and 65 in. ID.

(3) For cryogenic fluids, double-wall, vacuum-powder insulation assumed; for noncryogenics, single-wall, noninsulated vessels assumed; but for ammonia, single shell, foam insulation assumed.

(4) Projected tankage types assumed for these estimates detailed in Sec. 6.3.3.

(5) 6 M aqueous solution assumed.

(6) 5 M aqueous solution assumed.

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The tankage weight ratios expected to exist in five years as a result of directed research are included for several materials in the table and the storage and transportation of these materials is discussed in greater detail in Sec. 6.3.3. The vessels designed for liquid hydrogen and liquid oxygen service will have double walls of reinforced plastic and an advanced superinsulation between the walls. The vessel designed for liquid ammonia will have a single wall and an advanced foam insulation. The noninsulated vessels are considered to be constructed of reinforced plastic. These vessels and their anticipated dimensions are discussed in Sec. 6.3.3. These anticipated characteristics were employed in the calculation of the projected tankage weight ratios in the table.

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6.3.3 Projected Tankage Designs

Four types of vessels are projected for MED use in five years; these are discussed below.

6.3.3.1 Vacuum-Type Superinsulation with Plastic Liners. Present vacuum-type insulation in commercial and military use consists of double-shell aluminum tanks with vacuum and a powder (e.g., Microcel) between the walls. The inner and outer walls are about 1/4 and 3/4-in. -thick, respectively. The powder, which has a density of about 8 lb/ft³, fills the 6-in.-thick vacuum space. The vessel weighs about 23.3 lb/ft² of surface, excluding the carriage. The carriage will weigh approximately 5500 lb. A 7000-gal liquid hydrogen trailer employing vacuum and a 6-in. thickness of Microcel insulation exhibits a hydrogen vaporization of about 1.5 to 1.9 per cent of the hydrogen capacity per day. It has been estimated that a 7000-gal liquid hydrogen vessel employing about 1 in. of present-day superinsulation, e.g., Linde's SL-91, will exhibit a vaporization rate of approximately 0.5 per cent. Allowance has been made in this estimate for the heat leaking along the structural supports between the liners and along the interconnecting piping. It is estimated that the liquid oxygen boiloff in this vessel will be approximately 0.05 per cent per day. The bulk thermal conductivity of the above insulation material is reported to be 1.0×10^{-5} Btu/(hr)(ft)(°F).³³ The density of projected vacuum-type superinsulation is estimated at about that existing today, about 7 lb/ft³.

Fiberglass or asbestos-reinforced plastics are being developed for small, light vessels for high-pressure gas storage. The density of one piece of such a material was determined to be about 100 lb/ft³. It is anticipated that, as a result of extensive research and development, large reinforced-plastic vessels of the sizes and shapes common for bulk-storage containers will be available in five years. Reinforced-plastic inner and outer liners 3/16 and 1/2 in. thick, respectively, are considered possible for 4000-gal vessels. The projected over-all surface density of such a vessel with 1 in. of a vacuum-type superinsulation between the liners is about 6.3 lb/ft². For a 4000-gal vessel, 23 ft long and 65 in. ID, the vessel will weigh about 2770 lb and will hold about 2380 lb of hydrogen. The vessel will weigh approximately 1.2 lb/lb of hydrogen capacity. Because liquid oxygen is 16 times as dense as liquid hydrogen, the vessel will weigh about 0.075 lb/lb of oxygen capacity. These values are entered in the above table as the projected tankage weight ratios for hydrogen and oxygen.

Both the vessel-to-contents weight ratio and the liquid vaporization rate will vary as the size and shape of the vessel are changed. For a given material contained and for a given vessel shape (e.g., a given length-to-diameter ratio for a cylinder), the weight ratio and the vaporization rate will vary directly as the surface-to-volume ratio of the vessel. The larger the vessel, the lower the weight ratio and the boiloff rate.

This behavior is illustrated in Fig. 28, which presents the projected properties of the double-plastic-shell, vacuum type, superinsulated vessel described above. For the 4000-gal tank considered above, the length-to-diameter ratio is about 4, the vessel

FIG. 28. SPECIFIC-WEIGHT RATIO AND BOIL-OFF RATE OF A PROJECTED LIQUID HYDROGEN TANKAGE DESIGN
Cylindrical Vessels of Various Length/Diameter Ratios

assumed vessel construction:

outer liner: 1/2-in. reinforced plastic, $\rho = 100 \text{ lb/ft}^3$

inner liner: 3/16-in. reinforced plastic, $\rho = 100 \text{ lb/ft}^3$

insulation: 1-in. advanced vacuum-type superinsulation, $\rho = 7 \text{ lb/ft}^3$

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weight ratio is about 1.2 lb/lb of hydrogen contained, and the boiloff rate has been estimated at 0.25 per cent of hydrogen per day. The projected bulk thermal conductivity of the above insulation is 5×10^{-6} Btu/(hr)(ft)(°F). In current practice, with vacuum-powder--insulated bulk transports, vacuum pumps are not needed. The insulation requires only infrequent pumping, perhaps once or twice a year. Presently, a 3-hp pump weighing about 600 lb will pump down the insulation of a 7000-gal vessel overnight. Similar operating characteristics are expected for all the insulated vessels projected for MED use. One or two small vacuum pumps can be included in the synthesis depot to service the insulated transport vehicles, and there might be a small pump at the forward fuel distribution depot to service tanks or trucks. Miniature and low-capacity pumps on the using vehicles might be operated every few weeks during idling or other noncombat maneuvers. The data presented in Fig. 28 indicate the relative variation of the weight ratio and the boiloff rate with vessel size and shape for any vessel type. If the properties of a given type of insulated vessel are known at one vessel size and shape, the properties at other sizes and shapes can be determined from the curves presented in Fig. 28. Figure 29 gives gross vessel volume per unit capacity for a range of capacities.

6.3.3.2 Vacuum-Type Superinsulation with a Flexible Outer Liner. Present vacuum-type superinsulation cannot withstand the load of atmospheric pressure and must be enclosed in a rigid container. It is expected that vacuum superinsulations can be designed to withstand a bearing load of at least 15 psi. With such insulation, the replacement of the rigid outer liner with a very thin flexible film will reduce the vessel weight. This tankage design will be most useful for the small storage vessels on the using vehicle. The vessels may be placed inside the structure of the vehicle and positioned so that the flexible outer liner will be protected from damage.

The inner shell of such a vessel, containing about 230 gal of liquid hydrogen, the projected daily fuel required to operate a fuel cell powered Army tank, will have a thickness of about 1/8 in. of reinforced plastic. About 1 in. of vacuum-type superinsulation, having a density of about 7 lb/ft³, will be employed. The thin outer liner will not add significantly to the weight of the vessel. The surface density of such a vessel is projected to be about 1.6 lb/ft². The projected bulk thermal conductivity of this insulation is 5×10^{-6} Btu/(hr)(ft)(°F). A 230-gal vessel 3 ft ID and about 52 in. long will have a tare weight of approximately 90 lb, excluding supports. The vessel to contain the stoichiometric amount of liquid oxygen will have a tare weight on the order of 50 lb, excluding supports. For this calculation, it is assumed that the insulation will exhibit the same thermal conductivity as other superinsulations anticipated in five years. A 230-gal tank with a length-to-diameter ratio of about 1.5 will exhibit a boiloff rate of approximately 0.5 per cent hydrogen per day. It should be remembered that the using vehicle utilizes gaseous hydrogen in the fuel cell. The liquid boiloff will not be lost from the system during operation of the vehicle.

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FIG. 29. SPECIFIC VOLUME RATIO OF A PROJECTED LIQUID HYDROGEN TANKAGE DESIGN

Specific Volume Ratio for a Cylindrical Vessel:
Length/Diameter Ratio = 4

assumed vessel construction:

outer liner: 1/2-in. reinforced plastic, $\rho = 100 \text{ lb/ft}^3$

inner liner: 3/16-in. reinforced plastic, $\rho = 100 \text{ lb/ft}^3$

insulation: 1-in. advanced vacuum-type superinsulation, $\rho = 7 \text{ lb/ft}^3$

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6.3.3.3 Atmospheric-Type Foam Insulation. For materials such as ammonia, little insulation will be used on the storage vessel. About 2 in. of a foam insulation, having a density of 2 lb/ft³, is estimated to be sufficient. It is expected that in five years the techniques by which large foam vessels can be fabricated around reinforced-plastic inner liners will have been developed.

A 4000-gal vessel for the transportation of ammonia is estimated to involve, in five years, a 1/4-in.-thick inner liner of reinforced plastic and about 2-in. of foam insulation. The surface density of such a vessel will be about 2.4 lb/ft². The tare weight of a 23-ft-long, 65-in.-ID vessel is estimated to be 1060 lb, or 0.047 lb/lb of ammonia contained (the projected weight ratio included in Table 28).

6.3.3.4 Single-Shell, Plastic, Noninsulated Containers. The advanced fabrication techniques for the plastic liners for insulated vessels will be used for the construction of large, single-shell, noninsulated vessels. It is estimated that a 4000-gal vessel with a 1/4-in. reinforced-plastic wall will be available in five years. The surface density of this vessel will be about 2.1 lb/ft², for an assumed plastic density of 100 lb/ft³. The vessel will weigh about 924 lb or about 0.23 lb/gal. These values were utilized in the calculation of the projected weight ratios in Table 28 for the noncryogenic liquids.

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6.3.4 A Comparison of Field Distribution Equipment for the H_2-O_2 , NH_3-O_2 , and CH_3OH-O_2 Fuel Systems

Based on the materials survey presented in Sec. 6.3.1, and results generated under other subtasks of the over-all study, the hydrogen-oxygen, ammonia-oxygen, and methanol-oxygen fuel systems were selected for more extensive investigation. This section compares these three systems from the viewpoint of material distribution.

Over-the-road bulk transportation of these fluids is now being performed on a continuing basis. Simple precautions for each material allow safe handling by inexperienced personnel. Liquid hydrogen, liquid oxygen, and liquid ammonia do not lend themselves to efficient handling in small quantities, e.g., in 5-gal cans, but bulk handling permits complete transfer of these materials to the using vehicle quickly, efficiently, and with minimum exposure to personnel.

A small bulk-handling refueling vehicle is envisioned for the front-lines refueling mission. The refueler will carry enough fuel and oxidizer to service five Army tanks and will be able to negotiate rough terrain with reasonable ease. The hydrogen-oxygen refueler is described in detail in Sec. 6.3.5.

In Sec. 6.3.2, the recommendation was made that those materials which are gases at room temperature and pressure be handled as cryogenic liquids. The reasons for this recommendation are presented below in a comparison of the gaseous and liquid storage of hydrogen.

Hydrogen is the lightest of all gases. Its density at 70 F and 14.7 psia is 0.00521 lb/ft³. At 2000 psig, the standard cylinder gas pressure, the density of gaseous hydrogen is about 1 lb/ft³, and the commercial container required to contain this pressure weighs about 100 times its net capacity of hydrogen. Bulk storage at high pressure also involves the same 100-to-1 weight ratio. A vessel of about 135-ft³ capacity, and weighing about 13,500 lb, will be required for storage of the projected daily Army tank requirements of 230 gal of hydrogen as gas at 2000 psig. A similar high-weight storage situation will be encountered in any vehicle or storage depot containing gaseous hydrogen. The pressurized gas container is an explosion hazard, because penetration will cause complete destruction of the vessel and probably damage the surroundings, including personnel. The fuel and container loss after penetration will be 100 per cent.

Pressurized gas will be delivered to the using vehicle by pressure equalization. The tanker vehicle will be connected to the using vehicle, the blocking valves opened, and the gas allowed to flow into the using vehicle's tanks. When the pressures in the two tanks become equalized, the fuel transfer will be complete. The use of pumps will not be efficient, owing to the extreme range of pump inlet pressures. It must be pointed out also that with the pressure equalization method, the tanker vehicle will return to the depot with a significant fraction of its original load of gas. More important is the fact that the using vehicles fueled while the tanker is at lower pressure will receive only a partial load of fuel.

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Hydrogen is the lightest known liquid, with a density of 4.43 lb/ft³ at -423 F and 14.7 psia. In five years a vessel containing 230 gal of liquid hydrogen will weigh about 90 lb and will occupy approximately 33 ft³ (Sec. 6.3.3.2). The entire contents of a liquid hydrogen trailer will be deliverable to a user vehicle. During fueling in the field, hydrogen gas from the user's storage vessel can be vented back to the tanker to eliminate unnecessary venting to the atmosphere. The liquid hydrogen will normally be transferred by pressurizing the vessel to about 20 to 30 psig. The pressure will be created by controlling the vaporization and venting rates. An auxiliary liquid hydrogen pump will be included as part of a backup system.

A liquid storage vessel, normally operated at or near atmospheric pressure, may not be destroyed if the vessel is penetrated. If the vessel remains intact, fuel will be lost down to the level of the puncture, and it may be possible to deliver some of the remaining liquid to the user. The vessel may be repairable, either in the field or at a repair depot.

On the basis of this evaluation, it is recommended that all fluids be stored as liquids at or near atmospheric pressure.

Calculations have been performed to determine the size and weight of the loaded storage vessels aboard the refueler for the hydrogen-oxygen, ammonia-oxygen, and methanol-oxygen fuel systems. The tankage types projected for the containment of the materials were described in Sec. 6.3.3 and are the same as those assumed for the calculation of the anticipated tankage-to-contents weight ratios presented in the table in Sec. 6.3.2. The results of the present calculations appear in the following table. The daily fuel requirements are based on projections made under Task 5.0 of the characteristics of fuel cell powered Army tanks.

The calculation procedure was as follows (using hydrogen as an example): Each Army tank is projected to consume about 230 gal of liquid hydrogen in a day. To service five Army tanks, the refueler must carry at least 1150 gal. As an allowance for boiloff during transfer, the refueler will carry 10 per cent more fuel than that required to be delivered. A fuel load of 1250 gal, 744 lb, of liquid hydrogen has been assumed. The vessel will be designed for at least 10 per cent vapor space, or ullage. A vessel 16 ft long and 4 ft ID, with about 1410 gal of total capacity, has been selected for this preliminary sizing calculation. The length-to-diameter ratio for this vessel is 4. The data in Fig. 28 represent the anticipated properties of the vacuum-type superinsulation with reinforced-plastic liners projected for the hydrogen vessel. A 1410-gal vessel with a length-to-diameter ratio of 4 will exhibit a weight ratio of about 1.7. The weight of the vessel can be calculated:

$$\frac{1.7 \text{ lb vessel}}{\text{lb H}_2} \times \frac{0.595 \text{ lb H}_2}{\text{gal H}_2} \times 1410 \text{ gal H}_2 = 1430 \text{ lb vessel.}$$

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On this basis, the loaded vessel will weigh about 2200 lb, as indicated in Table 29.

TABLE 29

PRELIMINARY SURVEY OF FUTURE BULK-FUEL TRANSFER SYSTEM FOR FIELD OPERATION

material	daily need per vehicle ⁽¹⁾	tankage needed to refuel five vehicles ⁽¹⁾			
		ID, ft	length, ft	capacity, gal	wt of tankage ⁽²⁾ and fuel, lb
H ₂	230 gal	4	16	1410	2,200
O ₂	115 gal	3	13	690	6,900
NH ₃	221 gal	4	15	1410	7,400
O ₂	186 gal	4	12	1130	11,000
CH ₃ OH	157 gal	4	9	850	5,850
O ₂	162 gal	4	11	1030	9,700
KOH	3600 lb	8	18	6750	69,600 ⁽³⁾
K ₂ CO ₃	4450 lb	8	11	4140	51,300 ⁽⁴⁾

- (1) The vehicle considered is an Army tank powered by a fuel cell projected for use in five years. 100 per cent of fuel cell oxygen requirement supplied as liquid oxygen.
- (2) Enough fuel was added to allow for evaporation.
- (3) It has been assumed here that the potassium hydroxide is handled as a 6 M aqueous solution.
- (4) It has been assumed here that the potassium carbonate is handled as a 5 M aqueous solution. This material is returned from the fuel cell to the synthesis depot.

The remaining calculations were performed similarly. The projected weight ratios for future vessels for the other materials, as presented in the table in Sec. 6.3.2, apply to 4000-gal vessels with L/D = 4, and constructed as discussed in Sec. 6.3.3. With the weight ratio for 4000-gal vessels given for each material, the ratio for the appropriate size and shape of vessel was calculated from the curves in Fig. 28.

For the methanol fuel system, four vessels must be provided on the refueling vehicle. In addition to the fuel and oxidizer, potassium hydroxide must be delivered to and ultimately stored in the using vehicle. Potassium carbonate, a product of the fuel cell reaction, must be returned to the synthesis depot for reprocessing. The vessel sizes and weights shown in Table 29 are too large for all four vessels to be placed on one refueler.

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It should be mentioned that damage to the bulk transportation vessels or to the storage vessels in the Army tank may cause loss of methanol, potassium hydroxide, or potassium carbonate. Loss of these materials would interrupt the closed carbon cycle between the synthesis plant and the user's fuel cells, and reduce the capacity of the over-all MED system until the carbon supply could be replenished.

The hydrogen and ammonia fuel systems will involve the handling of only two liquids and will therefore be associated with simpler storage, transportation, and transfer than the methanol fuel system. Of the three fuel systems, hydrogen involves the smallest and lightest distribution equipment that will meet MED needs.

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6.3.5 Liquid H₂- O₂ Storage and Transportation

The following representative model has been assumed for this study. The nuclear power source and synthesis plant will be about 200 miles to the rear of the forward battle area. Improved roads will connect the depot with a forward distribution depot, about 20 miles from the battle area. The fuel is to be delivered to 22 Army tanks in the forward area.

Liquid hydrogen and liquid oxygen from the fuel synthesis plant will be delivered from the production plant directly into 4000-gal storage vessels. The recommended vessel design involves double walls of reinforced plastic and advanced vacuum-type super-insulation between the walls. On the basis of the properties calculated for this vessel in Sec. 6.3.3.1, the vessel will weigh about 0.71 lb/gal of capacity. The liquid hydrogen vaporization rate within these tanks is expected to be about 1/4 per cent per day. The vessels, skid-mounted and transportable either by air or on flat-bed trucks, will be about 25 ft long and about 6 ft OD. When a vessel has been filled, it will be loaded onto a flat-bed truck and hauled to the forward distribution depot. This storage module, which provides fuel storage at the synthesis depot and transportation to the distribution depot, will also serve as the fuel storage vessel at the distribution depot and, when empty, will be hauled back to the synthesis depot for reuse.

Instead of hauling hydrogen and oxygen in separate 4000-gal vessels, it may be advisable to carry stoichiometric amounts of hydrogen and oxygen in separate tanks on each module. This procedure will reduce the possibility that large quantities of one material will be lost owing to enemy action while the other material is in plentiful supply.

While the storage module is at the synthesis depot, the hydrogen and oxygen boiloff will be returned to the liquefaction plant. During transportation of the liquids, the boiloff will be used to supplement the fuel supply of fuel cell powered vehicles. This will decrease the effects of boiloff of the cryogenic liquids on the over-all MED system.

These large storage vessels will be air transportable while partially full of product, allowing some fuel needs to be met during synthesis-plant startup. Some of the products may be used to prime the liquefaction plant to shorten startup. Partially full storage modules will be transportable with the rest of the depot during site changes. These features will improve the energy efficiency of the entire MED.

A small, maneuverable refueling vehicle to service the user vehicles is envisioned. As presently conceived, the refueler will carry liquid hydrogen and liquid oxygen storage vessels, will possess some armor, and will be self-propelled on either large wheels or treads. It will be able to follow Army vehicles over rough terrain. The refueler will carry about 1250 gal of liquid hydrogen and 625 gal of liquid oxygen, amounts sufficient to service up to five Army tanks. The vehicle is estimated to weigh about 10,000 lb, of which about 2000 lb will be attributable to tankage and 8000 lb to the basic vehicle, armor, and liquid-handling equipment. The liquid load, weighing

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about 7000 lb, will raise the total to about 17,000 lb. The refueler will fit into a space about 8 ft high, 8 ft wide, and 20 ft long.

The refueler may be equipped to return pure product water from the user's fuel cells to the synthesis plant if this is desired. The 750-gal tank required to carry the water would not appreciably alter the basic design of the vehicle.

For refueling, the refueler will be parked next to the user vehicle. Extendable booms mounted on the refueler will be inserted into receptacles in the user's side. The liquid fuels will be quickly transferred into the user's storage tanks, and the booms will then be retracted and the refueler driven to the next user. The entire refueling operation will be controlled from the cab of the refueler by the operator, who will not be exposed at any time.

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6.3.6 Safety in Handling Liquid H₂ and O₂

"A new source of power, which burns a distillate of kerosene called gasoline, has been produced by a Boston engineer. Instead of burning the fuel under a boiler, it is exploded inside the cylinder of an engine. This so-called internal combustion engine may be used under certain conditions to supplement steam engines. Experiments are under way to use an engine to propel a vehicle.

"This discovery begins a new era in the history of civilization. It may some day prove to be more revolutionary in the development of human society than the invention of the wheel, the use of metals, or the steam engine. Never in history has society been confronted with a power so full of potential danger and at the same time so full of promise for the future of man and for the peace of the world.

"The dangers are obvious. Stores of gasoline in the hands of people interested primarily in profit, would constitute a fire and explosive hazard of the first rank. Horseless carriages propelled by gasoline engines might attain speeds of 14 or even 20 miles per hour. The menace to our people of vehicles of this type hurling through our streets and along our roads and poisoning the atmosphere would call for prompt legislative action even if the military and economic implications were not so overwhelming. The Secretary of War has testified before us and has pointed out the destructive effects of the use of such vehicles in battle. Furthermore, our supplies of petroleum, from which gasoline can be extracted only in limited quantities, make it imperative that the defense forces should have first call on the limited supply. Furthermore, the cost of producing it is far beyond the financial capacity of private industry, yet the safety of the nation demands that an adequate supply should be produced. In addition, the development of this new power may displace the use of horses, which would wreck our agriculture.

"... the discovery with which we are dealing involves forces of a nature too dangerous to fit into any of our usual concepts."

Thus reads a portion of the Congressional Record of 1875.

For any fire or explosion, three conditions must be satisfied simultaneously. There must be

- (1) a fuel,
- (2) an oxidizer (in appropriate proportions), and
- (3) a source of ignition energy.

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A safe condition may be created by the elimination of any of these conditions. The application of safety principles to the handling of hydrogen and oxygen may be reduced to such a program. During the handling of hydrogen (fuel) in normal environments (oxidizer-air) or the handling of oxygen (oxidizer) in equipment or around people (fuel), the first two conditions are satisfied. Therefore, both in the equipment design and in the operating procedure, the prevention of ignition will be important. The effect of contact of the cryogenic liquids with tissue will also be important.

Hydrogen, as well as gasoline and JP-4 and RP-1 (modified kerosenes), exhibits concentration limits, in air, beyond which it will not burn. These limits, 4.1 and 74.2 per cent, are wider than for any of the other fuels. However, the energy radiated by a hydrogen flame is lowest by a factor of 10, and the high evaporation rate and low gas density produce a short-lived fire having little effect on the surroundings. In other words, while a hydrogen fire is more easily obtained, it is far less dangerous than those fires produced by hydro-carbons.

Hydrogen may be handled safely by using precautions similar to those observed for the more common petroleum fuels: (1) grounding equipment properly to prevent sparking, and (2) purging lines before and after fuel transfer.

Purging is normally carried out with an inert gas, such as nitrogen or helium. These gases will not be readily available at the depot. It is believed that if quick-disconnect couplings are used, very little air will enter the system when lines are attached or detached. Purging with hydrogen gas is thought to be practical in this case. During infrequent purging, extreme care must be taken to eliminate all sources of ignition as long as the hydrogen concentration in the lines is within the flammable limits.

Three appendixes dealing with the safety of liquid hydrogen are included with this report. These appendixes support and amplify the information presented in this section and are of extreme importance to anyone desiring to learn of the safety of liquid hydrogen.

Appendix C is the transcript of a paper entitled "Liquid Hydrogen Safety" which was presented as Session V at the Cryogenic Safety Conference sponsored by Air Products and Chemicals, Inc., in 1959.³⁴ The transcript of Seminar No. 11, "Liquid Hydrogen," of the same Conference, is included as Appendix D.³⁵ Excerpts from a recent report of bulk liquid hydrogen spill tests, performed with the cooperation of Air Products and Chemicals, Inc., are presented as Appendix E;³⁶ comments are incorporated to relate the reported results to the MED feasibility study. A general conclusion to be drawn from this information is that the dangers of handling liquid hydrogen have been greatly overrated.

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Because liquid oxygen is handled in tonnage quantities at all missile bases without incident, it will be only lightly discussed here. "LOX compatibility" is a safety term used to signify that care should be exercised in the selection of materials to be used in oxygen service, so that, if the material is accidentally ignited in the presence of oxygen, little or no reaction will occur. These materials are not in themselves sensitive to the presence of oxygen! If ignition can be prevented completely by design or procedure, all construction materials can be considered compatible with oxygen.

Because liquid oxygen and liquid hydrogen are very cold (-297 F and -423 F, respectively), they will produce "burns" if allowed to contact the skin for more than a few seconds. The freezing will tend to destroy the tissues. However, the body's natural reaction to the burning sensation and the high vaporization rate of these liquids tend to reduce the severity of such damage considerably. Clothing that will either prevent the cold liquids from touching the skin or that have no pockets in which the liquid can accumulate will also aid in the safe handling of the materials.

The Liquid Propellant Information Agency (LPIA) has issued a Liquid Propellant Safety Manual³⁷ that gives an excellent resume of accepted safety precautions for the handling of liquid hydrogen, liquid oxygen, and other cryogenic liquids in common use in various missile systems. The Director of Defense Research Engineering has also published an excellent report³⁸ on this subject. Both of these are recommended to the interested reader.

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6.3.7 Transportation and Storage of Na

Sodium, water, and oxygen are necessary for fuel cell reaction. Oxygen can be supplied to the field vehicles as liquid oxygen; this is adequately discussed in other sections. Fuel cells can potentially operate on air with reduced output. Logistics and other considerations would dictate the use of oxygen or air.

Water for the reaction can be carried and stored in conventional tanks. If noncorrosive materials (plastic, iron, etc.) are used, the same tanks could be used to return sodium hydroxide and its solutions to the reactor and storage.

Sodium will react with air to form sodium oxide. The oxide crust that forms will usually protect the metal from further attack. Water and sodium react rapidly and violently to form sodium hydroxide. These factors would have to be considered in any method of sodium transportation.

Commercially, sodium is shipped in bricks packed in pails or drums or is cast solid in drums. These shipment forms do not appear too attractive for the MED. It may be possible to hand feed sodium bricks to the amalgamator on the field vehicle, but this process would have many practical disadvantages. The solid-cast sodium in drums or tanks could be placed in the field vehicle and heated to melt the sodium and allow it to blow into the amalgamator. The problems and energy involved in melting a large mass of sodium and keeping it in a molten state for ready use would be quite large.

New methods of transportation would probably have to be developed. It might be possible to cast the sodium in a large plastic "toothpaste" tube. The tube could be attached to the amalgamator and sodium extruded into the amalgamator in a manner similar to toothpaste. Similar tubes could be used to store the sodium hydroxide product.

The transportation and storage of sodium as a liquid could be considered. Insulations of the types used to keep heat from liquid oxygen might be used to keep heat in molten sodium. Heated transfer lines would be required.

It may also be desirable to consider a sodium-potassium alloy (NaK) as a fuel. Sodium-potassium alloy is a liquid at ambient temperatures; its chemical reactions in the over-all system would be quite similar to those of sodium.

One of the weakest logistic links in the entire sodium system is the transportation of sodium or sodium hydroxide. Leakage or loss of sodium or destruction of a transportation vehicle would remove a component of the system that could be replaced only with difficulty. This is in contrast to systems that depend on air and water as fuel-oxidizer sources, which are available at the depot site. A considerable portion of the sodium in the system is involved in the transportation portion of the system (up to one third). It is susceptible to loss on both the delivery and the return portions of the trip.

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7. FUEL UTILIZATION

7.1 APPLICATION OF SPECIAL FUELS FOR PROPULSION

7.1.1 Fuel Cells

7.1.1.1 Types of Fuel Cells. A fuel cell is an electrochemical device into which reactants are continually fed from an external source to produce electric energy as demanded by the load circuit. These cells are somewhat similar in internal construction to secondary storage batteries.

The internal cell construction consists essentially of porous metallic anodes and cathodes separated by a material containing an electrolyte.

The fuel can be any oxidizable gas, liquid, or solid. It is introduced into the anode compartment simultaneously with the admission of a reducible material (usually air or oxygen) into the cathode compartment.

A flow of current develops in the external circuit as demanded by the external electric load and consistent with the capacity of the cell. This is therefore a process for the direct electrochemical conversion of a fuel to electrical energy without the use of moving parts and without prior conversion to heat. See Appendix I for fuel cell efficiency.

This section is based primarily on "in house" data considered representative of current technology. Both current and projected data are summarized in Table 30. A report describing the current status of some of the work at Allis-Chalmers is included in Appendix J. Because some Allis-Chalmers fuel cell systems have been used to power large vehicles, the size of equipment and control systems required for vehicles can be accurately estimated. This is significant, because considerable technology is involved in scaling up laboratory fuel cells to a size suitable for operation in a vehicle. It is believed that such considerations account in part for the absence of vehicles powered by some of the more renowned high-performance laboratory fuel cells. A tractor operated by fuel cells is shown in Figs. 30 and 31.

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FIG. 30. FUEL CELL TRACTOR SCHEMATIC

FIG. 31. FUEL CELL TRACTOR IN OPERATION

TABLE 30

FUEL CELL PERFORMANCE DATA

fuel cell	present				projected			
	current density, amp/ft ²	voltage (cell), v	power/weight ratio, w/lb	power/volume ratio, kw/ft ³	current density, amp/ft ²	voltage (cell), v	power/weight ratio, w/lb	power/volume ratio, kw/ft ³
H ₂ -O ₂	130	0.78	22	1.5	130	0.87	33	3.5
H ₂ -air	78	0.78	13	0.9	78	0.87	20	2.1
NH ₃ -O ₂	130	0.3	3	0.18	130	0.6	15	1.0
N ₂ H ₄ -O ₂	100	0.6	15	1.41	100	1.0	25	2.3
CH ₃ OH-O ₂	50	0.3	3.2	0.57	50	0.6	7	1.0
NaHg-O ₂	-	1.6	-	-	-	-	-	6.0

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The fuel cell systems to be discussed have been sized to meet the following three applications.

Case A: A tank company of 22 tanks, each with a net power requirement of $700 \times 0.60 \times 0.746 = 313$ kw. It is shown elsewhere in this report that it is possible to employ an electric drive motor with at least 60 per cent of the horsepower of an internal-combustion engine to perform the equivalent task. From the duty cycle, also listed in this report, it can be seen that in an 8-hr day each tank consumes $8 \times 0.50 \times 313 = 1252$ kwhr.

Case B: A truck unit, each truck with a maximum net power requirement of $200 \times 0.60 \times 0.746 = 89.5$ kw. From the duty cycle, it can be seen that in a 7-hr day each truck produces $7 \times 0.50 \times 89.5 = 313$ kwhr.

Case C: Electrically powered military equipment consisting of 100-kw packages operating 24 hr/day at full power.

The quantity of available fuel will be considered constant for Case A, B, and C, and that needed for Cases B and C equal to that needed for Case A.

The total number of trucks and 100-kw power packages will thus be considered variables, which are determined by this quantity of available fuel. This simplifies the design of the chemical synthesis plants, as discussed previously.

7.1.1.1.1 H₂-O₂ Fuel Cells. The hydrogen-oxygen fuel cell system is the most thoroughly developed of currently available fuel cell power plants. Investigation into the fuel cell system using a hydrogen-oxygen fuel cell small enough and light enough for space travel shows that many of the items determined in that investigation are applicable to the study at hand. Such a system typifies the present state of the art of constructing high-power fuel cell modules. A 36-cell fuel cell module was designed; it produces 0.78 v/cell, or a total of 28.1 v for an output rating of 1260 w, and weighs 57 lb. This provides fuel cell outputs of 1.5 kw/ft³ and 22 w/lb. The cell operating temperature is about 170 F.

It is reasonable to expect that concentrated research effort spanning four to five years could produce significant advances in fuel cell technology. The improvements cited below reflect extrapolation of current experimentation.¹

A cell voltage of 0.87 v at a current density of 130 amp/ft² appears readily attainable. Even higher voltages may be possible as basic research progresses. This increase and a redesign of the fuel cell power pack should increase the power density to approximately 3.5 kw/ft³. The weight of the fuel cell would probably not change as drastically. A power-to-weight ratio of 33 w/lb is anticipated. This increase in cell efficiency should

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simplify the auxiliary controls and decrease the fuel and oxidizer requirements. A system-to-fuel cell volume ratio of 1.15 and a system-to-cell weight ratio of 1.06 will be used in the following computations. This fuel cell would have a thermal efficiency (Appendix I) of 62.5 per cent. The ΔH employed in computation is the "higher" heating value. Use of the "lower" heating value increases the efficiency to 73.4 per cent.

Employing these figures, the size and weight of the fuel cell system will be computed for Case A.

A 36-cell fuel cell module would produce 0.87 v/cell, for a total of 31.3 v. Assuming the power required for auxiliaries to be 7 per cent of the fuel cell power, a gross output of 335 kw would be required. This system (fuel cell and auxiliaries) would occupy 110 ft³ and would weigh 10,750 lb, not including the weight of the fuel and oxidizer.

The quantities of fuel and oxidizer may be determined for the system as follows: The net output would be 1252 kwhr. The auxiliaries would be operating at full power for the entire 8 hr, so they would require $313 \times 0.07 \times 8 \text{ hr} = 175 \text{ kwhr}$. Thus, a total of 1427 kwhr would be required (1252 + 175). A cell voltage of 0.87 v seems reasonable, as discussed above. This leads to figures of 0.0946 lb of hydrogen/kwhr and 0.757 lb of oxygen. The system would then require 135 lb (30.9 ft³) of hydrogen and 1080 lb (15.2 ft³) of oxygen per tank. The vessel for storing 135 lb (230 gal) of hydrogen would in the future weigh 90 lb and occupy 36.2 ft³. That for the oxygen would weigh 50 lb and occupy about 16.5 ft³.

Thus, the total volume of the fuel cell power system would be 156 ft³ and it would weigh 11,965 lb, not including the weights and volumes of the hydrogen and oxygen fuel tanks. These add about 90 lb and 5.3 ft³, and 50 lb and 1.3 ft³, respectively, to the system. The tank company would require 2970 lb of hydrogen and 23,760 lb of oxygen per day.

Methods of fitting this power plant into the tank and truck are discussed in Sec. 7.1.1.2. Radiator sizes are discussed in Sec. 7.1.1.4.

The gross power required for Case B would be 95.8 kw and 356.9 kwhr per truck. The volume of the fuel cell and auxiliaries would be 31.4 ft³, and the weight would be 3074 lb. Each truck would need 33.76 lb of hydrogen (7.65 ft³) and 270 lb of oxygen (3.8 ft³), for a total weight of 3378 lb and a volume of 42.9 ft³. A vessel weighing about 34 lb would be needed for the hydrogen; the oxygen vessel would weigh about 15 lb. The system weight, including tanks, would be 3427 lb and the volume would be about 44 ft³.

For Case C the gross power would be 107 kw and 2568 kwhr per unit. The volume of the fuel cell and auxiliaries would be 35.2 ft³ and the weight would be 3437 lb. Each unit would need 243 lb of hydrogen (55 ft³) and 1944 lb of oxygen (27 ft³) for a total weight of 5638 lb and a volume of 117.2 ft³. The fuel vessels would weigh about 160 lb for the hydrogen and about 90 lb for the oxygen. The volumes would be approximately 59 and 30 ft³ for the hydrogen and oxygen, respectively.

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7.1.1.1.2 H₂-Air Fuel Cell. The low space requirement of the advanced hydrogen-oxygen fuel cell leads to a number of interesting improvements in power-plant performance. The added available space could be used to carry extra fuel and oxygen, thereby increasing the operating range of the vehicle; or the fuel cell could be operated on hydrogen and air rather than hydrogen and oxygen.

It has been the experience of Allis-Chalmers and other organizations working in the fuel cell field that the substitution of air for oxygen significantly reduces fuel cell performance. In fact, it is estimated that 60 per cent of the fuel cell output is obtained when air is used in place of oxygen.

The efficiency of fuel utilization is controlled primarily by the fuel cell voltage. A cell voltage of 0.87 v, the same as that of the hydrogen-oxygen fuel cell, will be employed in computing fuel requirements. The analysis of this system, then, is similar to that for the hydrogen-oxygen fuel cell, except that the need for liquid oxygen and its storage facilities is obviously eliminated.

Case A: Employing the increase factor of 1.66 in fuel cell size described above, the fuel cell power plant would weigh 17,850 lb and occupy 183 ft³. The same cell voltage is used as in the hydrogen-oxygen fuel cell. Thus, each tank would require 135 lb (30.9 ft³) of hydrogen for a total system weight of 18,000 lb and a volume of 214 ft³. The hydrogen vessel would add 90 lb and about 5.3 ft³.

Case B: The fuel cell power plant for each truck would weigh 5100 lb and occupy 52 ft³. Each truck would require 33.76 lb of hydrogen (7.65 ft³) for a total system weight of 5134 lb and a volume of 60 ft³. The hydrogen vessel would add 34 lb and about 1 ft³.

Case C: The hydrogen-air power plant for each unit would weigh 5700 lb and occupy 58 ft³. Each power plant would require 244 lb (55 ft³) of hydrogen for a total system weight of 5944 lb and a volume of 113 ft³. The hydrogen vessel would add approximately 160 lb and about 4 ft³.

As an alternative to the sole use of air as oxidizer, it might be desirable to carry along a small amount of pure oxygen when operating the vehicle on the hydrogen-air fuel cell. This oxygen would be fed into the cells when peak power were required or when the tank were to operate under sealed conditions.

7.1.1.1.3 H₂-Air (O₂) Fuel Cell. A combination of air and oxygen as oxidizers will reduce the weight and volume of the power plant system. The hydrogen-oxygen fuel cell power plant is used at a fraction of its capacity most of the time. Under these conditions, it could operate with air. When greater power is needed, oxygen could be supplied to the cells to increase the output to the necessary level. The duty cycle for tanks and trucks is as follows:

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	<u>truck (7-hr day)</u>	<u>tank (8-hr day)</u>
full power	10% (O ₂)	20% (O ₂)
3/4 power	25% (O ₂ + air)	20% (O ₂ + air)
1/2 power	25% (air)	20% (air)
1/10 power (idle)	40% (air)	40% (air)

If the fuel cell with air operates at 60 per cent of the oxygen output, a hydrogen-oxygen cell in the tank will need pure oxygen for full power. At 3/4 power, 37.5 per cent of the cells will operate on oxygen and the remainder on air. Therefore, 20 per cent of the oxygen supplied to the hydrogen-oxygen cell system will be required at full power, and 7.5 per cent of the oxygen supplied to the hydrogen-oxygen cell will be needed at 3/4 power for the hydrogen-air (oxygen) system in the tank. Thus, 27.5 per cent of the oxygen requirement for the hydrogen-oxygen cell system will be needed for the hydrogen-air (oxygen) system in the tank.

The truck hydrogen-air (oxygen) system will require pure oxygen for full power. At 3/4 power, 37.5 per cent of the cells will operate on oxygen. Therefore, 10 per cent of the oxygen supplied to the hydrogen-oxygen system will be required at full power and 9.4 per cent of the oxygen will be required at 3/4 power. Thus, 19.4 per cent of the oxygen needed for the hydrogen-oxygen cell system will be needed for the hydrogen-air (oxygen) system in truck.

Case A: The same cell as that of the hydrogen-oxygen system would be used. It has a volume of 110 ft³ and a weight of 10,750 lb. The 135 lb (30.9 ft³) of liquid hydrogen would be contained in a vessel weighing 90 lb and having a volume of 33 ft³. The oxygen requirement is 27.5 per cent of that for the hydrogen-oxygen system. This is 297 lb (4.2 ft³). The oxygen vessel would weigh approximately 20 lb and occupy about 5.5 ft³.

The volume of the fuel cell power system would be about 149 ft³ and it would weigh 11,080 lb. The tank company (22 tanks) would require 2970 lb of hydrogen and 6530 lb of oxygen.

Case B: The same cell as that of the hydrogen-oxygen system would be used. It has a volume of 31.4 ft³ and weighs 3074 lb. The 33.76 lb (7.65 ft³) of hydrogen would be contained in a vessel weighing 34 lb, and having a volume of about 8.5 ft³. The oxygen requirement is 19.4 per cent of that of the hydrogen-oxygen system. This is 52.4 lb (7.4 ft³) of oxygen. The oxygen vessel would have a volume of about 1 ft³ and weigh about 10 lb.

The total system would weigh 3160 lb and have a volume of about 41 ft³.

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Case C: The stationary power plant would operate at full power throughout the day, so the supercharging of a hydrogen-air cell with oxygen is not applicable.

7.1.1.1.4 Gaseous $\text{NH}_3\text{-O}_2$ Fuel Cell. Allis-Chalmers has recently announced the combustion of ammonia in a fuel cell. This fuel is somewhat easier to handle than liquid hydrogen and is of commercial interest because of the low cost and available distribution system. An ammonia fuel cell power pack was constructed to power a fork-lift truck for experimental studies.

The work so far on the gaseous ammonia-oxygen fuel cell system has all been directed to the fuel cell itself. The circulating systems and controls have been of heavy construction suitable for testing and operating the fuel cell in a laboratory. Thus, the units have been many times larger and heavier than would be necessary for operation in a designed installation.

It has been estimated that the power required for the auxiliaries would be 15 per cent of the net output power. This increase over the hydrogen-oxygen system is due primarily to the need for an ammonia-nitrogen separator. The system-to-cell volume ratio would be 1.25; the system-to-cell weight ratio, 1.15; a power-volume density of 0.18 kw/ft^3 , and a power-weight density of 3 w/lb have been obtained in the laboratory.

A cell voltage of 0.6 v , a power-volume density of 1.0 kw/ft^3 , and a power-weight-density of 0.015 kw/lb appear to be attainable. The thermal efficiency (Appendix I) would be 62.8 per cent. The power for controls will probably not change as drastically, i.e., to 15 per cent.

Case A: The total power required is the net power (313 kw) plus the auxiliary power (313×0.15), or 360 kw gross. This would require a fuel cell volume of 360 ft^3 and an auxiliary volume of 90 ft^3 for a total volume of 450 ft^3 . This system would weigh 27,600 lb, not including the weight of fuel and oxygen.

The quantity of ammonia required for 1628 kwhr, the gross power, is 1262 lb (29.6 ft^3); 1780 lb (25 ft^3) of oxygen are also required. Thus, the total weight of the fuel cell power system would be 30,642 lb, and the volume 505 ft^3 .

Case B: The total power required per truck is 103 kw. This would require a fuel cell volume of 103 ft^3 and an auxiliary volume of 26 ft^3 . This system would weigh approximately 7900 lb. The quantity of ammonia required for the 408 kwhr is 318 lb (7.5 ft^3); 448 lb (6.3 ft^3) of oxygen would also be required. Thus, the total weight of the power system would be 8666 lb and the volume 143 ft^3 .

Case C: Applying these performance characteristics to the 100-kw (net) power plants, it can be shown that the fuel cell system (excluding fuel and oxygen storage)

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for each plant would occupy 125 ft³ and would weigh 9200 lb. A total of 2156 lb of ammonia (50.5 ft³) and 3040 lb of oxygen (42.7 ft³) would be needed for each unit. Each system, including fuel and oxygen, would weigh 14,396 lb and occupy 218 ft³.

7.1.1.1.5 Cracked NH₃, H₂-O₂ Fuel Cell. An alternative to the use of cryogenic hydrogen to power a hydrogen-oxygen fuel cell plant is the use of "cracked" ammonia. Allis-Chalmers has previously considered such a system in a contract proposal to the Bureau of Ships (PR660-28475) for generating hydrogen in a submarine. Similar investigations have been in progress at Air Products for a number of months.

Ammonia, when passed over a suitable heated catalyst, is rapidly dissociated into hydrogen and nitrogen. This hydrogen, after separation from the nitrogen and unreacted ammonia, can be oxidized in a fuel cell to provide useful power. A portion of the output hydrogen would be burned to heat the catalyst. With a well designed and well insulated catalytic reactor it is necessary to feed back a maximum of 25 per cent of the hydrogen.

Case A: The decomposition reaction is sufficiently simple that only a minimum of controls is needed. The catalytic reactor vessel itself is estimated to be cylindrical, 5 ft long and 2 in. in diameter. The auxiliary equipment would be small, so that a total volume of approximately 6 ft³ should readily contain the ammonia cracker unit. This volume of the cracking unit is sufficiently small to fit in a vehicle powered by a hydrogen-oxygen or hydrogen-air fuel cell. The weight of such a unit is minor compared with the weight of the fuel cells.

To power a tank, substitution of ammonia for hydrogen would increase the weight of fuel from 135 to 1115 lb and decrease the volume of the fuel from 31 to 22 ft³. The weight of the tank power plant would be approximately 14,000 lb, a distinct improvement over the 29,500 lb required for the direct ammonia-oxygen fuel cell. The vehicle cracker unit would operate according to the following diagram.

FIG. 32

SCHEMATIC DIAGRAM OF AMMONIA CRACKER

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Case B: The volume occupied by the cracking and separating equipment is estimated to be approximately 4 ft³. The weight of this equipment is equally small compared with the hydrogen-oxygen power plant. To power a truck, the use of ammonia would require 289 lb of fuel (5.7 ft³) and 305 lb of oxygen. The weight of the truck power plant (fuel cells plus chemicals) would be approximately 4000 lb, a distinct improvement of the 8666 lb required for the direct ammonia-oxygen fuel cell. Note that the same weight of fuel cells is used as with the hydrogen-oxygen fuel cell.

Case C: The volume occupied by the cracking and separating equipment is estimated to be approximately 5 ft³. The use of ammonia would require 1858 lb of fuel (36.4 ft³) and 1980 lb of oxygen. The weight of the power plant (fuel cells plus chemicals) would be approximately 7750 lb, a distinct improvement over the 14,346 lb required for the direct ammonia-oxygen fuel cell.

7.1.1.1.6 CH₃OH-O₂ Fuel Cell. The methanol-oxygen fuel cell is another system which Allis-Chalmers has scaled up and operated at relatively high power levels (600 w). A number of these systems have been operated successfully as demonstration units for five days without any evidence of significant cell deterioration. Most of the work so far has been directed to the fuel cell itself. The circulating systems and controls have been of heavy construction suitable for testing and operating the fuel cell in a laboratory setup. These have been many times larger and heavier than would be necessary for operation in a designed installation. The present characteristics of this fuel cell system are discussed below.

On the basis of experience with the 600-w modules, it is estimated that the power required for the auxiliaries would be 10 per cent of the net output power. The system-to-cell volume ratio would be 1.25, and the system-to-cell weight ratio 1.06. The power-volume density of the present modules is 0.57 kw/ft³ and the power-weight density, 3.2 w/lb.

A power-volume density of 1.0 kw/ft³ and a power-weight density of 7 w/lb appear reasonable. These improvements arise primarily from improvements in the cell performance rather than from a decrease in volume or weight brought about by system design. The controls for the methanol system can be improved somewhat to keep the system-to-cell volume ratio at 1.25. The system-to-cell weight ratio would be lowered to 1.05. It is further estimated that the power required for the auxiliaries would be 9 per cent of the net output power.

With further research, the cell voltage could be increased to 0.6 v. This would provide a thermal efficiency (Appendix I) of 49 per cent. This figure involves the use of the "lower" heating value. Methods are under investigation which should provide for the in situ rejection of carbon dioxide by the electrolyte. This would simplify the fuel cell design but would require some technique for preventing the loss of carbon dioxide to the atmosphere. The retention is necessary if the methanol system is to be a closed loop.

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Case A: The total power required is the net power (313 kw) plus the auxiliary power (313×0.09), or 341 kw gross. This would require a fuel cell volume of 341 ft³ and an auxiliary volume of 85 ft³, for a total volume of 426 ft³. This system would weigh 51,400 lb, not including the weight of the fuel, sodium hydroxide and oxygen. The volume of the mixing tank for methanol and sodium hydroxide should be approximately 30 ft³.

The quantities of material required per day for 1476 kwhr are 1030 lb (20.7 ft³) of methanol, 1525 lb of oxygen (21.5 ft³) and 2620 lb (19.7 ft³) of solid sodium hydroxide. Thus, the total weight of the fuel cell power system would be 56,325 lb and the volume 518 ft³. The tank company would require approximately 22,700 lb of methanol, 33,600 lb of oxygen, and 57,600 lb of sodium hydroxide per day.

Case B: The total power required, per truck, is 97.5 kw. This would require a fuel cell volume of 97.5 ft³ and an auxiliary volume of 24 ft³. This part of the system would weigh 14,000 lb, not including the weight of the fuel, sodium-hydroxide and oxygen. The volume of the mixing tank should be approximately 10 ft³.

The quantities of material required per day for 370 kwhr are 258 lb (5.3 ft³) of methanol, 382 lb (5.4 ft³) of oxygen, and 656 lb (4.8 ft³) of solid sodium hydroxide. Thus, the total weight of the fuel cell power system would be 5300 lb and the volume 147 ft³.

Case C: The total power (net plus auxiliaries) required per unit is 109 kw. This would require a fuel cell volume of 109 ft³ and an auxiliary volume of 28 ft³. This part of the system would weigh 15,571 lb, not including the weight of the fuel, sodium hydroxide, and oxygen. The volume of the mixing tank should be approximately 25 ft³.

The quantities of material required per day for 2643 kwhr are 1840 lb (37.2 ft³) of methanol, 2730 lb (40.0 ft³) of oxygen and 4690 lb (33.8 ft³) of solid sodium hydroxide. Thus, the total weight of the fuel cell power system would be 24,800 lb and the volume 273 ft³. Of this, the fuel cell occupies 109 ft³; 164 ft³ must be provided for storage and mixing.

7.1.1.1.7 N₂H₄-O₂ Fuel Cell. Allis-Chalmers has scaled up the hydrazine-oxygen fuel cell and operated it at high power levels. These systems have been operated continuously for 10 days without any evidence of cell deterioration. Most of the work so far has been directed to the fuel cell itself. The circulating systems and controls have been of heavy construction, suitable for testing and operating the cell in a laboratory setup. These have been many times larger and heavier than would be necessary for operation in a designed installation. The present characteristics of this fuel cell system are discussed below.

It is estimated that the power required for the auxiliaries would be 10 per cent of the output power. The system-to-cell volume ratio would be 1.25; and the system-to-cell weight

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ratio 1.06. The power-volume density of the present modules is 1.41 kw/ft^3 , and the power-weight density, 0.015 kw/lb .

A power-volume density of 2.3 kw/ft^3 and a power-weight density of 25 w/lb at an individual cell voltage of 1.0 v appear reasonable to expect in four years. This would provide a thermal efficiency of 76 per cent. The "lower" heating value was used as a reference. The system-to-cell volume ratio should be reduced to 1.15, and the system-to-cell weight ratio to 1.05. The power required for the auxiliaries should still be 9 per cent of the output power.

Case A: The total power required is the net power (313 kw) plus the auxiliary power (313×0.09), or 341 kw gross. This would require a fuel cell volume of 148 ft^3 and an auxiliary volume of 22 ft^3 for a total volume of 170 ft^3 . This system would weigh 14,300 lb, not including the weight of the hydrazine and oxygen. The volume of the surge tank should be approximately 20 ft^3 .

The quantities of material required per day for 1476 kwhr are 977 lb (22 ft^3) of hydrazine and 1030 lb (14.4 ft^3) of oxygen. Thus, the total weight of the fuel cell power system would be 16,300 lb, and the volume 226 ft^3 .

A total of 21,500 lb of hydrazine and 22,700 lb of oxygen would be required per day for the company of 22 tanks.

Case B: The total power required, per truck, would be 97.5 kw. This would require a fuel cell volume of 42 ft^3 and an auxiliary volume of 7 ft^3 . This part of the system would weigh 3900 lb, not including the weight of the fuel and oxygen. The volume of the surge tank should be approximately 10 ft^3 .

The material requirements for 370 kwhr per day are 246 lb (5.6 ft^3) of hydrazine and 260 lb (3.7 ft^3) of oxygen. Thus, the total weight of the fuel cell system would be 4400 lb, and the volume 68 ft^3 .

Case C: The total power (net plus auxiliaries) required per unit is 109 kw. This would require a fuel cell volume of 47.4 ft^3 and an auxiliary volume of 7 ft^3 . This part of the system would weigh 4360 lb not including the weight of the fuel and oxygen. The volume of the mixing tank would be approximately 15 ft^3 .

The material requirements for 2643 kwhr per day are 1600 lb (36.5 ft^3) of hydrazine and 1690 lb (24 ft^3) of oxygen. Thus, the total weight of the fuel cell power system would be 7700 lb, and the volume 47.4 ft^3 . An additional 76.5 ft^3 would have to be provided for fuel and oxygen storage.

The above sizes and weights of a military installation for electrically powered equipment are no more than for equivalent engine generator sets and fuel supplied.

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7.1.1.1.8 HCO₂Na-O₂ Fuel Cell. Among the newer fuel cells being developed at Allis-Chalmers is the system based on sodium formate as a fuel. The feasibility of oxidizing formate to carbonate in an ambient-temperature fuel cell has been proved by numerous experiments. However, further development of this system is desired before the construction of large modules can be justified. Nevertheless, the data are sufficiently good to indicate that, with a four- to five-year research program, a performance similar to that of today's hydrogen-oxygen fuel cell is possible, i.e., a current density of 100 amp/ft² at 0.8 v per cell. This provides a thermal efficiency of 52 per cent. The physical character of the cell should be similar to that of the methanol-oxygen fuel cell.

On the basis of these considerations, the following characteristics of the formate-oxygen fuel cell are reasonable, given a period of four to five years for research and development: a power-volume density of 1.2 kw/ft³; a power-weight density of 10 w/lb; a system-to-cell volume ratio of 1.25; a system-to-cell weight ratio of 1.05; and an auxiliary power requirement of 9 per cent of the net output.

Case A: The total power required is the net power (313 kw) plus the auxiliary power (313 x 0.09) or 341 kw gross. This would require a fuel cell volume of 284 ft³ and an auxiliary volume of 71 ft³, for a total volume of 355 ft³. This system would weigh 35,800 lb, not including the weight of the fuel, sodium hydroxide, and oxygen. The volume of the mixing tank should be approximately 30 ft³.

The material requirements for 1476 kwhr per day are 5700 lb (47.5 ft³) of sodium formate, 1210 lb (17 ft³) of oxygen, and 2980 lb (22.4 ft³) of solid sodium hydroxide. Thus, the total weight of the fuel cell system is 45,690 lb, and the volume, 411 ft³. The tank company would require 125,000 lb of sodium formate, 26,500 lb of oxygen, and 65,000 lb of sodium hydroxide per day.

Case B: The total power required, per truck, is 97.5 kw. This would require a fuel cell volume of 81.4 ft³ and an auxiliary volume of 21 ft³. This part of the system would weigh 10,200 lb, not including the weight of the fuel, sodium hydroxide, and oxygen. The volume of the mixing tank would be 10 ft³.

The material requirements for 370 kwhr per day are 1430 lb (12 ft³) of sodium formate, 304 lb (4.3 ft³) of oxygen, and 748 lb (5.6 ft³) of sodium hydroxide. Thus, the total weight of the fuel cell system is 12,682 lb and the volume, 134 ft³.

Case C: The total power (net plus auxiliaries) required per unit is 109 kw. This would require a fuel cell volume of 91 ft³ and an auxiliary volume of 23 ft³. This part of the system would weigh 11,445 lb, not including the weight of the fuel, sodium hydroxide, and oxygen. The volume of the mixing tank would be approximately 20 ft³.

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The material requirements for 2643 kwhr per day are 10,250 lb (85 ft^3) of sodium formate, 2170 lb (30.5 ft^3) of oxygen, and 5340 lb (4.0 ft^3) of sodium hydroxide. Thus, the total weight of the fuel cell power system would be 29,205 lb, and the volume 267 ft^3 (including the weight and volume of the chemicals). Of this the fuel cell occupies 91 ft^3 ; 176 ft^3 must be provided for storage and mixing.

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7.1.1.1.9 Na-Metal Fuel Cell Systems.

Sodium can be considered as an MED fuel in a closed-loop system; i.e., the sodium is cycled between the point of use in the field vehicle and the point of synthesis or production at the depot. This is in contrast to the hydrogen and ammonia systems, which would be open-loop systems; the oxidation products in the field vehicles in these systems do not have to be returned to the depot for reprocessing.

Sodium can be used with oxygen for field power generation in several ways. The net chemical reaction in each of these methods is:

The sodium hydroxide product from the reaction in the vehicle is returned to the depot for reprocessing. At the depot the net chemical reaction is the reverse of reaction (1). The oxidizer, oxygen, may be cycled in the process or oxygen from air may be used in the vehicle and discarded at the depot process.

Oxidizers other than oxygen could be considered, e.g., chlorine, bromine, iodine, and sulfur trioxide. The physical properties, toxicity, and corrosiveness of these materials make them presently undesirable as oxidizers, but in future evaluations of the closed-loop systems they should be considered in greater detail.

The manufacture and transportation of sodium, water, and oxygen are considered in other sections.

From reaction (1), it can be calculated that for every pound of sodium, 0.3478 lb of oxygen and 0.3913 lb of water are consumed to produce 1.739 lb of sodium hydroxide. Additional water may be needed to dissolve the sodium hydroxide in the fuel cell. A detailed analysis of reactants is given elsewhere.

Three ways of extracting energy from the sodium-oxygen reaction are discussed below:

- (1) physical amalgamation of sodium for use in a sodium amalgam-oxygen (air) fuel cell (Sec. 7.1.1.1.9.1)
- (2) electrochemical amalgamation of sodium for use in a sodium amalgam-oxygen (air) fuel cell (Sec. 7.1.1.1.9.2), and
- (3) sodium-steam fuel cell used in tandem with a hydrogen-oxygen (air) fuel cell (Sec. 7.1.1.1.9.3).

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These methods of utilization of the sodium-water-oxygen reaction are discussed in detail below. The analysis of the various ways of utilizing sodium as a fuel involves many assumptions and extrapolations. Experimental evidence and further study are needed to justify or adjust these judgments.

The analysis of the technical discussion of the various fuel cells and the quantities of reactants necessary to power field vehicles indicates that the system using physical amalgamation of sodium and a sodium amalgam-oxygen (air) fuel cell is the best of the three systems. The sodium amalgam cell has been demonstrated in large-scale power plants and would require the least development of the sodium systems to be adapted to field vehicles.

The electrochemical amalgamation of sodium uses less sodium per kilowatthour and is therefore more efficient, but the weight of the system makes it unattractive for vehicle use. Electrochemical amalgamation of sodium is in the basic research stage and many fundamental problems must be solved before even single-cell experiments can be performed. The water requirement for cell operation is the largest of the sodium systems.

The tandem system requires a rather large quantity of sodium per kilowatthour and would be quite heavy. The sodium steam cell is conceptual in design and would require research and development.

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7.1.1.1.9.1 NaHg-O₂ (Air) Cell with Physical Amalgamation of Na.

The sodium amalgam-oxygen (air) cell has been investigated by Yeager² and M. W. Kellogg Co.,³ principally for submarine propulsion application.

In the cell operation, the amalgam (with sodium weight concentration of about 0.5 to 0.6 per cent) is run over a steel electrode (the anode) placed in a sodium hydroxide electrolyte. At this anode, sodium leaves the amalgam, going into the aqueous electrolyte as sodium ion and releasing electrons at the anode. These electrons travel through the external power circuit to the oxygen electrode (the cathode). There, the electrons, water, and oxygen combine on a catalytic surface to produce hydroxyl ions. The net reaction is thus:

The cell designed for submarine application operates best when the sodium hydroxide concentration in the electrolyte is between 6 and 22 per cent, but can operate with significantly decreased output with a 50-per cent concentration. The cell temperature is from 140 to 150 F.

During the operation of the cell, sodium hydroxide is constantly being formed in the electrolyte, thus increasing the concentration. Water must be added to keep the total concentration at an optimum level. The amounts of water necessary to produce various levels of sodium hydroxide concentration per pound of sodium reacted are listed below.

<u>NaOH</u> <u>concentration, %</u>	<u>wt ratio,</u> <u>H₂O/NaOH</u>	<u>wt of dilution</u> <u>H₂O/lb NaOH, lb</u>	<u>wt of reaction</u> <u>H₂O + dilution</u> <u>H₂O/lb Na, lb</u>	<u>wt of total</u> <u>materials/lb Na, lb</u>
5	19.0	33.04	33.43	34.78
6	15.66	27.23	27.67	28.98
10	9	15.64	16.03	17.38
15	5.67	9.84	10.02	11.58
20	4	6.916	7.307	8.655
22	3.54	6.165	6.556	7.904
30	2.33	4.067	4.458	5.806
40	1.5	2.608	2.999	4.342
50	1	1.739	2.130	3.478
60	0.66	1.158	1.549	2.987
70	0.428	0.7443	1.135	2.483
71.42	0.40	0.6956	1.0869	2.434
80	0.25	0.4347	0.826	2.173
90	0.11	0.1930	0.584	1.932

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The major component in the reactants for the sodium amalgam cell is the water necessary for dilution. To maintain a 6-per cent concentration, 27.2 lb of water would have to be added to the electrolyte for every pound of sodium consumed; for a 22-per cent concentration, 6.165 lb of water; and for a 50-per cent concentration, 1.74 lb of water.

Several alternatives can be considered in the utilization of water in the amalgam cell in field vehicles:

- (1) the cell could be operated in the optimum 6- to 22-per cent range and sufficient water carried for dilution of the sodium hydroxide product (Sec. 7.1.1.1.9.1.1).
- (2) the cell could be operated in the 6- to 22-per cent range and sodium hydroxide solution overflow concentrated by evaporation or freezing; part of the water in the system would be cyclic (Sec. 7.1.1.1.9.1.2); or
- (3) the cell could be operated at high temperatures to reduce the quantity of water needed for operation (sodium hydroxide solubility in water increases with temperature; see Fig. 33) (Sec. 7.1.1.1.9.1.3).

7.1.1.1.9.1.1 Normal Cell Operation. For a sodium hydroxide concentration of 22 per cent, at least 6.556 lb of water per pound of sodium consumed will be necessary. Storage space must be provided in the vehicle for the sodium hydroxide solution. The water necessary for reaction makes the transportation of materials and storage on the vehicle unattractive.

7.1.1.1.9.1.2 Concentration of Product NaOH Solution. The water requirements for cell operation can be reduced if the electrolyte solution coming from the cell is concentrated and the water recycled. The cell could operate with a 20-per cent sodium hydroxide concentration. The sodium hydroxide solution could be concentrated by evaporation or freezing.

Evaporation of water from a sodium hydroxide solution requires considerable heat. A possible source of heat available in a tank is the sodium fuel reaction. The over-all reaction in the vehicle is

This reaction produces 6100 Btu/lb of sodium. If the fuel cell operates at 1.6 v, 2890 Btu of electrical energy are produced per pound of sodium. Therefore, there is a maximum 3210 Btu/lb of sodium available from the energy conversion device for concentrating sodium hydroxide.

Not all this heat is available for evaporation, as explained below. However, if it is assumed that it is, that there is a multiple-effect evaporator operating with a factor of 1.5, and that the cell operates with a 22-per cent sodium hydroxide concentration, then 100 lb

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FIG. 33. SOLUBILITY OF NaOH AS A FUNCTION OF TEMPERATURE

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of electrolyte overflow will consist of 22 lb of sodium hydroxide and 78 lb of water. This quantity of sodium hydroxide would be produced in the consumption of 12.65 lb of sodium. The maximum heat available for evaporation would be about 40,000 Btu. If 1000 Btu of heat will evaporate 1 lb of water from the caustic solution and a multiple effect factor of 1.5 is used, the heat available could evaporate a maximum of 60 lb of water. The solution remaining in the evaporator would then contain 22 lb of sodium hydroxide and 18 lb of water, i.e., a 55-per cent solution.

Unfortunately, the available heat is of low grade and large-surface-area heat exchangers would be required. The heat is produced in the amalgamation process and the working cell. The cell operates only intermittently and the heat is not constantly available. Much of the heat is used in maintaining the temperature of equipment, pumps, pipes, etc. Intermittent operation would have low efficiency. Energy is also needed to operate pumps, lowering the net electrical output of the cell. All these factors would probably combine to make only about 30 per cent of the maximum available heat useful. Therefore, only about 20 lb of water would be evaporated and the resulting sodium hydroxide solution would have a concentration of about 35 per cent. The difficulties of incorporating evaporating equipment on a moving vehicle, the relatively large space needed for heat exchangers, and the low efficiency of operation are problems that would have to be overcome. This operation would obviate the transportation to the vehicle of 3.1 lb of water per pound of sodium consumed.

The concentrations of various sodium hydroxide hydrates are listed in Table 31. If a sodium amalgam cell electrolyte of 22-per cent sodium hydroxide is cooled to the point at which solid sodium hydroxide hydrate is formed, the hydrate composition is $\text{NaOH} \cdot 7 \text{H}_2\text{O}$ (Fig. 33). The precipitation would occur at about -25°C . This hydrate contains 24 per cent sodium hydroxide. When the solid phase is returned to ambient temperatures, it melts and forms a 24-per cent solution. Cooling the electrolyte from the cell temperature of 150°F to the temperature of precipitation (about -15°F) would require about 800 Btu/lb of sodium hydroxide. An additional amount of energy equal to the heat of fusion would be required to form the solid hydrate phase. Energy would also be required to separate the solid phase from the solution. Similar effects would be noted at other concentrations. Thus, while refrigeration could be used to lower the amount of water needed for the cell, the concentrating effect is slight. The energy requirements and the engineering problems make the practical consideration of the process unattractive.

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TABLE 31

CONCENTRATIONS OF VARIOUS NaOH HYDRATES

<u>hydrate</u>	<u>% NaOH</u>
NaOH · 7 H ₂ O	24.09
NaOH · 5 H ₂ O	30.77
NaOH · 4 H ₂ O	35.71
NaOH · 3.5 H ₂ O	38.84
NaOH · 2 H ₂ O	52.63
NaOH · H ₂ O	70.14

7.1.1.1.9.1.3 High-Temperature NaHg Cell. The present sodium amalgam cell operates at about 60 C with a sodium hydroxide electrolyte concentration up to 22 per cent. Less water would be needed for dilution of the product sodium hydroxide at higher temperatures. Several technical factors must be considered for high-temperature operation. The solubility data (Fig. 33) indicate that the cell could be operated at about 65 C and keep the sodium hydroxide in solution up to a concentration of about 73 per cent (0.643 lb of water for dilution). At higher concentrations, the necessary cell operation temperature rises sharply. At a concentration of 78 per cent (0.490 lb of water for dilution), the cell would have to operate above 100 C.

The effect of concentration on conductivity of sodium hydroxide solution at various temperatures is shown in Table 32 and Fig. 34. The conductivity increases with temperature, but drops with increasing concentration. The conductivity of a 70-per cent solution at 100 C is about equal to that of a 22-per cent solution of 75 C.

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TABLE 32

CONDUCTIVITY OF NaOH-H₂O SYSTEM AT VARIOUS TEMPERATURES*

NaOH concentration, wt %	NaOH concentration, M	conductivity, ohm ⁻¹ cm ⁻¹								
		temperature, °C								
		0	25	50	75	100	125	150	175	200
5.75	2.67	--	0.249	--	0.462	--	--	--	--	--
7.45	3.50	--	0.302	--	0.580	--	--	--	--	--
14.45	7.07	--	0.420	--	0.915	--	--	--	--	--
15.73	7.76	--	--	--	--	--	1.31	1.56	1.73	--
23.31	12.04	0.154	0.378	0.645	1.02	1.57	--	--	--	--
26.36	13.87	--	0.334	--	1.02	--	--	--	--	--
30.92	16.78	--	--	--	--	--	1.71	2.02	2.41	--
33.23	17.24	0.077	0.261	0.514	0.938	1.50	--	--	--	--
36.04	20.24	--	0.214	--	0.930	--	--	--	--	--
44.70	26.69	0.025	0.151	0.375	0.817	1.44	2.03	--	--	--
45.35	27.45	--	--	--	--	--	1.67	2.17	2.67	--
46.85	28.38	--	0.140	--	0.822	1.48	--	--	--	--
51.22	32.10	--	--	--	--	--	--	2.21	2.81	3.12
55.05	35.55	--	--	--	0.703	1.23	--	--	--	--
56.11	36.54	--	--	--	--	--	--	--	2.57	2.95
60.81	41.13	--	--	--	0.636	1.18	--	--	--	--
65.02	45.56	--	--	--	--	--	--	--	2.36	2.92
69.30	50.67	--	--	--	0.504	0.974	--	--	--	--
69.92	51.14	--	--	--	--	--	--	--	2.21	2.78
71.51	53.04	--	--	--	0.489	0.995	--	--	--	--
74.40	56.69	--	--	--	--	--	--	1.67	2.00	2.47
77.11	60.27	--	--	--	--	--	--	--	1.75	2.16

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The electrochemical reaction in the sodium amalgam cell involves both anode and cathode half-cell reactions. The anode reaction is:

The simple Nerst half-cell reaction expression is:

$$E = E^{\circ} = RT/nF \log_e \text{Na}^+$$

in which

E = the observed half-cell voltage vs. H_2

E° = the standard potential

R = the universal gas constant

T = the absolute temperature, $^{\circ}\text{K}$

n = the number of electrons in the reaction

F = Faraday's constant

Na^+ = the activity of the sodium ion in solution

The activity of the sodium ion increases rapidly in concentrated salt solutions. This would lower the observed potential, because sodium is less likely to ionize and go into solution if the solution is highly concentrated in sodium ion.

The oxygen reaction at the cathode is complex and not well understood. The simple net reaction, however, is:

The corresponding Nerst equation is:

$$E = E^{\circ} - RT/nF \log_e \text{OH}^4 / \text{PO}_2 \text{H}_2\text{O}^2$$

in which PO_2 = pressure of O_2

and H_2O^2 = square of H_2O concentration.

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The activities of hydroxide ion and water play an important role in the reaction. A saturated sodium hydroxide solution at 100 C contains 340 g of sodium hydroxide in 100 g of water. The mole ratio of sodium hydroxide to water is $8.5/5.56 = 1.53$. The amount of water available for reaction at the cathode is quite limited. The activity of the hydroxide ion is low. From the conductivity data, it can be seen that the activity of the hydroxide ion and the degree of ionization at high temperatures and high concentrations are about the same as at lower temperatures and lower concentrations.

These factors would probably combine to give a lower output if the present sodium amalgam cell were operated at higher temperatures and higher concentration. M. W. Kellogg Co.³ has observed a 0.35-v reduction from the present cell output throughout the cell output curve with a 50-per cent sodium hydroxide electrolyte at 60 C. The actual cell output at high temperatures and concentrations would have to be determined experimentally. Basic chemical factors would probably result in optimization of cell conditions of about 50-per cent sodium hydroxide concentration and 75 to 80 C. It is difficult to project operating voltage and amperage; they will probably be no better than those of the present cell at these conditions, but the quantity of water necessary for reaction would be reduced.

The projected sodium amalgam fuel cell is assumed to have the same output characteristics as the present cell, but to operate with a 50-per cent sodium hydroxide electrolyte at 80 C. The future flat-plate-construction sodium amalgam cell would then produce 160 amp/ft² at 1.6 v. M. W. Kellogg Co. projects a future cell system of 6 kw/ft³ and 85 to 90 lb/ft³ with 1/16-in. cell width.

7.1.1.1.9.1.4 Amalgamation. The fuel fed to the sodium amalgam fuel cell is normally a 0.6-per cent amalgam. This amalgam can be prepared by mixing of sodium in mercury. The denuded mercury from the amalgam cell is returned to the amalgamator for renewal of sodium amalgam. M. W. Kellogg Co.³ extrudes molten sodium into mercury at 225 F. The amalgam is then cooled to the cell operating temperature. This heat could be used to concentrate sodium hydroxide effluent from the cell to permit recycling of water in the system.

If the overflow effluent from the cell is 50-per cent sodium hydroxide, 100 lb will contain 50 lb of water and 50 lb of sodium hydroxide. This quantity of sodium hydroxide would be produced by the consumption of 28.75 lb of sodium. The maximum amount of heat available from the reaction of this sodium (with the cell at 1.6 v) would be 92,000 Btu.

The engineering problems, heat losses, and small temperature differences would probably limit the effective utilization of the heat to about one-fifth of the maximum available. Vacuum distillation would probably be required for water removal. It is assumed that 20 lb of water per 100 lb of 50-per cent sodium hydroxide effluent could be recycled. The power requirement for this process is assumed to be 5 per cent.

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The recycle of 20 lb of water would reduce the water requirements for reaction and dilution to 1.087 lb of water per pound of sodium. The net effective sodium hydroxide concentration would be 71.42 per cent.

The characteristics of the projected fuel cell are listed in Table 33.

TABLE 33

CHARACTERISTICS OF NaHg-O₂(AIR) CELL WITH PHYSICAL AMALGAMATION OF Na

operating voltage	1.6 v
operating temperature	80 C
cell effluent	58% NaOH
heat-exchanger effluent	71% NaOH
power/ft ³ *	6 kw
weight/ft ³ *	85 to 90 lb
auxiliary power required	12%
weight of Na/kwhr	1.182 lb
weight of Na, reactant, and dilution H ₂ O/kwhr	2.467 lb
total weight of reactants/kwhr	2.8778 lb

*Additional weight and volume needed for evaporator pumps, condenser, etc., for water recycle system.

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7.1.1.1.9.1.5 Application in Vehicle. The sodium amalgam-oxygen cell has been extensively investigated by M. W. Kellogg Co.,⁴ whose information has been projected to a future fuel cell operating at 80 C with an electrolyte of 50 per cent sodium hydroxide. An evaporator system is used to concentrate the cell effluent to 71 per cent and thus cycle some water in the system.

This cell operates at 1.6 v (with a thermal efficiency of 54 per cent) and will consume the following weights of reactants per kwhr: 1.182 lb of sodium, 1.2874 lb of water (0.4625 lb for reaction and 0.8222 lb for dilution), and 0.4111 lb of oxygen. All the reactants would weigh 2.88 lb/kwhr.

This cell system (bare cell plus auxiliaries) would have a power-volume density of 6 kw/ft³ and a density of 90 lb/ft³. Additional volume and weight would be required for the evaporator. The evaporator size would not be a linear function of cell system size, but would depend on the particular application. The auxiliary power is estimated at about 12 per cent of the output power. In these calculations it was assumed that the auxiliaries were running only while the fuel cell was operating.

Case A: The total power needed per tank is the net power (313 kw) plus 12 per cent for auxiliaries (313 x 0.12); or 350 kw. The sodium amalgam-oxygen system of this power capacity would have a volume of 58.3 ft³ and a weight of 5250 lb. The weight and volume of the evaporator for this particular system are estimated at 500 lb and 15 ft³.

The material requirements for 1400 kwhr per day are 1655 lb (127.3 ft³) of sodium, 1802 lb (28.8 ft³) of water, and 575 lb (8.07 ft³) of oxygen. All the reactants would weigh 4032 lb and occupy 64.2 ft³. The products, which are solid below 65 C, would weigh 4032 lb and have a volume of 38.4 ft³.

The total system (fuel cell, evaporator, fuel, oxidizer, and product storage, exclusive of tanks) would have an approximate volume of 176 ft³ and weigh 9790 lb.

Case B: The total power needed per truck is the net power (89.5 kw) plus 12 per cent for auxiliaries (89.5 x 0.12), or 100.2 kw. The duty cycle would require fuel oxidant for 350 kwhr. This would require a volume of 16.67 ft³ and a weight of 1500 lb. The evaporator would weigh 100 lb and occupy 5 ft³.

The material requirements for 350 kwhr per day would be 413.7 lb (6.84 ft³) of sodium, 450.6 lb (7.22 ft³) of water, and 144 lb (2.07 ft³) of oxygen. All the reactants would weigh 1008.3 lb and have a volume of 16.13 ft³. The products, which are solid below 65 C, would weigh 1008 lb and occupy 9.8 ft³.

The total power plant system, exclusive of storage tanks, would have an approximate volume of 47.6 ft³ and weigh 2610 lb.

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Case C: Total power per unit is 100 kw net plus auxiliary power (100×0.12) or 112 kw. This would require a volume of 18.6 ft^3 and a weight of 1680 lb. The evaporator would weigh 150 lb and have a volume of 7 ft^3 .

The material requirements for 2688 kwhr per day would be 3177 lb (52.5 ft^3) of sodium, 3460 lb (55.3 ft^3) of water, and 1105 lb (15.4 ft^3) of oxygen. All the reactants would weigh 7742 lb and have a volume of 121.5 ft^3 . The products, solid below 65°C , would weigh 7742 lb and have a volume of 73.8 ft^3 .

The total power plant system, exclusive of storage tanks, would have a volume of 222 ft^3 and weigh 9570 lb.

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7.1.1.9.2. NaHg-O₂ (Air) Cell with Electrochemical Amalgamation of Na

Electrical energy could be derived from the amalgamation process. A concentration cell could be constructed with sodium in contact with sodium ion, and containing electrolyte in contact with denuded amalgam. Sodium will ionize, entering the electrolyte, and release electrons to the external circuit. Sodium ions move through the electrolyte to the mercury surface, where they are reduced by electrons from the external circuit, forming metallic sodium, which amalgamates with the mercury. The cell can be illustrated symbolically as Na-NaZ-NaHg, where NaZ is some electrolyte containing sodium ion. The denuded amalgam from the sodium amalgam cell passes through the concentration cell and becomes enriched in sodium. It is then passed to the sodium amalgam cell, completing the cycle. Such a cell has not been constructed, as far as can be determined.

The electrolyte in the concentration cell would have to be a fused sodium salt to prevent direct reaction of sodium metal with the electrolyte. The anion in the fused salt would have to be less easily reduced than sodium ion. The solubility of sodium and mercury in the electrolyte should be low to prevent electrochemical short circuiting. An electrolyte melting at 250 C and composed of a eutectic containing 53-per cent sodium hydroxide, 28 per cent sodium bromide, and 19 per cent sodium iodide has been used in a cell to produce sodium from sodium amalgam. This is the reverse of the above reaction. This electrolyte might be used, but the choice of electrolyte should be determined by more thorough evaluation of the system and by laboratory experiments.

In any case, the electrochemical amalgamation would probably take place at high temperatures and involve a fused sodium salt electrolyte. The theoretical voltage for the sodium concentration cell is about 0.8 v. If a suitable electrolyte could be found, outputs of several hundred amps/ft² at 0.4 to 0.6 v could probably be obtained. Cell construction would depend upon many presently unknown factors. A flat-plate construction is assumed. Because the order of densities is sodium, sodium salt, and mercury, the cell sandwich would be made up in this order. Denuded amalgam from the sodium amalgam cell would flow beneath the sodium salt electrolyte, and sodium would float on top of it. The average density, with equal thicknesses of sodium, sodium salt, and mercury, would be about 5.7 g/cm³. A cell thickness of 0.25 in. and outputs of 250 amp/ft² (gross) and 0.5 v are assumed. The bare cell output would be 6.0 kw/ft³ and it would weigh 350 lb. The concentration cell system, assuming a 25-per cent increase in volume and a 10-per cent increase in weight for auxiliaries, would produce 4.5 kw/ft³ and weigh 290 lb/ft³, at 0.5 v. Auxiliaries would require about 12 per cent of the power. One pound of sodium will produce 0.264 kwhr in this cell.

The extraction of some electrical energy from the amalgamation process prevents the practical utilization of the nonelectrical, or heat, energy from the oxidization of sodium for the concentration of sodium hydroxide.

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The sodium amalgam-oxygen cell would be connected in tandem with the concentration cell. This tandem arrangement of cells would produce 2.1 v/cell under operating conditions. Because the concentration of sodium hydroxide is not feasible, in this case the effluent from the cell would be 50 per cent sodium hydroxide.

The characteristics of the sodium amalgam-oxygen (air) fuel cell with electrochemical amalgamation are listed in Table 34.

TABLE 34

CHARACTERISTICS OF NaHg-O₂ (AIR) CELL
WITH ELECTROCHEMICAL AMALGAMATION OF Na

concentration cell system:

operating voltage	0.5 v
operating temperature	320 C
power/ft ³	4.5 kw
weight/ft ³	290 lb
auxiliary power required	12%
weight of Na/kwhr	3.788 lb

NaHg-O₂ cell:

operating voltage	1.6 v
operating temperature	80 C
heat exchanger effluent	50% NaOH
power/ft ³	6 kw
weight/ft ³	85 to 90 lb
weight of Na/kwhr	1.182 lb
weight of Na and reactant and dilution H ₂ O	3.699 lb
total weight of reactants/kwhr	4.11 lb

tandem system:

auxiliary power required	12%
power/ft ³	5.25 kw
weight/ft ³	190 lb
weight of Na/kwhr	0.901 lb
weight of Na and H ₂ O/kwhr	2.820 lb
total weight of reactants/kwhr	3.133 lb

7.1.1.1.9.2.1 Application in Vehicle. This system has a sodium amalgam cell complex in series with a sodium concentration cell. This cell system has a power-volume density of 5.25 kw/ft³ and a density of 190 lb/ft³. The cell requires 0.901 lb of sodium per kwhr, 1.918 lb of water per kwhr, and 0.313 lb of oxygen per kwhr. All the reactants weigh 3.13 lb/kwhr.

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Case A: The total power needed per tank is 313 kw plus 12 per cent for auxiliary power (3.13×0.12), or 350 kw gross. The cell volume for this capacity would be 66.6 ft³, and the weight, 12,654 lb.

The material requirements for 1400 kwhr per day are 1261 lb (20.8 ft³) of sodium, 2685 lb (42.9 ft³) of water, and 438 lb (16.1 ft³) of oxygen. All the reactants would weigh 4374 lb and have a volume of 69.8 ft³. The product would weigh 4374 lb and have a volume of 46 ft³.

The total system of cell, fuel, oxidizer, and products would weigh 17,028 lb and have a volume of 141 ft³.

Case B: The total power per truck is 89.5 kw plus 12 per cent for auxiliaries (89.5×0.12) or 100.2 kw. The duty cycle would require fuel for 350 kwhr. This would require a volume of 19.1 ft³ and a weight of 3629 lb.

The material requirements for 350 kwhr per day would be 315 lb (5.21 ft³) of sodium, 671 lb (10.7 ft³) of water, and 109 lb (1.58 ft³) of oxygen. All the reactants would weigh 1095 lb and have a volume of 17.9 ft³. The product would weigh 1130 lb and have a volume of 11.3 ft³. The total system of cells, fuel, oxidizers and product, exclusive of storage tanks, would have a volume of 47.9 ft³ and weigh 4725 lb.

Case C: The total power needed per unit is 100 kw plus 12 per cent for auxiliaries (100×0.12) or 112 kw. The system would have a volume of 21.3 ft³ and a weight of 4053 lb.

The material requirements for 2688 kwhr per day would be 2422 lb (40.0 ft³) of sodium, 5155 lb (82.48 ft³) of water, and 841.3 lb (11.77 ft³) of oxygen. All the reactants would weigh 8418 lb and have a volume of 87.55 ft³. The total systems of fuel cell, fuel, oxidizers and product, exclusive of storage tanks, would weigh 12,471 lb and have a volume of 243 ft³.

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7:1.1.1.9.3 Na-Steam Cell in Tandem with H₂-O₂ Fuel Cell.

Sodium might be used to generate power in the field vehicles using a sodium-steam cell and a hydrogen-oxygen cell in tandem. This system is in the conceptual-design stage and would require research and development.

The net reaction in the sodium-steam cell would be

The theoretical voltage for this cell is 1.62 v at 25 C. At 500 K, the ΔF (free energy) of reaction is -28.9 kcal. A voltage of 1.25 v can be computed at this temperature. A simple cell design would have liquid sodium in contact with fused sodium hydroxide at 320 C for the anode. The cathode would consist of porous nickel in contact with fused sodium hydroxide. The anode reaction is

Water vapor would react at the cathode according to this reaction:

Electrical connections would be made to the liquid sodium and the metal cathode. The sodium hydroxide product would be removed from the cell as liquid and returned to the reactor for reprocessing.

Sodium and water are soluble in fused sodium hydroxide and react in the electrolyte, lowering the efficiency of utilization of fuel. The current efficiency would probably be in the range of 70 to 50 per cent (0.37 to 0.265 amp-hr/lb) of sodium.

Because the cathode is a gas-evolution electrode, the polarization and overvoltage would be quite large. A cell voltage of 0.9 to 1.0 v at a reasonable voltage would be expected. The output of the cell can only be approximated. This analysis indicates a sodium-steam cell output of about 0.31 kw-hr/lb of sodium.

The products of reaction in the sodium-steam cell are sodium hydroxide and hydrogen. The hydrogen is formed at high temperatures and contains water vapor. The hydrogen could potentially be fed to a hydrogen-oxygen fuel cell to produce power. The product water could be taken to the sodium-steam cell for use as a reactant.

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Hydrogen-oxygen fuel cells fall into two broad classifications: low-temperature low-pressure, and high-temperature high-pressure. Both operate at temperatures less severe than those of the sodium-steam cell. Thus, the hydrogen from a sodium-steam cell would have to be cooled and dehumidified, and have its pressure adjusted, before it could be used in any hydrogen-oxygen cell. More work would be necessary to provide hydrogen for a low-temperature cell, but low-temperature cells are more advanced than high-temperature cells.

The product water is normally removed from the hydrogen-oxygen cell by circulating the gas streams through condensers. The water would have to be condensed out of the gas stream, converted into steam, and injected into the cell. This process would pose some engineering problems. For example, it would require considerable amounts of energy. The high-temperature cell has a somewhat higher voltage efficiency at a given current density than the low-temperature cell. However, to a first approximation, 1 lb of hydrogen will yield about 10 kwhr in both cells. The 0.0434 lb of hydrogen produced by reacting 1 lb of sodium will produce about 0.43 kwhr.

The total output of the tandem cell system would be about 0.67 to 0.80 kwhr/lb of sodium.

Cell auxiliaries would require power or heat energy. The sodium-steam cell must be maintained at over 300 C, which may require heaters. Pumps are also needed to pressurize the feed materials. Power is needed to treat the hydrogen product. There are other auxiliary requirements. The energy available to power the vehicle would probably be about 0.55 to 0.7 kwhr/lb of sodium.

The over-all efficiency of the total system can be approximated from above discussions. The production of sodium, oxygen, and water requires 6.6 to 7.34 kwhr/lb of sodium. The fuel cell system produces 0.60 to 0.70 kwhr/lb of sodium. This indicates an efficiency of less than 10 per cent for the conversion of electrical power at the reactor to electric drive power in the vehicle motor. Other factors not considered above, such as the fabrication of sodium into shipping form, would lower this efficiency.

The characteristics of the tandem system are listed in Table 35.

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TABLE 35

CHARACTERISTICS OF Na-STEAM CELL IN TANDEM WITH H₂-O₂ CELL

Na-steam cell:

operating voltage	0.95 v
operating temperature	320 C
power/ft ³	(not determined)
weight/ft ³	(not determined)
auxiliary power required	10%
weight of Na/kwhr	3.18 lb

H₂-O₂ cell:

operating voltage	0.95 v
operating temperature	170 F
power/ft ³	(not determined)
weight/ft ³	(not determined)
auxiliary power required	10%
weight of H ₂ /kwhr	0.1 lb

tandem system:

voltage	1.90 v
power/ft ³	(not determined)
weight/ft ³	(not determined)
auxiliary power required	10%
weight of Na/kwhr	1.34 lb
weight of Na and reactant H ₂ O/kwhr	1.855 lb
total weight of reactants/kwhr	2.318 lb

7.1.1.1.9.3.1 Application in Vehicle. This system consists of a sodium-steam cell in tandem with a hydrogen-oxygen cell. The hydrogen product from the steam cell is transferred to the hydrogen-oxygen cell. This unit has not been sized. The quantity of sodium required for Case A makes this system less attractive than other sodium systems. About 50 per cent more sodium is needed than in the sodium amalgam cell. This system requires 1.34 lb of sodium per kwhr, 0.524 lb of water per kwhr, and 0.466 lb of oxygen per kwhr.

Case A: The power needed per tank would be 313 kw plus 12 per cent for auxiliaries (313 x 0.12), or 350 kw. The reactants required for 1400 kwhr per day are 1876 lb (30.0 ft³) of sodium, 730 lb (11.68 ft³) of water, and 652 lb (9.12 ft³) of oxygen. All the reactants would weigh 3258 lb and have a volume of 23.80 ft³. The product would weigh 3258 lb and have a volume of about 26 ft³.

More sodium fuel is needed than in any of the other sodium systems. Because the weight of the reactants is so great, Cases B and C will not be considered.

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7.1.1.1.9.4 Comparison of Na Systems. The analysis of the various ways of using sodium as a fuel involves many assumptions and extrapolations. Experimental evidence and further study are needed to justify or adjust these judgments.

Each of the systems has several advantages and disadvantages. The sodium amalgam cell with physical amalgamation (Sec. 7.1.1.1.9.1) would require the least development (evaporators would require less development than a sodium concentration cell), uses an intermediate amount of total reactants, and is relatively compact and light. The sodium amalgam cell with electrochemical amalgamation (Sec. 7.1.1.1.9.2) uses the smallest amount of sodium but the greatest total amount of reactants, and is relatively heavy and bulky. Furthermore, the sodium concentration cell represents an unknown factor and would require research and development. The tandem system of sodium-steam cell and hydrogen-oxygen cell (Sec. 7.1.1.1.9.3) uses the smallest amount of total reactants but the largest amount of sodium, is still in the conceptual-design stage, and would require research and development.

7.1.1.1.10 LiH Fuel Cell. The lithium hydride fuel cell is in the class of thermally and electrically regenerative cell systems. It would potentially be considered for fuel cell power for field vehicles and for the production of power from the reactor thermal energy at the depot site.

In the lithium hydride regenerative cell, lithium is the fuel and hydrogen is the oxidizer.^{5,6,7} The reaction product of these materials is lithium hydride. The hydride ion formed at the cathode would not be stable in an aqueous solution, so the electrolyte used in the cell must be a fused salt. A lithium chloride-lithium fluoride eutectic melting at 932 F has been used. Normal cell operation temperature in this case is 950 F. The lithium hydride

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that forms in the cell reaction dissolves in the fused salt eutectic. This solution is removed from the cell and pumped to a regenerator. In the regenerator, the solution of lithium hydride in the eutectic is heated to 1650 F. The lithium hydride thermally decomposes to lithium and hydrogen and these materials distill from the melt at a pressure of about 10 mm Hg. Some lithium chloride also vaporizes. The vapors pass to a condenser and separator. The lithium and lithium chloride condense to liquids and are mixed in with the denuded eutectic coming from the regenerator. The eutectic containing lithium is then passed through heat exchangers and returned to the cell. In the heat exchangers, the electrolyte, containing lithium hydride coming from the cell, is preheated before entering the regenerator. The hydrogen from the condenser-separator system passes through heat exchangers and returns to the cell. Thus, the reactants are regenerated thermally and useful electric power is obtained from the cell. The theoretical efficiency of the cell is 32 per cent. Losses in pumping, heat exchange, and fuel cell inefficiencies, etc., lower the conversion to below 16 per cent.

The lithium hydride could be regenerated electrochemically.⁸ The eutectic containing lithium hydride could be passed into a regenerator of similar design as the fuel cell. In the electrolytic regenerator, lithium ion is reduced and deposited at one electrode as metal and hydride ion is oxidized at the other electrode and given off as hydrogen. This process is analogous to the electrolysis of water.

The voltage required to operate the cell would decrease with increasing temperature and increasing electrode area. The same amount of current must pass through the fuel cell during the production of lithium hydride as passes through the regenerator cell during the electrolysis. The difference in temperature and the electrode area determines the difference in operating voltage of the two units. The voltage difference and total amperage determine the useful electric work.

The Mine Safety Appliance Company, the Tapco Division of Thompson Ramo Wooldridge Company, the Argonne National Laboratory, and others have worked on the lithium hydride cell. Tapco's cell data can be used for discussion purposes.^{5,6,7} In a system designed for space applications, a 0.5-kw unit weighed 127 lb and had a volume of 0.688 ft³. The bare cell unit weight was 74 lb and its volume was 0.341 ft³. Each cell would operate at a closed circuit voltage of 0.45 v at 200 amp/ft². The hydrogen was supplied from the regenerator at 10 mm Hg. At a hydrogen pressure of 1 atm (760 mm), 1500 amp/ft² have been obtained by Tapco. At this current density, the bare cell would produce 11 kw/ft³ and the system would produce 5.46 kw/ft³. At 0.45 v cell, 1.45 lb of lithium and hydrogen are needed per kilowatthour. The electrolyte discharging from the cell contains less than 4 per cent by weight of lithium hydride.

In the MED concept liquid hydrogen or compressed hydrogen gas and lithium dispersed in a eutectic mixture would be carried to the vehicle. These would be combined in fuel cells to produce power. The lithium hydride containing eutectic overflow from the cells would be returned from the vehicle to the depot for reprocessing.

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If a 313-kw electric motor and 1250 kwhr/day (net) are assumed for tank requirements, some sizes and weights can be calculated. The present lithium hydride bare cell would have a volume of 213 ft³ and weigh 32,800 lb, if hydrogen is used at 10 mm. With the hydrogen at atmospheric pressure, the volume would be about 28 ft³ and the weight about 4300 lb. To supply 1250 kwhr, 1812.5 lb of lithium and hydrogen are needed. In addition, 44,000 lb of eutectic would be needed as a dispersant for the lithium and as a solvent for the lithium hydride reaction product to be returned to the reactor. The eutectic would have a volume of 324 ft³.

The cell auxiliaries might occupy one tenth as much space as the rest of the unit and weigh 200 to 300 lb. An additional 5 to 10 per cent of fuel may be needed to power the auxiliaries. The fuel cell system would then occupy 30.8 ft³ and weigh 4500 lb. The fuel would weigh about 1900 lb and the eutectic would weigh about 46,000 lb. The fuel and eutectic would occupy over 340 ft³.

Additional fuel and eutectic would be needed to keep the cell at an operating temperature of 950 F and to keep at least a portion of the fuel and eutectic at 950 F. The quantity is difficult to estimate because it would depend on the duty cycle, insulation factors, and ambient temperatures. The quantity necessary would probably be in the range of 10 to 20 per cent of the system.

The tank would thus have to be supplied with more than 2100 lb of lithium and hydrogen and 50,000 lb of eutectic per day. The volume of fuel and eutectic would be in excess of 380 ft³. The fuel cell system would occupy a volume of 33 ft³ and weigh about 4500 lb. The cell system, fuel, and eutectic would have a volume of over 400 ft³ and weigh over 56,000 lb. The volume available in M60 tank for fuel cells and fuel is less than 286 ft³; this tank presently weighs 95,000 lb.

The lithium hydride cell in the tank or field vehicle does not now appear feasible. The weight and volume of materials supplied to and removed from the tank each day would be excessive (over 50,000 lb). The volume of the complete cell and fuel system is too large by a factor of 1.45. Future improvements in the cell will not improve the situation much, because the major portion of volume and weight is fuel and eutectic. If some means could be found for separating lithium hydride from the eutectic in the vehicle, only lithium hydride would have to be returned to the depot. The eutectic would be cyclic in the vehicle fuel cell system. The weight transported would be quite small and the system would be more attractive.

In addition, the practical problem of maintaining the cell at a temperature of 950 F and the corrosion and handling problems associated with large weights and volumes of molten lithium, lithium fluoride, and lithium chloride in the field would be very great.

The lithium hydride regenerative system could be considered as a power generation device at the reactor. The lithium hydride reaction product could be regenerated to

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lithium and hydrogen electrochemically or thermally. Electrochemical regeneration has not been performed experimentally to our knowledge. If it is assumed that at 1650 F, the voltage required to reverse the fuel cell reaction would be 0.225 v and that the electrochemical regenerator is of the same weight and volume as discussed above, then the fuel cell would have an output of 1500 amp/ft² at 0.45 v/cell, produce 11 kw/ft³ and weigh 218 lb/ft³. The regenerator would weigh 218 lb/ft³ and consume 5.5 kw/ft³ at 0.225 v and 1500 amp/ft². The gross work output then would be 5.5 kw per 2 ft³ of cell. The associated pumps, heat exchangers, controls, etc., would probably add 1 ft³ and 80 lb to the system. The auxiliaries would probably require 10 per cent "in-house" power. A net output of 5 kw per 3 ft³ and 516 lb would be obtained. A unit producing 1 Mwe would occupy 600 ft³ and weigh 103,200 lb. The output per unit weight would have to be increased by a factor of about 9 to compete with the MCR power generation section weight.

Thermally regenerative systems for space applications have received attention. The Tapco cell system producing 1500 amp/ft² at 0.45 v produces 11 kw/ft³ at 218 lb/ft³, (bare cell) and 5.46 kw/ft³ at 186 lb/ft³ (system). Direct scale up to 1 Mwe is not entirely appropriate, but such a scaled up version (for all bare cell) would weigh 19,600 lb and have a volume of 90 ft³. The system would weigh 34,000 lb and have a volume of 183 ft³. This is too heavy by a factor of about 4, compared with the MCR power generation section weight.

Because the Tapco cell and system were designed for a space application where weight is a prime factor, it does not seem likely that weight reduction of several orders of magnitude will be possible in the near future. The major area of improvement would occur with better performance of the hydrogen electrode.

A large-scale power unit would have problems associated with the handling of molten salts and metals. Many problems relating to construction materials also remain to be solved.

In summary, the lithium hydride cell has high output per unit volume and weight. The weight of fuel and eutectic required to power field vehicles and the problems of maintaining 950 F cell temperatures preclude serious consideration of the use of the lithium hydride cell in such vehicles. The weight of the fuel cell and regenerative system preclude serious consideration of the total system as a means of power generation at the reactor.

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7.1.1.1.11 Summary. The daily requirements of the various fuel cell systems and silver-cadmium batteries (for comparison) are listed in Table 36.

TABLE 36

VOLUMES AND WEIGHTS OF TOTAL SYSTEM INCLUDING FUEL, REACTANT,
AND OXYGEN FOR CASES A, B, AND C

	<u>fuel and reactant weights, lb*</u>	<u>O₂ weight, lb*</u>	<u>total system volume, ft³**</u>	<u>total system weight, lb**</u>
<u>H₂-O₂ fuel cell</u>				
Case A	135	1,080	156	11,965
Case B	33.76	270	43	3,378
Case C	243	1,944	117	5,638
<u>H₂-air fuel cell</u>				
Case A	135	--	214	18,000
Case B	33.76	--	60	5,100
Case C	243	--	113	5,944
<u>H₂-air (O₂) fuel cell</u>				
Case A	135	297	149	11,080
Case B	33.8	52.4	41	3,160
<u>NH₃-O₂ fuel cell</u>				
Case A	1,262	1,780	505	30,642
Case B	324	454	143	8,666
Case C	2,156	3,040	218	14,346
<u>cracked NH₃, H₂-O₂ fuel cell</u>				
Case A	1,115	1,115	150	14,000
Case B	290	239	45	4,000
Case C	1,858	1,980	110	7,750

*These quantities are for average daily requirements; no reserve is provided in the vehicle. The fuel and oxygen required to equal present vehicle range on POL will be approximately twice the listed quantities.

**Does not include the fuel, reactant, and oxygen storage vessel volumes or weights. In the H₂-O₂ fuel cell, Case A, this adds 6.6 ft³ and 140 lb for a total system volume of 162.7 ft³ and a total system weight of 12,105 lb. The addition to other systems will be proportionally smaller.

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Table 36 - Volumes and Weights of Total System Including Fuel, Reactant, and Oxygen for Cases A, B, and C (cont'd)

	fuel and reactant weights lb*		O ₂ weight, lb*	total system volume, ft ³	total system weight, lb
<u>N₂H₄-O₂ fuel cell</u>					
Case A	977		1,030	226	16,300
Case B	246		260	68	4,400
Case C	1,600		1,690	47	7,700
<u>CH₃OH-O₂ fuel cell</u>					
	<u>CH₃OH</u>	<u>NaOH</u>			
Case A	1,030	2,620	1,525	518	56,325
Case B	258	656	382	147	15,300
Case C	1,840	4,690	2,730	273	24,800
<u>HCO₂Na-O₂ fuel cell</u>					
	<u>formate</u>	<u>NaOH</u>			
Case A	5,700	2,980	1,210	411	45,690
Case B	1,430	748	304	134	12,682
Case C	10,250	2,170	2,170	267	29,205
<u>NaHg-O₂ fuel cell</u>					
<u>(physical amalgamation)</u>					
	<u>Na</u>	<u>H₂O</u>			
Case A	1,655	1,802	575	176	9,790
Case B	413.7	450.6	144	47.6	2,610
Case C	3,177	3,460	1,105	222	9,570
<u>tandem cell: Na-steam and H₂-O₂</u>					
Case A	1,876	730	652	--	--
<u>NaHg-O₂ fuel cell</u>					
<u>(electrochemical amalgamation)</u>					
Case A	1,261	2,685	438	141	17,028
Case B	315	671	109	47.9	4,725
Case C	2,422	5,155	841	243	12,471
<u>Ag-Cd batteries</u>					
Case A	46,500 (batteries)	--	--	398	46,500
Case B	11,650 (batteries)	--	--	100	11,650
Case C	89,000 (batteries)	--	--	763	89,000

*These quantities are for average daily requirements; no reserve is provided in the vehicle. The fuel and oxygen required to equal present vehicle range on POL will be approximately twice the listed quantities.

7.1.1.2 Electric Drives.

7.1.1.2.1 Rating Factor. The nominal rating of internal-combustion engines of both the spark-ignition and the diesel types is based on the broke horsepower of the bare engine at the flywheel at sea level and at an air temperature of 60 F. This applies not only to passenger automobile engines, but also to heavy-duty truck, tractor and military vehicle engines.

The power output of a typical engine rated nominally at 200 hp was analyzed.⁹ The losses demonstrated for this engine with all its auxiliaries, under normal operating conditions, were approximately as follows:

muffler	14%
air cleaner	3%
cylinder deposits	4%
monifold heat	1 to 5%
automatic spark	1 to 6%
fan	3.5%
generator	1.0%
transmission	6.0%
differential	2.0%

The total losses average 42 per cent plus temperature and pressure corrections.

A nominal engine horsepower rating assumes a new engine with a clean combustion chamber, proper gap of spark plugs and points, individual adjustment of spork timing and mixture for maximum output of each test point, sea-level pressure, an air temperature of 60 F, no air-cleaner intake resistance, no muffler back pressure, and no losses owing to the fan, generator, manifold heat, torque converter, or differential.

An electric motor-fuel cell combination has an overload capability of several hundred per cent of normal for limited periods. With internal-combustion engines, this capability is only 25 to 30 per cent. The electric motor power plant is also insensitive to changes in ambient temperature and altitude. Consequently, larger safety factors must be incorporated in designs using internal-combustion engines than in those using electric motor drives. Precise numbers cannot be established until definitive designs are available. However, it is estimated that an electric motor-fuel cell power plant (using a 90-per cent efficient electric motor, including reduction gearing) can be rated conservatively at 60 per cent of the nominal gross internal-combustion engine horsepower rating.

7.1.1.2.2 Duty Cycle. From the duty cycle reported by Capt. Charles E. Sell, Project Engineer, on February 27, 1962 (Sec. 7.1.1.1.3), a "use factor" of 49 per cent was calculated for the tanks and 54 per cent for the trucks. These use factors were used to compute the fuel requirements for vehicles powered by internal-combustion engines. An average use factor of 50 per cent was used to compute the fuel requirements for all fuel cell powered vehicles.

7.1.1.2.3 Evaluation. In the application of the fuel cell power plant to military vehicles for more efficient utilization of MED special fuels, it is necessary to make a preliminary selection of a drive system to convert the fuel cell direct current into suitable mechanical power over the range required and deliver this power to the truck wheels or tank drive sprockets.

The basic problem involved in this application is that, although the load over the speed range desired requires constant horsepower, an electric motor is essentially a constant-torque device, and its available horsepower output is proportional to speed. When the motor is used over a range of speeds and torques, its equivalent horsepower output depends largely on the product of maximum torque and maximum speed, even though these two requirements do not occur simultaneously. Size largely depends on the maximum torque, regardless of speed.

For a given load cycle and speed range, there is a combination of drive motor and gearing that permits the most effective utilization of space within reasonable weight limits. The minimum modification to convert existing vehicles to fuel cell power would be to place a single direct-current motor in the usual engine location, to drive the vehicle through conventional clutches or torque converters, gear box, and differential. This arrangement would result in minimum motor size. An improvement or simplification of this system may be available by applying individual motors to axles, wheels, or sprockets through reduction gears without torque converters or gear box, but this requires motors of larger combined equivalent horsepower. The ultimate of this simplification would be the use of so-called electric wheel drive; this would include an individually controlled motor in each wheel or hub. Unfortunately, the smallness, large speed range, and high horsepower requirements of the military drive conflict with the space requirements for electric wheel drives. The electric wheel drive has been very suitable for some uses, both commercial and military, such as in graders and overland trains, both of which use a hub about 3 ft in diameter.

The advantages of electric motors compared with internal-combustion engines are as follows:

- (1) electric motors have high short-time overload torque availability above rated torque (several hundred per cent, compared with about 30 per cent for internal-combustion engines);
- (2) electric motors may have multiple speed ranges at constant torque, with the range changed by reconnecting motor windings electrically;
- (3) electric motors are suitable for high rotational speeds, with corresponding reduction in size and weight; and
- (4) electric motors have greater reliability and require less maintenance.

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No specific reports are available on operating experience with electric drives in either military or industrial tracked vehicles. Their uses in electric railways and trolley busses, etc., are well known, but they have also had industrial applications, such as in heavy-load trucks for mining. Reports of these applications list the following advantages of electric drives over internal-combustion engine drives (many of these advantages would also be valuable in military vehicles):

- (1) improved acceleration rate and smoothness;
- (2) controlled acceleration under heavy load;
- (3) controlled deceleration with dynamic or resistance braking;
- (4) elimination of wheel spinning by wheel-power control;
- (5) substantially increased tire life owing to the above factors;
- (6) suitability for fixed central electric power supplied through trolleys, eliminating the weight of the main engine, or engine-generator, and lowering the cost of power; this in turn permits
 - more engine power,
 - increase in load capability,
 - increase in grade ability, and
 - increase in speed on steep grades;
- (7) ease of control;
- (8) automation capability;
- (9) reduced maintenance;
- (10) improved ground flotation ability because there is a separate motor for each wheel;
- (11) improved traction, because there is power on all wheels;
- (12) more effective use of vehicle space;
- (13) suitability for supplying power to all vehicles in a train from a single power-generating vehicle; and
- (14) suitability for the power connection to and power transmission from light gas-turbine drives.

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Preliminary calculations have been made for three direct-current motor drive systems for the 700-hp tank (with internal-combustion engine) to approximate the weight and space requirements for two motors, as follows:

(1) Analysis of a 5000-rpm, 210-hp, constant-torque, direct-current motor, with variable voltage control, connected by a fixed-ratio gear reduction to the sprocket, indicates that the tractive effort available at low speed would be far less than that available with mechanical transmissions. This motor would weigh 1050 lb and be 17.5 in. OD and 29 in. long.

(2) Analysis of a 2400/4800-rpm, 210-hp, constant-horsepower, direct-current motor, over a 2-to-1 speed range, with variable voltage control, indicates that the available torque would be twice that of motor (1) but still inadequate unless a clutch and gear box were added. This motor would weigh 1800 lb and be 20 in. OD and 37 in. long.

(3) Analysis of a 300/2400-rpm, 210-hp, 80 C rise, direct-current motor, designed for constant horsepower over an 8-to-1 speed range, indicates that this motor may be adequate for the tank sprocket drive requirements. It would weigh 4600 lb and be 33 in. OD and 38 in. long. This size is equivalent to that of a 1200-hp motor for constant horsepower over a 1.5-to-1 speed range. This indicates the weight penalty associated with wide speed range at constant horsepower. The weight-to-power ratio based on the 210-hp rating is 21.9 lb/hp.

Similar considerations for the 5-ton truck indicate that a single 120-hp motor driving through the existing transfer box and the three axle differentials would be the most practical direct-current arrangement, and would eliminate the engine, clutch, and transmission.

The possibility of practical and compact alternating-current drives, powered from direct-current source arises from the recent development of silicon-controlled rectifiers of high power capacity for use as inverters or frequency changers.

A preliminary study of this type of alternating-current drive system was made recently for a 200-hp tracked military vehicle. In the preferred system selected in this study, the conventional engine would drive a high-frequency generator at essentially constant speed, and two static frequency converters would provide variable-frequency power to the two 50-hp sprocket drive induction motors. These motors would drive through a gear reduction to the sprockets. The two sprocket drive induction motors for the tracked vehicle were estimated to weigh 600 lb each and to be 17-in. OD and 23-in. long. This system could probably be developed for tanks and trucks without significantly increasing the over-all weight-to-power ratio and with improved utilization of vehicle space. The two SCR cycle converters are each 40 in. wide, 60 in. long, and 22 in. deep. These items may be located at the most convenient points for operation.

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The two sprocket drive alternating-current induction motors could also be driven by power from a fuel cell, if this power were inverted into variable frequency alternating current. This system was also the subject of a preliminary study, but did not show size or weight improvement over the other systems. All the systems reviewed have similar sizes and weights for a given operational performance. Final and specific results must await specific operational requirements, and detailed designs for each application.

It is concluded that electric drives and control systems using power from fuel cells will have no substantial weight or size advantages over conventional drives using mechanical power from conventional engines. However, the other potential advantages listed above may be significant, specifically the possibility of fitting fuel cells, controls, and drives into the available space more effectively, which would justify the continued study and development of electric drive systems.

7.1.1.3 Applications.

7.1.1.3.1 Case A. The use of fuel cells with an electric drive would necessitate considerable redesign of the M60 tank, which is considered representative of this application. It is estimated that with a minimal increase in vehicle length and width, i.e., 6 to 12 in., approximately 285 ft³ would be made available for the power plant and fuel storage. Thus, only the hydrogen-oxygen, hydrogen-air, hydrazine-oxygen, and sodium-oxygen fuel cell systems can be considered from a volume standpoint. Increasing the tank width by 1 ft and the length by 2 ft will increase the volume by about 375 ft³. Note that this volume constitutes a considerable safety factor in that only 162.7 ft³ are needed for the hydrogen-oxygen power plant and fuel storage.

The weight of the engine and fuel for the present M60 tank (with internal-combustion engines) is estimated to be 5000 lb (4 lb/hp and 350 gal of fuel). All the fuel cell and battery systems are at least twice as heavy. Thus the tank would have to be redesigned to accommodate the fuel cells, possibly with some sacrifice in range and effective horsepower, owing to weight considerations.

7.1.1.3.2 Case B. Each truck will have a maximum net power requirement of 89.5 kw and 313 kwhr. The M41 (a 5-ton cargo carrier) is considered representative of this application. The hydrogen-oxygen, hydrogen-air, and hydrazine-oxygen fuel cell systems can be considered as possible power plants for this application.

The volume available for the power plant is not a significant problem. For example, simply extending the length of the vehicle by 3 ft would provide 75 ft³ for the fuel cell power plant. Actually, the fuel cell power plant would probably be distributed throughout the vehicle, simplifying vehicle design and heat-radiation problems. One advantage in the use of fuel cells is that the entire fuel cell power plant need not be in one place in the vehicle, as with an internal-combustion engine.

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The weight of the present internal-combustion engine in the truck is estimated to be 1000 lb (5 lb/hp), and that of the fuel tanks, 210 lb. The fuel cell power plants are heavier than this. However, some redesign of the vehicle and a reduction in carrying capacity from 5 to 4 tons, would permit the use of a fuel cell power plant.

7.1.1.3.3 Case C. The weight and volume restrictions are less stringent in this application. The fuel cell power plant could be mounted on one MED module and the electrical power plant mounted in the conventional manner. Because the maximum weight of the MED module is 30,000 lb, all fuel cell systems, and the silver-cadmium system, are applicable.

7.1.1.4 Fuel Cell Cooling. Cooling methods for fuel cells are unusually flexible and adaptable to the design of the vehicle and to the special requirements of the intended service and environment. This results from the relatively large surface area of the fuel cell modules per unit of weight and horsepower, and from the fuel cells' inherent adaptability to dispersed, irregular spaces.

The relatively low heat rejection of the highly efficient fuel cell, combined with the large heat rejection area, permits a low rate of heat rejection per unit of area. This lends itself especially well to air cooling with simple ducts, without requiring high sweep velocities or large pressure drops in the air circuit. This permits the use of low pressure, quiet fans, and larger volumes of air without excessive power requirements, to reduce the temperature rise of the air to a low level so that detectable infrared radiation is at a minimum.

For applications where liquid cooling may be preferred, the fuel cell radiator size has been estimated as in Table 37, based on a temperature of 170 F in the liquid to the radiator. The M113 full-tracked personnel carrier radiator requirements are listed for comparison.

TABLE 37

FUEL CELL VEHICLE RADIATOR REQUIREMENTS

	M113 200-hp 75M engine	M60 tank 335-kw fuel cell	5-ton truck 96-kw fuel cell	generator 100-kw fuel cell
est. heat to radiator, Btu/hr	191,000	288,000	82,000	86,000
radiator frontal area, ft ²	4.0	6.05	1.7	1.8
% M113 radiator area .	100	151	43	45

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It is apparent that the cooling requirements of the fuel cell power plant can be met without difficulty and with minimum space requirements for military vehicles and generator applications. Some cooling effect might be obtained from evaporating the cryogenic fluids. Theoretical calculations indicate that cooling in the range of 20 per cent of the fuel cell heat output may be obtained. This factor should be considered in designing fuel cell power plants.

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7.1.2 Internal-Combustion Engines

An extensive bibliography of the use of special fuels in internal-combustion engines has been compiled and is included in Appendix H. Several of the fuels considered in this study are discussed in detail in the sections below (see Figs. 36 through 39 for comparative evaluation).

7.1.2.1 H₂ as an Internal-Combustion Engine Fuel. A great deal of work has been done with hydrogen as a fuel, dating from the time of lighter-than-air aircraft. It was felt that, if hydrogen was used in the engines to supplement the diesel fuel, rather than being released as the diesel fuel was used, costs and fuel loads would decrease.

In 1935, the National Advisory Committee for Aeronautics ran extensive single-cylinder tests using hydrogen as a supplementary fuel in a four-stroke diesel engine. Relatively weak hydrogen-air mixtures were used, and a small amount of diesel oil was required to ignite the mixture. There were problems with pre-ignition and detonation when hydrogen-air mixtures stronger than 12 per cent by volume were used. In any case, backfiring into the intake manifold occurred intermittently.

Recent research by Dr. King and associates at the University of Toronto has clearly defined the causes of pre-ignition, detonation, and knock. Pre-ignition (or auto-ignition) seems to be caused when any internal portion of the cylinder reaches the relatively low ignition temperature of the compressed hydrogen-air mixture. By using a cooled exhaust valve and a cool spark plug and cooling the engine pre-ignition has been overcome to the point at which the frequency of firing produces heat more rapidly than it can be carried away. At the present, this limit seems to be around 1800 rpm.

Pre-ignition is also caused by electrical discharge between dust particles in the fuel-air mixture. These particles may become charged by friction during passage through the manifold and around the intake valve. This may cause a minute spark between oppositely charged particles when the gases are compressed, and initiate combustion. This is easily overcome by filtering the intake air and using hydrogen that is free of solid impurities.

Detonation is attributed to fine particles in the cylinder that act as nuclear centers of combustion. Some of these particles may be produced by incomplete combustion of oil from the lubricating system that has entered the cylinder, either by leaking past the rings or by some other route. This is particularly likely when rich hydrogen-air mixtures are burned if there is insufficient oxygen for combustion of the oil, resulting in the production of fine carbon particles in the cylinder. By proper attention to the intake-air filter, the ring design, and the valve stem, this problem has been overcome.

Knock is attributed to the high flame velocity of the highly compressed gases, but compression ratios of up to 20:1 have been used satisfactorily in engines modified by Dr. King to avoid carbon accumulations and hot spots.

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Numerous engines have been run with hydrogen, or gases consisting principally of hydrogen, as fuel. These engines have generally been successful, sometimes in spite of pre-ignition and detonation problems, frequently (but not always) by operating at low speed and power. It is felt that with proper attention to the known causes of pre-ignition and detonation, particularly with regard to sufficient engine cooling, a satisfactory high-speed, high-power engine can be developed.

The Erren combustion cycle, a different method of using hydrogen as fuel, was developed by the Germans during World War II for use in submerged submarines. Hydrogen and oxygen produced by the electrolysis of water are burned to superheated steam in a diesel-engine cylinder, providing the driving force for the piston. The steam is cooled, recycled, and superheated again by the combustion of additional hydrogen and oxygen. Apparently no development work has been done with this combustion cycle since it was used in submarines during World War II.

Hydrogen has also been used successfully as a turbojet and ramjet fuel, although little specific information was available concerning these applications.

7.1.2.2 H₂O₂ as Internal-Combustion Engine Fuel. Hydrogen peroxide is most easily used as a turbine fuel, in which case its catalytic decomposition produces superheated steam. It has also been used notably in the Walther turbine for German submarines, as an oxidizer, with diesel fuel and water injection to produce steam and carbon dioxide to run the turbine. This method has been successful, and it appears probable that any fuels of interest in this report could be substituted for the diesel fuel, with or without water injection to cool the gases suitably for a turbine.

A great deal of work has been done with hydrogen peroxide for auxiliary power generators, portable power generators, and control rockets. Most of this work has been with regard to the catalytic decomposition of hydrogen peroxide to produce steam for a turbine, in applications as diverse as torpedoes and submarines. There is a portable steam generating plant weighing 200 lb and operating on hydrogen peroxide; this could easily be applied to a turbine.

7.1.2.3 NH₃ and C₂H₂ as Internal-Combustion Engine Fuels. There have been substantial investigations and tests of ammonia as a fuel, with acetylene and other additives, during the war years (1938-1945). Two methods are reported to have been successful.

The first is the catalytic dissociation of the ammonia before it enters the cylinder. By passing the ammonia over a proper catalyst, such as platinum, it can be made to dissociate into hydrogen and nitrogen. The hydrogen then initiates the burning process. In practice, the ammonia is first released from a high-pressure storage tank and vaporized. An exhaust gas heater then heats a chamber containing the catalyst to about

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850 F; the ammonia then breaks down into nitrogen and hydrogen, and this mixture is introduced into the cylinder (Fig. 35).

Ammonia can also be used as engine fuel by adding acetylene or ether for initial ignition.

It was expected that ammonia could be used as a fuel with some sacrifice in power and economy, partly due to low heat of combustion, in engines designed specifically for other fuels. It was found that, with proper engine compression ratio modification and fuel additives, ammonia was adequate to operate a fleet of buses for over 100,000 miles without significant reduction in performance.

The report, "Ammonia - A Fuel for Motor Buses" (Journal of the Institute of Petrol, July, 1945, pp. 213-23), on the use of ammonia as a fuel for a passenger bus line in Belgium in World War I, does not mention any unacceptable exhaust products. The reported absence of any trace of corrosion upon complete engine inspection after 10,000 miles of operation indicates that oxides of nitrogen are not produced in appreciably greater quantities than when hydrocarbon fuels are used. No mention was made that any other unacceptable combustion products were formed.

7.1.2.4 N₂H₄ as an Internal-Combustion Engine Fuel. The physical and chemical characteristics of hydrazine and of some of its compounds offer advantages over other potential MED fuels of the types that are relatively easy to separate or synthesize, such as hydrogen, ammonia, and acetylene.

Under normal ambient conditions, hydrazine is a fluid whose specific gravity, viscosity, freezing point, and boiling point are close to those of water. The freezing point can be lowered to -40 F, by combining hydrazine with water to form hydrazine hydrate. Other solutions can be used, such as hydrazine-alcohol or hydrazine-ammonia, to lower the freezing point without loss of heat value. The eutectic solution of 13 per cent hydrazine and 87 per cent ammonia has a freezing point of -80 C, or -112 F.

Hydrazine is combustible and highly reactive chemically. However, anhydrous hydrazine has the disadvantage of instability, decomposing exothermically in the presence of catalysts. Therefore, hydrazine systems must be kept thoroughly clean and free from rust. Stainless steel is a preferred containment material; brass and copper are not permissible.

The heat of combustion of anhydrous hydrazine is slightly less than that of ammonia, but the elimination of pressure container requirements would give hydrazine a moderate advantage over ammonia in energy output per unit weight of system (including container), except for the probable necessity of dilution with water and other additives to improve the stability of hydrazine and aid its ignition in engines.

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FIG. 35. AMMONIA FUEL SUPPLY SCHEMATIC FOR APPLICATION TO GASOLINE ENGINES

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Patents on fuels that contain hydrazine and on engines that use hydrazine indicate that some additive is required to prime the ignition of hydrazine-air mixtures, or that a preliminary decomposition of hydrazine, such as by electric discharge, may be necessary to secure satisfactory combustion. The use of an additive such as ether or acetylene dissolved in hydrazine for ignition priming would reduce the engine modifications required, so that only the fuel tank and the carburetor or fuel-injection system material would have to be changed to eliminate copper, brass, and rust-forming materials.

It is concluded that the potential advantages of hydrazine are chiefly in reduced container weight and increased ease of handling, and that these are not sufficient to offset the considerably increased equipment and energy required to synthesize hydrazine, compared with such fuels as hydrogen and ammonia.

7.1.2.5. Alcohol as an Internal-Combustion Engine Fuel. Alcohol is readily used as a fuel in both spark-ignition and compression-ignition internal-combustion engines. The problems involved are generally minor, and several more-or-less convenient solutions have been offered for all of them.

Alcohol may be used satisfactorily in a spark-ignition internal-combustion engine without major modification of either the engine or the carburetor. Problems in low-speed operation, starting, and loss of efficiency where alcohol is used alone (owing to uneven distribution of the fuel-air mixture) have been overcome by redesigning the intake manifolds and carburetors.

Special carburetors have been designed to facilitate the use of alcohol in spark-ignition engines at low temperatures, at which the low volatility of alcohol inhibits proper ignition in the cylinder.

With suitable modifications to secure proper fuel vaporization in the carburetor and distribution in the manifold, and with the higher compression ratio that alcohol will tolerate, substantial increases in power have been produced. In these cases, alcohol is used without an anti-knock and engine life is increased substantially, owing to lower temperatures in the combustion chamber and lack of abrasive combustion products. Acid corrosion presents a problem because the alcohol forms acetic acid and formic acid when the engine is shut off.

Alcohol, when used with gasoline in a spark-ignition engine, substantially increases the power and efficiency of the engine with a minimum of problems; the gasoline acts as an ignition agent for cold starting and low-speed operation. Ether and ketones have been added to alcohol blends to produce the same effect.

Alcohol has been successfully employed as an alternate fuel in compression-ignition engines with some increase in power output. Alcohol has also been blended with diesel fuels with similar results.

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An increase in bore wear has been noted in engines operating with alcohol as a principal fuel, but this may be caused by the anti-knock agents added to the alcohol.

Alcohol has been successfully used as an injected fuel, and diesel engines have been successfully run on alcohol by a combination of injection and carburetion. It is felt that with sufficient attention to the selection and proportion of anti-knock agents, with the proper injector design and injection timing, and with an appropriate injector pump, alcohol can be successfully used in a compression-ignition engine of high power, speed, and efficiency. In particular, injector-nozzle design, position, and timing seem to be important, because an injector nozzle that sprays too fine a mist, that sprays the mist against a hot portion of the cylinder, or that sprays before the piston has reached the top of the cylinder, will tend to cause knock.

These designs and techniques have already been developed, and incorporating all of them into a single engine would probably lead to the development of a high-speed, high-power compression-ignition engine operating on alcohol as the sole or principal fuel.

7.1.2.6 Evaluation of MED Fuels for Conventional Engines. The MED fuels that appear most suitable as internal-combustion engine fuels, on the basis of availability, synthesis equipment and energy requirements, combustion heat, transportability, and adaptability, are hydrogen, ammonia, hydrazine, and possibly alcohol (if carbon can be made available). Reports on the use of hydrogen, ammonia, and alcohol as internal-combustion engine fuels indicate that thermal efficiencies comparable with those of typical diesel and gasoline engines using conventional fuels are possible with these MED fuels.

Testing and operation have also established that conventional engines are adaptable to the MED fuels with little or no loss of power if the fuel container, fuel distribution equipment, and engine carburetion and compression ratios are modified.

The combined effect of density and heat value reduces the operating range presently possible with these fuels, compared with equal volumes or weights of conventional hydrocarbon fuels, if the additional volume and weight of cryogenic or pressure vessels are taken into account where applicable. The fuels are compared in Tables 38 and 39. The five-year projections (Figs. 37 and 39) indicate that hydrogen will be superior to gasoline on a weight basis, and would therefore be suitable for helicopters and other liaison or reconnaissance aircraft.

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TABLE 38

OPERATING CHARACTERISTICS OF M60 TANK ON EQUAL VOLUMES AND WEIGHTS OF CONVENTIONAL AND MED FUELS
(with Equal Thermal Efficiencies of 30%)

	JP-4	liquid H ₂		NH ₃		N ₂ H ₄ · H ₂ O	CH ₃ OH
		present	projected	present	projected		
<u>Equal Volumes:</u>							
fuel tank capacity, gal	350	159*	292*	193**	292**	350	350
fuel tank volume, ft ³	46.8	21	39	26	39	46.8	46.8
fuel specific gravity	0.83	0.07	0.07	--	--	1.03	0.82
fuel capacity, lb	2450	93	171	1320	1970	3010	2400
heat of combustion, Btu/lb	18,000	51,623	51,623	8001	8001	5800	8550
total heat available, Btu	44x10 ⁶	4.8x10 ⁶	8.8x10 ⁶	10.6x10 ⁶	15.8x10 ⁶	17.4x10 ⁶	20.5x10 ⁶
% of diesel fuel energy	100	10.9	20	24	36	40	47
equivalent range, miles	250	27	50	60	90	100	117
<u>Equal Weights:</u>							
estimated tank weight, lb	200	2236***	1060***	757****	126****	200	200
fuel weight, lb	2450	414	1590	1893	2524	2450	2450
total fuel and containment weight, lb	2650	2650	2650	2650	2650	2650	2650
fuel volume, gal	350	730	2720	365	371	285	357
total heat available, Btu	44x10 ⁶	21.7x10 ⁶	82.0x10 ⁶	15.2x10 ⁶	20x10 ⁶	14.2x10 ⁶	20.9x10 ⁶
% of diesel fuel energy	100	49	186	35	45	32	47
equivalent range, miles	250	122	465	88	113	80	117

*Container-to-contents volume ratios of 2.2 (present) and 1.2 (projected) used.

**Container-to-contents volume ratios of 1.8 (present) and 1.2 (projected) used.

***At 5.4 lb of tank/lb of H₂ present for 700-gal tanks and 0.67 lb/lb projected.

****At 0.4 lb of tank/lb of NH₃ present and 0.05 lb/lb projected.

TABLE 39

OPERATING CHARACTERISTICS OF M54 TRUCK ON EQUAL VOLUMES AND WEIGHTS OF CONVENTIONAL AND MED FUELS
(with Equal Thermal Efficiencies of 25%)

	80-octane gasoline	liquid H ₂		NH ₃		N ₂ H ₄ · H ₂ O	CH ₃ OH
		present	projected	present	projected		
<u>Equal Volumes:</u>							
fuel tank capacity, gal	78. *	32.5*	60*	43.3**	60***	78	78
fuel tank volume, ft ³	9.5	3.94	7.3	5.3	7.3	9.5	9.5
fuel specific gravity	0.74	0.07	0.07	--	--	1.03	0.82
fuel capacity, lb	480	19	35.1	295	372	672	533
heat of combustion, Btu/lb	18,000	51,623	51,623	8001	8001	5800	8550
total heat available, Btu	8.6x10 ⁶	0.98x10 ⁶	1.8x10 ⁶	2.36x10 ⁵	3.1x10 ⁶	3.9x10 ⁶	4.6x10 ⁶
% of gasoline energy	100	11.4	21	27.4	33.7	45	53
equivalent range, miles	214	24	45	59	75	96	114
<u>Equal Weights:</u>							
estimated fuel tank weight, lb	120	529***	241***	170****	29****	120	120
fuel weight, lb	480	31	359	430	571	480	480
total fuel and containment weight, lb	600	600	600	600	600	600	600
fuel volume, gal	78	53	614	63	84	56	70
total heat available, Btu	8.6x10 ⁶	1.6x10 ⁶	19x10 ⁶	3.47x10 ⁶	4.6x10 ⁶	2.8x10 ⁶	4.1x10 ⁶
% of gasoline energy	100	19	220	40	53	32	47
equivalent range, miles	214	41	471	86	113	69	100

*Container-to-contents volume ratios of 2.4 (present) and 1.3 (projected) used.

**Container-to-contents volume ratios of 1.8 (present) and 1.3 (projected) used.

***At 7.5 lb of tank/lb of H₂ present in 250-gal tanks and 0.67 lb/lb projected.

****At 0.4 lb of tank/lb of NH₃ present and 0.05 lb/lb projected.

On the basis of equal volume, the M60 tank and M54 truck ranges are compared in Table 40 for the preferred MED fuels and conventional fuels (see Figs. 36 and 38).

TABLE 40

EQUAL-VOLUME RANGE COMPARISON OF FUELS FOR M60 TANK AND M54 TRUCK

fuel	tank range, miles		truck range, miles	
	present	projected	present	projected
hydrocarbon . . .	250 (JP-4)	--	214 (80-octane gasoline)	--
CH ₃ OH	117	--	114	--
N ₂ H ₄ · H ₂ O . . .	100	--	96	--
NH ₃	60	90	59	75
liquid H ₂	27	50	24	45

On the basis of equal weight (including the weight of special containment), the ranges are compared in Table 41 (see Figs. 37 and 39):

TABLE 41

EQUAL-WEIGHT RANGE COMPARISON OF FUELS FOR M60 TANK AND M54 TRUCK

fuel	tank range, miles		truck range, miles	
	present	projected	present	projected
hydrocarbon . . .	250 (JP-4)	--	214 (80-octane gasoline)	--
H ₂	122	465	41	471
CH ₃ OH	117	--	100	--
NH ₃	88	113	86	113
N ₂ H ₄ · H ₂ O . . .	80	--	69	--

The heat energy of fuel required for the average 8-hr battlefield day would be equivalent to a range of 110 miles.

These estimates emphasize the need for more frequent refueling, larger fuel carrying capacity, or more efficient use of fuel, to offset the reduced range of the preferred MED fuels at present when used in conventional internal-combustion engines.

The most promising possibilities for more efficient use of MED fuels appear to lie in the development of fuel cells, and in potential improvements in the Stirling engine. These are discussed in separate sections of this report.

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FIG. 36. RANGE OF M-60 TANK ON MED FUELS COMPARED WITH JP-4

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FIG. 37. RANGE OF M-60 TANK ON MED
FUELS COMPARED WITH JP-4

Basis: Equal Weight of Fuel and Containers
Equal Thermal Efficiencies

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FIG. 38. RANGE OF M-54 6 X 6 5-TON TRUCK ON
MED FUELS COMPARED WITH GASOLINE

Basis: Equal Volume of Fuel and Containers
Equal Thermal Efficiencies

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FIG. 39. RANGE OF M-54 6 X 6 5-TON TRUCK ON MED FUELS COMPARED WITH GASOLINE

Basis: Equal Weight of Fuel and Containers
Equal Thermal Efficiencies

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7.1.3 Gas Turbines

The survey and analysis of the suitability of preferred MED fuels for use in gas turbines was held to a minimum for the reasons discussed below.

Gas turbines are well known to be inherently suitable for use with any fuel that does not have severe corrosion characteristics, erosive particles, or combustion products that would damage or coat the blades. The preferred MED fuels appear well suited for use in gas turbines.

Gas turbines with the preferred MED fuels are expected to be similar in power output capability and duration or range to internal-combustion reciprocating engines with these fuels. Thus, the full power rating of the gas turbine, or internal-combustion engine, should be attainable at thermal efficiencies equal to those obtained with POL, by burning the MED fuels at a rate inversely proportional to their heats of combustion as compared with hydrocarbon fuels. Similarly, the range of a turbine or a reciprocating engine will vary with the density and heat of combustion of the fuel, to an extent depending on the weight or volume criteria selected and on the containment requirements.

The use of gas turbines in the military vehicles under consideration is not expected to be extensive for many years, because the space and weight reductions are not sufficient to offset the higher fuel consumption rates in the low power range of ground vehicles. If consideration of the use of MED fuels is extended to airplanes and helicopters, where additional fuel can be carried conveniently, the inherent suitability of the gas turbine for a wide variety of fuels will have considerable significance for both the short-range and the long-range MED evaluations.

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7.1.4 Stirling Engines

The potentially high efficiency of engines based on the Stirling cycle, which was patented in 1816, has stimulated intensive development in Europe and in the United States in recent years. The Phillips Research Laboratories in Holland initiated their development work on Stirling engines in 1937, and North American Phillips of New York contracted with the Bureau of Ships in 1946 for further Stirling engine studies. A highly improved regenerative heat exchanger developed by Phillips resulted in the achievement of a brake thermal efficiency of 39 per cent in a single-cylinder, 40-hp engine, reported in 1958. Phillips also built a four-cylinder, 350-hp Stirling engine at that time.

General Motors Research Division is reported to have started a co-operative program with Phillips in 1958.

The most complete report of recent work on the Stirling engine is a paper by Flynn, Percival, and Haffner in the SAE Journal, April, 1960. In this report, performance was tabulated for a small Stirling engine compared with small four-stroke and two-stroke gasoline engines of similar displacement per cylinder, and for a larger Stirling engine compared with a six-cylinder two-stroke diesel engine and a V-8 automobile engine.

This comparison indicates that the Stirling engine probably can be developed to compare favorably, in horsepower per pound, with the lighter diesel engines in the required horsepower range for military vehicles, and that the Stirling engine has the potential to reduce fuel consumption to 90 per cent or less of that of the best diesel engines. The most significant advantage of the Stirling engine for the MED application is its ability to run on any fuel or heat source with little modification and with high efficiency. Its secondary advantages are its quiet and vibration-free operation, cool exhaust with little smoke or odor, and potentially low maintenance requirements.

It appears unavoidable that the Stirling engine with its accessories will be larger and more expensive to manufacture than conventional engines of equal horsepower.

It is concluded that use of the Stirling engine is not essential to the successful short-range development of the MED or to the utilization of MED fuels in military vehicles. Stirling engines in their present state of development probably could not be reduced sufficiently in size to be applied in the space now available for engines in military vehicles, without reducing the available power output significantly. It is recommended that further consideration be given to the Stirling engine as its development progresses, for the long-range MED system and vehicle improvements, where its potentially high fuel economy and multi-fuel capability could prove advantageous.

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7.1.5 Battery-Powered Systems

Considerable information has been published about batteries and their applications. The power output of a battery, in kilowatts per pound or kilowatthours per cubic foot, is a function of its rate of discharge. The relative capabilities of various batteries are indicated here and the application for batteries based on only one system. The present battery systems considered were the lead-acid, the silver-cadmium, the nickel-cadmium, the zinc-silver oxide, the mercury alkaline, and the LeClanche cells. Future systems using magnesium, such as the organic depolarized cell, the magnesium cell, the aluminum cell, and the copper oxide-zinc alkaline cell, were also considered.

Of these systems, only the lead-acid cell, the silver-cadmium cell, and the nickel-cadmium cell will be considered further, owing to the low recharge cycle ability of the other cells. It would be impractical to power equipment with batteries that could not be recharged a number of times. The lead-acid battery is the only one that has been used for heavy power applications, and representative types may be considered as those covered by Specifications Mil-B-15758 and Mil-B-17981. These specifications provide for a power battery suitable for hard shocks and rugged duty, and complete with built-in coolers to permit them to operate in enclosures with little or no ventilation. These specifications define a battery of the ratings listed in Table 42.

TABLE 42

126-CELL LEAD-ACID GROUP

specified ratings		calculated ratings				
time, hr	current, amp	average voltage	average kw	kwhr	whr/lb	whr/in. ³
1	4340	212.4	923	923	7.26	0.724
3	1835	230.9	424	1270	10.0	0.994
5	1220	236.2	288	1440	11.35	1.13
6	1045	237.7	248	1490	11.75	1.17
10	685	241.2	165	1658	13.0	1.29
20	370	244.1	90.4	1808	14.1	1.40
48	165	246.8	40.7	1955	15.4	1.53

The cell jars are 50 per cent natural and 50 per cent synthetic laminated hard rubber in accordance with Specification Mil-V-16128. The jars are $14,000 \pm 0.064$ in. wide, $14,160 \pm 0.064$ in. long, and $50-9/16 \pm 3/32$ in. high (including feet). The average cell weight is 1008 lb when filled with electrolyte (sp gr 1.265).

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This information indicates that a battery rating increases greatly (by 79 per cent) from a 1-hr to a 10-hr discharge rate. This is important in the evaluation of batteries where there is both an energy and a power requirement.

For comparative purposes, the Journal of the Electrochemical Society (March, 1961), lists these 10-hr ratings:

<u>battery</u>	<u>whr/lb</u>	<u>whr/in.³</u>
lead-acid (ironclad)	13.1	1.35
nickel-cadmium sintered	11.5	0.88
silver-cadmium	30 to 45	2 to 3

These ratings are in fair agreement with the information published in the Energy Conversion Systems Reference Handbook (EOS Report 390 - Final, September, 1960).

With equal load characteristics, the nickel-cadmium battery would be 14 per cent heavier and 53 per cent larger than the lead-acid battery, and the silver-cadmium battery would be one-third as heavy and half as large as the lead-acid battery. On the basis of these figures, the application of the lead-acid battery was determined and compared by ratio with the other systems for each application.

7.1.5.1 Case A. The 4-hr battery rating was selected for the power level specified. From the information on batteries, the 4-hr battery ratings would be 1.07 whr/in.³ and 10.75 whr/lb for the lead-acid battery.

Using the figures above, the batteries to power this tank would weigh 116,500 lb and occupy 1,170,000 in.³ (677 ft³), plus the weight and volume of the radiator or cooler and controller.

The evaluation of such a system should also account for space for connections and cable auxiliary equipment (this may be as much as an additional 10 per cent). Based on the previous years of development work on batteries, it can be assumed that the possibility of any further great improvement in these units is quite limited. It is believed that sufficient design changes in the tank are not feasible for operation on lead-acid batteries either now or in the foreseeable future. If the lead-acid battery is not feasible, then the nickel-cadmium battery, which is larger and heavier, is unsuitable for similar reasons. The silver-cadmium battery would weigh 38,800 lb and occupy 338.5 ft³.

A company of 22 tanks, if powered by batteries, would require the delivery of 14,894 ft³ of lead-acid batteries weighing 2,563,000 lb or 7447 ft³ of silver-cadmium batteries weighing 854,300 lb each day.

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7.1.5.2 Case B. For both the 89.5-kw and the 313-kwhr ratings, we have considered the most adverse conditions, namely, the production of 314 kwhr at 89.5 kw, or a 3-1/2-hr rating. For this application, however, the 4-hr rating condition of Case A will be used. The batteries to power this truck would weigh 29,200 lb and occupy 294,000 in.³ (170 ft³) plus the weight and space of the radiator or cooler and controller.

Because no space has been allowed for connections or for cable or auxiliary equipment (approximately an additional 10 per cent), and because it is believed that the years of development work in batteries have reduced the potential for further improvement in these units, no factor of development improvement has been allowed. Insufficient design change is contemplated in today's truck to allow installation of the necessary lead-acid batteries. Using the comparative ratio, the silver-cadmium battery would weigh 9700 lb and occupy 85 ft³. A feasible modification of the truck design could make silver-cadmium battery power suitable for the trucks in Case B from a volume standpoint. Nickel-cadmium batteries, however, being larger and heavier than lead-acid batteries, are unsuitable.

A company of 75 trucks, if powered by batteries, would require the delivery of 12,750 ft³ of lead-acid batteries weighing 2,180,000 lb or 6370 ft³ of silver-cadmium batteries weighing 726,000 lb each day.

7.1.5.3 Case C. For this study, it is assumed that the electrical power requirements will be in 100-kw lots. Dividing the figures by 2 will make the results applicable to 50-kw installations.

Using the 20-hr rating, the lead-acid batteries for 2400 kwhr would weigh 168,500 lb and occupy 1,700,000 in.³ (985 ft³). The nickel-cadmium batteries would weigh 192,000 lb and occupy 1510 ft³, and the silver-cadmium batteries would weigh 56,160 lb and occupy 493 ft³.

It would be feasible to have the above units transported to the location of electrically powered military equipment. The weight, however, makes the application of batteries less desirable than some other methods. The most suitable battery would be the silver-cadmium battery, and the next most suitable, the lead-acid battery.

The Case C power plants would require the delivery of 4920 ft³ of lead-acid batteries weighing 842,000 lb, 7550 ft³ of nickel-cadmium batteries weighing 960,000 lb, or 2480 ft³ of silver-cadmium batteries weighing 280,000 lb each day.

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7.1.6 Comparison of Fuel Cells with Internal-Combustion Engines

The use of hydrogen in an internal-combustion engine was determined as follows. The hydrogen equivalence to fuel oil is 0.35 lb of hydrogen to 1 lb of fuel oil. The POL requirements are estimated at 0.4 lb fuel/hp-hr. The ammonia equivalence to fuel oil is 2.25 lb of ammonia to 1 lb of fuel oil. Thus, from the horsepower-per-hour requirements listed elsewhere in this report, the following tables were developed (per unit).

TABLE 43

DAILY POL, H₂, AND NH₃ REQUIREMENTS FOR INTERNAL COMBUSTION ENGINES

use	POL		H ₂		NH ₃	
	lb	ft ³ *	lb	ft ³ *	lb	ft ³ *
tank	1094	22	381.9	87.4	2461	48.2
truck	302	6	105.7	24.2	680	13.3
stationary power . .	1612	32	574	131	3627	71.1

*The densities used in calculation were: for POL, 50 lb/ft³; for liquid hydrogen, 4.37 lb/ft³; and for liquid ammonia, 51 lb/ft³.

TABLE 44

NUMBER OF VEHICLES POWERED BY AVAILABLE FUEL

mode of propulsion	quantity of fuel, lb	power to produce fuel, Mw/hr	number of tanks	number of trucks	number of 100-kw stationary power units
H ₂ -O ₂ fuel cell	2,970	95.2	22	87	12
H ₂ -air fuel cell	2,970	85.6	22	87	12
H ₂ -air (O ₂) fuel cell	2,970	88.2	22	87	(not applicable)
H ₂ -O ₂ fuel cell (H ₂ from NH ₃ cracking)	22,300	99.8	22	87	12
H ₂ -internal-combustion engine	2,970	85.6	7	29	5
NH ₃ -O ₂ fuel cell	27,700	125	22	87	12
NH ₃ -internal-combustion engine	27,900	125	11	40	7.6
Na-O ₂ fuel cell	36,410	194	22	87	12

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7.2 APPLICATION OF SPECIAL FUELS TO HEATING AND COOKING

Liquefied hydrogen or ammonia supplied from the mobile reactor can be readily adapted to a field army's energy requirements for heating and cooking. The most efficient conversion of a fuel is direct oxidation, by which about 89 per cent of the available energy is converted to heat; electrical generation, using internal-combustion engine generators followed by electric resistance heating, yields a net efficiency of around 17 per cent.

The estimated total heating and cooking energy requirement for a field army is 25 per cent of its total POL requirement (CECD-59-7) (SECRET), Requirements for Mobile Nuclear Power Plants, 1960 - 1970). The estimated POL requirement for heating in temperate zones is 1.0 gal/man/day (1 gal POL = 112,000 Btu), and for cooking, using typical field equipment, 0.1 gal/man/day (11,200 Btu).

Current field heating equipment uses liquid petroleum products, such as gasoline, diesel fuel, jet fuel, etc. Some permanent installations have used compressed hydrocarbon gases. Two types of heaters are available for field use: a 45,000-Btu/hr tent stove and a 250,000-Btu/hr maintenance tent heater. Central heating has not been adaptable to mobile field facilities.

Field kitchen equipment is primarily heated at present with POL, as is hot water for sanitary and hospital uses.

Liquefied hydrogen or ammonia could be obtained from the liquefaction unit directly or supplied to each shelter in appropriately sized "Dewar" vessels. These supply vessels could be kept outside the shelters and the vaporized fuel piped to the space-heater elements. The hydrogen could be doped with some volatile odorous additive for leak detection.

Ammonia would probably require special provision for ignition, but no difficulty is anticipated in this regard.

Hydrogen will provide about 52,000 Btu/lb and ammonia about 8000 Btu/lb on thermal oxidation. Therefore, because the energy requirement for heating and cooking is 123,200 Btu/man/day, the field soldier would require 2.36 lb of hydrogen or 15.4 lb of ammonia per day for this purpose.

In the MED hydrogen system, 2970 lb of liquid hydrogen are produced per 16-hr day with a power input of 5.35 Mwe; the ammonia system produced 27,700 lb of liquid ammonia

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per 16-hr day with an input of 7.79 Mwe. The hydrogen system would provide heating for 1258 men, and the ammonia system, for 1800 men. However, the systems have different energy inputs. With the input of the ammonia system, the hydrogen system would supply 1830 men. Thus the efficiency of the two systems on the basis of conversion of nuclear energy to thermal energy in the tent is about equal. On a weight basis, the hydrogen plant produces 2900 Btu/lb of plant per 16-hr day, and the ammonia plant produces 1440 Btu/lb of plant per 16-hr day.

A secondary advantage of the utilization of liquid hydrogen or ammonia in heating or cooking facilities is the adaptation of these materials to refrigeration processes. The vaporization of these liquids in appropriate heat-exchange coils would provide the elements for this refrigeration.

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8. INTEGRATED MED SYSTEMS

Several integrated energy systems have been completely examined and evaluated: the production of hydrogen by electrolysis or steam reforming for use in hydrogen-oxygen or hydrogen-air fuel cells; the production of ammonia from electrolytic hydrogen for catalytical cracking to hydrogen and use in hydrogen-oxygen fuel cells; the production of ammonia from electrolytic or steam-reformed hydrogen for use in ammonia-oxygen fuel cells; several variations of the sodium amalgam system; and battery power supplies.

The quantities of fuel and oxidizer needed for the 22 tanks employing the projected hydrogen-oxygen fuel cell are 2970 lb of hydrogen and 23,760 lb of oxygen. For the applications in trucks and stationary power plants, the amount of hydrogen produced (2970 lb) is considered a constant and the number of trucks or power plants operated on this fuel is considered a variable. This avoids the practical problem of redesigning the synthesis plants to accommodate differing fuel demands. Generally, a given chemical plant has a minimum size (i.e., produces a minimum amount of fuel) to avoid excessive power consumption, weight, and volume.¹ It is generally less difficult to scale a plant up than to scale it down.

All the systems are sized to furnish the fuel needed to power the representative unit of 22 tanks. This provides an equal basis on which to compare the number of modules and total MED weight required by each system. Table 45 shows the number of tanks, trucks, and stationary power plants supported by each MED system. In the hydrogen and ammonia cases the number of trucks powered by internal-combustion engines with this quantity of fuel is also given.

TABLE 45

NUMBER OF VEHICLES SUPPORTED BY ONE MED

fuel consumer	systems			
	H ₂	NH ₃	Na	batteries
tanks powered by fuel cell*	22	22	22	22
trucks powered by fuel cell*	87	87	87	87
stationary 100-kw electrical power				
plants (fuel cell)*	12	12	12	-
trucks powered by internal-				
combustion engines	29	40	-	-

*5-year projection.

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Approximately four to five years would be needed to design the MCR, built it, and evaluate it. The chemical plants heretofore referred to as five-year projections are at the same stage of development as the MCR. Therefore, existing ("on-the-shelf") hardware will be discussed only insofar as it substantiates these five-year projections.

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8.1 H_2 - O_2 FUEL CELL SYSTEM USING ELECTROLYTIC H_2

In this system, hydrogen and oxygen are produced by the electrolysis of water, and the gases are liquefied and transported to the vehicles. The electrical power is supplied by the nuclear reactor-generator system. The system envisioned would operate as shown in Fig. 40.

FIG. 40

The electrolysis units can be considered as reversed hydrogen-oxygen fuel cells. In these units, water is decomposed into hydrogen and oxygen by electric power. An electrolysis module would contain a water purification unit, a means of transferring water to the cells, the electrolytic cells, electrical connections, a product removal duct, switch-gear, and controls. A module capable of producing 2970 lb of hydrogen gas and 23,760 lb of oxygen gas in 16 hr would have the specifications listed in Table 46.

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TABLE 46

SPECIFICATIONS FOR H₂-O₂ ELECTROLYTIC CELLS

weight of electrolysis plant	26,000 lb
weight of water purifier	1000 lb
weight of supports	3000 lb
weight of module	30,000 lb
volume of module	1060 ft ³
weight of plant/(lb of H ₂ + 8 lb of O ₂)/16 hr	10.1 lb
number of modules required	1
volume of plant/(lb of H ₂ and 8 lb of O ₂)/16 hr	0.357 ft ³
power required	3.49 Mwe
total power consumed in 16 hr	55.8 Mwhr

Based on five-year projections of the characteristics of process equipment, the liquefaction module, excluding the power supply, but including the compressors, drives, storage, and controls, will have the characteristics listed in Table 47.

TABLE 47

SPECIFICATIONS OF LIQUEFACTION PLANT FOR H₂-O₂ SYSTEM
USING ELECTROLYTIC H₂

module weight	23,500 lb
module size	30 x 8.5 x 8.5 ft
number of modules required	1
power required	2.46 Mwe
total power consumed in 16 hr	39.4 Mwhr

The efficiency of utilization of fuel and oxygen in the projected fuel cell is shown in Table 48.

TABLE 48

POWER UTILIZATION IN H₂-O₂ FUEL CELL SYSTEM USING ELECTROLYTIC H₂

power required for H ₂ O electrolysis and purification	3.49 Mwe
power required for liquefaction of H ₂ and O ₂	2.46 Mwe
total power required	5.95 Mwe
electrical power consumed in 16 hr	95.2 Mwhr
nuclear reactor thermal power required	25.6 Mwt
power available to vehicles	27.6 Mwhr
chemical system efficiency	29.0%
over-all efficiency	6.8%

The determination of the power available at the vehicle is discussed earlier in this report. The efficiency figure of 29.0 per cent includes the fuel cell efficiency of 73 per cent and the efficiency of the electric drive motor, which is estimated at 90 per cent.

The efficiency of the nuclear reactor system in converting the thermal energy of fission into electrical energy is estimated at 23.3 per cent for a regenerative-cycle MCR.

It would be desirable to be able to store a seven-day supply of fuel and oxidizer at the depot. This would mean providing storage for $7 \times 2970 = 20,800$ lb of hydrogen and $7 \times 23,760 = 166,320$ lb of oxygen. The density of liquid hydrogen is 0.59 lb/gal, and that of liquid oxygen, 9.54 lb/gal. Thus, there must be facilities for the storage of $20,800/0.59 = 35,200$ gal of hydrogen and $166,320/9.54 = 17,400$ gal of oxygen.

It is proposed that the liquid hydrogen and liquid oxygen from the fuel synthesis plant be delivered directly into 4000-gal double-wall storage vessels. The walls will be of reinforced plastic. Advanced vacuum-type superinsulation will occupy the space between the walls. The over-all wall thickness will be about 1 in. The vessel will weigh about 0.87 lb/gal of capacity. The product loss rates are not expected to exceed 1/4 per cent per day. The vessels will be skid mounted, to be transportable either by air or on flat-bed trucks. The modules will be 20 ft long and 6 ft OD. When empty, the vessel and structure will weigh about 3500 lb. When a vessel has been filled, it will be loaded onto a flat-bed truck and hauled to the forward distribution depot. This storage module, which provides fuel storage at the synthesis depot and during transportation, will also serve as the fuel storage vessel at the distribution depot. When empty, the module will be hauled back to the synthesis depot for reuse.

Nine vehicles would be needed to transport the 35,200 gal (20,800 lb) of hydrogen. Because of the greater weight of the oxygen, the vehicles become weight limited. The maximum load of 30,000 lb is assumed. The vessel itself will weigh 0.87 lb/gal, so the maximum volume is 2880 gal. The data for the seven-day storage system are as follows:

	<u>H2</u>	<u>O2</u>
volume	35,200 gal	17,400 gal
weight	20,800 lb	166,320 lb
number of storage modules	9	7

8.2 H_2-O_2 FUEL CELL SYSTEM USING H_2 FROM STEAM-REFORMED HYDROCARBONS

It has been shown that the POL capability can be significantly increased if the hydrocarbon is reformed and the hydrogen used in a hydrogen-oxygen power plant. This is only possible if a nuclear reactor is the source of power for reforming and liquefaction. Some increase can also be achieved if the reactor is used only for liquefaction. The source of this increase in capability is in the reduced power requirements of the electric drive motor and the increased efficiency of the hydrogen-oxygen fuel cell. If hydrogen is produced by reforming hydrocarbons, using a nuclear reactor as the source of power for reforming and liquefaction, the present internal-combustion engine can increase POL capability by a factor of 1.19; the projected hydrogen-oxygen fuel cell would increase it by a factor of 3.40.

This section discusses only the gross characteristics of the system components. Details of operation will be found elsewhere. The system envisioned would operate according to Fig. 41.

FIG. 41

H_2-O_2 FUEL CELL SYSTEM USING STEAM-REFORMED H_2

If the hydrogen were to be used in an internal-combustion engine, the air separation plant would be unnecessary, as it would be with the projected fuel cell operating on hydrogen and air. These two systems will be discussed individually and are mentioned here only for comparison purposes.

The specifications for the reformer, listed in Table 49, are taken from data presented by M. W. Kellogg Company.² The reformer unit, with a palladium diffusion separator, would

weigh 11,700 lb and produce 182.2 lb of hydrogen in 16 hr. This unit was scaled up to a size compatible with an MED module (27,000 lb), and to a production of 420 lb of hydrogen in 16 hr.

TABLE 49

REFORMER SPECIFICATIONS FOR H₂-O₂ FUEL CELL SYSTEM
USING STEAM-REFORMED H₂

H ₂ produced per day	2970 lb
hydrocarbon reformed per day	7160 lb
weight of plant	190,000 lb
volume of plant	10,500 ft ³
number of modules required	7
power required	2.86 Mwt
thermal power consumed in 16 hr	45.8 Mw _{hr}

Hydrogen will be liquefied in a Claude cycle operating at about 60 atm, with a closed-cycle liquid-air refrigerator for precooling and oxygen liquefaction. The liquefaction plant specifications are the same as for electrolytic hydrogen (Sec. 8.1). The power required, not including oxygen liquefaction, is 1.86 Mwe.

Because oxygen is not available from electrolysis of water, an air separation plant is required. This plant was originally sized to produce 39,100 lb of oxygen during a 16-hr day. However, only 23,760 lb (61 per cent) of the oxygen are needed in this application. In scaling down, the compressor was not altered. The distillation columns were decreased to 70 per cent of their original size. The plant specifications are listed in Table 50.

TABLE 50

O₂ PLANT SPECIFICATIONS FOR H₂-O₂ FUEL CELL SYSTEM
USING STEAM-REFORMED H₂

liquid O ₂ produced	23,760 lb
weight of compressor	10,000 lb
volume of compressor	120 ft ³ (4 x 3 x 10 ft)
weight of separator	20,000 lb
volume of separator	1600 ft ³
number of modules required	1
power required for compressor and separator	0.6 Mwe
total power consumed in 16 hr	9.6 Mw _{hr}

The efficiency of utilization of hydrogen and oxygen in the projected fuel cell is shown in Table 51. Only the reactor power is considered input; i.e., the heating value of the input hydrocarbon is not included.

TABLE 51

POWER UTILIZATION IN H₂-O₂ FUEL CELL SYSTEM USING STEAM-REFORMED H₂

thermal power required for reformer	2.86 Mwt
power required for H ₂ liquefaction	1.86 Mwe
power required for O ₂ liquefaction	0.6 Mwe
total electrical power required	2.46 Mwe
electrical power consumed in 16 hr	39.4 Mwhr
nuclear reactor thermal power required	13.5 Mwt
power available to vehicles	27.6 Mwhr
chemical system efficiency	32.4%
over-all efficiency	12.8%

This high over-all efficiency results from the direct use of the reactor heat in the reformer. In this manner, the efficiency losses in converting heat to electricity are avoided. Any system that uses reactor heat directly would be expected to afford a highly efficient synthesis system.

The efficiency of the nuclear reactor system in converting fission energy into electrical energy is estimated at 23.3 per cent for a regenerative-cycle MCR.

As mentioned previously, POL capability can also be increased if the nuclear reactor is employed only to provide power for air and hydrogen liquefaction. In this system a portion of the input hydrocarbon would be burned to provide heat for the reformer. This system, used in conjunction with the projected hydrogen-oxygen fuel cell would increase the POL capability by a factor of 1.70.

The plant specifications would be identical with those listed above, except that the heat for the reformer would be supplied by the burning of hydrocarbon rather than by a nuclear reactor. The reactor thermal power would be reduced to about 10.6 Mwt.

Fuel and oxidizer storage requirements are the same as those discussed in Sec. 8.1.

8.3 H₂-AIR FUEL CELL SYSTEM USING ELECTROLYTIC H₂

On the basis of the improved performance of the projected hydrogen-oxygen fuel cell, it is reasonable to consider the substitution of air for oxygen. This would decrease the current density at the operating voltage, so that more fuel cells would be needed in the vehicle to provide the same over-all voltage. However, with the anticipated decrease in fuel cell size, it would be possible to fit these additional units into the vehicles being considered. The size of the fuel cell power plant and its compatibility with the vehicle are discussed in Sec. 7.1. The efficiency of fuel utilization is a function primarily of fuel cell voltage. A cell voltage of 0.87 v, the same as that of the hydrogen-oxygen fuel cell, will be employed in computing fuel requirements. The analysis of this system is thus similar to that of the hydrogen-oxygen fuel cell system using electrolytic hydrogen (Sec. 8.1). However, there is obviously no need for liquid oxygen or its storage facilities.

In this system, hydrogen is produced by the electrolysis of water, liquefied, and transported to the vehicles. The electrical power is supplied by the nuclear reactor generator system. The system envisioned would operate as shown in Fig. 42.

FIG. 42

H₂-AIR FUEL CELL SYSTEM USING ELECTROLYTIC H₂

The electrolysis units will be the same as for the hydrogen-oxygen fuel cell and will be capable of producing 2970 lb of hydrogen gas in 16 hr. This quantity of hydrogen would be sufficient to operate the numbers of vehicles given in Table 45.

The liquefaction plant will have the same characteristics as that discussed in Sec. 8.1, except that the power required will be 1.86 Mwe, instead of 2.46 Mwe, because no power is required for oxygen liquefaction.

The efficiency of utilization of fuel in the projected fuel cell is given in Table 52.

TABLE 52

POWER UTILIZATION IN H₂-AIR FUEL CELL SYSTEM USING ELECTROLYTIC H₂

power required for H ₂ O electrolysis and purification	3.49 Mwe
power required for liquefaction of H ₂	1.86 Mwe
total power required	5.35 Mwe
electrical power consumed in 16 hr	85.6 Mwhr
nuclear reactor thermal power required	23.0 Mwt
power available to vehicles	27.6 Mwhr
chemical system efficiency	32.2%
over-all efficiency	7.5%

Fuel storage would be the same as for the hydrogen-oxygen fuel cell system, except that liquid oxygen would not have to be stored.

8.4 H₂-AIR FUEL CELL SYSTEM USING H₂ FROM STEAM-REFORMED HYDROCARBONS

The analysis of this system is similar to that of the system employing steam-reformed hydrocarbon hydrogen in a hydrogen-oxygen fuel cell (Sec. 8.2). However, there is obviously no need for the air separation plant to produce liquid oxygen or for the storage facilities for oxygen.

The increase in POL capability for the projected hydrogen-air fuel cell, as for the hydrogen-oxygen fuel cell, is by a factor of 3.40. The system envisioned would operate according to Fig. 43.

FIG. 43

Because the hydrogen-air fuel cell voltage is the same as that used previously for the hydrogen-oxygen fuel cell, the fuel requirements will be the same. The characteristics of the reformer are given in Sec. 8.2. The liquefaction plant specifications are the same as for electrolytic hydrogen (Sec. 8.1) except that the power required will be 1.86 Mwe, because no power is required for oxygen liquefaction.

The efficiency of the utilization of fuel in the projected fuel cell is summarized in Table 53. Only the reactor power is considered input; i.e., the heating value of the input hydrocarbon is not included.

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TABLE 53

POWER UTILIZATION IN H₂-AIR FUEL CELL SYSTEM USING STEAM-REFORMED H₂

power required for reformer	2.86 Mwt.
power required for liquefaction	1.86 Mwe
electrical power consumed in 16 hr	29.8 Mwhr
nuclear reactor thermal power required	10.9 Mwt
power available to vehicles	27.6 Mwhr
chemical system efficiency	36.5%
over-all efficiency	15.8%

This high over-all efficiency results from the direct use of reactor heat in reforming, which avoids the efficiency losses of converting heat to electricity. The efficiency of the nuclear reactor system in converting fission energy into electrical energy is estimated at 23.3 per cent for a regenerative-cycle MCR.

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8.5 H₂-AIR (O₂) FUEL CELL SYSTEM USING ELECTROLYTIC H₂

The hydrogen-oxygen fuel cell can be operated on air with an output reduced to 60 per cent of peak power. However, the fuel cell power plant is not operating at full capacity at all times. During most of the duty cycle, the cell can operate on air; during heavy power demand the cell can be supplied with air enriched in oxygen or with pure oxygen. Only 27.5 per cent of the oxygen indicated for the hydrogen-oxygen cell is required when operating in this manner. This allows an optimization of the weight and volume of the fuel cell power plant, the fuel, and the oxidizer.

The system envisioned would operate as shown in Fig. 44.

FIG. 44

The electrolysis units will be the same as those of the hydrogen-oxygen fuel cell system and will be capable of producing 2970 lb of hydrogen gas and 23,760 lb of oxygen gas. Some of the oxygen will be vented and some will be liquified. The liquefaction plant will be essentially the same as that for the hydrogen-oxygen system. The power requirements will, however, be lower. The liquefaction of hydrogen will require 1.86 Mwe and the liquefaction of about 27.5 per cent of the oxygen will require about 0.165 Mwe, for a total power of 2.025 Mwe.

The efficiency of utilization of fuel and oxygen in the projected fuel cell is given in Table 54.

TABLE 54

POWER UTILIZATION IN H₂-AIR (O₂) FUEL CELL SYSTEM USING ELECTROLYTIC H₂

power required for H ₂ O electrolysis and purification	3.49 Mwe
power required for liquefaction of H ₂	1.86 Mwe
power required for liquefaction of O ₂	0.165 Mwe
total electrical power required	5.515 Mwe
electrical power consumed in 16 hr	88.2 Mwhr
nuclear reactor thermal power required	23.7 Mwt
power available to vehicles	27.6 Mwhr
chemical system efficiency	31.3%
over-all efficiency	7.3%

The discussion of hydrogen and oxygen storage in Sec. 8.1 applies here. The liquid oxygen storage requirement is, however, reduced to 27.5 per cent of the system described in Sec. 8.1. The data for the seven-day storage system are as follows:

	<u>H₂</u>	<u>O₂</u>
volume	35,200 gal	4,790 gal
weight	20,800 lb	45,740 lb
number of storage modules	9	2

8.6 H₂-AIR (O₂) FUEL CELL SYSTEM USING H₂ FROM STEAM-REFORMED HYDROCARBONS

The analysis of this system is similar to that for the systems employing steam-reformed hydrocarbon hydrogen in the hydrogen-oxygen fuel cell. The air separation plant to produce liquid oxygen and storage facilities for oxygen need be only 27.5 per cent as large.

POL capability is increased for the projected hydrogen-air (oxygen) fuel cell, as for the hydrogen-oxygen fuel cell, by a factor of 3.40.

The system would operate according to Fig. 45.

FIG. 45

H₂-AIR (O₂) FUEL CELL SYSTEM USING STEAM-REFORMED H₂

The efficiency of the utilization of fuel and oxygen in the projected fuel cell is summarized in Table 55. Only the reactor power is considered input; i.e., the heating value of the input hydrocarbon is not included.

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POWER UTILIZATION IN H₂-AIR (O₂) FUEL CELL SYSTEM USING STEAM-REFORMED H₂

power required for the reformer	2.86 Mwt
power required for liquefaction of H ₂	1.86 Mwe
power required for liquefaction of O ₂	0.165 Mwe
total electrical power required	2.025 Mwe
electrical power consumed in 16 hr	32.4 Mwhr
nuclear reactor thermal power required	11.6 Mwt
power available to vehicles	27.6 Mwhr
chemical system efficiency	35.3%
over-all efficiency	14.9%

The fuel and oxidizer storage requirements are the same as discussed in Sec. 8.5.

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8.7 MODIFIED H₂-O₂ FUEL CELL SYSTEM (NH₃ FORMED FROM ELECTROLYTIC HYDROGEN AND CRACKED AT POINT OF USE)

Ammonia dissociates to nitrogen and hydrogen at high temperatures over catalytic surfaces, producing the equilibrium concentration of nitrogen, hydrogen, and ammonia at the temperature of dissociation. Hydrogen can be separated from the nitrogen and ammonia by diffusion through palladium-silver alloy foil.³ Other materials are available for this purpose, which, though less expensive, are less efficient.

A system could be designed to crack ammonia, separate the hydrogen from the nitrogen and the unreacted ammonia, and supply the hydrogen to a hydrogen-oxygen fuel cell. Allis-Chalmers has proposed such a system to the Navy for submarine application (PR660-28475).

The dissociation and separation processes are endothermic. Energy could be supplied to the system by burning the off-gases from the separator. It is estimated that 75 per cent of the hydrogen in the ammonia can be supplied to the hydrogen-oxygen fuel cell. The other 25 per cent would be used to supply energy to the dissociator and separator.

The 22 tanks of Case A require 2970 lb of hydrogen. This is equivalent to the 75-per cent conversion of 22,300 lb of ammonia.

A chemical plant will be sized to produce 22,300 lb of ammonia and 23,760 lb of oxygen in a 16-hr operating day.

Air, of course, will be the source of nitrogen for the ammonia synthesis, and the hydrogen will be produced by electrolysis. The system would operate according to Fig. 46.

FIG. 46

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An electrolysis module capable of producing 4134 lb of H₂ gas would weigh 50,000 lb and require 4.84 Mwe, or 77.4 Mwhr in 16 hr.

Ammonia would be synthesized by the Claude process. This process is representative of other ammonia synthesis reactions, and has the advantages of an anhydrous liquid product, relatively high conversion efficiency, and compactness. The specifications of the Claude plant and the air separation plant (for 22,300 lb of ammonia and 23,760 lb of oxygen in 16 hr) are given in Table 56.

TABLE 56

SPECIFICATIONS FOR MODIFIED H₂-O₂ FUEL CELL SYSTEM*

<u>module function</u>	<u>number of modules</u>	<u>module weight, lb</u>	<u>module size, ft (L x W x H)</u>	<u>power required, Mwe</u>
H ₂ O electrolysis and purification	2	50,000	25 x 8.5 x 5	4.84
air compressor, heat exchanger, and Deoxo unit	1	15,000	15 x 8.5 x 5	0.78
air separator	1	30,000	30 x 8.5 x 8.5	-
N ₂ -H ₂ compressor	1	30,000	30 x 8.5 x 8.5	0.62
NH ₃ synthesis	1	<u>25,000</u>	30 x 8.5 x 8.5	<u>0.0**</u>
		150,000		6.24

*This plant is a factored reduction of the 27,700-lb/day plant. A more detailed engineering analysis of the individual units would be necessary to obtain more precise data.

**The reaction is exothermic, so no heat must be added to maintain the reactant temperatures once the plant is in operation.

The efficiency of utilization of the fuel and oxygen in the projected fuel cell is shown in Table 57.

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TABLE 57

POWER UTILIZATION IN MODIFIED H₂-O₂ FUEL CELL SYSTEM

power required for electrolysis	4.84 Mwe
power required for air separation	0.78 Mwe
power required for N ₂ -H ₂ compressor	0.62 Mwe
total power required	6.24 Mwe
electrical power consumed in 16 hr	99.8 Mwhr
nuclear reactor thermal power required	26.8 Mwt
power available to vehicles	27.6 Mwhr
chemical system efficiency	27.6%
over-all efficiency	6.4%

The efficiency includes the assumed efficiency of the electric drive, 90 per cent.

It would be desirable to be able to store, at the depot, a seven-day supply of fuel and oxygen. The data for the seven-day storage system are as follows:

	<u>NH₃</u>	<u>O₂</u>
volume	22,900 gal	17,500 gal
weight	156,100 lb	166,300 lb
number of storage modules	6	5

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8.8 $\text{NH}_3\text{-O}_2$ FUEL CELL SYSTEM USING ELECTROLYTIC H_2

The chemical plants for the synthesis of ammonia have been sized for the production of 27,700 lb of liquid ammonia and 39,100 lb of liquid oxygen during 16 hr of operation per day. This is sufficient fuel to operate (with fuel cells) 22 tanks, 87 trucks, or 12 stationary electrical power plants, or 40 trucks with internal-combustion engines.

Air, of course, will be used as the source of nitrogen for the ammonia synthesis, and the hydrogen will be produced by electrolysis. The system would operate according to Fig. 47.

FIG. 47

$\text{NH}_3\text{-O}_2$ FUEL CELL SYSTEM USING ELECTROLYTIC H_2

An electrolysis unit capable of producing 5136 lb of hydrogen gas would weigh 53,500 lb, occupy two modules, and require 6.02 Mwe, or 96.3 Mwhr in 16 hr.

The oxygen produced by this plant could be fed to the air separation plant, decreasing the quantity of air to be processed.

Ammonia will be synthesized by the Claude process (see Sec. 8.7). The specifications of the Claude plant and the air separation plant (for 27,700 lb of ammonia and 39,100 lb of oxygen in 16 hr) are given in Table 58.

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TABLE 58

SPECIFICATIONS FOR $\text{NH}_3\text{-O}_2$ FUEL CELL SYSTEM USING ELECTROLYTIC H_2

<u>module function</u>	<u>number of modules</u>	<u>module weight, lb</u>	<u>module size, ft (L x W x H)</u>	<u>power required, Mwe</u>
H_2O electrolysis and purification	2	53,500	25 x 8.5 x 5	6.02
air compressor, heat exchanger, and Deoxo unit	1	15,000	15 x 8.5 x 5	0.98
air separator	1	30,000	30 x 8.5 x 8.5	-
$\text{N}_2\text{-H}_2$ compressor	1	30,000	30 x 8.5 x 8.5	0.79
NH_3 synthesis.	1	<u>25,000</u>	30 x 8.5 x 8.5	<u>0.0*</u>
		153,500		7.79

*The reaction is exothermic, so no heat must be added to maintain the reactant temperatures once the plant is in operation.

The efficiency of utilization of the fuel and oxygen in the projected fuel cell is shown in Table 59.

TABLE 59

POWER UTILIZATION IN $\text{NH}_3\text{-O}_2$ FUEL CELL SYSTEM USING ELECTROLYTIC H_2

power required for electrolysis	6.02 Mwe
power required for air separation	0.98 Mwe
power required for $\text{N}_2\text{-H}_2$ compressor	0.79 Mwe
total power required. $\text{N}_2\text{-H}_2$	7.79 Mwe
electrical power consumed in 16 hr	124.6 Mwhr
nuclear reactor thermal power required	33.4 Mwt
power available to vehicles	27.6 Mwhr
chemical system efficiency	22.2%
over-all efficiency	5.2%

This efficiency includes the 90-per cent efficiency assumed for the electric drive.

It would be desirable to be able to store, at the depot, a seven-day supply of fuel and oxygen, i.e., 193,900 lb (28,450 gal) of ammonia and 273,700 lb (28,700 gal) of oxygen. It is proposed to deliver liquid ammonia and liquid oxygen directly into 4000-gal storage vessels. When a vessel has been filled, it will be loaded onto a flat-bed truck and hauled to the forward distribution depot. This storage module, which provides fuel storage at the synthesis depot and during transportation, will also serve as the fuel storage vessel at the distribution depot. When empty, the module will be hauled back to the synthesis depot for reuse. The data for the seven-day storage system are as follows:

	<u>NH₃</u>	<u>O₂</u>
volume	28,450 gal	28,700 gal
weight	193,900 lb	273,700 lb
number of storage modules	8	10

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8.9 $\text{NH}_3\text{-O}_2$ FUEL CELL SYSTEM USING H_2 FROM STEAM-REFORMED HYDROCARBONS

Hydrogen for ammonia synthesis can also be produced by steam reforming hydrocarbons. Oxidizing ammonia, produced from this hydrogen, in a fuel cell will increase the POL capability by a factor of 2.24. A small increase in POL capability (by a factor of 1.05) is obtained if this ammonia is oxidized in the present internal-combustion engine.

The over-all system would operate according to Fig. 48.

FIG. 48

$\text{NH}_3\text{-O}_2$ FUEL CELL SYSTEM USING STEAM-REFORMED H_2

The chemical plants have been sized for the production of 27,700 lb of liquid ammonia and 39,100 lb of oxygen during 16 hr of operation per day. Products generated during the remainder of the day will be placed in reserve storage. This amount of ammonia will require 5136 lb of hydrogen. A reformer plant producing this quantity of hydrogen would have the specifications shown in Table 60.

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TABLE 60

REFORMER SPECIFICATIONS FOR NH₃-O₂ FUEL CELL SYSTEM
USING STEAM-REFORMED H₂

H ₂ produced per day	5136 lb
hydrocarbon reformed per day	12,400 lb
weight of plant	290,000 lb
volume of plant	43,200 ft ³
number of modules required	12
power required	5.94 Mwt
thermal power consumed in 16 hr	95.0 Mwhr

The specifications of the Claude plant and the air separation plant are the same as when electrolytic hydrogen is used (Sec. 8.8).

The efficiency utilization of fuel and oxygen in the projected fuel cell is shown in Table 61.

TABLE 61

POWER UTILIZATION IN NH₃-O₂ FUEL CELL SYSTEM USING STEAM-REFORMED H₂

thermal power required for reformer	5.94 Mwt
power required for air separation	0.98 Mwe
power required for N ₂ -H ₂ compressor	0.79 Mwe
total electrical power required	1.77 Mwe
electrical power consumed in 16 hr	28.3 Mwhr
nuclear reactor thermal power required	13.5 Mwt
power available to vehicles	27.6 Mwhr
chemical system efficiency	22.4%
over-all efficiency	12.7%

This efficiency includes the 90-per cent efficiency assumed for the electric drive. Only the reactor power is considered input; i.e., the heating value of the input hydrocarbon is not included.

The data for the seven-day storage of fuel and oxidizer are identical with those for the production of ammonia from electrolytic hydrogen (Sec. 8.8).

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8.10 Na PRODUCED BY ELECTROLYSIS OF NaOH FOR USE IN NaHg FUEL CELL POWER PLANT

The system involving physical amalgamation of the sodium and utilization of the amalgam in a sodium amalgam fuel cell is shown in Fig. 49. The sodium hydroxide from the fuel cell reaction is returned to the depot for reprocessing.

The sodium production plant can be considered in two sections. The first is a sodium amalgam cell run in reverse. The sodium amalgam produced is transferred to a sodium concentration cell where the sodium amalgam is electrolytically transformed into sodium metal. These units are conceptual in design and would require research and development. The plant will be required to convert about 86,600 lb of a 71-per cent sodium hydroxide solution into 36,410 lb of sodium, 39,644 lb of water, and 12,650 lb of oxygen, in 16 hr.

Some of the module characteristics for a system of sodium separation from sodium hydroxide via sodium amalgam are listed below, for a plant producing sodium at the rate of 2275 lb/hr.

TABLE 62

Na SEPARATION FROM NaOH VIA NaHg

<u>function</u>	<u>number</u>	<u>volume, ft³</u>	<u>weight, lb</u>	<u>power, Mwe</u>
electrolysis of NaOH to NaHg . . .	2	2000	45,000	7.96
NaOH solution concentrator	-	-	-	1.0
NaHg to Na (concentration cells)	2	4000	58,000	2.85
liquefaction of oxygen	1	2000	20,000	0.32
	5	8000	123,000	12.13

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With projected sodium amalgam-oxygen fuel cells the reactants could power 87 trucks, 22 tanks or 12 100-kw stationary power plants. Conventional engines cannot operate on Na, H_2O and O_2 .

The efficiency of the utilization of the reactants, sodium, water, and oxygen, in the projected fuel cell is given in Table 63.

TABLE 63

POWER UTILIZATION IN NaHg- O_2 FUEL CELL
USING ELECTROLYTIC Na FROM NaOH

power required for electrolysis of NaOH solution	7.96 Mwe
power required for evaporation of NaOH solution	1.0 Mwe
power required for concentration cell (NaHg to Na)	2.85 Mwe
power required for liquefaction of air to produce liquid O_2	0.32 Mwe
total power required	12.13 Mwe
electrical power consumed in 16 hr	194.1 Mwhr
nuclear reactor thermal power required	52.2 Mwt
power available to vehicle	27.6 Mwhr
chemical system efficiency	14.2%
over-all efficiency	3.3%

FIG. 49. SODIUM AMALGAM- O_2 FUEL CELL, Na FROM NaOH BY ELECTROLYSIS

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8.11 BATTERY SYSTEM

The applications of present batteries to vehicles are described in detail in Sec. 7.1.4. The most feasible of these systems is the silver-cadmium battery. The data in Table 64 are based on the "ultimate" power density of this system⁴ as estimated by Yardney Electric Corporation: 40 whr/lb and 3.3 whr/in.³. These estimates are substantiated by data given in the Journal of the Electrochemical Society (March, 1961).

TABLE 64

SPECIFICATIONS OF THE PROJECTED Ag-Cd BATTERY POWER PLANT

<u>use *</u>	<u>weight of each plant, lb</u>	<u>volume** of each plant, ft³</u>
Case A	46,500	398
Case B	11,650	100
Case C	89,000	763

* No power allotted for auxiliaries.

** A 10% increase in volume has been allotted for connections, cables, and auxiliary equipment.

The volume requirements for Cases A and B are similar to those for the present hydrogen-oxygen fuel cell. It is assumed that the battery system will be charged once a day in providing electrical power for a 24-hr day.

The system is complicated by the fact that the number of charge-discharge cycles is controlled by the discharge depth. For example, for deep discharges of the silver-cadmium battery, of about 50 per cent, a cycle life of 300 to 500 might be anticipated. With a discharge depth of less than 10 per cent, cycle lives of about 2000 to 3000 might be expected, on the basis of Signal Corps test results.

Furthermore, during continued cycling the capacity of the silver-cadmium battery will drop to approximately 80 per cent of its original value after 200 cycles. Under battle conditions, the life expectancy of vehicles is not extreme, so that a discharge depth of at least 75 per cent and its lower number of cycles (under 300) would be reasonable. Thus, the average "practical" power density figures are $0.75 \times 0.80 \times 40 = 24$ whr/lb and 2.0 whr/in.³, or 3.46 kw/hr/ft³.

These batteries are reportedly extremely rugged, and have successfully passed missile-launch shock and acceleration requirements.

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By nature of the system, either the battery-operated vehicle would have to return to the depot for recharging, or the battery power plant would have to be trucked to the vehicle in the field. The first materially reduces the range of the vehicle, and the second poses the problem of handling and transferring heavy weights in the field. Of the two possibilities, the second would probably be more effective.

The vehicle design would be similar to that for the fuel cell, except that the power pack would have to be transferrable. Electric drive motors would convert the electrical power into mechanical motion.

The system would operate according to Fig. 50.

FIG. 50

BATTERY SYSTEM

The replacement of the tank power plant in the field presents a problem, because the battery power plant weighs 46,500 lb per tank. This is over the weight limit for MED modules (30,000 lb). Similarly, a semi-trailer of this type could transport approximately three truck power plants. The stationary electrical plant would have to be broken down into at least three units for transportation back to the depot for recharging. This problem could be solved by lowering the kilowatthour requirements, probably by recharging more frequently.

The "reactor-to-wheel" efficiency is the product of the efficiencies of discharge, storage, and drive.

A figure of 70 per cent has been cited⁴ as the storage efficiency (in watthours) of the nickel-cadmium battery. This figure is used as representative of the silver-cadmium battery. The electric drive efficiency is estimated at 90 per cent. The discharge efficiency is estimated as $1.1/1.4 \text{ v} = 78.6 \text{ per cent}$.

Thus, the over-all efficiency is $0.70 \times 0.786 \times 0.90 = 49.5 \text{ per cent}$.

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On the basis of this efficiency, it is possible to compute the reactor power needed to charge the batteries. The 87 trucks will require 27,318 kwhr. Thus 55,187 kwhr would have to be supplied by the reactor in 16 hr, and the reactor power must be 3.45 Mwe.

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8.12 EVALUATION AND COMPARISON OF INTEGRATED MED SYSTEMS

The fuel (POL) requirements are estimated at 0.40 lb/hp-hr. Test curves of the Allis-Chalmers 21,000 series diesel engine, rated at 340 hp at 2000 rpm, indicate a fuel consumption rate of 0.37 lb/bhp-hr and list competitive diesel engine fuel consumption rates of 0.39, 0.41, 0.42, and 0.46 lb/bhp-hr. Ignoring the poorest case, an average value of 0.40 lb/bhp-hr was selected as a representative fuel consumption rate. Therefore, the POL requirement is estimated to be 24,100 lb/day/22 tanks.

The performance of each fuel produced by a synthesis system developed for the MED is compared with this figure in terms of "crossover point." The crossover point (as shown in Table 65 and derived in Figs. 51 through 64) is the number of days during which the weight of POL consumed would equal the weight of a given MED system. For example, the weight of the hydrogen-oxygen fuel cell system (with hydrogen produced by electrolysis) would equal the weight of the POL consumed in 11.2 days; 11.2 days is thus the crossover point for this MED system. Table 66 lists the numbers of modules required in various MED systems.

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TABLE 65

SUMMARY OF SYSTEM SPECIFICATIONS

(Each: MED Sized to Fuel 22 Tanks or 87 Trucks - Fuel Cell Powered)

system	reactor thermal power, Mwt	weight of reactor, lb	weight of chemical plant, lb	crossover point, days	energy to chemical plant	chemical system efficiency, %	over-all efficiency, %
H ₂ -O ₂ fuel cell (H ₂ from electrolysis)	25.6	215,200	53,500	11.2	5.95 Mwe	29.0	6.8
H ₂ -O ₂ fuel cell (H ₂ from reforming)	13.5	120,100	243,500 plus 7160 lb naphtha/day	21.5	2.86 Mwt 2.46 Mwe	32.4*	12.8*
H ₂ -air fuel cell (H ₂ from electrolysis)	23.0	202,100	53,500	10.6	5.35 Mwe	32.2	7.5
H ₂ -air fuel cell (H ₂ from reforming)	10.9	104,200	213,500 plus 7160 lb naphtha/day	18.8	2.86 Mwt 1.86 Mwe	36.5*	15.8*
H ₂ -air (O ₂) fuel cell (H ₂ from electrolysis)	23.7	206,000	53,500	10.9	5.51 Mwe	31.3	7.3
H ₂ -air (O ₂) fuel cell (H ₂ from electrolysis) (two modified 14-Mwt MCR's)**	28.0***	281,800***	53,500	13.9	5.51 Mwe (plus 1.01 Mwe for services)	31.3	7.3
H ₂ -air (O ₂) fuel cell (H ₂ from reforming)	11.6	108,200	243,500 plus 7160 lb naphtha/day	20.8	2.86 Mwt 2.02 Mwe	35.3*	14.9*

H ₂ -O ₂ fuel cell (H ₂ from electrolysis; H ₂ dissociated from NH ₃)	26.8	229,600	150,000	15.8	6.24 Mwe	27.6	6.4
NH ₃ -O ₂ fuel cell (H ₂ from electrolysis)	33.4***	325,600***	153,500	19.8	7.79 Mwe	22.2	5.2
NH ₃ -O ₂ fuel cell (H ₂ from reforming)	13.5	111,900	390,000 plus 12,400 lb naphtha/day	42.9	5.94 Mwt 1.77 Mwe	22.4*	12.7*
NaHg-O ₂ fuel cell (Na from NaOH via NaHg)	52.2***	447,200***	123,000	23.7	12.13 Mwe	14.2	3.3
Ag-Cd batteries	14.8	152,300	1,013,500	48.4	3.45 Mwe	49.5	11.5
H ₂ -air internal- combustion engine (H ₂ from electrolysis) (only 29 trucks)	23.0	202,100	153,500	29.3	5.35 Mwe	10.7	2.5
NH ₃ -air internal- combustion engine (H ₂ from electrolysis) (only 40 trucks)	33.4***	325,600***	153,500	39.8	7.79 Mwe	10.2	2.4

*Heating value of input naphtha not included.

**Recommended first prototype.

***Using two MCR-type reactors.

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TABLE 66

NUMBER OF MODULES - SYSTEM

(Each MED Sized to Fuel 22 Tanks or 87 Trucks - Fuel Cell Powered)

<u>system</u>	<u>no. of modules reactor*</u>	<u>no. of modules chemical plant</u>	<u>total no. of modules</u>
H ₂ -O ₂ fuel cell H ₂ from electrolysis	6	2	8
H ₂ -O ₂ fuel cell H ₂ from reforming	3	9	12
H ₂ -air fuel cell H ₂ from electrolysis	6	2	8
H ₂ -air fuel cell H ₂ from reforming	3	8	11
H ₂ -air (O ₂) fuel cell H ₂ from electrolysis	6	2	8
H ₂ -air (O ₂) fuel cell H ₂ from electrolysis (two modified 14 Mwt MCR's)	8**	2	10
H ₂ -air (O ₂) fuel cell H ₂ from reforming	3	9	12
H ₂ -O ₂ fuel cell (H ₂ from dissociated NH ₃) H ₂ from electrolysis	6	6	12
NH ₃ -O ₂ fuel cell H ₂ from electrolysis	10**	6	16
NH ₃ -O ₂ fuel cell H ₂ from reforming	3	16	19
NaHg-O ₂ fuel cell (Na from NaOH via sodium amalgam)	12**	5	17
Ag-Cd batteries	4	34	38

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Table 66 Number of Modules - System (Cont'd)

<u>system</u>	<u>no. of modules reactor*</u>	<u>no. of modules chemical plant</u>	<u>total no. of modules</u>
H ₂ -air internal combustion engine H ₂ from electrolysis (only 29 trucks)	6	2	8
NH ₃ -air internal combustion engine H ₂ from electrolysis (only 40 trucks)	10**	6	16

* For highway transport, air transport will be more.

** Two reactors per MED.

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FIG. 51. POL CROSSOVER POINT FOR MED SUPPORTING 22 TANKS

H₂-O₂ FUEL CELL SYSTEM, H₂ FROM ELECTROLYSIS

Weights	
Reactor	215,200 lb
Chemical Plant	53,500 lb
Total	268,700 lb

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FIG. 52. POL CROSSOVER POINT FOR MED SUPPORTING 22 TANKS
H₂-O₂ FUEL CELL SYSTEM, H₂ FROM STEAM REFORMING NAPHTHA

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FIG. 53. POL CROSSOVER POINT FOR MED SUPPORTING 22 TANKS
H₂-AIR FUEL CELL SYSTEM, H₂ FROM ELECTROLYSIS

Weights	
Reactor	202,100 lb
Chemical Plant	53,500 lb
Total	255,600 lb

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FIG. 54. POL CROSSOVER POINT FOR MED SUPPORTING 22 TANKS
 H_2 -AIR FUEL CELL SYSTEM, H_2 FROM STEAM REFORMING NAPHTHA

Weights	
Reactor	104,200 lb
Chemical Plant	213,500 lb
Total	317,700 lb

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FIG. 55. POL CROSSOVER POINT FOR MED SUPPORTING 22 TANKS
H₂-AIR(O₂) FUEL CELL SYSTEM, H₂ FROM ELECTROLYSIS

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FIG. 56. POL CROSSOVER POINT FOR MED SUPPORTING 22 TANKS
 H_2 -AIR (O_2) FUEL CELL SYSTEM, H_2 FROM ELECTROLYSIS
 (Using 2 Modified 14 Mwt MCR's)

	Weights
Reactors (2)	281,800 lb
Chemical Plant	53,500 lb
Total	335,300 lb

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FIG. 57. POL CROSSOVER POINT FOR MED SUPPORTING 22 TANKS
H₂-AIR (O₂) FUEL CELL SYSTEM, H₂ FROM STEAM REFORMING NAPHTHA

Weights

Reactor	108,200 lb
Chemical Plant	243,500 lb
Total	351,700 lb

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FIG. 58. POL CROSSOVER POINT FOR MED SUPPORTING 22 TANKS
H₂-O₂ FUEL CELL SYSTEM, H₂ FROM ELECTROLYSIS
H₂ DISSOCIATED FROM NH₃ AT VEHICLE

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FIG. 59. POL CROSSOVER POINT FOR MED SUPPORTING 22 TANKS
NH₃-O₂ FUEL CELL SYSTEM, H₂ FROM ELECTROLYSIS

Weights

Reactors (2)	325,600 lb
Chemical Plant	153,500 lb
Total	479,100 lb

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FIG. 60. POL CROSSOVER POINT FOR MED SUPPORTING 22 TANKS
 $\text{NH}_3\text{-O}_2$ FUEL CELL SYSTEM, H_2 FROM STEAM REFORMING NAPHTHA

Weights	
Reactor	111,900 lb
Chemical Plant	390,000 lb
Total.	501,900 lb

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FIG. 61. POL CROSSOVER POINT FOR MED SUPPORTING 22 TANKS
NaHg -O₂ FUEL CELL SYSTEM, Na FROM NaOH VIA NaHg

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FIG. 62. POL CROSSOVER POINT FOR MED SUPPORTING 22 TANKS
SILVER-CADMIUM BATTERY SYSTEM

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FIG. 63. POL CROSSOVER POINT FOR MED SUPPORTING 29 TRUCKS
H₂-AIR INTERNAL COMBUSTION ENGINE SYSTEM, H₂ FROM ELECTROLYSIS

Weights

Reactor	202,100 lb
Chemical Plant	53,500 lb
Total	255,600 lb

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FIG. 64. POL CROSSOVER POINT FOR MED SUPPORTING 40 TRUCKS
NH₃-AIR INTERNAL COMBUSTION ENGINE SYSTEM, H₂ FROM ELECTROLYSIS

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8.13 REFERENCES

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2. M. W. Kellogg Co., "Preliminary Progress Studies on the Generation of Hydrogen for Small Fuel Cell Systems," ASTIA Report AD 256709.
3. C. and E. News, April 16, 1962, p. 61.
4. "Energy Conversion Systems Handbook," EOS Report 390 - Final (September, 1960).

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9. GLOSSARY

1. Chemical system efficiency---per cent of energy input (both electrical and thermal) into the chemical process that is delivered to the vehicle's wheels as motive power.
2. Dewar---a double-walled vessel for containment of cryogenic fluids.
3. HRE---Homogeneous Reactor Experiment.
4. MCR---Military Compact Reactor.
5. ML-1---a mobile low-power nuclear power plant.
6. Over-all efficiency---per cent of reactor thermal power that is delivered to the vehicle's wheels as motive power.
7. Plant day---16 hr/day. The MED is sized to produce all the fuel required by its supported vehicles in 16 hr. The over capacity is provided to allow for movement of the MED, and accumulation of stores for peak operations.
8. POL---petroleum, oil, and lubricants.
9. Rating factor---a factor used to estimate horsepower requirements for identical vehicles powered by different types of drives (i.e., internal-combustion engines vs. electric motors).
10. Refractory metals---molybdenum, niobium (columbium), tantalum, and tungsten.
11. Reversed fuel cell---an electrolytic cell whose construction is similar to a fuel cell and which is operated to cause a chemical decomposition by the action of an electric current.
12. Ullage---the amount by which a tank of liquid falls short of being full.
13. Use factor---a factor used to estimate fuel requirements under use conditions. This factor corrects for the portion of the battle day during which the vehicle is operating at partial power.

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