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MATERIALS REQUIREMENTS FOR ADVANCED ENERGY SYSTEMS - NEW FUELS. VOLUME 3: MATERIALS RESEARCH NEEDS IN ADVANCED ENERGY SYSTEMS USING NEW FUELS

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This program sought to identify materials-critical aspects of the use, production, transportation, and storage of new fuels derived from nonfossil sources. Hydrogen was the principal new fuel studied; hydrogen-derived fuels considered were ammonia, hydrazine, boranes, silanes, carbon monoxide, and methyl alcohol. The materials implications of the use of oxygen (produced as a by-product in hydrogen generation) as a fuel oxidizer and of the use of active metals in batteries were also examined during the program.

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19. KEY WORDS (Continued)

20 ABSTRACT (Continued)

The report consists of three volumes

Volume 1: Interactions of Materials and New Fuels
Volume 2: Materials Aspects of the Use, Production, Transportation and Storage of New Fuels
Volume 3: Materials Research Needs in Advanced Energy Systems Using New Fuels.

Materials research programs are recommended in the areas of hydrogen/materials interactions, high-temperature materials, properties of materials at cryogenic temperatures, materials for electrochemical systems (fuel cells, batteries, electrolysers), and catalysis. It is concluded that while a significant materials research and testing effort is needed in support of advanced energy systems using new fuels, materials requirements will not constitute a major impediment to the implementation of such systems.

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FOREWORD

This report contains the results of a research study supported by the Advanced Research Projects Agency under ARPA order No. 2484. The ARPA Project Officer was Dr. Stanley Ruby, Materials Sciences.

This report is presented in three volumes, containing the following major sections.

Volume 1. Interactions of Materials with New Fuels

- I Introduction
- II General Characteristics of New Fuels
- III Behavior of Engineering Materials in New Fuel Environments

Volume 2. Materials Aspects of the Use, Production, Transportation and Storage of New Fuels

- IV Materials Aspects of the Use of New Fuels
- V Materials Aspects of the Production of New Fuels from Nonfossil Sources
- VI Materials Aspects of the Transportation of New Fuels
- VII Materials Aspects of the Storage of New Fuels

Volume 3. Materials Research Needs in Advanced Energy Systems Using New Fuels

- VIII Correlation and Analysis of Materials Requirements
- IX Research Recommendations and Priorities

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VIII CORRELATION AND ANALYSIS OF MATERIALS REQUIREMENTS

CONTENTS

VIII CORRELATION AND ANALYSIS OF MATERIALS REQUIREMENTS

TABLES

VIII CORRELATION AND ANALYSIS OF MATERIALS REQUIREMENTS

VIII CORRELATION AND ANALYSIS OF MATERIALS REQUIREMENTS

This section summarizes the materials research, development and testing programs identified in Sections IV through VII (Volume 2) needed to support the use, production, transportation, and storage of the new fuels. The summary is presented in tabular form in Tables VIII-1 through VIII-4. Table VIII-1 summarizes the materials research, development, and testing needs related to the use of new fuels and Table VIII-2 provides this information for the production of new fuels. Tables VIII-3 and VIII-4 summarize the transportation and storage aspects, respectively, of the study.

The primary grouping used in these tables is the major equipment or process class. The significance of the various column headings is described in more detail below.

Item Number (Column 1)

The item number appearing in the first column is a three-digit number that identifies a specific research, development, or testing need listed in Column 7. The first of the three digits identifies the major equipment or process class to which the item relates. For example, in Table VIII-1 the initial digit 1 refers to the major equipment class of Turbines. The second digit is allocated to a subclass of equipment or process associated with a particular fuel. For example, the second digit 1 in Table VIII-1 is associated with conventional steam turbines burning hydrogen, while the second digit 2 is associated with conventional gas turbines burning hydrogen with air; the second digit 5 is associated with conventional gas turbines burning ammonia. The final digit refers to a specific materials research, development, or testing need itemized in Column 7 of the table.

Equipment Class (Column 2)

The equipment or process class is shown in Column 2 of the table, with the actual heading varying according to the major topic--use-production, transportation, or storage--with which the table is concerned. The major equipment or process class is shown capitalized in association with a single digit in Column 1. Under each major class a number of subclasses of equipment or processes are listed to further define the problems and solutions associated with each major class. For example, in Table VIII-2 under the major process class of Advanced Electrolyzers, the various electrolyzer types are subclassified according to the electrolyte used. Each electrolyte is indicated by a different second digit in the item number, as explained above.

Fuel (Column 3)

Column 3 lists the particular fuel with which the research, development, and testing need is associated. In some instances, where there is an option of burning the fuel with air or oxygen, the use of one or the other is noted.

Problem Area (Column 4)

Column 4 shows the general problem area in which the research, development, and testing need exists. This is generally a particular part of the specific equipment or process listed in Column 2. In some instances, it is a generalized statement of a problem, which may or may not have particular materials aspects. For example, in Table VIII-2 conventional electrolyzers of both unipolar (Item 1.1.1) and bipolar (Item 1.2.1) types do not suffer from any major materials problem but are generally deficient in the problem area of efficiency and cost, for which the only solution appears to be a major improvement in the overall technology.

Type of Solution (Column 5)

Column 5 defines the type of activity needed to solve the problem described in Column 4. This may be a materials activity described by general terms, such as materials research or materials selection, or by more specific terms, such as catalyst development. In some instances the activity required may be of a type, such as engineering design, to which materials oriented activities do not directly contribute. In many instances, the type of solution involves both materials oriented and other types of activity.

Materials Problems (Column 6)

Column 6 identifies specific materials problems, that are components of the general problem area listed in Column 4. Several materials problems may, of course, be identified within a single problem area. In other instances, such as those where the type of solution indicated in Column 5 does not include a materials activity, Column 6 contains a negative entry, such as "none" or "none expected."

Materials R, D, and T Needs (Column 7)

Column 7 lists the specific program required to solve the materials problems identified in Column 6. Where possible these programs are described in sufficient detail to identify the specific materials activity. In some instances, an entry is made that indicates general support for engineering design or development activities. In these cases, the precise nature of the materials research, development, and testing needs cannot be identified until the engineering effort is in progress. Each entry in this column is specifically identified by the item number in Column 1, even when no specific materials research, development, and testing needs exist.

Remarks (Column 8)

Column 8 contains comments to clarify the problem area or the program suggested. In addition, references are made to other items in which similar or related work is suggested. No comment is indicated by a dash.

Report References (Column 9)

Column 9 is a specific topic reference to Volume 2 of the report. Additional information and discussion of each problem area can be located in Volume 2 by using this topic reference in conjunction with the Table of Contents of the relevant report section.

TABLE VIII-1
MATERIALS RESEARCH DEVELOPMENT AND TESTING NEEDED TO SUPPORT THE USE OF NEW FUELS

Table VIII-1

MATERIALS RESEARCH DEVELOPMENT AND TESTING NEEDED TO SUPPORT THE USE

Item No.	Equipment Class	Fuel	Problem Area	Type of Solution	Materials Problems	Material
1.	TURBINES					
1.1.1	Steam, conventional.	H_2/air.	Fuel supply system exposed to hydrogen.	Materials selection.	H_2 environment effects.	Test materi environment operating 1
1.1.2			Modified burners required. Higher flame temperature.	Design; materials selection.	Increased operating temperature.	Component t
1.2.1	Gas, conventional (including industrial, aircraft, marine, and automotive types).	H_2 (gas or liquid) /air.	Fuel supply systems, heat exchanger/gasifier exposed to hydrogen.	Materials selection.	Cryogenic temperatures, H_2 environment effects.	Determine t erties of c purity and H_2 gas envi approximate
1.2.2			Modifications required for compressor/turbine matching.	Design.	None expected.	None.
1.2.3			Combustors, vanes, blades, affected by higher flame temperatures, high H_2O content combustion gases.	Materials research, development and testing.	Effects of high-temperature, high H_2O content environments on combustor and turbine materials.	Fundamental temperature on Si_3N_4, C
1.2.4						Determine c and oxidatio candidate al ings in sim gases.
1.2.5				Engineering design and development of advanced cooling methods.	Materials behavior in fuel or water-cooled combustors, vanes or blades.	Erosion/corr and ceramics temperature
1.2.6						Behavior of ceramics in mately 2500°
1.2.7					Fabrication of components for advanced cooling systems.	Materials en design and c cooling syst
1.3.1	Gas, hydrogen expansion.	H_2 liquid, gasified and burned with air.	Fuel supply system, heat exchanger/gasifier, and turbine exposed to hydrogen.	Materials selection.	Effects of high purity H_2 environment on materials of construction from -423°F to 1500°F under steady and fluctuating stresses.	Materials ar long times i Effect of H_2 ture toughne of stainless brazing allo

Table VIII-1

ARCH DEVELOPMENT AND TESTING NEEDED TO SUPPORT THE USE OF NEW FUELS

Solution	Materials Problems	Materials R, D, and T Needs	Remarks	Report Reference in Vol. 2, Sect. IV
selection.	H_2 environment effects.	Test materials and components in H_2 environments to establish safe operating limits.	-	A-1.1, A-4.4, A-5.4
aterials n.	Increased operating temperature.	Component testi-t.	Life of boiler tubing likely to increase due to clean fuel.	A-1
selection.	Cryogenic temperatures, H_2 environment effects.	Determine tensile and fatigue properties of candidate materials in high purity and deliberately contaminated H_2 gas environments from -423°F to approximately 600°F.	Candidate materials include Al alloys austenitic stainless steels, nickel alloys, and special brazing alloys,	A-2.2, A-4.4, A-5.4 (See also Vol. 1, Section III-A).
	None expected.	None.	Advanced composite and Ti alloy materials and fabrication programs for conventionally fueled gas turbines are relevant.	A-2.1, A-4.1
research, ent and	Effects of high-temperature, high H_2O content environments on combustor ar urbine materials.	Fundamental studies of effect of high-temperature, high-H_2O environments on Si_3N_4, Cb alloys, coatings.	Development and testing of high-temperature alloys, coatings and ceramics, proceeding for conventionally fueled gas turbines, is relevant. R, D, and T programs need expanding to include modified environments due to change of fuel.	A-2, A-4, A-5.2
		Determine creep and fatigue properties and oxidation/corrosion resistance of candidate alloys, ceramics and coatings in simulated H_2/air combustion gases.		A-2, A-4, A-5.2
ing design and ent of advanced methods.	Materials behavior in fuel or water-cooled combustors, vanes or blades.	Erosion/corrosion of candidate alloys and ceramics in high-velocity, high-temperature H_2O.	Required if water cooling is feasible.	A-2, A-4, A-5.2
		Behavior of candidate alloys and ceramics in H_2 from -423° to approximately 2500°F.	Required if hydrogen fuel cooling is feasible.	A-2, A-4, A-5.2
	Fabrication of components for advanced cooling systems.	Materials engineering support for design and development of advanced cooling systems.	-	A-2, A-4, A-5.2
selection.	Effects of high purity H_2 environment on materials of construction from -423°F to 1500°F under steady and fluctuating stresses.	Materials and component testing for long times in high-purity H_2 gas. Effect of H_2 on tensile, creep, fracture toughness and fatigue behavior of stainless steels, superalloys and brazing alloys from -423°F to 1500°F.	Overlaps items 1.1.1 and 1.3.1.	A-2.2, A-4.3.5, A-4.4, A-5.4

Table VIII-1 (Continued)

MATERIALS RESEARCH DEVELOPMENT AND TESTING NEEDED TO SUPPORT THE USE OF

Item No.	Equipment Class	Fuel	Problem Area	Type of Solution	Materials Problems	Materials R
1.	TURBINES (Con't)					
1.4.1	Hydrogen/oxygen.	H_2 (gas or liquid)/O_2 (gas or liquid).	H_2 supply system.	Materials selection.	Cryogenic temperatures, H_2 environment effects.	See item 1.2.1
1.4.2			O_2 supply system.	Establish and adhere to safety standards.	Ignition of metals and organic materials.	None.
1.4.3			Combustors and turbine components exposed to very high temperatures and high-temperature H_2O environment.	Engineering design and development of advanced cooling methods. Materials R, D, and T.	Effects of high temperature and H_2O environments on candidate metallic and ceramic materials of conconstruction.	None at this t
1.5.1	Gas, conventional.	NH_3	Fuel supply system.	Materials selection.	Stress corrosion cracking of steels, copper alloys.	Establish lim regard to ste level and typ nant concentr
1.5.2			Compressor and turbine.	Design for optimum performance.	No special problems expected.	None.
1.6.1	Gas, conventional.	Methanol.	Fuel supply system.	Materials selection.	Avoid Ti alloys.	None.
1.6.2			Compressor and turbine.	Design for optimum performance.	None.	None.
1.7.1	Gas, conventional.	CO	No problems expected in fuel supply systems.	-	None.	None.
1.7.2			Compressor and turbine.	Design for optimum performance.	None.	None.
2.	HYPERSONIC AIRCRAFT ENGINES					
2.1.1	Scramjet.	H_2/air	Engines and heat exchangers.	Design, materials selection, development and testing.	High-pressure hydrogen environments from cryogenic to high temperatures; high-temperature oxidizing environments, high aerodynamic stresses, high-frequency fatigue, thermal fatigue, severe thermal shock and thermal stresses.	Not clearly d

Table VIII-1 (Continued)

3 RESEARCH DEVELOPMENT AND TESTING NEEDED TO SUPPORT THE USE OF NEW FUELS

Type of Solution	Materials Problems	Materials R, D, and T Needs	Remarks	Report Reference in Vol. 2, Sect. I
erials selection.	Cryogenic temperatures, H_2 environment effects.	See item 1.2.1.	See item 1.2.1.	A-1.3, A-5.3
ablish and adhere safety standards.	Ignition of metals and organic materials.	None.	-	See Vol. 1, Sect. III-F
ineering design and elopment of advanced ling methods. erials R, D, and T.	Effects of high temperature and H_2O environments on candidate metallic and ceramic materials of construction.	None at this time.	Initiation of materials R, D, and T should await further concept development. Items 1.2.3. through 1.2.7 will generate relevant data.	A-1.3, A-4.2, A-5
erials selection.	Stress corrosion cracking of steels, copper alloys.	Establish limits of phenomena with regard to steel composition, stress level and type, and ammonia contaminant concentration.	Research programs primarily directed to materials problems in the transportation of ammonia will provide most of this data.	A-3. See also Vol. 1, Sect. III D.1.
ign for optimum formance.	No special problems expected.	None.	-	A-3
erials selection.	Avoid Ti alloys.	None.	-	A-3. See also Vol. 1 Sect. III-E-1
ign for optimum formance.	None.	None.	-	A-3
	None.	None.	-	A-3
ign for optimum formance.	None.	None.	-	A-3
ign, materials ection, development testing.	High-pressure hydrogen environments from cryogenic to high temperatures; high-temperature oxidizing environments, high aerodynamic stresses, high-frequency fatigue, thermal fatigue, severe thermal shock and thermal stresses.	Not clearly definable at this time.	Relevant data will be produced by Items 1.2.1, 1.2.3, 1.2.4, and 1.3.1.	B.1

Table VIII-1 (Continued)

MATERIALS RESEARCH DEVELOPMENT AND TESTING NEEDED TO SUPPORT THE USE OF NE

Item No.	Equipment Class	Fuel	Problem Area	Type of Solution	Materials Problems	Materials R,
3.	ROCKET PROPULSION ENGINES					
3.1.1	Hydrogen/oxygen.	H_2/O_2	Turbine drive units for fuel pumps. Heat exchangers/gasifier (thrust chamber cooling).	Materials selection.	High-pressure hydrogen or hydrogen/water environments. Temperature range determined by design, but spans -423°F to about 1500°F. Principal problems at higher temperatures.	I termination of toughness, cree erties of candi steels, Ni allo high-pressure H_2 environments at the range -428°
3.1.2			Long life combustion chamber and nozzle.	Design, materials selection, materials development and fabrication.	High-pressure, V. high-temerature, high-velocity H_2O environment. Thermal shock, thermal fatigue.	Materials and c
3.2.1	Monopropellant.	Hydrazine.	Very long life decomposition catalysts.	Catalyst research and development.	Present iridium catalysts tend to lose activity and alumina catalyst support material deteriorates after long-term intermittent use.	Fundamental stu mechanism of ca deterioration.
3.2.2						Development of catalyst.
4.	M.H.D. SYSTEMS					
4.1.1	Hydrogen fueled.	H_2/air or H_2/O_2	H_2 cooled magnets. Hot gas channel. Electrode materials.	Materials selection. Engineering design and development.	H_2 environment effects. High-H_2O, high-temperature gas stream.	None at this ti
5.	INTERNAL COMBUSTION ENGINES					
5.1.1	Spark or diesel.	H_2/air	Fuel system components exposed to hydrogen.	Materials selection.	Possible H_2 environment effects.	Long-term engin failure analysi
5.1.2			Minor engine modifications.	Engineering development.	None.	None.
5.2.1	Spark or diesel.	NH_3	Fuel systems exposed to NH_3 and H_2 if fuel is partly dissociated to improve combustion.	Materials selection.	NH_3 and H_2 environment effects.	None.
5.2.2			Engine modifications and addition of NH_3 dissociation equipment.	Engineering development.	None.	None.
5.3.1	Spark or diesel.	Hydrazine.	Not defined.	-	-	-
5.4.1	Spark or diesel.	Methanol.	None.	-	-	-

Table VIII-1 (Continued)

ARCH DEVELOPMENT AND TESTING NEEDED TO SUPPORT THE USE OF NEW FUELS

Solution	Materials Problems	Materials R, D, and T Needs	Remarks	Report Reference in Vol. 2, Sect. IV
selection.	High-pressure hydrogen or hydrogen/water environments. Temperature range determined by design, but spans −423°F to about 1500°F. Principal problems at higher temperatures.	Determination of tensile, fracture toughness, creep and fatigue properties of candidate stainless steels, Ni alloys, Co alloys in high-pressure H_2 and $H_2 + H_2O$ environments at temperatures in the range −428°F to 1500°F.	Overlaps with item 1.3.1 Continuation and extension of current programs.	B-2.[illegible], B-3
aterials , materials at and fabri-	High-pressure, V. high-temperature, high-velocity H_2O environment. Thermal shock, thermal fatigue.	Materials and component rig testing.	Possible long-term application to Item 1.4.3.	B-2.1
research and nt.	Present iridium catalysts tend to lose activity and alumina catalyst support material deteriorates after long-term intermittent use.	Fundamental studies to elucidate mechanism of catalyst and substrate deterioration.	For small hydrazine decomposition control and accessory engines. No major problems with large hydrazine/oxidizer engines.	B-2.2
		Development of improved mixed-metal catalyst.	-	B-2.2
s selection. ing design and nt.	H_2 environment effects. High-H_2O, high-temperature gas stream.	None at this time.	Clean H_2 fuel superior to fossil fuels for large systems. Initiation of materials R, D, and T should await further engineering design.	C
s selection.	Possible H_2 environment effects.	Long-term engine tests, and materials failure analysis.	No major difficulties in use of H_2 fuel expected.	D-2, D-5
ing develop-	None.	None.	-	D-2, D-5
s selection.	NH_3 and H_2 environment effects.	None.	NH_3 is a poor fuel for I.C engines, especially for diesels.	D-3, D-5
ing develop-	None.	None.	-	D-3, D-5
	-	-	-	D-4, D-5
	-	-	Existing practice.	D-1, D-5

Table VIII-1 (Continued)

MATERIALS RESEARCH DEVELOPMENT AND TESTING NEEDED TO SUPPORT THE USE OF NEW

Item No.	Equipment Class	Fuel	Problem Area	Type of Solution	Materials Problems	Materials R, D
6.	EXTERNAL COMBUSTION ENGINES					
6.1.1	Steam, reciprocating.	All new fuels.	Fuel supply system and burners.	Design, materials selection.	No major problems.	None.
6.2.1	Stirling cycle (heating system).	All new fuels.	Fuel supply system and burners.	Design; materials selection.	No major problems.	None.
6.3.1	Stirling cycle (H_2 working fluid).	All new fuels.	Heater tubes, heat exchanger, operate at high temperatures with high internal H_2 pressures. Working chambers must contain H_2 with minimum loss. High H_2 reservoir pressures.	Materials development, selection.	High pressure (5000 psi) H_2 environment effects from subzero temperatures to 1500°F on heat-resisting alloys.	Determination of toughness, creep, properties of can steels, Ni alloys 5000 psi hydrogen subzero to 1500°F
6.3.2					Coatings to reduce hydrogen permeation through working chamber and heat exchanger tubing at high temperatures. Thermal shock and thermal fatigue.	Determination of for candidate all and 1500°F.
6.3.3						Develop coatings H_2 permeation at with substrate al stand thermal fat
7.	SPACE AND WATER HEATING					
7.1.1	Open flame combustion.	H_2/air.	Fuel supply system and burners.	Design; materials selection.	No major problems.	None.
7.2.1	Catalytic combustion.	H_2/air.	Catalytic burner to operate efficiently at low temperatures for long times.	Improved catalyst.	Low-cost, long-life, high-activity catalyst system tnat is resistant to poisoning by contaminants.	Fundamental studi catalytic oxidati transition metal with empirical de improved H_2 oxida
7.3.1	Open flame combustion.	NH_3 (dissociated).	Efficient, low-cost NH_3 dissociation equipment.	Improved catalyst.	Low-cost, long-life, high-activity catalyst system.	Development of [illegible] iation catalysts,
7.4.1	Catalytic combustion.	NH_3	Catalytic burner to operate efficiently at low temperatures for long times.	Improved catalyst.	Low-cost, long-life, high activity oxidation catalyst that favors N_2 and H_2O oxidation products.	Development of im

Table VIII-1 (Continued)

SEARCH DEVELOPMENT AND TESTING NEEDED TO SUPPORT THE USE OF NEW FUELS

of Solution	Materials Problems	Materials R, D, and T Needs	Remarks	Report Reference in Vol. 2, Sect. IV
materials ion.	No major problems.	None.	Careful attention to materials selection for H_2 fuel systems will be needed.	E-1, E-4
materials ion.	No major problems.	None.	Careful attention to materials selection for H_2 fuel systems will be needed.	E-2, E-4
ls develop- election.	High pressure (5000 psi) H_2 environment effects from subzero temperatures to 1500°F on heat-resisting alloys.	Determination of tensile, fracture toughness, creep, and fatigue properties of candidate stainless steels, Ni alloys, Co alloys in 5000 psi hydrogen at temperature from subzero to 1500°F.	Range of materials operating conditions covered by Items 1.3.1 and 3.1.1.	E-2, E-4
	Coatings to reduce hydrogen permeation through working chamber and heat exchanger tubing at high temperatures. Thermal shock and thermal fatigue.	Determination of H_2 permeability data for candidate alloys up to 5000 psi and 1500°F.	-	E-2, E-4
		Develop coatings that are resistant to H_2 permeation at 1500°F, compatible with substrate alloy and will withstand thermal fatigue.	-	E-2, E-4
materials n.	No major problems.	None.	-	F-1.1, F-6
catalyst.	Low-cost, long-life, high-activity catalyst system that is resistant to poisoning by contaminants.	Fundamental studies of mechanism of catalytic oxidation of H_2, e.g., by transition metal carbides, combined with empirical development of improved H_2 oxidation catalysts.	-	F-2.1, F-2.3, F-6
catalyst.	Low-cost, long-life, high-activity catalyst system.	Development of low-cost NH_3 dissociation catalysts.	Relates to use of NH_3 in fuel cells. This work would probably also relate to the development of improved NH_3 synthesis catalysts.	F-2.1, F-2.3, F-6
catalyst.	Low-cost, long-life, high activity oxidation catalyst that favors N_2 and H_2O oxidation products.	Development of improved catalyst.	-	F-2.2, F-2.3, F-6

MATERIALS RESEARCH DEVELOPMENT AND TESTING NEEDED TO SUPPORT THE USE OF NE

Item No.	Equipment Class	Fuel	Problem Area	Type of Solution	Materials Problems	Materials R,
7.	SPACE AND WATER HEATING (Con't)					
7.5.1	Open flame combustion.	CO, Methanol.	None.	-	None.	None.
7.6.1	Catalytic combustion.	CO, Methanol.	Catalytic burners to operate efficiently at low temperatures for long times.	Improved catalysts.	Low-cost, long-life, high-activity catalyst systems.	Development of ba
8.	FUEL CELLS					
8.1.1	Alkaline electrolyte.	H_2/air (or O_2).	Anode catalyst.	Catalyst development.	Physical stability of non-noble anode catalysts.	Nonnoble anode ca physical stabilit
8.1.2			Cathode catalyst.	Catalyst development.	Corrosion of nonnoble cathode catalysts.	Nonnoble cathode polarization, low and improved phys
8.1.3						Noble metal catal activity and stab catalyst loadings
8.1.4			Electrode structure.	Materials development.	Wetting and instability of polymer-bonded electrodes at 150°C and above.	Hydrophobic polym materials for wor 150°C.
8.1.5					Fabrication of gas-diffusion electrode structures with controlled porosity.	Improved controll materials for ele
8.1.6			Electrolyte matrix.	Materials development.	Present asbestos matrix cannot operate above 100°C.	Low-cost matrix m operate at 150°C.
8.1.7						Improved ion-exch
8.2.1	Acid electrolyte.	H_2/air (or O_2).	Cathode catalyst.	Catalyst development.	Relatively low activity, high polarization of platinum catalyst for O_2 reduction in acid electrolyte.	Improved noble me improved activity stability at low
8.2.2						Low-cost, nonnobl with moderate act stability and cor
8.2.3			Electrolyte matrix.	Materials development.	Less expensive, more robust matrix materials.	Improved ion-exch
8.3.1	Molten carbonate electrolyte.	H_2/air (or O_2).	Anode and cathode catalysts.	Materials development.	Lack of catalyst stability.	Anode and cathode with improved sta

Table VIII-1 (Continued)

RESEARCH DEVELOPMENT AND TESTING NEEDED TO SUPPORT THE USE OF NEW FUELS

of Solution	Materials Problems	Materials R, D, and T Needs	Remarks	Report Reference in Vol. 2, Sect. IV
	None.	None.	-	F-4, F-5, F-6
ed catalysts.	Low-cost, long-life, high-activity catalyst systems.	Development of base-metal catalysts.	-	F-4, F-5, F-6
t development.	Physical stability of nonnoble anode catalysts.	Nonnoble anode catalyst with improved physical stability at 150°C and above.	Relatively low corrosivity of alkaline electrolyte permits wide choice of materials of construction.	G-3.1.1, G-3.1.6, G-3.9.1
t development.	Corrosion of nonnoble cathode catalysts.	Nonnoble cathode catalyst with lower polarization, lower corrosion rate and improved physical stability.	-	G-3.1.3, G-3.1.6, G-3.9.1
		Noble metal catalysts with high activity and stability at lower catalyst loadings.	-	G-3.1.2, G-3.1.6, G-3.9.1
als development.	Wetting and instability of polymer-bonded electrodes at 150°C and above.	Hydrophobic polymeric bonding materials for service at above 150°C.	-	G-3.1.3, G-3.1.6 G-3.9.2
	Fabrication of gas-diffusion electrode structures with controlled porosity.	Improved controlled-porosity materials for electrode structures.	-	G-3.9.2
als development.	Present asbestos matrix cannot operate above 100°C.	Low-cost matrix materials able to operate at 150°C.	-	G-3.1.4, G-3.1.6 G-3.9.3
		Improved ion-exchange membranes.	-	
st development.	Relatively low activity, high polarization of platinum catalyst for O_2 reduction in acid electrolyte.	Improved noble metal catalyst with improved activity and physical stability at low catalyst loadings.	Acid electrolyte limits choice of materials of construction.	G-3.2.2, G-3.2.6, G-3.9.1
		Low-cost, nonnoble metal catalysts with moderate activity, and high stability and corrosion resistance.	-	G-3.2.2, G-3.2.6 G-3.9.1
als development.	Less expensive, more robust matrix materials.	Improved ion-exchange membranes.	-	G-3.2.6, G-3.9.3
als development.	Lack of catalyst stability.	Anode and cathode catalysts with improved stability.	Molten carbonate cells require use of CO_2 addition to cathode reactant (air).	G-3.3.1, G-3.3.2, G-3.3.6, G-3.9.1

TABLE VIII-1 (Continued)

MATERIALS RESEARCH DEVELOPMENT AND TESTING NEEDED TO SUPPORT THE USE OF

Item No.	Equipment Class	Fuel	Problem Area	Type of Solution	Materials Problems	Materials R,
8.	FUEL CELLS (Con't)					
8.3.2	Molten carbonate (Con't)	H_2/air (or O_2)	Electrode structure.	Materials development.	Need for ceramic structure analogous to hydrophobic polymer-bonded systems for low-temperature cells.	Ceramics which c of wetting angle
8.3.3			Electrolyte matrix.	Materials development.	Thermal cracking of the ceramic electrolyte matrix tile.	Ceramic matrix m controlled poros resistance to th
8.4.1	Inorganic solid electrolyte.	H_2/air (or O_2).	High operating temperature.	Materials development and design.	Differential expansion between cell components, low conductivity of electrolyte, contact between matrices and electrodes head and gas leakage.	Development of c matching expansi thin, stable, hig matrix materials.
8.4.2				Basic materials research.	Inorganic solid electrolyte operating at lower temperatures.	Study of low-tem conducting inorg
8.5.1	Direct methanol fuel cells.	Methanol.	Low activity of methanol electrode.	Catalyst development.	Anode catalyst.	Higher activity a
8.5.2			Cross-over of methanol to cathode.	Materials development.	Methanol dissolved in electrolyte diffuses through matrix.	Matrix material (to methanol.
8.5.3					Air electrode structure wetted by cross-over methanol.	Electrode structu can control wetti
8.5.4				Catalyst development.	Platinum cathode catalyst also catalyses direct oxidation of cross-over methanol.	Selective cathode more oxygen reduc methanol oxidatio
8.6.1	Indirect methanol fuel cells.	Reformed methanol (H_2, CO, CO_2).	Same as hydrogen fuel cells.	-	-	-
8.7.1	Hydrazine fuel cells.	Hydrazine.	Chemical decomposition of hydrazine at anode.	Catalyst development.	Anode catalyst may decompose hydrazine, oxidize hydrogen formed, cause NH_3 evolution.	Selective anode c hydrazine oxidati position, or the
8.7.2			Cross-over of hydrazine to cathode.	Materials development.	Hydrazine dissolved in electrolyte diffuses through matrix.	Matrix material (to hydrazine.

TABLE V.II-1 (Continued)

SEARCH DEVELOPMENT AND TESTING NEEDED TO SUPPORT THE USE OF NEW FUELS

of Solution	Materials Problems	Materials R, D and T Needs	Remarks	Report Reference in Vol. 2, Sect. IV
development.	Need for ceramic structure analogous to hydrophobic polymer-bonded systems for low-temperature cells.	Ceramics which can provide control of wetting angle in molten carbonate.	-	G-3.3.3, G-3.9.3
development.	Thermal cracking of the ceramic electrolyte matrix tile.	Ceramic matrix materials with controlled porosity and improved resistance to thermal cycling.	-	G-3.3.4, G-3.9.3
development n.	Differential expansion between cell components, low conductivity of electrolyte, contact between matrices and electrodes head and gas leakage.	Development of cell materials with matching expansions, development of thin, stable, high-conductivity matrix materials.	Operating range 700° to 1000°C.	G-3.4, G-3.4.4
erials	Inorganic solid electrolyte operating at lower temperatures.	Study of low-temperature, ion-conducting inorganic solids.	Breakthrough analogous to discovery of β-alumina needed.	G-3.4.3, G-3.4.4
development.	Anode catalyst.	Higher activity anode catalyst.	-	G-3.5, G-3.5.1
development.	Methanol dissolved in electrolyte diffuses through matrix.	Matrix material (separator) impervious to methanol.	-	G-3.5, G-3.5.1
	Air electrode structure wetted by cross-over methanol.	Electrode structure materials that can control wetting angle.	-	G-3.5, G-3.5.1
development.	Platinum cathode catalyst also catalyses direct oxidation of cross-over methanol.	Selective cathode catalysts that promote oxygen reduction but not methanol oxidation.	-	G-3.5, G-3.5.1
	-	-	Reformed methanol can be used in acidic, molten carbonate or solid electrolyte fuel cells.	G-3.5
development.	Anode catalyst may decompose hydrazine, oxidize hydrogen formed, cause NH_3 evolution.	Selective anode catalyst that promotes hydrazine oxidation but not its decomposition, or the oxidation of hydrogen.	-	G-3.6, G-3.9
development.	Hydrazine dissolved in electrolyte diffuses through matrix.	Matrix material (separator) impervious to hydrazine.	Equivalent to Item 8.5.2.	G-3.6, G-3.9

Table VIII-1 (Continued)

MATERIALS RESEARCH DEVELOPMENT AND TESTING NEEDED TO SUPPORT THE USE OF NE

Item No.	Equipment Class	Fuel	Problem Area	Type of Solution	Materials Problems	Materials R, D,
8.	FUEL CELLS (Concluded)					
8.7.3	Hydrazine fuel cells. (Con't)	Hydrazine	Hydrazine cross-over.	Catalyst development.	Cathode catalyst catalyses decomposition or oxidation of cross-over hydrazine.	Selective cathode motes oxygen reduc zine decomposition
8.8.1	Direct NH_3 cells.	NH_3	Anode.	Catalyst research.	Anode activity decreases with time.	Basic studies to d decline in anode a
8.9.1	Indirect NH_3 fuel cells.	NH_3 (dissociated to N_2 and H_2).	Same as hydrogen fuel cells.	-	-	-
8.10.1	Regenerative fuel cells.	H_2/O_2	Variations of electrode potential as cell operation is reversed.	Catalyst development.	Decreased catalyst life.	Electrocatalysts t to potential cycli
8.10.2				Electrode structure development.	Dual function electrode structures.	Electrode structu tinct catalysts.
8.10.3					Dual electrode structures.	Two electrode stru appropriate cataly
8.11.1	Fuel cells--general.	Various	Polymeric materials for electrical insulators and seals for service above 150°C.	Design; materials and fabrication development.	Polymeric materials with long-term, high-temperature stability above 150°C.	Polymeric material testing.
8.11.2			Reactant supply systems.	Materials selection.	H_2, NH_3, hydrazine environments.	See item headings
8.11.3			Theory of electrocatalyst behavior.	Basic electrocatalysis.	Mechanism of electrocatalysis.	Studies of effects electrolytes, and on electrocatalyst face.
8.11.4			Electrocatalyst screening.	Measurements of single electrode characteristics.	Empirical selection of electrocatalysts.	Determination of d materials.
9.	HIGH ENERGY DENSITY BATTERIES					
9.1.1	Aqueous, electrically rechargeable, Zn/air, Zn/O_2.	Zn	Zn electrode.	Design and engineering; basic research.	Shape change (dendrite growth) of Zn electrode.	Studies of mechani growth.
9.1.2			Air electrode; poor charge/discharge cycle efficiency.	Catalyst development, electrode design.	High catalyst loadings required.	Dual function or t catalysts for oxyg oxygen reduction.

Table VIII-1 (Continued)

IALS RESEARCH DEVELOPMENT AND TESTING NEEDED TO SUPPORT THE USE (NEW FUELS

ype of Solution	Materials Problems	Materials R, D, and T Needs	Remarks	Report Reference in Vol. 2, Sect. I
alyst development.	Cathode catalyst catalyses decomposition or oxidation of cross-over hydrazine.	Selective cat!ode catalysts that promotes oxygen reduction but not hydrazine decomposition or oxidation.	-	G-3.6, G-3.9
alyst research.	Anode activity decreases with time.	Basic studies to determine cause of decline in anode activity.	-	B-3.7
	-	-	Can be used in all H_2 fuel cell types including alkaline.	G-3.7
alyst development.	Decreased catalyst life.	Electrocatalysts that are insensitive to potential cycling.	-	G-3.8, G-3.9
ctrode structure elopment.	Dual function electrode structures.	Electrode structures with two distinct catalysts.	-	G-3.8, G-3.9
	Dual electrode structures.	Two electrode structures each with appropriate catalysts.	-	G-3.8, G-3.9
ign; materials and rication development.	Polymeric materials with long-term, high-temperature stability above 150°C.	Polymeric materials development and testing.	Will probably be satisfied by improved commercial products.	G-3.9.4
erials selection.	H_2, NH_3, hydrazine environments.	See item headings 1 through 7.	Requirements common to other uses of new fuels.	G-3.9.4
ic electrocatalysis.	Mechanism of electrocatalysis.	Studies of effects of reactants, electrolytes, and applied potential on electrocatalyst/electrolyte interface.	-	G-3.9.4
surements of single ctrode characterics.	Empirical selection of electrocatalysts.	Determination of data for candidate materials.	-	G-3.9.4
ign and engineering; ic research.	Shape change (dendrite growth) of Zn electrode.	Studies of mechanism of dendrite growth.	Future of this battery depends on solving Zn electrode problem.	H-3.1.1, H-3.1.3
alyst development, ctrode design.	High catalyst loadings required.	Dual function or two separate catalysts for oxygen evolution and oxygen reduction.	-	H-3.1.3

Table VIII-1 (Continued)

MATERIALS RESEARCH DEVELOPMENT AND TESTING NEEDED TO SUPPORT THE USE OF

Item No.	Equipment Class	Fuel	Problem Area	Type of Solution	Materials Problem	Materials R,
9.	HIGH ENERGY DENSITY BATTERIES (Continued)					
9.2.1	Aqueous, mechanically rechargeable, Zn/air.	Zn	Electrolyte leakage.	Improved design, seal materials.	Seal materials.	Support to engi
9.3.1	Aqueous, Zn/Ni.	Zn	Zn electrode.	See Item 9.1.1.	See Item 9.1.1.	See Item 9.1.1.
9.4.1	Aqueous Zn/Cl_2.	Zn	Zn electrode.	See Item 9.1.1.	See Item 9.1.1.	See Item 9.1.1.
9.4.2			Cl_2 electrode.	Materials development.	Polarization of Cl_2 electrode.	More active Cl_2
9.5.1	Aqueous Li/Ni.	Li	Li electrode; shelf life.	Materials development, corrosion research.	Li corrosion reaction in the absence of external current flow.	Alloying of Li to limit Li cor
9.5.2			H_2 evolved, must be vented.	Materials selection.	H_2 environment effects.	None.
9.6.1	Aprotic solvent Li batteries.	Li	Li electrode; low power density, shelf life, slow start-up due to electronic passivation.	Electrochemical studies, battery design.	Electrode/electrolyte interactions.	Support to elec studies.
9.7.1	Molten salt, high temperature, Li/Cl_2 battery.	Li	Li electrode.	Electrode material development.	Dissolution and migration of lithium.	Development of maximum cell vo
9.7.2			Cl_2 electrode; low current capacity.	Electrode and electrolyte development.	Electrode and electrolyte materials.	Support for ele development stu
9.7.3			Materials of construction.	Materials development and selection.	Attack of materials by molten Li.	Ceramics and co molten Li.
9.7.4					Corrosion by molten alkali-halide electrolyte.	Alloys and coat molten halides.
9.7.5					Electrical feed-throughs.	Containment mat brazing alloys coefficients.
9.7.6					Containment of high temperature Cl_2 gas.	Alloys and coat Cl_2 gas.
9.8.1	Li/S molten salt, battery.	Li	Sulfur electrode.	Materials development and selection.	Attack of sulfur on materials of construction.	Materials compa electrode mater

Table VIII-1 (Continued)

ALS RESEARCH DEVELOPMENT AND TESTING NEEDED TO SUPPORT THE USE OF NEW FUELS

pe of Solution	Materials Problem	Materials R, D, and T Needs	Remarks	Report Reference in Vol. 2, Sect. 1
oved design, seal rials.	Seal materials.	Support to engineering development.	-	H-3.1.1
Item 9.1.1.	See Item 9.1.1.	See Item 9.1.1.	Electrically rechargeable.	H-3.1.4
Item 9.1.1.	See Item 9.1.1.	See Item 9.1.1.	Electrically rechargeable	H-3.1.5
rials development.	Polarization of Cl_2 electrode.	More active Cl_2 electrode substrate.	Would improve power density.	H-3.1.5
rials development, osion research.	Li corrosion reaction in the absence of external current flow.	Alloying of Li or use of inhibitors to limit Li corrosion.	Primary or mechanically rechargeable battery.	H-3.1.6
rials selection.	H_2 environment effects.	None.	-	H-3.1.6
trochemical ies, battery gn.	Electrode/electrolyte interactions.	Support to electrochemical and design studies.	No H_2 evolved. Can be sealed for use as primary battery.	H-3.1
trode material lopment.	Dissolution and migration of lithium.	Development of solid Li alloys giving maximum cell voltage.	Operates from 350° to 650°C depending on electrolyte composition.	H-3.3.1
trode and electe development.	Electrode and electrolyte materials.	Support for electrode and electrolyte development studies.	-	H-3.3.1
rials development election.	Attack of materials by molten Li.	Ceramics and coatings resistant to molten Li.	-	H-3.3.1
	Corrosion by molten alkali-halide electrolyte.	Alloys and coatings resistant to molten halides.	-	H-3.3.1
	Electrical feed-throughs.	Containment materials, insulators and brazing alloys with matching expansion coefficients.	-	H-3.3.1
	Containment of high temperature Cl_2 gas.	Alloys and coatings resistant to hot Cl_2 gas.	-	H-3.3.1
ials development election.	Attack of sulfur on materials of construction.	Materials compatibility testing or electrode materials modification.	Operates at 375° to 400°C.	H-3.3.1

MATERIALS RESEARCH DEVELOPMENT AND TESTING NEEDED TO SUPPORT THE USE OF

Item No.	Equipment Class	Fuel	Problem Area	Type of Solution	Materials Problem	Materials R,
9.	HIGH ENERGY DENSITY BATTERIES (Concluded)					
9.9.1	Molten salt, low-temperature Al/Cl_2 battery.	Al	Materials of construction.	Materials selection.	None.	None.
9.10.1	Solid electrolyte Na/S battery.	Na	β-alumina electrolyte.	Materials research; ceramic processing development.	Improved Na-ion conductivity, resistance to intergranular attack, to thermal cracking and mechanical strength.	Modification and alumina composit
9.10.2						Investigation of conductors.
9.11.1	General.	Various.	Materials of construction.	Battery design and development, materials development and selection.	Materials compatibility with electrodes and electrolytes; seals, feedthroughs, insulators, etc.	Supporting mater development stud battery R, D, an
9.11.2			Solid electrolytes.	Materials research and development.	Improved solid electrolytes and cation/anion exchange membranes.	Search for new i ducting solids.

Table VIII-1 (Concluded)

EARCH DEVELOPMENT AND TESTING NEEDED TO SUPPORT THE USE OF NEW FUELS

olution	Materials Problem	Materials R, D, and T Needs	Remarks	Report Reference in Vol. 2, Sect. IV
selection.	None.	None.	Operates at 60° to 150°C.	H-3.3.2
research; rocessing t.	Improved Na-ion conductivity, resistance to intergranular attack, to thermal cracking and mechanical strength.	Modification and optimization of β-alumina composition.	Operates at about 300°C.	H-3.4
		Investigation of alternative Na-ion conductors.	-	H-3.4
esign and t, materials t and selec-	Materials compatibility with electrodes and electrolytes; seals, feedthroughs, insulators, etc.	Supporting materials engineering and development studies as part of battery R, D, and T programs.	-	H-3.1
research and t.	Improved solid electrolytes and cation/anion exchange membranes.	Search for new low-temperature ion-conducting solids.	-	H-3.5

TABLE VIII-2
MATERIALS RESEARCH DEVELOPMENT AND TESTING
NEEDED TO SUPPORT THE PRODUCTION OF NEW FUELS

Table VIII-2

MATERIALS RESEARCH DEVELOPMENT AND TESTING NEEDED TO SUPPORT THE PRODUCT

Item No.	Process	Fuel Produced	Problem Area	Type of Solution	Materials Problem	Materirl
1.	CONVENTIONAL ELECTROLYZERS					
1 1.1	Unipolar tank type.	$H_2(O_2)$	Efficiency and cost.	Advanced electrolyzers.	No major problems.	None.
1.2.1	Bipolar, filter press type.	$H_2(O_2)$	Efficiency and cost.	Advanced electrolyzers.	No major problems.	None.
2.	ADVANCED ELECTROLYZERS					
2.1.1	Alkaline electrolyte.	$H_2(O_2)$	Higher temperature operation to increase efficiency.	Materials development.	Corrosion of positive (oxygen) electrode.	Materials wit superior to n
2.1.2					Present diaphragm material (asbestos) limited to 100°C	Higher temper (200°C desira
2.1.3					Present frame materials (polysulphones) limited to 150°C.	Higher temper materials, an
2.1.4			Reduction of over-potentials.	Materials development and design.	Relatively low conductivity and bulky diaphragm materials.	High-conducti higher temper diaphragm (ma
2.1.5					Effective area of electrodes.	High effectiv materials.
2.1.6				Catalyst development.	Electrode activity.	Improved nonn catalysts.
2.2.1						
2.2.1	Solid polymer electrolyte.	$H_2(O_2)$	SPE membrane.	Materials research and development.	Present SPE membrane is expensive, temperature limited (125°C) and somewhat lacking in mechanical and chemical stability.	Development o perature SPE (anion or cat improved mech bility.
2.2.2			Electrodes.	Catalyst development.	High loadings of noble metal catalysts.	Nonnoble meta
2.2.3				Engineering and materials development.	Electrode/membrane contact resistance.	Support for e
2.3.1	Inorganic solid electrolyte.	$H_2(O_2)$	Very high operating temperature (1000°C).	Materials R and D.	Solid inorganic electrolyte membranes with good ionic conductivity below 400°C.	Basic studies erties of cer
2.3.2			Materials and engineering development.	Materials and engineering development.	Materials of construction.	Materials wor neering devel

Table VIII-2

RESEARCH DEVELOPMENT AND TESTING NEEDED TO SUPPORT THE PRODUCTION OF NEW FUELS

pe of Solution	Materials Problem	Materials R, D, and T Needs	Remarks	Report References in Vol. 2, Sect. V
ced electrolyzers.	No major problems.	None.	Established technology.	A-2.1.1
ced electrolyzers.	No major problems.	None.	Established technology.	A-2.1.2
ials development.	Corrosion of positive (oxygen) electrode.	Materials with corrosion resistance superior to nickel.	Nickel is now used.	A-2.2.1, A-4
	Present diaphragm material (asbestos) limited to 100°C	Higher temperature diaphragm materials (200°C desirable).	-	A-2.2.1, A-4
	Present frame materials (polysulphones) limited to 150°C.	Higher temperature, low-cost frame materials, and methods of fabrication.	-	A-2.2.1, A-4
ials development esign.	Relatively low conductivity and bulky diaphragm materials.	High-conductivity, compact, (and higher temperatures - Item 2.1.2) diaphragm (matrix) materials.	Less bulky diaphragm would permit closer electrode spacing and less voltage drop in the electrolyte.	A-2.2.1, A-4
	Effective area of electrodes.	High effective surface area electrode materials.	-	A-2.2.1, A-4
yst development.	Electrode activity.	Improved nonnoble, low-cost electrocatalysts.	Ni and Fe electrode materials now used are moderately effective.	A-2.2.1, A-4
ials research and opment.	Present SPE membrane is expensive, temperature limited (125°C) and somewhat lacking in mechanical and chemical stability.	Development of low-cost, higher temperature SPE membranes with high ionic (anion or cation) conductivity and improved mechanical and chemical stability.	-	A-2.2.2, A-4
yst development.	High loadings of noble metal catalysts.	Nonnoble metal catalysts.	Noble metal catalysts probably acceptable for DoD uses, but probably not for large-scale industrial use.	A-2.2.2, A-4
eering and ials development.	Electrode/membrane contact resistance.	Support for engineering development.	-	A-2.2.2, A-4
ials R and D.	Solid inorganic electrolyte membranes with good ionic conductivity below 400°C.	Basic studies of ion-conducting properties of ceramics.	High-temperature electrolyzers have limited actual thermal efficiencies.	A-2.2.3, A-4
ials and engi- ing development.	Materials of construction.	Materials work in support of engineering development.	Problems similar to those of high-temperature fuel cells (Item 8.4.1 in Table VIII-1).	A-2.2.3

Table VIII-2 (Continued)

MATERIALS RESEARCH DEVELOPMENT AND TESTING NEEDED TO SUPPORT THE PROD

Item No.	Process	Fuel Produced	Problem Area	Type of Solution	Materials Problem	Mater
2.	ADVANCED ELECTROLYZERS (Concluded)					
2.4.1	Acid electrolyte.	H_2 (O_2)	Oxygen electrode.	Materials selection.	Corrosion of oxygen electrode materials and associated conductors.	Materials se operational
2.5.1	General.	H_2 (O_2)	Materials resources availability.	Technoeconomic analysis of materials supply needs for competing electrolyzer technologies.	-	None.
2.5.2			Materials of construction, auxilliary equipment.	Materials selection.	H_2 environment and O_2 environment effects.	Materials te electrolyzer of temperatu
3.	THERMOCHEMICAL SPLITTING					
3.1.1	Several multistep cycles (all are now at a conceptual stage).	H_2 (O_2)	Materials of construction.	Materials development and selection; engineering design and development.	High-temperature corrosion of metallic and ceramic materials in halogens, halides, metal oxides, liquid metal, hydrogen, oxygen, steam.	Materials an possible nee materials an
4.	HYDROGEN LIQUEFACTION					
4.1.1	Compression liquefaction of H_2 gas.	Liquid H_2	Compressor development.	Engineering design and development; materials development and selection.	Materials for use as cylinder liners, pistons, piston rings, seals, bearings, turbine blading in advanced compressors at ambient and cryogenic temperatures in H_2 environment.	H_2-resistant, weight mater
4.1.2						Low friction binations fo
4.1.3						Seal materia low-expansio

Table VIII-2 (Continued)

DEVELOPMENT AND TESTING NEEDED TO SUPPORT THE PRODUCTION OF NEW FUELS

lution	Materials Problem	Materials R, D, and T Needs	Remarks	Report Reference in Vol. 2, Sect. V
ction.	Corrosion of oxygen electrode materials and associated conductors.	Materials selection and small-scale operational testing.	Acid electrolytes reject CO_2 and are of interest for use in life support systems.	A-2.2.4
analysis supply ting tech-	-	None.	Essential background for policy decisions.	A-4
ction.	H_2 environment and O_2 environment effects.	Materials testing under electrolyzer operating conditions of temperature and pressure.	Information required will be provided by work relating to Section IV of this report. (See Table VIII-1.)	A-4
lopment engi- and	High-temperature corrosion of metallic and ceramic materials in halogens, halides, metal oxides, liquid metal, hydrogen, oxygen, steam.	Materials and component testing; possible need for corrosion-resistant materials and coatings development.	Specific programs can be planned when further feasibility studies have been made and prototype process cycles have been selected.	B-1, B-2, B-3, B-4
sign and aterials d selec-	Materials for use as cylinder liners, pistons, piston rings, seals, bearings, turbine blading in advanced compressors at ambient and cryogenic temperatures in H_2 environment.	H_2-resistant, high-strength lightweight materials.	Materials support for engineering dev· opment.	C
		Low friction and wear materials combinations for service in H_2.	-	C
		Seal materials, bearing materials, low-expansion alloys.	-	C

MATERIALS RESEARCH DEVELOPMENT AND TESTING NEEDED TO SUPPORT THE

Item No.	Process	Fuel P Produced	Problem Area	Type of Solution	Materials Problem	Ma
5.	AMMONIA PRODUCTION					
5.1.1	Modified Haber Process.	NH_3	Pressure vessels.	Materials selection and design.	Effects of long time exposure of pressure vessel materials to high pressure H_2, N_2, NH_3 at moderate temperatures.	Probably
5.1.2					Improved on-site and in-service nondestructive testing techniques.	Probably
5.1.3				Alternative designs and materials, e.g. metal lined, pre-stressed or fiber reinforced cements or concrete vessels.	Materials for very large pressure vessels.	Developm reinforc material
5.1.4			Ancillary equipment, compressors.	Materials selection.	H_2 environment effects.	Material high pre
5.1.5			NH_3 condensation and storage.	Materials research; materials selection.	Stress corrosion cracking of quenched and tempered steels in liquid ammonia.	Material mechanis of SCC i testing material
6.	HYDRAZINE PRODUCTION					
6.1.1	Modified Raschig process.	Hydrazine	Possible problems in scaled-up production.	Materials selection; engineering.	-	None at
7.	PRODUCTION OF BORANES AND SILANES					
7.1.1	Various small-scale methods.	Boranes and silanes	Possible problems in scaled-up production.	Materials selection; engineering.	-	None at

Table VIII-2 (Continued)

ARCH DEVELOPMENT AND TESTING NEEDED TO SUPPORT THE PRODUCTION OF NEW FUELS

of Solution	Materials Problem	Materials R, D, and T Needs	Remarks	Report Reference in Vol. 2, Sect. V
selection a.	Effects of long time exposure of pressure vessel materials to high pressure H_2, N_2, NH_3 at moderate temperatures.	Probably no special programs required.	Necessary test data will be collected from related industrial experience and test programs.	D-1.1.1
	Improved on-site and in-service nondestructive testing techniques.	Probably no special programs required.	Appropriate NDT and E techniques will be developed for nuclear power plants.	D-1.1.1
ve designs ials, e.g. ed, pre- or fiber d cements e vessels.	Materials for very large pressure vessels.	Development and testing of fiber-reinforced cement and concrete materials and structures.	Likely to be of broad general application.	D-1.1.1
selection.	H_2 environment effects.	Materials and component testing in high pressure H_2.	Would profit from advanced compressor development, Items 4.1.1, 4.1.2, 4.1.3.	D-1.1.2
research; selection.	Stress corrosion cracking of quenched and tempered steels in liquid ammonia.	Materials research to establish mechanism and limiting conditions of SCC in liquid ammonia and testing of candiate SCC-resistant materials.	See Volume 1, Section III-D-1, same as Item 1.5.1 in Table VIII-1.	D-1.1.2
selection; g.	-	None at this time.	Reexamine if large-scale production becomes likely.	D-2
selection; r.	-	None at this time.	Reexamine if large-scale production becomes likely.	D-2

Table VIII-2 (Concluded)

MATERIALS RESEARCH DEVELOPMENT AND TESTING NEEDED TO SUPPORT THE PRO

Item No.	Process	Fuel Produced	Problem Area	Type of Solution	Materials Problem	Mate:
8.	PARTIALLY OXYGENATED FUELS					
8.1.1	H_2 production.	H_2 intermediate	See Items 1, 2, and 3.	See Items 1, 2, and 3.	See Items 1, 2, and 3.	See Items 1
8.2.1	CO_2 production from the air.	CO_2 intermediate	Advances in compressor and CO_2 adsorption methods.	Engineering design and development. Process development.	None.	None.
8.2.2	CO_2 production from limestone.	CO_2 intermediate	Mining and materials handling (nuclear reactor problems excluded).	Engineering and materials development.	Low-cost materials with high abrasion resistance.	Probably no
8.3.1	Co production.	CO	No existing production process.	Process development; catalyst selection.	Effective, long-life catalyst.	Catalyst dev
8.4.1	Methanol production.	Methanol	None.	-	-	None.
8.5.1	Methanol production (electrolytic).	Methanol	Conceptual process.	Process development; catalyst development.	Electrocatalyst research and development.	Development methanol ele

Table VIII-2 (Concluded)

DEVELOPMENT AND TESTING NEEDED TO SUPPORT THE PRODUCTION OF NEW FUELS

Solution	Materials Problem	Materials R, D, and T Needs	Remarks	Report Reference in Vol. 2 Sect. V
2, and 3.	See Items 1, 2, and 3.	See Items 1, 2, and 3.	H_2 required for production of CO and methanol.	E, A, B,
esign and Process	None.	None.	CO_2 required for production of CO_2 and methanol.	E-1
nd elopment.	Low-cost materials with high abrasion resistance.	Probably none required.	Calcination using nuclear heat. Improved, low-cost abrasion-resistant materials provided by industry development.	E-2
lopment; ction.	Effective, long-life catalyst.	Catalyst development.	Reversed shift reaction.	E-3
	-	None.	Existing technology	E-4.1
lopment; elopment.	Electrocatalyst research and development.	Development of electrocatalysts for methanol electrode.	Materials of construction of plant similar to Item 2.1.	E-4.2

TABLE VIII-3
MATERIALS RESEARCH DEVELOPMENT AND TESTING
NEEDED TO SUPPORT THE TRANSPORTATION OF NEW FUELS

Table VIII-3

MATERIALS RESEARCH DEVELOPMENT AND TESTING NEEDED TO SUPPORT THE TRANSPORT

Item No.	Mode of Transportation	Fuel	Problem Area	Type of Solution	Materials Problem	Mater
1.	EXISTING PIPELINES					
1.1.1	H_2 pipelines.	H_2 gas.	Acceptability of existing pipelines for H_2 transmission and distribution.	Materials testing.	H_2 environment effects over long times on mechanical properties of material and welds of existing pipelines.	Long-term line mater hydrogen a minor quan and illumi from -60° unnotched toughness, static loa
1.1.2				Full-scale pipe testing.	H_2 environment effects over long times on service behavior of existing pipelines.	Full-scale and used p taminated tures and tuating) c service an
1.1.3				Basic research.	Role of surfaces in adsorption and dissociation of H_2.	Study of e sulfide, a on mechani
1.2.1	NH_3 pipelines.	NH_3 liquid.	Acceptability of existing pipelines for transmission and distribution of NH_3.	Materials testing.	Stress corrosion cracking of steels in liquid NH_3.	Long-term new and us in NH_3 as structure stress, no and NH_3 pr
1.2.2				Full-scale pipe testing.	Stress corrosion cracking of steels in liquid NH_3.	Full-scale pipelines NH_3 enviro pressures service an
1.2.3				Basic research.	Stress corrosion cracking of steels in liquid NH_3.	Studies to problem of liquid NH_3
1.3.1	CO pipelines.	CO	Acceptability of existing pipelines for transmission and distribution of CO.	Materials testing.	Possible environmental effects of CO at high pressures for long times on pipeline materials.	Long-term line steel deteriorat properties contaminat
1.4.1	**Menthanol pipelines.**	Methanol.	None.	-	None.	None.
2.	NEW PIPELINES					
2.1.1	H_2 pipelines.	H_2 gas.	Acceptability of new metallic pipeline materials and installations for H_2 service.	Materials testing and selection.	H_2 environment effects over long times on higher strength pipeline steels.	Long-term line steel H_2 contami of O_2, H_2(Test data 160°F on r strength, failure ur fatigue.

Table VIII-3

[DEV]ELOPMENT AND TESTING NEEDED TO SUPPORT THE TRANSPORTATION OF NEW FUELS

Solution	Materials Problem	Materials R, D, and T Needs	Remarks	Report Reference Vol. 2, Sect. VI
testing.	H_2 environment effects over long times on mechanical properties of material and welds of existing pipelines.	Long-term testing of new and used pipeline materials and welds in pure hydrogen and hydrogen contaminated with minor quantities of O_2, H_2O, odorants and illuminants. Test data required from -60° to + 160°F on notched and unnotched tensile strength, fracture toughness, delayed failure under static load and low cycle fatigue.	This data, together with that from Item 1.1.2 will permit drafting of specifications covering safe operation of existing pipelines with H_2 gas.	A-4, A-6
pipe	H_2 environment effects over long times on service behavior of existing pipelines.	Full-scale testing of sections of new and used pipelines in pure and contaminated H_2 environments at temperatures and pressures (steady and fluctuating) corresponding to most severe service and line test conditions.	-	A-4, A-6
arch.	Role of surfaces in adsorption and dissociation of H_2.	Study of effects of surface oxide, sulfide, and other contaminant films on mechanisms of H_2 entry into metals.	-	A-4, A-6
testing.	Stress corrosion cracking of steels in liquid NH_3.	Long-term delayed failure tests of new and used pipeline steels and welds in NH_3 as a function of contaminants, structure and yield strength of steel, stress, notches, flaws, temperature and NH_3 pressure.	Problem especially relevant to higher strength pipelines. Data produced also relevant to Items 2.3.1, 4.2.1 and 4.2.2	D-1.1
pipe	Stress corrosion cracking of steels in liquid NH_3.	Full-scale testing of new and used pipelines in pure and contaminated NH_3 environments at temperatures and pressures corresponding to most severe service and line-test conditions.	-	D-1.1
arch.	Stress corrosion cracking of steels in liquid NH_3.	Studies to define the limits of the problem of the SCC of steels in liquid NH_3.	-	D-1.1
testing.	Possible environmental effects of CO at high pressures for long times on pipeline materials.	Long-term tests of new and used pipeline steels to establish if any deterioration of their mechanical properties can occur in pure or contaminated CO at high pressures.	-	E-1
	None.	None.	-	E-2
testing and	H_2 environment effects over long times on higher strength pipeline steels.	Long-term testing of candidate pipeline steels and welds in pure H_2 and H_2 contaminated with minor quantities of O_2, H_2O, odorants and illuminants. Test data required from -60°F to + 160°F on notched and unnotched tensile strength, fracture toughness, delayed failure under static load and low cycle fatigue.	Extension of programs under Items 1.1.1 to higher strength candidate pipeline steels.	A-5.1, A-5.3, A-6

Table VIII-3 (Continued)

MATERIALS RESEARCH DEVELOPMENT AND TESTING NEEDED TO SUPPORT THE TRANSP

Item No.	Mode of Transportation	Fuel	Problem Area	Type of Solution	Materials Problem	Mate
2.	NEW PIPELINES (Cont.)					
2.1.2	H_2 pipelines. (Continued)	H_2 gas.	Protection of pipeline materials from H_2 environments.	Fabrication development.	Fabrication and assembly of vented-lining type pipe.	Feasibili lining ty assembly.
2.1.3				Materials development, fabrication development.	Development and application of coatings with low H_2 permeability.	Determine steels co etc. Inv mechanica after exp
2.1.4			Nonmetallic pipeline materials.	Materials selelction	Long-term mechanical behavior of plastics and composites in high pressure H_2, H_2O, and saline environments.	Investiga polymers ments ait pressure ments.
2.1.5				Fabrication development.	Costly, slow fabrication. Materials selection.	Develop l methods.
2.2.1	Cryogenic H_2 pipelines.	H_2 liquid.	Piping systems for cryogenic transmission service.	Design and materials engineering.	Materials selection.	Materials neering d
2.2.2			The "Energy Pipe."	Engineering and system design.	Materials availability and economics.	Supportin of techni
2.2.3				Materials research and development.	Improved superconducting alloys and composites.	Not speci
2.3.1	NH_3 pipelines.	NH_3 liquid.	Acceptability of new metallic pipeline materials for transmission and distribution of NH_3.	Materials research and testing.	Stress corrosion cracking of steels in liquid NH_3.	Long-term candidate welds, as
2.4.1	O_2 pipelines.	By-product O_2 gas.	Safe, large-scale, economic pipeline transmission and distribution of O_2.	Materials qualification	Long-term compatibility of low-cost materials of construction with O_2 at high pressures.	Determina pipeline pipe con
2.4.2.				Materials research.	Lack of fundamental knowledge concerning effects of long-term exposure to high pressure O_2 on mechanical behavior of metals.	Studies o sure of m and conta mechanica dition.
2.4.3				Engineering and system design; hazard analysis, economic analysis	-	Supportin aspects o economic
2.5.1	Cryogenic O_2 pipelines.	By-product O_2 liquid.	Safe distribution of liquid O_2 by pipeline.	Materials selection	Compatibility of metals and polymers with liquid O_2.	None.

Table VIII-3 (Continued)

LOPMENT AND TESTING NEEDED TO SUPPORT THE TRANSPORTATION OF NEW FUELS

lution	Materials Problem	Materials R, D, and T Needs	Remarks	Report Reference Vol. 2, Sect. VI
evelop-	Fabrication and assembly of vented-lining type pipe.	Feasibility study of low-cost vented-lining type pipe and methods of assembly.	-	A-5.1, A-5.3, A-6
elopment, evelop-	Development and application of coatings with low H_2 permeability.	Determine rate of entry of H_2 into steels coated with Cd, Pb, Sn, glasses, etc. Investigate deterioration of mechanical properties of coated samples after exposure to H_2.	Exploratory study only.	A-5.1, A-5.3, A-6
elction	Long-term mechanical behavior of plastics and composites in high pressure H_2, H_2O, and saline environments.	Investigate mechanical properties of polymers and glass fiber reinforcements after long term exposure to high pressure H_2, H_2O, and saline environments.	H_2 as internal pipe environment; H_2O, saline as external pipeline environment.	A-5.2, A-5.3,
evelop-	Costly, slow fabrication. Materials selection.	Develop low-cost, rapid fabrication methods.	-	A-5.2
terials	Materials selection.	Materials testing to support engineering development.	Short-distance pipelines only. Some scale-up of state-of-the-art technology.	B-1
nd system	Materials availability and economics.	Supporting studies of materials aspects of technical and economic feasibility.	Concept development will require cooperation between groups concerned with hydrogen fuel and groups concerned with electric power distribution.	B-5, B-6
earch and	Improved superconducting alloys and composites.	Not specifically identified.	-	B-5
earch and	Stress corrosion cracking of steels in liquid NH_3.	Long-term delayed failure tests of candidate new pipeline steels and welds, as for Item 1.2.1.	See Item 1.2.1 Data also relevant to Items 4.2.1 and 4.2.2.	D-1.1
lifica-	Long-term compatibility of low-cost materials of construction with O_2 at high pressures.	Determination of ignition hazards for pipeline steels in actual or simulated pipe configurations.	Large-scale O_2 pipeline system might be important aspect of overall hydrogen economy.	F.
earch.	Lack of fundamental knowledge concerning effects of long-term exposure to high pressure O_2 on mechanical behavior of metals.	Studies of effects of long-term exposure of metals to high-pressure, pure and contaminated O_2 on their mechanical behavior and surface condition.	-	F.
nd system d analysis, ysis	-	Supporting studies of materials aspects of engineering, hazard, and economic evaluations.	-	F.
ection	Compatibility of metals and polymers with liquid O_2.	None.	State-of-the-art technology. Only short distance pipelines likely.	F.

Table VIII-3 (Concluded)

MATERIALS RESEARCH DEVELOPMENT AND TESTING NEEDED TO SUPPORT THE TRANSPOR

Item No.	Mode of Transportation	Fuel	Problem Area	Type of Solution	Materials Problem	Mate
3.	PRESSURE VESSELS					
3.1.1	High pressure H_2 vessels.	H_2 gas.	Higher operating pressures.	Establishment of safe operating practices. Limitation of permissible H_2 pressures.	Effects of H_2 environment on candidate pressure vessel materials.	Determine and low-c candidate taminated pressure.
4.	SURFACE AND AIR TRANSPORTATION					
4.1.1	Barge, railroad car, tank truck.	H_2 liquid.	H_2 losses; cost.	Engineering design and development. Materials development.	Improved insulation.	None.
4.2.1	Various surface.	NH_3 liquid.	Tank materials.	Materials research; materials selection.	Stress-corrosion cracking of quenched and tempered steels in liquid NH_3.	Materials mechanism
4.2.2						Testing of materials
4.3.1	Various surface.	Hydrazine.	Tank materials.	Materials selection.	Corrosion of container materials.	None.
4.3.2					Catalytic decomposition of N_2H_4 by container materials.	None.
4.4.1	Various surface.	Methanol.	None.		None.	None.
4.5.1	Ocean tanker.	H_2 liquid.	Tanker design (liquid H_2 tanks not considered a problem area).	Engineering design.	None.	None.
4.6.1	Air tanker.	H_2 liquid.	Aircraft design optimization.	Engineering design.	-	None.
4.6.2			Liquid H_2 tanks.	Materials selection and design optimization.	High strength, high stiffness, light weight, low thermal conductivity and low thermal expansion materials desirable.	Determine properties for candid at -423°F.
4.7.1	Transfer and delivery systems for use with surface and air tankers.	H_2 liquid.	Heat leaks due to penetration of tank walls by transfer vent lines.	Engineering design; materials development.	Low thermal flux tubing.	Materials support fo programs.
4.8.1	Transportation of hydrogen as metal hydrides	H_2 gas.	Containment vessels.	Materials selection.	H_2 environment effects on container materials.	None.

Table VIII-3 (Concluded)

MENT AND TESTING NEEDED TO SUPPORT THE TRANSPORTATION OF NEW FUELS

tion	Materials Problem	Materials R, D, and T Needs	Remarks	Report Reference Vol. 2, Sect. VI
of safe tices. permis- ures.	Effects of H_2 environments on candidate pressure vessel materials.	Determine threshold stress intensities and low-cycle fatigue properties of candidate materials in pure and contaminated H_2 gas as a function of gas pressure.	For small quantity distribution only.	A-3, A-6
ign and terials	Improved insulation.	None.	Improvements likely to be provided by industry developments.	B-2
rch; ction.	Stress-corrosion cracking of quenched and tempered steels in liquid NH_3.	Materials research to establish mechanism and limiting conditions.	See Vol. 1, Section III-D.1 Overlaps Items 1.2.1	D-1.2
		Testing of candidate SCC resistant materials and welds.	Overlaps Items 1.2.1 and 2.3.1	
ction.	Corrosion of container materials.	None.	Existing technology.	D-2
	Catalytic decomposition of N_2H_4 by container materials.	None.	Existing technology.	D-2
	None.	None.	Standard practice.	E-2
ign.	None.	None.	Low density cargo. Liquid H_2 tanks similar to LNG tanks.	B-2
ign.	-	None.	Low density cargo.	
ction imiza-	High strength, high stiffness, light weight, low thermal conductivity and low thermal expansion materials desirable.	Determine physical and mechanical properties as needed for design for candidate composite materials at −423°F.	-	B-3
ign; lop-	Low thermal flux tubing.	Materials development and testing support for engineering design programs.	-	B-4
ction.	H_2 environment effects on container materials.	None.	Not attractive for H_2 transportation on a large scale.	C

TABLE VIII-4
MATERIALS RESEARCH DEVELOPMENT AND TESTING
NEEDED TO SUPPORT THE STORAGE OF NEW FUELS

Table VIII-4

MATERIALS RESEARCH DEVELOPMENT AND TESTING NEEDED TO SUPPORT THE

Item No.	Type of Storage	Fuel	Problem Area	Type of Solution	Materials Problem	
1.	NATURAL FORMATIONS (Natural or modified)					
1.1.1	Depleted oil or gas reservoirs, aquifers, natural or mined caverns.	H_2, CO gases, and NH_3.	Porosity of formation.	Grouting.	None.	None.
1.2.1	Underwater storage.	H_2, CO gases.	Design and construction.	Engineering design; materials selection.	Materials employed must be resistant to aqueous (or salt water) corrosion and effects of H_2 (or CO) environments.	None
2.	MAN-MADE BULK STORAGE SYSTEMS (GASES)					
2.1.1	Pipelines, capped pipe, welded steel vessels for moderate pressures (≤ 2000 psi).	H_2 gas.	Acceptability of low and medium strength steels for H_2 storage.	Materials testing and selection.	H_2 environment effects over long times on low and medium strength steels.	Long- and w from requi unnot tough stati
2.1.2			Protection of materials of construction from H_2 environments.	Fabrication development.	Fabrication and assembly of vented-lining type vessels.	Devel and a
2.1.3				Materials development, fabrication development.	Development and application of coatings with low H_2 permeability.	Deter steel etc. mech after
2.2.1	Welded alloy vessel for high pressures (> 2000 psi).	H_2 gas.	Acceptability of high-strength alloys for H_2 storage.	Materials testing and selection.	H_2 environment effects over long times on high-strength alloys.	Deter on me high-
2.3.1	Filament-wound fiber-reinforced plastic vessels.	H_2 gas.	Acceptability of high-strength FRP vessels for H_2 storage.	Materials testing.	Long-term mechanical behavior of FRP in high-pressure H_2.	Deter to hi prope
2.3.2				Fabrication development.	Present fabrication methods are expensive, slow, and size-limited.	Devel scale
2.4.1	Lined, fiber-reinforced and/or polymer-impregnated cement vessels.	H_2 gas.	Design and construction.	Engineering development and evaluation; materials testing.	Long-term materials data for design is lacking.	Deter erties compos

Table VIII-4

MENT AND TESTING NEEDED TO SUPPORT THE STORAGE OF NEW FUELS

n	Materials Problem	Materials R, D, and T Needs	Remarks	Report Reference Vol. 2, Section VII
	None.	None.	Practice similar to existing storage of natural gas.	B-1, C-2.1
n; n.	Materials employed must be resistant to aqueous (or salt water) corrosion and effects of H_2 (or CO) environments.	None at this time.	Concept only.	B-1
and	H_2 environment effects over long times on low and medium strength steels.	Long-term testing of candidate steels, and welds in pure and contaminated H_2 from -60°F to +160°F. Test data required includes notched and unnotched tensile strength, fracture toughness, delayed failure under static load, and low-cycle fatigue.	"Line-packing" of transmission pipelines is a standard method of natural gas storage. Data would permit specification of safe design and operating standards.	B-2, B-3
op-	Fabrication and assembly of vented-lining type vessels.	Development of low-cost fabrication and assembly methods.	Vented-lining techniques employed in high pressure, chemical process vessels containing H_2.	B-2, B-3
ent, op-	Development and application of coatings with low H_2 permeability.	Determine rate of entry of H_2 into steels coated with Cd, Pb, Sn, glasses, etc. Investigate deterioration of mechanical properties of coated samples after exposure to H_2.	-	See Section VI-A 5.1
and	H_2 environment effects over long times on high-strength alloys.	Determine effects of high-pressure H_2 on mechanical properties of candidate high-strength alloys and welds.	-	B-2, B-3
.	Long-term mechanical behavior of FRP in high-pressure H_2.	Determine effect of long-term exposure to high-pressure H_2 on mechanical properties of FRP.	-	B-2, B-3
op-	Present fabrication methods are expensive, slow, and size-limited.	Develop low-cost, rapid, and large-scale fabrication methods.	-	B-2, B-3
lopment ater-	Long-term materials data for design is lacking.	Determine long-term mechanical properties of various types of cement composites.	Possible low-cost, large-scale storage vessels.	B-3

Table VIII-4 (Continued)

MATERIALS RESEARCH DEVELOPMENT AND TESTING NEEDED TO SUPPORT THE STORA

Item No.	Type of Storage	Fuel	Problem Area	Type of Solution	Materials Problem	Mate
3.	BULK STORAGE SYSTEMS (LIQUIDS)					
3.1.1	Conventional systems (vacuum jacketed) up to 3 x 10^6 gal.	H_2 liquid.	Tanks and auxiliary equipment.	Materials selection.	None.	None.
3.2.1	Metal or metal-lined concrete tanks > 3 x 10^6 gal.	H_2 liquid.	Design and construction.	Engineering development; materials selection.	None.	None.
3.3.1	Reinforced plastic tanks.	H_2 liquid.	Design and construction.	Engineering and fabrication development.	Present fabrication methods expensive, slow and size-limited.	Develop l scale fab
3.3.2				Materials testing.	Materials data for design at cryogenic temperatures is lacking.	Determina ical prop ites at c
3.3.3				Materials development.	Chill-down stresses would be reduced by low-expansion materials.	Develop a composite trolled o advanced or zero
3.4.1	Fiber reinforced impregnated cement tanks.	H_2 liquid.	Design and construction.	Engineering development and evaluation; materials testing.	Materials data for design at cryogenic temperatures is lacking.	Determina ical prop cements a
3.5.1	All liquid H_2 bulk storage systems.	H_2 liquid.	Insulation materials.	Engineering design and development; materials development.	Improved, low-cost internal and external insulation materials.	Materials engineeri
3.5.2			Auxiliary components.	Materials selection, component testing.	Effects of high-purity H_2 environments on materials.	Test comp at servic
3.6.1	Double wall, perlite insulated steel tanks.	NH_3 liquid.	None using conventional low-strength steel construction.	-	None.	None.
3.6.2			Use of higher strength steels.	Materials research and testing.	Stress corrosion cracking of steels in liquid NH_3.	Materials mechanism steels in
3.6.3						Testing o materials
3.7.1	Methanol bulk storage tanks.	Methanol	None.	-	None	-

Table VIII-4 (Continued)

OPMENT AND TESTING NEEDED TO SUPPORT THE STORAGE OF NEW FUELS

ion	Materials Problem	Materials R, D, and T Needs	Remarks	Report Reference Vol. 2, Sect. VII
ion.	None.	None.	Existing technology.	C-1.1, C-1.5
lop-	None.	None.	Double or single wall construction.	C-1.1, C-1.5
fabri- t.	Present fabrication methods expensive, slow and size-limited.	Develop low-cost, rapid, and large-scale fabrication methods.	Strength requirements not as great as Item 2.3.1.	C-1.1, C-1.5
s.	Materials data for design at cryogenic temperatures is lacking.	Determination of physical and mechanical properties of candidate composites at cryogenic temperatures.	-	C-1.1, C-1.5
ment.	Chill-down stresses would be reduced by low-expansion materials.	Develop and test reinforced polymeric composites and structures with controlled orientation of graphite or advanced organic fibers to give low or zero expansion coefficients.	For smaller tanks. Costs likely to be too high for large vessels.	C-1.1
lop- ion; s.	Materials data for design at cryogenic temperatures is lacking.	Determination of physical and mechanical properties of fiber reinforced cements at cryogenic temperatures.	-	C-1.1, C-1.5
n and rials	Improved, low-cost internal and external insulation materials.	Materials D and T support for engineering development.	-	C-1.4
ion, s.	Effects of high-purity H_2 environments on materials.	Test components in high-purity H_2 at service conditions.	-	C-1.1
	None.	None.	Standard practice.	C-2.1
ch and	Stress corrosion cracking of steels in liquid NH_3.	Materials research to establish mechanism and limits of SCC of steels in liquid NH_3.	See also Vol. 1 Sect. III-D.1 and Vol. 2, Sect. VI-D.1. Same as Item 1.5.1 in Table VIII-1.	C-2.1
		Testing of candidate SCC resistant materials.	-	C-2.1
	None	-	Standard practice.	C-2.2

Table VIII-4 (Continued)

MATERIALS RESEARCH DEVELOPMENT AND TESTING NEEDED TO SUPPORT THE STO

Item No.	Type of Storage	Fuel	Problem Area	Type of Solution	Materials Problem	Mat
4.	SMALL CONTAINER STORAGE--GASES					
4.1.1	FRP vessels.	H_2 gas.	Lighter vessels needed.	Develop and qualify filament-wound reinforced plastic tanks.	Long-term mechanical behavior of FRP in high pressure H_2.	Determir to high erties c
5.	SMALL CONTAINER STORAGE--LIQUIDS					
5.1.1	Vacuum-jacketed tanks.	H_2 liquid.	Low-cost, mass-produced storage tanks.	Design and fabrication development.	None.	Material port for grams.
5.2.1	Insulated tanks.	NH_3 liquid.	Low-cost, mass-produced storage tanks.	Design and fabrication development.	None.	None.
5.3.1	Uninsulated tanks for hydrazine.	Hydrazine.	Very long-term (10 year) storage.	Design, materials development and testing, chemical studies.	Long-term compatibility of metallic and nonmetallic materials with hydrazine.	Developm inert ma
5.4.1	Uninsulated tanks for methanol.	Methanol.	None of significance.	-	None.	None.
6.	AIRCRAFT AND SPACE VEHICLE FUEL TANKS					
6.1.1	All aircraft and space vehicles.	H_2 liquid.	Flight-weight tank design.	Engineering design and development using advanced composites.	Lack of design data for cryogenic temperatures.	Determine properti at cryog
6.1.2				Fabrication and materials development.	Chill-down stresses would be reduced by low-expansion materials.	Develop composite trolled advanced or zero
6.1.3					Adhesive for use in contact with liquid H_2.	Develop -423°F.
6.1.4					Flexible membrane materials for liquid H_2 or H_2 vapor barriers.	Develop materials
6.2.1	Subsonic aircraft	H_2 liquid.	Fuel tank insulation.	Engineering and materials development.	Safe, efficient insulation for temperature range -423°F to -180°F.	Develop a losed-po ermal c ructura +180°F.

Table VIII-4 (Continued)

...CH DEVELOPMENT AND TESTING NEEDED TO SUPPORT THE STORAGE OF NEW FUELS

...f Solution	Materials Problem	Materials R, D, and T Needs	Remarks	Report Reference Vol. 2, Sect. VII
...and qualify ...-wound rein- ...lastic tanks.	Long-term mechanical behavior of FRP in high pressure H_2.	Determine effects of long-term exposure to high pressure H_2 on mechanical properties of FRP.	-	B-2, B-3
...d fabrication ...nt.	None.	Materials development and testing support for engineering development programs.	Essenatial for use of liquid H_2 by vehicles, small boats, portable equipment.	C-1.2
...nd fabrication ...nt.	None.	None.	-	C-2.1
...aterials ...nt and ...chemical	Long-term compatibility of metallic and nonmetallic materials with hydrazine	Development and testing of highly inert materials or coatings.	Short-term small container storage of hydrazine poses no serious problems.	C-2.1
	None.	None.	Corrosion may be a slight problem.	C-2.2
...ing design and ...nt using ...composites.	Lack of design data for cryogenic temperatures.	Determine physical and mechanical properties of candidate composites at cryogenic temperatures.	Storage times required are relatively short.	C-1.3
...ion and ...s develop-	Chill-down stresses would be reduced by low-expansion materials.	Develop and test reinforced polymeric composites and structures with controlled orientation of graphite or advanced organic fibers to give low or zero expansion coefficients.	Same as Item 3.3.3.	C-1.3
	Adhesive for use in contact with liquid H_2.	Develop adhesives for service at -423°F.	-	C-1.3
	Flexible membrane materials for liquid H_2 or H_2 vapor barriers.	Develop high-strength flexible membrane materials for service at -423°F.	-	C-1.3
...ing and ...s development.	Safe, efficient insulation for temperature range -423°F to +180°F.	Develop and test fire-resistant closed-pore foams with very low thermal conductivity and good structural strength from -423°F to +180°F.	Foams may be fiber reinforced.	C-1.3, C-1.4

Table VIII-4 (Continued)

MATERIALS RESEARCH DEVELOPMENT AND TESTING NEEDED TO SUPPORT THE STO

Item No.	Type of Storage	Fuel	Problem Area	Type of Solution	Materials Problem	Mate
6.	AIRCRAFT AND SPACE VEHICLE FUEL TANKS (Concluded)					
6.3.1	Supersonic aircraft.	H_2 liquid.	Fuel tank insulation.	Engineering and materials development.	Hot-face insulation temperature may reach 350°F.	Material neeering
6.4.1	Hypersonic aircraft.	H_2 gas.	Fuel tank insulation.	Engineering and materials development.	Target for insulation operating range is -423°F to +650°F.	Materials neeering c
7.	STORAGE OF NEW FUELS AS SOLIDS					
7.1.1	Storage of hydrogen as metal hydrides.	H_2 gas	Technical and economic feasibility.	Cost/benefit analysis of hydride systems compared with liquid and gaseous H_2, for various storage capacities and applications.	Estimate materials component of system costs.	Assistanc technical study.
7.1.2			Lack of operational experience.	Build, test, and develop engineering prototype systems based on Mg and FeTi.	Not applicable.	Assistanc
7.1.3			Performance improvements.	Materials research and development.	Absorption and desorption kinetics.	Studies c desorptic candidate
7.1.4						Investiga additions systems.
7.1.5					Limited cycle life, especially for deep discharges.	Examine e H_2O, odor life.
7.1.6						Investiga charge re and bed c bed struc
8.	STORAGE OF BY-PRODUCT OXYGEN					
8.1.1	Bulk storage as gas in geological caverns.	By-product O_2 gas	Possible ignition hazards.	Engineering studies.	None	None

Table VIII-4 (Continued)

MENT AND TESTING NEEDED TO SUPPORT THE STORAGE OF NEW FUELS

	Materials Problem	Materials R, D, and T Needs	Remarks	Report Reference Vol. 2, Sect. VII
nt.	Hot-face insulation temperature may reach 350°F.	Materials D and T support to engineering development programs.	-	C-1.3
nt.	Target for insulation operating range is -423°F to +650°F.	Materials D and T support to engineering development programs.	Hot-face insulation temperatures will depend on aircraft or vehicle design.	C-1.3, C-1.4
is d n-	Estimate materials component of system costs.	Assistance in materials aspects of technical and economic feasibility study.	Study needs to be done in depth. Published comparisons are not considered adequate.	D-4
i.	Not applicable.	Assistance and consultation.	One program using FeTi initiated at Brookhaven National Laboratory.	D-4
and	Absorption and desorption kinetics.	Studies of H_2 absorption, storage and desorption characteristics for new candidate systems.	-	D-4
		Investigate effects of minor alloy additions on performance of known systems.	-	D-4
	Limited cycle life, especially for deep discharges.	Examine effects of contaminants (O_2, H_2O, odorants, illuminants) on cycle life.	-	D-4
		Investigate cycle life/depth of discharge relationships for various rates and bed conditions. Develop improved bed structures.	-	D-4
s.	None	None	Analagous to current practice with natural gas.	E

Table VIII-4 (Concluded)

MATERIALS RESEARCH DEVELOPMENT AND TESTING NEEDED TO SUPPORT THE STORAGE OF

Item No.	Type of Storage	Fuel	Problem Area	Type of Solution	Materials Problem	Materials
8.	STORAGE OF BY-PRODUCT OXYGEN					
8.2.1	Bulk storage as gas in man-made systems.	By-product O_2 gas.	Safety of storage vessels.	Materials qualification.	Long-term compatibility of low-cost materials of construction with O_2 at high pressures.	Determination materials of c ditions simula sure.
8.2.2				Materials research.	Lack of fundamental knowledge concerning effects of long-term exposure to high pressure O_2 on mechanical behavior of metals.	Studies of eff sure of metals and contaminat behavior and s
8.2.3				Engineering and system design; hazard analysis; economic analysis.	-	Supporting stu aspects of eng and economic e
8.3.1	Bulk storage as liquid in man-made systems.	By-product O_2 liquid.	Safety of storage vessels.	Materials selection.	Compatibility of metals and other materials with liquid O_2.	None.

Table VIII-4 (Concluded)

WELOPMENT AND TESTING NEEDED TO SUPPORT THE STORAGE OF NEW FUELS

ution	Materials Problem	Materials R, D, and T Needs	Remarks	Report Reference Vol. 2, Sect. VII
lifica-	Long-term compatibility of low-cost materials of construction with O_2 at high pressures.	Determination of ignition hazards for materials of construction under conditions simulating most severe exposure.	-	E
earch.	Lack of fundamental knowledge concerning effects of long-term exposure to high pressure O_2 on mechanical behavior of metals.	Studies of effects of long-term exposure of metals to high pressure pure and contaminated O_2 on their mechanical behavior and surface condition.	-	E
d system d nomic	-	Supporting studies of materials aspects of engineering, hazard, and economic evaluation.	-	E
ection.	Compatibility of metals and other materials with liquid O_2.	None.	Existing technology and practice. Safety standards must be enforced to prevent accidents.	E

CONTENTS

IX RESEARCH RECOMMENDATIONS AND PRIORITIES

CONTENTS (Concluded)

TABLES

IX RESEARCH RECOMMENDATIONS AND PRIORITIES

IX RESEARCH RECOMMENDATIONS AND PRIORITIES

This section collates and reclassifies the materials research, development, and testing needs identified in Tables VIII-1 through VIII-4 into ten major programs as follows:

Table IX-1

Program A: Effects of Hydrogen on Materials

Table IX-2

Program B: Effects of Hydrogen Carriers and Partially Oxygenated Compounds on Materials

Table IX-3

Program C: Effects of Oxygen (By-Product) on Materials

Table IX-4

Program D: High-Temperature Materials Studies

Table IX-5

Program E: Materials for Service at Cryogenic Temperatures

Table IX-6

Program F: Materials for Fuel Cells and Electrolyzers

Table IX-7

Program G: Materials for High Energy Density Batteries

Table IX-8

Program H: Catalysts (Excluding Electrode-Catalysts)

Table IX-9

Program J: Miscellaneous Materials Development and Fabrication

Table IX-10

Program K: Technoeconomic and Engineering Feasibility and Evaluation Studies.

A number of specific projects are described within each major program. The relevance of each project to DoD is estimated and a priority is suggested. The tabular form employed and the significance of the individual table columns are described below.

Project Number (Column 1)

Column 1 lists the project number which consists of the major program letter (A through K) followed by a number that identifies the individual project within the major program.

Project Description (Column 2)

Column 2 gives a project title and a short description of the suggested scope of the study. In some instances the project is divided into subprojects, identified by lower case letters in parentheses, e.g., (a).

Activity Type (Column 3)

Column 3 contains a simple description of the type of activity involved in the performance of the project; for example, "Basic research" or "Materials testing and interpretation."

Fuel (Column 4)

Column 4 lists the fuel or fuels to which the project relates.

Problem Area (Column 5)

Column 5 gives an abbreviated description of the problem area to which the proposed project or subproject relates. A horizontal line running from Column 4 (Fuels) through Column 10 separates the information contained in these columns according to the problem area indicated in Column 5. In some instances, a single project, for example, project A-1 in Table IX-1, is related to several problem areas. In some other cases, individual subprojects are related to separate problem areas; in this instance, the relationship is clarified by the subproject identifying letter given before the problem area description, for example, project A-5(a) and A-5(b) in Table IX-1.

Reference to Section VIII (Columns 6 and 7)

These columns list the table and item numbers of the materials research, development, and testing needs identified in Section VIII that the project or subproject described in Column 2 aims to solve. The relevant textual matter of Sections IV through VII in Volume 2 can be traced using these Section VIII item numbers and table numbers.

Relevance to DoD (Column 8)

This column indicates our judgment of the relevance of the project or subproject to DoD requirements. The relevance is indicated as "high," "moderate." or "low" and reflects the highest degree of relevance among the items listed in Column 7. (These items do, of course, vary in their relevance to DoD even though their solution is provided by the same project or subproject.)

Priority (Column 9)

Column 9 indicates our rating on a scale of 1 (high) to 5 (low) of the priority that should be accorded to the project or subproject in the context of the specific problem area shown in Column 5. A project may be assigned a high priority in relation to one problem area and a low priority in regard to another, since given problem areas will be of varying importance and may require solutions in different time-frames. The listed priority rating is based on a combination of the importance of the problem, the urgency of the need for a solution and the relevance of the problem to the DoD. It must be emphasized that the priority judgments represent our interpretation of the information uncovered during the performance of this study and that new information or changes in DoD policy might necessitate a corresponding update of the priority ratings.

Remarks (Column 10)

Explanatory comments are made in this column either to clarify the relevance or priority ratings in Columns 8 and 9, or to provide additional general information on the problem area or the nature of the project.

IX-A. DISCUSSION OF RESEARCH RECOMMENDATIONS

The suggested materials research, development, and testing projects are briefly described in the following paragraphs under the programs of which they are a part. An overall summary (Section IX-B) discusses the most important materials aspects of the use of new fuels in advanced energy systems.

1. PROGRAM A: EFFECTS OF HYDROGEN ON MATERIALS

In spite of the extensive literature on the effects of hydrogen on metallic materials, this study has shown that there are still serious deficiencies in our knowledge, particularly with regard to the behavior of materials of practical engineering significance under conditions that might be encountered in a hydrogen economy. This is especially true of the use of aerospace materials in hydrogen-fueled aircraft or rockets and of the use of general engineering materials for pipeline transmission and distribution of hydrogen. While the materials requirements for these two application areas are completely different the two cases have in common the fact that the materials employed are used at the highest possible level of performance. This common performance requirement is dictated in the case of aerospace materials by the need to minimize weight in flight structures of all kinds, and, in the case of pipeline materials, is a consequence of economic considerations.

Projects A-1 and A-2 relate to the use of aerospace structural materials in hydrogen environments. These are the materials employed in components extending from on-board fuel tanks through the point where the hydrogen fuel is burned. The materials testing and interpretation work recommended would encompass temperatures ranging from liquid hydrogen temperatures up to 1500°F and to significantly higher temperatures in special cases, such as those that might occur if hydrogen were used to cool the hot components of turbine or rocket engines. Because of the different testing techniques required, the measurement and interpretation of the mechanical properties of aircraft structural materials in hydrogen environments has been divided into two separate projects, projects A-1 and A-2. Project A-1 is related to property measurements from -423°F to 300°F, while project A-2 is related to temperatures from 300°F upwards. For both projects, tests should be conducted both in an inert atmosphere, such as helium, and in hydrogen, to obtain an indication of the property degradation due to the hydrogen environment. Much of this work would extend and continue such programs as those summarized in Table IV-2 (Volume 2). Since it is likely that advanced composite materials with polymeric as well as metallic matrices may be employed over the low and moderately elevated temperature ranges, we believe testing of these materials should be included, since no definitive information appears to exist as to the behavior of this category of materials in hydrogen environments.

The information obtained from the suggested test projects can be employed to determine the critical stresses (or stress intensities) below which the materials can be used safely when exposed to the most severe environmental conditions likely to be encountered in service. However, these design data will be of more value if the mechanisms causing property degradation are fully understood. For this reason, an important part of both projects will be to analyze and interpret the test results in terms of the composition, microstructure, and surface condition of the material, and the details of the test environment.

The effects of hydrogen environments on pipeline materials is the highest priority item under Project A-3: Hydrogen Environment Effects on Engineering Materials. The enormous capital investment in pipeline transmission and distribution systems makes it essential that a conclusive answer be provided to the question of whether or not present-day and future pipeline steels (and welds) are acceptable for use with hydrogen, and if so, what factors of safety should be applied to the design of the system.

Three aspects of the effects of hydrogen on the behavior of aerospace and general engineering materials are worthy of special mention:

- Hydrogen-assisted fatigue cracking.
- The effect of contaminants in the gas on the mechanical behavior of materials in hydrogen environments.
- The role of surface films and surface contaminants on the adsorption and dissociation of hydrogen.

The first two topics have been included in the mechanical properties investigations covered by Projects A-1, A-2, and A-3. The third topic is the subject of a separate project (A-6). The results of this project will have an important bearing on understanding the mechanical behavior of practical materials in hydrogen environments under actual service conditions.

Permeation of hydrogen through metallic and nonmetallic materials is not of general importance; however, the two specific studies shown under A-5 have been included. Project A-5(a) relates to the particular requirements involved in the use of hydrogen as the working fluid for Stirling cycle engines; its importance will depend on the extent of industry and DoD interest in this type of engine.

Project A-5(b) relates to the possible use of protective coatings to prevent the entry of hydrogen into metals. This project should be exploratory in nature, since the possibilities of practical success for such an approach would appear to be limited.

While most interactions of hydrogen with metals are considered as having unfavorable implications, the use of hydrides for storage of hydrogen represents an attractive possibility for utility peak shaving requirements and possibly for the on-board storage of hydrogen fuel for vehicles. Continuation and extension of metal hydride studies under Project A-7 has been assigned a priority rating of 2, but the level of effort should, in our view, depend on the outcome of technoeconomic and prototype studies to determine the potential advantages of this system compared with gaseous or liquid fuel storage.

In addition to the extensive materials testing studies identified under Project A-?, new or existing pipelines cannot be recommended for use with hydrogen until extensive full-scale pipe testing has been safely completed. This activity is identified under Project A-8 and is accorded a priority equal to the associated materials testing studies, as they relate to pipeline materials.

Project A-9 includes various materials development, testing, and consultation activities required to support engineering development and component testing programs in a variety of different problem areas. Since the potential effects of hydrogen on a wide variety of materials may be deleterious to varying degrees it is essential that adequately qualified materials experts are involved at all stages of the engineering design. development, testing, and production of equipment or components exposed to hydrogen environments to ensure maximum reliability and safety of operation.

It is our overall conclusion that the effects of hydrogen on materials will not constitute an insurmountable barrier to the safe and effective use of hydrogen as a fuel for military, industrial, commercial and residential use. However, before hydrogen fuel can be successfully introduced, extensive additional information must be developed. Program A represents a tentative suggestion of the materials research, development, and testing programs required to provide this information.

2. PROGRAM B: EFFECTS OF HYDROGEN CARRIERS AND PARTIALLY OXYGENATED COMPOUNDS ON MATERIALS

The use of the various hydrogen-derived fuels constitutes an alternative to the direct use of hydrogen itself. These alternative fuels are grouped as hydrogen carriers and partially oxygenated compounds. The principal hydrogen carrier is ammonia, with hydrazine second in importance; the hydrogen carriers borane and silane also discussed in Volumes 1 and 2 of this report are not considered of sufficient importance to justify significant research effort at this time. The partially oxygenated compounds carbon monoxide and methanol derived from the hydrogen reduction of nonfossil carbon dioxide are also considered as alternatives to hydrogen fuels. Program B, Table IX-2 summarizes research, development, and testing programs considered necessary to support the use of these alternative fuels.

The choice of ammonia as an alternative fuel poses few serious materials problems, with one important exception: the stress corrosion cracking of steels in liquid ammonia, which now constitutes an unsolved problem important to the transportation of ammonia by tank truck.

The basic research proposed under Project B-1(a) and the materials testing and interpretation investigations proposed under Project B-1(b) are considered of high priority with regard to the transportation of ammonia by pipeline or surface methods. At the present time the actual extent of the phenomenon is not known and investigations to determine the limits of stress corrosion cracking with respect to the steel composition and microstructure, stress level and type of stressing, and the type and concentration of contaminants deliberately or accidentally present in the liquid ammonia should be instituted at an early date. These basic studies should be accompanied by long-term delayed-failure and fatigue tests of presently used and future candidate materials for ammonia pipeline or transportation vessels to select and qualify suitable materials of construction and to define safe materials design criteria. Full-scale testing of pipeline sections would also be necessary before the safety of new or existing pipelines for ammonia transportation could be assured.

Hydrazine is not, in our view, likely to become a major fuel for general use. For most military uses of hydrazine, adequate materials information already exists but additional compatibility studies are required for applications involving the long-time storage of hydrazine for periods of up to ten years. These investigations are included in Project B-3.

Of the partially oxygenated fuels, methanol does not appear to have any deleterious effects of importance on materials, with the exception of the well-known stress corrosion cracking of titanium in methanol environments. The reactions of carbon monoxide with metals at elevated temperatures are well understood and common materials of construction are generally considered to be inert to carbon monoxide at near-ambient temperatures and pressures. However, some uncertainty exists regarding the long-term effects of high-pressure carbon monoxide on the mechanical properties of metals. It is considered advisable to institute a materials testing and interpretation project to establish whether any deterioration of the mechanical properties of metals occurs under these conditions in pure and contaminated carbon monoxide. The priority accorded to this program at the present time is low, although it may be advisable to raise the priority if the general use of carbon monoxide fuel is projected.

Thus, the most important materials research and development projects concerned with the effects of hydrogen carriers and partially oxygenated compounds on materials are those directed towards solving the problem of the stress corrosion cracking of steels in liquid ammonia. We believe that significant support should be accorded these projects at an early date.

3. PROGRAM C: EFFECTS OF OXYGEN (BY-PRODUCT) ON MATERIALS

The mechanical properties of engineering materials are normally measured in air and it is assumed that oxygen environments do not change the property values. However, this assumption has not been adequately substantiated for long-term exposure to high-pressure oxygen when flaws or cracks are present in the material or when it is subjected to high- or low-cycle fatigue. A fundamental project to provide definitive information on this point is therefore suggested as a necessary preliminary to the large-scale use of oxygen and is relevant to the safety of existing systems. Safety considerations have also led us to recommend a study of ignition hazards in oxygen pipelines containing surface cracks or flaws when subjected to rapid stressing, impact, or fatigue. (Project C-2.)

Probably the most important topic for study in connection with the large-scale general distribution and use of by-product oxygen is the question of whether such distribution is, in fact, technically and economically feasible. To arrive at an early judgment of this question, an in-depth engineering system study including hazard analysis and economic analysis is considered desirable.

4. PROGRAM D: HIGH-TEMPERATURE MATERIALS STUDIES

Once the hydrogen fuel reaches the point of combustion, we have assumed that the effects of hydrogen itself on materials are no longer of concern. In some cases, momentary exposure of materials to hydrogen-containing combustion gases may exist where the mixture is momentarily fuel-rich but we consider that such transient situations can generally be neglected.

The principal differences between the combustion of hydrogen and of fossil fuels are the somewhat higher flame temperatures experienced with hydrogen, the different combustion conditions, and the fact that the combustion gases have a higher water content--pure water in the case of hydrogen combustion with oxygen. This last factor is approached from two different viewpoints in projects D-1 and D-2. Project D-1 proposes a fundamental investigation of the kinetics of reaction of candidate gas turbine materials with high water content environments. Silicon nitride and silicon carbide are considered important materials to be examined in this study because of the considerable government support of programs aimed at the use of these ceramics in both large and small gas turbines. In addition to this basic research project we consider it necessary to institute an extensive materials testing and evaluation project to determine the high-temperature mechanical and environment endurance of present and future candidate gas turbine materials in actual or simulated hydrogen/air and hydrogen/oxygen combustion gases. Both of these projects will be important to advanced gas turbine design and development and are therefore considered of high relevance to the Department of Defense and have been accorded a 1 priority. Project D-2 consists essentially of an expansion of existing gas turbine materials programs to include the modified environment due to the change of fuel from hydrocarbon to hydrogen.

If water cooling of high-temperature gas turbine components, or components of oxygen/hydrogen combustion systems, is found to be feasible, the cooling channels will be subjected to high-velocity, high-temperature water which could produce rapid oxidation or corrosion due to the accelerating effect of erosion. Evaluation of this possibility is recommended if water cooling is adopted for high-temperature components.

5. PROGRAM E: MATERIALS FOR SERVICE AT CRYOGENIC TEMPERATURES

Use of liquid hydrogen fuel will involve the extensive use of materials and components at temperatures near -423°F. While considerable data exists on the low-temperature behavior of a wide variety of materials, much of the information does not extend to or below the boiling point of hydrogen. An extensive project of materials property determination and evaluation will be required to support engineering design and development of equipment associated with the use, production, transportation, and storage of liquid hydrogen. These investigations, grouped in Project E-1, will be of moderate to high relevance to DoD and of variable priority according to the specific application. Work related to aircraft liquid hydrogen fuel tanks will be of special concern to DoD and of high priority.

Materials development is recommended in two separate areas in connection with aircraft and space vehicle liquid hydrogen fuel tanks. In the first area (Project E-2), possibilities exist of reducing chill-down stresses in tanks and associated structures by the development of polymeric composite materials with low thermal conductivity and low or zero thermal expansion coefficients. Low thermal expansion coefficients can be obtained by the use of selected and accurately controlled orientations of reinforcing fibers of graphite or advanced organic fibers such as Kevlar 49[R] that have negative coefficients of expansion. While these materials are likely to be expensive, the potential advantages of such materials and structures probably justify significant development work of high priority.

Highly efficient cryogenic insulation systems are of obvious importance in the handling of liquid hydrogen. While significant advances have been made in recent years, there appear to be two areas that would justify further materials development effort. The first area is the development of improved low-cost insulation systems for bulk liquid hydrogen storage (Project E-3). For the second area, insulation systems for aircraft and space vehicle liquid hydrogen tanks, continuation and expansion of existing projects is recommended. Two special requirements exist in this case. The first is for a high degree of fire resistance, and the second, applicable to supersonic and hypersonic aircraft, is that the insulation be able to function with high hot-face temperatures, which may in some instances reach 650°F. Materials support for the engineering development of improved insulation systems for this application is considered of high relevance to DoD and has been assigned a high priority.

6. PROGRAM F: MATERIALS FOR FUEL CELLS AND ELECTROLYZERS

To allow fuel cells to realize their potential for wide application in a nonfossil fuel economy, improved materials will be required for electrocatalysts, electrode structures, and electrolyte matrices. At the present time, it appears that alkaline hydrogen fuel cells (including regenerative types) are the most attractive class of cells for use in a hydrogen-based fuel system and high priorities in the materials research and development have therefore been accorded to programs associated with fuel cells of this type.

Advanced electrolyzers based on fuel-cell technology appear at the present time to have the best potential for reducing the basic cost of hydrogen fuel. In our view, the status of development of thermochemical splitting methods for the production of hydrogen is not yet sufficiently advanced to permit realistic estimates of the cost of hydrogen produced by this method. Since the feasibility and acceptability of a nonfossil hydrogen economy will depend to a large extent on the cost of hydrogen in comparison with the cost of alternative fuels, we believe that the materials-related programs in support of advanced electrolyzer development may constitute the most important scientific and technical effort related to the hydrogen economy.

Because of the close ties between advanced electrolyzer and advanced fuel-cell technology, these two subjects have been included in a common program. Projects F-1 through F-4 are concerned with improvements in electrocatalysts, a critical area for improving the efficiency of both fuel cells and electrolyzers. Projects F-1 and F-2 are principally directed at reducing the capital cost of the fuel cell or electrolyzer systems by lowering the loading of noble metal catalysts required or by developing nonnoble metal catalysts of high activity and durability. Special purpose electrocatalysts included in Project F-4 are generally accorded lower priorities. Project F-3 is concerned with work of general application of both a fundamental and empirical nature. Fundamental studies of electrocatalysts are required to provide a scientific basis for electrocatalyst development. In this connection it should be pointed out that electrocatalyst behavior and the mechanisms of the electrocatalytic process differ markedly from those for general chemical process catalysis.

Problems associated with electrode materials and electrode structures and with the matrix or diaphragm materials are the subject of the investigations listed in Projects F-5 and F-6. The highest priority in these two projects is accorded to efforts to increase the operating temperature of alkaline fuel cells and alkaline electrolyzer systems, since in both cases higher temperature operation would result in increased efficiency.

Project F-7 involves additional basic materials research and materials development studies associated with the ionic behavior of solids. Project F-7(a) is directed at uncovering inorganic solids that have good ionic conducting properties at moderate temperatures. A significant breakthrough in this area could result in a reduced operating temperature for inorganic solid electrolyte fuel cells and electrolyzers, and by so doing, increase their efficiency and reduce the general materials problems of high-temperature operation. Research concerned with ion-conducting behavior in solid polymeric materials could make important contributions to increasing the efficiency and reducing the cost of the attractive solid polymer electrolyte electrolyzer systems. Among the general materials problems associated with the construction of fuel cells and electrolyzers, the most important is concerned with the frame materials for alkaline electrolyzers. The presently used material, polysulphone is limited to 150°C operation. If higher temperature operation is to be obtained, improvements in the frame materials must accompany other advances in the technology.

The materials research and development associated with fuel cells and electrolyzers generally is of such a nature that it must be conducted in close collaboration with the electrochemical and engineering research and development activities. We suggest this consideration should be borne in mind in the planning and funding of materials research, development, and testing programs associated with fuel cell and electrolyzer development.

7. PROGRAM G: MATERIALS FOR HIGH ENERGY D. SITY BATTERIES

High energy density batteries are generally a topic of high or moderate relevance to the Department of Defense since portable power supplies are an essential requirement in almost all defense systems. Our review of this area clearly indicates that materials problems encountered in the development of a battery system are highly specific to the particular combination of electrodes and electrolyte involved in that system. Solutions developed to materials problems for one battery system are unlikely to apply to other systems because of the different environmental compatibility requirements. As a consequence, we believe that the materials research and development projects included under Program G should be undertaken as an integral part of battery development programs rather than as independent, materials-oriented studies. A possible exception to this generalization is Project G-2, in which studies of the ion-conducting behavior of solids are proposed. This work bears a close relationship to similar topics proposed in

Program F (Materials for Fuel Cells and Electrolyzers) and some combination of the research effort in these topics would be possible and advantageous.

8. PROGRAM H: CATALYSTS (EXCLUDING ELECTROCATALYSTS)

Three projects have been identified in the area of catalysis. The first of these relates to a specific DoD requirement for very long life catalysts for the catalytic decomposition of hydrazine within small monopropellant rocket engines.

The second group of catalyst research and development studies is associated with the catalytic combustion of new fuels (Project H-2). Catalytic combustion offers a highly efficient low-temperature heat source for space and water heating. Moderate priority is accorded to work associated with fundamental and developmental studies of the catalytic combustion of hydrogen, while relatively low priorities are given to the catalytic combustion of ammonia or other alternative new fuels.

The third project in this program is related to the possible use of methanol or carbon monoxide as alternative new fuels. In either case, the production of carbon monoxide by the hydrogen reduction of nonfossil carbon dioxide is necessary and is accomplished by the reversed shift reaction. Although this reaction is well known, it has not been of commercial significance as has the forward shift reaction, which results in the formation of hydrogen from carbon monoxide and water. If carbon monoxide and/or methanol become adopted as general purpose fuels, the development of catalysts to improve process efficiencies will be highly desirable. A low priority is accorded to this project in relation to the production of carbon monoxide (and not methanol) as a general fuel, while a higher priority is associated with the production of methanol, which we regard as a more likely fuel, particularly for vehicle use.

9. PROGRAM J: MISCELLANEOUS MATERIALS DEVELOPMENT AND FABRICATION

In this program we have collected various materials development and fabrication projects not covered (or not covered completely) in other programs.

Because of its important relation to advanced gas turbines systems and rocket engine development, Project J-1,consisting of materials support for the development of advanced cooling systems,is accorded a high priority and is considered highly relevant to DoD.

Project J-2, the development of fiber-reinforced cement and concretes,is a project of wide general applicability. These materials may offer a significant alternative to large-scale steel construction for pressure vessels and storage tanks.

Vented-lining construction of high-pressure process vessels for hydrogen service has been adopted in the process industry to provide protection for the steel pressure shell by the use of a thin hydrogen-resistant lining material. This type of construction is too expensive for general use but it is possible that low-cost manufacturing and assembly methods for such items as line pipe and plate for storage tanks might be feasible. Project J-3 is therefore suggested as an exploratory manufacturing development study program that could make possible the use of highly efficient high-strength steel structures in hydrogen environments.

Project J-4 includes three development studies related to the use of fiber-reinforced composites for a variety of large and small pipe and tankage applications. Project J-4(c), also listed in Program E, is accorded the highest priority in view of its relevance to DoD in relation to aircraft and space vehicle liquid hydrogen fuel tanks.

Project J-5 is a small project of significance with regard to moving components operating in hydrogen environments and is particularly related to hydrogen compressors and hydrogen pumps. The relatively low priority accorded this project could be increased if engineering experience indicates a higher level of need.

10. PROGRAM K: TECHNOECONOMIC AND ENGINEERING FEASIBILITY AND EVALUATION STUDIES

In the performance of this study, we have uncovered three areas in which we feel necessary policy or strategy judgments require extensive technoeconomic or engineering feasibility and evaluation studies and analyses. The first of these, accorded the highest priority, relates to the production of hydrogen by electrolytic methods and to the large-scale use of fuel cells. The large-scale manufacture of these types of equipment will introduce new requirements for specialty polymers and ceramics, and noble and nonnoble electrocatalysts. Of particular concern is the possible need for vast quantities of platinum, far in excess of current usage or production. Questions of materials availability are likely to be critical in policy decisions relating to competing fuel cell and electrolyzer technologies and to general defense materials requirements. Project K-1 is therefore considered highly relevant to DoD and has been accorded a priority of 1.

The second project suggested relates to the use of by-product oxygen. A critical element in judgments as to the desirability of distributing and using the oxygen produced as a by-product of hydrogen production processes as compared with venting it and burning the hydrogen fuel with air will be the feasibility and cost of the general transmission and distribution of by-product oxygen. Project K-2 is therefore regarded as a necessary preliminary step before significant funding is committed to development or engineering expenditures in this area. Project K-3 is more specific in nature and proposes a cost/benefit analysis of hydride systems compared with liquid and gaseous hydrogen storage for various applications, including peak shaving and vehicle uses. It is considered that adequate in-depth comparisons have not been made in this area and are needed before a definitive judgment as to the economic viability of hydride storage systems can be made.

IX-B. MATERIALS REQUIREMENTS FOR ADVANCED ENERGY SYSTEMS--NEW FUELS; SUMMARY AND OVERVIEW

This study sought to identify materials-critical aspects of the use, production, transportation, and storage of new fuels derived from nonfossil sources. Hydrogen was the principal new fuel studied; hydrogen-derived fuels considered were ammonia, hydrazine, boranes, silanes, carbon monoxide, and methyl alcohol. The materials implications of the use, transportation, and storage of oxygen (produced as a by-product in hydrogen generation) and of the use of active metals in batteries were also examined during the study. Previous volumes of this report are concerned with:

Volume 1: Interactions of Materials with New Fuels

Volume 2: Materials Aspects of the Use, Production, Transportation, and Storage of New Fuels

In this volume (Volume 3), the results of the study have been correlated and analyzed in Section VIII, while Section IX provides a listing of ten major research development and testing program areas within each of which specific projects are described. The relevance of these projects to DoD is noted and a judgment is given of their relative priorities in the context of the problem area to which they are related.

Of the four program areas--use, production, transportation, and storage--the materials requirements related to hydrogen production are probably the most important, since the viability of a hydrogen fuel economy depends above all on our ability to produce hydrogen with the most efficient use of energy and at the lowest possible cost. At the present time, the production of hydrogen by the thermochemical splitting of water is not at a sufficiently advanced stage to permit any clear assessment of its competitive status. It is therefore considered that the electrolysis of water is the most likely route by which hydrogen can be produced in the quantities required, and it is in this area that we believe a major research and development effort should be concentrated. The efficiency of electrolyzer systems is highly dependent on advances in electrocatalyst materials, materials for electrode structures and electrolyte matrices, and electrolyte materials.

The second question of key importance to the implementation of a hydrogen economy is whether hydrogen can be transported safely and economically in pipelines constructed of low-cost, readily available materials. This judgment will depend on definitive technical information that does not now exist. An extensive program of materials testing and research should therefore be implemented at an early date on a scale sufficient to ensure that the necessary information is available when needed.

The use of hydrogen as a fuel in a wide variety of equipment does not appear to pose any insurmountable obstacles, although extensive materials research, development, and testing programs will be required to ensure maximum safety, reliability, and efficiency in hydrogen-using equipment. It is in the area of use that materials projects of highest relevance to DoD are found. Problem areas of particular importance to DoD requiring materials support include the use of hydrogen as an aircraft fuel, the further development of fuel cells for the direct conversion of hydrogen fuel to electrical energy, and the use of active metals in high energy density batteries.

Materials problems related to the storage of hydrogen and of the other new fuels do not appear to be a pacing factor. In this area, items of highest relevance to DoD are concerned with the on-board storage of liquid-hydrogen fuels in aircraft.

Among the alternative fuels, ammonia poses some problems in the area of transportation and storage that require materials research and testing. The economic production of methanol from nonfossil sources may present difficulties but this fuel appears otherwise attractive, particularly for vehicle use and presents no major materials problems.

In conclusion, we are confident that the materials requirements for advanced energy systems based on new fuels can be satisfied by a program of materials research, development, and testing of the type outlined in tabular form in this section of the report, coupled with the diligent and careful use of existing materials information.

Table IX-1

PROGRAM A: EFFECTS OF H_2 ON MATERIALS

Project No.	Project Description	Activity Type	Relates to: Fuel	Relates to: Problem Area	Reference to Section VIII: Table No.	Reference to Section VIII: Item No.	Rele to
A-1	Degradation of Mechanical Properties of Aerospace Structural Materials in Hydrogen Environments; -423°F to 300°F Properties: tensile, notched tensile, high- and low-cycle fatigue, fracture toughness, crack growth, delayed failure. Materials: Al-alloys, stainless steels, nickel- and cobalt-base alloys, brazing alloys, Ti-alloys, advanced composites, polymers, reinforced plastics. Variables: temperature, H_2 pressure, contaminants, exposure time, strain rate, stress level, stress intensity, material composition and microstructure, welds.	Materials testing and interpretation.	H_2	Fuel supply and heat exchanger/gasifier for all types of H_2-burning gas turbines, hypersonic aircraft and rocket engines.	1	1.2.1 1.3.1 1.4.1 2.1.1	Hig
			H	H_2 expansion turbines for aircraft and rocket fuel pumps.	1	1.3.1	Hig
			H_2	H_2-cooled turbine components.	1	1.2.6	Mod
			H_2	Stirling Cycle engines.	1	6.3.1	Mod
			H_2	Compressor components.	2	1.1.1	Low
			H_2	Pressure vessels.	3 4	3.1.1 2.2.1 2.3.1	Hig
			H_2	Aircraft and space vehicle fuel tanks, air tanker.	3 4	4.6.2 6.1.1	Hig
A-2	Degradation of Mechanical Properties of Aerospace Structural Materials in Hydrogen Environments; 300°F to 1500°F With Extension to Higher Temperatures if Required. Properties: tensile, notched tensile, high- and low-cycle fatigue, fracture toughness (where applicable) crack growth, delayed failure, creep. Materials: Al-alloys, stainless steels, nickel- and cobalt-base alloys, Cb-alloys, brazing alloys, Ti-alloys, Si_3N_4, SiC, advanced composites, polymers. Variables: temperature, H_2 pressure, contaminants, exposure time, strain rate, stress level, stress intensity, material composition and microstructure, welds.	Materials testing and interpretation.	H_2	Fuel supply and heat exchanger/gasifier for all types of H_2-burning gas turbines, hypersonic aircraft, and rocket engines.	1	1.2.1 1.2.6 1.3.1 1.4.1 2.1.1 3.1.1	Hig
			H_2	H_2 expansion turbines for aircraft and rocket fuel pumps.	1	1.3.1 3.1.1	Hig
			H_2	Stirling cycle engines.	1	6.3.1	Mod

Table IX-1

PROGRAM A: EFFECTS OF H_2 ON MATERIALS

Relates to: Fuel	Relates to: Problem Area	Reference to Section VIII: Table No.	Reference to Section VIII: Item No.	Relevance to DoD	Priority	Remarks
H_2	Fuel supply and heat exchanger/gasifier for all types of H_2-burning gas turbines, hypersonic aircraft and rocket engines.	1	1.2.1 1.3.1 1.4.1 2.1.1	High	1, 2	Continuation and extension of existing programs. See Vol. 1 Section III for review of current status, and Vol. 2, Tables IV-2, IV-3. Priority 1 for hypersonic aircraft, space vehicles; priority 2 for H_2-burning supersonic and subsonic aircraft.
H_2	H_2 expansion turbines for aircraft and rocket fuel pumps.	1	1.3.1	High	1, 3	Necessary data for safe engine operation. Priority 1 for rocket engine fuel pump drive turbines. Priority 3 for H_2 expansion aircraft engines.
H_2	H_2-cooled turbine components.	1	1.2.6	Moderate	5	Long-term engine development.
H_2	Stirling Cycle engines.	1	6.3.1	Moderate	Uncertain	Depends on DoD vehicle and small engine policy. High industry interest.
H_2	Compressor components.	2	4.1.1	Low	5	Likely to be industry activity, but may become of higher DoD relevance and priority if energy depot concepts pursued.
H_2	Pressure vessels.	3 4	3.1.1 2.2.1 2.3.1	High	1	Needed to establish safety standards.
H_2	Aircraft and space vehicle fuel tanks, air tanker.	3 4	4.6.2 6.1.1	High	1, 2	Priority 1 for hypersonic aircraft, space vehicles; priority 2 for H_2-burning supersonic and subsonic aircraft engines.
H_2	Fuel supply and heat exchanger/gasifier for all types of H_2-burning gas turbines, hypersonic aircraft, and rocket engines.	1	1.2.1 1.2.6 1.3.1 1.4.1 2.1.1 3.1.1	High	1, 2	Priority 1 for hypersonic aircraft, space vehicles; priority 2 for H_2-burning supersonic and subsonic aircraft engines.
H_2	H_2 expansion turbines for aircraft and rocket fuel pumps.	1	1.3.1 3.1.1	High	1, 3	Necessary data for safe engine operation. Priority 1 for rocket engine fuel pump drive turbines, priority 3 for H_2 expansion aircraft engines.
H_2	Stirling cycle engines.	1	6.3.1	Moderate	Uncertain	Relevance and priority depend on DoD vehicle and small engine policy. High industry interest.

Table IX-1 (Continued)

PROGRAM A: EFFECTS OF H_2 ON MATERIALS

Project No.	Project Description	Activity Type	Relates to: Fuel	Relates to: Problem Area	Reference to Section VIII: Table No.	Reference to Section VIII: Item No.	R
A-3	Hydrogen Environment Effects on General Engineering Materials, -60°F to +160°F with extension to higher temperatures for some applications. Properties: tensile, notched tensile, high- and low-cycle fatigue, fracture toughness, crack growth, delayed failure. Materials: low- and medium-strength steels, plastics, reinforced plastics, fiber-reinforced cements. Variables: temperature, H_2 pressure, contaminants, exposure time, strain rate, stress level, stress intensity, material composition and microstructure, welds.	Materials testing and interpretation.	H_2	Fuel supply systems for industrial commercial, and residential equipment, I.C. and E.C. engines.	1	1.1.1 5.1.1 6.1.1 6.2.1 7.1.1	M
			H_2	Process and ancillary equipment.	2 4	2.5.2 3.1.1 4.1.1 5.1.1 5.1.3 5.1.4 3.5.2	Lo
			H_2	Materials of existing pipelines.	3	1.1.1	In
			H_2	Steels for new pipelines.	3	2.1.1	In
			H_2	Candidate nonmetallic pipeline materials.	3	2.1.4	In
			H_2	Hydride containers.	3	4.8.1	Mo
			H_2	Large and small pressure vessels (metal).	3 4	3.1.1 2.1.1 2.2.1	Mo
			H_2	Large and small pressure vessels and tanks (reinforced plastics).	4	2.3.1 4.1.1	Mo
A-4	Hydrogen Permeability Studies: (a) Of high temperature alloys and permeation-resistant coatings up to 1500°F and 5000 psi. (b) Of coatings of Cd, Pb, Sn, glasses etc. at -60°F to +160°F and 1000 to 3000-psi H_2.	Materials research and development.	H_2	(a) Stirling cycle engines.	1	6.3.2 6.3.3	Mo
			H_2	(b) Transportation and storage of H_2 gas.	3 4	2.1.3 2.1.3	Lo
A-5	Role of Surfaces in Adsorption and Dissociation of Hydrogen. Study of the effects of surface oxides, sulphides and other contaminant films on the mechanisms of hydrogen entry into metals.	Fundamental research.	H_2	Use of H_2 in existing pipelines.	3	1.1.3	Lo

Table IX-1 (Continued)

PROGRAM A: EFFECTS OF H_2 ON MATERIALS

	Relates to:		Reference to Section VIII				
Activity Type	Fuel	Problem Area	Table No.	Item No.	Relevance to DoD	Priority	Remarks
rials testing interpretation.	H_2	Fuel supply systems for industrial commercial, and residential equipment, I.C. and E.C. engines.	1	1.1.1 5.1.1 6.1.1 6.2.1 7.1.1	Moderate	4	Adequate materials can probably be selected for most case: on the basis of available knowledge.
	H_2	Process and ancillary equipment.	2 4	2.5.2 3.1.1 4.1.1 5.1.1 5.1.3 5.1.4 3.5.2	Low	3	Materials for some process equipment may require testing at temperatures above 160°F or below -60°F. In most case: adequate materials can be selected on the bases of vailal knowledge.
	H_2	Materials of existing pipelines.	3	1.1.1	Indirect	1	Indirectly relevant to DoD, but very important to the general introduction of H_2 fuel system.
	H_2	Steels for new pipelines.	3	2.1.1	Indirect	1	Indirectly relevent to DoD, but very important to the general introduction of H_2 fuel system.
	H_2	Candidate nonmetallic pipeline materials.	3	2.1.4	Indirect	4	Long-term pipeline development.
	H_2	Hydride containers.	3	4.8.1	Moderate	4	Adequate materials can probably be selected on the basis of available knowledge.
	H_2	Large and small pressure vessels (metal).	3 4	3.1.1 2.1.1 2.2.1	Moderate	2	Higher strength materials will need careful screening for use at high pressures. Needed to establish safety standards.
	H_2	Large and small pressure vessels and tanks (reinforced plastics).	4	2.3.1 4.1.1	Moderate	2, 4	Priority 2 for small high-pressure containers for DoD nee((will be relevant to other gases). Priority 4 for large industrial vessels. Latter will probably be done by industry.
ials research velopment.	H_2	(a) Stirling cycle engines.	1	6.3.2 6.3.3	Moderate	Uncertain	Depends on DoD vehicle and small engine policy. High industry interest.
	H_2	(b) Transportation and storage of H_2 gas.	3 4	2.1.3 2.1.3	Low	4	Exploratory study only. If successful, study should be expanded and priority raised.
ental rch.	H_2	Use of H_2 in existing pipelines,	3	1.1.3	Low	1	Previous studies of H_2 entry into metals have used clean (or nominally clean) surfaces. In order to obtain result: relevant to practical systems, it is necessary to obtain an understanding of the effects of surface films on H_2 adsorption, dissociation and absorption. This work is particularly applicable to the use of H_2 in existing pipelines but would obviously have wide general applicability and importance.

Table IX-1 (Concluded)

PROGRAM A: EFFECTS OF H_2 ON MATERIALS

Project No.	Project Description	Activity Type	Relates to: Fuel	Relates to: Problem Area	Reference to Section VIII: Table No.	Reference to Section VIII: Item No.	Rc
A-6	Metal Hydride Studies (a) Studies of H_2 adsorption and desorption kinetics for candidate new alloying systems and modifications of existing systems. (b) Studies of cycle life of H_2 storage beds as a function of: rates and depth of discharge; design, structure and condition of bed; contaminants in the H_2.	Materials research and development.	H_2	Medium-scale and small-scale storage of H_2.	4	7.1.3 7.1.4 7.1.5 7.1.6	Mo
A-7	Full-Scale Testing of Pipes with Hydrogen (a) Sections of new and used pipes (including girth welds), typical of existing pipelines, API 5LX Grades 42 to 70, pressurized with pure and contaminated H_2 at temperatures and pressures (both steady and fluctuating) corresponding to the most severe service or line-test conditions. Detailed examination and comparison of pipe and weld materials before and after H_2 exposure.	Full-scale materials engineering testing and interpretation.	H_2	(a) Safety of pipeline transportation of H_2 in existing pipelines.	3	1.1.2	In
	(b) Extension of test series to candidate new high strength pipe materials.		H_2	(b) Specification of new pipelines for H_2 use.	3	2.1.1	In
A-8	General Materials Support to Engineering Development and Component Testing Programs. Testing of equipment, components, required to operate in H_2 environments under actual or simulated conditions corresponding to most severe service. Examination of exposed and failed components. Materials selection and consultation. Specialized materials development programs.	Materials testing and evaluation; special materials development.	H_2	Fuel supply systems.	1	1.1 2 1.2.1 1.3.1 2.1.1 3.1.1 4.1.1 5.1.1 5.2.1 5.2.2 6.1.1 6.2.1 7.1.1 7.3.1 8.11.2	Va
			H_2	Other H_2 using equipment.	1	1.3.1 2.1.1 3.1.1 6.3.1	Va
			H_2	Process equipment.	2	2.3.2 2.5.2 3.1.1 4.1.1 5.1.1 5.1.4	Va
			H_2	Transportation systems.	3	2.2.1 4.7.1 4.8.13	Va
			H_2	Storage systems.	4	1.2.1 3.5.1 3.5.2 5.1.1 7.1.1 7.1.2	Va

Table IX-1 (Concluded)

PROGRAM A: EFFECTS OF H_2 ON MATERIALS

ivity ype	Relates to: Fuel	Problem Area	Reference to Section VIII Table No.	Item No.	Relevance to DoD	Priority	Remarks
ls research elopment.	H_2	Medium-scale and small-scale storage of H_2.	4	7.1.3 7.1.4 7.1.5 7.1.6	Moderate	2	Applicable to utility peak shaving requirements and the on-board storage of H_2 for vehicles. Continuation and extension of existing programs. Level of effort should depend on outcome of technoeconomic and prototype studies (items 7.1.1 and 7.1.2 in Table VIII-4).
le mater- gineering and inter- on.	H_2	(a) Safety of pipeline transportation of H_2 in existing pipelines.	3	1.1.2	Indirect	1	Full-scale pipe testing under practical operating conditions is needed in addition to materials testing (Project A-3) determine safety of existing pipelines for use with H_2.
	H_2	(b) Specification of new pipelines for H_2 use.	3	2.1.1	Indirect	1	Required if new pipelines are to be qualified for H_2 use.
s testing uation; materials ont.	H_2	Fuel supply systems.	1	1.1.2 1.2.1 1.3.1 2.1.1 3.1.1 4.1.1 5.1.1 5.2.1 5.2.2 6.1.1 6.2.1 7.1.1 7.3.1 8.11.2	Variable	Variable	In all programs concerned with the development of engineering or manufacturing systems using, producing, transporting, or storing hydrogen, it is imperative that adequate materials expertise is available to and used by the engineering staff in order to ensure that costly errors in materials selection and use will not imperil the safety or reliability of the equipment.
	H_2	Other H_2 using equipment.	1	1.3.1 2.1.1 3.1.1 6.3.1	Variable	Variable	As above.
	H_2	Process equipment.	2	2.3.2 2.5.2 3.1.1 4.1.1 5.1.1 5.1.4	Variable	Variable	As above.
	H_2	Transportation systems.	3	2.2.1 4.7.1 4.8.13	Variable	Variable	As above.
	H_2	Storage systems.	4	1.2.1 3.5.1 3.5.2 5.1.1 7.1.1 7.1.2	Variable	Variable	As above.

Table IX-2

PROGRAM B: EFFECTS OF HYDROGEN CARRIERS AND PARTIALLY OXYGENATED COMP

Project No.	Project Description	Activity Type	Relates to: Fuel	Relates to: Problem Area	Reference to Section VIII: Table No	Reference to Section VIII: Item No	Re t
B-1	Stress Corrosion Cracking of Steels in Liquid Ammonia. (a) Establish the limits of the phenomenon with respect to steel composition and microstructure; stress level and type of stressing; contaminant type and concentration.	Basic research.	NH_3	Fuel supply systems for NH_3-fueled equipment.	1	1.5.1	Un
	(b) Long-term delayed fatigue and fatigue tests of presently used and candidate materials for NH_3 pipelines, storage tanks and fuel supply systems as a function of contaminants; steel type composition and heat treatment; stress level; stress intensity; temperature; NH_3 pressure.	Materials testing and interpretation.	NH_3	NH_3 transportation	3	1.2.1 1.2.3 2.3.1 4.2.1 4.2.2	Un
			NH_3	NH_3 storage.	2 4	5.1.5 3.6.2 3.6.3	Un
B-2	Full-Scale Testing of Pipes with Liquid Ammonia (a) Testing of sections of new and used pipe including girth welds, API 5LX Grades 42 to 70, pressurized with pure and contaminated NH_3 at temperatures and pressures (both steady and fluctuating) corresponding to the most severe service or line-test conditions. (b) Extension of test series to candidate new high strength pipe materials; and transportation or storage tank materials.	Full-scale materials engineering testing and interpretation	NH_3	(a) Safety of pipeline transportation of liquid NH_3 in existing pipelines.	3	1.2.2	Low
			NH_3	(b) Specification of pipelines, transportation and storage tanks for liquid-NH_3 use.	3 4	2.3.1 4.2.2 3.6.3	Low um
B-3	Hydrazine Compatibility Studies. Development and testing of highly inert materials or coatings for storage of hydrazine for periods up to 10 years. Long-term compatibility of elastomeric materials for seals, expulsion bladders, diaphragms and hoses.	Materials development and testing chemical studies, design.	N_2H_4	Long term storage of hydrazine	4	5.3.1	Mod to
B-4	Carbon Monoxide/Metal Interactions at High Pressures. Tensile, notched tensile, and fatigue tests of new and used pipeline steels after long-term exposure to high-pressure pure and contaminated CO to establish if any deterioration of their mechanical properties occurs.	Materials testing and interpretation	CO	Materials of existing pipelines	3	[illegible]	Low

Table IX-2

EFFECTS OF HYDROGEN CARRIERS AND PARTIALLY OXYGENATED COMPOUNDS ON MATERIALS

…y	Relates to: Fuel	Relates to: Problem Area	Reference to Section VIII: Table No	Reference to Section VIII: Item No	Relevance to DoD	Priority	Remarks
…arch.	NH_3	Fuel supply systems for NH_3-fueled equipment.	1	1.5.1	Uncertain	5	Relevance to DoD depends on decisions concerning energy depot concept and choice of fuel. Priority would be raised if NH_3 selected for DoD use or as general civilian fuel.
…testing …reta-	NH_3	NH_3 transportation.	3	1.2.1 1.2.3 2.3.1 4.2. 4.2.:	Uncertain	1	Existing unsolved problems of importance to DoT and industry. Will be important for any general use of NH_3 as a fuel.
	NH_3	NH_3 storage.	2 4	5.1.5 3.6.2 3.6.3	Uncertain	4	Priority would be raised if higher strength steels were needed [illegible] storage vessels.
…engi- …sting …reta-	NH_3	(a) Safety of pipeline transportation of liquid NH_3 in existing pipelines.	3	1 2 2	Low	3	Also needed to assure safety of NH_3 pipelines for nonfuel uses, and set maximum operating conditions. Priority based on this need.
	NH_3	(b) Specification of pipelines, transportation and storage tanks for liquid-NH_3 use.	3 4	2.3.1 4.2.2 3.6.3	Low or uncertain	5	Choice of materials will depend on results from project B-1
…develop- …sting; …tudies.	N_2H_4	Long term storage of hydrazine.	4	5.3.1	Moderate to high	Uncertain	Compatibility of materials with hydrazine is more limited by effects of materials on the decomposition of hydrazine than by the effects of hydrazine on the materials.
…testing …reta-	CO	Materials of existing pipelines.	3	1.3.1	Low	5	Priority will increase if general use of CO fuel is projected. Work should be extended to new pipeline materials if any deterioration of properties of existing pipeline steels is discovered.

Table IX-3

PROGRAM C: EFFECTS OF OXYGEN (BY-PRODUCT) ON MATERIA

Project No	Project Description	Activity Type	Relates to: Fuel	Relates to: Problem Area	Reference to Section VIII: Table No.	Reference to Section VIII: Item No.	Rel to
C-1	Mechanical Properties of Metals in High-Pressure Oxygen. Studies of the effects of long-term exposure of metals to high-pressure pure and contaminated O_2 on their mechanical behavior and surface condition. Mechanical tests should include crack-growth rates and high- and low-cycle fatigue.	Materials research.	O_2	Oxygen pipelines and storage vessels.	3	2.4.2	Moc to
C-2	Ignition Hazards in Oxygen Pipelines. Determination of ignition hazards for pipeline steels in actual or simulated pipe configurations and containing surface cracks or flaws, when subjected to high stress rates, impact, or fatigue in the presence of high-pressure pure or contaminated O_2.	Materials engineering, testing and evaluation.	O_2	Safety of oxygen pipelines and storage vessels.	3	2.4.1 8.2.1	Moc to
C-3	Materials Support for Engineering Studies. Supporting studies of materials aspects of engineering and system design, hazard analysis, economic analysis.	Materials consultation.	O_2	Feasibility of large-scale O_2 transportation.	1 3 4	1.4.2 2.4.3 2.5.1 8.2.3 8.3.1	Mod low

Table IX-3

PROGRAM C: EFFECTS OF OXYGEN (BY-PRODUCT) ON MATERIALS

ity	Relates to		Reference to Section VIII		Relevance to DoD	Priority	Remarks
	Fuel	Problem Area	Table No.	Item No.			
s research.	O_2	Oxygen pipelines and storage vessels.	3	2.4.2	Moderate to low	3	Apparent lack of fundamental knowledge concerning possible effects of long-term exposure of metals to high-pressure oxygen. Relevant to existing as well as projected oxygen usage. Priority based on existing and future usage.
s engi- testing uation.	O_2	Safety of oxygen pipelines and storage vessels.	3	2.4.1 8.2.1	Moderate to low	3	Needed to confirm safety of O_2 transportation and storage systems. Relevant to existing as well as projected oxygen usage. Priority based on existing and future usage.
s con- n.	O_2	Feasibility of large-scale O_2 transportation.	1 3 4	1.4.2 2.4.3 2.5.1 8.2.3 8.3.1	Moderate to low	2	Large-scale O_2 pipeline and storage system might be an important aspect of the overall hydrogen economy. An early technical and economic judgement on this question is desirable. See Table IX-10, Program K, Project K-2.

Table IX-4

PROGRAM D: HIGH-TEMPERATURE MATERIALS STU

Project No.	Project Description	Activity Type	Relates to: Fuel	Relates to: Problem Area	Reference t Section VIII Table No.	Item N
D-1	Reactions of Water Vapor with Metals and Ceramics at High Temperatures Fundamental kinetic studies of reactions of high H_2O-content environments with candidate gas turbine materials, including Si_3N_4, SiC, Cb alloys, and oxidation-resistant coatings.	Basic research.	H_2	High-temperature components of gas turbines, scramjets, MHD systems.	1	1.2.3 1.4.3 2.1.1 4.1.1
D-2	Creep, Fatigue and Oxidation Resistance of High-Temperature Materials in Hydrogen Combustion Gases Determination of high temperature mechanical and environmental endurance of present and candidate future gas turbine materials in actual or simulated H_2/air and H_2/O_2 combustion gases. Materials to be tested should include Ni- and Co-base superalloys, Cb-alloys, dispersion-strengthened alloys, protective coatings, Si_3N_4 and SiC.	Materials testing and evaluation.	H_2	High-temperature components of gas turbines, scramjets, MHD systems.	1	1.2.4 1.4.3 2.1.1 4.1.1
D-3	Erosion-Corrosion of High-Temperature Materials in High-Velocity, High-Temperature Water Simulation and investigation of combined effects of erosion and oxidation/corrosion expected if high-velocity water is passed through cooling channels in gas turbine combustors, vanes or blades, or other H_2/air or H_2/O_2 combustion systems.	Materials testing and evaluation.	H_2	Watercooled high-temperature gas turbine or H_2/O_2 combustion components.	1	1.2.5 1.4.3 3.1.2

Table IX-4

PROGRAM D: HIGH-TEMPERATURE MATERIALS STUDIES

Relates to: Fuel	Relates to: Problem Area	Reference to Section VIII: Table No.	Reference to Section VIII: Item No.	Relevance to DoD	Priority	Remarks
H_2	High-temperature components of gas turbines, scramjets, MHD systems.	1	1.2.3 1.4.3 2.1.1 4.1.1	High	1	Basic information needed for use of H_2 as a gas turbine fuel. High temperature H_2O reaction with Si_3N_4 and SiC likely to be important for present studies concerned with use of these materials in large and small turbines. Basic studies will guide further materials and coating development.
H_2	High-temperature components of gas turbines, scramjets, MHD systems.	1	1.2.4 1.4.3 2.1.1 4.1.1	High	1	Information needed for use of H_2 as an aircraft fuel. Project entails expansion of existing gas turbine materials R, D, and T programs to include modified environment due to the change of fuel from hydrocarbons to H_2.
H_2	Watercooled high-temperature gas turbine or H_2/O_2 combustion components.	1	1.2.5 1.4.3 3.1.2	Low	4	Need for project depends mainly on demonstration of the engineering feasibility of water cooling for hot components of stationary or marine H_2/air or H_2/O_2 gas turbines. Long-life nozzles for H_2/O_2 rocket engines may have related erosion-corrosion problems, but endurance required is very different.

Table IX-5

PROGRAM E: MATERIALS FOR SERVICE AT CRYOGENIC TEMPE

Project No.	Project Description	Activity Type	Relates to: Fuel	Relates to: Problem Area	Reference to Section VIII: Table No.	Reference to Section VIII: Item No.
NOTE	Projects A-1 and A-2 include the measurement of the mechanical properties of materials in H_2 environments at temperatures down to -423°F. At this temperature, the effect of H_2 environments on the mechanical behavior of materials is likely to be less important than the influence of temperature. The low-temperature data from Projects A-1 and A-2 will therefore contribute to Program E.					
E-1	Properties of Materials at Cryogenic Temperatures Determination of physical and mechanical properties of metallic, polymeric and composite materials at cryogenic temperatures as required to support: • Engineering design and development of H_2 liquefaction equipment, liquid H_2 pipelines, transportation and storage vessels, and transfer and delivery systems. • Materials development of low-expansion composites. • Materials/engineering development of insulating materials.	Physical and mechanical testing and interpretation.	H_2 Liquid	Liquid H_2 pipelines, transport and storage vessels, transfer and delivery systems.	2 3 4	4.1.1 4.1.3 2.2.1 4.6.2 4.7.1 3.3.2 3.3.3 3.4.1 3.5.1 6.1.1 6.1.2 6.1.3 6.1.4 6.2.1 6.3.1 6.4.1
E-2	Development of Low-Expansion, High-Strength, Light-Weight Composites for Liquid Hydrogen Fuel Tanks and Transfer Piping Development of polymeric composite materials and structures using selected controlled orientations of graphite or advanced organic fibers to provide low or zero expansion coefficients and low thermal conductivity in high-strength, stiff, light structures.	Materials development.	H_2 Liquid	Aircraft and other lightweight liquid hydrogen tanks and piping.	3	4.6.2
E-3	Development of Improved Cryogenic Insulation Materials and Systems Materials development support to engineering development of improved internal and external insulation for (a) Improved low-cost insulation systems for bulk liquid H_2 storage systems. (b) Insulation systems for aircraft and space vehicle liquid hydrogen tanks able to function with hot-face temperatures of 180°F, 350°F and 650°F.	Materials development.	H_2 Liquid	(a) Bulk or transportation storage of H_2 liquid.	3 4	4.3.1 3.5.3
				(b) Aircraft and space vehicle liquid H_2 fuel tanks.	4	6.2.1 6.3.1 6.4.1

Table IX-5

PROGRAM 8: MATERIALS FOR SERVICE AT CRYOGENIC TEMPERATURES

Related to: Fuel	Related to: Problem Area	Reference to Section VIII: Table No.	Reference to Section VIII: Item No.	Relevance to DoD	Priority	Remarks
H_2 Liquid	Liquid H_2 pipelines, transport and storage vessels, transfer and delivery systems.	2 3 4	4.1.1 4.1.3 2.2.1 4.6.2 1.7.1 3.3.2 3.3.3 3.4.1 3.5.1 6.1.1 6.1.2 6.1.3 6.1.4 6.2.1 6.3.1 6.4.1	Moderate to high	Variable	Work related to aircraft liquid H_2 fuel tank materials is of special concern to DoD and high priority (Items 4-6.1.1 through 6.4.1).
H_2 Liquid	Aircraft and other lightweight liquid hydrogen tanks and piping.	3	4.6.2	High	2	Likely to be relatively high-cost materials. Low-expansion cryogenic tank materials reduce chill-down stresses in tanks and associated structures. See also Table IX-3, Project J-4(c).
H_2 Liquid	(a) Bulk or transportation storage of H_2 liquid.	3 4	4.1.1 3.5.1	Moderate	3	Relevant to DoD storage of liquid H_2 aircraft fuel.
	(b) Aircraft and space vehicle liquid H_2 fuel tanks.	4	6.2.1 6.3.1 6.4.1	High	2	Insulation requirements are dependent on vehicle design details.

Table IX-6

PROGRAM F: MATERIALS FOR FUEL CELLS AND ELECTROLYZE

Project No.	Project Description	Activity Type	Relates to: Fuel	Relates to: Problem Area	Reference to Section VIII: Table No.	Reference to Section VIII: Item No.	R
F-1	<u>Improved Noble Metal Electrode Catalysts.</u> Noble metal electrocatalysts with high activity and stability at lower catalysts loadings for: (a) Alkaline and acid fuel cell cathodes.	Materials and engineering development.	H_2	(a) Fuel cell efficiency and cost.	1	8.1.3 8.2.1	Hi
	(b) Solid polymer electrolyte electrolyzer electrodes.			(b) SPE electrolyzers.	2	2.2.2	Hi
F-2	<u>Nonnoble Metal Electrode Catalysts.</u> Nonnoble metal catalysts with high activity and high chemical and physical stability at ≥ 150°C for: (a) Alkaline and acid fuel cell cathodes and/or anodes, and alkaline electrolyzer electrodes.	Materials and engineering development.	H_2	(a) Fuel cell efficiency and cost.	1	8.1.1 8.1.2 8.2.2 2.1.6	Hi
	(b) Molten carbonate fuel cell electrodes.			(b) Molten carbonate fuel cell life.	1	8.3.1	Lo
	(c) Solid polymer electrolyte electrolyzer electrodes.			(c) SPE electrolyzers.	2	2.2.2	Hi
F-3	<u>General Electrocatalyst Studies.</u> (a) Fundamental studies of the mechanism of electrocatalysis.	Basic research and screening studies.	Various	(a) Electrocatalysis.	1	8.11.3	Hi
	(b) Measurement of single electrode characteristics of candidate electrocatalyst materials.			(b) Electrocatalyst selection.	1	8.11.4	Hi
F-4	<u>Special Purpose Electrocatalysts.</u> (a) Higher activity anode catalyst and selective cathode catalyst for direct methanol fuel cells.	Catalyst development.	Methanol	(a) Direct methanol fuel cells.	1	8.5.1 8.5.4	Mo
	(b) Electrocatalysts that would permit the direct electrolytic production of methanol.			(b) Electrolytic production of methanol.	2	8.5.1	Mo
	(c) Selective anode and cathode catalysts to reduce parasitic reactions in hydrazine fuel cells.		Hydrazine	(c) Hydrazine fuel cells.	1	8.7.1 8.7.3	Mo
	(d) Electrocatalysts for regenerative fuel cells that are insensitive to potential cycling.		H_2	(d) Regenerative H_2/O_2 fuel cells.	1	8.10.1	Mo
	(e) Anode catalysts with improved long-term activity for direct ammonia fuel cells.		NH_3	(e) Direct NH_3 fuel cells.	1	8.8.1	Lo
F-5	<u>Electrode Materials and Structure Development.</u> (a) Improved hydrophobic polymer bonding materials for alkaline fuel cells for service > 150°C.	Materials and engineering development.	H_2	(a) Alkaline fuel cell electrodes.	1	8.1.4	Hi
	(b) Improved gas-diffusion electrode structures with controlled porosity for alkaline fuel cells.			(b) Alkaline fuel cell electrodes.	1	8.1.5	Mo
	(c) High surface area electrodes for alkaline electrodes.			(c) Alkaline electrolyzers.	2	2.1.5	Mo
	(d) Ceramics that can control wetting angle in molten carbonate fuel cells.			(d) Molten carbonate fuel cells.	1	8.3.2	Lo
	(e) Materials that can control wetting angle in direct methanol fuel cells.		Methanol	(e) Methanol fuel cells.	1	8.5.3	Mo
	(f) Dual function electrode structures of dual electrode structures for regenerative fuel cells.		H_2	(f) Regenerative fuel cells.	1	8.10.2 8.10.3	Mo
	(g) Electrode materials and conductors with improved corrosion resistance.			(g) Acid and alkaline electrolyzers.	2	2.1.1 2.4.1	Lo

Table IX-6

PROGRAM F: MATERIALS FOR FUEL CELLS AND ELECTROLYZERS

...ivity Type	Relates to: Fuel	Relates to: Problem Area	Reference to Section VIII: Table No.	Reference to Section VIII: Item No.	Relevance to DoD	Priority	Remarks
...ls and ...ring ...ment.	H_2	(a) Fuel cell efficiency and cost.	1	8.1.3 8.2.1	High	2	Lower noble metal loadings needed to reduce cost and resource availability. DoD may be able to accept high loadings for critical applications.
		(b) SPE electrolyzers.	2	2.2.2	High	1	As above.
...ls and ...ring ...ment.	H_2	(a) Fuel cell efficiency and cost.	1	8.1.1 8.1.2 8.2.2 2.1.6	High	1	Efficient nonnoble metal electrode systems are needed to reduce cost.
		(b) Molten carbonate fuel cell life.	1	8.3.1	Low	4	Most readily applicable to fossil fuel reformates.
		(c) SPE electrolyzers.	2	2.2.2	High	1	Nonnoble metal catalysts needed to reduce cost.
...search and ... studies.	Various	(a) Electrocatalysis.	1	8.11.3	High	2	Long-range basic studies necessary to provide sound fund... mental basis for theoretical understanding and future advances in fuel cell and electrolyzer technology.
		(b) Electrocatalyst selection.	1	8.11.4	High	1	Provide essential basis for empirical selection of candidate electrocatalysts.
...t ...ment.	Methanol	(a) Direct methanol fuel cells.	1	8.5.1 8.5.4	Moderate	3	Methanol fuels cells would be of greater importance to DoD if methanol were adopted as a general vehicle fuel.
		(b) Electrolytic production of methanol.	2	8.5.1	Moderate	4	Conceptual process. Exploratory study may be worthwhile
	Hydrazine	(c) Hydrazine fuel cells.	1	8.7.1 8.7.3	Moderate	2	Would improve efficiencies of hydrazine fuel cells.
	H_2	(d) Regenerative H_2/O_2 fuel cells.	1	8.10.1	Moderate	2	Regenerative fuel cells offer possible electric power storage system.
	NH_3	(e) Direct NH_3 fuel cells.	1	8.8.1	Low	4	Relevance to DoD and priority could increase if energy depot concept with NH_3 fuel was developed.
...s and ...ring ...ent.	H_2	(a) Alkaline fuel cell electrodes.	1	8.1.4	High	1	Higher temperature operation would increase efficiency.
		(b) Alkaline fuel cell electrodes.	1	8.1.5	Moderate	2	Alternatives to polymer bonded structures in (a) above.
		(c) Alkaline electrolyzers.	2	2.1.5	Moderate	3	Would reduce electrode overpotentials.
		(d) Molten carbonate fuel cells.	1	8.3.[illegible]	Low	4	Equivalent of hydrophobic electrode structures used in alkaline fuel cells.
	Methanol	(e) Methanol fuel cells.	1	8.5.3	Moderate	3	Needed to control methanol cross-over problem.
	H_2	(f) Regenerative fuel cells.	1	8.10.2 8.10.3	Moderate	2	Alternative to electrocatalysts that are insensitive to potential cycling, Project F-4(d).
		(g) Acid and alkaline electrolyzers.	2	2.1.1 2.4.1	Low	4	Longer life electrode structures.

PROGRAM F: MATERIALS FOR FUEL CELLS AND ELECTROLY

Project No	Project Description	Activity Type	Relates to: Fuel	Relates to: Problem Area	Reference to Section VIII: Table No.	Reference to Section VIII: Item No.
F-6	Improved Matrix (Diaphragm) Materials.					
	(a) Low-cost, compact, high-conductivity matrix materials for alkaline fuel cells and electrolyzers, able to operate above 150°C.	Materials and engineering development.	H_2	(a) Matrix materials for higher temperatures in alkaline electrolyzers.	1 2	8.1.6 2.1.2 2.1.4
	(b) Improved ion-exchange membranes for alkaline and acid fuel cells.			(b) Matrix systems for fuel cells and electrolyzers.	1	8.1.7
	(c) Ceramic matrix materials with controlled porosity and improved resistance to thermal cycling for molten carbonate fuel cells.			(c) Molten carbonate fuel cells.	1	8.33
	(d) Matrix materials impervious to methanol.		Methanol	(d) Methanol fuel cells	1	8.5.2
	(e) Matrix materials impervious to hydrazine.		Hydrazine	(e) Hydrazine fuel cells.	1	3.7.2
	(f) Thin, stable, high-conductivity matrix materials for inorganic electrolyte fuel cells.		H_2	(f) Inorganic solid electrolyte fuel cells.	1	8.4.1
F-7	Ion-Conducting Properties of Solids.					
	(a) Inorganic solids with ion-conducting properties at moderate temperatures.	Basic research and materials development.	H_2	(a) Inorganic solid electrolyte fuel cells and electrolyzers.	1 2	8.4.2 2.3.1
	(b) Low-cost, solid polymer electrolytes with higher temperature capability, high ionic conductivity, good mechanical and chemical stability.			(b) SPE electrolyzers	2	2.2.1
F-8	Other Materials of Construction.					
	(a) Cell materials with matching coefficients of expansion, seals, electrical contact materials for inorganic solid electrolyte fuel cells and electrolyzers.	Materials and engineering development.	H_2	(a) High operating temperature.	1 2	8.4.1 2.3.2
	(b) Higher temperature, low-cost frame materials for alkaline electrolyzers, and low-cost methods of fabrication.			(b) Alkaline electrolyzers.	2	2.1.3

Table IX-6 (Concluded)

PROGRAM F: MATERIALS FOR FUEL CELLS AND ELECTROLYZERS

...ity	Relates to:		Reference to Section VIII		Relevance to DoD	Priority	Remarks
	Fuel	Problem Area	Table No.	Item No.			
...ard	H_2	(a) Matrix materials for higher temperatures in alkaline electrolyzers.	1 2	8.1.6 2.1.2 2.14	High	1	A key item in increasing the efficiency of alkaline fuel cells and electrolyzers.
		(b) Matrix systems for fuel cells and electrolyzers.	1	8.1.7	Moderate	3	An alternative to electrolyte-retaining matrix materials (a) above.
		(c) Molten carbonate fuel cells.	1	8.33	Low	4	Present materials have limited life.
	Methanol	(d) Methanol fuel cells.	1	8.5.2	Moderate	3	Would control methanol cross-over.
	Hydrazine	(e) Hydrazine fuel cells.	1	8.7.2	Moderate	3	Would control hydrazine cross-over.
	H_2	(f) Inorganic solid electrolyte fuel cells.	1	8.4.1	Low	5	Lower temperature cells (See Project F-7(a)) would be preferable.
...arch ...als	H_2	(a) Inorganic solid electrolyte fuel cells and electrolyzers.	1 2	8.4.2 2.3.1	Moderate	2	Breakthrough, analogous to discovery of β-alumina, needed to reduce operating temperature of inorganic solid electrolyte fuel cells and electrolyzers.
		(b) SPE electrolyzers	2	2.2.1	Moderate	1	Higher efficiency and reduced cost SPE electrolyzers.
...ed	H_2	(a) High operating temperature.	1 2	8.4.1 2.5.2	Low	5	Lower temperature systems generally preferred. Project F-7(a) could increase the importance of inorganic solid electrolyte systems.
		(b) Alkaline electrolyzers.	2	2.1.3	Moderate	2	Presently used polysulphones are limited to 150°C. Increases in electrolyzer temperatures (See Project F-2(a) and F-6(a)) would need corresponding improvements in frame materials.

Table IX-7

PROGRAM G: MATERIALS FOR HIGH ENERGY DENSITY BATTER

Project No.	Project Description	Activity Type	Relates to: Fuel	Relates to: Problem Area	Reference To Section VIII: Table No.	Reference To Section VIII: Item No.	P
G-1	Shape Change in Zinc Electrodes. Investigation of dendrite growth and methods for controlling it.	Basic materials research and engineering development.	Zn	All electrically rechargeable Zn batteries.	1	9.1.1 9.3.1 9.4.1	Hi
G-2	Ion-Conducting Solids. (a) Optimization of β-alumina electrolyte composition for Na/S battery for improved conductivity, and chemical, thermal and mechanical stability.	Materials research; ceramic processing.	Na	(a) Electrolyte for Na/S battery.	1	9.10.1	Mc
	(b) Search for new ion-conducting solids with good conductivity at moderate temperature.		Various	(b) New battery systems.	1	9.10.2 9.11.1	Hi
	(c) Improved cation and anion exchange membranes.		Various	(c) New battery systems.	1	9.11.1	Hi
G-3	Battery Electrode Catalysts and Substrates. (a) Dual function, or two separate catalysts for O_2 evolution and O_2 reduction.	Catalyst development.	Zn	Charge/discharge efficiency of Zn/air, Zn/O_2 batteries.	1	9.1.2	Hi
	(b) More active Cl_2 electrode substrate for Zn/Cl_2 battery.	Materials development.	Zn	Polarization of Cl_2 electrode.	1	9.4.2	Mc
G-4	Materials Compatibility with Battery Environments. Materials support for the solution of battery design and construction problems according to specific battery requirements. Includes: problems of corrosion by Cl_2, molten salts, liquid metals, and sulfur; materials with matching expansion coefficients; materials for cases, seals, electrical feedthroughs, current collectors, electrical insulators, separators, etc; thermal insulation; electrode and diaphragm materials.	Materials development and selection.	Various	Battery design and construction.	1	9.2.1 9.5.1 9.5.2 9.6.1 9.7.1 9.7.2 9.7.3 9.7.4 9.7.5 9.7.6 9.8.1 9.9.1 9.11.1	Va

Table IX-7

PROGRAM G: MATERIALS FOR HIGH ENERGY DENSITY BATTERIES

ctivity Type	Relates to: Fuel	Problem Area	Reference To Section VIII Table No.	Item No.	Relevance to DoD	Priority	Remarks
aterials h and ring ment.	Zn	All electrically rechargeable Zn batteries.	1	9.1.1 9.3.1 9.4.1	High	1	Future of Zn/air battery depends on solving shape-change problem in Zn electrode.
ls h; ceramic ing.	Na	(a) Electrolyte for Na/S battery.	1	9.10.1	Moderate	2	Needed for improvement of efficiency and life of Na/S battery.
	Various	(b) New battery systems.	1	9.10.2 9.11.1	High	2	Continuation and extension of work in progress. This project is related to Project F-7 and might be combined with it.
	Various	(c) New battery systems.	1	9.11.1	High	2	Continuation and extension of work in progress. This project is related to Project F-6(b), and might be combined with it.
t develop-	Zn	Charge/discharge efficiency of Zn/air, Zn/O_2 batteries.	1	9.1.2	High	2	Needed to improve battery efficiency and reduce catalyst loadings.
ls ment.	Zn	Polarization of Cl_2 electrode.	1	9.4.2	Moderate	3	Needed to improve power density.
ls ment ction.	Various	Battery design and construction.	1	9.2.1 9.5.1 9.5.2 9.6.1 9.7.1 9.7.2 9.7.3 9.7.4 9.7.5 9.7.6 9.8.1 9.9.1 9.11.1	Variable	Variable	Materials requirements are generally specific to particular battery and materials. R, D, and T should generally be undertaken as integral part of battery programs, rather than as independent, materials-oriented studies.

Table IX-8

PROGRAM H: CATALYSTS (EXCLUDING ELECTROCATALYS

Project No.	Project Description	Activity Type	Relates to: Fuel	Relates to: Problem Area	Reference to Section VIII: Table No.	Reference to Section VIII: Item No.
H-1	Long-Life Hydrazine Decomposition Catalyst Fundamental studies to elucidate mechanism of deterioration of iridium catalysts and alumina substrate; development of improved, long-life, mixed-metal catalysts.	Catalyst R and D.	Hydrazine	Hydrazine rocket engines.	1	3.2.1 3.2.2
H-2	Combustion Catalysts. (a) Fundamental studies of mechanism of the catalytic oxidation of hydrogen, e.g., by transition metal carbides.	Catalyst R and D.	H_2	(a) Catalytic combustion of H_2 for space and water heating.	1	7.2.1
	(b) Development of low-cost, long-life H_2 oxidation catalysts that are resistant to poisoning by contaminants.			(b) Catalytic combustion of H_2 for space and water heating.	1	7.2.1
	(c) Development of low-cost, long-life, high-activity catalyst for oxidation of NH_3 to $N_2 + H_2O$ without formation of NO_x.		NH_3	(c) Catalytic combustion of NH_3 for space and water heating.	1	7.4.1
	(d) Development of improved catalyst for dissociation of NH_3.		NH_3	(d) Dissociation of NH_3 for improved combustion and/or reconversion to H_2.	1	7.3.1
	(e) Development of base-metal catalysts for oxidation of CO and methanol.		CO, methanol	(e) Catalytic combustion of CO or methanol for space and water heating.	1	7.5.1
H-3	Reversed Shift Reaction Catalyst. Development of catalyst for reversed shift reaction for production of CO (and methanol) by hydrogen reduction of nonfossil CO_2.	Catalyst development.	CO, methanol	Production of CO and methanol from non-fossil sources.	2	8.3.1

Table IX-8

PROGRAM H: CATALYSTS (EXCLUDING ELECTROCATALYSTS)

tivity Type	Relates to:		Reference to Section VIII		Relevance to DoD	Priority	Remarks
	Fuel	Problem Area	Table No.	Item No.			
st R and D.	Hydrazine	Hydrazine rocket engines.	1	3.2.1 3.2.2	High	2	For small, long-life hydrazine monopropellant control and accessory rocket engines.
st R and D.	H_2	(a) Catalytic combustion of H_2 for space and water heating.	1	7.2.1	Low to moderate	3	Would provide fundamental basis for Project H-2(b).
		(b) Catalytic combustion of H_2 for space and water heating.	1	7.2.1	Low to moderate	3	Would permit efficient, low-temperature combustion of H_2 for space or water heating, in many cases without the need for venting combustion products.
	NH_3	(c) Catalytic combustion of NH_3 for space and water heating.	1	7.4.1	Low	5	Relevance and priority ratings would increase if energy depot concept was developed using NH_3 as the fuel.
	NH_3	(d) Dissociation of NH_3 for improved combustion and/or reconversion to H_2.	1	7.3.1	Moderate	4	For several applications of NH_3 as a fuel, including direct combustion, vehicle engines, and indirect NH_3 fuel cells. Work may also relate to improved NH_3 synthesis catalysts.
	CO, methanol	(e) Catalytic combustion of CO or methanol for space and water heating.	1	7.6.1	Low	5	Relevance and priority ratings would increase if energy depot concept was developed using methanol as the fuel. Priority would increase if methanol was generally adopted as nonfossil liquid fuel.
t ment.	CO, methanol	Production of CO and methanol from nonfossil sources.	2	8.3.1	Low	3,5	Needed for economic production process if CO (priority or methanol (priority 3) adopted as general fuels.

Table IX-9

PROGRAM J: MISCELLANEOUS MATERIALS DEVELOPMENT AND FAB

Project No.	Project Description	Activity Type	Relates to: Fuel	Relates to: Problem Area	Reference to Section VIII: Table No.	Reference to Section VIII: Item No.
J-1	Fabrication of Components for Advanced Gas Turbine and Rocket Engine Cooling Systems. (a) Materials engineering support for the design and development of advanced cooling systems for H_2/air and H_2/oxygen fueled gas turbines, combustion chambers, vanes, and blades.	Materials engineering.	H_2	(a) Higher H_2 combustion temperatures.	1	1.2.7
	(b) Materials engineering support for the design and development of cooled, long-life, rocket engine combustion chambers and nozzles.			(b) High-pressure, very high-temperature environment.	1	3.1.2 1.4.3 4.1.1
J-2	Fiber-Reinforced Cements and Concretes. Further development of cements and concretes reinforced with glass fiber or chopped steel wire for large pressure vessels or storage tanks. Materials may also be polymer-impregnated.	Materials and engineering development.	Various	Large pressure vessels and storage tanks.	2	5.1.3 2.4.1 3.4.1
J-3	Vented-Lining Type Construction for Hydrogen Pressure Vessels and Pipelines. Vented-lining design used for high-pressure process vessels for hydrogen service could provide protection of pipeline and storage tank materials from H_2 environments. This method might be economically feasible if low-cost manufacturing and assembly methods could be developed.	Materials and engineering development.	H_2	Pipelines and storage tanks.	3 4	2.1.2 2.1.2
J-4	Fabrication of Fiber-Reinforced Composites. (a) Development of low-cost, rapid, on-site methods for fabrication of large pressure vessels, pipe, and storage tanks.	Materials and engineering development.	Various	(a) Pipelines, pressure vessels, and storage tanks.	3	2.1.5 2.3.2 3.3.1
	(b) Rapid, low-cost methods for mass production of small and medium size high-strength, lightweight pressure vessels for high-pressure gas storage, and insulated cryogenic storage of liquid H_2, liquid NH_3, etc.		H_2 gas H_2 liq. NH_3 liq.	(b) Small containers and associated transfer and delivery piping.	3 4	4.1.1 4.7.1 4.1.1 5.2.1
	(c) Development and fabrication of special low- or zero-expansion composite materials and structures employing controlled orientations of graphite or advanced organic fiber reinforcements.		H_2 liq.	(c) Aircraft and space vehicle tanks; transfer and delivery piping.	3	4.6.2
J-5	Friction and Wear in Gaseous and Liquid Hydrogen. Study of friction and wear behavior of metals and plastics in gaseous and liquid hydrogen. Development of improved materials and materials combinations.	Materials research and development.	H_2	H_2 compressors and pumps.	2	4.1.2

Table IX-9

PROGRAM J: MISCELLANEOUS MATERIALS DEVELOPMENT AND FABRICATION

	Relates to:		Reference to Section VIII				
ty	Fuel	Problem Area	Table No.	Item No.	Relevance to DoD	Priority	Remarks
engi-	H_2	(a) Higher H_2 combustion temperatures.	1	1.2.7	High	1	Development of advanced cooling methods is likely to make the principal contribution to the use of higher combustion temperatures in gas turbines. This work would extend existing development programs.
		(b) High-pressure, very high-temperature environment.	1	3.1.2 1.4.3 4.1.1	High	1	Present application is for long-life, re-usable rocket engines but results will also apply to H_2/O_2 combustion systems for high-temperature industrial steam systems and MHD systems.
and ... t.	Various	Large pressure vessels and storage tanks.	2	5.1.3 2.4.1 3.4.1	Moderate	3	Materials system has wide general applicability.
and ... t.	H_2	Pipelines and storage tanks.	3 4	2.1.2 2.1.2	Low	4	Vented-lining design used for high-pressure chemical process vessels for hydrogen service might be employed more widely if low cost manufacturing and assembly methods could be developed.
and ... t.	Various	(a) Pipelines, pressure vessels, and storage tanks.	3	2.1.5 2.3.2 3.3.1	Low	4	Primarily of concern to utility industries.
	H_2 gas H_2 liq. NH_3 liq.	(b) Small containers and associated transfer and delivery piping.	3 4	4.1.1 4.7.1 4.1.1 5.2.1	Moderate	3	Relevant to DoD with regard to on-board vehicle and marine storage of new fuels, and fuel supply storage. Also relevant to high-pressure or cryogenic storage of other gases.
	H_2 liq.	(c) Aircraft and space vehicle tanks; transfer and delivery piping.	3	4.6.2	High	2	Possibly a superior approach to on-board aircraft storage of liquid H_2. Priority could be down-graded if initial efforts are discouraging. Likely to be high-cost materials.
and ... t.	H_2	H_2 compressors and pumps.	2	4.1.2	Moderate	4	Present knowledge of friction and wear behavior of materials in H_2 environments is limited.

Table IX-10

PROGRAM K: TECHNOECONOMIC AND ENGINEERING FEASIBILITY A

Project No.	Project Description	Activity Type	Relates to: Fuel	Relates to: Problem Area	Reference t Section VI Table No.	Reference t Section VI Item
K-1	Materials Supply Requirements for Electrolyzers. A study of the materials requirements and materials availability for competing advanced electrolyzer technologies. Materials would include construction materials, specialty polymers and ceramics, noble and nonnoble electrocatalysts.	Technoeconomic evaluation.	Various	Planning of research and development programs for the production of H_2.	2	2.5
K-2	Engineering Feasibility and Economics of Bulk Distribution of By-Product Oxygen. Materials support for an engineering system and economic study of the general distribution of oxygen produced as a by-product of hydrogen production. Study should include an analysis of potential hazards.	Engineering and economic evaluation.	By-product O_2.	Strategy decisions	3	2.4
K-3	Technical and Economic Evaluation of the Storage of Hydrogen as Metal Hydride. Cost/benefit analysis of hydride systems compared with liquid and gaseous H_2 for various storage capacities and applications, including peak shaving and vehicle uses. Materials requirements are a major cost element.	Engineering and economic evaluation.	H_2	Medium- and small-scale storage of H_2.	4	7.1

Table IX-10

PROGRAM K: TECHNOECONOMIC AND ENGINEERING FEASIBILITY AND EVALUATION STUDIES

Activity Type	Relates to: Fuel	Relates to: Problem Area	Reference to Section VIII: Table No.	Reference to Section VIII: Item No.	Relevance to DoD	Priority	Remarks
nceconomic uction.	Various	Planning of research and development programs for the production of H_2.	2	2.5.1	High	1	Information gathered would also relate to materials requirements for large-scale use of fuel cells. Of high relevance to DoD because of policy decisions relating to defense materials requirements.
ineering economic uation.	By-product O_2.	Strategy decisions	3	2.4.3	Moderate	2	If study results are favorable, a follow-up study of the technical and economic factors involved in the use aspects of hydrogen/oxygen fuel system. Distribution study is given first consideration because it is considered the key element in the overall H_2/O_2 system. General availability of low-cost oxygen would affect many DoD interests.
neering economic uation.	H_2	Medium- and small-scale storage of H_2.	4	7.1.1	High	2	Of high relevance to DoD with regard to use of hydrid for on-board vehicle or marine storage of H_2. Study needs to be done in depth. Published comparisɔ are not considered adequate.