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HYDROGEN

HEARINGS

BEFORE THE

SUBCOMMITTEE ON ENERGY RESEARCH, DEVELOPMENT AND DEMONSTRATION

OF THE

COMMITTEE ON SCIENCE AND TECHNOLOGY U.S. HOUSE OF REPRESENTATIVES

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HYDROGEN

TUESDAY, JUNE 10, 1975

House of Representatives,
Committee on Science and Technology,
Subcommittee on Energy Research,
Development and Demonstration,
Washington, D.C.

The subcommittee met, pursuant to notice, at 8:05 a.m., in room 2325, Rayburn House Office Building, Hon. Mike McCormack (chairman of the subcommittee), presiding.

Mr. McCormack. The meeting will come to order.

Good morning.

This morning the Subcommittee on Energy Research, Development and Demonstration undertakes the first of two investigative hearings on the subject of hydrogen—its production, utilization, and potential effects on our energy economy of the future.

Hydrogen is not a new source of energy. In a sense hydrogen has the potential of playing the same kind of role in our energy system as electricity does today. That is, it is an intermediate form of energy which must be produced from some other primary form, but it is, at the same time, extremely useful for specific applications.

Today we have proven technologies for producing hydrogen from water by electrolysis, and from natural gas by a steam reforming process. It is unlikely, however, that the presently accepted processes would be utilized on a large scale in the future. What we are looking for, therefore, is an economically feasible way of producing hydrogen in large quantities.

The production of hydrogen, even cheaply, is not the complete answer, however. If hydrogen is to take its place as a viable component of the energy economy of the future, we must also be able to store, transport, and utilize it in a manner that is consistent with requirements of our industrial, commercial, and residential energy needs. In a sense, we must undertake a systems approach in dealing with this potential new energy technology.

One of the most attractive aspects of hydrogen is its cleanliness. The combustion products of hydrogen are in no way detrimental or undesirable from an environmental point of view. This makes its use, especially in densely populated urban areas much more desirable than the use of fossil fuels.

Another attractive feature of hydrogen is its potential compatibility with our existing industrial infrastructure. As a gas it is easily transportable, and there is the possibility of using, with certain modifications, much of our investment in natural gas pipelines and ancillary equipment. This issue of compatibility is one that we will pursue in the hearings today and Thursday.

We must look at the drawbacks as well as the advantages of hydrogen. Safety is one. Cost is another. There may be unknown environmental hazards associated with new and innovative production processes. We must assure adequate feedstocks for hydrogen production. Another necessary ingredient, of course, is a great quantity of energy. Still another is ingenuity.

What we hope to uncover, during the hearings this week, is the ingenuity that would be required to obtain the energy, to use the feedstock to produce hydrogen, and then to use the hydrogen intelligently and effectively throughout our industrial system.

Our witnesses today are Dr. James Kane, Deputy Assistant Administrator for Conservation, Energy Research and Development Administration, accompanied by Dr. Jack Vanderryn, Assistant Director for Energy Storage, ERDA; Dr. Ray Zahradnik, Acting Director, Division of Coal Conversion and Utilization, ERDA; Dr. Harrison Schmitt, Assistant Administrator for Energy Programs, NASA, accompanied by Mr. R. D. Ginter, Director of the Energy Systems Division, Office of Energy Programs, NASA; and Dr. James E. Funk, Dean of the College of Engineering, University of Kentucky, at Lexington, Ky.

So we'll start out this morning with Dr. Kane. Jim, please make yourself comfortable at the witness table.

Dr. KANE. Thank you, Mr. Chairman.

I'd like to bring with me to the witness table Dr. Vanderryn and Dr. Ray Zahradnik, who is from our Fossil Energy Branch.

Mr. McCORMACK. Welcome, gentlemen.

Jim, if you have a prepared statement, you may put it in the record, and talk from it, or you may read your statement, or proceed in any way you wish.

Dr. KANE. Mr. Chairman, with your permission, I will read parts of my prepared statement, and skim over other parts of it.

I might register a mild complaint, that you have said a lot of what's in my prepared statement already.

Mr. McCORMACK. I am sorry about that.

There being no objection, we shall insert your entire statement in the record, and you may proceed as you like.

Dr. KANE. Thank you.

[The prepared statement of Dr. Kane follows:]

STATEMENT OF

DR. JAMES S. KANE

DEPUTY ASSISTANT ADMINISTRATOR

FOR CONSERVATION

ENERGY RESEARCH AND DEVELOPMENT ADMINISTRATION

FOR THE

SUBCOMMITTEE ON ENERGY RESEARCH, DEVELOPMENT, AND DEMONSTRATION

COMMITTEE ON SCIENCE AND TECHNOLOGY

HOUSE OF REPRESENTATIVES

JUNE 10, 1975

Mr. Chairman and Members of the Committee:

Much attention has been given in the past few years to the possible role of hydrogen in our Nation's future energy systems. These hearings are thus appropriate and timely in this regard, and should be helpful in placing the future uses of this interesting and somewhat unique element into proper perspective.

I intend to provide you today with a brief overview of ERDA's R&D activities related to hydrogen technology as well as indicate some possible future directions to which this technology may lead us. To assist me in this task, I am accompanied by Dr. Jack Vanderryn, Assistant Director for Energy Storage in Conservation, and Dr. Ray Zahradnik, Acting Director of the Division of Coal Conversion and Utilization in Fossil Energy. It should be noted that hydrogen-related activities are distributed throughout ERDA, and accordingly my testimony this morning will reflect activities related to a number of ERDA programs. Before describing ERDA's activities, I would first like to discuss the role of hydrogen in energy systems.

Free hydrogen does not occur naturally; it must be obtained from a primary source of energy such as fossil fuels, uranium or sunlight. Some energy is always lost in the process, that is, the amount of energy that can be obtained from the product hydrogen is less than that used to obtain it. That is the first point I wish to emphasize: hydrogen is not a source of energy itself, but rather a synthetic fuel that must be obtained using energy from another source. In spite of these losses associated with its production, it may be advantageous to synthesize hydrogen for many reasons, and I will give some of these reasons later in my testimony.

Hydrogen is widely used today; its production in 1972 amounted to 10 billion pounds. It was as follows:

Synthesis of ammonia	35%
Hydrocracking of petroleum	30%
Hydrotreating of hydrocarbons	21%
Synthesis of methanol	8%
Other	6%

You can see that the two major uses are for fertilizer and oil refining, where it is used to enhance the yield of gasoline and other products from crude oil. Its use for fertilizers is expected to more than double in the next ten years. An even greater increase can be expected in the 80's and 90's as we develop processes for converting heavier primary fuels, such as coal, to synthetic liquid and gaseous fuels.

By far the largest hydrogen-related program in ERDA is, therefore, that of our synthetic fossil fuel program. I sense, however, that this aspect of hydrogen technology is not what the Committee had in mind for this hearing. I will, therefore, make a few general comments on hydrogen as it relates to synthetic fuels, and go on to other topics. If the Committee wishes further information on this aspect of hydrogen production, I will defer to Dr. Zahradnik who is an expert in these matters. Let me give you my comments:

Hydrogen is currently produced almost entirely from natural gas and other highly hydrogenated hydrocarbons. The supply of these materials is decreasing and this decline will continue.

The hydrogen needed for coal-derived synthetic fuels will come from the reaction of carbon in coal with water. This reaction, in which the carbon removes the oxygen from the water molecule and thus releases hydrogen, is the first step in most of the synfuel processes being developed. Our programs to develop the synthetic fuel process thus include hydrogen synthesis on a very large scale. Most of the hydrogen produced would be subsequently used to obtain convenient fuels, such as methane (synthetic gas) or gasoline-like liquid fuels. These synfuel plants could also produce pure hydrogen, if required.

Non-fossil energy sources--fission, fusion and solar--will produce their energy in the form of heat or electricity. As these sources become more predominant, and especially if coal is relatively less available than expected, new technology would be required to be developed to obtain hydrogen from these sources.

This has been a brief introduction to the subject. In the rest of my testimony, I will deal more specifically with the details of our hydrogen program. I will not cover in detail, however, those aspects that are associated with its production from coal or its use in the coal-derived synthetic fuel programs, but I am sure Dr. Zahradnik could answer any questions you may have.

PRODUCTION OF HYDROGEN

Electric energy can be used to decompose water to obtain hydrogen and oxygen. This process is called electrolysis. Our current program includes research to improve the efficiency of the electrolysis process and to lower the capital cost of the associated equipment. Efficiencies are now about 60 percent; it may be possible to raise them to 90 percent. There are, of course, many uses for the by-product oxygen, which itself is a valuable substance.

It may also be possible to obtain hydrogen from water by the use of heat instead of electricity. This process, often called thermochemical watersplitting, cannot be done by simply heating water. It involves multi-step chemical reactions, some of them taking place at high temperatures; but the total process consumes only water and heat, and produces hydrogen and oxygen. Thermochemical processes, in contrast to electrolysis, have not yet been demonstrated on a practical scale. Programs are underway at several ERDA laboratories to determine if such processes can be developed to use solar or nuclear heat. There is also great interest in this concept in both the university and industrial communities.

Hybrid processes, using both electric energy and heat to obtain hydrogen and oxygen from water, may also be possible.

The processes by which hydrogen could be produced from coal could be made more efficient (less coal used per unit of hydrogen produced) if additional heat from a non-coal source, such as nuclear, were used. Current state-of-the-art coal gasification processes would require development of special, high temperature materials for such a process and this research is planned. An attractive alternative would be to develop gasification processes that operate at lower gasification temperatures, and thus avoid the difficult materials development. This also will be studied in the coming year.

USES OF HYDROGEN

Hydrogen can, in principle, serve as a fuel for all conventional uses of energy, including industrial applications, electric power generation, as well as for residential, commercial and transportation uses. It can also be used as a reducing agent in many metallurgical processes, such as steel making.

I have already pointed out that it takes energy to produce hydrogen--more energy, in fact, than is recovered when the hydrogen is used. It may still be advantageous, however, to produce and use hydrogen if its use results in a greater overall efficiency of the total system, or results in a greater capability of the system. The following are examples where this may prove to be true:

Load-Leveling in Utilities

Hydrogen offers a potentially attractive means of storing energy generated by large, central-station generating stations during periods of low demand for subsequent use at times of high demand. This "load-leveling," although it does not result in energy savings, greatly increases the efficiency of the very capital-intensive facilities. It also saves the oil or gas that is usually used for meeting peak demand.

It may also be desirable to use hydrogen as the energy storage system in conjunction with inexhaustable but intermittant energy sources such as wind or solar thereby increasing their usefulness.

The processes involved in these storage applications would be the electrolysis of water to produce the hydrogen, with storage, and finally reconversion to electricity using fuel cells. Improvements in each of these technologies would be required to lower cost and increase efficiency. Our planned FY 76 program includes R&D in improved electrolysis, storage using solid hydrides, and hydrogen fuel cells.

Electrical Generation

Electrical energy can be produced directly from hydrogen by using a high efficiency converter such as a fuel cell or by burning the hydrogen in a turbine. The hydrogen fuel cell is thought to have a potential efficiency of perhaps 60 percent. This, coupled with a possible 60 percent efficient coal-to-hydrogen process, would yield an overall efficiency of 36 percent from coal to electricity, which is competitive with conventional steam cycle after penalties for stack gas scrubbing are subtracted. The use of fuel cells have an additional benefit over centralized generation. The cells are modular and need not be installed initially in large size; more can be added as demand increases. They are quiet, safe, and can be located close to load centers, where there may be opportunities to use their waste heat. Fuel cells are also well suited for small utilities, such as those which are municipally owned.

To compete economically with current means of electrical generation, the hydrogen fuel cell would have to be priced at about $200/kw. The development cost goal of the more complicated hydrocarbon fuel cell is of this magnitude. Large scale hydrogen production and transmission, therefore, offers a more conservative route for achieving fuel cell introduction. Our program in FY 76 provides for R&D in both conversion technologies--fuel cell and turbines.

SUBSTITUTE FOR NATURAL GAS

Hydrogen can be used as a substitute for natural gas or may be mixed with natural gas to extend the use of this scarce resource. Up to 8 percent hydrogen can be added to natural gas without changing equipment for its transport and use. A detailed analysis of this near-term possibility will be performed in FY 1976.

Commercial, residential and industrial applications of hydrogen for heating will also be investigated in FY 1976. Experimental programs looking forward to this longer term application may also be instituted in FY 1976. Relative to synthetic natural gas, both capital and resource savings appear possible.

Automotive Applications

In order to use hydrogen as an automotive fuel, a suitable on-board storage method would require development.

It is doubtful that hydrogen would be carried in liquid form, since the liquefaction process is expensive and inefficient. It is also questionable whether liquid hydrogen could be safely stored in an automobile. In our view, the use of hydrogen for automotive applications depends on the development of solid hydride storage technology. We are seeking new hydrides for this application which will be lightweight and can use the exhaust heat to release the hydrogen from the hydride. The weight and cost of the hydrogen storage system, however, may be a major constraint on the range of the vehicle.

DELIVERY SYSTEMS

Hydrogen is known to embrittle some kinds of steel under certain conditions. Before a hydrogen delivery system could be put into service, it would be necessary to prove that the chemical effect of the hydrogen on structural materials would not lead to safety problems. Preliminary information indicates that a large part of our current distribution system could be modified to handle hydrogen safely. More information and R&D is needed, however, before we can be assured that our current high pressure pipeline system could be used to transmit hydrogen. We have an ongoing program to investigate hydrogen compatibility with structural materials such as those used in pipelines.

ENVIRONMENTAL EFFECTS ASSOCIATED WITH HYDROGEN

By far the largest environmental impact associated with hydrogen is that caused by the energy source used to produce the hydrogen. For most applications, the use of hydrogen will produce only water as a by-product. If the hydrogen is used to obtain very hot flames in air, there may be problems from the production of nitrogen oxides. Its use in fuel cells will not produce nitrogen oxides. When added to natural gas, hydrogen could reduce nitrogen oxide formation, since it will allow the gas to be burned "leaner" and hence cooler.

Safety problems associated with gaseous hydrogen are similar to and probably no worse than safety problems with other hazardous fuels. The previously mentioned embrittlement problem must be carefully considered in relation to pipeline and other pressure vessels. The examination of environmental, social, legal and economic factors has begun, and no insurmountable problems in the use of hydrogen are anticipated.

BASIC RESEARCH

In addition to the work already described, which is in direct support of hydrogen R&D, other ERDA research efforts contribute to our overall fund of knowledge in this area. Such activities include research on metal hydrides, photochemical processes, and fundamental materials and chemical research.

MAGNITUDE OF EFFORT

In FY 1975, hydrogen-related ERDA activities were dominated by the processes related to its production from coal; about $263 million was spent on synthetic fuels process development. About $10 million total was spent on the other technologies discussed in this testimony as follows: $1 million each on production from water, high temperature reactor technology, and storage and delivery systems; $3 million on photochemical research; and $4 million on basic and supporting research.

In FY 1976 we are planning substantial increases in effort, especially in hydrogen production from coal, high temperature reactor technology, and hydrogen conversion technology. Although ERDA has the major responsibility for the Federal hydrogen R&D effort, we intend to continue utilizing other Federal agencies and laboratories in carrying out the program. We will also continue to encourage current industrial activities where hydrogen-related efforts are currently being supported by companies such as Allied Chemical, Bethlehem Steel, General Motors, Gulf General Atomic, Pratt & Whitney, Rocketdyne and Teledyne.

Within ERDA we have established a Committee to coordinate our hydrogen energy R&D activities, to assist in identifying problem areas, issues and program planning, and to provide one means of coordinating with the efforts of others.

Internationally, we are cooperating with the major European countries, Canada and Japan under the auspices of the International Energy Agency.

CONCLUSION

In summary, we believe that it is desirable to explore the possibility that economically promising applications for hydrogen energy systems can be developed and we believe that ERDA is pursuing a balanced exploratory R&D program. The opportunities for hydrogen systems to compete for major energy markets will improve as advanced technologies are demonstrated in each aspect of use. Initially our interest in hydrogen was based on environmental considerations, but there now seems to be an equally promising potential for conservation.

Widespread use of hydrogen energy systems is not likely to come until late in the 1990's, and would require significant changes in our energy systems. Certain specialized applications such as storage and fuel cells for electric utility applications could come somewhat earlier. Applications showing capital or resources conservation are most likely to happen first.

It seems prudent to proceed with research, development and demonstration of all aspects of hydrogen technology, in order that the use of this unique material becomes a real option in our uncertain energy future.

STATEMENT OF DR. JAMES S. KANE, DEPUTY ASSISTANT ADMINISTRATOR FOR CONSERVATION, ENERGY RESEARCH AND DEVELOPMENT ADMINISTRATION; ACCOMPANIED BY DR. JACK VANDERRYN, ASSISTANT DIRECTOR FOR ENERGY STORAGE IN CONSERVATION, ERDA, AND DR. RAY ZAHRADNIK, ACTING DIRECTOR, DIVISION OF COAL CONVERSION AND UTILIZATION IN FOSSIL ENERGY, ERDA

Dr. KANE. Mr. Chairman and members of the committee, much attention has been given in the past few years to the possible role of hydrogen in our Nation's future energy systems. These hearings are thus appropriate and timely in this regard, and should be helpful in placing the future uses of this interesting and somewhat unique element into proper perspective.

I intend to provide you today with a brief overview of ERDA's R. & D. activities related to hydrogen technology, as well as indicate some possible future directions to which this technology may lead us.

As I pointed out, to assist me in this task, I am accompanied by Dr. Jack Vanderryn, Assistant Director for Energy Storage in Conservation, and Dr. Ray Zahradnik, who is Acting Director, Division of Coal Conversion and Utilizaton in Fossil Energy.

It should be noted that hydrogen-related activities are distributed throughout ERDA, and accordingly my testimony this morning will reflect activities related to a number of ERDA programs. There are representatives of these other programs here in the room today.

Before describing ERDA's activities, I would like to discuss the role of hydrogen in energy systems. I believe I'll jump over this first paragraph, since it repeats what you said. The misconception that I wanted to make, because there's lots of confusion, particularly in the press, is that hydrogen is some great new energy source. Of course, that is not true.

Hydrogen is an alternative form of energy. It's a synthetic fuel which we may chose to synthesize and use because of convenience, or because of some of its unique properties, but it is not in itself an energy source. You must always use more energy to get hydrogen than what you can get back from it when you finally use the hydrogen itself.

Mr. McCORMACK. Jim, if I may interrupt, I want to express my appreciation to you for making that point. I just wish that all the popular press could hear that statement and understand the simple fact that hydrogen is not a source of energy. It's a fuel that must be produced. I think if all of the press would help the public understand that, it would help us toward a more intelligent energy policy.

Dr. KANE. Thank you.

Hydrogen is widely used today. I have tabulated the uses. Ten billion pounds were produced in 1972, and its use is increasing.

The two uses that dominate in the table on page 2, of course, are the synthesis of ammonia, and the upgrading of crude oil to more useful products, generally gasoline. Uses are expected to increase, as I pointed out, and as you certainly know. The need to raise more food in this country can be expected to cause the fertilizer industry to grow. Later, as the processes come on line, which will derive synthetic fuel from coal, there will be an enormous increase in the demand for hydrogen. The largest hydrogen related program, then, is our synthetic fossil fuel program.

The first step of almost all the synthetic fuel program is to react coal with steam to get hydrogen, and, therefore, the synthetic fuel program produces, or will produce, an enormous amount of hydrogen. Of course, they'll turn right around and reuse it again by adding it to carbon atoms to get a hydrogenated synthetic fuel.

I sensed that this was not entirely what the committee wanted to hear about, so, in my statement, I didn't go into many of the details of our fossil fuel program. Dr. Zahradnik, who is directing this program, can certainly give you all the information you wish.

If you have questions related to any aspects of the production of hydrogen from coal, Dr. Zahradnik will be pleased to answer them.

Today essentially all of our hydrogen is derived from fossil sources. About 7 percent of the total methane, or natural gas consumed in this country is used for the production of hydrogen. It's cracked to give hydrogen. So if we are to have hydrogen in large supply in the future, it will either have to be methane derived, which is impossible with the decline in the supply of methane, or it will have to be coal derived, which is the process to be developed in the fossil energy program. Alternatively we could get it from some new sources of energy, such as nuclear or solar.

Now, these nonfossil energy sources produce their energy in the form of heat or electricity, and so as these sources become predominant, and especially if coal becomes relatively less available, new technology will be needed to produce hydrogen from these sources.

I will now address the production and use of hydrogen, and some of the problems and technologies associated with hydrogen. First, the production.

Electric energy can be used directly to decompose water to obtain hydrogen and oxygen. This process is called electrolysis. A current program within ERDA includes research to improve the efficiency of the electrolysis process and to lower the capital cost of the associated equipment. The efficiency of electrolysis is now about 60 percent. It may be possible to raise that to 90 percent. There are also, of course, many uses for the additional quantity of oxygen which would be produced. However, we've never taken credit for it in our calculations.

So electrolysis can augment the ways of getting hydrogen from natural gas and from coal. Electrolysis may not be the only way that we can get it in commercial amounts. However, it may also be possible to obtain hydrogen from water by the use of heat instead of electricity. This process is often referred to as thermochemical watersplitting, and from a practical point of view it cannot be done in one step, simply by heating water. The temperatures would be too high to decompose water just by heating it. So it involves a series of steps of chemical reactions. They're cyclic in nature. Some of them absorb energy at high temperatures; others reject energy at low temperatures; by a combination of these steps you can get an overall process which basically consumes only water and heat, and produces hydrogen and oxygen.

These thermochemical processes, as they are called, in contrast to electrolysis, have not yet been demonstrated on a practical scale. I emphasize the word "practical." There's no question they work in theory and on paper; however, the ingenuity you referred to in your introductory remarks will certainly be needed to make these practical processes. By "practical" I mean economical and feasible.

There is considerable interest in this concept in both the university and industrial communities, as I'm sure your subsequent witnesses will bear out.

Hybrid processes, using a combination of electric energy and heat to obtain hydrogen and oxygen from water, may also be possible.

As coal becomes expensive, or in situations where nuclear or solar energy would be competitive with coal, then we would want to use heat from these other sources to avoid burning coal. We could also in this way enhance the yield of hydrogen we get from coal. The first contender would certainly be nuclear heat from a high temperature gas-cooled reactor. Such processes could save a great quantity of coal. In other words, that would make the process of converting coal to hydrogen much more efficient.

This process, however, could not be implemented with the present state-of-the-art. You have to do one of two things. You would either have to use a reactor that generates higher temperatures, such as the graphite moderated gas-cooled reactor; or you would have to lower the temperature at which this process occurs. There are programs within ERDA directed toward both these goals.

USES OF HYDROGEN

I have not considered the use of hydrogen in either the aerospace field or in aeronautics, because I'm sure the subsequent witness, Dr. Schmitt, will be discussing these applications.

Hydrogen, as you know, in principle, can serve as a fuel that can replace conventional fuels almost anywhere, including industrial applications, electric power generation, and for residential, commercial, and transportation uses. By "can" I mean there's no technical reason you can't do it, though there may be practical and economic reasons why you might not wish to do it at the current time. Hydrogen can also be used as a reducing agent in metallurgical processes, such as steelmaking, where we presently use coal.

The theme that runs throughout my statement is that in the future, as coal becomes more costly, and if other forms of energy, such as fission, fusion, or solar become cheaper, we will, of course, be looking for ways of better utilizing these forms of energy.

Also, looking ahead to a possible fossil energy scarcity, which will happen some day, I suppose, it's good to think of processes by which we could use new forms of energy to replace coal.

Again, I want to bring out this point: Often there are some disadvantages to the use of hydrogen. You certainly do sacrifice energy to get hydrogen, in that you can never get as much back as you put in in the first place. But it still may be advantageous to go through this process, and I've picked out some examples where this may prove to be true. The first of these is load-leveling by the utilities. I'm sure I don't have to tell this committee of the enormous capital costs of our electrical system. Both the generation system and the distribution system is currently used, I believe, at 50 to 60 percent of its maximum capacity. The use of hydrogen as a load-leveling means for utility applications is not a saver of energy, but it may turn out to be a very large saver of capital, through the storage of electricity. The utilities must meet demand, and demand varies dramatically with the time of day. Thus, the full capacity of the system is not used for a good part of the day, and if it were possible to somehow generate energy in a convenient form that could be stored, and then use it subsequently in a period of high demand, this could be a more efficient use of the system.

It may be possible to use hydrogen technology to do this by the process of electrolyzing the water during periods of low demands, storing the hydrogen, and using it subsequently to generate electricity at periods of high demand. The processes that would have to be perfected in order to do this are electrolysis, storage, and fuel cell technology.

We haven't at all covered the processes, which have to be performed when you go from alternating current to direct current. It has to be rectified, and then if the fuel cells generate direct current it has to be interrupted, and reconverted back into alternating current. I'm not going to discuss this today.

I assume these processes are available, and, indeed, they are becoming available, on a commercial level, through solid-state technology and other means. Some further improvements will be required.

Mr. McCORMACK. Are you doing any studies to show the total efficiency of the hydrogen peaking system, including use of fuel cells?

Dr. KANE. Yes, we are, and Dr. Vanderryn will give you specific data on that, either now or subsequently, whichever you wish.

Mr. McCORMACK. Whenever you see fit.

Dr. KANE. The unit operations needed to use hydrogen for this load-leveling application are: Electrolysis, storage, and finally the reconversion to electricity, using fuel cells. Actually, it doesn't have to be fuel cells. You can burn hydrogen in a turbine, but the efficiency of the fuel cells certainly indicates that they would be useful.

All of these technologies need improvement to lower their cost and increase their efficiencies and our 1976 program includes R. & D. on all those technologies. I'll have Dr. Vanderryn go into the efficiencies at the end of this next section.

In addition to load leveling, hydrogen can also be used to produce electricity directly, using a high-efficiency converter such as the fuel cell, or by burning the hydrogen in a turbine. The hydrogen fuel cell is thought to have a potential efficiency of perhaps 60 percent. This could be coupled with a possible 60 percent efficient coal-to-hydrogen process. Dr. Zahradnik will perhaps expand on that.

You see, the idea is to start with a lump of coal and find the most efficient means to convert this to electricity. One route might be to burn the coal directly, and remove the sulfur, and so forth. Another route might be to convert the coal to a synthetic fuel, burn that under a boiler. The third route might be to use the coal to produce hydrogen and use that in a fuel cell.

The latter is what I'm discussing today. We think this route of coal-to-electricity would yield an overall efficiency of 36 percent, which approaches today's best fossil fuel plants which have an efficiency of about 40 percent. If you subtract out the penalties imposed by the clean up of the sulfur and the ash in conventional plants, I think the hydrogen fuel cell route would be competitive today.

I would like to point out additional advantages of fuel cells for electrical generation. The cells are modular and need not be installed initially in large size. I need not point out to the committee the problems that the utilities are having in bringing on the very large blocks of power in their central stations these days.

So the modular aspects of the fuel cells are very attractive. They're quiet, clean, and safe; they can be located close to the load centers, which reduces the need for the large overhead high voltage transmission lines, and by putting them close to the load centers there may also be opportunities to use their waste heat.

One promising, near-commercial fuel cell comes in a package about 25 megawatts, which is a very convenient size for large shopping centers, et cetera. If the waste heat is produced close enough to the consumer, you might think of using it.

Fuel cells are also well suited for small utilities, municipally owned utilities and some rural organizations, that don't need very large installation. The only way they can get their energy today is by forming cooperatives or buying power from a large utility.

To compete economically with present means of electrical generation, the hydrogen fuel cell would have to be priced at about $200 a kilowatt, and in my statement I pointed out that the development cost goal of the hydrocarbon fuel cell which is now under commercial consideration is approximately of this magnitude. Since the hydrogen fuel cell is almost surely simpler than the more complicated hydrocarbon fuel cell, if they can achieve their $200 a kilowatt goal, then the hydrogen fuel cell at $200 a kilowatt should be achievable too.

Our program in 1976 provides for R. & D. in both conversion technologies; fuel cells and turbines.

The next point I would like to make is that you can substitute hydrogen for natural gas, up to perhaps 8 percent. There's considerable R. & D. going on as to how much hydrogen you can put in natural gas and use the current system. I don't want to commit to a definite number because, as I point out, there are still a number of unknowns. One of them, which I'll discuss later, being the hydrogen embrittlement problem and the effect of hydrogen on the current pipeline transmission system. From the combustion standpoint, it certainly can be substituted for natural gas and burned in ordinary burners. If you wanted to extend the supply of natural gas and had a source of hydrogen, this would be a way you could use it.

AUTOMOTIVE APPLICATIONS

In transportation applications storage is the crucial question. We don't believe that liquid or high-pressure gaseous hydrogen would be a practical means of storage. Accordingly we have focused our efforts on solid-state storage, and by that I mean storing it in solid hydrides. These solid hydride materials represent a higher density method of storing hydrogen, many of them, than liquid hydrogen itself. In other words, a cubic foot of these hydrides can contain as much hydrogen as a tank of liquid hydrogen a cubic foot in volume. So they're a very efficient method of storing hydrogen.

I don't mean to imply that this is a fully developed technology. There remain great difficulties in this.

So our R. & D. program related to transportation emphasizes, very heavily, practical storage mechanisms with solid hydrides the chief candidates.

On delivery systems, I want to point out that pipelines are possible storage systems too. They not only deliver the gas to the customer, but they can store hydrogen in their volume, which is rather large, under high pressure. You can pump into the pipeline and then use it subsequently. It is a big storage mechanism.

Before a hydrogen delivery system could be put in service, it would have to be proven that the chemical effect of the hydrogen on the structural materials throughout would not lead to safety problems. We've given this problem some attention during the past year, and we plan to continue. Our preliminary information indicates that a large part of our current distribution system could be modified to handle hydrogen safely.

I'll ask Dr. Vanderryn this later, but I believe that, just as in the electrical business, the distinction is made between transmission and distribution. The big, high-pressure system is transmission, and the distribution system is the relatively low-pressure system that occurs under the streets out here, that's the distribution system.

Dr. VANDERRYN. Yes.

Dr. KANE. As you pointed out, Mr. Chairman, there are billions of dollars invested in the existing pipeline system. If we could use this, it would be a very attractive feature. So we have an ongoing program in this area.

As to environmental effects, I commented, as you did, that hydrogen looks very attractive from an environmental viewpoint. The largest environmental impact associated with hydrogen will certainly be that caused by the energy sources which are used to get hydrogen in the first place. For most part, water is the only byproduct.

Hydrogen is frequently used to obtain very hot flames in air. Because hydrogen does have such a high flame temperature, it has a tendency to form nitrogen oxides. But for most applications you don't have to burn it under the kind of conditions, where you get very high flame temperatures. In fact, for most uses of hydrogen I think the nitrogen oxide problem will be less than for other hazardous fuels. So it is an environmentally attractive fuel.

I mentioned the safety problems associated with gaseous hydrogen, which I'm sure Dr. Schmitt will talk about later.

Hydrogen has had a bad press, dating back to the *Hindenburg* accident. Actually, NASA has shown that hydrogen can be handled in large volumes safely. They have a long history of this. There are reasons, which I won't go into today, which actually make hydrogen safer to handle than other fuels. For instance, its very high diffusion rate and its low atomic weight, mean it rises and diffuses away quickly. Other hazardous fuels may tend to form a very dangerous pool, which persists. Although hydrogen may conjure up a picture of the *Hindenburg* burning, it can be a safe fuel if it's handled properly.

The previously mentioned embrittlement problem will have to be checked very closely. We have already started an examination of the overall environmental, legal, economic and social aspects of hydrogen use, and we see no insurmountable problems. We will continue this investigation.

In addition to the work I've already described, which you are acquainted with, and which is devoted to the more practical aspects, we have a considerable amount of basic research going on in ERDA to increase our overall fund of knowledge. Things like the basic properties of the hydrogen isotopes will be very important, in our fusion program, and in other programs. Work on hydrides, photochemical processes, and on the fundamental properties of hydrogen, and hydrogen's interaction with other materials are ongoing.

Before I close, I'll mention briefly the magnitude of our effort.

In 1975, hydrogen-related ERDA activities were dominated by programs related to synthetic fuels. Now, I don't mean to imply that all the money that the synthetic fuel people spent was specifically aimed at hydrogen, and Dr. Zahradnik will go into any aspect of that you care to pursue.

We spent $263 million on synthetic fuels process development, and much of that, of course, concerns the development of hydrogen-related processes. About $6 million could be specifically identified as concerned with hydrogen production. About $10 million total was spent on other technologies, as follows: About $1 million each on production from water, high temperature reactor technology, and storage and delivery systems; about $3 million on photochemical research; and $4 million on basic and supporting research.

In fiscal year 1976 we are planning substantial increases in effort, especially in hydrogen production from coal, high temperature reactor technology, and hydrogen conversion technology. By "conversion" I mean both the fuel cells and the turbines.

Although ERDA has the major responsibility for the Federal hydrogen R. & D. effort, we intend to use other Federal agencies and laboratories in carrying out this program.

I might also point out that there are some industrial activities, reflecting considerable interest in the industrial sector, in hydrogen.

Within ERDA we've established a committee to coordinate our hydrogen energy R. & D. activities to assist in identifying problem areas, issues, and program planning, and to provide one means of coordination with the efforts of others. It just can't stress this too much, that this committee includes representatives from almost every organization in ERDA.

In conclusion, we believe it's desirable to explore the possibility that economically promising applications for hydrogen energy systems can be developed, and we believe that ERDA is pursuing a balanced exploratory R. & D. program. The opportunities for hydrogen systems to compete for major energy markets will improve as advanced technologies are demonstrated in each aspect of its use. Initially our interest in hydrogen was based on environmental considerations, but there now seems to be an equally promising potential for conservation, and I use that "conservation" in the broadest sense, not only conservation of energy, but also conservation of capital resources.

Widespread use of hydrogen energy systems is not likely to come until the 1990's, and would require significant changes in our energy systems. Certain specialized applications, such as storage and fuel cells for electric utility applications, could come somewhat earlier.

Applications showing capital or resources conservation are most likely to happen first.

It seems prudent to proceed with research, development, and demonstration of all aspects of hydrogen technology, in order that the use of this unique material become a real option—and I want to emphasize that point. I think ERDA's business is the generation of options. We seek to make it possible that hydrogen use will become real option in our uncertain energy future.

That concludes my testimony, and I'll be glad to answer any questions you may have.

Mr. McCormack. Thank you, Jim. As always, it's a pleasure to have you here, and a pleasure to listen to your testimony. It's both constructive and stimulating.

I have a couple of quick questions.

Perhaps a year ago, I visited the KMS Laboratories in Ann Arbor, Mich. At that time they were talking about doing computerized research on the thermochemical production of hydrogen, trying to go through all the conceivable chemical combinations that might exist, and put the two-step, and the three-step, and the four-step, and the five-step reactions all in some sort of coherent pattern for analysis and come up with something that would be the most practical in terms of lowest possible temperature, and the most economical chemical reactors.

I'm curious to know if you know anything about this? Do you know whether you're supporting this program, or are you doing parallel work? Are you generally working in these areas?

Dr. Kane. I could try part of that, but I believe I'll ask Vanderryn to handle it. You mean the thermochemical processes? KMS was also interested in using fusion neutrons directly to dissociate water.

Mr. McCormack. At that time they were talking about the thermochemicals.

Dr. Vanderryn. We have talked with the KMS people, and the kind of approach that you mention, Mr. Chairman, on the thermochemical cycles is going on in a large number of laboratories in the United States and abroad.

We are supporting work at Los Alamos, Oak Ridge, and Argonne. There are also a number of industrial organizations including General Atomic and Westinghouse who are investigating these thermochemical cycles.

There are, as you mentioned, a large number of possible cycles, and the first step is to put these on a computer to examine the thermodynamics and determine the most favorable conditions for these cycles.

The work at KMS is supported by our Division of Military Applications. I am not certain whether they are supporting the thermochemical work in particular.

But there's a large effort going on in the United States, some of it supported by ERDA, looking at these various thermochemical cycles.

Mr. McCormack. One would think that the answers, that the best options, from such a study would be available in a relatively short time period, of a few months.

Is that too optimistic?

Dr. VANDERRYN. The problem with these cycles, as Dr. Kane mentioned, is not simply having the results from the paper studies. It's then going into the laboratory, and then going to a small engineering scale to really see whether one can engineer these processes and whether the efficiencies and their costs would be competitive.

So I would say it will be on the order of 3 to 5 years before we begin to get a reasonably good indication of whether, on an engineering scale, these processes might be competitive.

Mr. McCORMACK. I appreciate that, but I wonder if I could ask another quick question.

On paper at least, how long do you think it would take you to give you some good candidate processes?

Dr. VANDERRYN. We've beginning to get some good candidate processes on paper now.

Mr. McCORMACK. Good.

Have you considered also such matters as the use of byproduct oxygen in waste processes in the incinerating of waste?

Does that make any sense to include oxygen in your economic balance sheets for these purposes?

Dr. VANDERRYN. As Dr. Kane mentioned, in waste processing, oxygen certainly can be used. I'm not certain whether this use would be as large as the quantities that we might have available if we go into a large hydrogen economy, I'm not certain. I think the waste people would have to look at that more specifically. I cannot answer your question in detail. But we certainly could provide an answer to you.

Mr. McCORMACK. It really is a thought for consideration.

Mr. Brown.

Mr. BROWN. Thank you, Mr. Chairman.

Just a couple of points.

I'm very much interested in that particular area. Out in California there's a great deal of interest in hydrogen as an automotive fuel. Is it true that storage is the largest problem that inhibits the expedited use of hydrogen as a fuel, and would your research on hydrides resolve this problem in the near future, or are there other major programs with regard to its uses?

Dr. KANE. Jack, may I refer that to you?

Dr. VANDERRYN. While it has been shown that the internal combustion engine can operate on hydrogen successfully one would need to optimize engine design. It is an engineering problem.

We feel that the real problem is to find a suitable, safe and economic way to store hydrogen onboard. The problem is that the current hydrides that we have available, the iron-titanium hydride, for example, that is being looked at for stationary storage applications, is too heavy to use onboard. For the lighter materials, like magnesium hydride, it turns out that the energy required to drive the hydrogen off the hydride for use is probably too great for onboard vehicles. So one has to find a suitable hydride, perhaps other alloys, for onboard use. We don't understand enough about the fundamental behavior of hydrides to be able to exactly predict what compound this might be.

Thus it simply requires additional work to, hopefully, find a suitable compound that is cheap enough, light enough, and effective to be suitably used onboard the automobile.

Mr. BROWN. How much effort is put into this program?

Dr. VANDERRYN. The hydride work at ERDA is, I believe, about $3 million. Which includes fundamental and applied work. But I can get you a more exact number on that.

[The information follows:]

In fiscal year 1975, about $2.6 million was spent on hydride R. & D.

Mr. BROWN. There is a small firm in Utah that's worked diligently on the hydrogen processes for automotive propulsion. There's even a film out on this now, which I saw a couple of weeks ago, and there are some rather interesting economic projections, which indicate that the cost of using hydrogen as a fuel would be less than that of gasoline, given certain assumptions with regard to taxation, and so forth, which may or may not be true.

But if further development is being held up by the storage problem, I would think that possibly a substantial effort could be justified in trying to resolve that in the fairly near term future, in view of the amount of emphasis which is being put on reducing the demand for gasoline. The current debate on the energy bill, for example, illustrates this. I shall not press the point, but I would like to have it given some consideration.

Also, under basic research you mention photochemical processes, but I do not note any reference to the nature of those processes in your testimony, Dr. Kane. Could you elaborate just a little bit?

Dr. KANE. As I understand it, they are processes where photons produce hydrogen from water directly when they shine on certain oxides. Is there anyone here to address that?

Dr. VANDERRYN. Dr. Stevenson.

Dr. STEVENSON. There is some research going on, to better understand the photosynthetic process, which I believe is the research you're referring to. Some of this is being done at the University of California.

The idea here is to perhaps interrupt the natural process of separating, splitting, the hydrogen and oxygen in the water, and recovering the hydrogen separately. This is in the very early stages, and it would probably take a lengthy research effort to make this a viable process.

Mr. BROWN. Is this related to the thermochemical processes?

Dr. STEVENSON. No; this is not related to thermochemical. This is using solar energy for low temperature synthesis, as a source.

Mr. MCCORMACK. Would the gentleman yield on that?

Mr. BROWN. Certainly.

Mr. MCCORMACK. When you use the word "photosynthetic" are you using it in the classical sense, are you talking about the chlorophyll reaction, for instance?

Dr. STEVENSON. Yes. The photon enters into the chlorophyll reaction and causes, through a very complex mechanism, which is still not well understood, through electron transfer reactions, the splitting of the water molecule. In the photosynthetic process nature produces oxygen as its product. Man would like to be able to alter that in such a way that hydrogen is a new product, and not oxygen.

Mr. MCCORMACK. Are there not some reactions using solar energy enabling you to procure hydrogen directly, or is it methane?

Dr. STEVENSON. It's usually methane.

Mr. MCCORMACK. Thank you very much.

Mr. Brown, do you have further questions?

Mr. BROWN. I don't have any further questions.

I would just comment that Dr. Kane used the term, or the adjective, ubiquitous, in referring to hydrogen, and the general connotation is, with regard to the use of "ubiquitous," that it is an annoying situation. I hope that does not turn out to be true with hydrogen.

Mr. McCormack. Thank you, Mr. Brown.

Mr. Harkin.

Mr. Harkin. Thank you, Mr. Chairman.

Mr. Kane, on page 5 you talked about thermochemical watersplitting. Could you clarify one point for me? You said this splitting cannot be done by simply heating water. Then you said "the total process consumes only water and heat."

Dr. Kane. Yes. Let me try to explain that a little better.

Water, of course, is H_2O, and if you heat it hot enough it will come apart to its component atoms. But under normal conditions, that "hot enough" is so hot that it's not practical. So you can not just take a container, put water in it, and heat it until it comes apart to make oxygen and hydrogen.

Mr. Harkin. How high do you have to get it?

Dr. Kane. The higher you get it, the higher the pressures of its two components go. But to get any reasonable pressures you have to go to 2,500 degrees Centigrade, something like that, which is 5,000 Farenheit, very hot indeed. There are not any materials that you can use to hold the water at those temperatures. So, to take it apart in a single step, in which you just heat it, is totally impractical. It's possible, but totally impractical.

Mr. Harkin. I see. But it could be a part of a step of a process?

Dr. Kane. If you take a number of steps, and don't just take it apart in one step, but add heat to get products, and then cycle through other steps, then you can do it at lower temperatures. That's the whole point, yes.

Mr. Harkin. I see. What you are saying, then, is that it is inefficient to use some other source of energy to get those extremely high temperatures. Is that what you're saying?

Dr. Kane. It's now impossible with our knowledge of materials. There's no container that you could put it in to hold it at these high temperatures.

Mr. Harkins. I see. It is a container problem?

Dr. Kane. It's a materials and container problem. There may be other problems, but predominantly it's a materials problem, yes.

Mr. Harkins. I was thinking of that in terms of using intense en-energy, heat from the Sun, and that type of thing, to reach those temperatures, which could be done quite easily.

Dr. Kane. That's right. There is no material that you could contain the hydrogen in where it would dissociate appreciably.

Mr. Harkins. I see. Is there some research going into that?

Dr. Kane. Into the multistep approach, rather than trying to develop materials which are probably beyond the capability of technology to reach. Rather than do that, we've chosen to go the multistep process.

Mr. Harkins. Could solar energy, then, be used in that multistep process?

Dr. KANE. It's conceivable that it could be used, yes. In fact, the two candidates that most scientists talk about for doing this are nuclear energy and solar energy.

Mr. HARKIN. What is the magnitude of effort that actually would be going into something like that?

Dr. KANE. Within ERDA, Dr. Vanderryn can probably give you the number.

I want to point out that, so some of your later witnesses from the university sector will testify, there's a lot of academic interest in this now, and so ERDA doesn't represent all the effort.

Dr. Vanderryn, how much are we doing?

Dr. VANDERRYN. It's in the neighborhood of $1½ million per year at the present time. But, of course, there's other related fundamental research that is also going on.

What these cycles involve is adding various chemical substances to the water, which are than recycled in a closed system themselves. This permits us to lower the temperature at which we can get off the hydrogen and the oxygen.

Mr. HARKIN. I see. I am interested in that. Where is it being done?

Dr. VANDERRYN. It's being done at a number of institutions a number of ERDA laboratories, like Los Alamos, and Argonne. I think Dr. Funk, who's testifying later, will talk in more detail about that. He has done considerable work in this area at the University of Kentucky. Also, in a number of foreign laboratories work is underway, and also a number of commercial companies in the United States.

Mr. HARKIN. Is there no consumption of any of the chemical substances that are used?

Dr. VANDERRYN. Theoretically, there's no consumption. Of course, in any cycle like this, on an engineering scale, you will have small losses in the cycle. It's never 100 percent recyclable. The problem is to minimize the losses in such cycles especially if the cycle involves a fairly high cost chemical.

Mr. HARKIN. I see. Thank you.

Mr. MCCORMACK. Thank you, Mr. Harkin.

Mr. Thornton.

Mr. THORNTON. Thank you, Mr. Chairman.

At risk of either getting into an area where research is going on which I do not know of, or exploring an area where there may be scientific reasons why this cannot be done, still I want to ask whether—and the question occurred to me the other day when I was reading about the properties of hydrides and storing hydrogen more compactly and in greater densities than liquid hydrogen itself—has experimentation gone forward with, for example, uranium hydride?

Dr. KANE. Let me try to answer that.

There are many, many elements that form stable hydrides. Uranium hydride, for example, has a very high hydrogen content, but it also is very difficult to disassociate. Therefore, to get the hydrogen off you have to heat it to a very high temperature.

So the hydrides we're looking for should not only contain a high volume of hydrogen, but they must also give this hydrogen up at a reasonable temperature. Otherwise, you waste energy heating them to get the hydrogen back off. For instance, in transportation, you'd like to store the hydrogen so that you can use the heat from the exhaust of the engine to pull the hydrogen from the storage system.

Mr. THORNTON. I am pressing toward another point, and with some concern.

Uranium hydrides do exist?

Dr. KANE. Oh, yes.

Mr. THORNTON. How about the deuterium type rather than hydrogen, using uranium deuteride and using it in connection with laser devices, where presently liquid hydrogen, I believe, is used in a fusion reactor. Has that concept been explored?

Dr. KANE. I believe the use of deuterium would be impractical, unless you had it in a closed system where you recovered it. Deuterium is a naturally occurring material, but it costs to separate it from the hydrogen, in the first place. Deuterium is not too different from ordinary hydrogen.

I'm not sure I'm helping you, Mr. Thornton.

Mr. THORNTON. Are you familiar with the work, I believe it was at the KMS Laboratories, where the laser pellet system was used to achieve a release of energy from a fusion source? Is that pellet composed of, as I have supposed, just deuterium?

Mr. MCCORMACK. I think there are a number of modifications, a number of designs, of pellets, of deuterium pellets. And I think in pure theory there has been discussion all over the world of using uranium-235 with them so that you get some sort of a combination fusion-fission reaction.

Mr. THORNTON. Research has gone forward. The property of a hydride is interesting to me from the standpoint of storing deuterium in a very compact way, and I wanted to ask if research has been exploring that concept?

Dr. KANE. I might point out, without getting involved in classified subjects, that the Division of Military Applications for years has had quite an extensive program on all sorts of hydrides, and they have a lot of background information on that.

Mr. THORNTON. Thank you.

Mr. MCCORMACK. Thank you, Mr. Thornton.

May I ask a question, Dr. Kane?

How serious is hydrogen embrittlement in mild steel piping at ambient temperatures?

Dr. KANE. If you don't mind, there is a gentleman in the audience who has been doing a lot of this work for ERDA. Could I call upon him?

Mr. MCCORMACK. Certainly.

Dr. KANE. He's Dr. James Swisher from the Sandia Laboratories. Dr. Swisher, could you address that point?

Dr. SWISHER. We have an ongoing program that's been very active this fiscal year. We are investigating the properties of steels in hydrogen environments to see how low priced steels might compare with more expensive materials. What we have found is that ordinary mild steels are really not too bad, but they're not quite as good as stainless steels, which are 5 to 10 times more expensive.

Our feeling is that perhaps you might be able to use a coating, or a thin liner, to protect pipelines, or perhaps limit the operating stress.

We don't feel that the problems of putting hydrogen into existing natural gas pipelines are insurmountable.

Dr. VANDERRYN. I should also point out that it does depend on the pressure. In low pressure systems it's not a serious problem. As you increase the pressure, the problem would become worse.

Dr. KANE. That's why we distinguish between the distribution and transmission systems. As you probably know, there are many places in the world today using mixtures of carbon monoxide and hydrogen. As long as that's done in cast iron pipe, and low pressures, there is no problem. It's where you get to the very high pressures for things like transcontinental pipelines that you might get problems.

Mr. MCCORMACK. It would seem that a systems analysis of this entire question early on would be extremely helpful so that you could determine what the options are and what options you do not have with respect to hydrogen transmission questions.

Dr. KANE. Yes. I agree completely, and we intend to do this in our existing program.

Mr. MCCORMACK. You mentioned also the possibility of 36 percent efficiency from coal to electricity, and 60 percent efficient coal-to-hydrogen process, and the hydrogen fuel cell having a potential efficiency of 60 percent, but you sort of cast it in terms of for the future.

Do you have any idea when those efficiencies might be reached? Do you have any general projection in time?

Dr. KANE. I'd like to refer the gasification question to Dr. Zahradnik; and the hydrogen fuel cell question to Dr. Vanderryn.

Dr. ZAHRADNIK. The 60 percent figure is probably attainable for the coal-to-hydrogen process. If you were to arrange a more intimate swap of energy, it might be even better. We would go along with that figure, perhaps even add a few percent.

Mr. MCCORMACK. Thank you very much.

Dr. KANE. And the 60 percent in the fuel cells?

Dr. VANDERRYN. In certain kinds of fuel cells, the 60 percent is an attainable figure today, and I hope that perhaps with additional work we could improve that considerably.

Mr. MCCORMACK. Commercial size, 25 megawatt fuel cells?

Dr. VANDERRYN. We're not at that size as yet. Those really need to be fully demonstrated at that size level. But we certainly can attain 60 percent in laboratory size fuel cells.

Mr. MCCORMACK. Jim, gentlemen, thank you very much. We appreciate your testimony.

Our next witness is Dr. Harrison Schmitt, Assistant Administrator, Office of Energy Programs, National Aeronautics and Space Administration, accompanied by Dr. Ginter. Do you have Dr. Ginter with you?

Dr. SCHMITT. I think he's with me. If you can't see him, your eyes are worse than mine.

Mr. MCCORMACK. Mr. Ginter, Director of Energy Systems Division, Office of Energy Programs, for NASA.

Jack, it is always good to have you back again.

Dr. SCHMITT. Sir, it's good to be here.

Mr. MCCORMACK. If you wish, you may submit your statement for the record as it is and speak from it.

Dr. SCHMITT. I will do that, submit it as it is.

Mr. McCormack. With no objection, it will be submitted in the record as it is.

Dr. Schmitt. I may skip around a little bit.

[The prepared statement of Dr. Harrison H. Schmitt is as follows:]

STATEMENT OF DR. HARRISON H. SCHMITT, ASSISTANT ADMINISTRATOR, OFFICE OF ENERGY PROGRAMS, NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

Mr. Chairman and members of the committee: I appreciate the opportunity to discuss hydrogen with you this morning. As you know, hydrogen has played, and will continue to play, a very important role in meeting aerospace energy needs. We have nearly 20 years of experience in the use, handling, and storage of hydrogen. Hydrogen might, realistically, be called the space fuel. Liquid hydrogen propelled the Apollo-Saturn missions, provided power through the Apollo spacecraft fuel cells, fuels our Centaur launch vehicle, and will be used to fuel the Space Shuttle

Hydrogen is also a very important consideration in our Aeronautics program. It will be needed to manufacture liquid fuels from coal and, at some time in the future, it may fuel advanced transport aircraft.

I believe that other witnesses will testify concerning the unique nature of hydrogen, its place as the lightest chemical element, and the fact that it does not occur naturally in free form on earth. The fact that hydrogen must be manufactured is both an advantage and a disadvantage. From some standpoints, hydrogen is similar to electricity in that it must be created from other energy sources and that some energy is lost in the process. Both electricity and hydrogen, after being created, can be used to link a variety of energy sources with eventual consumers via transmission and distribution systems; power lines in the case of electricity and pipelines in the case of hydrogen. However, unlike electricity, hydrogen is more easily stored, particularly in its gaseous form.

Hydrogen is, therefore, a truly unique element, it is an important and necessary element in a large number of chemical processes; it can be used as a synthetic fuel; it is an "energy storage device"; and it can link energy sources to energy consumers.

Practically all the hydrogen now produced in this country is manufactured from natural gas. Obviously, if hydrogen is to be widely used in the future, regardless of how close to a "Hydrogen Economy" the Nation moves, it will be essential that it be produced someday from feed stocks other than natural gas.

Until the formation of ERDA, hydrogen research and technology was receiving little focused attention in the National Energy R&D planning efforts. Based on NASA's experience with hydrogen over about two decades, our recognized need to fully understand the advanced technology required to assure an economic and plentiful supply of hydrogen for aerospace needs, and an awareness that the use of hydrogen would most likely increase rather than decrease in the future, we initiated an in-house Hydrogen Energy Systems Technology (HEST) study about nine months ago.

Many other studies and reports on hydrogen have been prepared. Some of these have advocated the so called "Hydrogen Economy" while other have been much less optimistic. None of them, however, treated hydrogen as a distinct entity in Energy R&D planning, worthy of a focused technology advancement program to assure an economical supply capable of meeting the increasing demands.

The HEST study is designed as a two-phase effort during Fiscal Years 1975 and 1976. Our objective in the first phase is to define the technology advances which are necessary in relationship to the projected demands for hydrogen in all "use" categories. Our approach is to assess the status of hydrogen technology and then to outline the research and technology advancements required to meet various levels of projected demand.

We have formed a small study project at our Jet Propulsion Laboratory to lead the HEST study. An Inter-Center Working Panel, formed from the other NASA Centers, is being used to provide the broad base of experienced technology support which is required. The study is also supported by a special Review Group which has selected membership from other government agencies, industry, and universities. Our hope is that by using the experience of these people, and resolving their varying perspectives, we can achieve an objective definition of the work which must be done in Hydrogen Energy Technology.

HEST RESULTS

As expected, the initial results of the HEST study largely confirm many of the conclusions which have already been reached by others. It is also serving the criticaly important function of focussing the attention of a rather large representation from industry, government, and the academic community on the entire range of hydrogen technology problems at the same time. We have been encouraged by the remarkably consistent agreement which has developed among these various groups. Some general observations are as follows:

Hydrogen is now being widely used in a variety of applications and it represents a commodity value of over one billion dollars per year.

The major uses of hydrogen are:

Manufacture of ammonia for agriculture fertilizer.

Petroleum refining (hydrocracking and desulfurization).

Methanol Synthesis.

Production of chemicals.

Reducing agents.

Hydrogenation of fats and oils.

Clean combustion.

Industry fuel when hydrogen-rich gas is a by-product of other manufacturing, such as chlorine.

The use of hydrogen for the conversion of coal to liquid and gaseous forms, although not a major consumer of hydrogen at this time, will require extremely large amounts of hydrogen in the manufacture of these synthetic fuels.

Hydrogen is expected to become increasingly important in the reduction of iron in making steel.

In NASA's own programs, the Space Shuttle will require considerable amounts of liquid hydrogen in the future.

TECHNOLOGY STATUS

Without going into specific detail, the general status of hydrogen technology can be placed in perspective by viewing the problem as comprising three major areas: End-Use; Storage and Distribution; and Production.

The technology of end-use is relatively advanced. That is, we know how to burn hydrogen, and how to use it effectively and efficiently, when it is available at an economical price.

Storage and distribution technology is less advanced, but is probably adequate for immediate future requirements.

It is in the broad area of production where the need for technology advancement is most critical. As I have stated, the present supply of hydrogen is obtained almost entirely by using natural gas as a feed stock. This must be changed if there is to be hydrogen available to meet even the lowest levels of projected demands.

PRODUCTION

It is possible to use nearly any energy source to manufacture hydrogen. The critical questions are: (1) which of the many techniques, that do not require natural gas, are economically viable, and (2) which techniques can be developed and demonstrated in time to meet the expected demands.

Production techniques fall into three broad categories:

1. Conversion of hydrocarbon fuels in combination with water and oxygen to form hydrogen. Each such process requires that some form of hydrocarbon fuel (oil, natural gas, or coal) be available.

2. Conversion of electricity to hydrogen by electrolysis. The technique is relatively far advanced and available for use today. However, it demands that there be excess and inexpensive electric power generating capacity available. I should note that any non-technical factors must be considered when speaking of the conversion of electricity to hydrogen and that within the short time available today, it is not possible to place all of these in a proper perspective.

3. Thermal dissociation of water. This is an attractive, potential means of obtaining hydrogen. These processes could conceivably use any energy source, particularly nuclear and solar. I believe it is fair to state that the technology of thermal dissociation, regardless of heat source, is in its infancy. The promise

and potential is on paper. Our ability to efficiently and economically obtain hydrogen in this manner is critically dependent on the advances which can be made in a wide range of inter-related technologies. Some of the most important include high temperature materials; break-throughs in high temperature and efficient heat exchangers; more complete and detailed understanding of the physics and chemistry of the various processes; and a multitude of other factors too numerous to mention.

It may be that the importance of advancing the technology of hydrogen production can be best emphasized by recognizing that approximately 7% of the natural gas production of the Nation is now used to manufacture hydrogen. It appears to be imperative that we quickly learn how to obtain hydrogen economically from other energy sources.

These initial and preliminary results of the HEST study are not intended to represent new or startingly different data from what has been documented in other papers and testimony. They do reflect the perspective which has been developing in the broad hydrogen community and the baseline from which comprehensive and detailed technology advancement plans can be generated.

We expect to continue the second phase of this effort during Fiscal Year 1976. Using the general approach developed in the first phase, we will be exploring in considerable detail the definition of the technology advances actually required to assure that: hydrogen is available, can be properly stored, and safely used. Many of the potential uses of hydrogen, such as: "clean fuel"; energy storage; fuel for fuel cells; and as a fuel for selected transportation modes, will be analyzed in much more detail.

Our objectives are to document the needs for hydrogen in as realistic a manner as possible, to define the research and technology advances which are mandatory to obtain the quantity of hydrogen needed and to relate these in a comprehensive plan which could be implemented in the Fiscal Year 1977 period, if actually warranted. Our work will continue to be in direct cooperation with ERDA and in support of that Agency's developing National plans.

Speaking personally, I believe that there is no question but what we will eventually have some form of a "Hydrogen Economy." In fact, by my standards, the present billion dollar per year industry represents a good start.

There is also no question in my mind but that the need for hydrogen will continue to increase in the future. I suspect that we have just begun to appreciate the many uses for this unique element.

I believe that hydrogen, in addition to its uses in manufacturing, has a vital role in linking energy sources to energy consumers. I question whether the Nation can, or should, at this time, firmly commit only to electricity as our prime means of energy communication in the future.

I also know that we must be realistic in our expectations concerning the widespread availability of hydrogen as a means of energy distribution. Instead of taking extreme positive or negative positions, we must conduct the studies and implement the technology advancement plans which will enable the Nation to most effectively obtain and use this unique vital element.

STATEMENT OF DR. HARRISON H. SCHMITT, ASSISTANT ADMINISTRATOR FOR ENERGY PROGRAMS, NATIONAL AERONAUTICS AND SPACE ADMINISTRATION; ACCOMPANIED BY R. D. GINTER, DIRECTOR, ENERGY SYSTEMS DIVISION, OFFICE OF ENERGY PROGRAMS, NASA

Dr. SCHMITT. I think it's symbolic of the infancy of commercial hydrogen technology that we've all given each others' testimony this morning.

Not much has been done relative to future need, in my opinion, although much is being done, as Dr. Kane has indicated. ERDA has recognized this deficiency, as their entire testimony shows, and we are working with them to rectify it as rapidly as possible.

As you know, hydrogen has played, and will continue to play, a very important role in meeting the aerospace energy needs of the future and the present. We have in NASA nearly 20 years of experience in the use, handling, and storage of hydrogen. Hydrogen might, realistically, at the present time be called primarily a space fuel, which is its largest use as a fuel. Liquid hydrogen has propelled the Apollo-Saturn missions; it's provided power through the Apollo spacecraft fuel cells; at present fuels our Centaur launch vehicle for many of the unmanned satellite launches; and will be used as a fuel in the Space Shuttle.

Hydrogen is also a very important consideration in our aeronautics program, particularly the program of the future. It will be needed to manufacture liquid fuels from coal. As I have already noted, at some time in the future it may, in fact, fuel advanced transport aircraft.

The fact that hydrogen must be manufactured is both an advantage and a disadvantage to us. From some standpoints, hydrogen is similar to electricity in that it must be created from other energy sources and that some energy, as we have discussed already today, is lost in the process.

Both electricity and hydrogen, after being created, can be used to link a variety of energy sources with eventual consumers via transmission and distribution systems; power lines in the case of electricity, and pipelines in the case of hydrogen. However, unlike electricity, hydrogen is easier to store, and particularly in its gaseous form.

Practically all the hydrogen now produced in this country is manufactured from natural gas. Obviously, if hydrogen is to be widely used in the future, regardless of how close to a hydrogen economy the Nation moves, it will be essential that it be produced some day from feedstocks other than natural gas.

As you are aware, I am not quite as pessimistic as others are on the future supplies of natural gas, at least in the interim period of the next 10 years. If we do the right things, I think we can find lots of natural gas. But that doesn't mean we shouldn't look for another way of producing hydrogen.

Until the formation of ERDA, our hydrogen research and technology was receiving relatively little focused attention in the National Energy R. & D. planning efforts ,and, therefore, in mid-1974, we in NASA began to study the total problem, as we could define it. Based on our experience with hydrogen over two decades, our recognized need to fully understand the advanced technology required to assure an economic and plentiful supply of hydrogen for aerospace needs, and an awareness the the use of hydrogen would most likely increase rather than decrease in the future, we initiated an in-house hydrogen energy systems technology study about 9 months ago. The acronym, HEST, coincidentally and not by design, stands for horse in Norwegian, and so it's probably an appropriate ancronym.

Mr. McCormack. Not many persons besides you in NASA would know that.

[Laughter.]

Dr. Schmitt. Many other studies and reports on hydrogen have been prepared, and I'm sure your library shelf, like mine, has a fair stack of those. Some of these have advocated the so-called "Hydrogen Economy", while others have been less than optimistic. None of them, however, treated hydrogen as a distince entity in energy R. & D. planning, worthy of a focused technology advancement program to assure an economical supply capable of meeting the increasing demands.

The HEST study is designed as a two-phase effort during fiscal years 1975 and 1976. Our objective in the first phase is to define the technology advances which are necessary in relationship to the projected demands for hydrogen in all use categories. Our approach is to assess the status of hydrogen technology and then to outline the research and technology advancements required to meet various levels of projected demand.

We formed a small study project at our jet propulsion laboratory to lead the HEST study. An intercenter working panel was formed from the other NASA centers, and is being used to provide the broad base of experienced technology support which is required. The study is also supported by a special review group, which has selected membership from other Government agencies, such as ERDA, the NBS, the Department of Interior and the Department of Agriculture, and from industry and the universities. Our hope is that by using the experience of these people, and resolving their varying perspectives, we can achieve an objective definition of the work which must be done in hydrogen energy technology.

As expected, the initial results of the HEST study largely confirm many of the conclusions which have already been reached by others. It is also serving, maybe more importantly, the critically important function of focusing the attention of a rather large representation from industry, Government, and the academic community on the entire range of hydrogen technology problems at the same time. We have been encouraged by the remarkably consistent agreement which has developed among these groups.

Some general observations are as follows: First, that hydrogen is now being widely used in a variety of applications, as we've already heard today, and it represents a commodity value of over $1 billion per year, although that's a difficult number to estimate because it's an intermediate element of many processes.

Second, the major uses of hydrogen that we see are: The manufacture of ammonia for agriculture fertilizer; petroleum refining, which includes hydrocracking and desulfurization; methanol synthesis and the production of inorganic and organic chemicals such as reducing agents used in a variety of chemical processes; hydrogenation; clean combustion, particularly in the case of space fuels; and as an industry fuel, when hydrogen-rich gas is a byproduct of other manufacturing, such as that of chlorine.

Third, the use of hydrogen for the conversion of coal to liquid and gaseous forms, although not a major consumer of hydrogen at this time, will require extremely large amount of hydrogen in the manufacture of these synthetic fuels, as we look to satisfying the national goal of about 1 million barrels a day equivalent in 1985.

Fourth, hydrogen is expected to become increasingly important in the reduction of iron in making steel.

In NASA's own programs, the Space Shuttle will require considerable amounts of liquid hydrogen in the near future and on into the 1980's and subsequent years.

Mr. McCORMACK. What does this "million barrels a day equivalent in 1985" mean?

Dr. SCHMITT. The President's statement in February, I believe, where we're going to attempt to produce about——

Mr. McCORMACK. A million barrels a day, for instance, of synthetic fuel?

Dr. SCHMITT. In synthetic fuels. That will demand considerable hydrogen, which is quite a bit of pressure on us to come to an answer on the question which your committee is asking us as a nation, not us as NASA necessarily.

Mr. McCORMACK. Thank you.

Dr. SCHMITT. Without going into specific detail, the general status of hydrogen technology can be placed in perspective by viewing the problem as comprising three major areas: The end-use; storage and distribution; and production.

The technology of end-use for hydrogen is relatively advanced. That is, we know how to burn hydrogen, and how to use it effectively and efficiently, when its is available at an economical price.

The storage and distribution technology is less advanced, but is probably adequate in terms of its base for immediate future requirements.

It is in the broad area of production where the need for technology advancement is most crucial, and that has, of course, dominated our discussion today. As I have stated, the present supply of hydrogen is obtained almost entirely by using natural gas as a feedstock. This must be changed if there is to be hydrogen available to meet even the lowest levels of the projected demands.

It's possible to use nearly any energy source to manufacture hydrogen. The critical questions are: Which of the many techniques, that do not require natural gas, are economically viable; and which techniques can be developed and demonstrated in time to meet the expected demands.

The production techniques fall into three broad categories, as have been covered by Dr. Kane:

The conversion of hydrocarbon fuels;

The conversion of electricity to hydrogen by electrolysis; and

The thermal dissociation of water.

Our ability to efficiently and economically obtain hydrogen in this manner is critically dependent upon the advances which can be made in a wide range of interrelated technologies. Some of the most important include: High temperature materials; breakthrough in high temperature, efficient heat exchangers; and more complete and detailed understanding of the physics and chemistry of the various processes; and a multitude of other factors too numerous to mention, but which must be understood in a broad systems point of view, as you have suggested, Mr. Chairman.

It may be that the importance of advancing the technology of hydrogen production can be best emphasized by recognizing that approximately 7 percent, as Dr. Kane stated, for the natural gas production in the Nation is now used to manufacture hydrogen. It appears to be imperative that we quickly learn how to obtain hydrogen economically from other energy sources.

These initial and preliminary results of the HEST study are not intended to represent new or startlingly different data from what has been documented in other papers and testimony. They do reflect the perspective which has been developing in the broad hydrogen community and the baseline from which comprehensive and detailed technology advancement plans can be generated.

We expect to continue the second phase of this effort during fiscal year 1976. Using the general approach developed in the first phase, we will be exploring in considerable detail the definition of the technology advances actually required to assure that hydrogen is available, can be properly stored, and safely used. Many of the potential uses of hydrogen, such as: Clean fuel, an energy storage device, fuel for fuel cells, and as a fuel for selected transportation modes, will be analyzed in much more detail than we have today.

Our objectives are: First, to document the needs for hydrogen in as realistic a manner as possible; second, to define the research and technology advances which are mandatory to obtain the quantity of hydrogen needed; and, third, to relate these in a comprehensive plan which could be implemented in the fiscal year 1977 period, if it actually appears warranted. Our work will continue to be in direct cooperation with ERDA and in support of that Agency in developing national plans.

I probably should mention here that we are studying some of the questions that have been raised earlier this morning. In our Energy Conversion Alternative study, which has been performed at Lewis for ERDA and for the NSF, we are looking at electrical power generation modes from coal and coal-derived fuels, which include hydrogen, particularly as it is used in fuel cells. We also have a study involving high temperature process heat, which includes the thermal dissociation of water. This is part of the study referred to earlier that Westinghouse and General Atomics are undertaking, and that is also being done for ERDA.

Speaking personally, Mr. Chairman, I believe there is no question that we will eventually have some form of a "Hydrogen Economy." In fact, and I guess by my standards, the present $1 billion per year industry represents a good start.

There is also no question in my mind but that the need for hydrogen will continue to increase in the future. I suspect that we've just begun to appreciate the many uses for this unique element.

I believe that hydrogen, in addition to its uses in manufacturing, has a vital role in linking energy sources to energy consumers. I question whether the Nation can, or should, at this time firmly commit only to electricity as our prime means of energy communication in the future.

I also know that we must be realistic in our expectations concerning the widespread availability of hydrogen as a means of energy distribution. Instead of taking extreme positive or negative positions, we must conduct the studies and implement the technology advancement plans which will enable the Nation to most effectively obtain and use this unique and vital element.

I'd be happy to answer any questions, and, again, I appreciate the opportunity to be here.

Mr. McCormack. Thank you very much, Jack for your testimony, and I want to say I particularly appreciate the very obvious cooperative effort that your are putting together with ERDA.

I had a brainstorm as you were speaking, Jack. I'm curious to know—and I would like to ask both you and Dr. Kane this question—how close you are to achieving large volumes of high temperature gases in your R. & D. work?

Rather than have that question dangling out in space, I'll tell you what I was speaking about. We just decommissioned the Peachbottom HTGR, which was, I believe, 40 megawatts. This was, I think, decommissioned because it was no longer needed competitively in generating electricity. Here is a device close by that might be available, if we got to that general size of operation in the not too distant future.

Is there any comment on this, has this any value at all? Are you exploring this kind of approach, or is it unrealistic, the time scale, as to the production of high volumes?

Dr. SCHMITT. I'll defer, with a general answer, to Dr. Kane, Mr. Chairman. I would say that we feel that within the next year or so that research in high temperature materials is going to have to accelerate in many different areas, and in the use of high temperature gases, whether it's a closed cycle helium system for potential HTGR applications, or whether it's understanding the high-temperature properties of hydrogen and materials associated with it.

I'm not sure. Certainly, we are not prepared to detail what kind of program would be undertaken a year or two from now, but we think that is, in fact, an important part of our study, the HEST study, to look at those kinds of programs and how they would fit into the national R. & D. programs.

Jim, did you have some comments?

Dr. KANE. I can't give a nice, concise answer, but certainly if you look ahead to the future I'd say that we should try to replace fossil energies wherever possible. What can we replace them with in large quantities? And the first thing, the only thing, that looks like it's available in any kind of a time schedule is nuclear. So, therefore, where can you use nuclear as a source of high temperature process heat? And if you look at the places where you can make big inroads, there's a number of electroprocesses that use a large amount of heat, and they would be amenable to being located close to the reactor, for instance. We had at least one meeting on that, an interagency meeting, which the old AEC, or maybe ERDA sponsored, to look at just that question: What are the large consumers of commercial heat now supplied by fossil energy totally, and is there a chance that nuclear energy could replace this?

I might point out that there's an intensive effort in Germany on the same subject, and I think it's something we all should keep in mind, that someday we have to look very hard at the use of coal and fossil energy, and can we switch this to more permanent energy sources.

Now, my reaction to Peachbottom is that in general the big industrial consumers of heat demand a little higher temperature than the first generation of the gas-cooled reactors use. In other words, I think it would take an extension to perhaps the temperatures of the German Pebble-bed reactor before these really get interesting. I believe that's 900 centigrade.

Mr. MCCORMACK. Yes.

Dr. KANE. So I think in the future Peachbottom might be an interesting thing to solve some of the problems involved with coupling, but as far as supplying a high enough temperature for, say, reforming, or shift reactions, or some of the big consumers. Mr. Womack is here from R. & D. Would you mind if he spoke on that?

Mr. McCORMACK. I'd be delighted.

Mr. WOMACK. I think we spoke briefly on this about a year ago, about the possibility of using Peachbottom for some potential experimental program.

I believe, from some of the testimony this morning, and our view in that is, indeed, a quite promising area. The R. & D. that needs to be done in high-temperature materials and components for the processes, still puts it some years off from effectively teaming and coupling processes, teaming nuclear heat generation to hydrogen generation, and that the process development, particularly heat exchange development, can best be done in nonnuclear facilities during that period because it's considerably easier.

We do have a program, which has close cooperation with NASA and other parts of the RDA, in which we are trying to carry that forward in a way that will bring these things together some years hence, but retaining the Peachbottom reactor for that purpose did not appear to us to be the most effective way to do it, which is not to say we're not terribly interested in that.

Mr. McCORMACK. Thank you very much, because at least that means my question was not totally stupid.

Mr. Thornton.

Mr. THORNTON. Thank you, Mr. Chairman. Just a couple of questions, following the lines you just outlined.

A couple of years ago we restored to the NASA budget $10 million for continued research in several areas of nuclear power. That was Mr. Hechler's committee, and now Mr. Fuqua's committee.

Mr. HECHLER. The Thornton amendment.

Mr. THORNTON. Yes; it was. We restored a $10 million program, including such things as the high-temperature gas-cooled reactor, which was then being conceived for space propulsion purposes.

Does this reactor have the temperatures necessary to be useful in the hydrogen process, or gasification process?

Dr. SCHMIDT. Mr. Thornton, I'm going to have to supply that information for the record, unless Mr. Ginter has that answer.

The nuclear efforts that NASA has relative to space propulsion are in the research side of the OAST, the Office of Aeronautics and Space Technology, and we will have to get that information for you.

Mr. THORNTON. It seemed to me at the time that this was done that there was a discussion that this was a possibility, that the heat source from this unit would be of a sufficiently high temperature to be useful in coal gasification, and I would appreciate that being supplied.

Dr. SCHMITT. We will look into that. I do know that we've had some very interesting research going on in gas core reactors and this kind of thing as a result of this appropriation. We'll get you some information for the record.

Mr. THORNTON. Good. Thank you.

[The information follows:]

Question. Does this reactor have the temperatures necessary to be useful in the hydrogen process, or gasification process?

Answer. Under NASA OAST, studies and initial experiments are being conducted on gas core reactors which contain the nuclear fuel in the gaseous or vapor state in contrast to conventional reactors (including the gas cooled reactor) that contain the nuclear fuel in form of solid fuel rods. Because of the gaseous or vapor state of the fuel in gas core reactors, such reactors could be operated over wide ranges of temperature, up to many thousands of degrees. Operation at the very high temperatures is a long range research goal of NASA, for space propulsion at high thrust and high specific impulse.

The gas core reactor has the long term potential of meeting the temperature requirements for hydrogen production and coal gasification. An additional benefit in this category of application would be in the area of steel production, particularly in regions that have plentiful ore but little coal.

Mr. THORNTON. With regard to the use of natural gas as a source for hydrogen, we had a few moments ago the figure of an overall 36-percent efficiency, I believe, going from coal, to hydrogen, to electricity.

Dr. SCHMITT. Through the fuel cell.

Mr. THORNTON. Through the fuel cell, correct.

Can you tell me whether the dissociation of hydrogen from methane achieves similar efficiencies, or do you get that good a product when you use natural gas, or methane, or another source material?

Dr. SCHMITT. I suspect that the overall efficiency is somewhat less because of an extra step in there.

We'll work with Jim to get that supplied for the record also.

[The information requested follows:]

Question. Can you tell me whether the dissociation of hydrogen from methane achieves similar efficiencies, or do you get that good a product when you use natural gas, or methane or another source material?

Answer. Hydrogen, the present fuel required by fuel cells, can be more efficiently processed from methane than from coal. Therefore, fuel cells using methane the fuel feedstock will have higher efficiencies than those that use coal. First generation fuel cells, which should be commercially available about 1980, have achieved efficiencies of 37 to 40% in demonstration tests using methane as the fuel. Advance fuel cell systems located near the consumer will achieve significantly higher efficiencies from fuel cell performance improvements and by utilizing the waste heat.

Mr. THORNTON. I would like to have that supplied for the record, because I tend to agree with you that if natural gas can be efficiently converted to hydrogen, then this would be an efficient use of a diminishing natural resource, rather than consuming it in the process. But would the efficiency of the conversion be material?

Dr. SCHMITT. Mr. Thornton, that's unquestionably one of the motivations behind the large industry effort, which is also supported by the gas utilities, in the development of a commercial fuel cell. In the interim stage, when we still are going to be dependent upon the use of natural gas prior to a large coal gasification industry developing, it does provide a more efficient use of that scarce fuel. I think we have to remember that the fuel cell does offer the possibility of having a variety of hydrocarbon fuels and hydrogen as the initial starting fuel, and that even though you develop now to use natural gas, it can be converted quite easily, with time, into other fuels.

Mr. THORNTON. Jack, I want to thank you very much for your good testimony this morning.

Dr. SCHMITT. Thank you very much, sir.

Mr. MCCORMACK. And I want to thank you too, Jack. It was very nice of you to come.

Dr. SCHMITT. It's a pleasure. Thank you, sir.

Mr. MCCORMACK. Thank you.

Our next witness is Dr. James Funk, dean of the College of Engineering at the University of Kentucky.

Dr. Funk, make yourself at home.

Do you have anyone accompanying you that you would like to bring to the table with you?

Dr. FUNK. No, I don't.

Mr. MCCORMACK. OK. We welcome you to the hearing. Go right ahead and proceed in any way you wish.

[The statement of Dr. Funk follows:]

STATEMENT OF DR. JAMES E. FUNK, DEAN, COLLEGE OF ENGINEERING UNIVERSITY OF KENTUCKY

Dr. FUNK. I would like to pass over very quickly the market for hydrogen. Market questions are being addressed by a number of organizations, particularly the HEST study, and will indicate that there is indeed a substantial market for hydrogen now and in the future for the production of ammonia, methanol, for petroleum hydro-treating, chemical processing, gasification and liquefaction of coal, and for energy transmission and storage.

Our particular activity at Kentucky has been concerned since the mid-1960's with production techniques, and in order to introduce that program I would like to describe for you briefly the energy depot project conducted at the Allison Division of General Motors in the early sixties.

This program was supported by the Army Reactors Branch of the AEC. It was an attempt to use portable nuclear power to relieve Army fuel logistics problems. The idea was to produce a synthetic fuel on the site, using a portable liquid metal-cooled reactor.

The requirement that the fuel be produced from readily available materials led very quickly to a consideration of hydrogen, ammonia, and hydrazine. Of those materials, ammonia was chosen as the preferable fuel. There had been experience in Germany with the use of ammonia in buses, and there were some indications that ammonia could be used in an internal combustion engine without a great deal of trouble.

In the course of doing those design studies it became very clear very quickly that the efficiency of producing the hydrogen was the limiting step in the overall efficiency of the fuel production system. Water electrolysis was used as a reference process for the production of hydrogen. The efficiency limitation in this case is the efficiency of producing electricity from the thermal energy in the reactor, and we embarked on a thermochemical production project, which involved searching for chemical processes which would produce the hydrogen more efficiently from the thermal power source than water electrolysis. The idea was that if it is only possible to go from thermal energy to electricity at, say, 30-percent efficiency, why not search for a chemical process which will take the heat directly and dissociate the water.

At that time we invented and evaluated a large number of thermochemical processes. We talked with other chemical engineering people around the country, and, in fact, performed a detailed preliminary design to determine the cost-benefit ratio of a four-step thermochemical process involving vanadium chlorides.

The cost-benefit ratios were not attractive for the energy depot scheme in total, and that project was terminated.

The program at Kentucky started in the mid-1960's under the support of General Motors, and has subsequently been supported by NASA, Westinghouse, and, more recently, the Electric Power Research Institute.

Cycle invention is the first, most appealing, and most attractive part of thermochemical studies, and we indulged ourselves in cycle invention to some extent. Mainly, however, we tried to focus our efforts on understanding the characteristics of chemical processes which would be efficient.

The production of hydrogen from water is very similar to the production of electricity. The thermodynamic and fundamental aspects of the process are very similar. The characteristics of chemical reactions which will be efficient relate to considerations of Carnot efficiencies in the conversion of thermal energy to useful work, or electricity.

We have been cooperating in our program with the General Atomic Co., the Institute of Gas Technology. Westinghouse, the National Laboratories, including Argonne and Los Alamos, as well as some European laboratories: the Euratom Laboratory at Ispra; the work being done at the University of Aachen in West Germany; at Jülich; and with people at the University of Tokyo in Japan.

I would like to indicate my opinion of some of the important characteristics of the chemical processes, with the objective of outlining the necessary research and development programs which are required to develop an answer to this question in which we can have some confidence.

In the first place, a thermochemical process is a series of chemical reactions which, when written down and added up, simply sum to the decomposition of water. The work that's required to accomplish this process, or, if you will, the electricity required, depends on the changes in the thermodynamic properties of the chemical reactions.

One of the real problems with the direct dissociation of water accomplished simply by heating it up is that the work requirement does not decrease very rapidly as the temperature is increased. That's a result of the characteristic change in the entropy for that particular chemical reaction. If that characteristic is not attractive, the next thing to do is look for other reactions which do have appealing characteristic changes in thermodynamic properties, and which also sum to the decomposition of water.

It's very easy to write down chemical reactions which decompose water. What's more important to consider is the separation and recycling of the unreacted materials which occur in each of the reactions.

As was pointed out earlier, some reactions are run at high temperatures and some are run at low temperatures. None of the reactions will proceed completely to the right hand side. They won't go to completion. The products have to be separated and recycled. The work that has to be supplied to accomplish the separation of the equilibrium mixture for the chemical reactions is a very important consideration in determining the efficiency of the process.

I cite as an example the fact that 30 years ago nitrogen and oxygen could be separated from air at an efficiency of 15 percent, and a very detailed study of that process was prepared at that time which suggested that the efficiency might be increased to 20 percent, which, in fact, it is today. The same questions of separating the chemicals in the thermochemical process exist today.

Another important factor has to do with internal heat recovery. As I mentioned, the thermochemical process operates at different temperatures. This means that there are materials being heated and cooled, and the energy required to do that heating and cooling has got to be recovered inside the process in order to minimize the heat load on the primary energy source.

Materials of construction has been mentioned as a very important problem.

Another deals with catalysts. Many of the chemical reactions employed will be catalytic in nature, and efficient catalysts must either be found or developed.

The efficiency of the thermochemical process will vary with the operating temperature. There will be no chemical process which operates at ambient temperatures which will be more efficient than water electrolysis. The higher the temperature the more efficient will be the process, and, therefore, there is a need to develop high operating temperatures in order to develop high operating efficiencies.

I believe there is a twofold research and development program which should be undertaken in thermochemical hydrogen production. The first part is analytical or theoretical. It's the kind of thing that's done with a pencil and paper. It involves detailed thermodynamic studies, and I would like to make the analogy to the analysis of powerplants. The techniques for analyzing powerplants which produce electricity, either fossil fuel plants, nuclear plants, or fusion plants, are fairly straightforward. It's possible to do a lot of engineering and analysis on postulated power cycles without ever going into the laboratory. That same situation does not obtain in thermochemical hydrogen generation, and in my opinion needs to be developed so that variations and changes can be quickly and easly evaluated.

The evaluation procedure itself needs to be developed. We're very early on in the business of thermochemical hydrogen production, and evaluation procedures need to be developed and put into widespread use.

Thermodynamic data banks are fairly scarce, and there are a number of questions about thermodynamic data. The chemists like to say that there is at least a 50-percent chance of any data you pick out of the literature to use in any kind of an evaluation is wrong. That's something that needs to be improved.

Experimentally, we need a program of investigation of the chemical reactions to determine, first of all, what the equilibrium conditions are, how fast the chemical reactions go, what sort of catalysts might be needed, and, along with that program, material studies should be done to determine materials of construction.

The effect of temperature will also have to be evaluated in the laboratory.

These two programs, the theoretical or analytical program, and the experimental program, should be integrated. Those programs ought to be complementing and supplementing one another, so that we don't go off either doing all theoretical work or all experimental work, without making the connection. We should assure ourselves that what we are doing in the laboratory is, in fact, something that makes sense in theory, or that what we're trying to do theoretically is possible to do in the laboratory and on the commercial scale.

Mr. Chairman, that completes my statement.

Mr. McCormack. Thank you, Dr. Funk. Your statement is very much appreciated.

I have a couple of quick questions for you.

Is there open communication, including the international community, on thermochemical processing for hydrogen production?

Dr. Funk. I think the answer to that question in general is yes. The problem comes, naturally, with commercial organizations developing proprietary processes, and in that case there is some difficulty in getting information interchanged.

Mr. McCormack. Do you feel that you are able to keep up-to-date on this?

Dr. Funk. Yes; more or less.

Mr. McCormack. So that if someone is developing a new system in Yugoslavia you are going to know about it?

Dr. Funk. There was recently a seminar in Paris, France, on thermochemical hydrogen processes, and there were some 10 to 13 countries involved. There was generally quite good communication on the kind of work that's going on. I think it's going to be more difficult as the number of organizations involved in this business increases.

Mr. McCormack. Have there been any conferences on the subject in this country involving universities and industry during recent months, in the last year or so?

Dr. Funk. Oh; yes, indeed. I guess there have been six, six or seven, in the last couple of years.

Mr. McCormack. So there is good communication in this country and open literature, at least, is available to all?

Dr. Funk. Yes.

Mr. McCormack. And whatever forward movement that exists is more or less uniform in the various groups?

Dr. Funk. Yes. I believe there will be published shortly a Journal of Hydrogen Energy, which, hopefully, will bring together the information and identify the organizations and the work they're doing.

Mr. McCormack. Would you care to make any projections—for any given process at any given time in the future?

Dr. Funk. I think that we're probably talking a number like 5 years to a pilot plant, and to a demonstration plant it's; very difficult to speculate.

Mr. McCormack. Five years to a pilot plant. And then do you have any particular belief as to what process will be found?

Dr. Funk. No; I don't. I think there probably will emerge two or three very attractive processes. They're not clear to me at this time.

We're attempting now to do for EPRI a preliminary design and economic study, and the first task in that project is to choose a process.

Mr. McCormack. Thank you.

Mr. Hechler.

Mr. Hechler. Thank you, Mr. Chairman.

Dr. Funk, I would just like to ask two technical questions.

In our discussions in the hearings on helium I asked whether or not it would be possible to get helium from synthetic natural gas—whether it would be possible, even though it takes hydrogen to produce. In the process of coal gasification could you then obtain any hydrogen out of it? Is that true?

Dr. FUNK. Hydrogen could produce some coal-derived SNG in the same way that it's produced now, from naturally recoverable methane.

Mr. HECHLER. What is the relation then of the amount of hydrogen it takes in your coal gasification to what you could get out of your product?

Dr. FUNK. There is roughly one atom of hydrogen for every atom of carbon in the coal. So if that coal is going to be transformed into substitute natural gas, into methane, three atoms of hydrogen have to be found somewhere to add to that carbon.

Now, the process today will produce the hydrogen from water and the carbon in the coal, so some of the carbon will be used up. An alternate source of hydrogen from, say, a thermochemical process, would conserve carbon to that extent, which is quite considerable.

There wouldn't be, that I can see, much point in then producing hydrogen from the SNG that was just produced from the coal. I think if the objective is hydrogen from coal there are processes which may be similar to, for instance, the Koppers Totzek process, which might produce the hydrogen more directly.

I'm not sure I answered your question.

Mr. HECHLER. Yes; you did.

Could you spell out more specifically the relative amounts of hydrogen that would be obtained from the different qualities of coal? Is there any difference in the coal, in terms of the ash, or sulfur, or pure content of coal, as to how much hydrogen can be produced?

Mr. FUNK. That would be determined almost entirely by the carbon content of the coal. High grade bituminous coal, because it has more carbon, would produce more hydrogen than will a semi-bituminous coal or a lignite.

Mr. HECHLER. What about within the categories of bituminous coal that are above the lignite area? There are wide variances, you know, in the quality.

Dr. FUNK. Yes.

Mr. HECHLER. I just wondered if the carbon content is the sole determining factor.

Dr. FUNK. I think the carbon content is the primary determining factor.

Mr. HECHLER. I understand you cannot get it from anthracite. Is that right?

Dr. FUNK. I don't think I would be willing to say you can't get it from anthracite. I think you could gasify anthracite to produce a syngas from which hydrogen could be produced. From the carbon, the hydrogen could be produced.

Mr. HECHLER. Thank you, Mr. Chairman.

Mr. MCCORMACK. Mr. Fuqua.

Mr. FUQUA. Thank you, Mr. Chairman.

I am interested in what would be the relative cost of hydrogen production by thermochemical processes as compared to the conventional processes by which we get it today?

I am thinking primarily about ammonia, of which we are in very short supply in this country, particularly for agricultural purposes. How would the cost compare?

Dr. Funk. My impression is that with natural gas prices as they are today there will be no cheaper way to produce hydrogen.

The methane-steam reforming process is well-developed. The cost is very well known. If the feedstock costs 70 cents a million British thermal units, the hydrogen will probably come at a number like $1.30, something like that.

In water electrolysis, the major determinant of the cost is the cost of power, and in that event we may be talking about $3 or $4 a million Btu's. The cost of hydrogen from thermochemical——

Mr. Fuqua [interrupting]. And how much water are we talking about using? That also is a critical problem in some areas, and getting more critical in others.

Dr. Funk. Water as a feedstock for hydrogen production I don't think is a big problem.

But the cost of hydrogen production by thermochemical processes is not known. It's only very recently that cost estimates are being made, both here and in Europe, and there is some feeling that this is not the right time to be doing those kind of cost estimates because the processes are still too ill-defined.

Mr. Fuqua. Thank you, Mr. Chairman.

Mr. McCormack. Thank you, Mr. Fuqua.

Mr. Thornton.

Mr. Thornton. Thank you, Mr. Chairman. I have no questions, but I want to compliment the witness on his very interesting presentation.

Dr. Funk. Thank you.

Mr. McCormack. Now let me ask you one more question, Dr. Funk.

Perhaps I missed a point, but I was going to ask about your projection for the ultimate energy efficiency of producing hydrogen by thermochemical processses. What is your guess?

Dr. Funk. I would prefer not to make a guess at that number.

It goes like this: The process gets invented, and you calculate the efficiency at 65 percent, and then you begin to do some very preliminary sort of engineering work, considering questions of recycling, and separating, and it will drop to 50 percent. Then, the much more detailed kind of analysis will produce a number like 35 percent.

I think it's just too early to estimate what that ultimate efficiency will be, but I think we can say this: If it isn't 40 percent, then we won't have thermochemical processes, unless they are very much cheaper in terms of capital costs than water electrolysis, because water electrolysis will probably deliver efficiencies in the 35- to 40-percent range.

Mr. McCormack. But it might also depend on whether or not one used heat directly from HTGR's or accepted the penalty of 40 percent to go to electricity, followed by transfer of the electrical energy.

Dr. Funk. No; the efficiencies I mentioned are all on the same basis. The efficiencies I referred to went back to the thermal reactor power.

Mr. McCormack. I see. So, then you are not yet ready to project the cost per Btu, is that right?

Dr. Funk. That's right.

Mr. McCormack. So you are really just getting started.

Dr. Funk. Yes, I think that's the situation.

Mr. McCormack. Well, at least we are doing that. Perhaps this hearing, and the one that comes up next Thursday at 8 o'clock in room 2318 will continue the discussions.

I want to thank you all very much.

The meeting is adjourned.

[Whereupon, the subcommittee was adjourned at 9:48 a.m., to reconvene at 8 a.m., on Thursday, June 12, 1975.]

HYDROGEN

THURSDAY, JUNE 12, 1975

House of Representatives,
Committee on Science and Technology,
Subcommittee on Energy Research,
Development and Demonstration,
Washington, D.C.

The subcommittee met, pursuant to adjournment, at 8 a.m., in room 2318, Rayburn House Office Building, Hon. Mike McCormack, chairman of the subcommittee, presiding.

Mr. McCormack. The meeting will come to order.

I should like to welcome you to this second hearing on the potential for hydrogen to play a significant role in our energy economy of the future. As I mentioned on Tuesday, hydrogen is not a new source of energy, but rather an intermediate form like electricity. As a gas with properties somewhat similar to natural gas, it can play an important part in meeting our energy needs in the years ahead.

The key to using hydrogen is, of course, economical production and safe transmission and utilization. This means that new technology is required. The new technology will build on that developed in the past by NASA, which testified on Tuesday, the Defense Department, which appears today and other agencies and private industry.

The utilities have also given much thought to the opportunities offered by the hydrogen economy. We will hear from two such groups today.

[Mr. McCormack's welcoming remarks for Navy witnesses follow:]

Mr. McCormack's Welcoming Remarks for Navy Witnesses

Unfortunately, Mr. Goldwater is unable to be with us this morning because of a commitment out of town. If he were here, I am certain that he would take this opportunity to welcome all of you and to thank you for your participation in these hearings. Beyond that, though, I am sure that Mr. Goldwater would also take this opportunity to commend the farsightedness of the Navy in focusing early and very effectively on this Nation's acute need for a well-coordinated and well-integrated approach to energy R. & D., particularly the coordination and integration of energy R. & D. between the Defense Department and our civilian agencies.

As you are aware, this subcommittee has oversight jurisdiction for specified energy R. & D. throughout the Federal Government. Mr. Goldwater and I both intend to closely follow the activities of the Navy and the other services in energy R. & D. I know that he is considering recommending hearings later in the year to review these activities. In that regard, we have recently been encouraged by the timely 50 solar heating and cooling demonstration units planned at Defense Department bases (20 Navy) across the country which Admiral Hart testified about here last month.

We would certainly encourage the continued and enthusiastic participation of the Navy and the Defense Department in that and other national energy R. & D. programs, consistent, of course, with departmental mission constraints and requirements. The Defense Department, as the largest single consumer of energy in the Nation (consuming approximately 5% of the Nation's energy during peacetime), and undoubtedly the consumer with the largest single fuel bill in the United States (approximately five billion dollars in this fiscal year) certainly has a significant role to play in energy research.

In fact, DoD, with its aircraft, ground vehicles, housing, remote bases, ships, etc. represents a microcosm of the country's energy requirements and it can serve well as a cooperative partner with our civilian agencies in addressing the multitude of energy research issues.

On behalf of Mr. Goldwater, I should like specifically to commend Commander Paul Petzrick and Dr. Pete Waterman for their efforts in energy research. Mr. Goldwater and this subcommittee, as you know, have recently been joined by our minority staff counsel, who has brought to the Congress a very deep respect and a very great enthusiasm for your organization's activities in energy research and development. As a result, we are becoming increasingly aware and appreciative of those activities both within the Defense Department and their cooperation with the civilian agencies which we oversee.

Commander Petzrick, I personally recall our informal discussion in my office last fall. My recollection is that we focused then on the need for accelerated research in advanced concepts across the entire spectrum of energy sources, technologies and applications. That is our focus this morning with regards to hydrogen and really the overall focus of this subcommittee, where are we now in our energy technology and where must we go as a nation to achieve our national goals of long range energy sources which are economical, dependable, reliable and secure.

I note, Commander Petzrick, that you are a Civil Engineering Corps officer and I am certain that Mr. Goldwater would comment on his pride regarding the fine energy research activities at the Navy's civil engineering laboratory at Port Hueneme, He has worked closely with CEI and he has a particular interest in the energy conservation activity there, energy conservation being a major area of interest of this subcommittee also. Finally, I also note as an aside, Commander, that we are both in the energy reporting business—you, with your fine energy R. & D. SITREP for the Defense Department, which we here read weekly, and this subcommittee, with the energy news notes which we periodically publish here to keep all the members abreast of energy developments.

We welcome you here this morning and, on behalf of both myself and Mr. Goldwater, wish to commend you for your outstanding contributions in energy R. & D.

Mr. McCormack. Our witnesses today are Comdr. Paul Petzrick, Director, Navy Energy, Research and Development Office, Headquarters, Naval Materiel Command. He is accompanied by Dr. Peter Waterman, Special Assistant, Office of the Assistant Secretary of the Navy, Research and Development. Also with him is Mr. Homer Carhart of the Naval Research Laboratory and Mr. Carl Hershner, Naval Ship Research and Development Center.

We will then hear from Dr. Derek P. Gregory, Director, Energy Systems Research, Institute of Gas Technology and Mr. Sidney H. Law, Director of Research of Northeast Utilities. He will be accompanied by Dr. Michael Lotker, a scientist on advanced energy conversion at Northeast Utilities.

Commander Petzrick, you may come forward and bring your colleagues to the front table. If you wish, we can insert your entire statement in the record at this point. Then you can speak from it or summarize, whichever you prefer.

STATEMENT OF PAUL PETZRICK, DIRECTOR, NAVY ENERGY, RESEARCH AND DEVELOPMENT OFFICE, HEADQUARTERS, NAVAL MATERIEL COMMAND; ACCOMPANIED BY DR. PETER WATERMAN, SPECIAL ASSISTANT, OFFICE OF THE ASSISTANT SECRETARY OF THE NAVY, RESEARCH AND DEVELOPMENT, AND HOMER CARHART OF THE NAVAL RESEARCH LABORATORY AND CARL HERSHNER, NAVAL SHIP RESEARCH AND DEVELOPMENT CENTER

Commander PETZRICK. We have this statement for summary and insertion. Then I will make some remarks at this morning's meeting.

Mr. McCORMACK. Without objection, the complete statement will be inserted.

[The complete statement of Comdr. Paul Petzrick, USN, is as follows:]

STATEMENT OF COMMANDER PAUL PETZRICK, CEC, USN

(This summary highlights some of the Navy's recent research and development activities to evaluate hydrogen as a potential alternative to fossil fuels in naval applications.)

In mid-1973, at the request of Dr. Peter Waterman, Special Assistant, Office of the Assistant Secretary of the Navy (Research and Development), the Naval Research Laboratory (NRL) formed a hydrogen panel, with Dr. Homer W. Carhart as chairman, to conduct a special study of hydrogen as a Navy fuel. Both Dr. Waterman and Dr. Carhart are present and will be available to answer questions.

The results of the panel's work are contained in NRL Report 7754, Hydrogen As a Navy Fuel, Naval Research Laboratory, June 1974. A copy of this report is submitted and additional copies can be made available.

The conclusions of the study are that hydrogen has many desirable properties as a fuel. It can be burned efficiently in all burners and engines in widespread use today. Furthermore, it is a superior material for fuel cells with potential for efficiencies higher than conventional types of combustion.

A high heat of combustion is the property that makes hydrogen attractive. However, the low density of liquid hydrogen negates much of the advantage obtained by the heat of combustion, particularly for volume-limited vehicles. Thus, the use of hydrogen in major ships and carrier aircraft is not promising. Special applications, such as fueling small, weight-limited craft, may be practical. Remote naval facilities, if located near environmental sources of energy, could use the hydrogen fuel storage and transport idea.

Hydrogen is not a prime fuel, but must be produced by putting energy into chemical reactions. The most promising reactions today are based on fossil fuels, with coal having long-term resource potential. An expected trend to large-scale nuclear power generators should make the electrolysis of water the favored H_2 production process in the long term.

The hazards of gaseous hydrogen are greater than those of most combustible gases because of the wide flammability limits and the high flame velocity. Considerable experience with hydrogen-containing gases (town gas) has shown that suitable handling techniques are available. Experience with liquid hydrogen is limited, however, an explosion hazards must be examined in detail.

Storage techniques for liquid hydrogen are not satisfactory, and high boiloff losses would be experienced with containers that are satisfactory for liquefied natural gas. Hydrogen tank design for irregular shapes, as on ships and aircraft, is inadequate.

The cost of hydrogen between 1990 and 2000 will be several times that of current Navy fuels for equal amounts of energy. However, the present trend in crude oil price increases coupled with the decreasing oil reserves-to-production ratio indicates that H_2 will not be at as large an economic disadvantage then as it is today. The cost of H_2 should not be a deterrent to its use in the Navy if system performance shows significant advantages.

Concurrently with NRL's overview of hydrogen's general potential as a Navy fuel, the naval ship research and development center's Annapolis laboratory (NSRDC/A), with support from the Defense Advanced Research Projects Agency (DARPA), undertook a more detailed study of the mission capabilities of Hydrogen-Fueled Naval Force Elements and also an assessment of the state of hydrogen technology for the purpose of identifying any research and development that would be necessary for demonstrating the military effectiveness of hydrogen-fueled vehicles.

The project engineer for NSRDC's study contracts is Mr. Carlton Hershner, Sr., who is present and will be available to answer questions.

The assessment of the state of hydrogen technology is being compiled by a team of investigators at the Stevens Institute of Technology, Hoboken, New Jersey. A summary of their work through August 1974 is contained in their Report, Hydrogen As A Fuel, R. F. M. McAlevy, III, et al, NTIS No. AD–787 484/5WE, Stevens Institute of Technology, Hoboken, New Jersey, August 1974. A copy of this report is submitted and additional copies from the Defense Documentation Center can be made available.

The report summarizes the generation of hydrogen by electrolysis, coal gasification, and thermochemical proceses. It states that highly efficient electrolyzers are required if large-scale electrolysis of H_2 is to be economically feasible, owing to the ever-increasing cost of electricity. A review of current technology reveals that much of the present effort in electrolyzer design is directed toward achieving the high levels of efficiency that are theoretically possible. Based on the information available, however, it was impossible at this time to discern one that is universally superior.

Coal gasification appears practical for near-term and intermediate-term H_2 generation in the U.S.A. because of this country's large coal reserves and the growing world-wide shortage of petroleum. Two proven processes are already in commercial use in other countries, the Lurgi process and the Koppers-Totzek process (the latter being preferred for high H_2 yields). However, neither process is currently used in this country. Instead, H_2 is generally produced by steam reforming of natural gas and petroleum liquids, apparently as a result of economic constraints. Coal gasification processes will have no significant impact on H_2 generation in this country for 5 years or so.

In the long term, H_2 generation by thermochemical water-splitting processes appears promising, using nuclear heat sources. For the chemical processes proposed to date, sufficient fundamental information does not exist to permit selection of the most promising candidates. Generally, the thermochemical processes involve fewer reactions and higher efficiencies when higher maximum temperature heat is available. Thus, the thermochemical H_2 generation will be feasible with high-temperature gas-cooled reactors (temperature of coolant between about 800° C. and 1000° C) and probably is not feasible with the liquid metal fast-breeder reactor (coolant temperature between about 450° C and 575°C).

The report also surveys the work done by other investigators with hydrogen-fueled engines. It deals wih fundamental relationships derived between fuel properties and engine-performance parameters; operating experiences with H_2-fueled, reciprocating, spark-ignition engines are also comprehensively summarized. Together, these provide a rational basis for evaluation of H_2 as a fuel. Numerous comparisons are made between H_2 and gasoline use; it is shown that H_2 operation allows high efficiency and low pollutant emissions along with a control possibility ("quality control") which is impractical with gasoline. However, to gain these advantages of H_2 operation, engines must be operated fuel-lean at approximately one-half the stoichiometrically correct fuel/air mixture ratio. Under such conditions, the chemical-energy content of the lean fuel/air mixture is reduced, substantially penalizing the work (or power) output of the engine. Conventional supercharging or cylinder fuel injection can compensate for such a power penalty while maintaining the advantages of H_2 use. From many viewpoints, H_2 is an attractive alternative to gasoline and other hydrocarbons as engine fuels. Hydrogen use deserves further investigation both experimentally and analytically.

The study of the mission capabilities of hydrogen-fueled Naval forces is being conducted by the General Electric-Tempo, Center for Advanced Studies in Santa

Barbara, California. Their findings are contained in the report by B. Berkowitz, et al, Alternative, Synthetically Fueled Navy Systems: Force Element Missions and Technology, DDC No. AD/B–001 401L, General Electric Company—Tempo, November 1974. A copy of this report is submitted and additional copies can be made available.

The objective of this study is to determine the effects that the use of hydrogen, and synthetic fuels derived from hydrogen, would have on the design and performance of Navy ships and aircraft in assigned missions. The term "synthetic fuel," as used here, applies to those fuels which could be produced aboard a factory ship at sea or in a transportable, forward-based manufacturing complex having some primary energy source such as nuclear, solar, etc.

The ships which have been selected for this study represent a range of types which might be found in use by the Navy between the present and the end of this century. They include hydrofoils, a surface effect ship, and displacement type hulls ranging from 230 to 55,000 long tons in weight. The aircraft include a vertical-, or short-, take-off and landing (V/STOL) type as well as a carrier-based attack (VA) type. Helicopters and other Navy types of aircraft have not been investigated in detail, but their estimated fuel requirements have been included in the analyses of those ship types which carry aircraft. The ships and aircraft modeled in the study represent generic rather than specific designs. The primary emphasis is on the comparison of fuels rather than ship designs.

From the wide spectrum of synthetic fuels which could be produced aboard a factory ship, hydrogen obtained by decomposition of water is of primary interest. But, ammonia and hydrazine are also considered because they can be made from hydrogen and nitrogen, which can be obtained from air separation. Methane and methanol are also considered for the possibility that a source of carbon might be available with which to produce them from hydrogen. And finally, the methylamines have been considered since they can be made from methanol and ammonia.

It is a general characteristic of the synthetic fuels that their volumetric energy densities are smaller than those of petroleum-derived fuels. Consequently, for a synthetically fueled vehicle to achieve equivalent operating ranges, a greater volume must be allocated for fuel storage, resulting in increases in both structural weight and hydrodynamic and/or aerodynamic drag. Thus, within constant total weight constraints, there is a limit to the extent to which fuel storage volume can be increased and this leads to possible degradation in mission performance.

The method of comparing each of the synthetic fuels in each of the vehicles, therefore, is to establish a baseline design fueled with the Navy's standard Diesel Fuel Marine (DFM). Then, by varying dimensions, within certain constraints, to maximize the weight of synthetic fuel, the speed-power-fuel consumption characteristics of the modified design are calculated. From the fuel consumption data and a synthesized mission profile, the unrefueled range of each vehicle modified for each synthetic fuel is determined and compared.

The findings of the study are summarized as follows:

Ships modified to operate on hydrogen, methane, or methylamines achieve ranges comparable to those of the same ships operating on diesel fuel marine.

Ships modified to operate on hydrogen, methane, or methylamine achieve approximately twice the range of the same ships modified to operate on methanol, ammonia, or hydrazine and consequently would have to be refueled only half as often.

The dynamic lift ships, hydrofoils, and surface effects ships achieve a greater range performance when using hydrogen than for DFM or any of the other synthetic fuels.

For displacement hulls in the 3,000 to 6,000 ton class, the ships modified to operate on hydrogen and methane achieve approximately the same range performance as that of the DFM-fueled ship.

For the 14,000-ton and a new concept 55,000-ton aircraft-carrying ships, greater range performance is achieved for the DFM-fueled and methane-fueled ship than for the hydrogen-fueled ship.

For the 40,000-ton amphibious assault support ship, the range performance is approximately the same for the ship operating on either hydrogen, DFM, or methane.

Carrier-based aircraft modified to operate on hydrogen and methane, and assuming nonaccelerated flight, would be expected to suffer approximately a 10 percent range degradation for hydrogen and a 5 percent degradation for methane. The use of the other synthetic fuels would result in greater degradation.

The results of this investigation indicate that liquid hydrogen and liquid methane used in dimensionally modified ships and aircraft are potentially equivalent to conventional fuels in mission performance capability. However, if the carbon to produce methane must be transported from a continental land base to the factory ship as coal, this logistic burden is within 15 percent of DFM tonnage required for direct use. Therefore, liquid hydrogen remains as the most promising synthetic fuel alternative.

The study leaves unanswered, however, the question of whether optimum design from first principles would result in significantly different vehicle designs and performance parameters. The research and development, areas found to be critical to the improved potential of cryogenically fueled naval vehicles are fuel storage and handling and overall system design.

In the area of fuel storage, the metal hydrides being investigated by other agencies appear to impose too great a weight penalty for beneficial application to naval vehicles. In addition, the dissociation rates may not be acceptable for application in power systems with high demand rates.

Molecular hydrogen, as a cryogenic liquid, appears to be the most desirable form for storing hydrogen although its requirement for a high performance insulation is a disadvantage for naval designers. Unlike the aircraft application where relatively short mission times at high consumption rates permit the use of less efficient solid insulations, shipboard applications will require the low-, or no-loss storage of large quantities of liquid hydrogen for extended periods of low consumption rate; this requires the application of higher efficiency vacuum-type insulations. These not only add to the volume disadvantage of hydrogen, but also require additional structure which invokes a weight penalty. Consequently, more development of better insulation systems and structural designs for the weight-critical dynamic-lift will be required.

The hazards of hydrogen are fairly well known as the result of investigations undertaken for aerospace programs of the 1960's. However, the combat environment imposes new unknowns which must be studied in greater depth before militarily effective, hydrogen-fueled systems can be designed. For example, the storage of hydrogen in the hull of a ship can bring together all of the undesirable conditions of leakage, sources of ignition, and confinement under which hydrogen will detonate. When the risks of hostile weapons effects are added to this, the design of hydrogen systems for the combat environment becomes formidable.

As the result of continuing study and liaison with other agencies and organizations investigating the "hydrogen economy," it appears that hydrogen could be used effectively in some new designs of the Navy's weight critical surface ships and in special applications such as deep-diving submersibles, shore installations, etc. The design and development of combat systems, however, will require more extensive investigation.

No matter what potential is assumed for the hydrogen economy, the fundamentals of hydrogen technology will assume greater importance in future fuels. It is therefore recommended that those agencies responsible for development of basic fuel technology give extensive consideration to hydrogen. Their work will provide important background for our continued assessment of hydrogen in military applications.

Commander PETZRICK. Our statement is a summary of the highlights of the Navy's research and development activities to evaluate hydrogen as a potential alternative to fossil fuels in naval applications.

Mr. Chairman, our evaluation consists of three studies, one done by the Navy Research Laboratory and two studies done by private contractors.

I will discuss this matter briefly. In mid-1973, at the request of Dr. Peter Waterman, the Navy Research Laboratory formed a hydrogen panel with Dr. Carhart as chairman. Dr. Carhart is here this morning to answer questions.

The results of the panel's work are contained in NRL Report 7754. "Hydrogen as a Navy Fuel." Naval Research Laboratory, June 1974. A copy of this report is submitted and additional copies can be made available. (See appendix II, p. 673.)

The conclusions of the study are that hydrogen has many desirable properties as a fuel. It can be burned efficiently in all burners and engines in widespread use today. Furthermore, it is a superior material for fuel cells with potential for efficiencies higher than conventional types of combustion.

A high heat of combustion is the property that makes hydrogen attractive. However, the low density of liquid hydrogen negates much of the advantage obtained by the heat of combustion, particularly for volume-limited vehicles. Thus, the use of hydrogen in major ships and carrier aircraft is not promising. Special applications, such as fueling small, weight-limited craft, may be practical. Remote naval facilities, if located near environmental sources of energy, could use the hydrogen fuel storage and transport idea.

The hazards of gaseous hydrogen are greater than those of most combustible gases because of the wide flammability limits and the high flame velocity. Considerable experience with hydrogen-containing gases—town gas—has shown that suitable handling techniques are available. Experience with liquid hydrogen is limited, however, and explosion hazards must be examined in detail.

Storage techniques for liquid hydrogen are not satisfactory, and high boiloff losses would be experienced with containers that are satisfactory for liquefied natural gas. Hydrogen tank design for irregular shapes, as on ships and aircraft, is inadequate.

The cost of hydrogen between 1990 and 2000 will be several times that of current Navy fuels for equal amounts of energy. However, the present trend in crude oil price increases coupled with the decreasing oil reserves-to-production ratio indicates that H_2 will not be at as large an economic disadvantage then as it is today. The cost of H_2 should not be a deterrent to its use in the Navy if system performance shows significant advantages.

Concurrently with NRL's overview of hydrogen's general potential as a Navy fuel, the Naval Ship Research and Development Center's Annapolis laboratory—NSRDA/A—with support from the Defense Advanced Research Projects Agency—DARPA—undertook a more detailed study of the mission capabilities of hydrogen-fueled naval force elements and also an assessment of the state of hydrogen technology for the purpose of identifying any research and development that would be necessary for demonstrating the military effectiveness of hydrogen-fueled vehicles.

The project engineer for NSRDC's study contracts is Mr. Carlton Hershner, Sr., who is present, and will be available to answer questions.

The assessment of the state of hydrogen technology is being compiled by a team of investigators at the Stevens Institute of Technology, Hoboken, N.J. A summary of their work through August 1974 is contained in their report, Hydrogen as a Fuel, R. F. M. McAlevy III, et cetera, NTIS No. AD-787 484/5WE, Stevens Institute of Technology, Hoboken, N.J., August 1974. A copy of this report is submitted and additional copies from the Defense Documentation Center can be made available.

The report summarizes the generation of hydrogen by electrolysis, coal gasification, and thermochemical processes. It states that highly efficient electrolyzers are required if large-scale electrolysis of H_2 is to be economically feasible, owing to the ever-increasing cost of electricity. A review of current technology reveals that much of the present effort in electrolyzer design is directed toward achieving the high levels of efficiency that are theoretically possible. Based on the information available, however, it was impossible at this time to discern one that is universally superior.

The study of the mission capabilities of hydrogenfueled naval forces is being conducted by the General Electric—TEMPO, Center for Advanced Studies, in Santa Barbara, Calif. Their findings are contained in the report by B. Berkowitz, and others, "Alternative, Synthetically Fueled Navy Systems: Force Element Missions and Technology," DDC No. AD/B-001 401L, General Electric Co.—TEMPO, November 1974. A copy of this report is submitted and additional copies can be made available.

The objective of this study is to determine the effects that the use of hydrogen, and synthetic fuels derived from hydrogen, would have on the design and performance of Navy ships and aircraft in assigned missions. The term "synthetic fuel," as used here, applies to those fuels which could be produced aboard a factory ship at sea or in a transportable, forward-based manufacturing complex having some primary energy source such as nuclear, solar, et cetera.

From the wide spectrum of synthetic fuels which could be produced aboard a factory ship, hydrogen obtained by decomposition of water is of primary interest. But, ammonia and hydrazine are also considered because they can be made from hydrogen and nitrogen, which can be obtained from air separation. Methane and methanol are also considered for the possibility that a source of carbon might be available with which to produce them from hydrogen. And finally, the methylamines have been considered since they can be made from methanol and ammonia.

It is a general characteristic of the synthetic fuels that their volumetric energy densities are smaller than those of petroleum-derived fuels. Consequently, for a synthetically fueled vehicle to achieve equivalent operating ranges, a greater volume must be allocated for fuel storage, resulting in increases in both structural weight and hydrodynamic and/or aerodynamic drag. Thus, within constant total weight constraints, there is a limit to the extent to which fuel storage volume can be increased and this leads to possible degradation in mission performance.

The findings of the study are summarized as follows:

Ships modified to operate on hydrogen, methane, or methylamine achieve ranges comparable to those of the same ships operating on diesel fuel marine.

Ships modified to operate on hydrogen, methane, or methylamine achieve approximately twice the range of the same ships modified to operate on methanol, ammonia, or hydrazine and consequently would have to be refueled only half as often.

The dynamic lift ships, hydrofoils and surface effects ships achieve a greater range performance when using hydrogen than from DFM or any of the other synthetic fuels.

Carrier-based aircraft modified to operate on hydrogen and methane, and assuming nonaccelerated flight, would be expected to suffer approximately a 10-percent range degradation for hydrogen and a 5 percent degradation for methane. The use of the other synthetic fuels would result in greater degradation.

The results of this investigation indicate that liquid hydrogen and liquid methane used in dimensionally modified ships and aircraft are potentially equivalent to conventional fuels in mission performance capability. However, if the carbon to produce methane must be transported from a continental land base to the factory ship as coal, this logistic burden is within 15 percent of DFM tonnage required for direct use. Therefore, liquid hydrogen remains as the most promising synthetic fuel alternative.

The study leaves unanswered, however, the question of whether optimum design from first principles would result in significantly different vehicle designs and performance parameters. The research and development areas found to be critical to the improved potential of cryogenically fueled naval vehicles are fuel storage and handling and overall system design.

In the area of fuel storage, the metal hydrides being investigated by other agencies appear to impose too great a weight penalty for beneficial application to naval vehicles. In addition, the dissociation rates may not be acceptable for application in power systems with high demand rates.

Molecular hydrogen, as a cryogenic liquid, appears to be the most desirable form for storing hydrogen although its requirement for a high performance insulation is a disadvantage for naval designers. Unlike the aircraft application where relatively short mission times at high consumption rates permit the use of less efficient solid insulations, shipboard applications will require the low-, or no-loss storage of large quantities of liquid hydrogen for extended periods of low consumption rate; this requires the application of higher efficiency vacuum-type insulations. These not only add to the volume disadvantage of hydrogen, but also require additional structure which invokes a weight penalty. Consequently, more development of better insulation systems and structural designs for the weight-critical dynamic-lift ships will be required.

As a result of continuing study and liaison with other agencies and organizations investigating the hydrogen economy, it appears that hydrogen could be used effectively in some new designs of the Navy's weight critical surface ships and in special applications such as deep-diving submersibles, shore installations, et cetera. The design and development of combat systems, however, will require more extensive investigation.

No matter what potential is assumed for the hydrogen economy, the fundamentals of hydrogen technology will assume greater importance in future fuels. It is therefore recommended that those agencies responsible for development of basic fuel technology give extensive consideration to hydrogen. Their work will provide important background for our continued assessment of hydrogen in military applications.

Now, Mr. Chairman, that concludes the summary of our prepared statement. I would add a personal comment on reviewing programs of other agencies. I want to identify some key thrusts. I would hope that significant work to reduce the cost of producing hydrogen would result. This would have an immediate payoff to reduce the cost of fertilizer.

Second, we have attempted to burn hydrogen in existing combustors and engines. The program needs a key thrust for the development of a combustor that is exclusively designed and optimized to burn hydrogen.

My team is available at this time to answer your questions.

Mr. McCormack. I am curious to know this: Is the Navy conducting any research on thermochemical water, Commander. What programs are being carried out?

Commander Petzrick. I am not aware of any on thermochemical water, R. & D.

Dr. Waterman. Perhaps the closest program would be the efforts that we have with our submarines. Perhaps the closest related program would be in our efforts with nuclear submarines to produce oxygen by high pressure electrolysis of seawater.We get byproducts. Getting rid of hydrogen from those is a critical matter. Perhaps Mr. Carhart could speak further on that.

Mr. Carhart. The present generation, well, the generators are devices in which the oxygen and hydrogen are produced at high pressure of between 2,000 and 3,000 pounds. The reason for this is so that you avoid the necessity for having high compressors to put oxygen back into the high pressure vessels. Also, the hydrogen can be pumped overboard without use of a mechanical pump which is noisy.

There has been a fair amount of work that the Navy did on analytic devices for this purpose.

Mr. McCormack. This reaction goes even with high pressures, Mr. Carhart?

Mr. Carhart. Yes.

Mr. McCormack. I take it, from this, that the Navy is not doing any research into the chemical disassociation of water. Looking at the Navy from a great distance, it would seem to me that in the nuclear ships it would be perfectly satisfactory for producing hydrogen for fuel on a continuing basis if you wanted to use, for instance, on a nuclear carrier or for hydrogen-powered airplanes.

Commander Petzrick. This subject was addressed in these reports, the concept of a mother ship using nuclear power to generate hydrogen which would be used as a fuel for other ships and aircraft.

Mr. McCormack. Yes.

Commander Petzrick. From a military point of view, you might have too many eggs in one basket. If somebody gets your mother ship, you have then lost your fuel farm. This causes or poses significant problems, although it is the basis for our studies. That is, the fact that we are floating in an ocean of resources. If we use that means or any means of converting these resources to a useful fuel, this would be attractive.

Mr. McCormack. I would not think that you would need the hydrogen for anything but aircraft or on very small ships. Your carriers, frigates and cruisers would be nuclear powered in the future, wouldn't they? For mobility of submarines, they would use nuclear power. Hydrogen would be for the small ships and the aircraft.

Commander Petzrick. Yes, Mr. Chairman, in accordance with Title 8, the capital ships and the submarines will be nuclear. It looks like one of the synthetic fuels, such as hydrogen, would be satisfactory for small special mission ships. The difficulty, I think, will surround those ships, well, those in the destroyer size.

Mr. McCormack. Have you determined which fuel other than gasoline, would give you the maximum usable energy per unit volume? What would it be in a plane, for instance—hydrogen or methylamines or methanol or what?

Commander Petzrick. The jet fuel that we use, the JP–5, has about the maximum energy density considering cost. It is also very desirable because of the safety features. What we are interested in is the middle range of nonaromatic hydrocarbon jet fuels for the aircraft applications.

Mr. McCormack. Suppose that is not available and you went to synthetic fuel.

Commander Petzrick. If we went to the synthetic fuels, because of the advantages that are offered by energy density and safety factors, we probably would synthesize a synthetic fuel comparable to the present JP–5. This means that you would have to work a little harder, adding more hydrogen, say, if you started with a fuel such as coal, or removing more of the carbon, if you went in that direction. That way, you could synthesize the high density fuel rather than stopping with the methane or methanol level. Methanol would only give half of the range that you would get by going to a middle distillate fuel, sir.

Mr. McCormack. I see two options—preparing fuel for the gasification or for the liquefaction of synthetic fuels from coal, which would be hydrocarbons. Suppose you eliminated the hydrocarbons? Suppose that you went to the lower molecular weight fuels, lower density fuels, such as hydrazines and ammonia and methane. Have you any feeling at this time as to which is the best route to go?

Commander Petzrick. We think that the methylamines would give us the performance that is comparable to liquid hydrocarbon fuels on ships and planes. That is, sir, with some penalty in range to the aircraft and with a significant penalty in cost in the case of ships.

As is covered in these reports, the most attractive possibility appears to be methylamines.

Mr. McCormack. This could be fabricated on shore rather than on ships?

Commander Petzrick. We could manufacture these from nitrogen and hydrogen available at sea between the seawater and the air with our nuclear source.

Mr. McCormack. You would need a source of carbon.

Commander Petzrick. Yes. If we went to this, this would mean bringing out coal or some other source. There is a significant logistic disadvantage in going to that.

Mr. McCormack. The 10 percent penalty with respect to hydrogen, that is not prohibitive with respect to aircraft. You said there would be a 10 percent degradation. I presume that is in the overall performance of range.

Commander Petzrick. Yes.

Dr. Waterman. Mr. Chairman, there are several other factors that are other than just pure range loss. There is the problem of handling on a combatant ship and refueling it, that is, refueling aircraft, and doing this properly in combat. There is the problem of fires and explosions on the ships. Those have been very difficult to handle with conventional fuels. That is why we went to JP-5, because of the added safety.

The range alone cannot be the singular or single element that we consider.

Mr. McCORMACK. Is the Navy working on any projects involving ocean thermal gradient production or conversion of energy?

Dr. WATERMAN. Commander Petzrick.

Commander PETZRICK. The Navy is assisting ERDA, providing some expertise from our ocean engineering community. Some of our managers are assisting ERDA in analyzing the proposals. We are assisting them with concrete technology for those concepts being proposed. We are not sponsoring any specific ocean thermal gradient program of our own.

We agreed with ERDA that we would give them our expertise to support their programs, using their money. We will cooperate in a joint program rather than initiate anything on our own.

Dr. Avery, at one of our laboratory locations, has some thoughts on ocean thermal gradient power plants that are of interest relative to the concepts that we have been discussing, Mr. Chairman.

He would produce ammonia as the product at the powerplant rather than electricity to be piped ashore.

Mr. McCORMACK. A gentleman at Johns Hopkins University was working on that.

Commander PETZRICK. Yes.

Mr. McCORMACK. Do you feel that the research or the assessment of this technology being compiled is applicable to onshore use by the utilities? Have you studied the problem of hydrogen embrittlement and hydrogen cracking and the reaction with lubricants and reactions with the pumps?

Commander PETZRICK. We have additional information from submarine programs in this area. A good deal of information is contained in these reports. I do not feel that this particular field is exhausted. Significant additional work is required in this area. That is, if we went into the actual use or designing systems utilizing hydrogen.

Dr. WATERMAN. At this time the studies on hydrogen and the embrittlement and the problems that you mentioned, they are largely in the public domain. They are available to these people. We would be delighted to provide whatever assistance we can.

Mr. McCORMACK. This might be a situation where we are carrying on parallel programs, that is, doing the same research over and over again. Clearly, the fact that the Department of Defense carries on research has many advantages. There is also the possibility, however, that there is unnecessary duplication, and not the kind of information transfer that we would sometimes wish to have.

As we get into this particular arena, it seems extremely valuable to have the ERDA personnel working closely with the Navy Energy Research and Development Office to be sure that no time is wasted, that the ERDA research and that which is sponsored by NSF, that this does not necessarily overlap that which has been done by the Navy.

Mr. CARHART. That is right.

Dr. WATERMAN. We agree with you. Over the years, I think we have maintained good contact. One of the most important points is that we deal with the major suppliers of materials. We deal directly with them. They, in turn, deal with the other agencies. We have shared our research with those people or developers of materials. That provides a pretty direct coupling to us.

Commander PETZRICK. Our recent observation of programs initiated by NASA and ERDA suggests the strategy that we should go on to a holding pattern regarding our own work in hydrogen. The studies that we just reported on, they will probably be summarized so that we can have the benefit of the information that is developed in our continuing dialog with ERDA. Our program will then go on to a plateau. We will look to ERDA and the other agencies that work in this particular area to carry on the work rather than to initiate extensive work in the Navy.

Mr. McCORMACK. That is good. I hope that we can maintain close liaison. I think that this is really important.

Now, gentlemen, I wonder if, in light of the time problem this morning, that you would be willing to answer any subsequent questions that the committee members may put to you in writing.

Mr. CARHART. Yes.

Commander PETZRICK. Yes.

Mr. McCORMACK. I thank you very much for coming this morning.

Our next witness is Dr. Derek P. Gregory, director, Energy Systems Research, Instituted of Gas Technology. The clock is pushing us. Do you mind if both you and Mr. Sidney H. Law give your testimony. Then we could ask questions.

STATEMENT OF DR. DEREK P. GREGORY, DIRECTOR, ENERGY SYSTEMS RESEARCH, INSTITUTE OF GAS TECHNOLOGY

Dr. GREGORY. Yes, Mr. Chairman, that is fine.

Mr. McCORMACK. Your statement, Dr. Gregory, may be inserted in the record without objection.

[The complete prepared statement of Dr. Derek P. Gregory is as follows:]

INSTITUTE OF GAS TECHNOLOGY

THE ROLE OF HYDROGEN IN THE ENERGY FUTURE OF THE UNITED STATES

by

Derek P. Gregory

Testimony Submitted to the
HOUSE COMMITTEE ON SCIENCE AND TECHNOLOGY HEARINGS
SUBCOMMITTEE ON ENERGY RESEARCH,
DEVELOPMENT AND DEMONSTRATION

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THE ROLE OF HYDROGEN IN THE ENERGY FUTURE OF THE UNITED STATES

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1. The Role of a Gaseous Fuel in the Future

It is commonly believed that to sustain a healthy economic growth, the use of energy in the United States must also continue to grow. When we look at the alarming decline in the availability of oil and gas, we can clearly see that a major shift must be made toward other energy sources – nuclear, solar, and coal being the most abundant and important – if the United States is going to have the energy to continue this growth. The use of conventional technology stresses the conversion of these energy forms into electricity for delivery to the customer. Because electricity is not readily storable, is expensive to transmit, and is not immediately useful in the vast majority of industrial and domestic energy-consuming equipment, the alternative course of converting these abundant energy sources to a chemical fuel that is more compatible with today's energy distribution and utilization equipment has merit. In some applications, electricity will serve our needs best; in others, clean fluid fuels will be superior. Although synthetic substitutes for conventional fluid fuels – natural gas and oil – produced from coal are likely to play an important role for an extended period, hydrogen is the chemical fuel with the greatest long-range prospects because it can be produced from nonfossil energy sources. Thus, hydrogen combines the desirable characteristics of conventional gaseous and liquid fuels with the essentially unlimited supply feature stressed by advocates of the all-electric economy. The mixed hydrogen-electricity energy-delivery system may, therefore, well become the best long-term compromise.

In the past, the natural gas industry has provided an efficient, reliable, environmentally acceptable,and inexpensive energy transmission-distribution system to supply as much as 30% of our national energy needs to a wide spectrum of industrial, commercial, and residential customers. Much of the investment of the natural gas industry is in this underground delivery system, most of which has a life expectancy greater than that of the reserves of the fuel that it carries. Be delivering hydrogen as a fuel, the gas industry, which is already in the business of delivering gaseous fuels to its customers, can thus play as important a role in the future in meeting American's energy-delivery needs as it has in the past.

2. The Characteristics of Hydrogen-Energy

Studies carried out at IGT and elsewhere have already indicated the following characteristics of hydrogen as an energy source:

a. Hydrogen may be produced from water, using energy from nuclear, solar, or other sources by three distinct routes: electrolysis, using electric power; thermochemical decomposition, in which heat is used to drive a number of chemical steps in a cyclic sequence, all the components of the cycle except water, hydrogen, and oxygen being recycled; and by direct irradiation of water-bearing molecules by ultraviolet or nuclear radiation. The technology for each of these three routes is increasingly more complex in the order shown, but electrolysis technology is available today and provides a sound baseline case for economic studies.

b. Over long distances, hydrogen is cheaper and less unsightly to transmit than electricity. Underground hydrogen pipelines will be 3 to 5 times less expensive than overhead electric lines and 50 to 100 times less expensive than buried electric transmission cables. Moreover, although it has not yet been tested in practice, much of the existing 900,000 miles of gas transmission and distribution systems will probably be usable for hydrogen transmission. Since our future primary energy conversion plants, such as nuclear or solar plants, will be farther from major population centers than they are at present, long-distance energy transmission will become increasingly important.

c. Hydrogen can be stored economically in large quantities in facilities somewhat similar to those used for storage of natural gas, whereas it is quite costly and difficult to store substantial amounts of electrical energy. Storage is a vitally important key in the utilization of intermittent energy supplies such as tidal, solar, and wind power, and would be of great economic benefit in keeping high-capital-cost generating plants, such as nuclear plants, operating at high load factors.

d. Hydrogen can probably be used in most domestic and industrial natural-gas-burning equipment with only relatively minor modifications. Many industrial processes rely on the combustion of a fuel and the use of the resulting combustion gases for specific purposes that cannot be fulfilled by electricity. The complete replacement of all industrial and residential heating equipment with electrical equipment — some of which would have to be specially developed — will present a financial burden that must be shouldered by the user, not by the energy-supply company. Such capital costs are not included in usual estimates for developing an all-nuclear-electric system.

e. Hydrogen is an essential raw material for the production of many widely used chemicals including ammonia (for fertilizers) and methanol (for many petrochemical applications). Although it is currently produced from natural gas or oil, bulk hydrogen production from coal and, ultimately, nuclear energy, with pipeline delivery to the chemical plants, represents an attractive way of maintaining the present fast growth in the production rate of these important materials in the face of a declining supply of natural gas and oil.

f. Hydrogen can be used directly to replace coal or coke for iron and steelmaking, and is an essential component in the upgrading of fossil fuels [gasoline from crude, substitute natural gas (SNG) from coal or oil shale]. This represents the simplest way that the major industries of steelmaking and fossil-fuel-refining can make use of large amounts of nuclear energy in their processes.

g. Burning hydrogen and oxygen together is a very elegant way of producing the huge amounts of process steam required by industry. About 17% of all the end-use energy in the United States is used to produce process steam for industry.

h. Hydrogen is an excellent fuel for all types of internal-combustion engines because it allows greater efficiency of operation and very clean exhausts. Its unique property of being extremely light (only one-third of the weight of jet fuel for the same energy content) adds tremendous incentive for its use as an aircraft fuel. In spite of some major technological problems still to be resolved, hydrogen made from nuclear energy represents the technically simplest way of achieving a nuclear-powered automobile or airplane.

3. Is the Hydrogen-Energy Option Open to Us Now?

Based on these advantageous features of hydrogen, I believe the U. S. national energy policy should be directed toward the ultimate goal of a mixed hydrogen-electricity energy system because both of these energy forms can be made from a wide variety of abundant, domestic primary energy sources, including coal, oil shale, and geothermal, wind, tide, and solar energy.

Thus, once energy consumers have become accustomed to the use of either hydrogen or electricity, they will never have to be asked to make a change again because the energy industry would be able to adjust from one raw energy source to another without interfering with the consumer's equipment. This is in direct contrast to the present prospects, for example, of modifying automobiles to accept alternative blends of gasoline, alcohols, and diesel fuel or modifying industrial combustion equipment to allow the substitution of coal for natural gas and oil.

Although the electricity option is clearly open to us because enough experience has been gained with electric energy to enable us to assess its economics, efficiency, and technology quite accurately, the hydrogen-energy option is not available to us at present for a number of reasons, primarily questions of unattractive economics, resulting from relatively low system efficiencies, and questions of safety and compatibility of hydrogen with existing equipment. I believe that these questions should be resolved quickly so that we can determine whether the potential advantages of hydrogen energy are indeed likely to be realized in a practical and economically attractive way and can thus plan our nation's energy future accordingly.

4. What Needs to be Done Today

Relatively little research in hydrogen energy is going on in the United States today, and most of it is supported by various government departments. Because industry is rightfully mainly concerned with relatively short-term problems of energy supply, longer term programs such as the development of hydrogen energy become the responsibility of government for funding.

While I believe that a considerably increased overall research effort in hydrogen energy is required now, I feel that, even with the present overall level of effort, insufficient emphasis is being place on several areas:

a. Current hydrogen-energy research is primarily, and rightly, focused on the production area because this is an area where major improvements in efficiency may be made. However, significant efficiency losses are also apparent at the utilization end of the system, and considerable advances appear possible in designing or modifying combustion equipment to take advantage of the unique properties of hydrogen. The use of hydrogen in conventional natural-gas-fired burners appears to require only minor burner modifications, but, to date, detailed design and testing of modified burners has not been a significant feature of any hydrogen-energy research program.

Although no major conversion problems are envisaged, I am surprised that this particular end-use aspect of hydrogen energy has received so little attention, in contrast to the use of hydrogen in automobiles and aircraft. Fifty-two percent of total U. S. energy consumption is used for combined space heating, industrial process heating, and industrial process steam applications. About half of this amount is now being supplied by natural gas. The natural-gas-fueled equipment used in these applications could seemingly be converted to hydrogen far more easily and far more cheaply than to electricity. Not many people realize that the amount of energy used in the United States to produce industrial process steam alone is 17% of the total national energy consumption, about the same as that used to drive all of the automobiles in the country.

It seems to me that the conversion of this sector of the energy market to nonfossil fuels, through the use of hydrogen, should receive as much emphasis as the efforts now being made to develop hydrogen-fueled or battery-operated automobiles.

b. Considerable effort is being expended on the use of hydrogen as an energy-storage medium. Current work emphasizes the role of hydrogen in an "electricity in-electricity out" system, in which efficiency losses of the second electricity generation step are significant and reduce the attractiveness of the concept. I believe that more emphasis should be given to concepts that include the use of stored hydrogen as a direct supplementary fuel.

c. Much of the natural gas industrys' transmission and distribution equipment, including regulators, valves, meters, and pipework, will, I believe, be compatible with hydrogen, but little or no testing and demonstration work is being undertaken at present to prove this point. I feel that the accumulation of several years of experience in this area, by a demonstration project involving equipment away from public premises, would do much to dispel the doubts of those who have quite justifiable fears about the safety aspects of putting hydrogen into the hands of the public.

5. How Should Hydrogen Energy Research be Directed?

After having conducted 3 or 4 years of preliminary research into the hydrogen-energy concept, we can make a strong case for its serious consideration as a long-term contributor to the U. S. energy system — at least a strong enough case to justify as significant a research and demonstration effort as is now being applied to other concepts such as superconducting transmission, battery storage, and some advanced solar-energy systems. I also believe that the outstanding problems have been well-enough defined to allow a properly balanced research program to be formulated. What is not clear, at present, is where such a program should be located within the Federal Government's research organizations.

In December 1974 at least seven different Government agencies, including AEC, NASA, EPA, NSF, DOD, DOT, and the Department of Commerce, were conducting hydrogen-energy programs in at least six National Laboratories and at least five NASA field centers. Although this work is very valuable and well managed, it has not been adequately coordinated; the establishment of ERDA has not changed this situation materially. This may be because hydrogen does not have a logical and obvious "home" within the ERDA functional assignments. It certainly does not fit into fossil or nuclear energy, environment and safety, national security, or conservation. The most appropriate division is that of "Solar, Geothermal, and Advanced Energy Concepts," but because hydrogen is not an energy source, it does not fall into place alongside the other interests of this division. Since "Electric Power Transmission" and "Energy Storage" are assigned to the Division of Conservation, hydrogen may fit better here. We must be careful that, because of this division of responsibility, hydrogen energy is not neglected in Government energy research activities.

At present, there seems to be a distinct danger that several Government-sponsored "overview" activities in hydrogen are all likely to revert to the review and planning stage, so that much of the momentum and expertise gained by research teams is in danger of being lost.

6. Attachments for the Record

The following publications are appended to this testimony to provide background for the statements I have made:

- "The Hydrogen Economy," reprinted from Scientific American, provides a general background on the overall concept of hydrogen energy and its advantages.
- "What We Can Do Now as Utility Industry Management and Government Planners " is a paper given to an IGT Members' Symposium on "Pipeline Hydrogen — Fuel for the Nuclear Age." This outlines some recommendations for both Government and utility research planning in the field of hydrogen.

- "Worldwide Research Activities in Hydrogen Energy" discusses the objectives and timing of hydrogen research activities known to be in progress or completed in December 1974. It discusses the stepwise introduction of hydrogen into the fields of chemical feedstocks, fuel (oil and coal) refining, steelmaking, energy storage, supplementing natural gas, and transportation and the ultimate use of hydrogen as a natural gas replacement. The document also contains a comprehensive listing of worldwide hydrogen projects completed or now in progress.

- "Hydrogen Energy Technology Today and Tomorrow" summarizes significant hydrogen research that is in progress, its applications, and its shortcomings, and discusses in particular the reasons why overall systems efficiencies, which are at present lower for hydrogen than for electricity, can be expected to increase to values comparable to those of electric systems.

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The Hydrogen Economy

A case is made for an energy regime in which all energy sources would be used to produce hydrogen, which could then be distributed as a nonpolluting multipurpose fuel

by Derek P. Gregory

The basic dilemma represented by what has been termed the "world energy crisis" can be simply stated: At the very time that the world economy in general and the economies of the industrialized countries in particular are becoming increasingly dependent on the consumption of energy, there is a growing realization that the main sources of this energy—the earth's nonrenewable fossil-fuel reserves—will inevitably be exhausted, and that in any event the natural environment of the earth cannot readily assimilate the by-products of fossil-fuel consumption at much higher rates than it does at present without suffering unacceptable levels of pollution.

What is not generally recognized is that the eventual solution of the energy problem depends not only on developing alternative sources of energy but also on devising new methods of energy conversion. There is, after all, plenty of "raw" energy around, but either it is not in a form convenient for immediate use or it is not in a location close enough to where it is needed. Most of the research-and-development effort in progress in the U.S. on the energy problem is devoted to finding ways to convert chemical energy (derived from fossil fuels), nuclear energy (derived from fission or fusion reactions) and solar energy (derived directly from the sun) into electrical energy.

At present nuclear-fission plants supply about 1.6 percent of the electricity consumed in the U.S. (Of the remainder, fossil-fuel plants supply about 82 percent and hydroelectric plants about 16 percent.) Assuming that the development of economically feasible "breeder" reactors will soon eliminate any short-term concern about the resource limitation of nuclear energy, then by the year 2000 nuclear plants may be supplying as much as half of the nation's electricity.

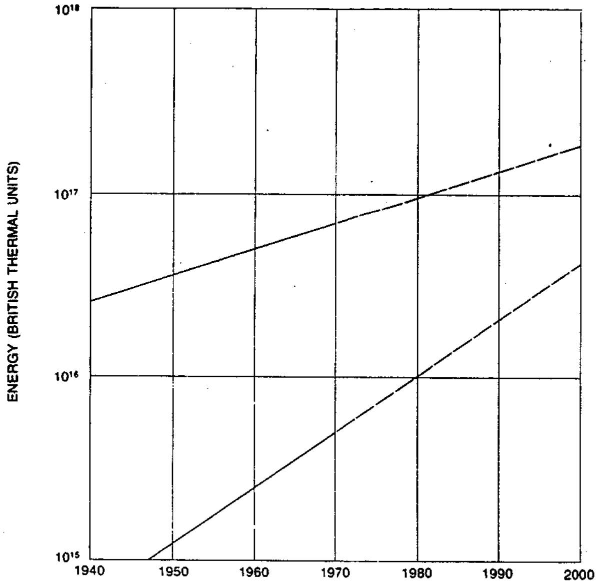
If this projection is correct, and if the "energy gap" of the future is to be filled with nuclear power made available to the consumer in the form of electricity, then the U.S. will have gone a long way toward becoming an "all-electric economy." This trend can be detected already: the demand for electricity is currently growing in the U.S. at a much higher rate than the overall energy demand [*see illustration on next page*]. It has been estimated that whereas the overall U.S. energy consumption will double by the year 2000, the demand for electricity will increase about eightfold, raising the electrical share of total energy consumption from about 10 percent to more than 40 percent.

The question naturally arises: How desirable is this trend toward a predominantly electrical economy? Specifically, are there any other forms of energy that can be delivered to the point of use more cheaply and less obtrusively than electrical energy can? Consider such major energy-consumption categories as transportation, space heating and heavy industrial processes, all of which are primarily supplied today with fossil-fuel energy, mainly for reasons of economy and portability. As the fossil fuels run out, they will become more expensive, making the direct use of nuclear electrical energy relatively more economical. In this situation a case can be made for utilizing the nuclear-energy sources indirectly to produce a synthetic secondary fuel that would be delivered more cheaply and would be easier to use than electricity in many large-scale applications. In this article I shall discuss the merits of what I consider to be the leading candidate for such a secondary fuel: hydrogen gas.

In many respects hydrogen is the ideal fuel. Although it is not a "natural" fuel, it can be readily synthesized from coal, oil or natural gas. More important, it can be produced simply by splitting molecules of water with an input of electrical energy derived from an energy source such as a nuclear reactor. Perhaps the greatest advantage of hydrogen fuel, however, at least from an environmental standpoint, is the fact that when hydrogen burns, its only combustion product is water! None of the traditional fossil-fuel pollutants—carbon monoxide (CO), carbon dioxide (CO_2), sulfur dioxide (SO_2), hydrocarbons, particulates, photochemical oxidants and so on—can be produced in a hydrogen flame, and the small amount of nitrogen oxide (NO) that is formed from the air entering the flame can be controlled. Moreover, assuming that the energy options are restricted to the use of effectively "unlimited" materials such as air and water, hydrogen is by far the most readily synthesized fuel.

In principle, then, one can envision an energy economy in which hydrogen is manufactured from water and electrical energy, is stored until it is needed, is transmitted to its point of use and there is burned as a fuel to produce electricity, heat or mechanical energy [*see illustration on opposite page*]. Such a hypothetical model is not without its problems and disadvantages, but on balance the benefits appear to be so great that I believe at the same time that we are moving toward an "electric economy" we should also be moving toward a "hydrogen economy."

Just as the food and beverage industry has found it uneconomical to collect and reuse empty containers, so the present energy industry cannot afford to collect and recycle used "energy containers": the by-products of the combustion necessary to produce the energy. The drawback in both cases is that the "no deposit, no return" system throws the burden of recovery and recycling onto the environment. Apart from the obvious harmful effect on the earth's atmosphere, this kind of energy cycle suffers from the further disadvantage of having an extremely slow step of several million years' duration for the re-formation of fossil fuels from atmospheric carbon dioxide [*see illustration on page 16*]. That is the basic reason we are running out of fossil-fuel reserves. In the hydrogen cycle, in contrast, only water is deposited into the atmosphere, where it rapidly equilibrates with the abundant and mobile water supply on the earth's crust. At another location the water is reconverted to hydrogen. The system is characterized by negligible delay and does not disturb the environment, yet it relies on the environment to carry out the "return empty" function. Assuming the availability of an abundant supply of nuclear or solar energy, this system can be operated as rapidly as the demand requires without depleting any natural resources.



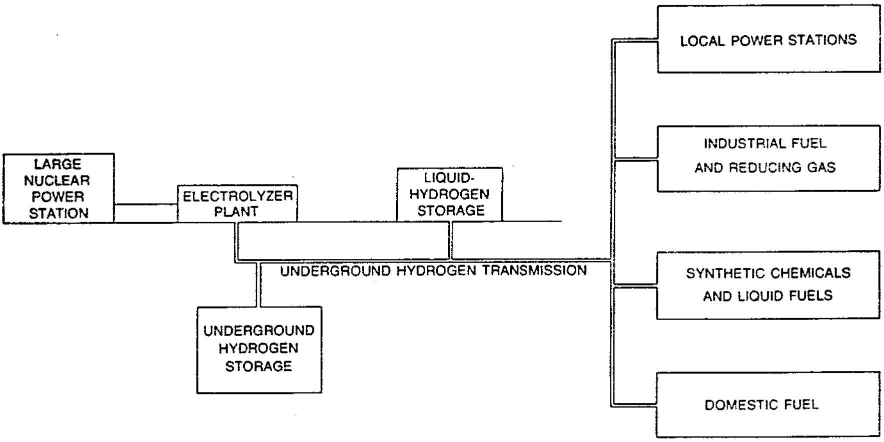
ACCELERATING TREND toward an "all electric" economy is evident in this graph, which shows that the demand for electricity (*bottom line*) is growing in the U.S. at a much higher rate than the overall energy demand (*top line*). Assuming that the trend continues, the U.S. is heading for a predominantly electrical economy sometime in the 21st century. The data are from the U.S. Department of Commerce and the Edison Electric Institute.

The idea of using hydrogen as a synthetic fuel is far from new. In 1933 Rudolf A. Erren, a German inventor working in England, suggested the large-scale manufacture of hydrogen from off-peak electricity. He had done extensive work on modifying internal-combustion engines to run on hydrogen, and the main object of his suggestion was to eliminate automobile-exhaust pollution and to relieve pressure on the importation of oil into Britain. (It is interesting to note that 40 years later the U.S. is concerned with the same two problems: automobile pollution and an increasing dependence on oil imports.)

Others have suggested using hydrogen as a fuel or as a means of storing energy. F. T. Bacon, a pioneer in the development of fuel cells in England since the 1930's, has always had as his ultimate objective the development of a hydrogen-energy storage system using reversible electrolyzer fuel cells. More recently the U.S. Atomic Energy Commission sponsored a series of studies during the 1960's of "nuplexes"—nuclear-agricultural-industrial complexes that derive all their energy from a single nuclear reactor. The AEC studies included the concept of water electrolysis to provide hydrogen as a precursor to the manufacture of fertilizers and chemicals. Within the past two years several articles have appeared in engineering and scientific journals proposing active studies of the production, transmission, storage and utilization of hydrogen in both combustion appliances and engines. Such studies are in progress at several universities and industrial research laboratories in the U.S. and abroad, including my own institution, the Institute of Gas Technology in Chicago, where our work is sponsored by the American Gas Association.

The difficulty of transporting hydrogen has historically prevented its use as a fuel. Clearly some better method than compressing it in steel cylinders has to be found. Storage and transportation as liquid hydrogen are already in use; metal hydrides and synthetic organic or inorganic hydrides have also been considered and have promise. There is no reason, however, why hydrogen should not be distributed in the same way that natural gas is distributed today: by underground pipelines that reach most industries and more than 80 percent of the homes in this country.

Before weighing the merits of the hydrogen-economy concept, it is instructive to consider the alternative: the all-electric economy. Suppose for a mo-



HYDROGEN ENERGY ECONOMY would operate with hydrogen as a synthetic secondary fuel produced from water in large nuclear or solar power stations (*left*). The hydrogen would be fed into a nationwide network of underground transmission lines (*center*), which would incorporate facilities for storing the energy, either in the form of hydrogen gas underground or in the form of liquid hydrogen aboveground. The hydrogen would then be distributed as it is needed to energy consumers for use either as a direct heating fuel, as a raw material for various chemical processes or as a source of energy for the local generation of electricity (*right*).

ment that one does not consider synthesizing a secondary chemical fuel; then one must face the prospect of generating and transmitting very large quantities of electricity. To meet the rising demand for electricity in the U.S. new generating stations are already being constructed in sizes larger than ever before. A few years ago a 500-megawatt power station was considered a giant. Today 1,000-megawatt stations are typical, and the electrical industry is contemplating 10,000-megawatt installations for the future.

In spite of the intensive efforts of their designers, the efficiency of steam-driven electric-power stations is still fairly low: about 40 percent for a modern fossil-fuel plant and 33 percent for a nuclear plant [see "The Conversion of Energy," by Claude M. Summers; SCIENTIFIC AMERICAN, September, 1971]. As a result the waste heat released from these large plants, or clusters of plants, is considerable. Accordingly they must be located near large bodies of water where ample cooling is available or in open country where cooling to the atmosphere will have no adverse local effects. Concern over the safety of nuclear reactors is also having a strong influence on the location of such plants. Because of these constraints the huge power stations of the future are likely to be built at distances of 50 miles or more from the load centers. Power stations located on offshore platforms floating in the ocean are already planned for the U.S. East Coast.

Power must be moved from the generating stations to the load centers. High-voltage overhead cables are expensive, in terms of both equipment costs and the land they occupy, and they are vulnerable to storm damage. Moreover, the electrical industry is encountering considerable resistance to the continued stringing of overhead power-transmission lines in many areas. Underground cables for carrying bulk power cost at least nine times (and sometimes up to 20 times) as much as overhead lines and thus are far too expensive to be used over long distances. Underground transmission is used only where the expense is justified by other considerations, such as aesthetic appearance or very expensive right-of-way. Much work is being done to develop cryogenic superconducting cables, which would allow large currents to be carried underground at a reasonable cost. At present, however, the technology is still at an early stage of development.

Some form of electrical storage would be of great value to the electrical industry, because power stations work most efficiently when operated at constant output at their full rated load. Since consumer demand varies widely both seasonally and during the day, however, the generating rate must be adjusted continuously. The only practical way available today to store large quantities of electrical energy is the pumped-storage plant, a reversible hydroelectric station; unfortunately only a limited number of sites are geographically suitable for such systems.

Thus it appears that several of the problems faced by the electrical industry—the siting of power stations, the expense of underground transmission and the lack of storage—are being amplified by factors that lead to larger and more remote power stations. The hydrogen-economy concept could help to alleviate these problems.

Hydrogen can be transmitted and distributed by pipeline in much the same way that natural gas is handled today. The movement of fuel by pipeline is one of the cheapest methods of energy transmission; hydrogen pipelining would be no exception. A gas-delivery system is usually located underground and is therefore inconspicuous. It also occupies less land area than an electric-power line. Hydrogen can also be stored in huge quantities by the very same techniques used for natural gas today.

Let us take a look at the existing gas-transmission network in the U.S. In 1970 a total mileage of 252,000 miles of trunk pipeline was in operation, carrying a total of 22.4 trillion cubic feet of gas during the year [*see illustration on pages 18 and 19*]. Such a pipeline system is needed because natural-gas sources are located in certain parts of the country, whereas markets for the gas exist in other areas.

In the hydrogen economy hydrogen gas would be produced from large nuclear-energy (or solar-energy) plants located in places that provide optimum cooling and other environmental facilities. Even coal-fueled hydrogen generators, located close to the mine mouths, could be integrated into this power-generation network. A pipeline transmission system would grow up to link these locations to the cities in a way analogous to the growth of the natural-gas transmission system.

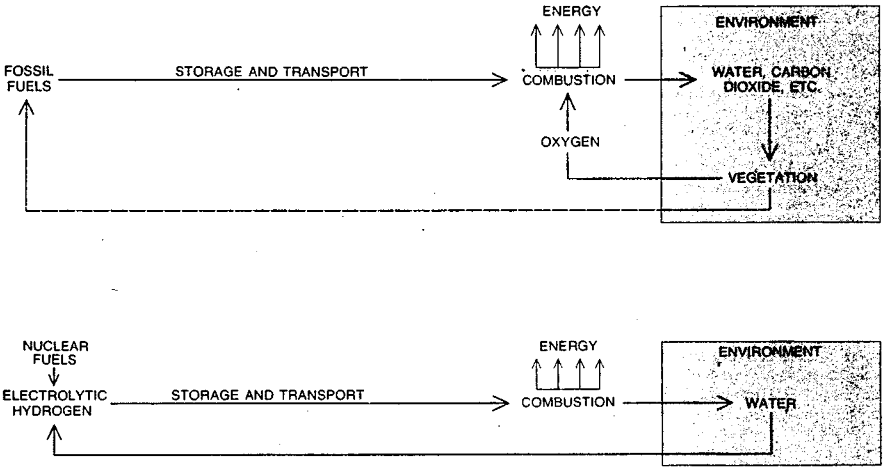
The technology for the construction and operation of natural-gas pipelines has been well developed and proved. A typical trunk pipeline, 600 to 1,000 miles long, consists of a welded steel pipe up to 48 inches in diameter that is buried underground with appropriate protection against mechanical failure and/or electrochemical corrosion. Gas is pumped along the line by gas-driven compressors spaced along the line typically at 100-mile intervals, using some of the gas in the line as their fuel. Typical line pressures are 600 to 800 pounds per square inch, but some systems operate at more than 1,000 pounds per square inch. A typical 36-inch pipeline has a capacity of 37,500 billion British thermal units (B.t.u.) per hour, or in electrical equivalent units 11,000 megawatts, roughly 10 times as much as a single-circuit 500-kilovolt overhead transmission line.

Natural gas is not the only gas to be moved in bulk pipelines, although no other gas is moved on such a scale. Carbon dioxide, carbon monoxide, hydrogen and oxygen are all delivered in bulk by pipeline. So far industry has had no incentive to pipeline hydrogen in huge quantities over great distances, but where it now pipelines hydrogen over short distances it uses conventional natural-gas pipeline materials and pressures. There is no technical reason why hydrogen cannot be pipelined over any distance required.

Because of the lower heating value of hydrogen (325 B.t.u. per cubic foot compared with about 1,000 B.t.u. per cubic foot for natural gas) three times the volume of hydrogen must be moved in order to deliver the same energy. Hydrogen's density and viscosity are so much lower, however, that the same pipe can handle three times the flow rate of hydrogen, although a somewhat larger compressor energy is required. Thus where existing pipelines happen to be suitably located, they could be converted to hydrogen with the same energy-carrying capacity.

In the hydrogen economy it will be possible to store vast quantities of hydrogen to even out the daily and seasonal variations in load. Natural gas is stored today in two ways: in underground gas fields and as a cryogenic liquid. At 337 locations in the U.S. natural gas is stored in underground porous-rock formations with a total capacity of 5,681 billion cubic feet. Whether hydrogen can be stored in underground porous rock can be finally ascertained only by future field trials. At present, however, 30 billion cubic feet of helium, a low-density gas with leakage characteristics similar to those of hydrogen, is stored quite satisfactorily in an underground reservoir near Amarillo, Tex.

Cryogenic storage of natural gas is a rapidly growing technique; at 76 locations in the U.S. "peak shaving" operations involving liquefied natural gas are in use or under construction. There is no technical reason why a similar peak-shaving technique cannot be employed with liquid hydrogen. Liquid hydrogen used to be considered a hazardous laboratory curiosity, but it is already being used as a convenient means of storing



ENVIRONMENTAL EFFECTS of the present fossil-fuel energy cycle and the proposed hydrogen-fuel energy cycle are compared here. When fossil fuels are burned to release their stored energy (*top*), the environment is relied on to accommodate the combustion by-products. The re-formation of the fossil fuels from atmospheric carbon dioxide takes millions of years (*broken line*). On the other hand, when hydrogen is burned as a fuel (*bottom*), the only combustion product is water, which is easily assimilated by the environment. The fuel cycle is completed rapidly without depleting limited resources or accumulating harmful waste products.

and transporting hydrogen over long distances. Liquid hydrogen is regularly shipped around the U.S. in railroad tank cars and road trailers. The technology for the liquefaction and tankage of hydrogen has already been developed, mainly for the space industry. Indeed, the largest liquid-hydrogen storage tank is at the John F. Kennedy Space Center; it has a capacity of 900,000 gallons, equivalent to 37.7 billion B.t.u. or 11 million kilowatt-hours [*see illustration at right*]. Although the energy content of this tank is only about 4 percent of the energy content of a typical liquid-natural-gas peak-shaving plant, its energy capacity is 73 percent of the capacity of the world's largest pumped-storage hydroelectric plant, located at Ludington, Mich.

The cryogenic approach to energy storage has the advantage of being applicable in any location, no matter what the geography or geology, factors that limit both underground gas storage and pumped hydroelectric storage.

ENERGY STORAGE in the form of liquefied hydrogen is already a routine practice in the space industry. This vacuum-insulated cryogenic tank at the John F. Kennedy Space Center, for example, contains 900,000 gallons of liquid hydrogen for fueling the Apollo rockets. It is the largest facility of its kind in existence. In terms of energy its contents are equivalent to 37.7 billion B.t.u. of heat or 11 million kilowatt-hours of electricity.

The simplest way to manufacture hydrogen using nuclear energy is by electrolysis, a process in which a direct electric current is passed through a conductive water solution, causing it to decompose directly into its elementary constituents: hydrogen and oxygen. Complete separation of the two gases is achieved, since they are evolved separately at the two electrodes. Salts or alkalis, which have to be added to the water to increase conductivity, are not consumed; thus the only input material required is pure water.

A number of large-scale electrolytic hydrogen plants are operated today in locations where hydrogen is needed (for example in the manufacture of ammonia and fertilizers) and where cheap electric power (usually hydroelectric power) is available. One of the largest commercial electrolyzer plants in the world is operated by Cominco, Ltd., in British Columbia [*see illustration on page 20*]. This plant consumes about 90 megawatts of power and produces about 36 tons of hydrogen per day for synthesis into ammonia. The by-product oxygen is used in metallurgical processes. Similar large plants are located in Norway and Egypt. Many smaller plants exist where hydrogen is produced from unattended equipment.

The theoretical power required to produce hydrogen from water is 79 kilowatt-hours per 1,000 cubic feet of hydrogen gas. In practice the large industrial plants are only about 60 percent efficient; a typical power-consumption figure is 150 kilowatt-hours per 1,000 cubic feet of hydrogen. This power requirement represents a major part of the plant's operating cost. Thus there is a considerable incentive—indeed, a real need—to increase the operating efficiency of such plants if one is to consider using electrolytic hydrogen as a fuel.

The fuel cell, the subject of intensive research and development as part of the space program over the past 15 years, is really an electrolyzer cell operating in reverse. The simplest fuel cell to build and operate is one that operates on hydrogen and oxygen, yielding water and electric power as its products. Hydrogen-oxygen fuel cells were selected and developed for both the Gemini and the Apollo programs because of their high efficiency, which reduces the amount of fuel needed aboard the spacecraft to supply its electric power. Much effort has gone into developing fuel cells with high efficiencies. This same technology can be applied to increase the efficiency of the reverse process: electrolysis. Electrolytic cells are operating in aerospace laboratories today with an efficiency of more than 85 percent.

Increasing the electrolyzer efficiency alone has relatively little merit as long as the present power-station efficiency in converting nuclear heat to electric power is only about 33 percent. This efficiency loss can, however, also be circumvented. For example, Cesare Marchetti at the Euratom laboratories in Italy has designed a chemical process for the thermal splitting of water to hydrogen and oxygen directly using the heat energy produced by a nuclear reactor. If water is to be split into its elements directly, it must be heated to very high temperatures—about 2,500 degrees Celsius—to achieve dissociation. Not only are such temperatures not available from nuclear reactors but also the gases cannot conveniently be separated from each other before they recombine. It is possible to conceive of a two-stage reaction in which a metal, say, reacts with steam at a reasonable temperature to produce hydrogen and a metal oxide. The hydrogen is easily separated from the metal oxide, which in turn could be decomposed to oxygen and the metal by the application of heat. Unfortunately there does not appear to be any suitable metal that undergoes such a series of reactions at temperatures low enough to be compatible with nuclear reactors, whose construction materials limit operating temperatures to about 1,000 degrees C.

Marchetti's concept, therefore, is a far more complex reaction sequence involving calcium bromide ($CaBr_2$), water (H_2O) and mercury (Hg), in which, except for the hydrogen and oxygen, all the reactants are recycled. Each of the reactions proceeds at temperatures below 730 degrees C., which can be achieved in a nuclear reactor. Although the process appears to be feasible, development work is still required to try to bring the overall efficiency up and the cost down to practical limits.

The quantities of hydrogen that the hydrogen economy would require are immense. For example, if we were to produce today an amount of hydrogen equivalent to the total production of natural gas in the U.S., we would have to provide during one year the same fuel value as 22.5 trillion cubic feet of gas, or 22.5 quadrillion (10^{15}) B.t.u. of energy. This corresponds to about 70 trillion cubic feet of hydrogen, which, if we could produce it at a steady rate all year round from nuclear electrolytic plants, would require an electrical input of more than a million megawatts. The present total electrical generating capacity in the U.S. is 360,000 megawatts, so that we are envisioning a fourfold increase in generating capacity, which would require the construction of more than 1,000 new 1,000-megawatt power stations. That is in addition to the rapidly increasing demand for electric power for other uses. During the past five years, in contrast, the electrical generating capacity in the U.S. has grown by "only" 105,000 megawatts.

Such a formidable task of increasing capacity, however, does not follow solely from our turning to a hydrogen economy. As our huge consumption of fossil fuels declines in future years, we must provide at least an equivalent alternative energy source. Such numbers give a taste of the energy revolution that must take place within the next half-century.

At present the cheapest bulk hydrogen is made from natural gas. Clearly since hydrogen from such a source cannot be cheaper than the starting material, it cannot therefore be expected to replace natural gas as a fuel. Electrolytic hydrogen is even more expensive, unless very cheap electric power is available. Today's electricity prices are based on supplying a fluctuating load, but the capability of hydrogen storage would even out the load and might reduce the price of electricity somewhat.

Although the cost of hydrogen produced from electricity must always be higher than the cost of the electricity, it is the lower transmission and distribution cost of hydrogen compared with electricity that makes it advantageous to the user. The latest economic figures published by the gas and electrical industries can be used to derive the production, transmission and distribution shares of average prices, charged to all types of customers, for gas and electricity, and these data can be compared in turn with corresponding figures for hydrogen made by electrolysis [*see illustration on page 21*]. The figures for hydrogen are derived from the hypothetical assumption that all the electricity generated in the U.S. in 1970 was converted to hydrogen, which was sent through the existing natural-gas transmission network (for an average distance of 1,000 miles) and was delivered to customers as a gaseous fuel. The electrolysis charge of 56 cents per million B.t.u. is derived from AEC estimates of the cost of building advanced electrolyzer cells. The hydrogen transmission and distribution costs are based on natural-gas costs, adjusted to take account of the different physical properties and safety factors for handling hydrogen.

Two things are obvious from such a comparison. One is that today it is far cheaper for the average customer to buy energy in the form of natural gas than it is in the form of electricity. The other is that it should already be possible to sell hydrogen energy to the gas user at a lower price than he now pays for electricity. Clearly, however, this hydrogen will find no markets while natural gas is as cheap as it is.

Looking to the future, we see that natural-gas prices, together with all fossil-fuel prices, will increase rapidly. These rises are brought about by their short supply, by the influence of pollution regulations and by such social pressures as land conservation and employee welfare applied to the mining industry. In contrast, the price of nuclear energy, although apparently rising fast now, can be expected to stabilize somewhat in the breeder-reactor era because there will then be no severe supply limit.

It is not possible at this time to forecast accurately what the cost of hydrogen energy is likely to be, but one can certainly look forward to considerably increased prices for all forms of energy. Even so, in the long run delivered hydrogen will be cheaper than delivered natural gas and very probably also cheaper than delivered electricity.

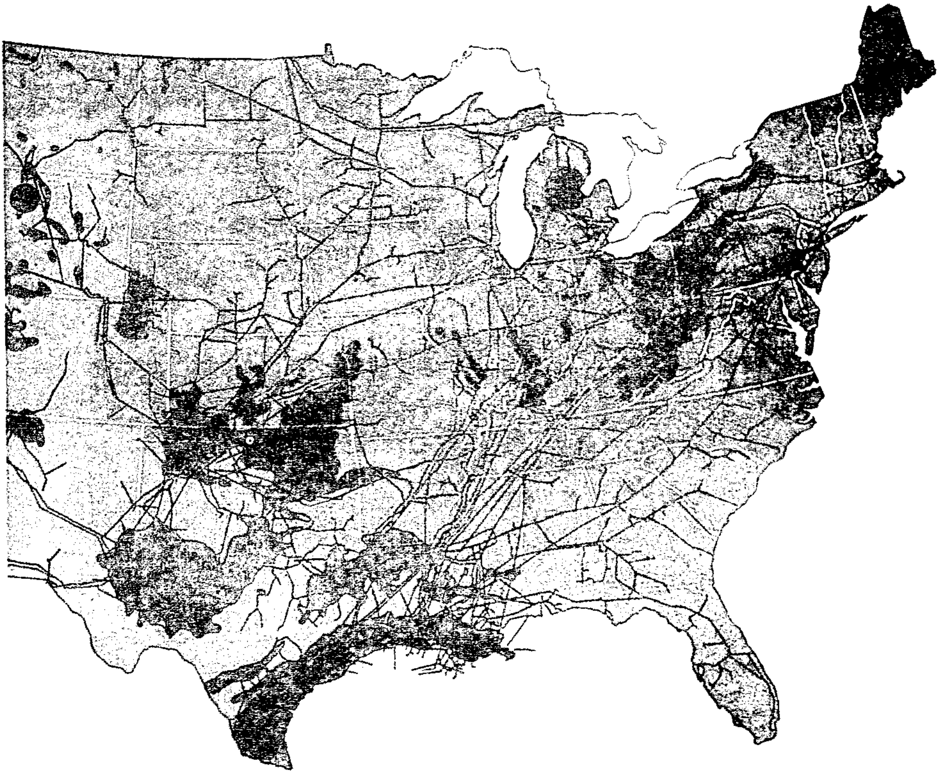
When hydrogen becomes as universally available as natural gas is today, it will easily perform all the functions of natural gas and others besides. Hydrogen can be used in the home for cooking and heating and in industry for heating; in addition it can serve as a chemical raw material in many industries, including the fertilizer, foodstuffs, petro-

TRUNK PIPELINES extending for 252,000 miles (*black lines*) already exist in the U.S. for transmission of natural gas from areas chemical and metallurgical industries. Hydrogen can also be used to generate electricity in local power stations.

The combustion properties of hydrogen are considerably different from those of natural gas. Hydrogen burns with a faster, hotter flame, and mixtures of hydrogen with air are flammable over wider limits of mixture. These factors mean that burners of hydrogen must be designed differently from those of natural gas and that modification of every burner will be necessary on changeover. Such widespread modification is not without precedent. A similar operation was carried out when the U.S. changed from manufactured gas (about 50 percent hydrogen) to natural gas; several European countries have recently undertaken the same conversion.

Hydrogen, because it burns without noxious exhaust products, can be used in an unvented appliance without hazard. Hence it is possible to conceive of a home heating furnace operating without a flue, thereby saving the cost of a chimney and adding as much as 30 percent to the efficiency of a gas-fired home heating system. More radical changes are possible, moreover, because without the need for a flue the concept of central heating itself is no longer necessary. Each room can have its heat supplied by unflued peripheral heating devices operating on hydrogen independently of one another. Indeed, the vented water vapor would provide beneficial humidification. Another radical change is the potential use of catalytic heaters. Since hydrogen is an ideal fuel for catalytic combustion, true "flameless" gas heating is possible, with the catalytic bed being maintained at any desired temperature, even as low as 100 degrees C. This prospect promises to revolutionize domestic heating and cooking techniques in the future. With such low temperatures it is virtually impossible to produce nitrogen oxides, thus eliminating the only possible pollutant from a hydrogen system.

Hydrogen is also the ideal fuel for fuel cells. The technological problems that have faced the development of practical, commercially economical fuel cells for

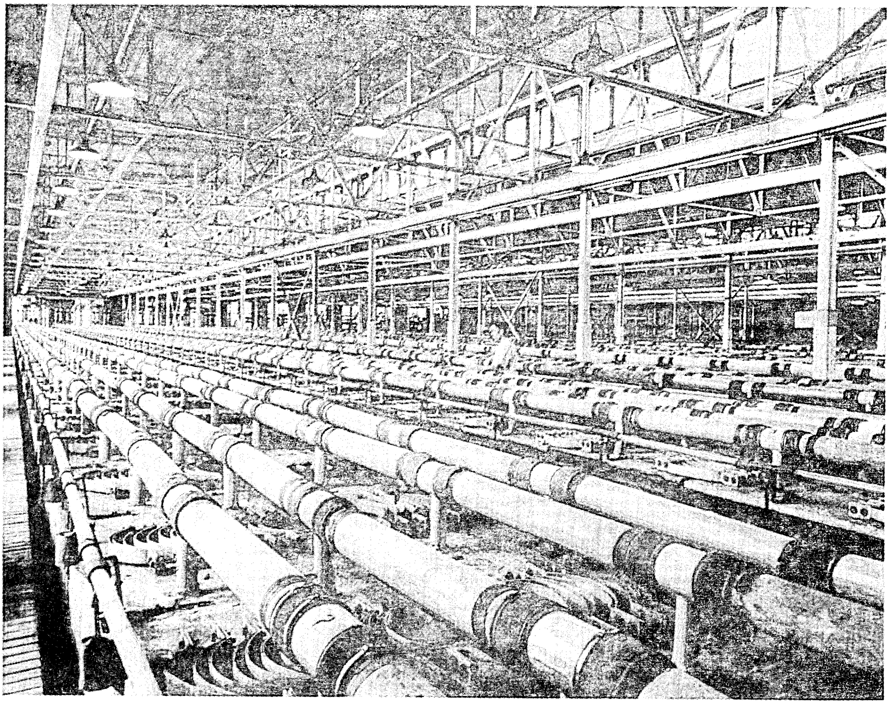


where the gas is produced (*gray*) to areas where it is consumed. The system, which is constructed almost entirely of welded steel pipe, carries approximately 61.4 billion cubic feet (or 1.5 million tons) of natural gas per day. Similar networks of underground hydrogen-gas pipelines would enable the giant nuclear (or solar) power stations of the future to be located far from the load centers.

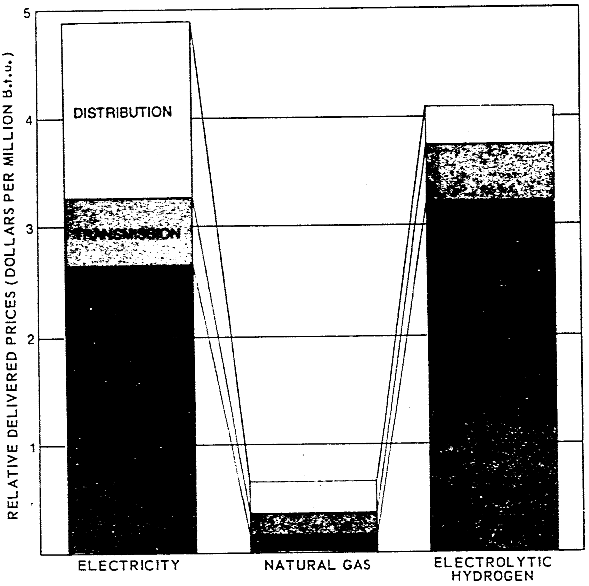
more than a decade are very much reduced if hydrogen can be used as fuel. Fuel-cell electricity generators operating on hydrogen should be at least 70 percent efficient and can realistically be expected to find a place in the home, in commercial and industrial buildings and in industry. Larger, urban electrical generating stations could be fuel-cell systems or could be hydrogen-fueled steam stations. An earlier concept of operating a closed-cycle steam-turbine system on a hydrogen-oxygen fuel supply could become practical through the use of rocket-engine technology. Workers at the Massachusetts Institute of Technology have proposed such a system for submarines; it has been reported that an overall efficiency of 55 percent can be anticipated from it.

Hydrogen is an excellent fuel for gas-turbine engines and has been proposed as a fuel for supersonic jet transports. For this kind of use fuel storage and tankage as liquid hydrogen are practical. Although the large volume required may make its use less attractive for subsonic aircraft, the very considerable saving in weight over an equivalent fuel load of kerosene gives hydrogen a distinct advantage. Conventional internal-combustion engines will also operate on hydrogen if they are suitably modified or redesigned. R. J. Schoeppel of Oklahoma State University and others have shown that if hydrogen is injected into the engine through a valve in a manner similar to the way fuel is injected into a diesel engine, the preignition characteristics of hydrogen are overcome. Others, including Marc Newkirk of the International Materials Corporation and Morris Klein of the Pollution Free Power Corporation, have reported satisfactory operation of conventional automobile engines on hydrogen using carburetor and manifold modifications. Meanwhile William J. D. Escher of Escher Technology Associates has proposed a radically different approach to automobile engine design, using a steam system fueled by both hydrogen and oxygen. The use of liquid hydrogen as a routine private-automobile fuel is questionable on the ground of safety, although it is probably applicable to fleet users, such as bus lines and taxicab fleets.

Richard H. Wiswall, Jr., and James J. Reilly of the Brookhaven National Laboratory have proposed the use of metallic hydrides to store hydrogen as a fuel for vehicles. A magnesium-alloy hydride will store hydrogen energy as efficiently (on a weight basis) as a tank of liquid hydrogen, but some technical problems must still be overcome. At present there seems to be no single, obvious way in which automobiles can be operated on hydrogen fuel, but considerable work is



LARGE ELECTROLYZER PLANT for the production of hydrogen by the electrical decomposition of water is operated by Cominco, Ltd., in British Columbia. The 3,200 electrolytic cells, which cover more than two acres, consume about 90 megawatts of power and produce about 36 tons of hydrogen per day for synthesis into ammonia. By-product oxygen is used in metallurgical processes.



RELATIVE DELIVERED PRICES of various forms of energy are broken down in this bar chart into the shares represented by production (*solid color*), transmission (*intermediate color*) and distribution (*light color*). The comparison reveals that at present it is much cheaper to buy energy in the form of natural gas than in the form of electricity. Moreover, the breakdown shows that although the cost of hydrogen produced from electricity must always be higher than the cost of the electricity, the lower transmission and distribution costs of hydrogen already make it possible to sell hydrogen energy to the gas user at a delivered price lower than what he now pays for electricity. It is expected that natural-gas prices, together with all fossil-fuel prices, will increase rapidly in the future.

going on to investigate the various options available. If one has to synthesize a suitable liquid fuel for automobiles and aircraft, the starting material for the fuel must be hydrogen in any case.

One of the main criticisms of the hydrogen-economy concept is that hydrogen is too dangerous for use in this way. Undoubtedly hydrogen is a hazardous material and must be handled with all due precautions. If it is handled properly, however, in equipment designed to ensure its safety, anyone should be able to use it without hazard.

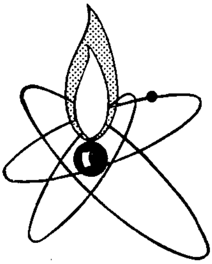
In the days of manufactured gas (gas made from coal), which consisted of up to 50 percent hydrogen and contained about 7 percent carbon monoxide, people managed to live with the fire and explosion hazards of hydrogen as well as the toxic hazards of carbon monoxide. Of course, it takes only one major disaster to alert everyone to a hazard. The most famous hydrogen accident, the *Hindenburg* airship disaster of 1937, is still remembered with awe. Indeed, the almost universal fear of hydrogen has been described as the "*Hindenburg* syndrome." Spectacular as it was, however, that fire was almost over within two minutes, and of the 97 persons on board, 62 survived.

Very strict codes are enforced for the use of natural gas today; even stricter ones are applied to industry for the use of hydrogen. Most of these codes are realistically based on reducing the chances of accidents. Just as we have designed apparatus and procedures to enable us to fill our automobile tanks with gasoline and carry the resulting 20-gallon "fire bomb" at speeds of up to 70 miles per hour along a crowded highway and park it overnight right inside our homes, we can surely devise safe practices for handling hydrogen.

Hydrogen cannot be detected by the senses, so that a leak of pure hydrogen is particularly hazardous. Odorants are routinely used to make natural-gas leaks obvious, however, and no doubt the same can be done with hydrogen. Hydrogen flames are also almost invisible and are therefore dangerous on this score. Hence an illuminant may have to be added to the gas to make the flame visible. The flammability limits of hydrogen mixed with air are very wide, from 4 to 75 percent. It is the lower limit, almost the same as that for methane (5 percent in air), that causes the fire hazard with a gas leak. On the benefit side, however, since hydrogen is so much lighter than air and diffuses away at a far greater rate than methane, a hydrogen leak could actually be less hazardous than a natural-gas leak. The most significant hazardous property of hydrogen is the extremely low energy required to ignite a flammable mixture: only a tenth of the energy required to ignite a gasoline-air mixture or a methane-air mixture and well within the energy levels of a spark of static electricity (a probable cause of the *Hindenburg* fire, which occurred just after a thunderstorm). Thus safety practices will have to be based on the assumption that if a hydrogen fire can occur, it will! Huge quantities of hydrogen are handled in industry quite safely and without accident precisely because proper precautions are taken.

To recapitulate briefly, our recoverable fossil-fuel supplies will sooner or later become exhausted; we are already feeling the effects of the limited supply by having to pay more for fossil-based energy. Within the next 50 years we must be prepared to pay considerably more for energy from all sources, particularly for fossil fuels. One way of handling nuclear and other energy sources is to use them to convert water to hydrogen in large central plants and then to use hydrogen as a clean, nonpolluting fuel. Technically this is already feasible; only relatively simple developments have to be made, not approaching the magnitude of the technical tasks of developing the alternative energy sources—breeder reactors and solar engines—themselves. Economics and safety are the two obstacles to developing such a hydrogen economy. A combination of technical development and the expected adjustment in relative energy prices can justify the economics, and proper practices and design can ensure safety. If and when we move into a hydrogen economy, the world will undoubtedly be a far cleaner place to live in than it is today.

PIPELINE HYDROGEN



THE FUEL FOR THE NUCLEAR AGE

A Panel Discussion at the
Thirty-third Annual Meeting of Members
and of the Board of Trustees of the
Institute of Gas Technology

IIT CENTER • CHICAGO, ILLINOIS • NOVEMBER 21, 1974

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Grover M. Hermann Hall
IIT Center
Chicago, Illinois 60616
November 21, 1974

PIPELINE HYDROGEN

THE FUEL FOR THE NUCLEAR AGE

INTRODUCTION

16 mm sound film and voice over (VO)

EARTH - The Watery Planet

No other planet in our solar system has adequate gravity and temperature conditions to support oceans that cover so much of its surface. Our "earth" is 70.8 per cent water.

If this seems contradictory, man has been living this contradiction since the beginning of time. His preoccupation with land has limited him to less than 30 per cent of his total world. His relationship to the sea is still that of primitive hunter.

In the past, he could afford this luxury of seeking the obvious. Today, our rapidly changing environment demands that he explore the potential alternatives of the sea as well as the land.

Soon man will turn to the ocean for his water supply, cultivate the ocean for much of his food, and eventually harness it as an energy source.

It is this energy source potential that we are concerned with today. The principal component of water is hydrogen . . . a combustible gas like natural gas. Hydrogen can even be pumped to high pressure like natural gas. And when it is cooled, it can be stored in cryogenic tanks like natural gas. Basically hydrogen can serve all the conventional applications of natural gas, but with some inherent advantages. Very often it is easier to utilize than natural gas. For example, the fuel cell is actually a hydrogen-consuming device. Before natural gas can be fed into a fuel cell, it must be converted to hydrogen in a reformer. Imagine the huge amounts of hydrogen that will have to be used in the production of SNG from coal.

Furthermore, there is a growing acceptance in the scientific community that hydrogen may be at least as good a product from nuclear heat as electricity. Or even a better product than electricity. And, as we move into a nuclear-based economy, this can be a very important alternative to more obvious solutions.

INTERVIEWER: Dr. Armand Luxo is Director of Research for Gaz de France. Dr. Luxo, Gaz de France has been conducting research into hydrogen for some years. Will you tell us about that please?

DR. LUXO: Why is Gaz de France so much interested in the production of hydrogen from water and atom? Well, we import, for the time being, two thirds of our primary energy from foreign sources as hydrocarbons and we have not sufficient resources in coal to produce large quantitites of substitute natural gas and then we have to rely upon another product coming from water and using nuclear energy for producing it. Hydrogen is not only a raw material useful as a petrochemical feedstock but also is an energy carrier able to extend the uses of nuclear energy. This is the main reason for our research. It could supply customers which could not otherwise be supplied by electricity. Then these considerations can let us understand why we are so much interested in hydrogen and justify the important efforts we have to make to reach this important goal and to study this important and difficult project.

VO: Hydrogen is becoming an important synonym for the future of the gas industry of the world. The growing deficit in energy supply must ultimately be met by nuclear energy. Until now, the practical use of nuclear energy has been limited to the production of electricity.

If this trend is continued we will be faced with two major problems.

First, the inherent high efficiency and low cost advantages of transporting and storing oil and gas are forever lost in an all-electric economy. The result could be an overall decline in efficiency of the U.S. energy system.

Secondly, if the consumer is to utilize electricity for applications now served by oil and gas, there will have to be very costly technological changes in consumer equipment.

Can our economy afford it?

Can the public afford it?

Can the gas industry afford it?

Hydrogen provides a solid alternative.

INTERVIEWER: Leslie Clark is the president of the International Gas Union and the chairman of the Northern region of the British Gas Corporation. Mr. Clark, you just appeared on a panel on the discussion of the future of hydrogen at the World Energy Conference in Detroit — Why is hydrogen being discussed now?

CLARK: I think that it is very important that we should discuss hydrogen because the gas industry of the world has become one of the major energy supply industries. It's supplying nearly a third of the world's energy in effective, useful, final energy terms. We also know that in some countries, in some parts of the world, that the supplies of natural gas are beginning to run short and it may well be that within 25 years some countries will need some other form of energy to replace the natural gas they're using now.

They already have in existence, of course, extensive transmission and distribution systems which are very effective. They do not offend the environment in any way, they're all below ground and it's a very efficient means of moving energy around.

So, we think of how we could replace the natural gas. It's possible to make substitute natural gas from coal but hydrogen is another means of doing this because we are thinking of the period when we shall have to depend very much more on nuclear energy and it is possible to produce hydrogen from nuclear power.

VO: Hydrogen isn't new as a fuel. For years the utility gas industry manufactured and distributed low-BTU gas which contained a large proportion of hydrogen.

Even natural gas is principally hydrogen. Methane, it's chief component contains one atom of carbon and four atoms of hydrogen.

More recently, hydrogen-fueled rockets sent men to the Moon.

Military planners talk about hydrogen as fuel for tanks and other combat vehicles.

Aviation planners talk about flying our commercial jet planes with hydrogen.

INTERVIEWER: Paul M. Ordin is manager for projects related to safety involving cryogenic fluids, the Aerospace Safety Research and Data Institute, Lewis Research Center, Cleveland.

ORDIN: Thank you. The Lewis Research Center has been concerned with hydrogen since 1950. Our initial efforts with hydrogen were its use as a rocket fuel. We started working at that time on about 100 lb. thrust engines using small quantitites of hydrogen. This we continued until we have our successful rocket program today.

About 1955, a program was started in our Center in cooperation with the Air Force to design or modify an existing aircraft that would use hydrogen as a fuel. This work, as I said, started in 1955, and by 1956, we were successful and had actually completed the first and second flight of a B57-B aircraft using hydrogen. Now, a B57-B aircraft is a two-engine aircraft. We modified it so that one of the engines used hydrogen. The system was designed so that the liquid hydrogen — we used liquid as the storage and it was in a wing-tipped tank - and the liquid in the tank was pressurized with helium. The liquid was sent through a ram-air heat exchanger on the aircraft and the gas was then injected into the engine.

VO: There are ecological values in the hydrogen alternative as well. It is a clean-burning fuel that can be readily and economically substituted for liquid fossil fuels in the transportation market. When hydrogen burns, its principal combustion product is water. Since it contains no carbon, it cannot form carbon dioxide or carbon monoxide when it burns.

And hydrogen is a safe fuel, though any form of concentrated chemical energy must be fully understood and handled with respect or it becomes a dangerous hazard.

Hydrogen has a safety track record like natural gas and gasoline. For years, liquid hydrogen has been safely transported by rail and over-the-road tankers. NASA utilizes hydrogen extensively in the space program. And, the by-word at NASA is safety.

INTERVIEWER: Addison Bain is Systems Engineer, Support Operations, Kennedy Space Center.

BAIN: The Apollo space vehicle which carried the astronauts to the moon was launched from the pad in the far background near the grey tower. The on-board quantity of liquid hydrogen for the launch vehicle was 340, 000 gallons which was supplied from the storage sphere which you see in the front. The storage sphere has a capacity of 850, 000 gallons. It transferred liquid hydrogen to the space vehicle (launch vehicle) at the rate of 10, 000 gallons a minute. The sphere itself is supplied by over-the-road tankers each of which have a 13, 000 gallon capacity. The tankers provided the liquid hydrogen from a production facility 700 miles away.

During the Apollo launch program, these tankers hauled over 16, 000, 000 gallons of liquid hydrogen and logged well over 2, 000, 000 miles. As we go into the next major program which is the space shuttle program, we're talking about 40 launches a year. These launches will start in 1979 and go to that activity in about the early 80's. During that time, we expect some 600, 000 gallons a week to be delivered to this site. We expect to use the same hardware, probably more tankers, with exactly the same design that you see here.

With an increased activity of 20-fold, we really don't expect any change to our operations. We think the safety guidelines, the operating procedures have all been well established.

VO: In spite of all this, there is not unanimous agreement in the scientific community about when, how, or if hydrogen fits into the overall energy supply picture.

INTERVIEWER: Dr. Edward Teller is a noted atomic scientist. Dr. Telle: it is widely known that you are a strong advocate for the development of nuclear energy. It has also been widely understood that in moving to a nuclear age, we also are moving to an all-electric economy. More recently we have heard advocation of what is known as The Hydrogen Economy to supplement the all-electric economy. Do you have any views on this?

DR. TELLER: We are not moving to an all-electric economy. Futhermore, we have exceedingly urgent problems and The Hydrogen Economy is something that is far in the future. I am not at all convinced that it will be an essential part of a long-range solution. I can see hydrogen as something important for special uses and special ways of producing it. I am advocating underground coal gasificiation. One of the products which can be isolated is hydrogen and because it burns cleanly, it could be used for some purposes although it is difficult to handle and it is dangerous because it is so light. It might be, it probably will become an ideal fuel for very big airplanes. But it has to be handled with extreme caution and it will not come soon. We have to deal with the energy crisis that is now upon us.

VO: There is a difference of opinion among experts about the potential of a mixed hydrogen-electric economy, just as there is disagreement as to how much oil and gas this country can produce and how fast it can produce it.

Despite these differences of opinion, hydrogen can provide a logical and economical transition into the nuclear-based 21st century for the consumer and the fossil fuel industry.

In the short term, hydrogen can be readily derived from our most plentiful fossil fuel. . . coal.

And in the long term, hydrogen can be produced from plentiful seawater by the use of nuclear heat.

Isn't it about time we stopped ignoring our greatest natural resource and got our collective feet wet?

Dr. Robert B. Rosenberg
Vice President, Engineering Research
Institute of Gas Technology

Good morning. I'm Bob Rosenberg. As you are no doubt aware, there is a great deal of discussion about hydrogen these days. A lot of new terms are being used, — "Hydrogen Energy Systems," "Hydrogen Economy," "Mixed Hydrogen-Electric Economy," "Universal Fuel" and so forth. You are probably questioning whether any of these systems are for real. Do they refer to an idealized energy system centuries hence? Will they be useful to me in the coal, oil or utility business today, or just in the years ahead?

We at IGT don't believe that hydrogen is an answer to all of our energy problems. Hydrogen is a secondary energy form. That means that some other energy source must be used to produce it. Thus, it is like electricity. However, once produced, hydrogen holds the promise of significant technical and economic advantages over other alternatives for various applications as we grow increasingly short of conventional fossil fuel and more dependent on nuclear energy.

The particular advantage of hydrogen will relate to its relative simplicity and reactivity as a chemical feed stock. Or to its relative cleanliness in combustion as a fuel. Or to its relative simplicity in substitution in utilization equipment developed primarily for conventional fossil fuels. Or to its use as an intermediate energy carrier where its relative ease in transportation and storage might be used to advantage. We believe the broad possibilities of incorporating hydrogen technology into our basic energy business warrant our serious examination.

To provide us with a basic set of facts, we have invited several people here this morning who, because of their past and present activities, have a special knowledge of hydrogen technology and its possibilities. We have asked them to discuss with you the status of hydrogen technology developments — what they see as the near and long-term role of hydrogen energy, particularly in the utility business — and what course of action you, as representatives of energy industry management, can take now to help assure that you realize the potential benefits of hydrogen energy.

I will first call on Mr. John A. Casazza. Jack is a Cornell graduate and, as many of you know, is vice president of planning and research for Public Service Electric and Gas Company, Newark, New Jersey. Jack's company, under his direction, has been extensively engaged in hydrogen work for more than four years — both in analysis of how it can fit into its gas and electric distribution operations, and in actual development of equipment relevant to the needs they foresee. Not only is Public Service a current leader in hydrogen technology development in the utility business, but Jack tells us it is a real pioneer in the field. Ancient corporate records reveal that the firm known today as Public Service Electric and Gas Company once bore the name of Oxy-hydrogen Company of the United States.

Thus he is backed with over 100 years experience when he talks this morning on "What Can Hydrogen Do For An Energy Company?"

John A. Casazza
Vice President, Planning and Research
Public Service Electric and Gas Co.
Newark, N. J.

WHAT CAN HYDROGEN DO FOR AN ENERGY COMPANY?

Introduction

In order to continue to meet the needs of this world we must use our resources wisely. These resources can be classified into three broad categories: natural, human, and capital. The natural resources consist of air, water, land and include such fuels as coal, oil, gas, and uranium. Our human resources, our scientists, engineers, and our skilled and unskilled labor are limited and must be used wisely. Our capital resources provide the tools through which our human resources can use our natural resources for the benefit of all the people of this earth. To conserve our limited capital we will have to make the best possible use of our existing energy systems.

In using these resources we need to recognize that energy is closely tied to all mankind's need including food and water supply. A total system optimization is needed. We cannot optimize the use of one resource to the detriment of the total system. In this process, it is essential that new technology be vigorously pursued and brought into use.

Moving Targets and the Age of Uncertainty

The role of hydrogen and hydrogen-related technology in utility systems will depend on future growth, cost trends, new technology, and environmental requirements. Each of these areas presents rapidly moving targets for hydrogen as well as other energy forms. Examples of the speed of change are the rapid excalation in fossil fuel prices and the shortage of capital which has resulted in more than 60,000 MW of new electric generating capacity being delayed or cancelled in the U.S.A. since the first of the year. To be able to meet such uncertainties in the future we must maintain as many options and as much flexibility as possible in developing our energy systems.

Why Hydrogen?

We in PSE&G believe that hydrogen can play an important role in providing additional options and flexibility in meeting our future national needs from energy to food to transportation. Hydrogen can make possible the use of our nuclear energy resources for many purposes.

With the intriguing future possibilities for the use of hydrogen, the fundamental question becomes: When and how should we pursue the development and use of hydrogen technology in our energy system?

Hydrogen can be produced from liquid and gaseous fossil fuels through catalytic oxidation and steam reforming, and from coal through partial oxidation and steam reforming. SNG plants and coal gasification plants have the potential, with some modification, of producing hydrogen.

It can also be produced from water, at the present time, through electrolysis. Considerable research is underway on the thermochemical splitting of water to obtain hydrogen including the efforts at Euratom in Italy, the efforts of General Atomics in California, and the work at IGT. The production of hydrogen by this mechanism is not likely to occur before 1990.

The Texas Gas Transmission Corporation is presently sponsoring work at the KMS Fusion Laboratories on the use of high-speed neutrons produced by laser fusion to split water molecules into hydrogen and oxygen. KMS predicts that it may be possible to produce hydrogen by such a process in the late 1970s. Another possibility for the production of hydrogen is to use the neutrons that will be produced by a device similar to the two-component Torus device (TCT) presently under consideration for installation at the Princeton Plasma Physics Laboratory in 1979. The TCT project is expected to be funded by the U.S. Government at approximately $200,000,000.

We in PSE&G felt several years ago that hydrogen research was justified if we were to develop the necessary technical expertise and the needed personnel to be able to cope with the problems of hydrogen in the future. Accordingly, we embarked on the following program:

PSE&G Hydrogen Activities

The approach selected for PSE&G in the area of hydrogen systems consists of both analytical studies and equipment and systems development.

Analytical studies using parametric analysis to determine breakeven costs and key variables include:

1. Long-range system economic evaluations of hydrogen production from off-peak nuclear energy and dedicated nuclear plants.
2. Comparison of costs of hydrogen storage systems with alternate forms of storing energy. (Included in this work is a study of all potential forms of energy storage funded by a grant from the AEC.)
3. Integration of our electric and gas systems using hydrogen to take advantage of the seasonal diversity between these systems.
4. Studies of the future uses for hydrogen in making steel, for transportation, as a fuel, and in the production of fertilizer.
5. Studies of the installation of fuel cells in individual customer premises versus installation of fuel cells in substations.

The equipment and systems development projects include:

1. Support of the fuel cell development program including the Pratt & Whitney 26 MW FCG-1 development and the gas industry Target Program. The total PSE&G investment in fuel cell research will be $6, 800, 000 by the end of 1976. A three-phase fuel cell installation at the PSE&G City Dock Substation was the first use of fuel cells on a working electric utility system.
2. Developing improved hydrogen storage methods, specifically the metal hydride storage concept working with the Brookhaven National Laboratory and the AEC.
3. Use of an electrolyzer-hydrogen storage fuel cell system in an actual power supply situation to obtain operating experience and costs, the vitally necessary training of people in the handling of hydrogen, and the data for "scaling up" to larger installations.

A brief description of some of the results of this work may be of interest.

Hydrogen Production From Off-Peak Nuclear Energy

One solution to the dwindling fossil fuel supply problem is the substitution of nuclear energy for fossil fuel energy. Because of variations in the patterns of usage of electric energy and the proportion of our electric requirements that will be provided from nuclear plants, we should have nuclear generation capacity available at certain off-peak times for use to produce hydrogen by electrolysis. Our studies have shown that this is a more economic approach and provides better utilization of capital than the installation of dedicated nuclear plants for the sole purpose of electrolytic production of hydrogen. Further optimization of scarce captial resources may also be achieved through the use of the existing gas system to distribute hydrogen, possibly blended with natural gas. A key question is-how much nuclear off-peak energy will be available and when?

Availability of Off-Peak Nuclear Energy

A study of the availability of off-peak nuclear energy on the PSE&G system and the key factors determining it was made about a year ago. This analysis considered not only the daily and seasonal load cycles that are forecast, but also the limitation in minimum acceptable boiler loadings and the need to dispatch generation so as to provide adequate geographical area coverage.

Figure 1 shows that once the nuclear capacity on an electric power system exceeds 30% of the total system capacity, rapidly increasing amounts of off-peak nuclear energy should become available with further nuclear generation additions. Since long-range plans for many systems call for about 50% of the generating capacity to be nuclear, extrapolation of this curve indicates that close to 10% of the total energy generated could be available in the form of off-peak nuclear energy.

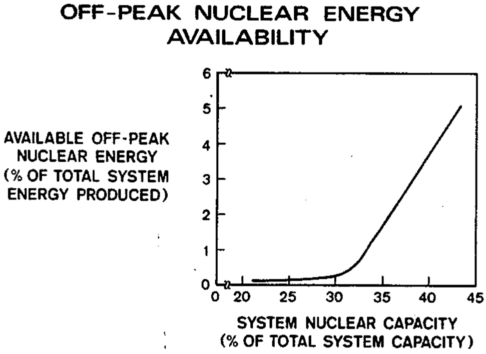


FIGURE 1

Another way of illustrating this trend is shown in Figure 2. The ratio of average incremental peak energy cost to average incremental off-peak energy cost is shown to rise from 1.5 in the mid-70s, to 7 by the year 2000, if no energy storage is provided. This tendency for the ratio between on-peak cost and off-peak cost to increase leads to greater desirability of using off-peak energy to provide some of the on-peak energy needs. The possibility of associated fossil fuel savings justifies increased attention to all forms of energy storage, not only hydrogen.

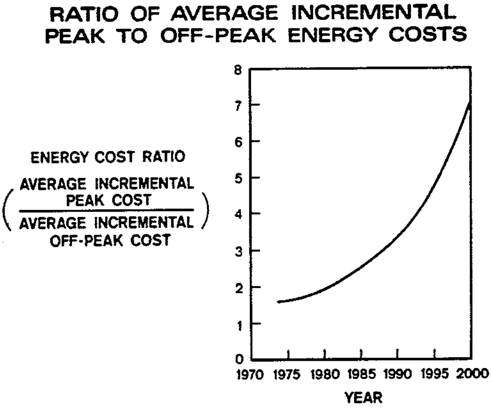


FIGURE 2.

"Electrolyzer" and "Reformer" Fuel Cells

Low-cost, off-peak power from nuclear plants could be used to electrolytically produce hydrogen which could be stored for later delivery to fuel cells during peak electric load periods. This concept of the "electrolyzer" fuel cell plant in which highly efficient electrolyzers would produce hydrogen needed by fuel cells was compared on a total cost basis with the "reformer" fuel cell where the fuel conditioning section or reformer converts hydrocarbon fuels to hydrogen gas which is then fed to the fuel cell power section.

Figure 3 shows the breakeven capital cost differential for the "electrolyzer" fuel cell over the "reformer" fuel cell based on operating cost savings. In this analysis, the breakeven differentials in capital costs will just offset the operating savings or penalties.

The curves show that based on off-peak energy costs in the order of 8 mills per kWh and fossil fuel costs approaching $1.50 per million Btu, the "electrolyzer" fuel cell plant will have to cost in the order of $100 less per kilowatt than the "reformer" fuel cell plant to be economic based only on operating savings. For off-peak energy costs of 3 mills per kWhr (nuclear) and fossil fuel costs of about $2.00 per million Btu, the "electrolyzer" fuel cell plant can be economically justified even if it costs $125/kW more than "reformer" fuel cells.

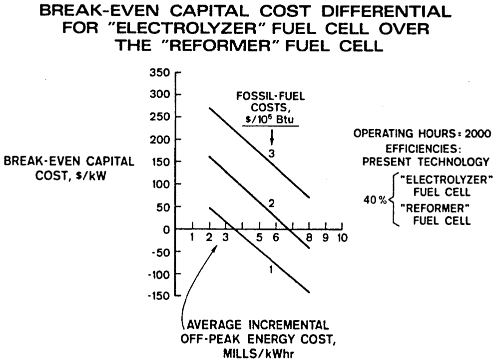


FIGURE 3

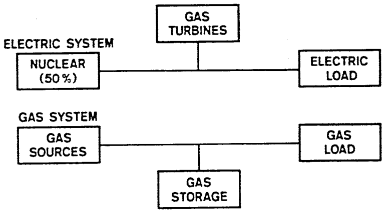
The "Electric/Gas Two-Way Energy Transformer"

The PSE&G system is located in a mixed urban and suburban area. The projected peak electric loads will be about 8,500 MW in 1980, increasing to about 20,000 MW in the year 2000. The generation system consists mostly of fossil-fuel steam and combustion turbine units. The major portion of additional capacity is being provided through the addition of large nuclear units. An extensive natural gas distribution system exists in the area which delivers approximately twice as many Btu's as the electric system.

Our electric system has a pronounced summer peak while our gas system has a predominant winter peak. While changes of utilization practices in the future, possibly influenced by rate policies, could change this situation, loss of load diversity is not considered likely. Because of the potential savings from coupling electric and gas networks, we have made some preliminary studies of how two such systems could be integrated.

Because of severe limitations in the supply of natural gas, our study was based on returning to the gas system at peak times all the energy removed from it at off-peak times. The extent of the diversity is limited by the capability of the electric system to return energy to the gas system during the electric system's off-peak period. With this limitation, the maximum interchange between the two systems is about 10% of the net annual energy generated by the electric system (or about 5% of the net annual gas system send-out).

Figure 4 illustrates the basic study approach. First, the electric system was assumed to be expanded independently with new generation capacity additions of 50% gas turbines and 50% nuclear generation. Similarly, the gas system was expanded independently by adding gas sources and gas storage.


ASSUMED ADDITIONS TO EXISTING ELECTRICAL AND GAS SYSTEMS FOR INDEPENDENT EXPANSION

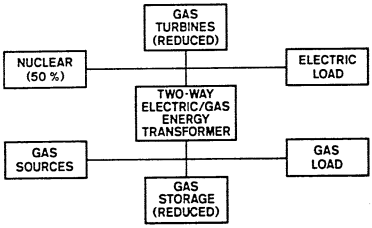

ASSUMED ADDITIONS TO EXISTING ELECTRICAL AND GAS SYSTEMS FOR COORDINATED EXPANSION

FIGURE 4

The integrated electric-gas-hydrogen system was formed by the link or connection between the gas and electric networks provided by a "two-way electric/gas energy transformer Figure 5 shows a conceptual idea of how such an energy transformer might function. The use of the electrolysis unit rectifier to also function as an inverter for the fuel cell, the condensation of water in the fuel cell exhaust to provide the water needed for electrolysis, and combining common components in the reforming and methanating equipment, all offer interesting possibilities for minimizing costs.

Depending on various parameters, the break-even capital costs range from a low of about $150/kW to a high of about $600/kW of output from the fuel cell.

CONCEPTUAL "TWO-WAY
ELECTRIC/GAS ENERGY TRANSFORMER"

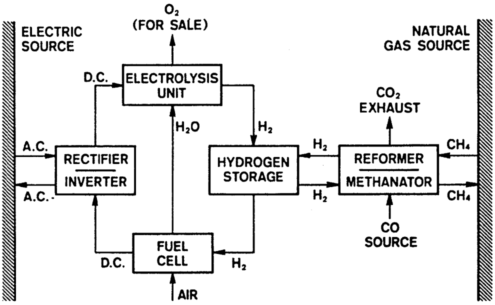


FIGURE 5

Hydride Storage

With the need for energy storage at dispersed urban locations in energy systems of the future, we became involved in research and development in the use of metals hydrides for hydrogen storage. Metal hydride storage can be viewed as a desirable compromise between the low temperatures of hydrogen cryogenic storage and the high pressures of compressed gas storage.

At the PSE&G Energy Laboratory we have in operation the first complete test facility for demonstrating the hydrogen energy storage concept on a utility system. In our facility, hydrogen is produced by a commercially available electrolyzer and stored in a hydride reservoir. The stored hydrogen is then released as fuel for a specially modified Pratt & Whitney 12.5 kW fuel cell which supplies a portion of the electrical requirements of our laboratory building. This fuel cell was developed in the Target Program.

The metal hydride storage unit is the result of AEC sponsored research at Brookhaven National Laboratory, where the Department of Applied Science built the unit to performance specifications supplied by PSE&G. The reservoir contains iron-titanium particles, a silvery sand, which costs about $2/lb. The hydride is a chemical compound of hydrogen and iron-titanium. Iron-titanium is attractive because hydrogen as a gas can be combined or removed from the metal at moderate working pressures (500 psi) and within a few degress of ambient temperature. Hydrogen can be stored at densitites comparable to those used in liquid storage without the associated energy expenditures of 5 kWhr/pound for liquefaction.

Preliminary tests of the unit at the Energy Laboratory have proven successful. Further testing will determine more precisely the relationship between hydrogen charging and discharging and the temperature and rate of flow of the circulating water which is used as a heat transfer medium. Another important question is whether repeated charging and discharging cycles will cause degradation of the iron-titanium particles.

This hydrogen test facility is providing valuable working expertise with hydrogen production, storage, and utilization.

Hydrogen Versatility

The versatility of hydrogen is especially attractive to combination utilities, like PSE&G, that provide both gas and electric service. It also provides a potential mechanism for electric and gas companies to coordinate for their mutual benefit. For example, studies indicate that up to 8 percent hydrogen could be added to the gas system to supplement our gas supplies without change in the gas distribution system.

The potential use of hydrogen for transportation and the need for hydrogen to produce fertilizer offer intriguing additional possibilities.

How to "Get There"

We believe the best way to get started is in an area that has the potential for a short-term payoff such as PSE&G efforts with fuel cells and the hydride storage unit. If short-term efforts are successful, further development and progress will undoubtedly evolve.

Future steps needed are:

1. Extensive research and development to improve efficiencies and to decrease capital costs of hydrogen production, storage, and distribution facilities.

2. The continuing growth of the nuclear industry for producing hydrogen either electro- or thermo-chemically. (The recent postponment of nuclear commitments throughout the country will delay the availability of off-peak nuclear energy for the production of hydrogen.)

3. A significant effort by the gas industry to determine the ability of existing gas transmission and distribution systems to transmit hydrogen both alone and blended with natural gas.

4. Increased government and industry funding of hydrogen R&D activities.

5. Social acceptance of a new energy system through public information and education. Safety aspects should be frankly discussed.

Energy conversion systems not dependent on fossil fuels will be the energy conversion systems of the future. Certainly, in the next 20 years, the need for synthetic or so-called secondary fuels will increase. Our diminishing fossil fuel reserves and increasing costs coupled with environmental requirements should provide the incentives for the broad expenditures for research and development work needed to develop uses for hydrogen.

In the long-term future, which could range anywhere from 20 to 100 years, as fossil feedstocks become scarce, nuclear energy will probably be used to produce hydrogen from water on a bulk scale either by nuclear or thermochemical means. Nuclear and solar devices will become the primary sources of energy while electricity and hydrogen will co-exist as the most important secondary energy forms.

Conclusions

While the role of hydrogen in the future is not yet clear, a number of conclusions can be drawn at this time:

1. We cannot afford to abandon our existing energy systems.
2. Hydrogen has the potential to complement both our electric and gas systems as well as helping in the solution of the world's transportation and food problems.
3. Hydrogen's future role will result in the need for more nuclear power, and possibly more electricity, than indicated by current projections.

In the past, we have reacted to change. In the future, we need to cause change. We need to prevent fires — not put them out. We need to move forward vigorously in determing hydrogen's future role.

* * * *

ROSENBERG: Thank you, Jack, for setting the perspective on hydrogen based on the work you are doing at Public Service. The concepts you described for achieving higher overall efficiency by interfacing your gas and electric systems with hydrogen are new to most of us here today. Moreover, your points on potential near-term applications of hydrogen are very important.

Next I would like to introduce Mr. John E. Johnson. Mr. Johnson is product manager for hydrogen, Linde Division of Union Carbide Corporation. He has been active in liquid hydrogen technology since 1958, including design and operational experience on all Linde liquid hydrogen plants. Linde of course has been marketing industrial gases including hydrogen for many years. Probably the most significant fact to our program this morning is that Linde was the prime supplier of hydrogen to the space program. This presented it with the unique problem of producing, distributing and handling hydrogen on a scale never before undertaken. It is from the vast experience gained in this endeavor that John will discuss "The Status of Hydrogen Technology Application."

John E. Johnson
Product Manager, Hydrogen
Union Carbide Corporation
Linde Division
New York, N.Y.

THE STATUS OF HYDROGEN TECHNOLOGY APPLICATION

The prospects for using hydrogen as an energy carrier has intriguing possibilities, particularly in view of the accomplishments already in hand for solving the many practical problems that would be involved with its introduction. I hope that I can give you a brief outline of this considerable capability already in existence.

Hydrogen has been produced and distributed as an industrial gas for about seventy-five years, which has resulted in the accumulation of an extensive technology inventory. A significant operating scale has already been achieved, and hence it is possible to easily extrapolate this experience to the larger requirements of energy distribution. Safety standards have been developed and tested in applicable operating environments. The data base available is certainly sufficient to assess the feasibility of the possible introduction scenarios. Accurate economic evaluations can be developed and the problems that need to be solved are also definable.

Initially, hydrogen was distributed as a compressed gas in the familiar "K" cylinder and tube trailer. Operations were carried on at a very modest scale until the late fifties when the space program provided the impetus to undertake and solve the problems of large-scale production and distribution of hydrogen. The Centaur Rocket was the first significiant application of "hydrogen energy."

The requirements of rocket technology for hydrogen in its liquid state imposed engineering standards which exceed those of energy transmission via hydrogen. Unique engineering solutions were required in order to make the general availability of the fuel that transported man to the moon a reality.

Hydrogen separation processes had to be developed to reduce impurity contents in hydrogen to less than one part per million to permit its liquefaction. The then largest cryogenic systems had to be provided to accomplish the liquefaction. This capability is exceeded today only by the large base load LNG systems installed overseas. And, finally, the establishment of a full-scale storage and distribution system for liquid hydrogen capable of operating on a nationwide basis was required. This resulted in the development of advanced insulation techniques and solved the basic problems of interfacing hydrogen in the industrial/public environment.

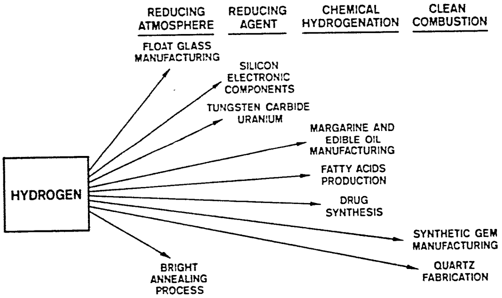
Although some liquid hydrogen was produced during and shortly after World War II in conjunction with experiments in high energy physics and fusion, the advent of the space program motivated the recent general interest in hydrogen. The Air Force constructed the first large-scale liquid hydrogen plant in Florida in 1958 to provide needed propellants for a then classified Pratt and Whitney rocket engine program. Also, during this period, aeronautical applications for hydrogen fuel were in an advanced development stage by Lockheed for a high-flying reconnaissance aircraft. With the requirement of liquid hydrogen for the subsequent NASA space program assured, the industrial gas industry provided the facilities to support these efforts. Union Carbide built the first industry-financed 3M cfd facility at Torrance, California in 1960. This was followed quickly by larger industry financed 12M cfd facilities in California and Louisiana. By 1965, over 80M cfd of capacity had been constructed and since then, approximately 100 billion cu. ft. of hydrogen have been distributed in support of the space program and other industrial requirements.

This buildup of capacity culminated in 1964 with Union Carbide's - and the world's - largest liquid hydrogen plant which was located in Sacramento, California. This 24M cfd facility consumed 30 megawatts of electrical energy and 12 million cu. ft./day of natural gas. The hydrogen production capability of this facility is approximately 1/10 the scale of today's proposed substitute natural gas plants. But, since these synthetic fuel plants are also to be multiple trains, the accomplishment at Sacramento is very significant in evaluating the scale-up problems involved in building a large hydrogen production facility for energy distribution.

The completion of the Apollo program resulted in dismantling much of this initial liquid hydrogen capacity, but half still exists to serve increasing industrial requirements for hydrogen. Additionally, two facilities have been developed in the northeast to serve the industrial requirements. Today, hydrogen is distributed virtually in every state in the Union, and the convenience of liquid hydrogen to distributors and users alike is making obsolete many of the older gaseous production and distribution systems.

Hydrogen is used for a variety of applications, including reducing atmospheres and reducing agents, chemical hydrogenation, and clean combustion applications. Many industries are dependent on obtaining this unique material which is used for the manufacture of glass, electronic components, food and drug products, reduction of heavy metal oxides, metallurgical finishing processes, and even in synthetic gem manufacture. The next challenge for hydrogen will be to fuel NASA's reusable space transport system — the Space Shuttle. We should review some of the accomplishments in hydrogen technology that were advanced in support of the space program and which will provide much of the needed technological base to support future development of hydrogen energy.

INDUSTRIAL APPLICATION FOR
DISTRIBUTABLE HYDROGEN



Hydrogen was manufactured by the process of steam reforming of natural gas where over half the H_2 was extracted from water. This technology has found continuing application in the present large scale hydrogen production units which have become common in oil refineries to supply their ever-growing needs for hydrogen. Many of the answers to the questions on material selection and operations analysis for the water splitting cycles will be provided from this type of experience.

The purification of hydrogen to one part per million was first carried out in cryogenic units which dissolved impurities from the hydrogen. Liquefied methane and propane, operating at -250° F were used as solvents to remove impurities. Because of the great flexibility of the cryogenic processes to selectively remove many varieties of impurities, they will find application in recovering hydrogen produced from the various energy resources which will be employed in the future.

Subsequent developments permitted carrying out this difficult purification requirement in one step at ambient conditions, employing the unique properties of Linde Molecular Sieve adsorbents to trap impurities. Although adaptive only to smaller scale operations, PSA adsorbers could typically find application in conjunction with fuel cells by supplying pure hydrogen from a hydrogen-rich low-Btu fuel gas system.

Large hydrogen compressors, which are necessary to develop the refrigeration requirements for liquefaction, also simulate the requirements for moving this fluid in pipeline service. The 11, 000 H. P. compressors at our Sacramento plant were the world's largest reciprocating compressors, and they represent the best experience to demonstrate large machine design capability in H_2 service.

Over-the-road transportation of liquid hydrogen required the development of high performance insulations and high-quality vacuum-insulated tanks. This technology has been advanced to the point of full-scale over-the-road capability which is similar in many aspects to your LNG operations.

Present industrial customers requiring hydrogen today routinely store liquid at their facilities. These customer stations are serviced weekly by over-the-road trailers which may travel as much as 400 to 500 miles to deliver their product.

In order to inventory stores of liquid hydrogen convenient to customer centers, Linde operates the only nationwide rail distribution network to link its inventory centers with production facilities. Railcars (28, 000-gallon) commonly move liquid hydrogen from Los Angeles to New England without venting any of their product on trips that may take two weeks or more. Automatic devices can safely dilute the hydrogen below its flammability limit in air and discharge the product unattended in the event of mishap. The development of this extraordinary capability clearly demonstrates the potentiality for safe design of future hydrogen energy transmission systems.

Although hydrogen was originally viewed as a very dangerous material, experience has surprisingly shown that in many ways its properties are more desirable than other fuels. The basic design and operating philosophy, as with any fuel, is to contain the material and prevent its possible admixture with air and to ventilate those areas where containment might fail — basically, fix leaks and prevent flammable concentrations from accumulating. These are fundamental rules in dealing with any fuel. Hydrogen has a wide flammable range, but its lower limit is not much different from other fuel gases; hence, the initial propensity to ignite is similar. Although more easily ignited, hydrogen generally does not explode, but burns rapidly. Its high characteristic diffusivity increases the tendency to dilute below flammable levels unless the area is substantially enclosed. Flames exhibit low radiation levels and the buoyancy of the fuel causes it to burn vertically which minimizes secondary effects in a hydrogen fire.

To date we have had only one minor plant damage incident where hydrogen was involved. Similarly our accident record in over-the-road and rail service is essentially no different from the other cryogens we transport. Product involved accident frequency rates are only in the order of five incidents per 100, 000 trips. In fifteen years of operation, I know of no liquefied-hydrogen-involved fatalities within the industrial gas industry.

Quality control is the essence of any hydrogen system design. Because of the low molecular weight and high diffusivity, hydrogen tends to leak more readily from its container than other fuels. But fuel leakage, under any circumstance represents a problem to a fuel gas distributor that must be solved. Specifications for construction materials must be carefully drawn to avoid porosity in construction materials, particularly in valve body castings; and joints must be adequately tested to insure their integrity. Seals on mechanical equipment should be under inert positive pressure and vented to prevent backward in-leakage of air.

Ventilation is the major defense for preventing a catastrophe in the event of a serious escape of hydrogen. Adequate space concepts, inerting and dilution techniques, and detection devices to give early warning of a mishap are the major methods to cope with a spill. Finally, ignition source avoidance represents an additional line of defense.

Hydrogen is capable of changing the metallurgical properties of many common construction materials, particularly steel, by a process known as embrittlement. The characteristics of this phenomenon are generally understood; and designs have been proven over years of operation which can demonstrate their adequacy. The basic design strategy is to select embrittlement-resistant steels and alloys, and prohibit operating pressures in excess of their known embrittlement limits. Certainly the totality of conditions which cause embrittlement phenomenon are not known, but experience to date provides substantial background on which to propose future designs.

The introduction of large-scale hydrogen energy systems will present new problems which will require further work to assure safe performance in energy distribution systems. The application of this industrial hydrogen experience base into the technological frontiers of energy distribution is already proceeding. As with the introduction of liquid hydrogen into industrial applications, much work must be done to gain an acceptance by energy consumers to utilize hydrogen. In coursing through the labyrinth of potential opportunities, the energy-intensive industries such as electric power distribution, aviation, and steel, are beginning to discover potential benefits in adopting this energy source. Hydrogen, as a secondary energy carrier, is not likely to be the lowest cost fuel; therefore, its other potential benefits must be exploited. In addition to the initially projected environmental benefits of employing hydrogen, tantalizing prospects for efficiency improvement in the various hydrogen energy conversion processes are now being reported which will accelerate the achievement of economic parity with conventional fuels. Overcoming the current limiting technologies in these various beneficiated applications, work on which is just now commencing, is the next requirement for motivating customer acceptance and proving design acceptability. Risk analysis must be performed as present capability is scaled up to the vastly increased requirements of energy systems. Typical questions that are yet to be resolved in respect to energy system design are:

> Will unsuspected embrittlement phenomena occur due to some unexperienced feature of a large hydrogen energy transmission system?

MOTIVATING CUSTOMER ACCEPTANCE OF HYDROGEN FUEL

INITIAL APPLICATION	BENEFIT	LIMITING TECHNOLOGY	INITIAL SOURCE
ELECTRICITY GENERATION AND DISTRIBUTION	EFFICIENCY	FUEL CELL COST/LIFE	COAL/REFUSE
	INTERMEDIATE ENERGY STORAGE/ DISTRIBUTION	CYCLE EFFICIENCY	OFF-PEAK NUCLEAR
AVIATION	INCREASED PAYLOAD	FLIGHTWORTHINESS	COAL
	RELEASE HYDROCARBONS	EFFICIENCY	NUCLEAR
IRON AND STEEL PRODUCTION	DECREASE POLLUTION	EFFICIENCY	COAL/REFUSE
	ENERGY SECURITY	EFFICIENCY	NUCLEAR

What are the effects of large quantity spills which could occur from energy delivery systems?

Are present gas distribution systems designed to permit hydrogen admission? Can they be easily adapted or must they be replaced?

What is the life expectancy of components before failure? Are the failure modes safe?

What additional precautions must be instituted if hydrogen fuel is to be introduced to the public sector?

As work proceeds toward prototype projects to gain experience and do the required reliability proofs, what present H_2 energy system component availability deficiencies exist? The major shortcoming will be in the area of gas compression. Much needs to be done to overcome the awkwardness of the reciprocating technology existent. Hydrogen compression in rotating machinery will require advances in large or high-speed dynamic machines to gain parity with other fuel transmission systems. The ultimate scale of hydrogen production equipment based on laws of diminishing return needs also to be determined. And, of course, an efficient process for the direct production of hydrogen from nonhydrocarbon energy sources remains a basic requirement.

Potential benefits included, and introduction costs excluded, hydrogen could be an economical energy carrier soon. Neither its exotic reputation nor economics of product availability should be used as a basis for deferring development efforts. In addition to possibly obtaining hydrogen from off-peak power, much of the effort in converting coal to substitute high-Btu gas involves hydrogen technologies. Both the Lurgi and Koppers/Totzek Processes are prolific hydrogen producers and can be as easily and efficiently adapted to hydrogen manufacture as methane.

Another possible way of producing hydrogen to serve potential introduction schemes is the PUROX process which is currently being developed by Union Carbide to convert refuse to a usable fuel gas. Refuse is charged into a vertical shaft furnace and reduced with oxygen to a slag and 300 Btu/cu. ft. fuel gas consisting mainly of carbon monoxide and hydrogen. This process can be easily adapted to pure hydrogen manufacture.

The technology soon to be available from processes such as these can economically supply the initial quantities of hydrogen to implement and develop critical early stages of hydrogen energy demonstration until hydrogen can be competitively derived from nonhydrocarbon energy sources.

Another major benefit of hydrogen in the nuclear age to the energy industry has been the projected benefits of achieving economic, and environmentally benign, energy distribution. The strategy for obtaining economical underground energy distribution is to maximize system capacity and maximize efficiency of energy conversion which then reduces total energy flow to the customer. Electrical transmission with its low energy flow requirement is striving toward these goals by research with superconducting cables. Hydrogen also offers opportunities to increase energy flow in a relatively simple conduit, because of the potential for high energy conversion efficiency relative to other fuels that might be conveyed underground. Although the tendency is to view these distribution systems separately, a major payout may be in a yet unexplored synergism between them where the cryogenic properties of liquid hydrogen could benefit superconducting electrical transmission, while sharing of energy generation facilities would benefit the coproduction of a more storable energy form as liquid hydrogen.

It is interesting to note that at the start of this century, the first requirements for hydrogen on an industrial scale were for use in aeronautical research where the unusual lifting properties of this lightest gas were sought. The initial requirement for industrial hydrogen was obtained as a by-product from the oxygen generated by electrolysis for the then newly emerging oxy-acetylene flame applications. Sabatier developed the first catalytic process for hydrogenating organic compounds. Other developments quickly followed, culminating in the Haber process for producing ammonia in 1913 — which demonstrated the capability for large-scale handling of hydrogen. Hydrogen now dominated requirements, and new methods were sought to produce this resource because of the inability to dispose of the excess oxygen from the electrolyzer profitably. Processes to crack water, using coal, soon became prominent. A cryogenic extraction process was even developed in Germany to separate hydrogen from "water gas" that was produced commonly in the "gas houses" of that era. By the end of World War I, electrolysis had become outmoded and hydrogen production became totally reliant on the lower cost and increasingly available hydrocarbon energy resources.

Now that the unique characteristics of hydrogen as an energy carrier need to be explored further, a new era of technology development is at hand. As with hydrogen's early introduction, the aeronautical sciences, electrochemical technology, and reduction processes are likely to provide the early impetus to expand the technology base. Fossil sources, no doubt, will supply the energy for manufacturing the initial requirements of hydrogen until the more refined nonhydrocarbon energy conversion systems based, first, on nuclear energy, begin to supplement.

I have had to cover an awful lot of ground in a short time. But I hope you now realize that there is a lot of ground to cover, and it seems to have been covered more than once. Many of the technologies of hydrogen energy systems are already in hand and not really "new." Extending the current technology limitations is the first requirement to develop the potential of hydrogen as a future energy carrier. These extensions can be accomplished by:

1. Effective demonstration of the benefits that accrue to potential users of H_2 (which are now merely gleams in the eye of the research community) so the existent technology may be rationally extended to energy dimension scale, and:

2. Improvement of the technology to extract hydrogen from water efficiently, from various non-hydrocarbon energy resources, in order to improve their respective interchangeability, storability, and portability, while increasing the competitiveness of these resources as a viable alternative to our decreasingly available fossil resources.

* * * *

ROSENBERG: Thank you, John. Although hydrogen is a somewhat unknown quantity for most of us, it is obvious from what we have just heard that it is a common day in and day out business with you. For most of us, the mere mention of hydrogen is immediately associated with overtones of safety questions. Certainly the experience of Linde is ample testimony that practical and safe methods can be established for large-scale use of hydrogen just as well as they have been for other fuels with which we are more familiar.

Next we would like to turn our attention to the questions of "How much will it cost?" And, "When might we expect hydrogen to play a significant role in the Energy Picture?" Dr. Kenneth C. Hoffman, who received his Ph. D. from the Polytechnic Institute of Brooklyn, is head of the engineering and systems division at Brookhave National Laboratory, and has been engaged in a number of hydrogen research projects. Under sponsorship of the Atomic Energy Commission, Dr. Hoffman has developed models of competitive systems for producing secondary energy and transporting it to the ultimate consumer.

These are the systems which are frequently talked about today — all-electric economy, hydrogen economy, and mixed hydrogen-electric economy. With the use of his models Dr. Hoffman has conducted what is undoubtedly the most systematic comparative economic analysis of these systems to date. Time will not permit him to describe his methodology and techniques in detail.

However, we have asked Dr. Hoffman to summarize the key conclusions of his studies as they pertain to the "Economics of Hydrogen Energy Systems."

Dr. Kenneth C. Hoffman
Brookhaven National Laboratory
Upton, New York

ECONOMICS OF HYDROGEN ENERGY SYSTEMS*

In evaluating a new energy technology, attention must be given to the prospective economic characteristics of that technology, and the economic circumstances under which that technology might be an important factor in the energy system. Given the hazardous nature of economic analyses for even existing technologies in a period of rapidly changing prices of labor and material inputs to production, it is important that the inherent uncertainties of economic analyses be recognized. The analysis of long-term options such as hydrogen energy systems must be broad in scope, encompassing questions of environmental impact, efficiency, and cost. The definition of a range of cost and efficiency parameters over which these systems might compete with alternative technologies is required to establish objectives for a research and development program.

Any technological option that is at an early stage of development should also be viewed in terms of the diversity and versatility that it can add to the energy system. Hydrogen, as a secondary energy form, is compatible with our abundant domestic resources including those that are renewable and can be used in virtually all of the functional end uses that are of interest. Since the more abundant U.S. resources of nuclear, coal, solar and geothermal energy may be used most effectively to produce electricity, the basic issue

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*Work performed under the auspices of the U.S. Atomic Energy Commission.

is the definition of the complementary roles of hydrogen and electricity in exploiting these resources. There are several end-uses that are best served by electric energy and several that are clearly best served by a portable chemical fuel such as hydrogen. In view of the rather unique advantages of each energy form, it is unreasonable to talk of an all-electric or all-hydrogen economy. Attention should focus more clearly on the question of the partition of the energy system between electric and non-electric energy forms.

At present, roughly 25% of the energy resource consumption in the U.S. is for the generation of electricity. This fraction has been projected to grow to nearly 50% by the year 2000, due primarily to the demand growth in those sectors that are totally reliant on electricity. Recent financial difficulties in the utility industry will clearly affect this trend if they persist. The balance of the energy resources are consumed as coal, oil, and gas at the point of end use. As these oil and gas reserves are depleted along with the more easily exploited coal reserves, a substitute general-purpose fuel such as hydrogen will be needed. The partition of the energy system will clearly depend on the relative price and efficiency at the point of end use of this fuel and of electric power.

It is instructive to consider the "efficacy" of hydrogen relative to electricity in specific end uses to be represented by the ratio of the units of electrical energy required to substitute for one unit of hydrogen. This parameter ranges in the limit from zero for those end uses where hydrogen is difficult to use to infinity for those end uses where electricity is not easily used. End uses such as aircraft fuel and petrochemical materials, where hydrogen has some unique properties-will have a high efficacy ratio, while in applications such as space heating, the efficacy ratio might be around one-fourth assuming that one-fourth of a unit of electricity operating a heat pump could replace a unit of energy in the form of hydrogen used in a burner.

Figure 1 illustrates the possible range of partition of the energy system and some typical end use efficacy ratios. Hydrogen is already being used in several high efficacy ratio applications in industry where its properties are unqiue. An area toward the top of the bar chart may be defined where hydrogen has a clear advantage. Similarly, a set of end uses may be specified where electricity has a unique advantage. The use of one or the other secondary energy forms for those end uses in the competitive zone will depend to a great extent on technological progress in the electric sector and in hydrogen energy systems.

If the demand for non-electric energy forms continues to increase, it is apparent that a transition must be made from fossil fuels to some non-fossil synthetic fuel. Figure 2 shows a long-run projection of the role of hydrogen in this transition. This projection was made by Professor Alan Manne using an energy system optimization model that determines the minimum supply cost and fuel mix given a set of overall resource constraints and input fuel costs. In the analysis it is assumed that non-electric demands grow at the rate of 2% per year. It is seen that hydrogen comes in rather strongly as oil and gas are depleted and as the production of other synthetic fuels from coal reaches a peak. The hydrogen required for coal conversion processes is not reflected in the hydrogen production curve. The hydrogen may be produced by electrolysis or by an advanced process such as the thermochemical

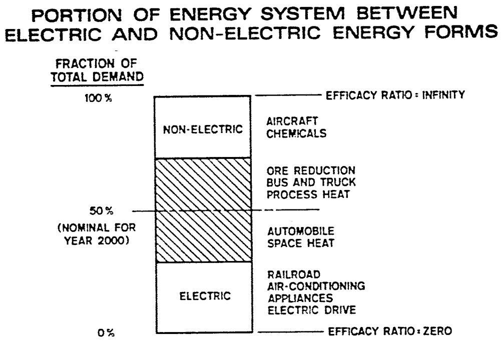


FIGURE 1

decomposition of water using a high-temperature reactor (HTR) as the heat source.

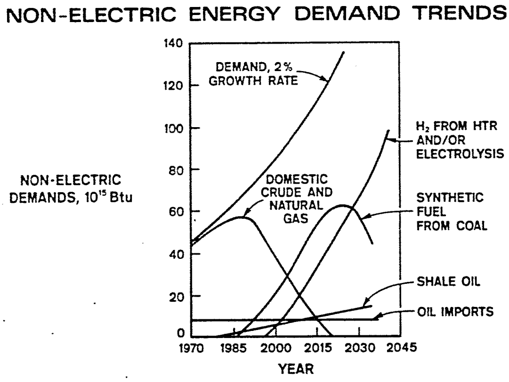


FIGURE 2

The resource demands in the electric sector are not shown here; however, this sector relies heavily on coal in the intermediate term and on nuclear fuel in the longer term. Additional nuclear capacity is required to produce the quantities of hydrogen employed in the non-electric sector.

It is anticipated that the course of implementation of hydrogen in the energy system may proceed in the following sequence:

1. Industrial uses for fertilizer, petrochemicals, and coal conversion,

2. Use by electric utilities for peak shaving with fuel cells and as a supplement to natural gas,

3. Transportation fuel in aircraft and fleet vehicles, and

4. Residential and commercial use as an alternative to all-electric homes and where load factors are poor.

Estimates of the possible level of implementation in these applications are given in Figure 3 for the years 1985, 2000, and 2020. These implementation levels represent the quantities of hydrogen used in each of the sectors and are based on estimates of market penetration. The industrial usage includes hydrogen for ammonia synthesis and other chemical uses but does not include the hydrogen used for coal gasification and liquefaction. The total energy consumption in 1970 and projections for future years are included for comparison purposes. This projection of hydrogen usage is more conservative in the long run than that given in Figure 3, but still represents a significant role in the energy system for this fuel. In addition to depending on technological progress in the production and delivery of hydrogen, these implementation levels depend on the attainment of satisfactory levels of reliability and safety in early applications.

HYDROGEN USAGE ESTIMATES
(10^{15} Btu)

	1970	1985	2000	2020
INDUSTRY	1	2	4	10
UTILITY		0.2	1	4
TRANSPORTATION		0.5	2	6
RESIDENTIAL AND COMMERCIAL			1	5
TOTAL HYDROGEN CONSUMPTION	1	2.7	8	25
TOTAL U.S. ENERGY CONSUMPTION	70	115	175	250

FIGURE 3

Despite the hazards inherent in economic projections, some estimates of the cost of hydrogen energy systems and the effect of technological advances are required. Figure 4 summarizes the cost and efficiency for various processes for the production, transmission, and storage of hydrogen. The characteristics of current and advanced technologies are indicated for each process.

The cost of hydrogen depends on the technical and economic characteristics of a sequence of processes that convert a primary resource, e. g., nuclear or solar energy, to electricity or heat which is used in the hydrogen production step. The hydrogen must then be transported to the point of use by pipeline or some other means. Consideration of this sequence of processes that determine the cost of hydrogen and the overall efficiency with which it is produced requires a systems approach.

PROCESS COSTS - HYDROGEN ENERGY SYSTEMS (CURRENT TECHNOLOGY - ADVANCED TECHNOLOGY)

PRODUCTION	EFFICIENCY	COST
ELECTROLYSIS	0.7 - 0.9	150 - 50 $/kW
ELEC. GENERATION - ELECTROLYSIS	0.23 - 0.45	650 - 500 $/kW
THERMOCHEMICAL	0.25 - 0.5	—
LIQUEFACTION	0.7 - 0.8	2.00 $/$10^6$ Btu

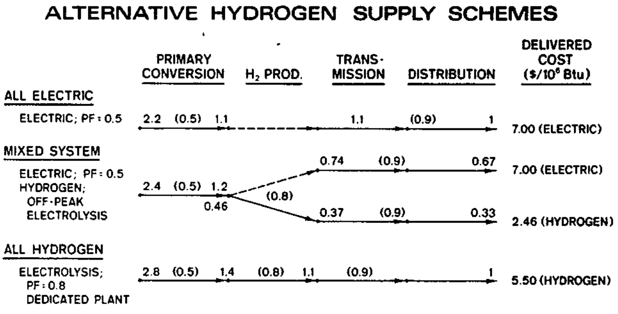
TRANSMISSION	EFFICIENCY	COST
GAS PIPELINE	0.9	8 ¢/10^6 Btu - 100 MILES
LIQUID	0.95	15 ¢/10^6 Btu - 100 MILES

STORAGE (10^6 SCF H_2)	EFFICIENCY	COST
GAS (2500 psi)	0.9	$9 X 10^6
LIQUID	0.7	$8 X 10^6
HYDRIDE	0.95	$4 X 10^6

FIGURE 4

Figure 5 presents four alternative energy conversion and delivery systems in a flow diagram format that has been widely applied to energy technology assessment. The flow diagrams indicate the sequence of processes that are required to deliver a Btu of energy in the form of electricity or hydrogen. Each process is represented by a link in the trajectory and the input energy to each is indicated above the link. The efficiency of the processes is given in the parentheses.

The all-electric system includes a nuclear power plant operating at a plant factor of 0.5; e.g., over a one-year period the plant produces only about half of the electric energy that it would were it operated at rated power for the same period. The reference transmission technology in this case is assumed to be over head high-voltage AC. The use of underground transmission would cause a significant increase in the cost of the delivered electricity. Superconducting technology provides an alternative transmission technology that may be feasible in the long term. If successful, this technology would provide the capability of moving very large blocks of electric power over long distances through limited rights-of-way without incurring an excessive cost penalty.



* NO FEASIBLE THERMOCHEMICAL CYCLE HAS BEEN DEVELOPED; THEREFORE, COST ESTIMATES MUST BE CONSIDERED AS R&D OBJECTIVES.

FIGURE 5

Thus, the technology might provide for more flexibility in the siting of large power complexes, but would not result in any significant decrease in the delivered cost of electric power.

In the mixed system, the nuclear plant is employed to deliver electricity with a plant factor of 0.5 as in the previous case, but it also operated during off-peak periods to produce hydrogen by the electrolysis of water. The plant is assumed to operate at an overall plant factor of 0.8 in delivering both electricity and hydrogen. The all-hydrogen cases consider dedicated plants delivering only hydrogen that is produced by two alternative processes, electrolysis and thermochemical water splitting.

The thermochemical process requires a high-temperature reactor (HTR) operating at about 1700°F as a heat source. To put both electricity generation and hydrogen production via thermochemical water splitting on a common basis, it is assumed that the high-temperature reactor, with a conversion efficiency of 50% for electric generation, is available for both applications.

The delivered costs indicated on Figure 5 include transmission and distribution cost elements that are appropriate for large-scale industrial users. It may be seen that hydrogen can be delivered at a lower cost than electricity from a dedicated nuclear plant using either electrolysis or thermochemical water splitting. The latter is of course a speculative technology and the cost estimates are quite uncertain. Hydrogen produced electrolytically from off-peak nuclear power could be delivered at an especially low incremental cost; however, only limited quantities would be available depending upon the extent that nuclear capacity exceeds normal base load requirements.

The input energy resources to each energy system indicate that the hydrogen systems are generally less efficient than the electric system. The one exception is the thermochemical production system which will be competitive with electricity if a 50% production efficiency can be attained.

Upon examination of the ultimate need for some non-fossil synthetic fuel and considering the near-term requirements for hydrogen in several industrial applications, it is apparent that an expanded research effort on production, storage, and transmission technologies is warranted. The current Federal R&D expenditures on hydrogen energy systems are estimated in Figure 6.

FEDERAL R&D ON HYDROGEN
ENERGY SYSTEMS ($1000)

	FY 1975
PRODUCTION	500
TRANSMISSION	100
STORAGE	500
END USES	
UTILITY	850
TRANSPORTATION	200
SYSTEM STUDIES	550
TOTAL	2700

FIGURE 6

Progress in improving the efficiency of hydrogen production could increase its role in the energy market. On the other hand, the successful development of such technologies by electric vehicles with high-performance batteries or economical heat pumps would result in an increased role for electricity. A balanced R&D program encompassing effective programs in all of these areas will ensure that the full benefits of these complementary secondary energy forms will be reaped.

* * * *

ROSENBERG: Thank you, Ken, for condensing the results of your extensive efforts into a very clear picture of how and when hydrogen could fit into the future U.S. energy mix. You have defined some very obvious economic incentives which should be of particular interest to utility management. I am sure that we all have a better perspective now of where hydrogen may fit.

Many of you know my associate, Dr. Derek Gregory, who is the next speaker on our program this morning. Derek is director of energy systems research at IGT. In this capacity he has published broadly in both the technical and popular press on the subject of hydrogen energy. During the past several years, he has successfully directed and personally contributed to more than a dozen research programs on various aspects of hydrogen from both industry and government. Derek also serves on several national advisory committees and has had the opportunity of reviewing both the objectives and plans of most of the organizations that are now active in the hydrogen field. From this vantage point we have asked him to discuss his views of "What We Can Do Now as Utility Industry Management and Government Planners."

Dr. Derek P. Gregory
Director, Energy Systems Research
Institute of Gas Technology

WHAT WE CAN DO NOW AS UTILITY INDUSTRY MANAGEMENT AND GOVERNMENT PLANNERS

I want to address the question of what the utility industry and the Government should be doing now about hydrogen energy. But before that, let me address a question that must have occurred to you; that is, why should the gas industry consider at all a change from natural gas, supplemented by SNG, as its basic commodity?

In a joint energy policy statement from the five major U.S. energy industry trade associations, the need for energy growth was stressed. They said, "For the benefit of all segments of our society, we must assume a growing energy requirement." Any substitution of existing energy sources with new ones should be capable of sustaining a high growth rate for a considerable period. Although SNG from coal, shale, and biomass are extremely important new energy sources, they may not be capable of sustained high growth for periods extending well into the next century. An additional and growing source of energy will be required to supplement these supplies. The previous speakers have made a good case to suggest that hydrogen made from nuclear energy could be the means of providing this supplement.

Let me emphasize the point made by Ken Hoffmann that hydrogen is an alternative to electricity. It should be compared with electricity on the basis of cost and usefulness, and can co-exist with electricity in a combined energy transmission system.

In the future we will not have enough fossil fuels to meet our needs. This shortage is already having an effect on the gas industry. Because of this, we will not have the choice between fossil fuels and hydrogen, and we should therefore not place emphasis on a comparison of the cost of hydrogen with today's conventional fuel prices. The choice we have for the future is hydrogen, or electricity.

Although it now appears that hydrogen may not actually enter widespread use as a fuel gas until after the year 2000, there are many special applications of hydrogen likely to become attractive in a shorter term. Several combination utilities like Jack Casazza's have already begun work on these. We must not take the attitude of doing nothing and waiting until the time when huge augmentation of natural gas by hydrogen is economically justified. The approach to this point will require a well-planned and controlled introduction of hydrogen over many years. We waited too long — until the natural gas supply actually stopped increasing - before we embarked on a sizable SNG program, and this delay resulted in the present unavailability of advanced SNG processes, and the need for crash programs. Let us not repeat this mistake.

It is commonly held in energy planning circles that the major source of growth of U.S. energy supply will be from nuclear, and later solar, sources. The nuclear industry and many government planning groups seem to be committed to using these growing energy sources via the electrical route. As an example of this type of thinking, I would like to quote from a widely appearing advertisement from Westinghouse:

> "A worldwide electric economy is inevitable. There will be little alternative once all the world's natural fuels are exhausted. . . . We must make an immediate global commitment to an electric economy, one ultimately powered by nuclear energy. It is the only viable long-term solution to the world's energy problem."

Hydrogen provides an alternative: The utility industry should be taking steps right now to adapt itself to delivering these energy resources to its conventional customers not only as electricity, but also as a combustible fuel gas, a form to which many of them are accustomed to using. This combination will serve their needs in the best way.

Hydrogen can be made from a nuclear or solar energy heat source in two different ways. Using presently available technology we can produce electricity and use this to run an electrolyzer. The efficiency of turning heat to hydrogen this way is about 30% and could be increased to 50% through research. Such research is justified because it makes use of already developed electricity generation technology. Alternatively, we can use the heat to drive a sequence of chemical reactions that produce hydrogen from water. Thermochemical processes, as these are called, are still in the laboratory stage, but research on both the chemistry and special type of nuclear reactor required is justified by the fact that such processes promise to have efficiencies greater than 50%.

ELECTROCHEMICAL

HEAT ➡ ELECTRICITY ➡ ELECTROLYZER ➡ HYDROGEN

30 ➡ 50%

THERMOCHEMICAL

HEAT ➡ CHEMICAL PROCESS ➡ HYDROGEN

50-55%

Some encouraging developments are beginning to take place that suggest that attention is at last being given by government agencies to the production and use of hydrogen as an alternative carrier of nuclear energy. Among the most significant of these developments are —

1. A study was begun several months ago by AEC on how nuclear process heat can be used in iron and steel production, petroleum refining, coal gasification, and hydrogen production. They are using the services of General Electric, General Atomic, Westinghouse, the American Iron and Steel Institute, EXXON, Oak Ridge National Laboratory, and NASA to perform these studies. Input to this program from the utility industry has only recently been sought.

2. Technoeconomic studies and some laboratory research is in progress at Brookhaven National Laboratory on the use of hydrogen to store off-peak nuclear power. This work, supported by AEC, is directed toward the use of stored hydrogen to generate peak load electricity, and is totally aimed at electric utility needs.

3. NASA is formulating its plans for a major program on hydrogen-energy applied to national energy needs (not just the use of hydrogen as an aircraft fuel). More than 3 million dollars are in next year's NASA budget for this purpose. While I am pleased that IGT has secured two NASA study contracts, I am disappointed that NASA's research plans have not in the past been well coordinated with those of the utility industry.

From the point of view of continuing these new programs, I am very concerned when I read the published details of the recent restructuring of Government R&D under ERDA. Although the stated roles of ERDA include "policy planning of . . . research and development respecting all energy sources and utilization techniques " and ". . . conducting research in extraction, conversion, storage, transmission and utilization energy phases, " in the original ERDA bill there was no mention of hydrogen. There seems to be no logical place for a comprehensive hydrogen-energy program under any of the six administrative divisions, which deal with fossil energy; nuclear energy; environment and safety; conservation; solar, geothermal and advanced conversion; and national security. However, the more recent National Energy Research and Development Policy Act, not yet signed into law, does include specific reference to hydrogen research, and the Senate version of the bill calls for demonstration of hydrogen as a fuel as a "mid-term" objective.

While we might hope and expect that the existing AEC hydrogen projects are transferred intact into ERDA, there is no provision for the transfer or support of the new and significant NASA hydrogen programs, and no NASA representation is included in the President's proposed Energy Resources Council, which is charged to "insure coordination among the Federal agencies that have responsibilities for the development and implementation of energy policy."

I belive that Government research and planning efforts on hydrogen energy should be better cordinated than they are at present. The following actions are required:

1. The hydrogen-energy option should be examined as thoroughly as corresponding work; for example, on electricity transmission, battery storage, and electricity utilization. An appropriate responsibility for the development of alternative energy delivery systems should be specifically assigned with ERDA's organization.

2. The hydrogen programs that have been initiated by AEC and by NASA should be protected during the formative stages of the new ERDA, and should be continued under ERDA's overall management.

3. Cooperative programs between the utility industry and government agencies must be developed in hydrogen-energy areas to insure that the long-range decisions being made by each are compatible with each other.

4. ERDA should collaborate with the nuclear industry and the gas industry to formulate a planned growth plan that will accommodate future gas and electric energy demands. It is important to recognize the long lead time (approaching 20 years) involved in implementing a substantial nuclear-hydrogen production industry.

5. ERDA should support a program of research and development on the special nuclear reactor engineering for high-temperature reactors of the type required for thermochemical hydrogen production. Neither the Conventional Pressurized Water Reactors nor the Liquid Metal Fast Breeder can provide high enough temperatures for this process. High-temperature reactor engineering is at present carried out under industrial, not government, sponsorship.

In addition to the present Government hydrogen-energy program, industrial support of research on nuclear-hydrogen energy is also on the increase. General Atomic has a team working on thermochemical hydrogen production from its High Temperature Gas-Cooled Reactor, General Electric is researching both electrochemical and thermochemical hydrogen production, the

Electric Power Research Institute is investigating the use of off-peak power to produce hydrogen for use as a petrochemical feedstock and several electric utilities are carrying out transmission and storage studies, the most impressive of which, at Public Service Electric and Gas Company of New Jersey, has been described by Jack Casazza. Gas-industry supported hydrogen research at the present time includes a five-man level A. G. A.-supported program at IGT on thermochemical hydrogen production, a somewhat smaller industrially supported program, also at IGT, on hydrogen gas appliance development, and a rather larger effort at KMS Industries on hydrogen production by nuclear fusion reactions.

I believe that the utility industry's present level of involvement in this challenging new area is inadequate in view of the potential importance of this entire subject.

What actions are needed by the utility industry today? First, companies which deal with natural gas need to take positive action to demonstrate to its investors that they have prospects for participating in a "perpetual" energy industry that is not subject to another resource depletion.

Secondly, suppliers of natural gas must convince their customers that a supply of a gaseous fuel is reasonably assured for at least as long as the expected life of any new gas-using plant that they are about to install.

Thirdly, the utility industry must demonstrate to government policymakers that a nuclear-hydrogen energy delivery system is indeed a viable alternative to an all-electric economy; that the industry will be ready to operate such a system as soon as it becomes economically justified, and that in doing so, it will not be thrusting upon the public a new, untried or unwelcome form of fuel.

Fourthly, the all-gas utilities must soon decide whether they will own their own nuclear plant, or will rely on the purchase of the product; and will this be electricity, heat or hydrogen? Some form of cooperation with the electric generating utilities seems inevitable since the latter have a 15-20 year lead in the experience of constructing, owning, and operating such plants.

Fifthly, the utility industry must soon persuade the nuclear industry to prepare to increase the growth rate of nuclear capacity so as to be able to meet the energy needs of many new and existing gas customers, as well as electricity customers, by the end of this century. To specify the number and types of nuclear plants required for hydrogen generation in the year 2010 requires a considerable research effort now into hydrogen production technology.

The utility industry cannot hope to make these impacts based on the meager level of study and research at present in effect. If the industry is to hope to demonstrate that hydrogen can be economically competitive with electricity, more research is needed to improve the efficiency and economy of both electrolytic and thermochemical production. If it is to convince the public, its customers and the regulatory bodies that hydrogen is indeed a safe and viable all-purpose fuel, research must be extended to the transmission and especially to the distribution, utilization, and safety areas.

* * * *

ROSENBERG: Our thanks to you, Derek, and to all of you; you may not have had time to answer all of the questions, but you have certainly supplied all of us with the basis for an effective action program.

We still have a few minutes left before we conclude this morning's program. We at IGT are frequently asked a number of questions about hydrogen. I'm sure our audience would be interested in your answers to some of them.

DISCUSSION

ROSENBERG: John Johnson has cited considerable industrial experience with the production, handling, and utilization of hydrogen in the space program, but this experience can't really be applied to domestic residences and apartment buildings. We don't have any experience in this area. Derek, people ask you this question quite frequently. Why don't you give us your answer.

GREGORY: I usually answer that question (and, you're right, it is one that comes up very frequently) by saying that we do indeed have experience in that area. In the days of manufactured gas, we were putting a gas that was 50 percent hydrogen right into peoples' homes, and they were cooking and heating with it. In this country, we tend to forget those days a bit. But in Europe and Japan, many consumers are still using manufactured gas that is 50 percent hydrogen. The safety problems that we foresee for the use of pure hydrogen are almost as severe as those with 50 percent hydrogen. So, from the fact that we don't see housewives blowing themselves up every day with hydrogen in Europe and Japan and that they weren't blowing themselves up in this country 20 years ago, I think we can make a good case that hydrogen can be handled safely.

ROSENBERG: John, you were talking before about the pipelining system and the fact that we do have experience in pipelining hydrogen. When we talk about converting to a hydrogen-electric economy, we are going to have to put that hydrogen in distribution system pipes that are now under the streets. Does Linde's experience in what we tend to term transmission pipelining have any bearing on natural gas distribution systems?

JOHNSON: Yes, I think it does. The first concern is the belief held by some that such a system would leak profusely. Well, if you have a natural gas line that is leaking, you can bet that hydrogen will leak from it also. But I think that the fundamental principle is that you don't want a leaky line for either fuel, and, thus, you build a transmission pipeline so that it has no pores. That's the basic requirement.

The second concern is that if you do have a leak, the volumetric flow of hydrogen from the line would be roughly 3 times that of methane. But, since the heating value of hydrogen is one-third that of methane, the energy flow is approximately similar so there is no extraordinary increase in the amount of energy seeping into the environment. The problem is that hydrogen tends to leak more readily; if it doesn't disperse, it then represents a hazard. That's basically the reason hydrogen has such a bad reputation. The basic rule with hydrogen is just don't let the leaks occur in the first place, and I am sure that's a rule of the gas industry, also.

The third concern of many people is the embrittlement phenomenon. Generally, embrittlement occurs only when pipeline pressures are about 2000 psi. However, since most hydrogen systems, particularly older ones, are nowhere near that pressure, I don't think this is a real concern. But again, it's an area where there is technology to draw upon. You can check your old designs to see if they conform with the codes and rules on how to beat the hydrogen embrittlement problem. Overall, the problems are not substantially greater in handling hydrogen than in handling methane.

ROSENBERG: We apparently have some experience then with domestic applications and some revelant technology concerning distribution systems. One area where we have some very definite experience is with the problem of converting from one fuel gas to another. We had a conversion in this country a number of years ago when we converted from manufactured gas to natural gas. At that time, we had a lot fewer appliances. Now, when we look forward to conversion to a hydrogen economy, we are talking about a tremendous population of gas appliances. Is that going to make conversion prohibitively expensive? Jack, do you want to discuss this?

CASAZZA: Yes, Bob. Frankly, I don't think we know. What we have so far is some good thinking and some experience, such as the work that Derek and John have mentioned. What we have to do is take a small sample area and start to get actual field data. I am a great believer in the need to get actual, observed experience under real-life conditions. Let's take a portion of one of our systems some day (I hope that it is in the near future); start blending some hydrogen in with the gas, perhaps even all the way to 100 percent hydrogen; and then make the necessary changes in the utilization apparatus. Let's get some good, hard data. Until we do that, we don't know if conversion is going to be prohibitively expensive or not.

ROSENBERG: How can I disagree with that? That's the way we learned so much in this industry, and it certainly has stood us in good stead. Let me turn from the hydrogen conversion problem to the production problem. We keep reading about the cost of nuclear reactors going up, the big delays, the cost of money, and electricity costs from nuclear reactors going up faster than those from fossil-fuel plants. Is this going to switch us from a nuclear-reactor-based electric economy to a fossil-fuel-based economy? Will it delay nuclear reactor construction or will it change some of the cost figures you gave in your prepared statement, Ken? The question is, will the cost of nuclear energy make hydrogen prohibitively expensive?

JOHNSON: I think, as Jack indicated, that there are a couple of things that are happening now that are going counter to the kind of future that we have been talking about. With regard to the cost of nuclear power, I think you've got to distinguish between the capital costs of the plant and the fuel cost. It is true that the capital costs have been escalating, but the fuel cost has been rather stable, and, I would guess, it would be considerably more stable than fossil fuel cost for quite a while. Concerning capital costs, I think a major component of those costs is the interest during construction. As you get out into periods of 10 years required to license and build a nuclear power plant, this is indeed hurting the nuclear power industry. I think we have got to shorten the licensing lag time and the construction time to get the costs down so that nuclear power can play its proper role in the near term. We also have to overcome some of the public concern about reactor safety and get on with the job.

ROSENBERG: Yes, this public concern is a key element. Jack, you've dealt with some of that concern firsthand. Is the public going to let us build the large number of nuclear reactors we need?

CASAZZA: Well, we think they are. As you know, we are working on this floating nuclear power plant concept. We believe that the public is getting closer to the point where they recognize how important nuclear power is to their overall quality of life. I think there have been some extremist people who have pointed up some of the potential hazards, while not letting the public know about the benefits. I think the fuel crisis that we have just been through and information on how much oil you can save by having one 1000-megawatt nuclear unit is the sort of information that is getting through to the public; I think they are beginning to evaluate both the pros and cons. While I can't say for sure, Bob, that siting and installation problems will be any easier, I think the trend is going in the right direction. If we can raise the capital, I believe we are going to be able to get the nuclear power plants in service that our society needs.

ROSENBERG: Let me direct one last question to all of you. We frequently hear that hydrogen is a long-range solution to our energy problems — one way off in the future; that it's going to be important across the board in the U.S. economy and, therefore, the National Science Foundation or some equivalent governmental organization should be funding it; and that people like the gas industry do not have to be concerned with it now and shouldn't have to spend their own money on it at this time. Does anybody want to tell us why the gas industry should be concerned and why it should be funding research and development activities now?

CASAZZA: Maybe I can start, because, very simply, we think our future is at stake. I think that on your own you ought to look into things that determine your future. We do this in our personal lives, and I believe that in our corporate and industry thinking we ought to take the same approach.

GREGORY: I think the really long-range research and the very expensive research is going to go into some of these new nuclear technologies and that research will have to be supported by the Federal Government. But unless industry sets the lead, indicates that it has the need, and is willing to participate and call the shots in the first place, I don't think the Government is going to be persuaded to put in the kind of money that is necessary. So, I think it's up to industry to take the lead — to sway the National Science Foundation, for example, toward long-term research in this direction.

JOHNSON: I think that any research project can be evaluated in terms of its potential benefit, of how quickly it will be paid off, and of the risk that is associated with it. So it becomes a question of whether any individual company or institution or government can afford the risk after the benefit has been analyzed. I think the types of things that Jack is doing are clearly within the province of industrial institutions because the benefits are unique to their operations. He should be trying to find applications for the technology. Applications like the hydrogen-fueled airplane, where billions of dollars are involved, are clearly beyond the province of the airline and aircraft industries. Such financing probably will have to come from the Federal Government. So it's this kind of trade-off, where you ask if you can afford the risk, that determines who should fund the research.

HOFFMAN: Well, I just would like to add a short note. I think it's evident that there are a number of near-term opportunities for increased efficiency and reduced cost in hydrogen energy systems and that such work is more appropriately done through the mechanism of industrial research.

ROSENBERG: Gentlemen, before we bring this session to a conclusion, let me take a few minutes and try to summarize some of the points that you have been making.

Ladies and Gentlemen, when you walked into this auditorium about 90 minutes ago, many of you were probably wondering what this hydrogen thing was all about. You were probably asking whether pipeline hydrogen in the nuclear era was one of those fine-sounding concepts that will have its day in the sun and then fade away, or, whether it is a real prospect for the future of the gas industry. Now, 90 minutes later, I hope that the question in your mind has been both clarified and changed. I hope you're now asking yourself what your company can do to help promote and to exploit the potential of pipeline hydrogen.

The four presentations we heard this morning were all very pro-hydrogen. We did hear a brief interview with Dr. Edward Teller, who said that the hydrogen economy was something for the future and may be unnecessary. There are some people who agree with him. But the speakers here this morning made a very strong case for the practicality of hydrogen. Jack Casazza even indicated that hydrogen had some very real near-term possibilities. He covered everything from using hydrogen in steel mills and in fertilizer plants to fuel cells and the integration of a natural gas-hydrogen-electric system. And more importantly, Jack cited actual tests now under way which could promote this near-term utilization of hydrogen.

Jack Casazza is with a combination company and this gives him something of an advantage over a straight gas company. One of the problems each utility must face is how to make hydrogen when they decide they want it. Combination companies are experienced with nuclear reactors, but straight gas utilities have no operating background or experience. Here the comments of John Johnson are instructive. John pointed out that hydrogen may be produced from coal before it is produced from nuclear energy. He said that Lurgi and the K/T processes are both prolific hydrogen producers and we're all aware that the development of these processes are the start of our SNG industry. It's kind of funny when you realize that once the gas industry gets fully involved in commercial SNG operation, we'll be making more hydrogen than the world has ever seen, even more than Linde.

Maybe you're convinced that your company can make hydrogen, but the question still remains whether you want it or not (or when you want it). Here Derek Gregory made a good point. He said that hydrogen could help convince both investors and utility customers that the industry and your company in particular is not dependent on natural gas supplies, or even on SNG, to stay in the gas business. If hydrogen really does that, it certainly has value for public relations and maybe it is even worth supporting some research. But consider those numbers that Ken Hoffman presented. Hydrogen sure looked good compared to electricity. It's not going to replace natural gas or SNG as long as reasonably priced supplies are available, but it is clear that special industrial applications are going to be attractive and maybe soon. Possibly your company can get in on the growing market for commodity hydrogen.

OK, this presentation was all pro-hydrogen, but it made a pretty good case for your company getting interested. It's inevitable that we'll encounter a lot of problems as we try to develop the pipeline hydrogen concept. That's why every one of the speakers made recommendations for immediate action. Each of them said that we need to improve efficiency in hydrogen production and lower costs, improve equipment and increase reliability. These are industry-wide problems which should be handled on a collective basis. But some of those other recommendations were interesting because they relate to how your company can get involved. What were they?

Cost benefit analyses to see just where and how soon hydrogen can be used by your company, specifically:

1. Public information and education programs to help formulate positive policies and attitudes.

2. Investor and customer seminars to establish our credibility as a long-term component of the energy industry.

3. Improved safety and hydrogen system demonstrations. . . everyone stressed the need for these. They certainly will affect the attitudes of both the public and the decision makers.

4. Support of industry-wide research to advance necessary hydrogen developments. And,

5. More cooperative efforts with Government, the nuclear industry, and others to establish our needs and priorities. The long-range plans now being made must have our inputs so that pipeline hydrogen can plan its rightful role in the nuclear era.

We hope that you have found this an enlightening morning and that you agree that this hydrogen idea may prove very useful. We also hope that when you receive your copy of this seminar in the mail, you'll circulate it and initiate the steps necessary to develop an action plan for your company.

Ladies and Gentlemen, if this is the conclusion and the resolve you've reached from this morning's presentation, we are gratified. Thank you for coming.

FILM REPRISE

VO: We have recognized hydrogen as a plentiful, clean-burning fuel that can be handled safely in large quantities.

Looking ahead we see hydrogen as a fuel that is economical to transport and store.

A fuel that can be readily and economically substituted for fossil fuels.

A fuel that a growing number of energy experts favor for the transition into a nuclear-based economy.

(MONTAGE OF PORTIONS OF INTERVIEWS WITH LUXO, CLARK, ORDIN, and BAIN)

We have offered evidence that substantial technology already exists.

And we know the present gas industry will obviously play a more important role in storing and handling nuclear heat as hydrogen than if the all-electric alternative is selective.

The research and development lead time required for major new technology has been dramatically illustrated in the present efforts to develop synthetic fossil fuels technology.

We must begin at once if we are to accomplish the formidable task of developing the nuclear-based hydrogen technology by the next century. That's just 26 years away.

WORLDWIDE RESEARCH ACTIVITIES IN HYDROGEN ENERGY

December 12, 1974

by

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Introduction

The concept of using hydrogen as an energy carrier and universal fuel is attracting a great deal of interest worldwide. Many studies and experimental projects are currently under way either evaluating the prospects for or preparing to participate in some sector of the hydrogen economy. This interest in hydrogen has grown significantly in the last 2 years and has obviously been stimulated by the realization of a worldwide fossil fuel shortage.

Significant hydrogen-energy research began in the United States and in the EURATOM laboratory in Italy 4 or 5 years ago, but has now developed to include work in Canada, Brazil, Australia, Japan, West Germany, France, and England. Early work concentrated on the concept of the "hydrogen economy," an energy economy in which hydrogen produced from nuclear or solar energy is used as a universal fuel for almost every energy application. However, many of the efforts now under way are aimed at one or more of the rather smaller segments of this "economy" — to produce and utilize hydrogen as an energy form for some specialized application and to compare it with other unconventional energy systems. We at the Institute of Gas Technology believe that many of these specialized applications are of direct interest to the gas industry and that their exploitation could grow into a mixed energy-supply system in which the customer load is shared by hydrogen, electricity, and other nonfossil energy forms.

Considerable emphasis is being placed on relatively short-term applications of hydrogen derived from fossil fuels, such as coal, to supplement or replace some conventional energy or feedstock systems. Hydrogen may be produced from coal or oil shale at efficiencies and costs similar to those involved in the production of SNG. For certain applications, hydrogen is superior to SNG. Thus, several companies are investigating the alternative of making hydrogen directly and pipelining it to the specialized user instead of making SNG and subsequently having the consumer turn it into hydrogen — for example, in an ammonia plant or steelworks. Just as is true for SNG, technology is available today for producing hydrogen from coal, but more economical and efficient processes can be developed in the future.

Hydrogen may also be produced by electrolysis using electric power. This route offers a way of using known technology and existing electric generator equipment. However, an electrolytic hydrogen plant fueled by a fossil fuel has little merit since hydrogen could be made chemically from the fossil fuel both more efficiently and more cheaply. Nonetheless, many recognize electrolysis as a short-term available option to make hydrogen from off-peak fossil-fuel-based electric power and from off-peak or base-load nuclear power. Since the load factor on a generating plant in the United States is about 55%, a great deal of generating capacity is potentially available. As nuclear capacity grows, the electric utilities predict an increasing availability of off-peak nuclear capacity, for which profitable off-peak uses should be found. Uses involving hydrogen that are being investigated include storing it for subsequent electricity generation and using it to supplement industrial hydrogen conventionally made from fossil fuels. We believe that the second of these options has the most merit. Electrolysis technology is available today, but like SNG processes, improvements in efficiency and economics are expected to be developed in the future.

A third hydrogen production method, and one that is receiving the most research support today, is the thermochemical splitting of water, using a heat source, without an electrical intermediate. Heat is used to drive a number of chemical steps in a cyclic sequence, all the components of the cycles, except water, hydrogen, and oxygen, being recycled. No commercial technology is available for this process today, but several research groups are conducting experimental trials of chemical reactions, and even more have carried out detailed thermodynamic analyses of the theoretical efficiencies of various cycles. Much of this work is held proprietary by the researchers. IGT has identified some 70 theoretically possible cycles, several of which possess calculated, and possibly attainable, heat-to-hydrogen efficiencies greater than 50%. In contrast, nuclear heat-to-electricity efficiencies are at present only about 35% and are only expected to rise above 45% in the future with some difficulty. Electrolyzer systems should be capable of delivering heat-to-hydrogen efficiencies in the same 35-45% range. IGT believes that EURATOM and IGT are the only two research teams in the field who have actually "demonstrated" all the steps of an efficient (above 40%) cycle in which all the chemical reactants have been physically recycled and all the product separations have been made.

One of IGT's chief concerns about the commercial application of thermochemical hydrogen production is the need for a special type of nuclear reactor capable of delivering high-temperature heat. Such a reactor, needed to produce the high efficiencies discussed earlier, would require several years of specialized development in nuclear engineering. Although such development is already going on, for example, at General Atomic Company, San Diego, California, and at Kernforschungsanlage (KFA), Jülich, West Germany, we recognize that the lead times required to develop a substantial business to produce thermochemical hydrogen are very long—about 20 years or more.

Because hydrogen can be made from a wide variety of energy sources, it is being considered as a transitional fuel to span the time when the U.S. energy supply is changing from fossil to nonfossil energy sources. Beginning with hydrogen made from oil and gas through hydrogen from coal, oil shale, and nuclear power, longer term programs aimed at harnessing solar, wind, and tidal energy in the form of hydrogen are already in the conceptual research stage, supported by the National Science Foundation (NSF) and its foreign equivalents.

Worldwide, research efforts on hydrogen energy topics range from a few small teams of a dozen or so people to many individual efforts in university laboratories. The efforts are uncoordinated and dispersed, both in the nature of the work and in the objectives. To present a picture of worldwide hydrogen efforts, we have classified them by application objectives in the following end-use categories:*

- Feedstock for ammonia and methanol
- Upgrading of oil, coal, and oil shale
- Iron and steel production
- Energy storage

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* Unique single applications of hydrogen such as in NASA's space efforts are not included.

- Supplement to natural gas and SNG
- Transportation fuel
- Replacement for natural gas.

The objectives of the work and a listing of some of the organizations supporting research are given in Appendix A.

We think hydrogen derived first from coal, and later from nonfossil energy, will reach significant usage in these applications in the order given. Use of hydrogen in each category will have significant impacts on the gas industry. Classification in this way makes the present hydrogen effort look more organized than it really is. Many activities are really more loosely directed and cannot be accurately classififed, while others are applicable to more than one end-use objective.

It is difficult to draw up an all-inclusive listing of hydrogen research or to assign dollar values to all of the research efforts. In some cases, the magnitude of the effort simply is not recorded. In others, funding officially assigned for one fiscal year is actually being spent in another. In Appendix B we have attempted to provide a comprehensive listing of worldwide hydrogen projects that we know about and have also attempted to assign a U. S. dollar value corresponding to our best estimate of the present level of activity. About 40 separate projects are at present being supported by six different U. S. Government agencies, about 15 U.S. companies are carrying out hydrogen-energy research with their own funds, and hydrogen programs are being conducted in at least 10 countries outside the United States. We estimate that about $10 million/yr is being spent worldwide on hydrogen research today.

Some Industrial and Government Opinions About Hydrogen as an Energy Medium

In the United States, the Atomic Energy Commission (AEC) and the majority of the "nuclear industry" have, for a long time, taken the attitude that a nuclear-energy economy is synonymous with an all-electric economy. This opinion is being voiced strongly by Westinghouse Electric Corporation in a series of widely appearing advertisements (although this view is not held by many senior research staff members at Westinghouse). Recently alternative applications of nuclear reactor heat have gained increasing attention for such purposes as steelmaking, coal gasification, oil-refining, and synthetic fuel production. The use of heat to generate hydrogen from water is a key step in all of these applications. The principal U.S. proponent of this approach is General Atomic, but in Europe, EURATOM, the German Center for Nuclear Research, and the U.K. Atomic Energy Authority (UKAEA) have had a longer and harder look at the concept. All of these organizations have access to high-temperature nuclear reactor technology, and all except the UKAEA have active research programs on thermochemical hydrogen production. The USAEC recently funded studies in all of these applications of nuclear heat and formed a coordinating committee to monitor their progress. IGT and A.G.A. were invited to serve on this committee, but were barred from the first meeting because of legal formalities within the AEC. Companies such as General Electric, General Atomic, and Westinghouse were admitted because they have AEC contracts.

Many electric and combination utilities view hydrogen energy with enthusiasm. Hydrogen can serve as a storage medium and as a form of inexpensive underground transmission, and integrates well with their proposed use of the fuel cell as a two-way link between their gas and electric systems. Many U.S. electric and combination utilities are supporting their own hydrogen research efforts, in addition to work supported by the Electric Power Research Institute (EPRI).

We note with interest the studies performed by a number of electric utilities that look very positively at the potential of hydrogen to serve as a relatively inexpensive medium for underground energy transmission. These studies are carried out mainly by the utilities serving the highly urbanized areas of the Northeast and southern California, where further overhead-line construction is being discouraged. The attitude of some of the all-electric companies carrying out this research is that an all-electric economy is more expensive and less efficient than a mixed hydrogen-electric energy system, and that the electric utilities themselves would be in the best position to make nuclear hydrogen and sell it to the gas industry, which would merely have to deliver it to its gas customers.

Several gas utility companies view hydrogen as a long-term solution to their supply problem, but are hesitant to support research directly, feeling that such research should be A.G.A.'s responsibility. At least two notable exceptions to this are Texas Gas Transmission Corporation, which has its own research effort in hydrogen production, and Southern California Gas Company, which has a ventless appliance program that is directly relevant to hydrogen utilization.

Gaz de France sees hydrogen energy as a necessary adjunct to the widespread introduction of nuclear energy in France. In a cooperative program with Electricité de France, it visualizes a mixed hydrogen-electric delivery system as being essential. British Gas seems to be complacent about its North Sea gas reserves and has no active program on hydrogen. Some German companies, such as Ruhrgas, believe that hydrogen transmission is not appropriate for their short transmission distances.

The Japanese have shown an extraordinary interest in U. S. hydrogen programs and are now beginning their own research efforts; the Ministry of International Trade and Industry has included a $1 million/yr effort on hydrogen as part of the "Sunshine Project."

The aircraft industry has long been enthusiastic about the light weight of hydrogen fuel. The possible use of hydrogen for subsonic passenger aircraft is viewed enthusiastically by NASA and Lockheed, which have research efforts in progress, but with some alarm by TWA and Pan-Am because of equipment cost and public acceptance. This subject has been extensively discussed by a National Academy of Engineering Committee on Alternate Aircraft Fuels. The U. S. atomobile industry is not openly active in hydrogen research, although many small independent projects are concerned with nonpolluting engines operating on hydrogen. In contrast, Daimler-Benz and Volkswagen both have some form of hydrogen-energy projects under way.

Among U. S. Government agencies, NASA, which has identified itself as the "lead agency" for hydrogen research, is currently funding about $1.5 million of hydrogen-energy effort, has $3 million or more earmarked for fiscal year 1976, and is enthusiastic about all aspects of hydrogen use. Most of the AEC-controlled national laboratories have hydrogen research projects, but these projects are not centrally coordinated. The AEC is currently spending about $2.0 million/yr on hydrogen. The Advanced Research Projects Agency of the Defense Department is studying hydrogen as an all-purpose military fuel for both vehicle and static applications; current spending is at the rate of about $400,000/yr. The Environmental Protection Agency sees hydrogen as an ultraclean vehicle fuel and is spending about $400,000/yr on methods of storing it or producing it on-board a vehicle. All of this government work is uncoordinated; even within each agency, nobody seems to have a clear picture of exactly what is going on in hydorgen research.

It appears that the Energy Research & Development Administration (ERDA) will have hydrogen research in its proposed program. It will automatically take over the AEC and EPA work, but not the NASA and DOD projects. Some guidance from the gas industry seems to be called for in this formative period for ERDA research policies.

Gas Industry Opportunities

The gas industry has a number of opportunities in hydrogen, which may be summarized as follows:

- The gas industry does not have to wait for the year 2000 before entering the hydrogen business. It can develop new and growing markets by making and delivering hydrogen to the petrochemical, oil-refining, iron and steel, and aviation industries. Such new markets could be developed in the 1980 to 2000 time frame, using coal as the source of hydrogen and providing a sound basis for the transition toward nonfossil hydrogen sources in the longer range.
- The gas industry can develop the technological know-how to produce hydrogen from nuclear energy and from solar energy. Research along these lines is very long term and probably has a 25-year or more payoff time. For example, estimates of the time required to pursue thermochemical hydrogen production through all the logical steps including bench test, pilot plant, and demonstration plant indicate that bench-scale research is needed now if plants are to be in commercial operation soon after the year 2000. The gas industry should regard this type of activity as "life insurance."
- The gas industry can influence national energy planning to include the option of using its existing transmission and distribution facilities to deliver hydrogen energy when the need arises. To do this, the industry must demonstrate that these facilities are compatible with hydrogen or can be easily modified to operate with it.
- The gas industry can gain the confidence of the public so that it will accept hydrogen as a clean and safe fuel. Public opposition to nuclear power, to electric transmission lines, and to mining operations has already done much harm to the utility industry. The clean nature of hydrogen combustion and its lack of an unsightly delivery system can be used to attract public support.

- All of the components of a demonstration hydrogen-energy system, from electrolytic production to pipelines and combustion equipment, are already available. While future research should be aimed at improving the economics, efficiency, and safety of these components, a short-term demonstration using the present state-of-the-art could be beneficial. A large ERDA program could involve the construction of a pilot-scale field test and the demonstration of a hydrogen-energy system. The gas industry has the opportunity to collaborate or lead in this demonstration activity, which can do much to project the image of an industry with a long-term supply availability.

- The gas industry can play a cooperative role with the electric industry in producing hydrogen from off-peak electric power and in pipelining it for use in such applications as fuel cell generators and petrochemical plants. As an alternative, the possibility of mixing this hydrogen with natural gas up to a point* that still has no effect on the utilization equipment could provide an appreciable supplement to supplies in the very short term. This off-peak storage activity, which could be developed in the 1985-2000 time frame, will also open up new marketing opportunities for by-product oxygen and heavy water.

- The gas industry could use its expertise in underground gas storage to provide seasonal storage capability to the nuclear- and solar-electric utility industry. Such storage capacity will be needed beginning in about 1990.

Required Thrust of a Gas Industry R&D Program on Hydrogen

1. Long-term research in thermochemical hydrogen production is justified because of the potentially lower cost and higher efficiency of the process. Close liaison with the high-temperature nuclear reactor industry is needed from now on, as both are carrying out experimental programs in chemistry of new processes and the chemical engineering of plant designs.

2. Because of the recognized materials problems in thermochemical hydrogen production and because of the dependence of thermochemical hydrogen production on a special type of nuclear reactor, an alternative means of producing hydrogen should also be developed. Improvement of the present electrolyzer technology is thus justified because electrolyzers would have the near-term potential of playing a major role in the use of off-peak electric power to supply a number of gas industry customers.

3. Close liaison and cooperation with the nuclear part of ERDA (the old AEC), the nuclear industry, and the Electric Power Research Institute appear necessary if we are to ensure that the planned

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* Perhaps 30% as indicated by some IGT work.

growth rate of nuclear plant capacity is not completely dominated by the needs of the electrical industry without consideration of possible gas industry needs.

4. Short-term emphasis should be placed on the development of economical and efficient means of producing, storing, and delivering hydrogen made from coal and oil shale to the petroleum-refining, petrochemical, iron and steel, aviation, and ground transportation industries. The gas industry's need for and capability of supplying itself with the vast quantities of hydrogen needed for SNG production should be closely integrated with this field of operation.

5. The capability of the gas industry to play a major role in delivering tomorrow's nuclear and solar energy in its existing equipment must soon be proved and demonstrated so that long-range commitments can be made. To do this, urgent attention should be applied to the materials, safety, and design problems of operating present transmission and distribution equipment on hydrogen.

APPENDIX A. Objectives in the Application of Hydrogen Research

The Growing Importance of Hydrogen

Hydrogen is used today as a chemical feedstock, as a metallurgical reducing agent, in food processing, and in many other applications. It is currently used only to a small extent as a fuel gas. We can identify a growing role for hydrogen in all of these applications, which would provide a good basis for the growth of a hydrogen-production business. Almost all hydrogen produced today comes from natural-gas- or naphtha-reforming. Since both of these feedstocks are in short supply, a growing demand for hydrogen can best be met by the development of processes that make hydrogen from a) coal, b) oil shale, and c) nuclear or solar energy sources. These processes would be applied to the production of hydrogen in the indicated order.

Hydrogen will grow in importance in the following applications:

1. As a chemical feedstock (ammonia and methanol)
2. For upgrading oil, coal, and oil shale to useful fuels
3. As a reductant in the production and manufacture of iron and steel
4. As an energy-storage medium
5. As a fuel to supplement the supplies of natural gas and SNG
6. As a fuel for transportation
7. As an ultimate replacement for natural gas.

Hydrogen is already used in the first three categories. It will come into use in the other categories and its use in all of these applications will increase, in the order given.

Hydrogen in Chemical Manufacture

The major uses of hydrogen today are for the production of ammonia and methanol, and in petroleum-refining. Ammonia and methanol production in the United States currently consumes about 1.2 trillion SCF/yr of hydrogen.

Most of this feedstock hydrogen is produced onsite from natural gas. Natural gas supplies are unable to keep up with the growing demand for ammonia, and the cost of ammonia is very sensitive to increasing natural gas prices. Ammonia is the basic raw material for fertilizers; methanol is a precursor to many industrial solvents and plastics.

Alternative sources of hydrogen include production from a central coal gasification plant, from off-peak electric power by electrolysis, and from dedicated nuclear-thermochemical plants. Economies of scale suggest that one central coal or nuclear plant should provide the most economical service to a number of conventionally sized ammonia or methanol plants. If off-peak hydrogen supplies are used, they must be gathered from a number of power stations, stored, and pipelined to the industrial users.

Some substitutions of hydrogen produced from these alternative sources for natural gas could be justified now. The application of pipelined hydrogen to chemical manufacturing could begin by 1980.

Work is under way on the following areas that are relevant to this application: production of hydrogen by electrolysis, coal gasification, and nuclear water-splitting; pipelining; and storage. Organizations carrying out this work include EPRI and some industrial pipeline companies.

Hydrogen in Fuels Production

One of the major uses of hydrogen today is in petroleum-refining, where it is used to upgrade heavy oils to lighter fractions such as gasoline and jet fuel. Some 800 billion SCF/yr of hydrogen are used for this purpose. In producing synthetic fuel from coal or oil shale, hydrogen fulfills the same "upgrading" function. A single 250 million SCF/day HYGAS plant would produce and consume about 100 billion SCF/yr of hydrogen (about one-tenth of the total U.S. use for ammonia). Thus, the gas industry is likely to become the world's largest user of hydrogen.

The present sources of hydrogen for petroleum-refining and SNG production are from oil or gas in the refinery, or from coal or oil shale in the SNG plant. Alternative sources of hydrogen include a central coal-gasification (hydrogen-producing) plant to supply refineries by pipeline and a central nuclear water-splitting plant to supply refineries and synthetic fuel plants. Adoption of such a scheme would reduce the consumption of oil and coal in the manufacture of conventional and synthetic fuels.

Economics of scale, especially for the nuclear case, suggest that a central production plant serving several customers by pipeline would be preferred.

Introduction of hydrogen from coal to oil-refining processes could be justified now and could enter service in 1980 to 1985. Introduction of hydrogen derived from electrolysis using nuclear energy and later from thermochemical processes to both oil-refining and synthetic fuel production may be possible in the 1990-2000 period.

Work is under way in the following areas that are relevant to the use of hydrogen to produce synthetic fuels: coal-to-hydrogen processes, nuclear water-splitting, and pipelining. Organizations that are working with this objective include AEC (ERDA), Oak Ridge National Laboratory, EURATOM, the German Government, General Atomic, and General Electric.

Hydrogen in Iron and Steelmaking

In the iron and steel industry, coal is currently used partly to supply a heating fuel, but primarily to provide a chemical reducing agent.

Large volumes of "atmosphere" gases for annealing and heat-treating operations are made from natural gas and naphtha. Concerns over rising coal prices, environmental protection requirements, and gas curtailments are causing the iron and steel industry to look for other energy sources.

Hydrogen can meet the reducing-agent, fuel-gas, and atmosphere-gas needs with known technology. Already, some direct iron ore reduction plants are operating on hydrogen (produced from natural gas).

Hydrogen produced from a central coal-gasification plant, serving several mills by pipeline, is an attractive alternative to the present system. Hydrogen produced from water by nuclear energy is also under serious consideration as a longer term project.

Work is under way on the following areas that are relevant to this application: nuclear water-splitting, nuclear-assisted fossil-fuel-reforming, and direct hydrogen reduction of ores. Organizations that have programs involving the use of hydrogen in iron and steelmaking include the AEC, the American Iron and Steel Institute, Atomic Energy of Canada Ltd., and the Steel Company of Canada, Ltd.

Hydrogen as an Energy-Storage Medium

A major need of the electricity transmission system is storage capability. Significantly funded research programs on compressed-air storage, hydraulic storage, batteries, flywheels, and hydrogen-storage systems are currently in progress. The need for the storage of electrical energy becomes more severe as —

1. Increasing nuclear capacity is installed; nuclear plants perform best at a constant output.
2. Electric energy takes over an increasingly growing share of the various areas of the traditional fossil fuel market, such as space heating, with its large seasonal peaks.
3. Transmission systems become overloaded during peak periods.
4. Solar, wind, and tidal energy sources become seriously considered.

The hydrogen-storage concept for electrical utilities has several forms; all rely on the use of electrolysis to produce hydrogen during periods of low demand. One option is to provide the necessary "spinning reserve" of power generation by a plant that normally produces electrolytic hydrogen on an interruptible basis. The hydrogen could be stored within the pipelines, in underground fields, in pressure vessels, as liquid hydrogen, and as chemical hydrides. Recovery of the energy can be by —

- Using central or decentralized fuel cells or hydrogen turbine generators
- Mixing hydrogen directly with an existing natural gas supply
- Supplying hydrogen to major petrochemical and industrial hydrogen users.

The need for large utilization of off-peak electrical capacity is imminent. The present load factor of all U. S. electrical generation plants is 55%. Application of hydrogen in this area could begin between 1980 and 1985.

Work is under way in the following areas that are relevant to the use of hydrogen as an energy-storage medium: electrolysis, hydride storage, pressure vessel storage, pipelining, fuel cell generation, hydrogen turbines, and integration with the gas and petrochemical industry. Organizations that have programs involving this application include the AEC; Brookhaven National Laboratory; Allied Chemical Corporation; Isotopes, Inc. (a subsidiary of Teledyne, Inc.);

General Electric Company; United Aircraft Corporation; Rocketdyne; and several elecrric and combination utilities including Public Service Electric and Gas Company of New Jersey, Niagara Mohawk Power Corporation, and Northeast Utilities. Solar, wind, and thermal power systems studies incorporating hydrogen storage are being studied by the National Science Foundation; TRW, Inc.; and Global Marine, Inc.

Hydrogen as a Supplement to Natural Gas and SNG

Energy demand and supply projections indicate a continually increasing shortfall in the supply of natural gas. By the 1980's, our natural gas supply will be enhanced by coal-based SNG as well as by imports of LNG from foreign sources. However, these new supplies will not be adequate to satisfy the deficit between demand for gaseous fuel and the supply. Hydrogen from nuclear power could further supplement this natural gas-SNG supply.

Nuclear-based hydrogen, using water electrolysis, is a particularly attractive technology for the 1980's because it would not be in competition with other fuel-synthesis processes for mined coal and because nuclear electrolysis plants could be sited in water-plentiful areas. Furthermore, off-peak nuclear power available to mixed electricity and gas utility systems could be used for hydrogen production until such time as base-load hydrogen systems are developed.

Today several utility companies are evaluating supplementing their pipeline gas supplies with hydrogen produced by electrolysis using off-peak power. Among these are Niagara Mohawk Power Corporation and Public Service Electric and Gas Company. The amounts of hydrogen that could be used depend upon the off-peak generating capacity, the current statutory limits for the heating value of delivered gas, and, ultimately, the maximum amount of hydrogen that is compatible with utilization equipment. This latest value might be as much as 30% hydrogen.

Hydrogen as a Transportation Fuel

Hydrogen is attractive as a fuel for transportation uses because —

- It is virtually nonpolluting.
- It has desirable ignition and combustion characteristics.

- It is lightweight compared with aircraft fuels on an equal-energy basis.
- It is potentially available in large quantities from domestic coal and nuclear resources.

Both piston engines and gas turbines have been converted to operate satisfactorily on hydrogen. The primary problems are associated with the storage of hydrogen on-board the vehicle, the design of distribution and vehicle filling stations, and public safety.

Because of its light weight, hydrogen has great technical advantages when considered for use as an aircraft fuel. Handling problems for ground vehicles are minimized when vehicles that refuel at specific locations, such as buses, trucks, and trains, are considered. This type of application of hydrogen could begin in 1995. Aircraft operation on hydrogen could also begin in the 1990's.

Work is under way in the following areas that are relevant to the use of hydrogen as a transportation fuel: hydrogen production from coal, improved hydrogen liquefaction techniques, hydrogen aircraft design, gas turbines, hydrogen piston engines, automobile fuel tanks, hydride systems, and technology assessments. Organizations that have programs involving this application include NASA, Linde, IGT, Lockheed, Boeing, United Aircraft, the EPA, Jet Propulsion Laboratory (JPL), Billings Energy Research, Cornell University, Beech Aircraft, Brookhaven National Laboratory, Allied Chemical, the University of Denver, and Stanford Research Institute.

Hydrogen as an Ultimate Replacement for Natural Gas

Hydrogen, made from nuclear or solar energy, is the simplest nonfossil synthetic fuel that could be used as an alternative to electricity. Many government and industrial advocates of nuclear and solar energy regard the "all-electric economy" as the only way to use these nonfossil energy sources. Hydrogen has several advantages over electricity in that it is cheaper to transmit, is storable, is potentially more efficient to produce, and can be used by present equipment with a minimum of replacement. The justification of the hydrogen-energy alternative depends upon the ability to produce sufficient quantities of hydrogen; to deliver it, primarily in existing transmission and distribution systems, at a price competitive with electric power; and to use it safely in all current applications met by natural gas.

Complete conversion of natural gas systems to hydrogen systems will probably not be justified until after the year 2000. The decision to convert is dependent on both a) the capacity for, and the cost of, producing hydrogen and b) the cost of delivering it to the customer. The decision must wait until there is an economic incentive for the consumer to switch from using a conventional fuel to using hydrogen rather than to electricity. New residential developments, unable to obtain gas supplies, possibly could be the first instances of an economically justified hydrogen-energy supply.

Research on hydrogen production, hydrogen-energy systems, and hydrogen-utilization equipment with the objective of using hydrogen as an ultimate replacement for natural gas is in progress at A. G. A., IGT, Gaz de France, EURATOM, the Institute for Systems Analysis, General Electric Company, the Department of Defense (ARPA), Texas Gas Transmission Corporation, and KMS Fusion, Inc.

APPENDIX B. Comprehensive Listing of Worldwide Hydrogen Projects Completed or Now in Progress

Even though this list is an attempt to include all projects that we know about, there is no official catalog or reference source on hydrogen research, even for the research supported by the U. S. Government, so this list is almost certainly incomplete. Dollar values are IGT's estimates of the present levels of activity, where known. Projects are classified into three categories according to the level of information available:

A. Programs well known to IGT by direct contact with researchers

B. Programs that IGT knows to be in existence through indirect contact

C. Programs that are known to IGT only by the existence of a research paper in the literature.

SG/JM

Table 1. HYDROGEN RESEARCH AT IGT

Sponsor	Descriptive Title	Year(s) Active	Total Cost
I. A.G.A. Research Programs			
A.G.A.	Analysis of the "Hydrogen Economy" Concept	1971	
A.G.A.	Thermochemical Hydrogen Production	1972-75 (Currently Active)	
A.G.A.	Optimization Calculations for Hydrogen Transmission Pipeline	1973	
A.G.A.	Analysis of Hydrogen Embrittlement of Pipeline Steels	1973	
A.G.A.	Survey of Hydrogen Research Outside the Gas Industry	1973	
II. Government Research Programs (Excluding Gasification)			
U.S. Navy (Stevens Institute Subcontract)	Assessment of Electrolyzer Technology	1974	$ 9,000
EPA	Assessment of Alternative Vehicle Fuels (including hydrogen)	1974	$133,000
EPA	Study of Automotive Storage of Hydrogen	1974 (Currently Active)	$ 37,000*
EPA (Engelhard Subcontract)	Hydrogen-Fueled Appliance Testing	1974	--
NASA	Economics of Coal Conversion to Hydrogen, Methane, and Kerosene for Aircraft	1974-75 (Currently Active)	$ 74,000*
NASA	Survey of Hydrogen Production and Utilization Methods	1974-75 (Currently Active)	$169,000*
III. Industry Research Programs (Excluding Fuel Cell Development)			
MAPCO, Inc.	Evaluation of Technology for Pure Hydrogen Production From Coal	1973-74	--
Pratt & Whitney Aircraft	Hydrogen From Oil for Fuel Cells	1973-74	--
Southern Calif. Gas Co.	Appliances to Use Hydrogen or Hydrogen-Rich Fuels	1972-74	--
Daimler-Benz	Study of Problems in Hydrogen-Fueled Vehicles	1974-75 (Currently Active)	--
Electric Power Research Institute	Economics of Hydrogen for Commodity Sale From Off-Peak Power	1974-75 (Currently Active)	--
			$233,000

* Amount funded for project including cost to date.

A-114-2127

Table 2. PROGRAMS SPONSORED BY NASA

Contractor	Investigation	Annual Funding, $1000	Category
In-house	Coordination of all NASA-sponsored work on hydrogen energy	100	A
Jet Propulsion Lab	Planning of NASA hydrogen-energy research program	300	A
NASA-Lewis	RFP issued for 6-month study to investigate hydrogen production using high-temperature nuclear reactors, September 1974	150	B
NASA-Lewis and Univ. of Kentucky	Theoretical evaluation of thermo-chemical water-splitting	35	A
NASA-Langley and Lockheed	Feasibility and design studies of a hydrogen-fueled subsonic aircraft	350	--
NASA-Langley and IGT	Comparison of cost and efficiency of making hydrogen and other synthetic fuels from coal	75	A
NASA-Langley and Linde	Systems studies on making hydrogen from coal and liquefying it for use as an aircraft fuel	34	B
NASA-Marshall and IGT	Survey of hydrogen production and utilization methods	170	A
NASA-Ames and Lockheed	Design of a hydrogen-fueled supersonic aircraft	100	B
NASA-Ames and Life-Systems	Electrolyzer development	--	B
U.S. Dept of Commerce, National Bureau of Standards	Hydrogen safety survey	110	B
NASA-KSC and Bendix	Conversion of vehicles to use hydrogen	--	B
NASA-Lewis	Emissions from engines running with hydrogen injection	--	A
Univ. of N. M.	Bibliography and literature search on hydrogen	--	A

A-114-2135

Table 3. PROGRAMS SPONSORED BY THE AEC

Contractor	Investigation	Annual Funding, $1000	Category
AEC-Headquarters	Coordination of studies on use of high-temperature process heat	--	B
NASA-Lewis	Thermochemical hydrogen production	--	B
Oak Ridge Natl. Lab	Thermochemical hydrogen production – experimental study	Total about 500	B
Los Alamos	Thermochemical hydrogen production – experimental study		B
Argonne Natl. Lab	Thermochemical hydrogen production – experimental study		B
Lawrence Livermore	Thermochemical hydrogen production –experimental study		B
Brookhaven Natl. Lab	Basic hydride storage research	--	B
Brookhaven Natl. Lab	Development of system for electrolysis, hydride storage, and fuel cell conversion for off-peak storage	800	A
Los Alamos	Field trials of liquid-hydrogen-fueled truck	--	B
Iowa State Univ.	Thermochemical hydrogen and basic hydride research	--	B

Table 4. PROGRAMS SPONSORED BY THE EPA

Contractor	Investigation	Annual Funding, $1000	Category
Jet Propulsion Lab	Generation of hydrogen from gasoline on-board vehicle, and studies of engines running with hydrogen injection	850	A
IGT	Generation of hydrogen on-board automobile	37	A
Exxon	Generation of hydrogen on-board automobile	--	B
Engelhard Industries, Inc.	Development of catalytic burners for hydrogen appliances	--	A
Brookhaven Natl. Lab	Lightweight metal hydride storage	30	B
Int. Harvester (Solar Div)	Metal hydride research	--	B
Argonne Natl. Lab	Motor vehicle storage of hydrogen using metal hydrides	88	B

Table 5. PROGRAMS SPONSORED BY OTHER GOVERNMENT AGENCIES

Sponsor	Contractor	Investigation	Annual Funding, $1000	Category
Natl. Sci. Foundation	Stanford Research Institute	Technology assessment of hydrogen energy	125	A
Natl. Sci. Foundation	Univ. of Mass.	Use of hydrogen storage and transmission in off-shore windmill and nuclear power systems	--	B
Dept. of Commerce	Natl. Bureau Std. — Boulder	Bibliography and literature search on hydrogen	--	
Advanced Research Projects Agency, Department of Defense	Stevens Institute	Survey of production, storage, and use of hydrogen	150	B
	General Electric (Tempo)	Systems studies of use of hydrogen as a military fuel	75	B
	Naval Syst R&D Lab Annapolis	Field trials of a hydrogen-fueled gas turbine ship; hydrogen embrittlement studies	75	
Dept. of Transportation	Univ. of Calif. Los Angeles	Field-testing of liquid-hydrogen-fueled jeep; hydride storage	55	B
Dept. of Transportation	Cornell Univ.	Emissions from hydrogen-fueled engines	30	B

Table 6, Part 1. PROGRAMS SPONSORED BY INDUSTRY

Sponsor	Contractor	Investigation	Annual Funding, $1000	Category
Northeast Utilities	General Atomic	Production of hydrogen by thermochemical water-splitting	--	B
Southern Calif. Edison Co.				
General Electric	General Electric (Schenectady)	Production of hydrogen by thermochemical water-splitting	--	B
General Electric	General Electric (Lynn)	Electrolyzer development	--	B
Northeast Utilities	Burns and Roe	System study for hydrogen transmission	--	B
Niagara Mohawk Power Co.	In-house	Hydrogen off-peak electricity storage	--	B
Mountain Fuel Supply Co.	Billings Energy Research	Hydrogen appliance conversion	--	B
Southern Calif. Gas Co.	IGT	Appliances to use hydrogen on hydrogen-rich fuels	--	A
Winnebago and Others	Billings Energy Research	Conversion of motor home and other vehicles to run on hydrogen	--	B
Public Service Electric and Gas Co.	In-house	Electrolyzer, hydride storage, and fuel cell system demonstration and evaluation	--	B
Texas Gas Transmission Corp.	KMS Fusion, Inc.	Production of hydrogen from laser fusion reactors	--	B

Table 6, Part 2. PROGRAMS SPONSORED BY INDUSTRY

Sponsor	Contractor	Investigation	Annual Funding, $1000	Category
American Iron and Steel Institute	Bethlehem Steel	Production of steel using hydrogen from nuclear energy	--	B
Allied Chemical	In-house	Hydride storage, basic research	--	B
A. G. A.	IGT	Thermochemical hydrogen production	250	A
Rocketdyne	In-house	Hydrogen embrittlement and pipeline materials research	--	—
Isotopes, Inc. (A subsidiary of Teledyne, Inc.)	In-house	Electrolyzer development	--	B
General Motors	In-house	Hydrogen production from gasoline on-board automobiles	3	B
Beech Aircraft	In-house	Liquid-hydrogen storage tanks for automobiles	3	B
Minnesota Valley Engineering	In-house	Liquid-hydrogen storage tanks for automobiles	--	B
Westinghouse	In-house	High-temperature electrolyzer development	--	C
Electric Utilities – Gas Utilities	Pratt & Whitney Aircraft	Fuel cell development – small program on hydrogen cells	--	B
Business Communications	In-house	Hydrogen-energy system assessment	--	C

Table 6, Part 3. PROGRAMS SPONSORED BY INDUSTRY

Sponsor	Contractor	Investigation	Annual Funding, $1000	Category
Boeing Aerospace Co.	In-house	Hydrogen fuel systems	--	B
Consolidated Edison Co. of N. Y.	Brookhaven Natl. Lab	Development of storage device for hydrogen as a hydride	--	B
Northeast Utilities	Futures Group	Feasibility of energy delivery system based on hydrogen	--	B
Southern Calif. Edison, Oak Ridge National Lab., and General Electric	General Electric (Tempo)	Eco-energy (Advanced Concepts in Energy Systems Using Hydrogen)	--	B
Northeast Utilities	In-house	Storage of hydrogen	--	B

Table 7. U.S. PROGRAMS WITH UNKNOWN SPONSORS

Contractor	Investigation	Annual Funding, $1000	Category
University of Miami	General hydrogen systems studies and literature review	--	C
University of Denver	Hydride research	--	C
Cornell University	Hydrogen embrittlement of steels	--	C
M. I. T.	Hydride-storage system study	--	C
University of Miami	Hydrogen-engine research	--	C
Univ. of Oklahoma	Hydrogen-engine research	--	C
Oklahoma State Univ.	Hydrogen-engine research	--	C
Univ. of Washington*	Hydrogen-energy system research	--	C
Avco Corporation	Thermochemical hydrogen	--	C
United Aircraft	Liquid hydrogen as an aircraft fuel	--	C
Southwest Research	Use of hydrogen as a military fuel	--	C
University of Calgary	Hydrogen-engine research	--	C

* Seattle Light and Power.

Table 8. OVERSEAS PROGRAMS

Sponsor	Contractor	Investigation	Annual Funding, $1000	Category
EURATOM	Joint Nuclear Research Center, Ispra, Italy	Thermochemical hydrogen production, materials research, and systems study	2000	A
--	Kernfurschungsanlage, W. Germany	Thermochemical hydrogen production from high-temperature nuclear reactor	--	B
--	Univ. of Aachen, W. Germany	Thermochemical hydrogen production	--	B
Gaz de France	In-house and at five universities	Thermochemical hydrogen production, transmission, storage research	--	B
Electricité de France	In-house	Electrolyzer development, fuel cells	--	B
Pechiney Ugine Kulmann, Paris	In-house	Thermochemical hydrogen production	--	B
Inst. for Applied Systems Analysis	(Austria)	Hydrogen-energy systems studies	--	B
--	Battelle, Geneva	Hydride-storage research	--	C
--	Philips, The Netherlands	Hydride research	--	C
Brazilian Govt	Fianaciadona de Estudo é Projetos	Hydrogen-energy systems study, transmission research	--	B
Japanese Govt	Misc Japanese agencies	Hydrogen-energy storage and transmission as part of the solar energy program	1000	B
British Steel Corp.	In-house	Use of nuclear hydrogen in steelmaking	--	--

Table 8, Cont. OVERSEAS PROGRAMS

Sponsor	Contractor	Investigation	Annual Funding, $1000	Category
Shell Research Ltd.	In-house (England)	Hydrogen-energy studies	--	C
Daimler-Benz	IGT	Study of problems in hydrogen-fueled vehicles	--	A
British Gas	--	Hydrogen-energy system assessment	--	C
British Electricity	--	Electrolytic hydrogen-storage study	--	C
German Ministry of Research	7 German companies	Comprehensive review of hydrogen as a future fuel	--	C
Atomic Energy of Canada, Ltd.	--	Study of thermochemical hydrogen production – use of hydrogen in industry	--	C
Steel Co. of Canada	In-house	Use of hydrogen in iron and steel production	--	C

Table 9. COMPLETED PROJECTS (Excluding A. G. A.)

Sponsor	Contractor	Objective	Date	Category
Office of Sci. and Technol.	Brookhaven Natl. Lab	Energy technology assessment	1971	A
Office of Sci. and Technol.	Oak Ridge Natl. Lab	Hydrogen and synthetic fuels – study panel	1972	A
Dept. of Defense	Army Engineers	"Energy Depot" – nuclear-based synthetic fuel study	1970	B
NASA	NASA-Johnson	Summer program – hydrogen energy	1973	A
NASA	NASA-Langley	Energy supplies for aircraft	1973	A
NASA	NASA-Langley	2-day workshop on hydrogen aircraft	1973	A
Northeast Utilities	Futures Group	Hydrogen-energy system study	1972	A
Southern Calif. Edison Co.	General Electric (Tempo)	Hydrogen systems for electric energy	1972	A
Hudson Institute	In-house	Hydrogen-energy system study	1972	A

INSTITUTE OF GAS TECHNOLOGY

HYDROGEN-ENERGY TECHNOLOGY – TODAY AND TOMORROW

by

Derek P. Gregory

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Hydrogen-Energy Technology – Today and Tomorrow

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Abstract

The concept of using hydrogen as a possible alternative to electric power to carry energy from central energy-production stations directly to the user has received an increasing amount of attention in the past 2 or 3 years and is now the subject of a considerable amount of study and research effort in various parts of the world. This paper presents a brief review of some of the ongoing research projects and discusses some technological and policy requirements that are needed before hydrogen can be considered as a significant and viable future alternative to the fossil fuels. The scope of this paper is confined to the potential role of hydrogen as a fuel gas and does not extend to the important role that hydrogen must play in the production of synthetic fuels from fossil energy resources.

Delivery of hydrogen as a fuel gas is the only way that the almost 30% of the nation's overall energy needs now being supplied by natural gas can be supplied from nuclear sources without the complete replacement of both the energy-distribution equipment and the consumer's plant. This 30% includes much of the domestic heating and cooling, industrial processing, and industrial steam-raising loads. For these "direct heat" applications, overall energy system efficiencies of about 16% could be achieved today with hydrogen, compared with about 27% with electricity. Nevertheless, most of the hydrogen-energy research under way – and more is still needed – is aimed at increasing this overall efficiency. Values of 32% to 42% appear to be reasonable objectives.

Research in hydrogen-energy technology appears to be technically justified, and preliminary results are encouraging. However, a considerable investment in research by both industry and government will be required to make hydrogen acceptable from the standpoints of economics, abundance, and safety.

Background

Perhaps I should begin by outlining the basic objectives and advantages of a hydrogen-energy delivery system. Repeating this once again, in the light of the wide coverage already given hydrogen energy by the technical and popular press, may be superfluous to many people, but I believe it is important to ensure that the basic importance of the concept is understood and that my later remarks are not misinterpreted.

When we look at the alarming decline in the availability of the conventional fossil fuels, particularly oil and gas, we can clearly see that a major shift must be made toward other energy sources – nuclear and solar being the most abundant and important. The use of conventional technology will stress the conversion of these energy forms into electricity for delivery to the customer. Because electricity is not readily storable, is expensive to transmit, and is not immediately useful in the vast majority of industrial and domestic energy-consuming equipment, the alternative course of converting these non-fossil energy sources to a chemical fuel that is more compatible with today's energy distribution and utilization equipment has merit. In some applications, electricity will serve our needs best; in others, hydrogen will be superior. A mixed hydrogen-electricity energy-delivery system may well become the best long-term compromise.

The attractiveness of using hydrogen as an energy-delivery medium depends upon the following assumptions:

- Hydrogen may be produced from water by the input of energy, using electrolysis or thermochemistry, or by chemical reactions energized by direct solar or nuclear radiation.
- Hydrogen may be transported as a fuel gas by long-distance pipelines in much the same way as we transport natural gas today.
- Hydrogen can be stored by the same techniques used for natural gas storage — either in underground rock formations or by liquefaction.
- Hydrogen may be delivered to existing gas customers in existing gas distribution pipes, and burned in existing gas-combustion equipment that has undergone only minor modifications.

If these assumptions are valid, then hydrogen made from tomorrow's nuclear or solar energy can, in principle, replace today's natural gas with only a minor disruption of the consumer's equipment. The use of hydrogen is the only way that the 30% of national energy needs now being supplied with natural gas can be provided with nuclear-based energy without the complete replacement of the already existing distribution and consuming equipment.

Research work already carried out has shown a) that electrochemical, thermochemical, and radiochemical processes for the production of hydrogen are all technically feasible, but require increasing technological advances in the order shown; b) that pipeline transmission and distribution of hydrogen is technically feasible at costs that are significantly below those of moving electricity; c) that the storability of hydrogen either underground or as a liquid is feasible; and d) that this feature could lead to considerable savings resulting from improvements in the load factors of the generation and transmission facilities. On the negative side, however, the overall efficiency of a hydrogen-energy delivery system, using conventional technology available today, will be somewhat less than that of an all-electric system. It is thus assumed to be economically unattractive. Although it may be possible to trade this loss in efficiency for the economic advantages of transmission and storage, much of today's hydrogen-energy research is directed toward improving the efficiency of hydrogen-energy systems and is mainly aimed at the hydrogen production stage.

Sparked by the promise of a hydrogen-energy analog of the natural gas system, some enthusiasts have broadened the scope of the concept to allow other attractive features of hydrogen energy to be exploited. Because hydrogen is the lightest of all fuels (51,500 Btu/lb compared with 18,500 Btu/lb for jet fuel), it is a superior aircraft fuel, and much has already been done to tackle the problems confronting its use in this application. Because it is almost nonpolluting, its use as an automobile fuel would eliminate many environmental problems, which has stimulated research into this application. In these applications where specialized advantages can be claimed, the objective of using hydrogen is not dependent upon producing it from non-fossil fuels. For this reason, the production of clean hydrogen from coal could be considered for use in these applications. Finally, the ready "interchangeability" of electricity and hydrogen, via the electrolyzer and the fuel cell, has stimulated research into the possible use of hydrogen storage as a peakshaving or load-levelling device for electric utilities.

Present Research Activities

Significant hydrogen-energy research began in the United States and in Italy 4 or 5 years ago, and has now expanded to include work in Canada, Brazil, Switzerland, Australia, Japan, West Germany, France, and England.

Even though early work concentrated on the concept of the overall "hydrogen economy," a concept in which hydrogen produced from nonfossil fuel is used as a universal fuel for almost every energy application, many of the efforts today are aimed at one or more of the rather smaller segments of the overall concept — the production and use of hydrogen as an energy form for some specialized applications.

Most of today's hydrogen-energy research is concerned with the production of hydrogen from water. The production of hydrogen by electrolysis, using electric power, is a way of using known technology and existing generating equipment. Electrolysis technology is available today; indeed, several large electrolyzer plants are in operation (although none in the United States), producing electricity from hydrogen at an efficiency of about 70%. Several quite small research programs are aimed at making improvements in electrolyzer efficiency, without significantly increasing capital costs. Most researchers in the field believe that electricity-to-hydrogen efficiencies in the 90% to 95% range can be achieved, so that overall heat-to-hydrogen efficiencies of 35% to 38% can be predicted, using advanced nuclear-electricity generation technology. To achieve these higher electrolyzer efficiencies, there is a need for the development and testing of new materials capable of withstanding higher temperature operation than at present, and there are benefits to be gained from the operation of electrolyzers at high pressure, which would allow hydrogen to be delivered directly to the pipelines. However, because the electrolyzer-manufacturing industry is a small one, it cannot afford to fund the research necessary to make dramatic improvements in its product. Such research must be supported by the potential users of the hydrogen that these improved electrolyzers would produce.

A second hydrogen-production method, and the one that is receiving the most research support today, is the thermochemical splitting of water, using a nuclear or solar heat source, without an electrical intermediate. Heat is used to drive a number of chemical steps in a cyclic sequence, all the components of the cycles, except water, hydrogen, and oxygen, being recycled. Although no commercial technology is available for this process today, several research groups are conducting experimental trials of chemical reactions, and an even greater number have carried out detailed thermodynamic analyses of the theoretical efficiencies of various cycles. Much of this work is held proprietary by the researchers. The Institute of Gas Technology (IGT) has identified some 70 theoretically possible cycles, several of which possess calculated heat-to-hydrogen efficiencies greater than 50%. In contrast, nuclear heat-to-electricity efficiencies are at present only about 35% and are only expected to rise to about 45% in the future.

One of the chief concerns about the commercial application of nuclear thermochemical hydrogen production is the need for a special type of nuclear reactor, probably the high-temperature gas-cooled reactor (HTGR) capable of delivering high-temperature heat to a chemical process rather than to an electricity generator. Such a reactor, needed to produce the high efficiencies discussed earlier, would require several years of speciaized nuclear engineering. Although such development is already going on, it appears to be the "poor relation" of the nuclear industry. We recognize that the lead times required to develop a substantial business to produce thermochemical hydrogen are very long — about 20 years or more.

A small amount of work is going on in the area of hydrogen transmission, mainly to calculate the cost of moving hydrogen in pipelines over long distances. IGT's studies have shown that, using natural gas pipeline technology, transmission costs over several hundred mile distance are about 3.5¢ to 5.5¢/million Btu-100 miles, in contrast to overhead electrical transmission costs of 40¢ to $1.05/million Btu-100 miles. Our studies have also shown that the energy needed to pump hydrogen through a pipeline is less than 1% of the total energy throughput per 100 miles, compared with an energy loss of about 10% in moving electricity over the same distance.

Investigation of the effect of hydrogen on the embrittlement of conventional pipeline steels has just begun in several laboratories; no research results have yet been published.

Conceptual, system, and techno-economic assessments of the prospects for moving energy from offshore wind- and solar-power stations using hydrogen pipelines or seagoing tankers have also recently commenced.

The storage of hydrogen as a chemical hydride is receiving significant research attention. Hydrides of magnesium, iron-titanium alloys, and the rare earths can all be formed spontaneously by reacting the finely divided metal with hydrogen gas; the hydrogen can then be recovered by heating the hydride. Because waste heat is released in the hydride-formation step, the storage process is not 100% efficient. In general, known hydrides are either too inefficient, too heavy, or too costly to be completely satisfactory for mobile storage applications (e.g., for hydrogen automobiles). Small programs of basic research on the understanding of alloy hydride chemistry are under way in the hope that improved formulations can be developed. Meanwhile, engineering studies on relatively large scale stationary storage systems using an iron-titanium alloy hydride are aimed at the electrical peakshaving application.

Hydrogen can also be stored by liquefaction or in underground rock formations or depleted gas and oil wells. Some studies to improve the efficiency of hydrogen-liquefaction processes have been begun, but no work appears to be in progress to demonstrate the feasibility of bulk underground hydrogen storage.

The utilization of hydrogen as an automobile fuel has received much well-publicized attention, but, in fact, remarkably little funding has been applied to this application. Some "over-the-road" demonstrations, carried out by student teams on "shoe-string budgets," have done little more than to show that it is relatively easy to convert conventional automobile engines to operate well and extremely cleanly on hydrogen. The major and unsolved problems are in the handling of the fuel itself, both in the vehicles and in the distribution and storage network needed to supply the refueling stations. At this time, surprisingly, very little reliable and systematic data are available on the actual test-bed performance, efficiency, and emissions of hydrogen engines; on the design of engines specifically engineered to take advantage of the properties of hydrogen; or on such fundamental information as the octane number of hydrogen, which appears to be well over 100.

The use of hydrogen as an aircraft fuel has been discussed a great deal. Design studies that have recently been completed for hydrogen-fueled wide-bodied passenger jet aircraft show very considerable potential improvements in efficiency, performance, and noise over the conventional jet-fueled version. Even though NACA (the predecessor of NASA) actually flew a hydrogen-fueled experimental jet aircraft in 1956 and an aircraft gas turbine specially designed to operate on hydrogen was developed and tested in industry at about the same time, since then no actual tests of a hydrogen-fueled airplane have been conducted, nor are there any plans to do so known at this time.

I believe that the regulators, valves, meters, and pipework now used in conventional gas systems will be compatible with hydrogen, but, apparently, no significant testing or demonstration of this aspect of hydrogen's application has been carried out yet. Similarly, the use of hydrogen in conventional natural-gas-fired burners appears to require only minor burner modifications, but, to date, detailed design and testing of modified burners has not been a significant feature of any hydrogen-energy research program.

Although no major conversion problems are envisaged, I am surprised that this particular end-use aspect of hydrogen energy has received so little attention, in contrast to the use of hydrogen in automobiles and aircraft. Fifty-two percent of the total U.S. energy consumption is used for combined space heating, industrial process heating, and industrial process steam applications. About half of this amount if now being supplied by natural gas. The natural-gas-fueled equipment used in these applications could seemingly be converted to hydrogen far more easily and far more cheaply than to electricity. Not many people realize that the amount of energy used in the United States to produce industrial process steam alone is 17% of the total energy budget, about the same as that used to drive all the automobiles in the country.

It seems to me that the conversion of this sector of the energy market to nonfossil fuels, via hydrogen, should receive as much emphasis as the efforts now being made to develop hydrogen-fueled or battery-operated automobiles.

Some significant work is under way on the development of catalytic burners for use with hydrogen. Since hydrogen "oxidizes" (rather than "burns") at low temperatures without a flame on a catalyst bed, this technique has merit for many domestic and industrial heat applications. A nonflame catalytic hydrogen burner can be made to produce no nitrogen oxides, and because its only combustion product is water, can be operated without a vent or flue. At IGT, hydrogen-fueled water heaters with efficiencies of about 85% have been demonstrated, and without a flue, 100% of the heating value of hydrogen can be used in a space heating plant. The importance of these developments is apparent when we consider the efficiencies of hydrogen versus electricity systems.

Overall System Efficiency

Recently, an efficiency comparison of a hydrogen system and an all-electric system was published (Ref. 1) in which the automobile was chosen as the end-user of the energy. The relative overall efficiencies, starting with nuclear heat and ending with useful work at the wheels, were hydrogen, 3% and electricity, 19%. These figures were derived by assuming the efficiencies for the various parts of the system, as shown in Table 1.

Table 1. COMPARISON OF ELECTRIC AND HYDROGEN ENERGY SYSTEMS, ACCORDING TO SIMPSON (Ref. 1)

Hydrogen System	%	Electric System	%
Thermo-electrochemical Plant	65	Nuclear Electric Plant	35
Hydrogen Pipeline	90	Electric Transmission	90
Hydrogen Liquefier	50	Battery Automobile	60
Hydrogen Automobile	10		
Overall	3	Overall	19

Even though I would argue about the relative transmission efficiencies of hydrogen versus electricity (especially over very long distances) and with the efficiency assigned here to the hydrogen automobile (which corresponds to that of a gasoline car with its pollution control equipment), I am forced to agree that the hydrogen automobile will use more nuclear fuel than its electric counterpart. To do a complete comparison, the relative costs of an electric vehicle and its energy-delivery system must also be compared with those of the hydrogen version: neither set of costs are known as yet.

Let us look, however, at the "direct heat" applications of energy, the applications, which include domestic space heating, industrial process heating, and industrial steam-raising, are accounting for 52% of U.S. energy demands, and are much more attractive applications than the automobile for pipeline hydrogen. Following the technique applied in the automobile example, we can draw the comparisons shown in Table 2.

Table 2. COMPARISON OF VARIOUS HYDROGEN- AND ELECTRIC-ENERGY SYSTEMS FOR THE "DIRECT HEAT" APPLICATIONS

Case 1. Electrolytic Production, Existing Combustion Equipment, Today's Technology

	%
Nuclear-Electric Plant	30
High-Pressure Electrolyzer	75
Hydrogen Pipeline (100 miles)	99
Hydrogen Heating	70
Overall	16

Case 2. Thermochemical Production, Catalytic Combustion Equipment, Future Technology

	%
Nuclear-Thermochemical Plant	50
Hydrogen Pipeline (100 miles)	99
Hydrogen Heating	85
Overall	42

Case 3. Electrolytic Production, Catalytic Combustion Equipment, Future Technology

	%
Nuclear Electric Plant	40
High-Pressure Electrolyzer	95
Hydrogen Pipeline (100 miles)	99
Hydrogen Heating	85
Overall	32

Case 4. All-Electric System, High-Temperature Nuclear Reactor

	Present Technology	Future Technology
	%	
Nuclear Electric Plant	30	40
Electric Transmission (100 miles)	90	90
Electric Heating	100	100
Overall	27	36

In Case 1, we consider present technology, using electrolyzers and conventional gas-burning equipment, involving no major replacement of user's equipment. In Case 2, we consider what might be achieved with a successful thermochemical production development and the replacement of consumer's burners with efficient catalytic burners. In Case 3, we assume a significant, but not unreasonable, improvement in electrolyzer efficiency, coupled with the use of catalytic burners. In Case 4, the all-electric case, complete replacement of the delivery system and the utilization equipment is assumed. Efficiencies for the hydrogen-system components have been assigned according to values calculated or measured in IGT studies. Two different electricity-generation efficiencies are shown: one corresponding to what is achieved in today's "conventional" nuclear plants and one corresponding to future technology reactors operating at higher temperatures. A full treatment of energy efficiencies cannot be presented at this time; these figures are to be used only as guidelines. However, Table 2 does make it apparent that hydrogen-energy efficiencies do not fundamentally have to be lower than electricity efficiencies, but that improvements to both production and utilization parts of the system will have to be made.

Actions Required for Hydrogen-Energy Development

I would like to close my remarks with a list of policy actions that I believe are required by industry and by government to accelerate a proper evaluation of the hydrogen-energy option, and to develop technology in those areas needed to bring about major use of hydrogen as an "energy vector."

What actions are needed by the utility industry today?

1. Companies that deal with natural gas need to take positive action to demonstrate to their investors that they have prospects for participating in a "perpetual" energy industry that is not subject to another resource depletion.

2. Suppliers of natural gas must convince their customers that a supply of a gaseous fuel is reasonably ensured for at least as long as the expected life of any new gas-using plant that they are about to install.

3. The utility industry must demonstrate to government policy-makers that a nuclear-hydrogen energy delivery system is indeed a viable alternative to an all-electric economy, that the industry will be ready to operate such a system as soon as it becomes economically justified, and that, in doing so, it will not be thrusting upon the public a new, untried or unwelcome form of fuel.

4. The all-gas utilities must soon decide whether they will own their own nuclear plants or rely on the purchase of the product. They must also decide whether this product will be electricity, heat, or hydrogen. Some form of cooperation with the electricity-generating utilities seems inevitable because these utilities have a 15 to 20 year lead in the experience of constructing, owning, and operating such plants.

5. The utility industry must soon persuade the nuclear industry to prepare to increase the growth rate of nuclear capacity to be able to meet the energy needs of many new and existing gas customers, as well as electricity customers, by the end of this century. To specify the number and types of nuclear plants necessary for hydrogen generation in the year 2010 will require that a considerable research effort into hydrogen production technology be undertaken immediately.

The utility industry cannot hope to make these impacts based on the meager level of study and research currently being conducted. If the industry is to hope to demonstrate that hydrogen can be economically competitive with electricity, more research is needed to improve the efficiency and economy of both electrolytic and thermochemical hydrogen production. If it is to convince the public, its customers, and the regulatory bodies that hydrogen is indeed a safe and viable all-purpose fuel, the utility industry must extend research to the transmission and, especially, the distribution, utilization, and safety areas.

What Government actions are needed? I believe that Federal Government research and planning efforts in the area of hydrogen energy should be better coordinated than they are at present. The following actions are required:

1. The hydrogen-energy option should be examined as thoroughly as corresponding work — for example, on electricity transmission, battery storage, and electricity utilization. An appropriate responsibility for the development of alternative energy-delivery systems (not just storage systems) should be specifically assigned within the Energy Research and Development Administration (ERDA).
2. The hydrogen programs that were initiated by the Atomic Energy Commission and NASA before the formation of ERDA should be continued without the temporary interruptions that now appear likely. These programs currently include electrochemical and thermochemical hydrogen production, hydrogen storage, and the utilization of hydrogen in fuel cells, automobiles, and aircraft, and should be broadened to include the residential and industrial use of hydrogen for "direct-heat" applications.
3. Cooperative programs between the utility industry and Government agencies must be developed in hydrogen-energy areas to ensure that the long-range decisions of each are compatible with those of the other.
4. ERDA should collaborate with the nuclear industry and the gas industry to formulate a growth plan that will accommodate future gas and electric energy demands. It is important to recognize the long lead time (approaching 20 years) involved in implementing a substantial nuclear-hydrogen production industry.
5. ERDA should support a program of research and development on the special nuclear reactor engineering for high-temperature reactors of the type required for thermochemical hydrogen production. Neither the Conventional Pressurized-Water Reactors nor the Liquid-Metal Fast Breeder can provide high enough temperatures for this process.

Conclusion

After 3 or 4 years of preliminary research into the hydrogen-energy concept, I believe that we can make a strong case for its serious consideration as a long-term contributor to the U.S. energy system — at least a strong enough case to justify as significant research and demonstration effort as is now being applied to other concepts such as superconducting transmission, battery storage, and some advanced solar energy systems. I also believe that the outstanding problems have been well-enough defined to allow a properly balanced research program to be formulated. What is not clear, at present, is what the relative roles of Government and industry should be and where such a program should be located within the Government's research organizations.

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He graduated from the University of Southampton, England, and carried out research for his Ph. D. in electrochemistry at Southampton. After some nuclear materials work at the Atomic Weapons Research Establishment, Aldermaston, he joined Shell Research Ltd., to work on basic fuel cell research at their Thornton Research Center, Chester. Later, he moved to the U. S. and joined Pratt & Whitney Aircraft, where he was responsible for applied research on fuel cell projects, and became closely involved with the engineering aspects of fuel cell systems. In 1966, he returned to England to join Energy Conversion, Ltd., as Research Manager, responsible for research on fuel cells and high energy batteries. He returned to the U. S. to IGT in 1970.

Dr. Gregory is the author of several technical papers and two textbooks on fuel cells, batteries, and automobile fuels.

Dr. GREGORY. I would like at this time to make some somewhat less formal comments in summary.

We have had a program on hydrogen-energy at IGT under my direction for about 5 years. We have depended on support for this program from the American Gas Association and the Electric Power Research Institute, NASA, the NSF and from some industrial companies, Mr. Chairman.

At present, we have no ERDA projects, as such, on hydrogen energy.

Now, I would like to tackle a number of questions that are raised about hydrogen, such as why we need hydrogen as a synthetic fuel.

I think that your committee has already heard a number of advantages claimed for a fluid chemical fuel: A gaseous or liquid fuel. We think it is obviously important to keep an existing system intact so as to be able to use the fuels that would be available when we go into future raw energy supplies of nuclear and fossil fuels. Hydrogen does supply a possible means to link up the conventional users of gas-using equipment with the future raw energy supplies.

The advantages of hydrogen, such as the storage and long distance transmission capabilities have been much talked about. I think its major usefulness is in being able to use hydrogen as gaseous fuel in existing oil- and gas-burning equipment with only relatively minor modifications.

Why not go to electricity as the link between nuclear and solar energy and conventional use? We certainly should do that, too, although electricity has its problems. It is not so easy to store. Transmission tends to be expensive compared to moving conventional fuels.

Therefore, the cost of delivered electricity is rather expensive. We feel that a mixed energy delivery system that uses hydrogen and electricity is an ideal optimum to strive for in the future.

As to coal conversion, where does the gasification of coal to synthetic natural gas fit in? The conversion of coal to fluid fuels will play an important role in the future. As a long-term investment, we also have to look beyond the time when coal availability begins to decline.

Hydrogen is a synthetic gaseous fuel that can be made from coal. It can be integrated with nuclear and solar energy. In the longer time scale, hydrogen appears to be more attractive. In the shorter time scale, if you have the coal, you should convert it to an existing conventional fuel such as methane or oil. Hydrogen will play a very important role in the chemistry of the conversion of coal and shale to synthetic fuels. That is outside the scope of what we are talking about here today. My remarks are confined to the use of hydrogen, specifically as a fuel, not as a feedstock into the synthetic fuel production.

Now, why do we select hydrogen? Where do we stand today in the technology? Hydrogen production is somewhat unique. We can make hydrogen from a whole variety of raw energy sources. It can be made from coal, nuclear energy, solar energy, from all forms of this, such as windpower, hydropower and agricultural crops; also waste materials. Thus, like electricity, it is a universal secondary energy form that can be produced from a wide range of raw energy courses.

There are three primary methods of making hydrogen from nonfossil fuels. The first is electrolysis of water, which is used in industry today. Compared to other ways of making hydrogen in progess today, electrolysis is considerably more expensive.

When we looked into the reasons for this, we found that this is really because the cost of the process is tied closely to the price of electricity and the efficiency of the overall process is closely tied to the efficiency of electricity generation. We believe today, with electric or electricity generation, say, at about 30 percent efficiency, and that the electrolyzer, at about 70 percent. We have an overall conversion of heat to hydrogen of 20 percent. That is not very promising.

Therefore, we believe, by improving technology now in both in electricity generation and in the electrolyzer itself, that we can get this to 50 percent overall efficiency. The cost of the hydrogen using 10 mill power would be in the order of $5 to $8 per million Btu's. This represents a fairly expensive fuel price.

Mr. McCormack. Virtually all of the cost is the cost of electricity?

Dr. Gregory. About two-thirds. About two-thirds of this is electricity and one-third is the amortization of the plant.

The second process is thermochemical hydrogen production. We have quite a lot of experience with this. This is a cyclic chemical system in which heat is used to drive a number of chemical reactions. All the components of these reactions except for water going in and hydrogen and oxygen coming out are recycled. We need a lot more chemical engineering work in this technology. But not only do we need a lot of development in chemical engineering; this kind of process also needs a high temperature source of heat, 1,800 to 2,000 degrees Fahrenheit.

As far as nuclear sources are concerned, we have to have parallel development to push the temperature of the existing high temperature nuclear reactors up by about 200 degrees beyond where they are. The cart is in front of the donkey here.

The efficiency from heat to hydrogen by a thermochemical process promises to be in the 40 percent to 50 percent region. We thus have the opportunity to be able to beat the electrolysis method on an overall efficiency basis. The cost of thermal chemical production is not yet known.

The third process is the use of direct radiation to decompose water. There are speculative research projects going on, using neutron radiation directly from a fusion type of reaction or radiation of sunlight in some photochemical process. I think you must remember that these processes are possible options to make hydrogen, although they are very much in the speculative stage.

As to the transmission of hydrogen, you can move hydrogen in conventional natural gas transmission pipes. The technology that we have suggests that the natural gas system is probably OK for hydrogen, although not yet put to the test. There is, however a question of embrittlement. We believe, with present pipelines and materials, that as long as you keep pressures down to that used in pipelines today, then we will be OK.

The cost of hydrogen transmission is of the order of 3 to 5 times lower than those of overhead electric transmission and it may be as much as 50 to 100 times lower than underground electric transmission. This provides the incentive to look at hydrogen as a long distance transmission option.

The local distribution equipment used today for natural gas should be compatible with hydrogen. It has not been put to the test, however, Mr. Chairman.

As to the storage of hydrogen, we hear a lot said that hydrogen is easy to store. It really is not "easy." It is certainly easier to store than electricity, but it is harder to store than oil. We should not kid ourselves that hydrogen is an easy material to store. It is easy to store it as a high pressure gas, but the costs are prohibitive. Hydrogen can be stored in bulk rather less expensively by condensing it to a liquid. We have the technology to do this but the efficiency of liquefaction is 70 percent to 80 percent. If we put the hydrogen into a chemical storage form—for instance a metal hydride—the efficiency is between 70 percent and 90 percent. The underground storage of hydrogen looks as though it is a cheap and efficient way of storing large quantities of energy. We do this with natural gas. It is only appropriate on a scale applicable to large scale bulk storage of hydrogen.

It is untried, but there appears to be no reason why it shouldn't work. Considering solar energy systems where the need for bulk energy storage, which is vital, hydrogen storage appears at this time to be very attractive.

In the use of hydrogen, we can burn hydrogen in conventional gas burning equipment if we modify the burner slightly. If you put hydrogen into an existing burner, it will flash back because of the high flame speed.

We know how to convert burners, although the conversions themselves, to some extent, are untested. We believe that one can mix hydrogen into natural gas up to 8 percent to 10 percent by volume before you get any flashbacks. This represents something that is somewhat untested, but very important.

The modification of industrial equipment is going to be easier than that of domestic equipment. It is run under more controlled conditions and there are fewer burners to convert. I think at this time that one has to look at the comparison of the conversion of industrial gas and oil burning furnaces to allow them to run on hydrogen, and to compare this with the problems of converting the equipment to run on electricity, the other long term option: Conversion to hydrogen seems simpler and cheaper.

I would like to mention the prospects for catalytic burners. Hydrogen will oxidize at low temperatures on a catalyst. One can devise catalytic burners which burn hydrogen without flames very cleanly with no pollution, also very efficiently. These are still very much in the laboratory stage but they do look very promising at this time.

Hydrogen is used today as a feedstock in the chemical industry. It is used to make ammonia, which producers fertilizer; it is used to make methanol and it is also used in the refinery business; in the future hydrogen will be used in steelmaking. It will be used for synthetic gaseous and liquid fuel production. These needs are relatively small compared to the needs that we see at this time to meet the unfilled demands for liquid fuels and gaseous fuels. By the year 2000 we will need 5 or 6 times as much hydrogen to fill the deficit in natural gas than we will need to provide all of the industrial hydrogen we forsee being used for the chemical feedstock uses.

The use of hydrogen in engines is important. Automobile type engines will run cleanly and efficiently on hydrogen with minor modification to the carburetor. The problem is more with the fuel tank and fuel distribution system: (how to get hydrogen to the gas station) than how to actually run the engine.

I would like to make a special case for hydrogen as an aircraft fuel, say, for domestic cargo and passenger carrying. There, you have a different situation than with fighting aircraft referred to by the previous witness. The light weight of hydrogen offers a tremendous advantage in range and in takeoff weight. Hydrogen is the lightest chemical fuel we know of. There is only one-third of the weight involved compared to jet fuel on an energy basis. However, it is three times as bulky. You need three times as big a fuel tank, but it weighs only one-third as much.

Hydrogen, Mr. Chairman, is an extremely good fuel for fuel cells. The fuel cell development that is now going on depends, to some extent, on converting the fuel feed to a hydrogen mixture before entering the fuel cell proper.

Now; is the hydrogen energy option open to us now? I think that the answer to this question is "No," compared to electricity. We now know enough about the electricity system and of its economics to say that we can use it. As to hydrogen, we don't know enough about it in order to make up our minds. The major problems with hydrogen are: That it costs too much; the overall energy efficiencies are not high enough; there is some question about the compatibility of hydrogen with the existing delivery systems; and about the matter of safety.

Mr. Chairman, I think that all of these questions can be answered and solved by improved research and development.

I would like to endorse the thought that we have to get the cost of production down. What should be done? We should have an overall increase in research. But if we look at what is going on nationally, research at this time seems to be top heavy in the hydrogen production area. There seems to be a good reason to be doing research on the transmission and the utilization of hydrogen. It is all very well to learn to produce it cheaply, but we also have to learn how to use it.

Therefore, I would like to see a setup on research in the production of hydrogen, but I also would like to see more emphasis placed on use of hydrogen in stationary burners. Fifty-two percent of American energy consumption. That is about the same number of Btu's needed to steam generation. Half of that is supplied by natural gas. These applications represent somewhat simpler modifications to turn these over to hydrogen, than to convert applications like automobiles and airplanes. The process steam used in industry alone accounts for 17 percent of our energy consumption. That is about the same number of Btu's needed ot drive all the automobiles in the country. Hydrogen from nuclear or solar power could be considered as a way to get this large sector of industrial energy utilization over the nonfossil fuels in a relatively simple way. I see no work going on in this direction at all.

Now, in the storage area, hydrogen is being considered in the electricity use, that is to say stored as hydrogen, and reconverted to electricity on the way out. I would like to see more emphasis on using the stored hydrogen as a supplementary fuel rather than converting this back to electricity where you suffer another efficiency loss.

In the demonstration of the transmission and distribution of hydrogen, I would like to see more demonstration trials and experimental work to find out if we really can handle hydrogen in the existing natural gas systems. We need to gain operating experience, safety information and confidence.

If we look at the Government program on hydrogen at present, we need leadership; we need funding; we need coordination at this time. We know what to do. We can put a sensible, sound hydrogen program together. We took stock last December of what was going on in Government-funded hydrogen research. There were seven agencies involved, including the AEC, NASA, Environmental Protection Agency, NSF, DOD, Department of Transportation, and the Department of Commerce. They all have hydrogen programs. There are hydrogen energy programs in six national laboratories and in five NASA field centers.

At the time, this work seemed to be rather uncoordinated. I believe that a certain amount of duplication is occurring. Much the same situation exists now, but there are certain efforts within ERDA to coordinate and plan the work. Where, in ERDA, does hydrogen fit? I find it, personally, difficult to see whether there is a real home for hydrogen energy research in ERDA. Perhaps it ought to fit with geothermal and advanced energy concepts. It is not a raw material or an energy source. It does not fit into the slot very logically.

Electricity transmission and energy storage are in the domain of the conservation division. This is where, perhaps, hydrogen should fit to parallel electricity transmission work. I am concerned at this time that hydrogen technology might fall between the rungs of the ladder, because different divisions think it is the other guy's responsibility.

I think that it is somewhat alarming that there has been no statement to say that hydrogen fits into this particular area.

Finally, Mr. Chairman, I want to say that I feel that we have studied hydrogen, almost studied it to death over the last few years. Many repetitive studies are going on. There is the danger of losing the momentum gained in the Federal agencies and by the outside contractors by going into a holding pattern. I fear that some of the agencies that are sponsoring the work we are going back into the planning and review stage. We could lose a lot of momentum and time. I feel that this is a very urgent problem.

Thank you, gentlemen. I will be glad to answer any questions later.

Mr. McCORMACK. Thank you, Dr. Gregory. That was an excellent statement.

Our next witness this morning is Mr. Sidney H. Law, Director of Research, Northeast Utilities. He is accompanied by Mr. Michael Lotker, a scientist involved in advanced energy conversion research at Northeast Utilities.

We will insert your entire statement into the record at this point. It is done without objection. You may speak as you wish or give a summary.

STATEMENT OF SIDNEY H. LAW, DIRECTOR OF RESEARCH, NORTHEAST UTILITIES; ACCOMPANIED BY MICHAEL LOTKER, SCIENTIST, NORTHEAST UTILITIES

Mr. LAW. I would like to insert my prepared statement into the record and make my presentation much shorter, since my friend, Dr. Gregory, covered many of the areas that I was going to cover.

Mr. McCormack. Very well. Your statement will be inserted into the record. Mr. Lotker's may also be inserted.

[The complete prepared statements of Sidney H. Law and Michael Lotker are as follows:]

TESTIMONY OF

SIDNEY H. LAW, DIRECTOR - RESEARCH

AND

MICHAEL LOTKER, SCIENTIST, ADVANCED ENERGY CONVERSION RESEARCH

NORTHEAST UTILITIES

Before

The Energy Research, Development, and Demonstration Subcommittee
of the Committee on Science and Technology
United States House of Representatives

June 12, 1975

SUMMARY:

Northeast Utilities is one of a number of utilities that have been extremely interested in the potential for hydrogen energy systems over the past few years. We have supported several analytical studies in the past and are currently sponsoring work on thermochemical generation of hydrogen at General Atomics Company in San Diego. Ultimately we feel that there will be only four essentially non-depletable energy sources; fission, fusion, solar, and geothermal, and two energy transportation media; electricity and hydrogen. By as early as the 1980s, hydrogen generated from nuclear sources could have a wide impact on technologies ranging from fertilizer production to coal gasification. If generation efficiency can be improved sufficiently, it could later find wide use as a premium utility fuel for energy storage and peaking. This is, therefore, an important subject for our utility industry; we may be producers and marketers of hydrogen, taking full advantage of our financial and technical experience in management of large energy conversion facilities, as well as consumers of hydrogen as a fuel.

INTRODUCTION:

My name is Sidney H. Law, and I have been Director of Research of Northeast Utilities in Hartford, Connecticut, for the past eight years. My associate, Michael Lotker, has been on my staff for the past three years and is concerned with advanced energy conversion research, including studies in the hydrogen energy systems area. He has authored several technical papers on hydrogen energy systems, and we both serve on various Electric Power Research Institute (EPRI), Institute of Electrical and Electronics Engineers (IEEE), and Energy Research and Development Administration (ERDA) advisory committees. More complete biographies are included as Appendices A and B.

We are happy to appear before you today to discuss hydrogen energy systems from a utility perspective. I will limit my remarks to the utility view since I am certain that other experts will have adequately discussed the technical details and broader implications of the so-called Hydrogen Economy. Since electricity is importantly involved in this view of our energy future, I prefer to call it the Hydrogen-Electric Economy and will refer to it this way in my testimony.

I would also like to point out that while we have endeavored to examine the Hydrogen-Electric Economy from a utility point of view, the views reflected in this testimony are those of Northeast Utilities only. There is still no real consensus within our industry on the future or importance of such systems, although EPRI is currently evaluating them.

NORTHEAST UTILITIES' INTEREST IN HYDROGEN:

Northeast Utilities became interested in hydrogen energy systems through its participation in fuel cell research. Hydrogen is, of course, the ultimate fuel for fuel cells and can be easily piped to such power plants, located in individual neighborhoods, thereby reducing dependence on transmission and increasing efficiency with minimum impact on the environment. In 1972 we funded a study which assessed the Hydrogen-Electric Economy scenario in its entirety and concluded that there was indeed long-range promise in this concept. This study was followed up by a more narrowly defined consideration of the early application of hydrogen in connection with our proposed fuel cell work. Our continuing interest led us to formulate a program with General Atomic Company to identify and develop thermochemical cycles for generating hydrogen. The goal of the program, which has received nearly 400,000 dollars from our company to date, is to develop a technique for hydrogen production directly from nuclear heat at a greater efficiency and consequently at a lower cost than is possible with electrolysis.

Our interest in hydrogen is, we feel, a logical extension of our responsibilities in connection with electricity supply. Hydrogen, like electricity, is a synthetic energy medium or energy carrier. Both require attention to the technology of generation, transmission, distribution, and consumption by the ultimate user.

ELECTRIC UTILITY INTEREST IN HYDROGEN--WHEN?

I would now like to discuss how electric utility interest in hydrogen may develop in the future. I've divided the future into three time frames: short range (1975-1985), intermediate range (1985-2000), and long range (beyond the year 2000).

Short Range (1975-1985):

The only general use for hydrogen today in the electric utility is as a coolant for the windings in large electrical generators. Hydrogen will probably not be important as either an energy storage medium or as a fuel for electric utilities during the next ten years (fuel cells, supplied by fossil fuels, could have an impact in this time frame however). Hydrogen may, of course, be in great demand in other sectors of the energy and chemical industry as those preceding me have detailed. Given a large demand at a premium price by such users, electrolytic generation of hydrogen in selected cases may well find a substantial market. This is especially true where advantage may be taken of relatively inexpensive sources of electricity, such as hydroelectric and, in special cases, off-peak nuclear generation. This would, of course, represent an electrical load for our industry which might eventually grow into a meaningful business activity.

Intermediate Range (1985-2000):

In the intermediate range, production capacity will expand to meet growing chemical markets, and limited quantities of hydrogen may become available to utilities with particular environmental constraints as a premium peaking fuel. Then, if cheaper techniques are identified, hydrogen production as a fuel for intermediate loaded devices, such as fuel cells, may be viable. It is not likely that electrolysis will be the source of a significant amount of electric utility fuel since it would probably be more economical to use the original electricity rather than suffer the multiple inefficiencies of conversion to hydrogen and then back to electricity.

Of course, as the utility industry gets further involved in hydrogen production, it will assume additional markets in connection with chemical uses. A very significant such application would be in connection with coal gasification plants where use of an external source of hydrogen, such as from a nuclear plant using water as the hydrogen source, can result in significant savings of coal for the same yield of synthetic pipeline gas. Thus, utilities have the opportunity for participation in a new business area, the production of hydrogen for external sales in addition to internal fuel uses, before the end of this century.

Long Range (Beyond 2000):

In the longer range there are few ultimate energy sources; fission, fusion, solar, and (depending on resource extent) geothermal. Moreover, there appear to be only two long-term energy carriers; electricity and hydrogen. We are already beginning to realize that our irreplaceable hydrocarbon assets have value as chemical resources that far exceed their worth as simple fuels.

Hydrogen and electricity in the long term can serve complementary roles in fulfilling energy markets. As energy carriers, each has specific applications for which it is the best and most cost-effective choice. Between them, most if not all future end users of energy can be satisfied.

The challenge is for the electric utilities to recognize their future as Energy Utilities, potential suppliers of both electricity and hydrogen. We would like to submit for the record a paper in which the long-range possibilities of hydrogen for the electric utilities are discussed at greater length. It appears as Appendix C.

ELECTRIC UTILITY INTEREST IN HYDROGEN--WHY?

Today's electric utility is concerned with securing primary energy resources, converting them into a conveniently transported and utilized synthetic energy form (electricity), distributing the energy to the customer in a configuration optimized to his needs, and ultimately monitoring consumption and billing the energy user. If another synthetic energy form (hydrogen), also derivable from primary energy sources, easily transported and consumed and easily converted to and from electricity, were identified, it would be a logical extension of the utility industry's present activities to include the production, distribution, and sale of this second product alongside these identical roles with respect to electricity. Hydrogen may well become the product transmitted from certain energy generation concepts such as solar, wind, or ocean thermal gradient schemes, or applications of conventional forms of generation such as remote nuclear parks.

The nuclear and solar power sources that are expected to provide primary energy for the Hydrogen-Electric Economy are all characterized by small or absent fuel costs and high capital costs. This economic fact of life will define the fiscal structure of any company that hopes to earn a return on investment by selling hydrogen. Today the electric utility industry is by far the most heavily capitalized industry. Gas, oil, and coal companies are basically distributors of bulk materials. Their product is, in many cases, delivered in essentially the same form as when it left the original source. Electric utilities, as noted above, sell synthetic energy. They have considerable operating experience in treating the raw energy of flowing water, coal, oil, gas, and the atom and optimizing conversion and delivery processes with the consumer, stockholder, and government regulator in mind.

Given an appropriate regulatory climate, the growth of electric utilities into energy utilities, which would supply both hydrogen and electricity, may be an attractive possibility. A possible combination might be to utilize the strength of the electric utilities in ownership of large-scale energy conversion devices with the gas utilities' expertise in transmission and distribution of gaseous energy. With both hydrogen and electricity in the delivery system, energy storage should come much more naturally than it does in an all-electric system. Moreover, transformation from electricity to hydrogen and back again using fuel cells and electrolytic devices can be easily accomplished where warranted in order to meet peak demands for either energy form.

Thinking of the long-range future, and assuming economic methods of production are developed, it is instructive to examine some of the more apparent effects upon energy system reliability and economics when hydrogen and/or electricity locally produced from hydrogen is delivered to the customer. Since the energy delivery system is underground, most outages associated with weather problems would not exist. Current low utilization factors on electrical generation and transmission equipment could be increased substantially, reducing overall costs. Energy storage comes automatically with hydrogen pipelines by varying pressure in the pipelines. Even a small amount of such storage combined with fuel cell power plants should significantly reduce the cost of maintaining the level of instantaneous reliability that our customers presently enjoy. These and other technical issues are discussed more completely in the attached Appendix C.

IMPORTANT RESEARCH AREAS:

I will now address the research areas that we feel will be important from a utility perspective.

Generation:

Obviously, research on hydrogen production techniques, using nonfossil energy sources, should command a top priority. The development of advanced electrolyzers, having increased efficiency relative to existing units, would have a significant impact on the near- and intermediate-term production of hydrogen for premium uses. The thermochemical technique for generation of hydrogen offers the potential for still higher efficiencies and further cost reductions. This promise merits increased activity in the area of thermochemical cycle discovery and chemical engineering analysis in order to better predict production efficiencies and costs. Hydrogen produced from coal may be an important option during the transition from the fossil to renewable energy economies, and deserves further examination. Other techniques for hydrogen generation such as photolysis, direct thermal dissociation, and production using biological means, are principally of longer term interest.

Transmission:

Although some experience exists in the handling and transmission of hydrogen, a considerable amount of work will be required to make this technology generally applicable to large hydrogen transmission networks and use by the general public. Other key questions include determining the extent to which existing natural gas pipelines need to be upgraded in order to handle hydrogen, and what, if any, special precautions will be required to insure employee and public safety.

Storage:

While it has not been established that hydrogen storage holds advantages over other proposed and existing techniques for near-term storage of energy on an electric utility system, storage concepts such as liquid hydrogen, metal hydrides, and so forth, will play an essential role in almost all activities contemplated within the hydrogen systems concept. Advances in electrolyzer, fuel cell, and hydrogen storage areas could, of course, make these technologies useful to electric utility grids as load leveling devices.

Utilization:

In the utilization area, the major questions are those associated with safety and with the technical problems in conversion from natural gas to hydrogen uses in the home and in industry. Development of hydrogen-oxygen and hydrogen-air fuel cells, catalytic burners, and other devices will, of course, be significant.

Legal, Environmental, and Economic Issues:

The resolution of the many legal issues associated with the massive change in energy systems from today's natural gas and petroleum dominated economy to tomorrow's combined hydrogen and electric economy will determine the ease with which this change can be made. While hydrogen is generally thought to be environmentally benign, environmental issues associated with all phases of hydrogen energy systems need careful and continuous evaluation. In the economic area, the key question will be whether hydrogen will compete via the actions of the marketplace in increasing the price of alternatives, or by direct governmental incentives for conservation of fossil supplies. The danger is that the market price of fossil fuels will be low enough over the next few decades to preclude substitution by synthetic fuels. This would result in rapid resource depletion and a delayed, but more difficult, transition to nondepletable energy sources.

CONCLUSIONS:

Our fossil resources are, of course, finite; renewable sources of energy must eventually be brought to bear to feed an economy and society that is becoming increasingly energy intensive. To meet all our needs, synthetic energy forms in addition to electricity will certainly be needed. Hydrogen and hydrogen-rich fuels, such as methanol or ammonia, have chemical and physical properties that make them excellent candidates for such application. The arguments raised in opposition to the development of hydrogen energy systems are those of efficiency and cost. Efficiency will, of course, become less of a factor with utilization of the virtually infinite nuclear and solar energy resources. The cost argument will fall with the rising costs of alternative energy sources and with the realization that our fossil resources are far too limited and too valuable to burn.

At Northeast Utilities we have a substantial commitment to further investigate hydrogen energy systems for our long-range future. It is our belief that hydrogen production facilities may become important consumers of electricity within a time scale not much longer than that of present utility planning and in the long run hydrogen, as an energy carrier, may well be as important to our industry as electricity.

We shall be happy to answer any questions.

Appendix A

BIOGRAPHY

SIDNEY H. LAW

DIRECTOR - RESEARCH

A graduate of Cornell University, Mr. Law received his bachelor of electrical engineering degree in 1948. He has also attended the U. S. Air Force Meteorology School at MIT and has completed the Public Utility Executive Program at the University of Michigan and the Power Systems Engineering course at General Electric.

Mr. Law began his utility career with Western Massachusetts Electric Company in 1948 as an engineer in system planning. He became protection engineer in 1956 and system planning engineer two years later. In 1961 he was named senior supervising engineer and transferred to Northeast Utilities Service Company as research engineer in 1966. He became director of technical research in 1967.

Prior to the formation of the Electric Power Research Institute, he was a member of the Edison Electric Institute's Committee on Advanced Developments and was Chairman of its Electrochemical and Energy Storage Task Force. He was also a member of the Electric Research Council's Task Force on Secondary Batteries and a member of the ERC Underground Transmission Research Projects Steering Committee and Chairman of several of its subcommittees involved in Gas Dielectric Research. With the formation of EPRI, Mr. Law became a member of its Fossil Fuel and Advanced Systems Divisional Committee and Chairman of its Electrochemical Energy Conversion and Storage Program Committee. He is the Company's representative to the "TARGET" fuel cell research program, and a member of the Steering Committees for the FCG-1 Electric Utility Fuel Cell Research Program and Chairman of its Technical Subcommittee.

He was also a member of several of the FPC Task Forces charged with preparing parts of the 1974 National Power Survey. He is a member of the IEEE Energy Development Committee and is a former chairman of the Springfield Section of IEEE.

He served with the U. S. Air Corps from 1943 to 1946, rising to the rank of first lieutenant in the Weather Service.

Appendix B

MICHAEL LOTKER

SCIENTIST
ADVANCED ENERGY CONVERSION RESEARCH

Mr. Lotker received his bachelor's degree in Physics from Queens College of The City University of New York in 1970, graduating Magna Cum Laude, and with The Physics Prize. He received his M.S. from the University of Illinois in 1972. As a student he participated in research programs at Brookhaven and Argonne National Laboratories, principally in the area of superconductivity.

As Scientist responsible for Advanced Energy Conversion Research, Mr. Lotker supervises Northeast Utilities' activities in Hydrogen Energy Systems, Fusion, Solar, Geothermal, and other advanced concepts. He serves on several Electric Power Research Institute committees including its Advanced System Task Force, and is Chairman of EPRI working groups in fusion and solar energy areas. In addition, he is a member of the IEEE Standing Technical Committee on Fusion Technology and the Brookhaven National Laboratory Utility Coordinating Committee which advises the BNL hydrogen energy storage and production work. He has authored a number of technical publications and reports in the solar, fusion, and hydrogen areas.

Mr. Lotker is a member of Phi Beta Kappa and the American Association for the Advancement of Science.

Appendix C

HYDROGEN FOR THE ELECTRIC UTILITIES LONG RANGE POSSIBILITIES

Michael Lotker
Associate Research Physicist
Northeast Utilities
Hartford, Connecticut

Presented at the 9th Intersociety Energy Conversion
Engineering Conference

August, 1974

HYDROGEN FOR THE ELECTRIC UTILITIES - LONG RANGE POSSIBILITIES

Michael Lotker
Northeast Utilities
Hartford, Connecticut

ABSTRACT

The "hydrogen economy", a concept in which abundant primary energy resources are converted into a synthetic form, hydrogen, to be distributed throughout the energy market, is attracting increased attention as part of an optimal solution to the problems of energy supply. While substantial thought and research is going into the concept's technological challenges, little effort has been spent examining the institutional considerations that will be crucial to industries contemplating activity in this area. In this paper the hydrogen economy is examined as a possible business area for the electric utilities in the long term. Specifically, it is seen as a logical extension of this industry's production, transmission and sales of another synthetic energy form, electricity. The advantages and problems of such a "hydrogen-electric economy" are considered.

INTRODUCTION

Electric utilities have always been in the business of planning for the future. Today, when an electric company decides to construct a nuclear plant, the ten-year lead time means that it is actually making a financial commitment through the year 2014. A long term consideration for fuel availability over the life of a proposed plant, is already a factor in the increased orders for nuclear reactors. Even longer term considerations, such as the eventual depletion of fossil and fissile (U^{235}) energy resources has stimulated utility sponsored research on fast breeder reactors, fusion and solar energy in order to provide primary energy sources sufficient to give thousands, millions, or even billions of years of environmentally and economically sound service. Many authors, including those at this session on "Hydrogen Energy Systems," have recognized that such energy resources can serve virtually all the needs of society if they produce hydrogen in addition to electricity. The electric utilities may need to expand their activities and become "energy utilities" supplying both energy forms in order to best serve their customers' requirements.

Below we examine the long-range (beyond the year 2000) possibilities for hydrogen in the electric utility industry. We shall see that the industry's present technical and financial structure makes it uniquely qualified to meet the demands of the hydrogen economy and that hydrogen holds several attractions for the industry in fulfilling its charter with the public to provide reliable, inexpensive and clean energy. Possible obstacles to utility venture in this area are also discussed.

A LOGICAL EXTENSION

Man's earliest uses of energy were limited by his own metabolism and that of the animals he domesticated. The energy source was food and primary application motive power. Use of fire for warmth, cooking, and as a weapon opened up the multitude of ways that energy could be used and misused. Nevertheless, it represented a singular developmental advance for humanity. The energy source was a variety of organic materials and the applications limited to the obvious thermal annd optical properties of fire. Water power, tapped in the first century, B.C., served as the prime mover for the industrial revolution in western Europe while use of wind power, first appearing in the 12th century, was more limited in its scope.[1] The energy source for water power was site limited and variations in local weather limited wind power to intermittent operation. The development of the steam engine freed man from such limitations on his prime mover and represented the first significant use of energy conversion, namely fuel to heat to mechanical energy. All of these early uses of energy suffered the same basic limitation; the point of energy generation was necessarily the point of energy consumption.

About one hundred years ago, the commercial generation of a synthetic energy form was accomplished. Electric energy was the first energy form which could be remotely consumed, freeing the user from the technical and financial burden of owning and maintaining his own prime mover. As utility companies grew, the economies of scale and of load diversity actually allowed electricity costs to decrease steadily. Subsequent developments identified uses for electricity that could not be met by other energy forms. Furthermore, electrical energy could now serve as energy's common denominator, allowing man to make use of almost any energy resource for much of his energy needs.

Today's electric utility is concerned with securing primary energy resources, converting them into a conveniently transported and utilized synthetic energy form, distributing the energy to the customer in a configuration optimized to his needs, and ultimately monitoring consumption and billing the energy user (Figure 1). If another synthetic energy form, also derivable from primary energy sources, easily transported and consumed, were identified, it would be a logical extension of the utility industry's present activities to include the production, distribution, and sales of this second product alongside these identical roles with respect to electricity. As many others have noted, hydrogen may indeed be this second product with a potential market even wider than that presently served by electricity (Figure 2).

THE INDUSTRY'S CAPABILITIES

The nuclear and solar power sources that are expected to provide primary energy for the hydrogen economy are all characterized by small or absent fuel costs and high capital costs. This economic fact of life will define the fiscal structure of any company that hopes to earn a return on investment by selling hydrogen. Today the electric utility industry routinely amortizes its plant over some 30 years and up to as much as 75 years for hydroelectric installations. It is the most heavily capitalized industry in this country by a substantial margin. For example, the estimated capital spending by the electric utilities in 1973 was $16.25 billion as compared to $5.41 billion for the petroleum industry and $2.84 billion for the gas industry (the total for all business was $100.08 billion).[2] This in spite of the fact that the gas and petroleum industries presently supply more energy to their customers than do the electric utilities.

Gas companies are basically transporters of energy. Their product is delivered in essentially the same form as when it left the well. The early initiatives to produce synthetic gas from coal will begin to test this industry's capabilities in energy conversion. The petroleum industry is principally a bulk supplier of raw materials, albeit heavily refined in most instances. Electric companies, as noted above, sell synthetic energy. They have considerable operating experience in treating the raw energy of flowing water, coal, oil, gas and the atom and optimizing conversion and delivery processes with the consumer, stockholder, and government regulator in mind. This expertise will be especially important in the nuclear area which promises to play a significant role in the developing hydrogen-electric economy.

POSSIBLE ROADBLOCKS

The most obvious obstacle to the electric industry expanding its role to include hydrogen production and sales is the likely public and political objection to increasing the scope of the monopoly under which these companies presently operate. Combination gas and electric companies would doubtlessly have an easier time making the transition but even they may have problems in serving synthetic chemical and transportation markets. Indeed, recent public and legal indications would promise a tendency toward reduction and not increase in both vertically and horizontally integrated energy companies. It is expected that the protection provided the public by state and federal regulatory bodies combined with the advantages of an early introduction of hydrogen into the energy market will overcome the apparent legal obstacles. An encouraging note in this direction was sounded by Professor of Law, T. C. Cady, who noted that "the (energy) law is flexible and can be readily adjusted...into a Hydrogen Economy."[3]

The electric utilities will be only one of several industries which may wish to go into the hydrogen business. The gas industry has a large stake in this technology which will grow as the domestic supply of natural gas diminishes. A large fraction of their experience, expertise, and capital plant may be directly applicable or convertible to hydrogen. The orderly transition from natural gas to hydrogen will be difficult, if not impossible, without the active cooperation of the gas industry. An optimal solution to this potential conflict may be to combine the strength of the electric companies in ownership of large scale energy conversion devices with the gas companies' strength in transmission and distribution of gaseous energy. In such a configuration the electric utility would own and operate the means of hydrogen generation and sell the product in bulk to gas (or other) companies not unlike the manner in which the Tennessee Valley Authority sells bulk electric power to distribution companies.

The capital requirements of a hydrogen based energy economy are truly staggering. For example, to meet one-half the estimated shortfall in the demand for natural gas in the year 2000 with electrolytic hydrogen would require some 350,000 MWe of nuclear power plants and electrolyzers costing roughly $250 billion. Utilities are presently having problems raising enough capital to suupport their present electrical expansion plans; the added burden of hydrogen generation facilities will be considerable.

Federal and state authorities may for security and balance of trade reasons encourage hydrogen production and consumption in several ways. Presently the expenses incurred during construction of an electrical generating plant are not applied to a company's rate base until the plant is actually generating electricity. The result is that the interest on the funds during construction becomes part of the total capitalization of the plant. This amount can be in excess of one-third of the direct costs of a nuclear plant.[4] An adjustment by the state regulatory commissions to include costs as incurred would reduce the overall capitalization of such plants. In addition, federal, state, or even local governments could substantially ease the problem of obtaining capital and reduce the cost of hydrogen by providing tax exempt status to bonds issued for hydrogen production facilities. Other forces of tax relief, i.e. from property taxes and point of consumption (gasoline, sales) taxes would serve to smooth the transition from more conventional fuels to hydrogen until the latter became more economically competitive.

THE ENERGY UTILITY

A great lesson to be learned from the emerging energy crisis is the importance of a system treatment of energy related matters. As we have seen, shortages of one energy form will have direct and indirect impacts throughout the entire economy. Electric utilities, large consumers and sellers of energy in all forms, have been especially sensitized to this fact. In the past, a strong motivation for the existance of combination gas and electric companies was the expectation that the utility would serve the energy needs of his customer in an optimal way. These advantages will be expanded if hydrogen, with its wide spectrum of uses, is delivered in combination with electricity. The two energy forms can serve virtually all the energy needs of industrial, commercial, and residential customers. Furthermore, since hydrogen and electricity are easily and efficiently interconverted using electrolyzers and fuel cells, the energy utility would have considerably expanded operational flexibility.

An extremely appealing advantage for the utilities (and, through regulatory control, the public) of a developed hydrogen-electric economy will be to stabilize the economics of energy supply. Primary resources for fission, fusion, and solar energy are all domestically available in an abundance sufficient to remove the impact of international politics. Perhaps less obvious, but significant too, will be the stabilizing effect of broadening the business base of the utility. As changes in energy consumption patterns occur, a company tied to but one energy form or to a limited customer category may face severe economic displacements. These changes promise no such problems for the energy utility, which now has no economic barrier to encourage the wisest energy use for all segments of the energy market. The economies of scale associated with such an expanded business base should also translate into economic savings for the ultimate consumer.

Energy storage is an area of no small importance to an electric utility. As other authors at this session detail,^{5,6} the conversion of electricity to hydrogen during off-peak hours for eventual reconversion during periods of maximum demand may be the industry's first step into the hydrogen field. Later on with a fully developed hydrogen-electric economy, energy storage becomes an element of almost every subsystem. Furthermore, the incremental costs associated with such storage may well be limited to the hydrogen handling facilities themselves since the energy conversion devices will have already been installed. Storage can be distributed to make optimal use of both generation and transmission capacities, minimizing the total amount of either.

One of the most basic technical constraints on an electric utility system stems from the fact that its product must be produced almost simultaneously with its remote, uncontrolled consumption. By generating hydrogen as an energy transmission medium this constraint disappears. It is instructive to examine some of the more apparent effects upon system reliability and economics when hydrogen and/or electricity locally produced from hydrogen, is delivered to the customer.

- Since the energy delivery system is underground, the more severe outages associated with weather problems simply would not exist.

- The current low utilization factor on electric transmission lines (about 30 percent) is as much a reflection of the necessity for redundancy as well as the hourly and seasonal variations in load. Hydrogen and hydrogen pipelines would increase this utilization factor, hence reduce overall energy transmission costs, by decreasing the need for redundancy and increasing the load factor via energy storage at the customer end of the pipeline.

- A gas system is not subject to the delicate system stability difficulties that a modern AC transmission grid may incur. A major problem in a gas system would propagate at or less then the speed of sound. Corrective diagnosis and control of such a problem (pressure and temperature sensors, valves, etc.) can be electrically accomplished at speeds approaching the speed of light. This should provide for a relatively straightforward technique for system protection. On an electrical grid, however, protective devices that operate on the millisecond timescale are required to prevent the rest of the system from becoming unstable.

- In today's electric system, even a momentary failure in a generating plant can mean loss of service to customers unless additional power can be supplied immediately. In practice, this means that a system must have standby generation or reserve sufficient to cover the loss of its largest unit plus some additional safety factor. Utilities may, at times, have to resort to brownouts (voltage reductions) or rotating blackouts to retain some measure of this reserve. If, however, the generating plant were separated from the customer by a high pressure hydrogen pipeline, short interruptions in generation (such as those associated with control problems in nuclear reactors) would not require reserve protection and more importantly would not affect the customer at all.

- The electric system is currently characterized by high reliability for each and every component; to do less would impose unacceptable reserve criteria. Again, by the insertion of a gaseous "energy cushion" with surge capacity at both ends of the utility to customer link, the reliability consequences of momentary malfunction (with the exception of safety related failures) is minimized. This should, in principle, reduce the cost of such systems without sacrificing quality of service.

- For these reasons, the reserve requirements for the hydrogen generators would be reduced, possibly in quantity, but almost certainly in the speed in which they must be brought on line relative to current electrical practice. Presently, some fraction of the electrical reserve must be available within five minutes, with the remainder available within 30 minutes to an hour. With a pipeline system, the natural storage provided by the volume and pressure of the contained gas may well serve as a large fraction of the reserve needed to insure reliability.

The alternative to expanding the energy delivery system to include a synthetic fuel such as hydrogen is to consider a strictly electrical expansion which would make use of our nuclear and solar energy resources. The problem in supplying electrical transmission in future decades will be staggering when one considers the difficulties presently encountered by utilities in installing needed overhead lines in populated or scenic areas. Technological and environmental limitations on the maximum voltage of such lines will mean that the need for new and expanded rights-of-way will lag not far behind load growth. Underground cable, including superconducting and DC technologies, will almost certainly be required with their attendant high costs and operational difficulties. There will still be energy needs which cannot be fulfilled by electricity and which can, in the absence of fossil fuels, be adequately met by hydrogen.

CONCLUSION

As the fossil age draws to a close, society will have to make widespread use of synthetic energy forms to meet its varied energy needs. Electricity, the first of such forms, will almost certainly be joined by hydrogen to meet the energy markets in the future. The present electric utility industry is seen to have the technical and financial capabilities along with considerable incentives to act as the institutional basis for hydrogen production, transmission, and sales in conjunction with these identical roles regarding electricity.

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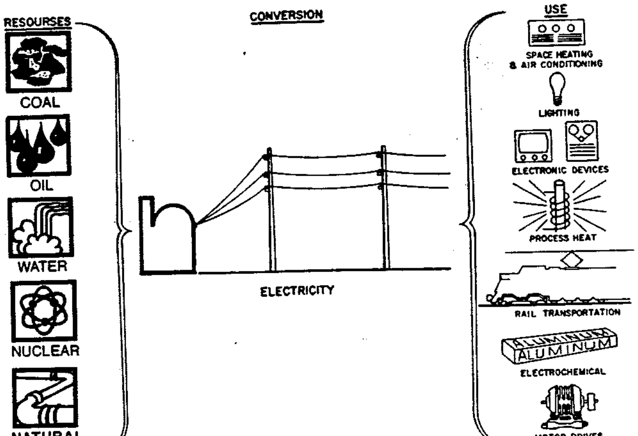
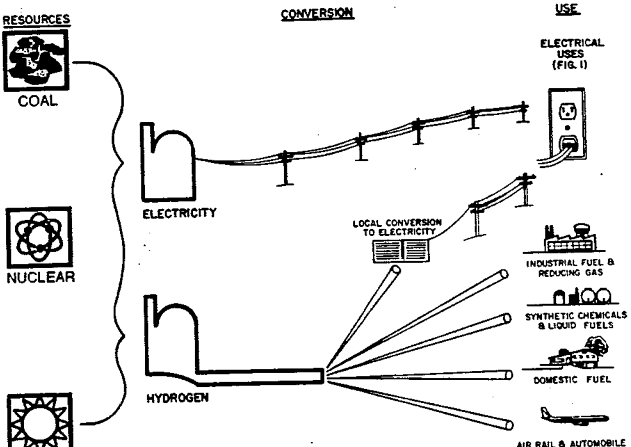


PRESENT ELECTRIC UTILITY
FIG. 1



FUTURE ENERGY UTILITY
FIG. 2

Hydrogen As An Electric Utility Fuel

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And

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INTRODUCTION

Today's electric utility is in the business of energy conversion and distribution. It transforms primary energy sources, such as coal, oil, natural gas, uranium, and flowing water into electricity, a more convenient energy form. In this way, the consumer can use nuclear energy to light his home, coal to run his computers, and flowing water to power rail transportation. Electricity is, then, a synthetic energy form with properties sufficiently desirable to warrant the expense and inefficiencies associated with its production. If another synthetic energy form, also easily transportable, and producible from primary energy resources is recognized, it would then be a logical extension for the electric utility industry to expand its traditional roles of production, transmission, distribution, and sales to include this new energy form, assuming, of course, that the new form offered features which allowed it to fill needs not otherwise readily satisfied.

Such needs do exist. There is, for example, a need for a synthetic energy form which can be transported cheaply by methods having minimal visible impact. There is also a need for synthetic energy forms which can be stored, so that maximum use can be made of primary generation facilities. Coupled with the prospects of dwindling oil and natural gas supplies in the future, the potential ability of hydrogen to fill these needs is the motivation for electric utility interest in hydrogen as a fuel.

The Hydrogen Economy

With appropriate storage and transmission, hydrogen has application in almost every sector of the energy market, as indicated in Figure 1. Hydrogen can be substituted for natural gas in domestic and industrial space heating, and since the only combustion product is water vapor, the need for a flue may be eliminated and only dehumidification required. This would increase the efficiency of furnaces and allow for individual room controls as is the case today with electric heat alone. Hydrogen also has large potential markets as a chemical in the production of other chemicals, and in petroleum refining. In the transportation sector, hydrogen fueled automobile and aircraft operation has already been successfully demonstrated.[1,2] Here, the major technical challenge will be storage, with either metal hydrides[3] or liquid hydrogen as possible options. In regard to electric energy, hydrogen fuel could be converted to electricity via fuel cells, devices which produce electricity directly from chemical energy at efficiencies up to about 55 percent. Even more efficient conversion of hydrogen to electricity may be possible with high temperature hydrogen-oxygen combustors. Hydrogen could, in principle, also be used to store energy for an electric system in a manner analogous to pumped hydroelectric energy storage.[4]

Safety

An examination of hydrogen's chemical properties indicates that it is about as safe as natural gas (methane). While a hydrogen-oxygen mixture has wider flammability limits than does a methane-oxygen

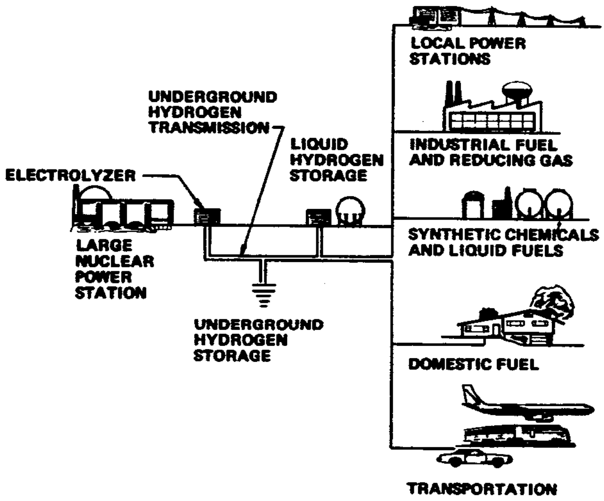

Figure 1. Hydrogen in the Energy Market

mixture, the more significant lower limits are comparable. Although hydrogen leaks more rapidly due to its smaller molecular size and mass, it has less energy content per unit volume and disperses more rapidly. Hydrogen, like methane, is odorless and will probably require an artificial odorant. In addition, it burns with an invisible flame, an advantage in that it would reduce radiative heat damage during a major fire, but may create a possible hazard for home use, where an additive to make the flame visible may be necessary. The space program has demonstrated that large quantities of hydrogen can be handled safely over a period of years.

Present Status

The previous discussions represent a crystalization of current thinking which envisions a "hydrogen economy", as a unified energy system revolving around the fuel, hydrogen. The potential advantages of a "hydrogen economy" have been thoroughly explored.[5] Some elements of the hydrogen economy, as it is currently envisioned, may displace present-day practices relatively rapidly. Others may evolve more slowly or perhaps be set aside in favor of economically preferable approaches. Regardless, the gap between the realization of the long range hydrogen economy and the present-day hydrogen utilization is striking. The annual world production of hydrogen stands at three trillion standard cubic feet. This amount would roughly satisfy the present-day annual fuel needs of only a single large American electric utility. Most of the world production is accomplished by reforming natural gas or naphtha; roughly three percent is obtained by electrolysis, primarily in countries with substantial hydroelectric resources. The American space effort consumes a large share of the world production. The average cost of liquid hydrogen used by NASA is nearly \$4/M Btu, which exceeds by a substantial margin the average \$/Btu cost of fuels currently used by electric utilities. Note that \$4/M Btu is roughly equivalent to oil at \$24/barrel.

Production Considerations

The cost mentioned above perhaps only reflects present-day small scale production operations, but it nevertheless represents a major obstacle to introduction of hydrogen into the energy market. Moreover, it is apparent that the "hydrogen economy", if it expands as envisioned, cannot continue to be based on conversion of liquid fuels or natural gas, the long term availability of which is not assured. Unfortunately, hydrogen derived from other primary energy sources will similarly have high costs, for reasons to be discussed.

Hydrogen, unlike fossil fuels, is not naturally available except as a constituent of other materials. Because it readily reduces other elements, it resides in compounds, notably water (H_2O), and fossil fuels such as methane (CH_4). These compounds are very stable; it is necessary to supply energy to break them apart to release their store of hydrogen. For example, in the case of water the entire heat of combustion of the hydrogen, plus process losses, must be supplied. Thus, the cost of the hydrogen produced must be reckoned in terms of both a primary energy cost and a cost associated with equipment in which the conversion process takes place. Primary energy can be supplied as heat or electricity, or both, and it is easily demonstrated that the cost of primary energy will dominate cost comparisons among major alternatives. For example, if hydrogen were to be produced by electrolysis using electricity from a nuclear plant constructed in the mid-1970's, the energy cost alone would be more than $5/M Btu, or roughly 90% of the total cost of production.

Alternatives to Electrolysis

There are several alternatives to electrolysis to fulfill future demands for hydrogen. For example, it is possible that biological processes may eventually be employed. Bacteria obtain energy for growth through a series of dehydrogenation or coupled oxidation-reduction reactions. Certain organisms have the ability to form hydrogen gas or methane in the dehydrogenation process. By proper manipulation of culture conditions it may be possible to derive either CH_4 or H_2 from organic matter.

In the foreseeable future, processes for production of hydrogen directly from coal or nuclear heat represent the major alternatives to electrolysis. In these cases the utilization of primary energy resources could, at least in principle, be more efficient than in the case of electrolysis. There is some uncertainty as to the extent of economically recoverable nuclear ores and coal reserves, but most estimates of the number of years to deplete these resources are consistent with the view that ample time remains to develop economically feasible means of tapping the virtually inexhaustible energy resources (solar, fusion, and geothermal) for hydrogen production.

Role of Electric Utilities

In moving toward a "hydrogen economy", what appears to be needed at this time is a first step toward large scale production and non-specialty use of hydrogen. Electric utilities may play a key role in determining when and how, and perhaps whether, this first step is to be taken. For example, possible utility uses for hydrogen may appear within the next decade as a result of current investigations into the fuel cell as a peaking and intermediate load device. Avenues from hydrogen production to electricity generation which involve fuel cells as users and fossil fuels as a source may be the most feasible in the near future. These avenues are highlighted in Figure 2, which is a schematic representation of the part of overall hydrogen economy that is of special interest to electric utilities.

The fuels for the first generation of fuel cell generators, number 2 oil or lighter grades, cost between $2.50 and $3.00/M Btu in the current fuel squeeze. Although future costs for these fuels are highly uncertain, it is significant to note that the primary energy costs for deriving hydrogen from coal and from a nuclear thermochemical cycle appear to be in this same general range or below.

HYDROGEN PRODUCTION

This section briefly analyzes the major production options identified in the above section, including electrolytic and thermochemical processes, and conversion of coal to hydrogen or hydrogen