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THE IMPORTANCE OF SAFETY IN ACHIEVING
THE WIDESPREAD USE OF HYDROGEN AS A FUEL

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THE IMPORTANCE OF SAFETY IN ACHIEVING THE WIDESPREAD USE OF HYDROGEN AS A FUEL

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Abstract

The advantages of hydrogen fuel have been adequately demonstrated on numerous occasions. However, two major disadvantages have prevented any significant amount of corresponding development. These disadvantages have been in the economics of producing sufficient quantities of hydrogen and in the safety (both real and perceived) of its use. To date work has mostly been properly centered on solving the economic problems. However, a greater effort on the safety of new hydrogen systems now being proposed also deserves consideration.

To achieve the greatest safety in the expansion of the use of hydrogen into its wide-spread use as a fuel, attention must be given to four considerations. These are, obtaining knowledge of all the physical principles involved in the new uses, having in place the regulations that allow the safe interfacing of the new systems, designing and constructing the new systems with safety in mind, and the training of the large number of people that will become the handlers of the hydrogen.

Existing organizations that produce, transport, or use hydrogen on a large scale have an excellent safety record. This safety record comes as a consequence of dedicated attention to the above-mentioned principles. However, where these principles were not closely followed, accidents have resulted. Some examples can be cited.

As the use of hydrogen becomes more wide-spread, there must be a mechanism for assuring the universal application of these principles. Larger and more numerous fleet operations with hydrogen fuel may be the best way to begin the indoctrination of the general public to the more general use of hydrogen fuel. Demonstrated safe operation with hydrogen is vital to its final acceptance as the fuel of choice.

1. Introduction

Hydrogen as a portable fuel is the inevitable replacement for fossil based fuels. A more general introduction of hydrogen fuel should begin soon for three reasons: First, it is necessary to alleviate the continuing insult to the environment caused by present use of fossil fuels. Second, fossil fuels will eventually be exhausted. There is general agreement on this point, but not on the time that the supply will be exhausted. However, fuel supply problems become difficult to accommodate long before the time when fossil fuels are exhausted. The time of peak production capability occurs much earlier than total exhaustion of the source. When the production capacity begins to decrease, then the inequity of distribution of the decreasing supply and competition for what is left become disruptive to society in several ways. Third, the longer the time available for a change-over to a new fuel, the less disruptive and less expensive will be the transition.

2. Barriers to the Large-scale Introduction of Hydrogen Fuel

In the past there have been two major barriers to the large-scale introduction of hydrogen fuel. The first barrier is that of economics. Hydrogen does not naturally occur in its free form to any significant degree. Currently, most hydrogen production is from fossil fuel, which is not a long-term solution to the energy problem. To offer a long-term solution the hydrogen must be produced in a different manner, which is usually at the expense of more energy being used in its production than will be generated in its combustion. To date most of the work on hydrogen fuel is being expended on finding more economical ways to produce hydrogen, and this effort continues to be useful and necessary.

The second barrier is that of safety. There is a wide-spread distrust of the safety of hydrogen as a fuel. Probably most of the people at this meeting have personal experiences of the existence of this distrust. I have experienced this distrust of hydrogen on numerous occasions, and the literature continues to mention this distrust.^{1,2}

As with any fuel, there are legitimate reasons to be concerned about the safety of a new and different fuel. However, by its very nature, any fuel can cause accidents, and a strong case can be made that hydrogen is no more dangerous than any other commonly used fuel. Much of the fear is an over-reaction to past accidents with the consequence that the perceived fear is greater than can be justified and is therefore somewhat irrational. In spite of that fact, the barrier still exists and the successful introduction of the wide-spread use of hydrogen fuel will require education of the general public, a task that can only be effective if the safe handling and use of hydrogen as a fuel are convincingly demonstrated.

3. The Fear of Hydrogen and the Possible Effect upon Future Developments

Until about a half-century ago hydrogen fuel was accepted without any great trepidation. City gas, containing roughly equal portions (by volume) of hydrogen and carbon monoxide, was produced by the action of steam on coke and then the "city gas" was delivered by pipeline to many homes, offices, and commercial establishments for lighting, water heating and cooking purposes. The home of my youth was one such house. Because of the toxicity of carbon monoxide, a case might be made that its presence in the city gas caused more harm than did the hydrogen, by causing deaths both inadvertently and intentionally by suicides by "taking the gas pipe". In any case there was no wide-spread fear of this energy source, and it was universally accepted.

However, one spectacular, high profile accident that was reported in a very emotional manner was that of the airship, Hindenburg. Recently, Bain³ has made a convincing argument that hydrogen was not the primary cause of that accident. However, the fear lives on. The publicity for that accident, plus the development of the hydrogen bomb, have led to the general public distrust of hydrogen being used as a fuel. The common response to our work with hydrogen fueled vehicles clearly demonstrated that this distrust still exists.

A similar accident⁴ with liquefied natural gas (LNG) in Cleveland, Ohio in 1944 is often blamed for a 20 to 40 year set-back in the development of LNG storage and transport. If the development of hydrogen's use as a fuel is to occur in a timely manner, it can ill afford a further set-back caused by public reaction to any future accidents. Safety, or at least the perception of safety must still be regarded as a barrier to the implementation of a successful hydrogen fuel program. Thus, safety must be a primary concern in all phases of the development of any hydrogen utilization project. The continuing demonstration that hydrogen can be used safely is necessary so that the general public will eventually accept hydrogen fuel as a benefit rather than as a feared hazard.

4. Conditions for Safe Operation with Large-scale Use of Hydrogen Fuel

To achieve the highest degree of safety in a hydrogen operation there are four major considerations that must be taken into account.

4.1. FUNDAMENTAL UNDERSTANDING OF SAFETY REQUIREMENTS

First, for each new application, all of the pertinent physical principles and potential hazards involved in the production, transport, storage, and use of the fuel must be understood. As new uses are proposed, or as applications change, they must be examined to see if new, or different physical principles become important. In some cases, additional experimental investigation could be required.

Incomplete knowledge of the operation of a system is an invitation to disaster. Pilatre de Rozier's experience of combining a hydrogen balloon with a Montgolfier (hot air) balloon provides an example of the problem that can arise from having only a

partial understanding of the physical principles involved in a given situation.⁵ De Rozier believed that by having the hydrogen balloon placed above the Montgolfier, thus at a higher elevation than that of the flame of the Montgolfier, there would not be the problem of a fire if the hydrogen were to leak. The lower density of the hydrogen would cause it to rise and travel further away from the flame. It is true that hydrogen's buoyancy is a faster mechanism for the dispersion of the hydrogen than is diffusion. However, convection currents and atmospheric winds can be much more potent dispersion forces than either of the previously mentioned mechanisms. The lack of realization of this fact made de Rozier its victim when there was a hydrogen fire and the balloon crashed, killing De Rozier and his fellow passenger. Thus for the use of hydrogen fuel to become universal and safe, it is first necessary to understand, for each system, all of the physical principals that are involved and also the various ways in which accidents can occur for the specific systems being used. Where the lack of operating data or experience is encountered, further safety research will be required.

4.2. SECOND, REGULATIONS

For safe operation involving different organizations and different nations it will be necessary to have regulations in place that give guidelines for safe design and operation. An important reason for the existence of regulations is to ensure the safety of interfacing one system with another. Systems must be built to be capable of safe interaction between different organizations and across national boundaries. Although there may be more than one safe way to operate an isolated system, for most cases it is necessary that each system be compatible with the other systems with which it must interface. This is becoming increasingly important on an international basis.

4.3. THIRD, SYSTEM DESIGN AND CONSTRUCTION

The entire system must be designed and constructed with due consideration to its safety of operation and its compliance with the regulations mentioned in section 4.2. Thus, safety must be the primary consideration from the initial design stage through the entire process of final design, construction and testing of the finished product. Design reviews must be made by people knowledgeable in the possible hazards that can accompany hydrogen, and that are not directly involved with the promotion of that particular project. For each new system the application of the techniques of failure modes and effects analysis, or HAZ-OP investigations will be necessary. The degree to which the approach to producing a safe system has been achieved will depend upon the knowledge and understanding developed in the requirement described in section 4.1. In reaching the goal of producing a "safe system" it must be realized that this is a necessary, but not necessarily sufficient condition for safe operation. The belief that one has built a "fool-proof" device neglects to take into account the "ingenuity of fools".

4.4. FOURTH, EDUCATION AND TRAINING

It is necessary to educate, or train the producers, transporters, and users in the safety of operation. Training must be an ongoing, continuous part of operation. Also training must not merely rely upon each new employee being trained by the current workers. A necessary part of the training must be from a primary source, designed for the particular application. If training is merely passed on from one employee to the next, after several iterations of this procedure there can be great departures from the established safe procedures. On-the-job training can be a valuable part of training, but must be reinforced by fundamental training involving an exposure to the principles that are basic to the safety practices.

Once the general public becomes involved, safety training becomes more difficult. One can see examples of the type of attempt now being made to educate the public in safe operation. One might see a label attached to a ladder stating that the user should not stand on either of the top two steps because "you might lose your balance and fall". This simple solution might be adequate for such an unsophisticated application. However, as the degree of complication, and possible hazard increases, a more significant effort will be required. A more technical example can be found in the widespread sale of automobiles with anti-lock brakes. Experience shows that very little is said to the purchaser of a new automobile about the proper method to apply the brakes under slippery conditions, and that this method is different from previous practice. Lack of such information has led to accidents, and has made it necessary to try to educate the public with television programs. Actually, a better training method would involve instruction to the prospective buyer followed by giving him the opportunity to try out the braking system in a safe way before a panic stop becomes necessary. In the case of hydrogen, it is of particular importance to convince prospective users of the necessity of properly maintaining the hydrogen system. A look at many of the vehicles entering the average self-service gasoline refueling stations gives one cause for concern over what to expect for the maintenance of a hydrogen system.

5. What Can Be Done to Meet These Requirements

5.1. UNDERSTANDING SAFETY REQUIREMENTS

Safety problems continue to exist and as new applications of hydrogen fuel arise, new problems will also arise and require further investigation to understand the potential hazards that the new application of hydrogen fuel might present. Although it is possible to anticipate some facets of the safety of handling hydrogen that need further investigation, it must be remembered that new applications must each be examined to look for additional safety problems that a specific new use of hydrogen might entail. Different applications will favor the use of different types of hydrogen storage. Probably all forms of hydrogen storage will be used in one case or another.

In some cases it will be necessary to examine the effect of hydrogen

embrittlement on new materials involved in structural applications in systems using gaseous and/or hydride storage systems. A number of research laboratories are still pursuing the study of hydrogen embrittlement. Problems that might be encountered with systems using liquid hydrogen include cold embrittlement of new structural materials that are subjected to cold temperatures. For each specific system, appropriate purging techniques must be developed for refilling operations as well as for the performance of any maintenance operation requiring disassembly of the system. Inadequate purging procedures have been responsible for a number of hydrogen accidents.⁶

The possibility and consequence of hydrogen leakage should be studied for each new application. Zalosh and Short⁶ analyzed over 400 accidents that involved hydrogen. Most of these accidents occurred in industrial facilities during the period from 1965 to 1977. They report that 25% of these accidents were caused by undetected hydrogen leakage. Thus, undetected leakage is one of the most important causes of the accidents that have occurred with hydrogen. The development of inexpensive, and reliable systems for the detection of leakage of hydrogen is important. Several new detection systems are now under development at US National Laboratories and appear promising.⁷

Theoretical studies have been made of the consequences of hydrogen releases.^{5,8} Swain⁹ has studied experimentally the distribution of hydrogen leakage and the consequent size of a combustible plume that results. The spread of hydrogen after liquid spills has been investigated experimentally by Witkofsky¹⁰ and Schmidchen.¹¹ These studies are all valuable, and give a good indication of the way hydrogen will disperse after being spilled, or vented into open spaces and also into semi-confined spaces. However each new application might introduce new and different circumstances so that this work can not be considered to be complete.

Because of the ease of ignition of hydrogen and the lack of visible evidence of a hydrogen fire, an investigation should be made of the available fire detection devices and their suitability for the various applications of hydrogen being proposed. An important consideration is that the detection devices not be a source of ignition. In an unconfined atmosphere the ignition of a hydrogen-air mixture as a simple combustion (or deflagration) generally does not cause much damage to anything not directly in the flame area. Overpressures that result usually are not very high. However, if confined, very destructive pressure can be produced even from a simple deflagration. Zalosh and Short⁶ found that hydrogen explosions have been more serious than other hydrogen accidents when considering casualties, property damage, and number of incidents. The destructive power of a hydrogen explosion becomes much greater if the combustion occurs as a detonation. The conditions necessary for the transition from deflagration to detonation are understood. However, the environment through which the flame will travel can influence the progress of the flame as it encounters obstructions that could induce turbulence in the flame and thus increase its velocity and tendency for transition from deflagration to detonation.

5.2. REGULATIONS

There are numerous safety guidelines, codes, standards, and regulations that address, either directly or indirectly, the safe handling of hydrogen. In the USA, the overriding safety requirements for hydrogen are in the Code of Federal Regulations (CFR). In some places the CFR specifically addresses hydrogen, and in other places the inclusion of hydrogen is by inference. In some places sections of various standards, such as those of the ASME or the ANSI, are written into the code. In other places these standards are included by reference. The individual states, or even cities or other localities can have additional restrictions, but this is not too common. Other countries have similar regulations that are suited to their particular needs.

Hydrogen applications have already become international in character. Fortunately the International Standards Organization has already begun the process of writing the international standards that must be available to ensure safety in the pursuit of international projects by forming a technical committee, ISO/TC 197, Hydrogen Technologies. The Bureau de Normalisation du Quebec, on behalf of ISO member, the Standards Council of Canada, has taken over the responsibility of secretariat and the scope of the committee has been expanded to include "Standardization in the field of systems and devices for the production, storage, transport, measurement and use of hydrogen". The committee wishes to ensure that all countries become aware of, and become interested in its work because the final standards will have world-wide influence. Eleven countries are members with active participation including the right to vote, to attend meetings, and to appoint experts for the working groups that will prepare drafts of the standards. Sixteen other countries are also committee members as observers with the right to attend meetings and give comments.

To date four working groups (WG) have been formed and are formulating standards addressing hydrogen safety. WG-1/2 consists of 12 experts appointed by members from Canada, Germany, Japan, Switzerland, and the USA. These groups are convened by Dr. Robert Hay of Canada. WG-1 has been working on Standard #13984, Liquid Hydrogen - Land Vehicles Fuelling System Interface and on Standard #13985, Liquid Hydrogen - Land Vehicle Fuel Tanks. WG-2 is working on Standard #13986, Tank Containers for Multimodal Transportation of Liquid Hydrogen and Standard 13987, Ships for Liquid hydrogen Transportation. WG-3 consists of 7 experts appointed by members from Canada, Japan, Republic of Korea, and the USA and is convened by Mr. Addison Bain of the USA. WG-3 is working on Standard #14687, Hydrogen Fuel - Product Specification. WG-4 consists of 6 experts appointed by members from Canada, Germany, Japan, and The Russian Federation and is convened by Mr. Norbert Rostek of Germany. WG-4 is working on Standard 15594, Airport Hydrogen Fuelling Facility. Three more working groups, WGs 5, 6, and 7) have been proposed to consider the topics of Hydrogen and Hydrogen Blends for Vehicular Fuel Systems, Basic Requirements for Gaseous Hydrogen Vehicles Fuel Containers, and Basic Requirements for the Safety of Hydrogen Systems.

It takes about three years to process a standard, so it is fortunate that these present efforts are underway.^{12,13}

5.3. SAFE DESIGN OF SYSTEMS

A great deal of advice that is helpful to the designers of new systems is available in the literature.^{4,5,14-16} Safety must be considered and be a part of any new proposal for the production, storage, transport, or use of hydrogen. Safety analysis must be done anew to specifically address each new system. Such techniques as failure modes and effects analysis, or HAZ-OP methods must be included. There is a need to understand the causes and consequences of accidents and design the system to avoid accidents and to allow remedial actions to mitigate their consequences. Where two or more competing systems are proposed to solve the same problem, a safety analysis can give valuable guidance to assigning priorities for their development.

5.4. EDUCATION AND TRAINING

The importance of education and training of the workers that handle the hydrogen can not be overemphasized. The cause of the accidents discussed in section 6 can be directly attributed to the lack of training of the workers involved.

Ordin¹⁷ analyzed 96 accidents and incidents involving hydrogen that occurred at the US National Aeronautics and Space Administration (NASA) facilities and those of NASA contractors. In 80 of these incidents there was some release of either gaseous or liquid hydrogen. In 25 of these releases there was no ignition of the hydrogen. Of the total accidents, about half were attributed to causes that were procedural or operational. Examples of these causes include such actions as failure to follow established procedures, not having proper procedures, and improper purging. In most cases better training of the operators might have precluded these accidents. Ordin gave the precaution that operation must be based on knowledge of the potential hazards of hydrogen and personnel education in these potential hazards as well as technical knowledge of the system.

Careful attention to training of personnel can result in safe operation. An example of effective training is that used by Air Products and Chemicals, Inc.¹⁸ Their standard practice for drivers that deliver liquid hydrogen is 18 hours in the classroom, 3 hours of video training, and about two months of on-the-job training. This is supplemented by systematic retraining and review programs. The excellent safety record of their transport and distribution of liquid hydrogen testifies to the success of this training.

In principle, fleet operation of hydrogen vehicles should also be able to attain an excellent safety record. The question must be asked, what can be done to assure similar care in operation by the general public if the use of hydrogen fuel is to become universal? Perhaps the best way to start is the publicizing of the precautions being taken in successful and safe fleet operations. Once there is a widespread general knowledge of the safe practice of using hydrogen fuel, the training of users before they take possession of a system would be more effective. Additional measures might be necessary for the control of resale of hydrogen powered vehicles. The large percentage of hydrogen accidents that is caused by hydrogen leakage makes it important that all potential users become aware of the requirement for excellent maintenance of

hydrogen containing systems. Obviously the methods of assuring safe operation and satisfactory maintenance of hydrogen powered vehicles used by the general public require thorough investigation.

6. Hydrogen Accidents

Although the large-scale handling of hydrogen has an excellent safety record, some accidents have occurred. Frequently these accidents can be attributed to inexperience of operators, or in their failure to follow established procedures.

In one laboratory with very little experience in handling hydrogen, workers were investigating the Charpy impact strengths of metal specimens at liquid hydrogen temperature (20 K or -253 °C). They carried out the experiment by starting with the specimen immersed in an open Dewar of liquid hydrogen. As the pendulum was released but before it had fallen far enough to contact the test specimen, the Dewar was lowered to expose the sample to the path of the pendulum. The workers did not realize that the open Dewar would allow solid air to condense in the liquid hydrogen, and that as the cold specimen was exposed to the atmosphere it would also liquefy air that would then drop into the liquid hydrogen. An explosion resulted, injuring the technician that was performing the experiment. The consequences could have been much worse.

In another case a shed had its sides blown off when a valve was opened into a line from a gas storage container containing hydrogen gas at 225 atm (2.25 MPa) pressure. Upstream of the valve that was opened there were two other closed valves also believed to be closing off the high pressure hydrogen. However, these valves had leaked hydrogen into the intervening line in large enough quantity that when flowing into the shed it could create a combustible atmosphere. There were numerous ignition sources within the shed and an explosion resulted. There were several people working inside the shed at the time of the explosion, but fortunately, the injuries were limited to some ruptured ear drums and one broken heel.

In another case, an inexperienced operator connected a hydrogen tube trailer to the same manifold as an oxygen tube trailer. This was followed by a series of errors that led to oxygen (coming from a tube at a pressure of 120 atm, or 12 MPa) flowing into the hydrogen tube (initially at a pressure of 15 atm, or 1.5 MPa). The resulting deflagration transited to a detonation, rupturing the tube and throwing fragments of the vessel as far as 350m. Fortunately, no injuries were caused by the fragments, but two workers suffered serious burns.

Adequate training and the existence of well understood procedures would have precluded all of the above accidents.

7. Conclusion

There is no question that hydrogen can be handled safely. In spite of the above-mentioned incidents, the overall safety record of hydrogen production, transport and usage attests to the fact that the above conditions for safe operation are well met at the present scale of handling hydrogen.

An example can be found in the liquid hydrogen transportation industry.¹⁸ Air Products and Chemicals, Inc., the largest distributor, has not lost any liquid in over 25 years, in spite of the fact that vehicle accidents have occurred. The company delivers annually about 250 million standard cubic meters (9 billion cubic feet), 92% of which is as liquid, involving 14,000 deliveries. Their trucks cover about 8 million miles per year, and on a given day there are about 70 trucks en route.

However, in industrial operation the number of people involved is limited, the operators are well trained, and rigid maintenance schedules are followed. What will happen as many more people become involved in the use of hydrogen? Some proposals for hydrogen fuel involve John Doe being able to produce hydrogen in his garage and then use it to fuel his automobile. One could imagine parking structures with hundreds of such vehicles in closed areas. The previously cited accidents show that often people do not wait to learn what dangers exist before acting. Improvising remedies for unexpected situations can be especially disastrous, and the importance of good maintenance is paramount.

Conditions for the introduction of a new technology are different now from what they were when gasoline fuel was introduced. It would be interesting to try to anticipate the difficulty of introducing gasoline as a fuel today if it were not already accepted and in use. Many of the hydrogen accidents that have occurred can be attributed to inexperience of operators, or in their failure to follow established procedures. If future users are sufficiently well trained and if they are dedicated to following well established safety practices, the acceptance of hydrogen fuel can be more easily and quickly accomplished. Major incidents that cause injuries and property damage will delay the much needed impact of hydrogen fuel on our energy systems.

The record shows that hydrogen can be handled safely, although this has not always been the case. Will it be safely handled in the future? The successful transition to its larger scale use as a fuel depends upon how safely it is used. Obviously it will first be necessary to introduce hydrogen fuel to fleet operations where there can be better control, better training of operators, and better adherence to maintenance schedules. If such operations can demonstrate a sufficient degree of safety for a long enough period of time, then these safety principles will diffuse into the public consciousness and a more general usage can be attempted.

In conclusion, for hydrogen to be widely accepted as the fuel of choice to replace gasoline and other fossil based fuels, the new hydrogen systems must be safe, and also must be convincingly demonstrated to be safe.

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