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Applications Analysis of Fixed Site Hydrogen Storage

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APPLICATIONS ANALYSIS OF FIXED SITE HYDROGEN STORAGE

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ABSTRACT

The potential applications and requirements for fixed site storage in a scenario of wide spread hydrogen use are examined and quantified. An envisioned hydrogen production/distribution/end-use cycle is scrutinized to identify the storage needs for both continuous and intermittent sources including solar. The most pressing need for storage is found to be at the distribution point, in concurrence with current natural gas practice. Caverns and similar underground storage techniques are shown to be the most promising modes due to their low cost relative to all other options examined. Since a large volume of natural gas storage is presently in service, a pressing need to develop fixed site hydrogen storage technology (beyond the conversion of this underground storage to hydrogen) has not been identified.

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APPLICATIONS ANALYSIS OF FIXED SITE HYDROGEN STORAGE

I. Introduction and Highlight Summary

Widespread utilization of hydrogen may depend on the ability to store appreciable quantities to smooth mismatches between supply and demand. Storage of hydrogen presents special materials challenges due to hydrogen embrittlement phenomena and hydrogen's low heat content, which may lead to different trade-offs in storage design and performance than occur with natural gas. The necessity, viability and preliminary economics of bulk hydrogen storage are examined in this memo.

It has been assumed in this work that (1) hydrogen will be plentiful and available in all regions of the country; (2) the widest possible usage of hydrogen will be as a substantial replacement for natural gas in heating and electrical generation applications by distribution through existing natural gas pipelines and/or a similar pipeline system. Feedstock applications are also examined.

Storage of hydrogen (as with any fuel) will only be desirable if there are mismatches between production, distribution and usage rates. While this is true for any energy commodity, it is especially true for hydrogen, as it is neither a source of energy nor a necessary element in any envisioned energy economy. However, it may be an attractive medium of energy transport, distribution, end-use, etc. Hydrogen will be produced as a gas. Storage of gaseous fuels is usually unattractive; however, there may be instances when the storage of hydrogen would be beneficial and perhaps necessary. Consider the examples of oil or natural gas--these are produced at a constant rate, not at the convenience of a utility company as hydrogen might. It may be cheaper to transmit hydrogen at the maximum production rate, rather than to store it to smooth the flow rate. Alternatively it might be better to adjust the production rate to match the instantaneous transmission capacity. At any rate, avoidance of storage at the production site may be a viable possibility. It may even be possible to avoid storage of hydrogen at a distribution site by adjusting production rates to match the actual or predicted consumption rates. This concept of storage avoidance is not an attempt to skirt the issue but rather to get to the heart of the matter; hydrogen storage is expensive in any form (as is the storage of any gas), and industry will avoid its storage whenever economically or operationally possible. The necessity of hydrogen storage is herein examined by investigating likely sources and patterns of hydrogen production, distribution limitations and end-use consumption scenarios. To determine the needs and characteristics of hydrogen storage, the hydrogen energy cycle was broken into three sectors: production, distribution, and end use. In each of these sectors storage of hydrogen may be beneficial towards smooth and economical operation.

Hydrogen storage at constant production rate sites will not be needed (as there is not advantage to storing at all). Variable production rate locations (such as solar powered conversion plants) present a slightly different picture. Here a tradeoff exists between the cost of storage (to smooth transmission rates and hence lessen pipeline sizes and costs) versus the cost of the transmission line. As will be shown for the solar hydrogen production case, storage is a more expensive option than simply oversizing the transmission lines to handle the maximum production rate. This result, of course, depends on the cost of storage and the cost and length of the transmission line, but nonetheless is quite broadly applicable. Unless extremely inexpensive storage is available (less than 100$/MBTU, 1972 dollars) or the length of the line is extremely long (say, more than 100 miles), storage is not the preferred option. The case of using off peak electricity for electrolysis is very similar to the solar case and for similar reasons storage is not attractive here either.

Hydrogen storage is most important and beneficial at distribution sites. This storage will be seasonal in nature (as natural gas storage is used currently). Even accounting for hydrogen's lower heating value (with respect to natural gas) the current underground natural gas storage facilities would provide almost all of the seasonal storage requirements envisioned. Should this or similar storage not be acceptable for hydrogen service, the next best alternative may be above ground constructed vessels in the 1000 $/MBTU range. Since currently $7x10^9$ MBTU of natural gas storage is used, a rough estimate of the cost of above ground hydrogen storage would be $7x10^{12}$ (seven trillion) dollars. This would probably be unacceptable to both hydrogen utilities and customers. Hence effort should be put into assuring the viability of inexpensive storage, such as conversion of current facilities to hydrogen service.

Storage at the end use point is not really an issue. In a postulated scenario of widespread hydrogen usage, hydrogen will be available on demand from distribution and delivery networks as natural gas now is. Residential users will almost never be interrupted and industrial and commercial users will prefer oil as a back-up heat source rather than expensive hydrogen storage. Thus storage at the end-use point will rarely be required.

II. General Hydrogen Storage Considerations

In our postulated hydrogen economy storage of hydrogen could be useful at three locations--at the production site, in the distribution network or at the end-use point. The production site could be almost anywhere, producing hydrogen either chemically or by electrolysis, continuously or periodically. In all probability a pipeline will carry the hydrogen to a distribution center somewhat closer to the demand centers. The distribution center may collect hydrogen from many sources and supply hydrogen to many end-users. The end-users may be quite diverse ranging from homes and commerical buildings to light and heavy industry including chemical plants. The necessary or desirable storage characteristics at these locations may differ appreciably. While no definitive statement can be made as to the best (most economic) parameters at each of these three potential storage locations, ranges of values can at least be enumerated.

The desirable storage pressures at each location are dependent on several factors. While an individual production facility might find it beneficial to produce and store hydrogen at as low as atmospheric pressure, this would cause complication when this storage was to be discharged into the high pressure transmission system. (A compressor would be needed to elevate the pressure to allow discharge.) Thus the production point storage pressure is not totally decoupled from the transmission pressure. Detailed analysis beyond the scope of this work will be required to determine exactly what pressures would be most economical for the system as a whole, but storage at the production point will probably never drop below the production pressure (probably between 100 and 500 psia) or rise much above the transmission pressure (probably less than 1000 psia). This leads to a range of 100 to 1000 psia storage. For energy conservation reasons, the storage pressure at the distribution point will probably approximate the transmission pressure, but this need not be the most economical pressure if high pressure vessels, for instance, were very inexpensive. The end use storage pressure could be almost any value but probably will range from atmospheric to the distribution pressure of 1000 psia. This pressure, like the other two, will coupled to economics at the site plus coupling to the system as a whole.

The capacity of storage will probably be largest at the distribution point, intermediate at the production point (if necessary) and potentially smallest at the end use point. Based on natural gas consumption, a distribution point serving a city of one million and storing 30 average days consumption, would require storage of 81 million pounds of hydrogen. A large solar hydrogen production plant (100 MW_e) might produce only 60,000 pounds of hydrogen in 12 hours, meaning that a storage capacity of 30,000 pounds might be appropriate to keep the transmission line full at night and perhaps (2 12 hour shifts pounds production) might be stored in a weekend for an alternate situation where consumption was low on weekends and poor weather was approaching. The desirable storage capacity at the end use point will be very dependent upon the specifics of the situation. No hydrogen storage may be desirable at homes while many thousands of pounds may be useful for a chemical plant.

The cycling rate and residence time for hydrogen storage will differ greatly among the three potential storage locations. At the production point cycling (filling and emptying of storage) will probably be daily or weekly. Thus some hydrogen might always be in storage as a backup, but at most would be in storage for less than one week. If natural gas practice is any guide, seasonal storage will be employed at the distribution point with a gradual build up of supply over a three to nine month period. The end use point cycling may be random or regular with stored hydrogen being used daily or hardly at all, depending on the specific end use.

Purity, size, weight, and safety factors all come into play in different ways for different application locations also. Production and distribution sites may or may not be tightly constrained in available land but weight of such storage might not be a great concern. End use storage will more than likely be constrained in size due to incorporation into a larger and more diverse (e.g., chemical) production plant; here weight may come into consideration if, for example, the hydrogen were to be stored on a roof top. Chemical purity may be crucial at the production and distribution sites since high quality hydrogen may be expected by some of the end users. However, some end users may not care at all about methane contamination, for example, and might be able to use a storage technology which allows such impurities.

Two observations can be made after examining these considerations as summarized in Table I. First, no single storage system is obviously best for all three of these application locations. It is not even clear that one type of storage could be readily and acceptably adapted for universal application throughout. Second it is not clear what effect the economics of storage may have on desirable pressures, sizes, etc. What is clear is that since storage is not free, some analysis must be performed to properly integrate hydrogen storage into a postulated scenario of widespread use. The remainder of this report deals with that integration and the general principles for fixed site hydrogen storage which emerge.

Table I

Desirable Ranges of Storage Parameters

Parameters	at Production Site	at Distribution Point	at End-Use Point
Pressure Range	Production Pressure 100-1000 psi	Distribution Pressure 500-1000 psi	End-Use Pressure Any
Capacity	Half-Day's Production to Weekend's Production	Seasonal Use Size 10-30 days useage	Any
Cycling	Daily or Weekly	Weekly or Seasonal	Random or Daily
Residence Time	Continuous w/Daily Cycling	3-9 Months	Any 1 Day to 1 year
Purity	High	High	May Not be Critical
Size	Possible Limitation	Possible Limitation	Limitation
Weight	No Limitation	No Limitation	Possible Limitation
Safety Factor	Very High	Very High	High

III. Storage at the Production Point

It is useful to classify hydrogen production techniques as to their constancy of rate since this directly impacts their storage requirements. Sources of hydrogen can be broken into two types: continuous and intermittent, as summarized in Table II. Dedicated baseload electrolysis will be a continuous source by definition. In general, chemical process off-gases will be constant since most chemical plants operate 24 hours per day. This would include a plant dedicated to hydrogen production from plentiful and available feedstocks such as coal. Such plants will probably operate continuously to pay back their high capital investment.

Table II

Storage at the Production Point

Continuous Sources	Intermittent Sources
Dedicated Baseload Electrolysis	Solar
Chemical Process Off-Gas	Off-Peak Electric
Thermal Water Splitting	
Coal Cracking	

It appears that the only envisioned time-varying sources of hydrogen will be either off-peak electrolytic production or solar-based production of any kind. The former plant would operate most nights and weekends, depending on the availability of inexpensive electricity. The latter type (solar) will have the expected daily plus weather-induced variations in production rate.

While small amounts of storage might be warranted at any production site to carry over through maintenance schedules, continuous sources will not need any sizable storage (of the type of interest here) at the production site. A continuous source has no need for storage since its transmission rate will in general be designed to match its output. Intermittent production _may_ need storage. The two probable intermittent hydrogen sources are examined separately and in some detail below.

A. Solar Hydrogen Production

Solar is one source of hydrogen whose nature is basically periodic and hence may require storage of hydrogen. If such a solar plant has its own inherent storage, whether in the form of batteries or thermal storage, this periodicity will be greatly smoothed and the need for storage of hydrogen reduced. To provide an upper bound for the desirability of hydrogen storage, the assumption of _no_ inherent solar plant storage was used.

From experience in solar energy applications[1,2,3] it has been shown that by far the most economical, justifiable, and important storage requirement is that for diurnal (nightly) needs. Although the length of night varies somewhat over the year, a simple on/off 12 hour night model was used. The basic question then asked was: "Does it make sense to build storage to smooth out the transmission rate of hydrogen, or should the pipe be (over) sized to take the full production rate?" With this simplified solar model, this latter case really means doubling the hydrogen carrying capacity of the pipe. It was further assumed that the hydrogen would be transmitted to a load center (end use point) or a distribution center (with its own storage) or to a larger transmission pipe capable of handling as much hydrogen as one could give it.

A uniform periodic hydrogen source with a sink some distance away is thus being considered. It is clear that for inexpensive storage and expensive piping, hydrogen will be stored to smooth the transmission rate unless the distance is extremely small. Conversely, if storage is expensive and piping is inexpensive, one could afford to build an oversized pipe of considerable length. Thus, the answer of whether storage is preferable to pipe oversizing or not must depend on the relative costs of storage and transmission and the pipe length.

Using consistent costs from Gregory's "A Hydrogen-Energy System"[4] there is a break-even distance below which one transmits and above which one stores. This distance is 3.2 miles times the storage capital cost in 1972 dollars per million BTU. (Throughout, MBTU is used as an abbreviation for million BTU). This curve is shown in Figure 1. Here, the storage cost estimates from the same reference are also shown. The technologies are briefly described in the Appendix.

The "liquid dewar only" cost is just that, and does not include liquefication capital or energy costs which will drive it far to the right. The equivalent add on capital cost due to liquefication plant costs is 8000 $/MBTU (assuming $40 million for a 10000 MBTU/day plant[5] operating continuously with storage emptying nightly). The equivalent add on capital cost due to liquification energy requirements is 10950 $/MBTU (assuming 6KWhr/lb, a low 10 mills/KWhr, 10950 cycles over a 30 year period, escalation rate for electricity equal to the discount rate). The sum of these costs completely swamps the "dewar only" costs moving liquid hydrogen storage far to the right. This leaves a large gap between cavern and steel constructed storage costs.

Figure 1 tells us, for example, that if steel pipe storage is the cheapest available the transmission pipe would be oversized up to a length of over 500 miles to avoid storage. The cavern storage break-even distances range from 10 to 60 miles. The question thus remains of the characteristic distance from hydrogen solar source to sink. Major gas transmission lines already pass through the heart of the solar rich Southwest and one would be hard pressed to locate a hydrogen plant more than 500 miles from such a line as seen in Figure 2. To give the reader some idea of typical solar plant distances from transmission lines: a strip of land 6.4 miles wide the length of one major Southwest transmission line could conservatively produce an enormous quantity of hydrogen, 5 Quads or one fourth of the annual U.S. natural gas consumption. This would imply transmission feeders up to 3.2 miles in length. Thus, steel constructed storage will probably never make sense for solar hydrogen but cavern storage might make sense for plants relatively remote from the major gas lines.

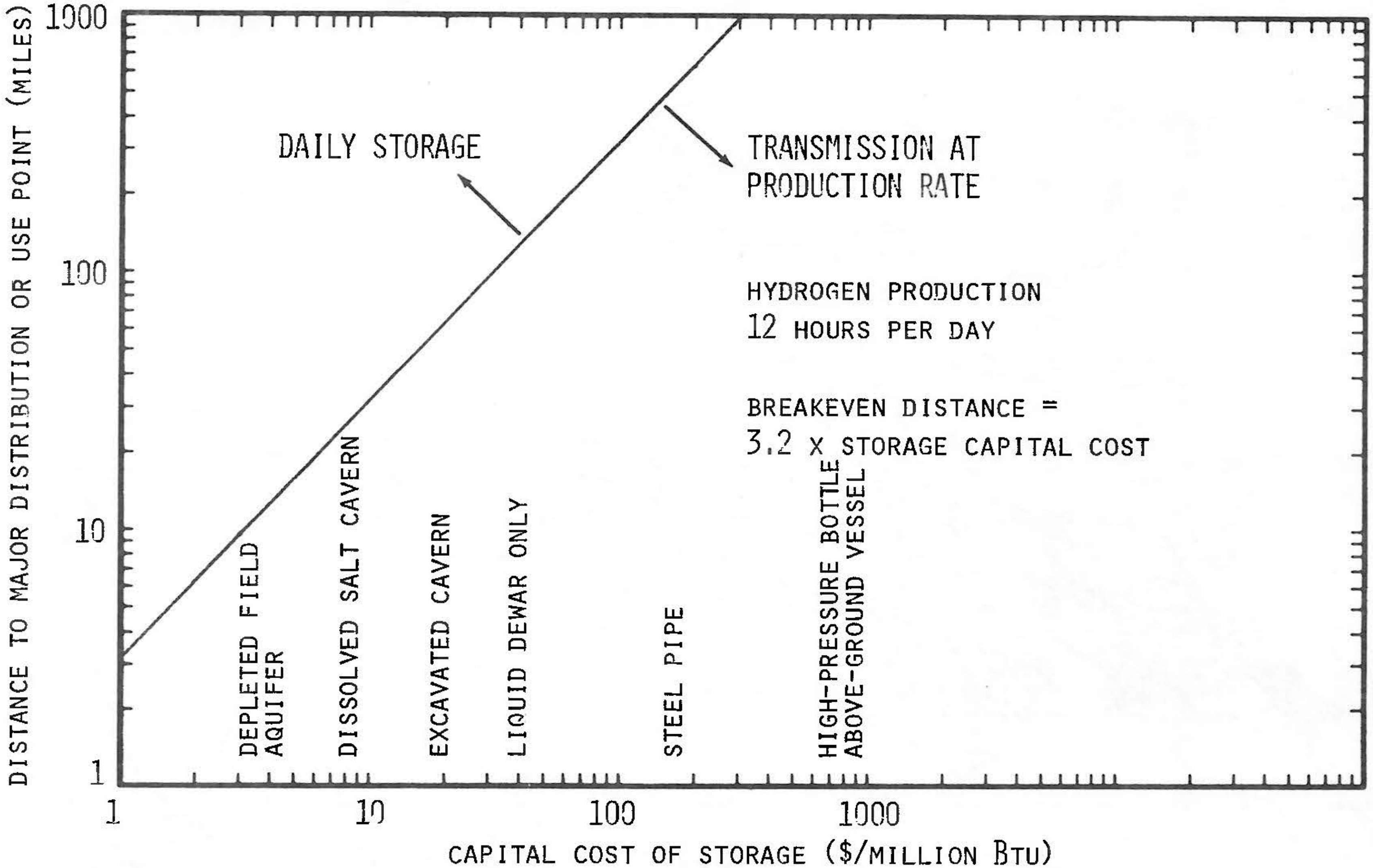

FIGURE 1: BREAKEVEN TRANSMISSION DISTANCE VERSUS CAPITAL COST OF STORAGE FOR SOLAR HYDROGEN PRODUCTION

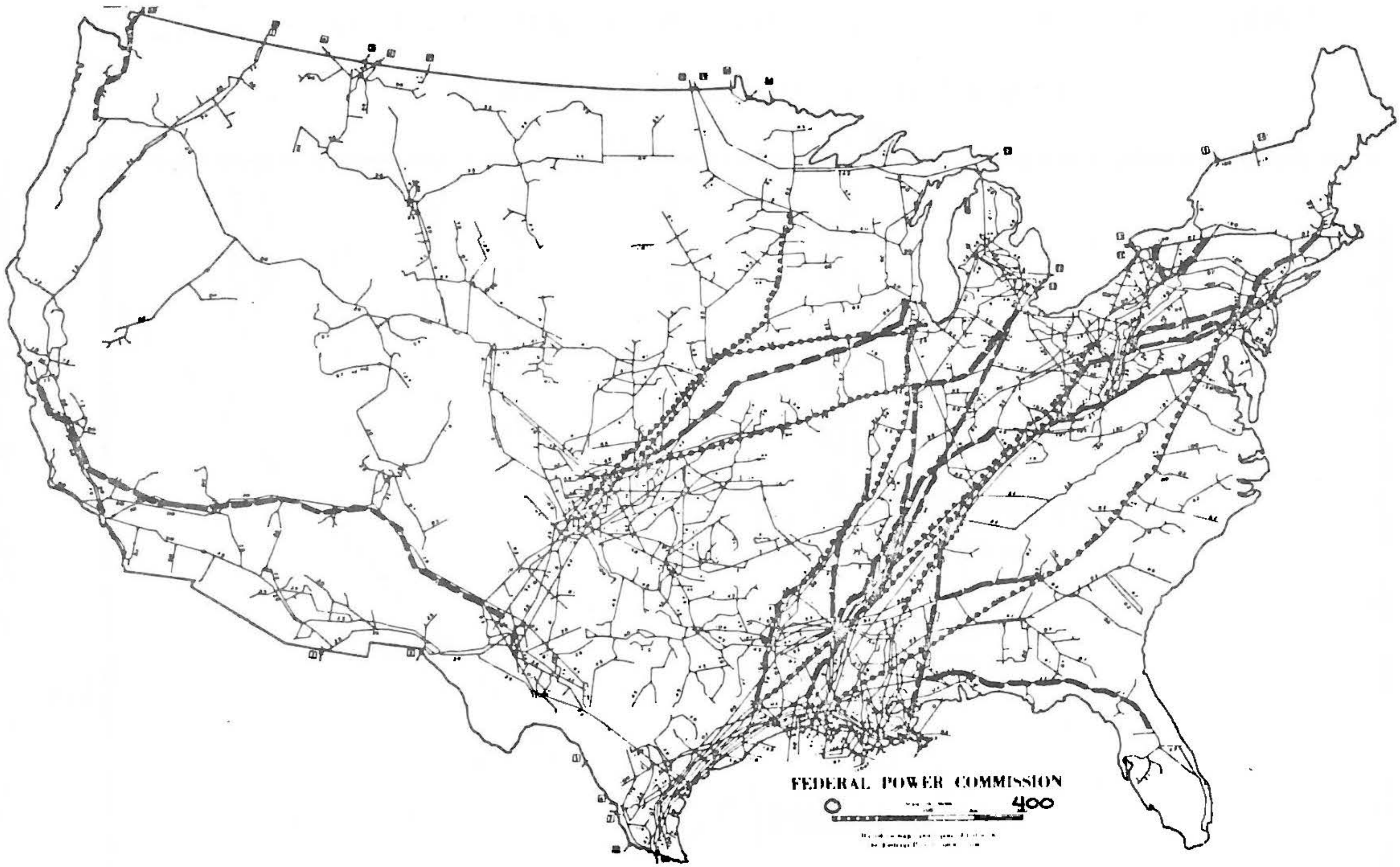

Figure 2. Major Natural Gas Pipelines [13]

The assumptions used above are slanted toward favoring storage in several ways. First, it was assumed that doubling the carrying capacity of the pipe would double the cost. This is not true since only one right-of-way needs to be purchased and there may also be some economy of scale with respect to carrying capacity (relatively reduced pipe costs, compressor installation costs). Perhaps more important is the assumption of one plant/one pipe. In actuality, plants may well be clustered able to smooth hydrogen production rates and to share right-of-ways and the above-mentioned economies of scale. The result is then quite broad and pessimistic as to the value of hydrogen storage for solar hydrogen production. Even cavern storage may not be economically justifiable if the plant is with 10 to 60 miles of a large transmission line, a likely situation as can be seen in Figure 2, a map of major gas pipelines.[6] In almost all cases, then, the transmission line from the plant should be sized to handle the peak production rate, and storage is not necessary.

B. Off-Peak Electrolysis Hydrogen Production

The second likely intermittent hydrogen source is electrolysis from off-peak electricity. A utility might replace an intermediate or peaking load plant with a less expensively fueled baseload plant. Off-peak power would then be available at low cost for uses such as electrolysis of water. These off-peak periods are typically at night and on weekends continuously. Again an isolated electrolysis plant is analyzed to see if storage of this hydrogen can be justified as opposed to oversizing the gas transmission system. The same type of analysis as in the solar case yields the same conclusion with two important differences. First, the weekend production of say 60 straight hours might make the amount of storage required about five times larger than the solar case; this makes the breakeven transmission distance longer by approximately that factor. Second, off-peak power will mostly be available even closer to major gas pipelines or end use points (sinks) than in the solar case. (Most of the electric power is produced near and certainly transmitted into population centers, where pipelines are plentiful.) For these reasons hydrogen storage appears even less economically justified for off peak electrolysis than it is for solar. Of course, if very inexpensive cavern storage were available, it might be utilized.

A reasonable solution to this storage problem might be to place the electrolyzers near the envisioned regional distribution storage location (see below) and use the off-peak electricity from many baseload plants to charge one large storage system. This eliminates both hydrogen storage at the electric plant and hydrogen transmission from the electric source to the distribution point and provides better utilization factors for the large electrical grid already in place.

IV. Storage at the Distribution Point

Storage at the distribution point is the most likely place to smooth mismatched production and end-use rates for hydrogen. It will probably take the form of seasonal storage with weekly fluctuations due to weekend production and consumption variations. This is consistent with current natural gas practice of sizable storage at such distribution points. Currently storage of 20 to 30 average day's consumption of natural gas is sufficient to smooth seasonal variations in demand.[7] The assumption is made here that this many BTU's of hydrogen is a reasonable quantity of stored gas for a scenario of widespread hydrogen use. It is interesting to note that while natural gas supply and consumption have recently been declining, the utility storage capacity has risen steadily for over 30 years.[8,9] (See Figures 3 and 4.) This situation is not likely to reverse itself in the forseeable future. Indeed, currently there is sufficient storage volume to hold over 100 days of U.S. consumption[7] as opposed to the 20 to 30 days actually used. Not all of this excess capacity is readily usable for gas storage as it represents a reserve margin and cushion gas to assure rapid discharge rates.[10] However, even accounting for hydrogen's reduced heating value (with respect to natural gas), sufficient energy capacity already exists for almost all of the envisioned seasonal requirements for hydrogen at the distribution point, in these currently used volumes.

There may be some remaining technical, institutional, and safety considerations which might eliminate the use of present cavern and similar storage for hydrogen storage, and thus it is important to examine the surprising cost of the alternatives. Currently 7×10^9 million BTU of natural gas is in storage in the U.S.; should this or similar underground storage be infeasible for hydrogen, the next best alternative may be above-ground constructed vessels in the \$1000 per million BTU range (capital cost, 1972 dollars). This results in an initial capital investment (1972 dollars) for hydrogen storage of 7×10^{12} (seven trillion) dollars. With an optimistic fixed charge rate of 15% this works out to an incremental expense (due to storage) of \$50 per million BTU delivered (1972 dollars) for a typical year's consumption rate of 20×10^9 million BTU per year. This 50 dollar per million BTU expense should be compared to the current delivered natural gas cost of approximately 2 dollars per million BTU. To bring this incremental expense due to storage alone down to \$2 per milion BTU the storage capital costs will have to drop to \$40 per million BTU, well below any possible constructed vessel costs.

It appears then that unless reasonable underground storage is available, that operating storage as it is now done will not be viable due to extremely high costs. Another way to put this potential 7 trillion dollar expenditure in perspective is to compare it to the cost of replacing the entire current natural gas pipeline system. When costs from Gregory[4] with pipe lengths and carrying capacity estimates[6] are used, a ballpark cost of 110 billion dollars (60 billion for transmission, 50 billion for distribution lines) is obtained. This is still an enormous cost, but it is one sixtieth of the storage cost estimate. In other words, if inexpensive underground storage is infeasible, the pipeline economics become trivial compared to the storage problem.

V. Storage at the End-Use Point

The final location for consideration of hydrogen storage is at the end-use point. Of course, hydrogen storage will not be necessary if hydrogen is available on demand as natural gas is now. Residential hydrogen end-use

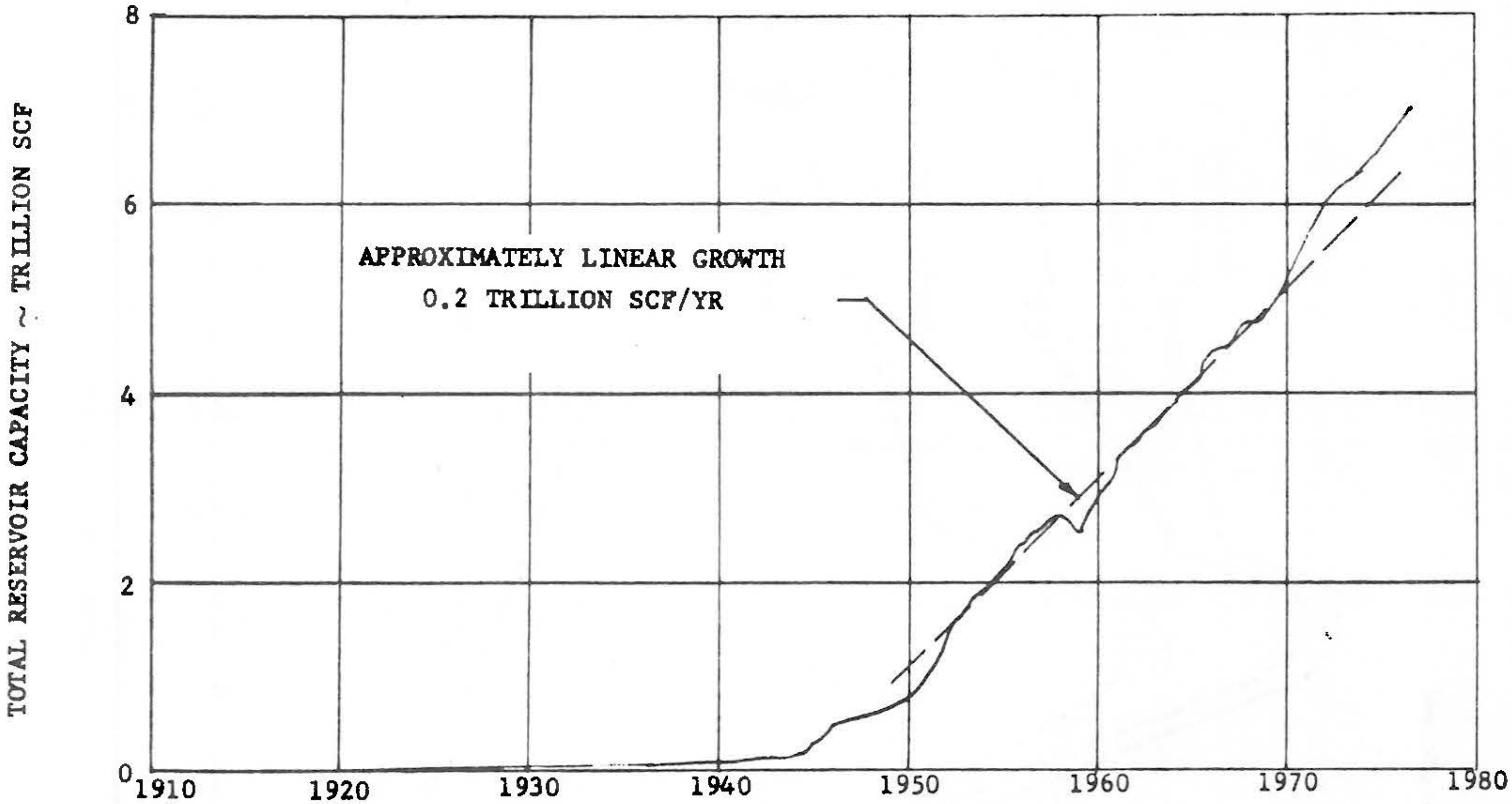

Figure 3. Growth of Underground Gas Storage in the United States from Fugita [9]

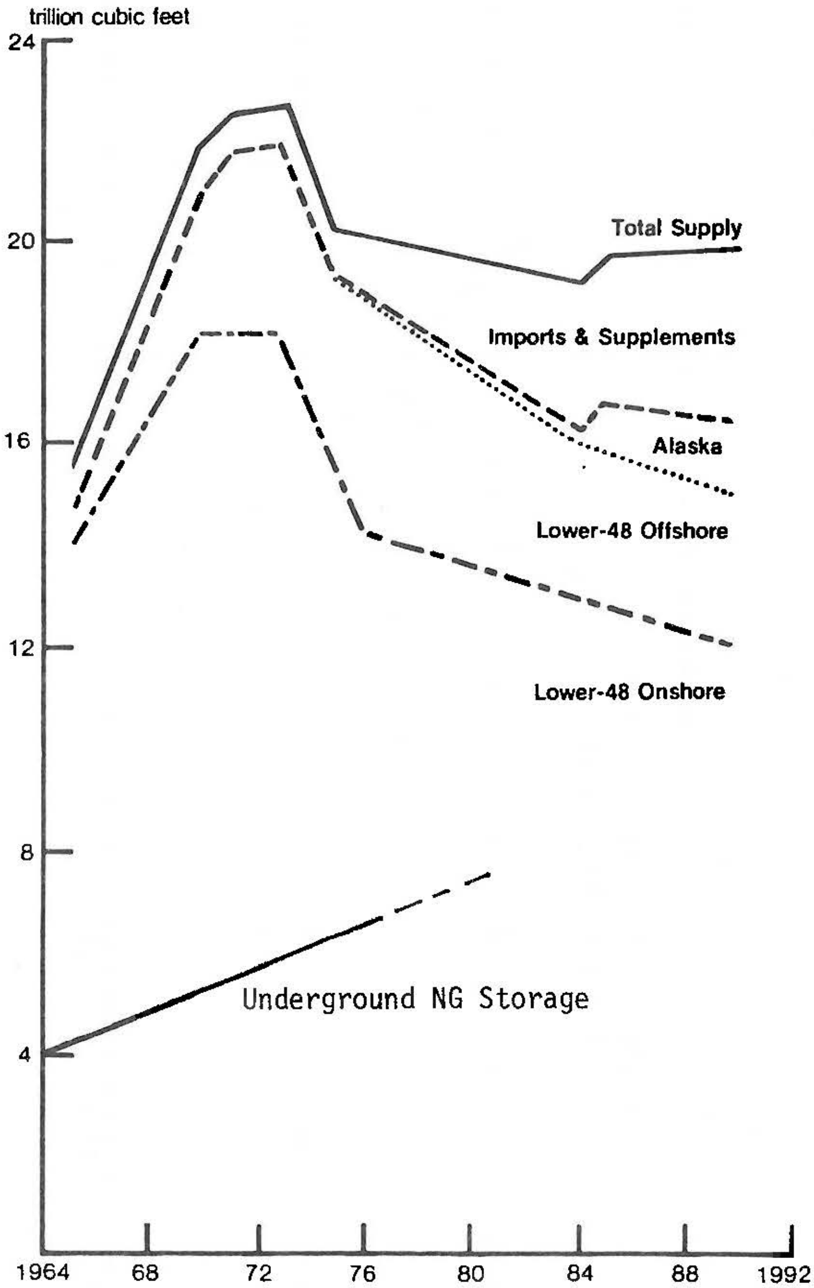

Figure 4. Projected U. S. Natural Gas Supply and Storage Capacity [8,9]

will be provided by a hydrogen utility and will probably parallel current natural gas consumption patterns and regulations. This residential service will be of the highest priority and will be rarely, if ever, interrupted. No widespread storage will then be needed in homes. For commerical and industrial users, while natural gas is now offered to larger customers on a utility interruptable basis only, very few, if any of these currently, store natural gas in any quantity for both safety and economic reasons. Oil storage is currently much preferred to gas storage. If oil remains a viable backup fuel, its storage will be even more preferable to hydrogen storage since hydrogen will be many times more expensive per BTU to store than natural gas. Beyond these arguments the underlying assumption of an abundant hydrogen supply implies very few interruptions, especially if there is seasonal storage at the distribution point and a well sized distribution system.

The primary non-residential uses are envisioned[11] to be as a feedstock for other chemicals such as ammonia, methanol, and others. These will no doubt be large, capital intensive chemical plants, as they are now. Such plants normally operate 24 hours per day with a more or less continuous demand for and consumption of hydrogen. At present these plants would have no alternative but to store hydrogen for their needs since no hydrogen distribution system exists, but if hydrogen were as plentiful as natural gas is now, they would merely connect to the distribution network. Some small scale storage might be worthwhile, such as a plenum to smooth out possible pressure fluctuations or for other unknown reasons.

VI. Conclusions

The storage requirements in a scenario of widespread hydrogen use are shown in Table III. While solar and off-peak electric intermittent production of hydrogen might seem to demand storage at first, closer examination shows

Table III

Summary of Storage Requirements

Application	Storage Requirements
Continuous Production Point	None
Intermittent Production Point	Cavern Storage Viable Only
Distribution Point	Current Natural Gas Technology And Capacities May Be Sufficient
End Use Point	None

that oversizing the transmission pipes from them is preferable to all but the least expensive storage. Continuous production or envisioned end-use points have no inherent need for storage at all. As with current natural gas consumption, the overwhelming need for storage will be at the distribution point to satisfy seasonal demand variations. Due to a decline in gaseous fuel consumption and an increase in underground storage capacity, the current natural gas storage capacities may be of sufficient capacity for future hydrogen use, even accounting for its lower heating value.

Hydrogen storage in a scenario of widespread usage should be a serious concern. Unless the majority of the current underground natural gas storage can be converted to hydrogen use or similarly low cost storage techniques can be developed, the envisioned hydrogen supply system will be burdened with an enormous capital investment of many trillions of dollars for new storage. This size investment for storage alone is unspeakable. This storage concern is potentially much more economically serious than the possible replacement of the entire gas transmission and distribution system.

Several studies[9,10] have shown that underground storage of hydrogen may well be feasible. If this should prove to be the case, storage wil resume its natural place as a moderately low cost component in the network. Should this not be the case, the only alternative to these large storage costs will be to change this nation's gaseous fuel consumption pattern wholesale; this does not seem feasible.

There may be site specific conditions for which underground storage is infeasible or smaller scale applications where the economics do not favor underground storage. These possibilities are explored in a companion paper.[12] At present, a general or pressing need to develop large, fixed site hydrogen storage technology beyond the conversion of underground storage from natural gas to hydrogen has not been identified.

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APPENDIX

Description of Storage Technologies

Although described in some detail in other sources,[4,12] it may be useful to the reader to have a brief description of the storage technologies shown in Figure 1.

Underground storage techniques are depeleted gas and oil fields, aquifers, dissolved salt caverns, and excavated caverns. Currently depleted gas and oil fields are in extremely wide use for natural gas storage.[7] These fields and aquifers are basically deep underground regions of porous permeable rocks, usually sedimentary in nature. In the case of depleted fields, this porous rock region is bounded by impermeable caprock and the storage pressure is usually held below the 1 psi per foot of depth rule of thumb to ensure the integrity of the "vessel." Aquifers differ slightly in that the impermeable barrier is a domed caprock above and a moveable water interface below. The gas is stored essentially as a bubble; as the pressure is increased, the water interface recedes slowly downward. The gas displaces the water in the rock pores. As gas is withdrawn, the water level rises slowly. Regarding gas tightness for hydrogen service, if an aquifer or depleted field has been used successfully in natural gas service, it should also be gastight in hydrogen service. In both these storage techniques, the sealing mechanism is physical and not chemically selective.[4] Dissolved salt caverns and other mined cavities involve large void spaces. Salt caverns can be and have been, formed by leaching with water and pumping out the brine. Gases have been stored in such caverns. Mined hard rock caverns are more expensive as they are produced by standard mining techniques, either by blasting and hauling or by boring to avoid unnecessary fracturing of the walls. Such excavated caverns may have to be made gastight; at least one abandoned coal mine is currently in natural gas service.[7].

Liquid hydrogen storage, discussed in some detailed in the text, consists of a liquefaction plant, piping to storage, a dewar and piping to handle boil-off recovery. The dewar itself may not be expensive but the liquefaction plant will be costly. Further, liquefaction is fairly energy intensive requiring 4.5 to 6 kWhe per pound of hydrogen liquefied.

Steel pipe storage consists of sections of large transmission line pipe joined together and pressurized for high pressure storage of hydrogen. A special case of pipe storage is called linepack; here no special pipe vessel is constructed, but rather the transmission line is overpressurized (beyond pumping pressure requirements) allowing storage in the transmission system itself. This may or may not be feasible for hydrogen service. The upper bound pressure of a hydrogen system will be set by chemical constraints on embrittlement, lower than the mechanical strength of the pipe itself. The transmission system will probably be at or near this pressure limit almost continuously, allowing no freedom to linepack. Above ground pressure vessels are of standard high pressure design, either tube or bullet type of vessels or larger thick walled tank designs. These are plentiful in both natural gas and hydrogen service.

A wider range of hydrogen storage technologies are described and costed in greater detail in Reference 12.

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