

On-Board Hydrogen Generator for a Partial Hydrogen Injection Internal Combustion Engine

John Houseman and D. J. Cerini

Jet Propulsion Lab., California Institute of Technology

THE REDUCTION of NO_x emissions from an internal combustion (IC) engine continues to be a difficult problem, particularly when the constraint of maintaining high engine efficiency is added. This paper deals with selected aspects of a modified fuel system, so-called partial hydrogen injection, that substantially lowers NO_x emissions and also increases engine efficiency considerably.

The production of NO_x is strongly dependent upon the flame temperature of the combustion process. When combustion is carried out under stoichiometric conditions, the flame temperature is close to the maximum value, and consequently NO_x formation is close to a maximum. The flame temperature can be lowered by operating either fuel-rich or fuel-lean.

Note: This paper presents the results of one phase of research carried out at the Jet Propulsion Laboratory, California Institute of Technology, under Contract No. NAS7-100, sponsored by the National Aeronautics and Space Administration.

Fuel-rich operation has the disadvantage of requiring exhaust-gas aftertreatment to oxidize residual hydrocarbons and carbon monoxide. The heat of combustion of the secondary oxidation step cannot be utilized efficiently, and consequently fuel-rich combustion systems have lower overall efficiencies.

Lean combustion thus seems an obvious choice over rich combustion. However, hydrocarbon fuels have a fairly narrow flammability range, and the extent of lean combustion is limited by the lean flammability limit of the fuel. For instance, in an IC engine, misfiring starts at air/fuel ratios (A/Fs) above 18. This figure varies considerably from engine to engine, depending on the uniformity of the A/F from cylinder to cylinder. Complete combustion in a single cylinder CRF engine up to an A/F of 24 has been demonstrated. However, to decrease NO_x formation to the order of 0.4 g/mile, one can project that an A/F of approximately 30 would be required (1)*. Clearly, this is not possible with hydrocarbon fuels.

*Numbers in parentheses designate References at end of paper.

ABSTRACT

A compact onboard hydrogen generator has been developed for use with a hydrogen-enriched gasoline internal combustion engine. The unit uses gasoline and air in a partial oxidation reactor to produce a gaseous product containing hydrogen, carbon monoxide, minor amounts of methane, carbon dioxide and water, and nitrogen. A study of the theoretical equilibrium product composition has indicated an optimum operating point at an air/fuel ratio of 5.15, where a hydrogen/fuel mass ratio of 0.136 can be obtained under soot-free conditions. This is based on a gasoline with an atomic hydrogen to carbon ratio of 1.92.

Both thermal and catalytic reactors have been tested. The thermal unit requires a reaction temperature of 2400°F to obtain 80% of the theoretical hydrogen yield. Soot formation tends to be a problem. The catalytic reactor yields close to theoretical yields at an operating temperature of 1800°F without any soot formation. A commercial nickel catalyst is used. A 100 h test with the catalytic unit showed no signs of performance degradation, using fully leaded Indolene 30.

The calculated effect of hydrogen generator operating conditions on the fuel efficiency of a generator/engine combination is presented.

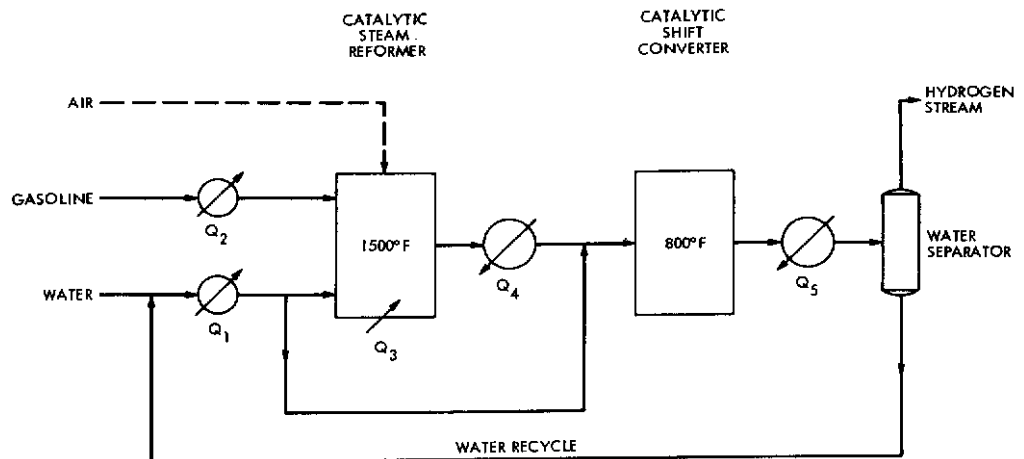


Fig. 1 - Process schematic of industrial hydrogen generation

A solution to this dilemma has now been found by using a mixed fuel consisting of gasoline and a small amount of hydrogen. It has been demonstrated that mixtures of hydrogen and gasoline will burn at an air to (mixed) fuel ratio of 30, resulting in very low NO_x levels and increased efficiency. (1)

The basic explanation for this phenomenon lies in the extremely low lean flammability limit of hydrogen, which occurs at an A/F of approximately 340 (on a mass basis). The lean limit of gasoline /hydrogen mixtures thus extends over a range of A/Fs from 24 to 340, the actual ratio depending on the relative amounts of hydrogen and gasoline. As indicated earlier, the low flame temperature associated with ultra lean combustion accounts for the low NO_x formation. The lower flame temperature also reduces the energy losses to the radiator cooling fluid and to the surroundings, thus increasing engine efficiency. The excess air in the combustion gas dilutes the carbon dioxide and water content of the conventional exhaust, thus decreasing the triatomic molecular content. This reduces the specific heat ratio c_p/c_v of the combustion gas, which also increases engine efficiency.

There are some obvious advantages in a system that utilizes mixtures of hydrogen and gasoline rather than all hydrogen. The main ones are better acceleration response and a smaller hydrogen generator. (2)

The feasibility of using hydrogen/gasoline mixtures was first demonstrated in a single-cylinder CRF engine, subsequently in a 350 in³ V8 on a dynamometer, and finally in an automobile. This vehicle uses two K bottles of compressed pure hydrogen gas to supplement the gasoline fuel. The results of these tests, including CVS driving cycle tests, have recently been reported. (2)

To translate the partial hydrogen injection concept into a practical engine system for an automobile, a satisfactory onboard source of hydrogen must be found. This paper is concerned with the work carried out at the Jet Propulsion Laboratory (JPL) to solve this problem. Engine dynamometer tests with the hydrogen generator described in this paper are currently in progress, and the results will be reported in the near future.

ONBOARD SOURCES OF HYDROGEN

Hydrogen is a very light gas and can only be stored in liquid form at cryogenic temperatures. It appears that onboard storage of cryogenic liquid hydrogen and subsequent frequent refilling represents too many problems to be a practical solution. Storage of hydrogen as a solid mixed hydride (3) appears to have some promise but is still in too early a stage of development to be considered for a near-term application. The obvious choice is to generate the hydrogen onboard from gasoline. Processes for generation of hydrogen from hydrocarbons have been in industrial operation for a long time. The most common of these processes is the steam reforming process, which is depicted schematically in Fig. 1. A mixture of steam and hydrocarbon fuel is heated over a nickel catalyst at a high temperature to yield a mixture of hydrogen and carbon monoxide.

The carbon monoxide is reacted with more steam over a "shift-conversion" catalyst at a lower temperature to yield more hydrogen and carbon dioxide. The excess steam is condensed out and separated from the hydrogen stream. The various heat exchangers and their heat loads are represented by Q_1 - Q_5 . A small-scale unit (4) based on this process has been developed to make hydrogen from natural gas for use in a fuel cell. The major drawback of this process is its complexity. The operation of the steam reformer at a specified temperature, followed by shift conversion at a specified lower temperature, followed by water separation represent temperature and flow control problems that were considered to be too complex for an automotive application.

It was decided to simplify the system by using only the steam reforming step. Steam reforming is a highly endothermic reaction, and external heat Q_3 has to be transferred to the reactants. Industrially, this is accomplished by mounting the reaction tubes containing the catalyst inside a direct fired furnace. In such a configuration, the external wall temperature of the reactor is considerably higher than the reactant temperature, the rate of reaction is normally heat transfer limited. Some work has been done on developing a small-scale steam reformer for automotive use without using a catalyst. (5)

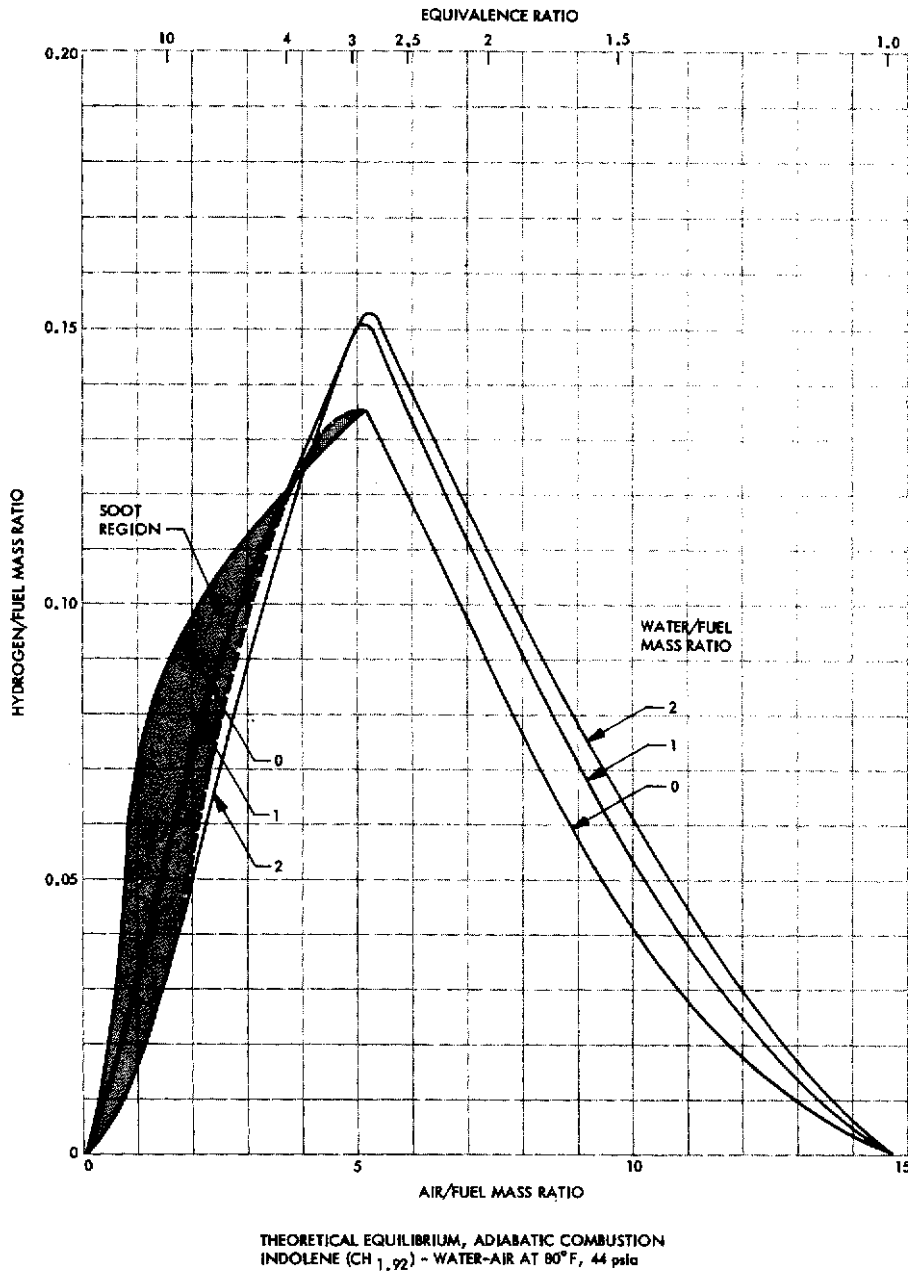


Fig. 2 - Hydrogen-to-fuel mass ratio

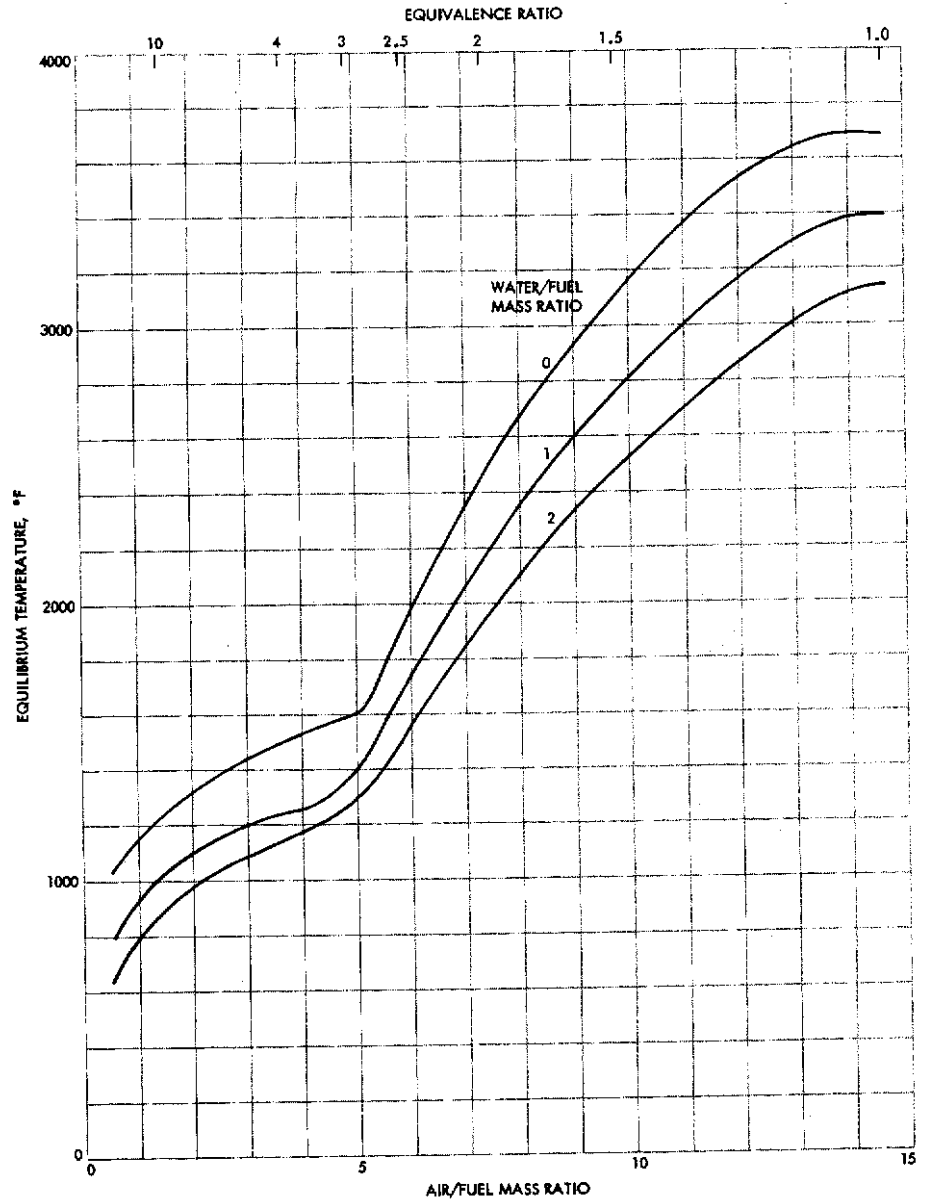
Considerable difficulties were encountered with soot formation and in finding suitable materials of construction for the high temperature heat exchanger.

Another way to supply the energy Q_3 for the steam reforming reaction is to add some air to the reactants, as indicated by the dotted line in Fig. 1. This produces internal heat release by partial oxidation of the hydrocarbon. In this manner, the external heat supply can be eliminated. The disadvantage of this method is the presence of nitrogen in the product gas. However, for an automotive application, this is not a major cause for concern, as all of the hydrogen generator product gas is fed to the IC engine. The latter is to be operated with a large excess of air so that the presence of the relatively small amount of nitrogen from the generator is of minor consequence.

Thus, the partial oxidation steam reforming process was

selected as the most promising one for onboard hydrogen generation. Partial oxidation steam reforming can be carried out with or without a catalyst. The use of a catalyst always has a potential catalyst poisoning problem, in this instance, by sulfur or lead components in the gasoline or by carbon formation. Industrial partial oxidation steam reforming processes have been developed that avoid catalysts. Specific examples of these processes are the Texaco and Shell processes, which use oxygen, naphtha, and steam as reactants. Both processes produce a definite amount of soot. (6) One such plant was operated with air (rather than oxygen) for several months because the oxygen plant had not been completed. (7)

Based on these considerations, experimental work was started to develop a small-scale hydrogen generator based on the thermal partial oxidation steam reforming process, using air, gasoline, and water to produce a hydrogen-rich gas.



THEORETICAL EQUILIBRIUM, ADIABATIC COMBUSTION
INDOLENE ($CH_{1.92}$) - WATER-AIR AT 80°F, 44 psia

Fig. 3 - Equilibrium temperature

INITIAL WORK ON PARTIAL OXIDATION STEAM REFORMING

A pneumatic atomizer was used to produce a spray of extremely fine gasoline droplets that were burned within a mixture of steam and air preheated to about 600°F. Reasonable yields of hydrogen were obtained, but objectionable amounts of soot were formed. It was found that by vaporizing the gasoline and premixing it with steam and air, the soot production could be greatly reduced. Under these conditions, the use of steam did not greatly increase the hydrogen yield, but it did act as a soot suppressant.

It was originally estimated that a 5 gal water tank would be required to carry the necessary amount of water. The additional cost of a water tank and the cost of providing service station facilities for refilling regularly with pure water on a

national scale would represent an enormous investment. In cold weather, the addition of an antifreeze agent to the water or the use of heaters to prevent freezing of the water amounts to another complication. Consequently, a strong effort was made to develop a hydrogen generator that does not use water. Attention was then focused on hydrogen generation by direct partial oxidation of hydrocarbons with air.

THEORETICAL BACKGROUND

In order to discuss the hydrogen yield and soot formation in any hydrocarbon-steam-air system, the equilibrium condition should be considered. Fig. 2 represents the theoretical yield of hydrogen that can be obtained from the adiabatic combustion of mixtures of air, hydrocarbon, and water. In these calculations, an atomic hydrogen-to-carbon ratio of 1.92 was

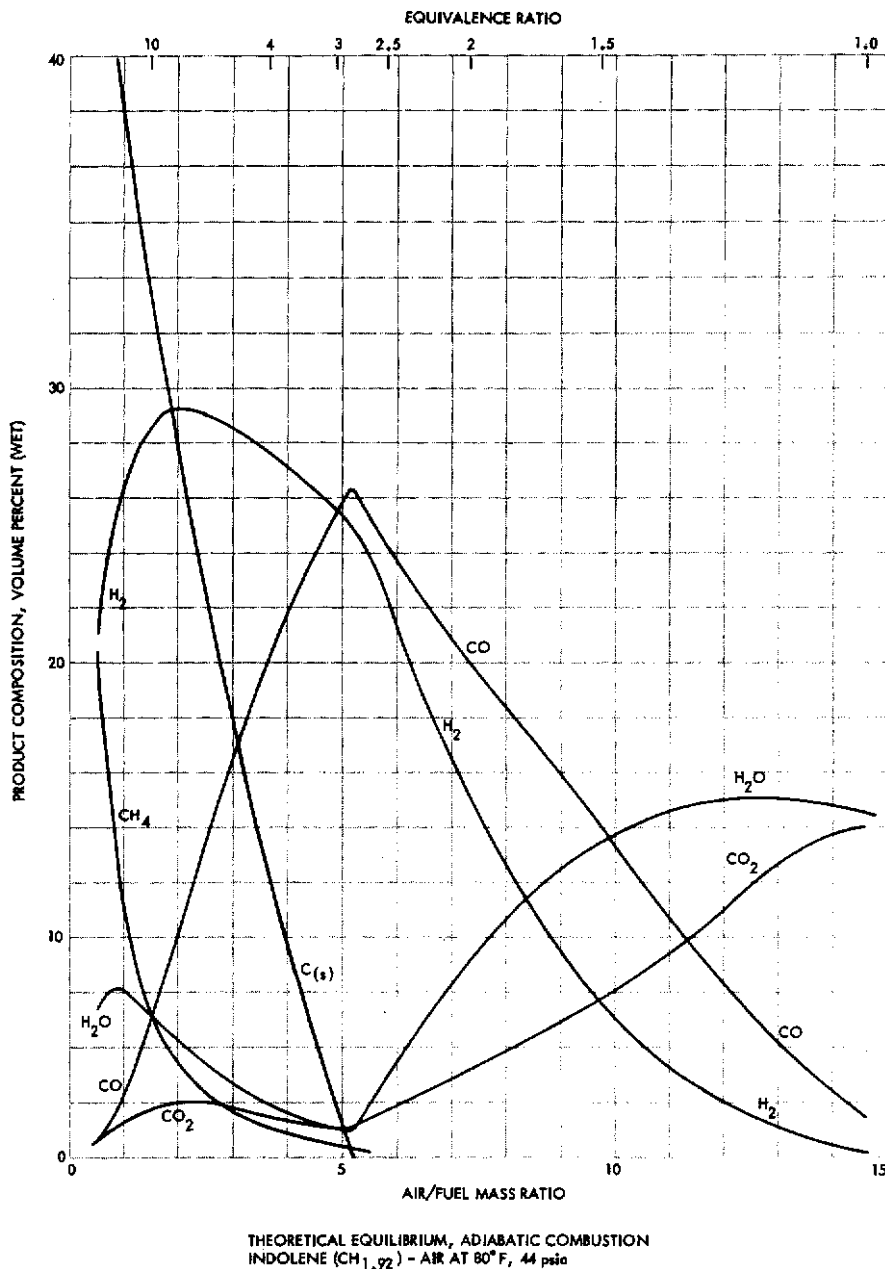


Fig. 4 - Product composition

used. This is about the same value as for Indolene (federal test gasoline). Diagrams for other hydrocarbon fuels are very similar. It should be realized that in actual practice the chemical kinetic rate of reaction may control the product formation. Chemical equilibrium thus represents only a goal which may or may not be achievable. The hydrogen yield in Fig. 2 is expressed as the mass of hydrogen produced per unit mass of fuel, as a function of the air/fuel mass ratio and for water/fuel mass ratios of 0, 1, and 2. The adiabatic flame temperature as a function of the same parameters is shown in Fig. 3. The air/fuel mass ratio scale is also shown in terms of equivalence ratio at the top of the figures. Fig. 4 shows the distribution of the various species as a function of the A/F when no water is added.

As seen in Figs. 2 and 4, for zero water addition, the hydrogen yield increases from zero at stoichiometric air/fuel with

decreasing A/Fs until it reaches a maximum at an A/F of 5.15, where soot formation starts. The production of soot increases considerably at lower A/Fs. The addition of water does not greatly increase the hydrogen yield, as shown in Fig. 2, and strictly on this basis the considerable complexity of adding water does not seem warranted. However, the water addition has another very valuable function; it suppresses soot formation. For instance, with a water-to-fuel ratio of 1, soot should only form below an A/F of 3.9, compared to an A/F of 5.15 without water. The soot suppression value of water addition is of particular importance when a spray of liquid droplets is being burned in air. There will normally always be some local region around a droplet where the local ratios of air to fuel and water to fuel fall within the soot region. Thus, some amount of soot will always be produced. This problem can be minimized by very fine atomization so that the droplets vapor-

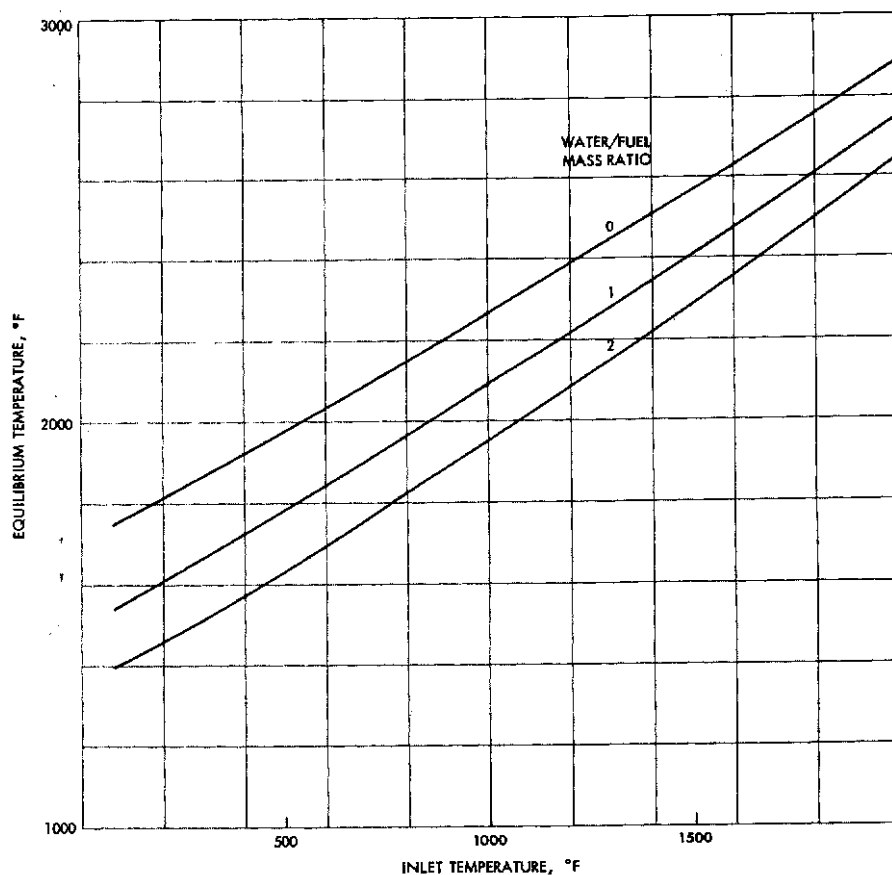


Fig. 5 - Effect of preheat on equilibrium temperature

THEORETICAL EQUILIBRIUM, ADIABATIC COMBUSTION,
INDOLENE (C_8H_7) - WATER - AIR AT 44 psia
AIR/FUEL RATIO = 5.5

Table 1 - Effect of Preheat Temperature on Theoretical Product Composition, Air/Indolene Mass Ratio = 5.5

Inlet Temperature, °F	80	980	2060
Outlet Temperature, °F	1750	2260	2920
Product Composition, mole %			
Combustibles			
H ₂	22.0	21.8	21.5
CO	23.4	23.8	24.1
Inerts			
CO ₂	1.2	0.8	0.6
H ₂ O	1.7	2.0	2.1
N ₂	51.7	51.6	51.7
Total	100.0	100.0	100.0

ize and mix with an air-steam mixture before ignition occurs, thus avoiding local soot regions. This process was tried in the first experiments described above with partial success. Another solution to this problem is to vaporize the liquid hydrocarbon and thoroughly mix it with the air (and possibly steam) before feeding the mixture to an ignition zone. This process assures a uniform A/F for all of the fuel. Experiments have verified that

it is more difficult to avoid carbon formation with liquid drop-let combustion than with a vaporized premixed feed system.

Figs. 2-4 represent the conditions when the reaction has gone to completion; that is, equilibrium conditions have been reached. In practice, the rate at which a reaction proceeds toward equilibrium may be so slow that equilibrium will not be obtained in a finite time period. However, the rate of reaction often increases exponentially with temperature. The partial oxidation of hydrocarbons is such a case. It has been found that higher reaction temperatures result in a closer approach to equilibrium. Higher reaction temperatures, that is, flame temperatures, can be obtained by preheating the air. The equilibrium product composition is hardly affected by the higher temperature. Table 1 shows the equilibrium volume percentage of the various components in the product at three preheat temperatures, and they change very little with temperature.

Fig. 5 shows the effect of the air preheat on the final equilibrium temperature, which is considerably higher with preheat than without preheat.

Summarizing these theoretical considerations:

1. Carbon formation can be avoided by vaporizing the fuel and mixing it with the air prior to ignition, even without water addition, provided the A/F is above 5.15.
2. The addition of steam will yield a greater margin of

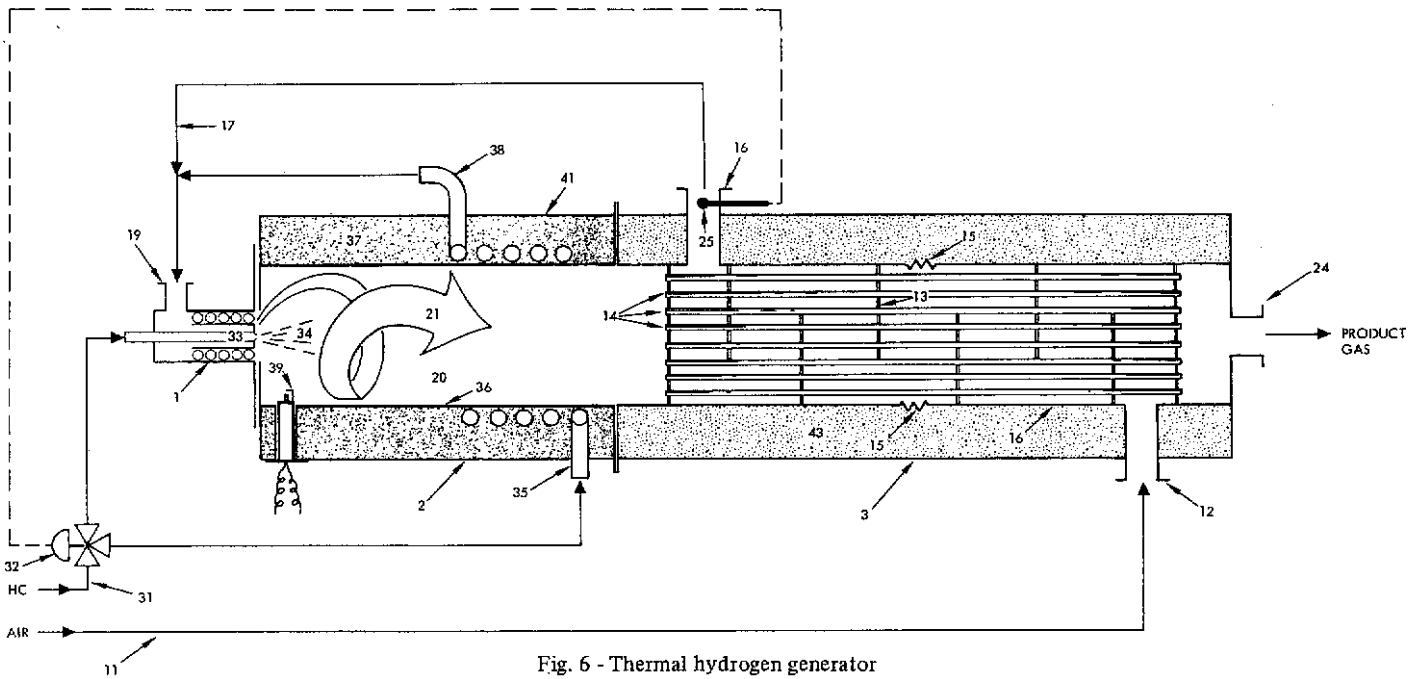


Fig. 6 - Thermal hydrogen generator

safety in carbon suppression and extends the soot-free region to a lower A/F.

3. Higher reaction rates can be obtained by preheating the air, resulting in a closer approach to equilibrium and higher hydrogen yields.

THERMAL PARTIAL OXIDATION

A hydrogen generator was designed based on start-up with liquid fuel injection and steady operation with a vaporized premixed feed stream. Fig. 6 presents a cross section of the unit, which consists of three assembled parts: a burner, a combustion chamber, and a heat exchanger.

The unit is started by flowing air, 11, to the shell side of the heat exchanger, 3, through inlet flange, 12. The air passes from the exit flange, 16, through the burner inlet flange, 19, into the combustion chamber space, 20. Liquid hydrocarbon fuel, 31, passes through a two-way control valve, 32, to the start-up nozzle, 33, which produces a spray, 34, of liquid droplets in the combustion chamber, 20. The fuel is ignited by means of a spark plug, 39. The hot combustion gases enter the tubes, 14, of the heat exchanger and leave through product flange, 24, after being cooled by counter-current heat exchange with incoming cold air stream, 11. Several baffles, 13, provide for cross flow of the air across the tubes, 14, for effective heat transfer. An expansion bellows, 15, in the shell, 16, eliminates thermal stress in the shell or tubes. During this start-up period the A/F is maintained above the normal operating value to allow for fast start-up and to prevent soot formation in the burning spray of fuel droplets, 34. When the air temperature at exit flange, 16, as measured by thermocouple, 25, exceeds a preset value, the two-way valve, 32, is switched to the vaporized fuel position so that the liquid fuel stream, 31, now enters the fuel vaporization coil at the coil inlet, 35.

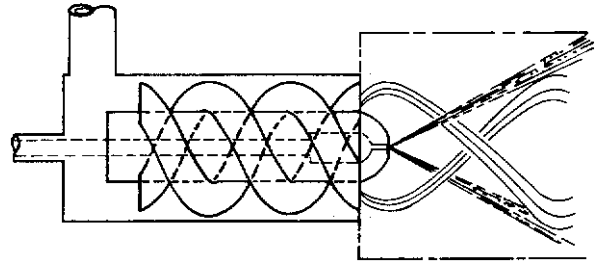


Fig. 7 - Burner details

The A/F is reduced to the operating value when the valve is switched. The vaporization coil is wound on the inner metal combustion shell, 36, and is embedded in the cast ceramic insulation layer, 37. The vaporized fuel leaves the coil exit, 38, and mixes with the heated air stream, 17. The premixed vaporized fuel/air stream now passes through the burner, 1, into the combustion chamber, 20, where partial oxidation of the fuel takes place to produce a hydrogen-rich gas.

The burner, 1, is shown in more detail in Fig. 7. Two lengths of tube are wound in a screw-thread fashion on an inner cylinder. The premixed feed gases pass through the resulting helical passages and enter the combustion chamber, 20, as a strongly outward rotating annulus of gas, 21. The length of the flame can be tailored by changing the angle of the helical path in the burner, a steeper angle resulting in a longer flame. There is a trade-off between the length of flame and the fact that the longer flame keeps the hottest part of the flame in the center and off the walls.

In Fig. 6 the hot inner cylinder, 36, is structurally a floating item and only supported by the cast ceramic, 37. The cast ceramic insulator sets up a considerable temperature gradient so that the outer wall, 41, is at a much lower temperature.

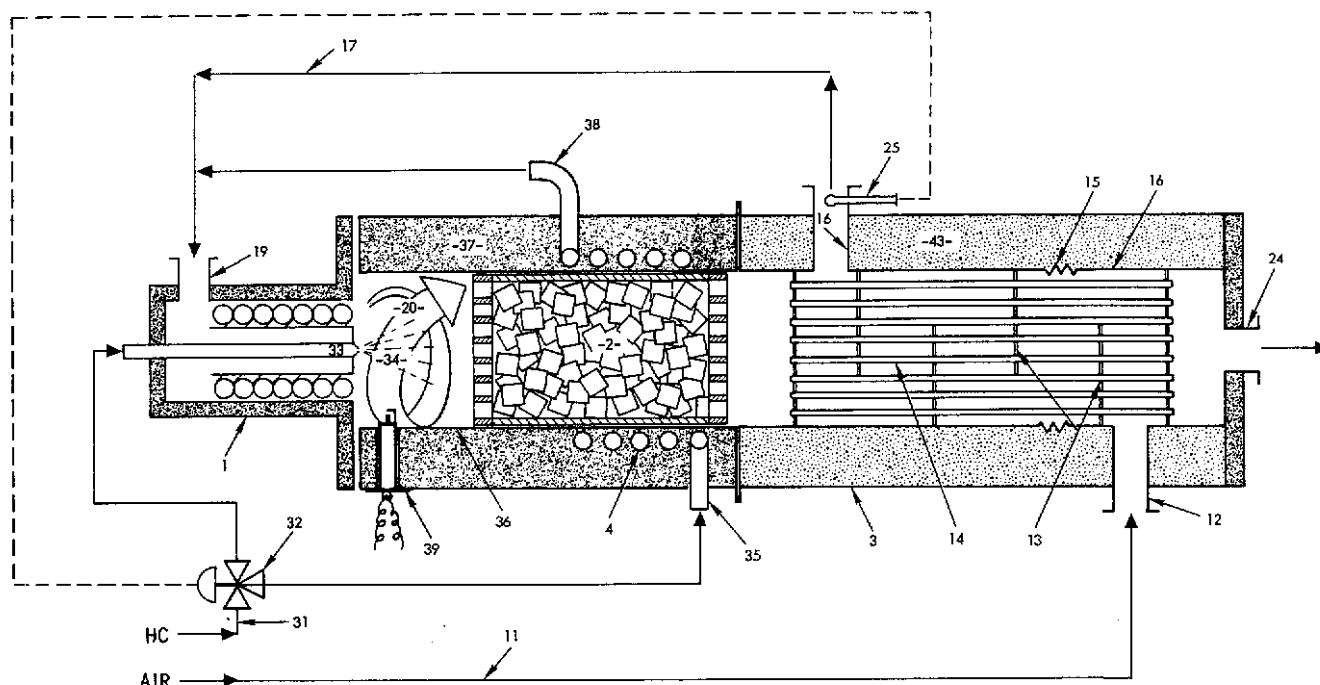


Fig. 8 - Catalytic hydrogen generator

The cold outer wall thus seals the unit and provides the structural strength. The heat exchanger, 3, also has an insulation layer, 43, to ensure a high air preheat temperature at flange, 16.

The unit is shut down by shutting off the hydrocarbon supply pump first while the air remains on for a few seconds. This purges the system of residual hydrogen-rich gases that may represent a potential safety hazard. There is insufficient mixing between the air and the hydrogen-rich gas during this operation to have any appreciable heat release in the heat exchanger or in the lines beyond.

When it is desired to operate the unit at extremely low A/Fs where soot formation becomes a problem, water addition can be used for soot suppression. The water is added in with the fuel at the entrance, 35, the the fuel vaporization coil. This applies to steady-state operation. Start-up would be accomplished in the normal manner without water.

The unit shown in Fig. 6 produced hydrogen yields of the order of 80% of theoretical yield, provided air preheat temperatures of 1200°F were used. Traces of soot were still present at or below A/Fs of 6. By preheating the reactants (hydrocarbon and air) to a temperature of 1200°F, the flame temperature reaches 2400°F. Even so, chemical equilibrium was not obtained. It is believed that the rate of reaction of the partial oxidation reaction was still too slow to obtain equilibrium yields.

Normally, the rate of a chemical reaction increases considerably with an increase in temperature. Higher yields could be expected by using still higher reactant preheat temperatures. However, this would have several practical disadvantages:

1. The high preheat requires a larger heat exchanger, which has a greater weight.
2. High preheat results in high operating temperatures for

the reactor and the heat exchanger, and the high-temperature resistance of materials like Hastelloy and Inconel becomes marginal, requiring the use of ceramics. The latter increases the weight of the unit.

3. The higher the preheat temperature required, the longer the start-up time. Not only does the start-up time increase with an increase in operating temperature, but on account of factors 1 and 2, the mass of the unit also increases, resulting in yet longer start-up times.

Consequently, the use of high reaction temperatures to obtain higher yields has some practical disadvantages associated with it. A catalyst was then used to try and speed up the chemical reaction, to enable the reaction to go to completion at lower reaction temperatures.

CATALYTIC PARTIAL OXIDATION

It was found that a nickel catalyst speeds up the partial oxidation reaction of hydrocarbons with air to yield a hydrogen-rich gas. The nickel catalysts used were commercially available catalysts known as steam reforming catalysts. Such catalysts are normally used to catalyze the reaction between steam and vaporized hydrocarbons. It was found that such steam forming catalysts are very effective as partial oxidation catalysts. In addition, it was found that the nickel catalyst has a strong soot-suppressing action. Thus, under conditions where soot would be found in the thermal reactor, not a trace of carbon was found with the use of the catalyst.

It was even possible to operate at A/Fs down to about 4 before carbon formation started, that is, below the theoretical A/F of 5.15 where carbon formation starts, according to the equilibrium calculations. The thermal reactor shown in Fig. 6 was fitted with a catalyst bed as shown in Fig. 8.

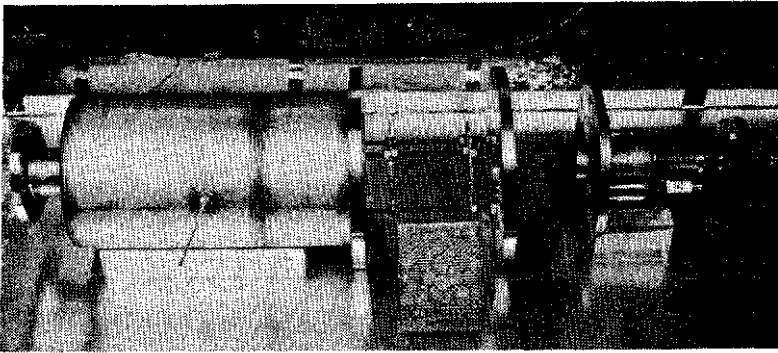


Fig. 9 - Exploded view of catalytic hydrogen generator

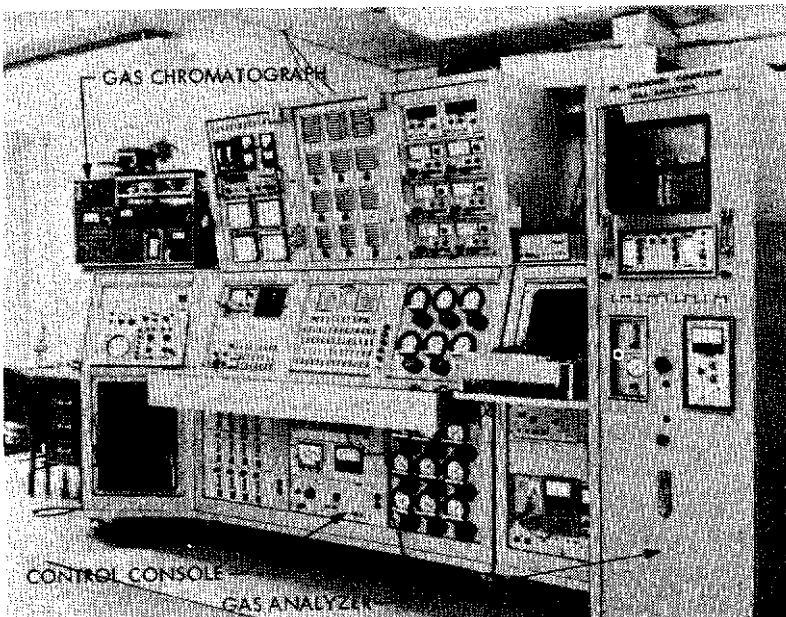


Fig. 10 - Instrumentation and control console

A photograph of the reactor with the catalyst bed is shown in Fig. 9. This reactor is 10 in long and contains a catalyst bed that is 4 in in diameter and 6 in long.

The control console for operating the reactor, together with associated instrumentation, is shown in Fig. 10. The gas analysis console on the right-hand side of the photograph contains on-line instruments for continuous analysis of the product gas. Hydrogen is measured by a thermal conductivity detector, while a flame ionization instrument is used to measure hydrocarbons. Nondispersive infrared analyzers are used to find the carbon monoxide and carbon dioxide content. A gas chromatograph (left-hand side of Fig. 10) is used to take spot samples to determine the identity and quantity of the components in the hydrocarbon fraction.

All input and output measurements, together with operating temperatures and pressures, are recorded on a digital tape. The tape is processed by means of a time-share computer terminal, and near real-time printout of the reduced data takes place in the test cell control room.

The reactor shown in Fig. 9 is started with liquid gasoline at an A/F of 9 to prevent soot formation. When the air temperature at the heat exchanger exit, 16, was at 450°F, the

valve, 32, was switched to the vaporized fuel position at an A/F of 5.15. During this switchover, the flame went out in front of the catalyst bed, and the partial oxidation reaction then proceeded within the catalyst bed, 2, in a flameless manner. The air preheat temperature of 450°F is just sufficient to prevent any condensation of the vaporized gasoline. The catalyst bed operated at approximately 1800°F. A typical set of operating conditions is shown in Table 2, together with a breakdown of the product gas composition.

A hydrogen-to-fuel yield ratio of 0.12 was obtained, compared to the theoretical value of 0.136. The generator efficiency is defined as the net heat of combustion of the product gas relative to the net heat of combustion of the fuel. An efficiency of 0.785 was obtained, which corresponds to 96% of the theoretical value. In summary, close to equilibrium yields were obtained without a trace of soot.

To obtain an indication of any potential poisoning of the catalyst, a 100 h test was conducted with Indolene 30, the federal test gasoline containing 3 g/gal of lead. No deactivation of the catalyst was noted. It should be kept in mind that the operating temperature of 1800°F is much higher than engine exhaust temperatures. Consequently, the results from en-

Table 2 - Typical Catalytic Generator Operating Conditions*

Input Condition	Value		
Airflow rate, lb/h	45.6		
Fuel flow, lb/h	8.9		
A/F	5.15		
Equivalence ratio	2.83		
Generator pressure, psig	1.4		
Catalyst temperature, °F	1774		
Output Condition	Mole Fraction	Mass Fraction	Mass Output, lb/h
H ₂	0.2160	0.0194	1.06
CO	0.2360	0.296	16.19
CH ₄	0.0103	0.0074	0.404
C ₂ H ₄	0.0009	0.0011	0.062
CO ₂	0.0123	0.024	1.326
H ₂ O	0.0120	0.0097	0.529
N ₂	0.5125	0.0642	35.15
	1.0000	1.000	54.72
Mean molecular weight	22.33		
H ₂ /hydrocarbon mass ratio	0.12		
H/C atomic ratio	1.925		
Exit pressure, psig	1.0		
Exit temperature, °F	1527.0		
Generator efficiency	0.785		

*Run 15-4 used as reference.

gine exhaust treatment catalyst tests do not necessarily apply here. Further tests are in progress to assess any degradation in performance as a function of time with various lead and sulfur contents in the fuel.

Shrinkage and settling of the catalyst pellets were experienced in early tests. This caused bypassing problems with horizontal operation. Subsequent operations with vertical downward flow eliminated this problem.

EFFECT OF HYDROGEN GENERATOR EFFICIENCY ON OVERALL SYSTEM EFFICIENCY

The partial oxidation reaction is an exothermic reaction, and the heat release results in a temperature rise in the hydrogen product gas. Unfortunately, the IC engine cannot derive any mechanical energy from the sensible heat in the hydrogen product gas. This is in contrast to a gas turbine where preheat of the fuel does increase the cycle efficiency. In an IC engine only the net heat of combustion of the hydrogen product gas makes a contribution.

We define the thermal efficiency of the hydrogen generator as the net heat of combustion of the product gas divided by the net heat of combustion of the gasoline feed. This thermal efficiency has been calculated for the equilibrium yield case and is plotted in Fig. 11 as a function of the A/F and the

water/fuel ratio. No credit has been taken for the heat of combustion of carbon. At stoichiometric conditions (A/F = 14.65), the thermal efficiency is zero, and it increases with a decrease in A/F. For the case of zero water, the curve reaches a maximum of 80.5% and then decreases rapidly when soot starts to form at an A/F of 5.15. With higher water/fuel ratios, soot formation starts later, but the maximum thermal efficiency does not increase much with the addition of water. For instance, at a water/fuel ratio of 1, soot formation starts at an A/F of 3.9, where the efficiency is 81.5%. Again, there is very little benefit from using water except the soot suppression value.

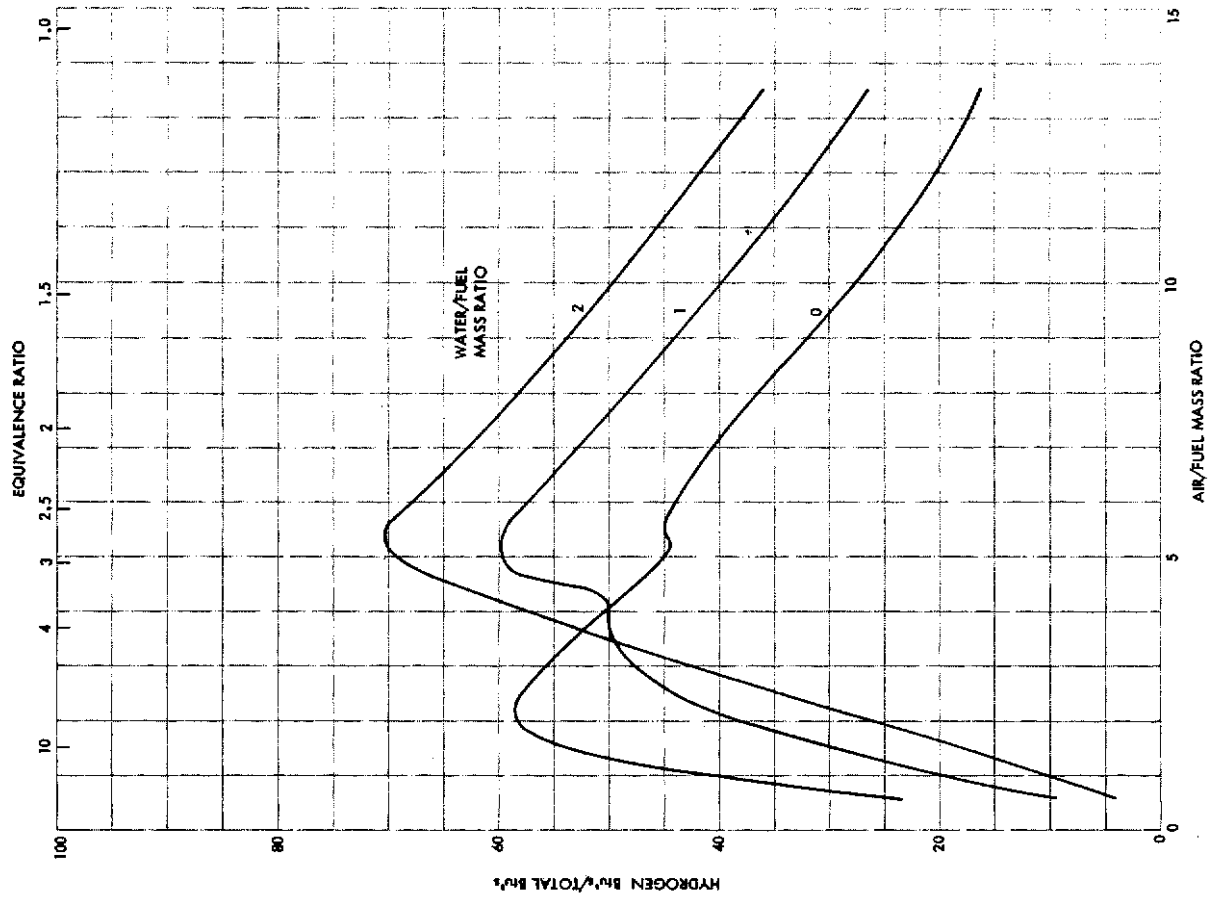
The combustible gases in the product gas are hydrogen, carbon monoxide, and methane. Fig. 12 shows the fraction of the Btus from the hydrogen in the gas relative to the total Btus from all three components. Only for this parameter does the addition of water show a distinct increase over the zero water case. For instance, at an A/F of 5.5, the hydrogen Btus/total Btus parameter increases from 45% to 70% as the water/fuel ratio is increased from 0 to 2. However, the critical parameter is the yield of hydrogen per unit of fuel, and this parameter does not change much with water addition.

If we now consider an integrated hydrogen generator/IC engine system, it becomes obvious that the hydrogen generator throughout must be minimized for maximum system efficiency. There is an energy penalty associated with the generation of hydrogen. The function of the hydrogen in the engine is to extend the flammability limit of the other combustibles, that is, the gasoline, and the carbon monoxide and methane in the generator gas. Thus, some of the hydrogen is used up to allow lean combustion of the carbon monoxide and the methane in the generator gas. The overall system efficiency will be maximized if we can minimize the ratio of hydrogen to fuel in the engine to obtain complete combustion at a given equivalence ratio.

In order to correlate the overall system efficiency with the generator efficiency, it is convenient to use a hydrogen-to-(engine) fuel mass ratio. A considerable amount of work has been done with partial injection of 100% hydrogen with an IC engine. (2) To enable comparison of such results with generator-gas injection, the methane and carbon monoxide of the generator gas have been converted to an equivalent amount of gasoline. This was done by summing the products of the heat of combustion and the amounts of carbon monoxide and methane, and dividing the sum by the heat of combustion of gasoline to arrive at the equivalent amount of gasoline. By adding this equivalent amount of fuel to the amount of liquid fuel fed directly to the IC engine, we obtain an amount of fuel which we shall call "other fuel" in contrast to the hydrogen.

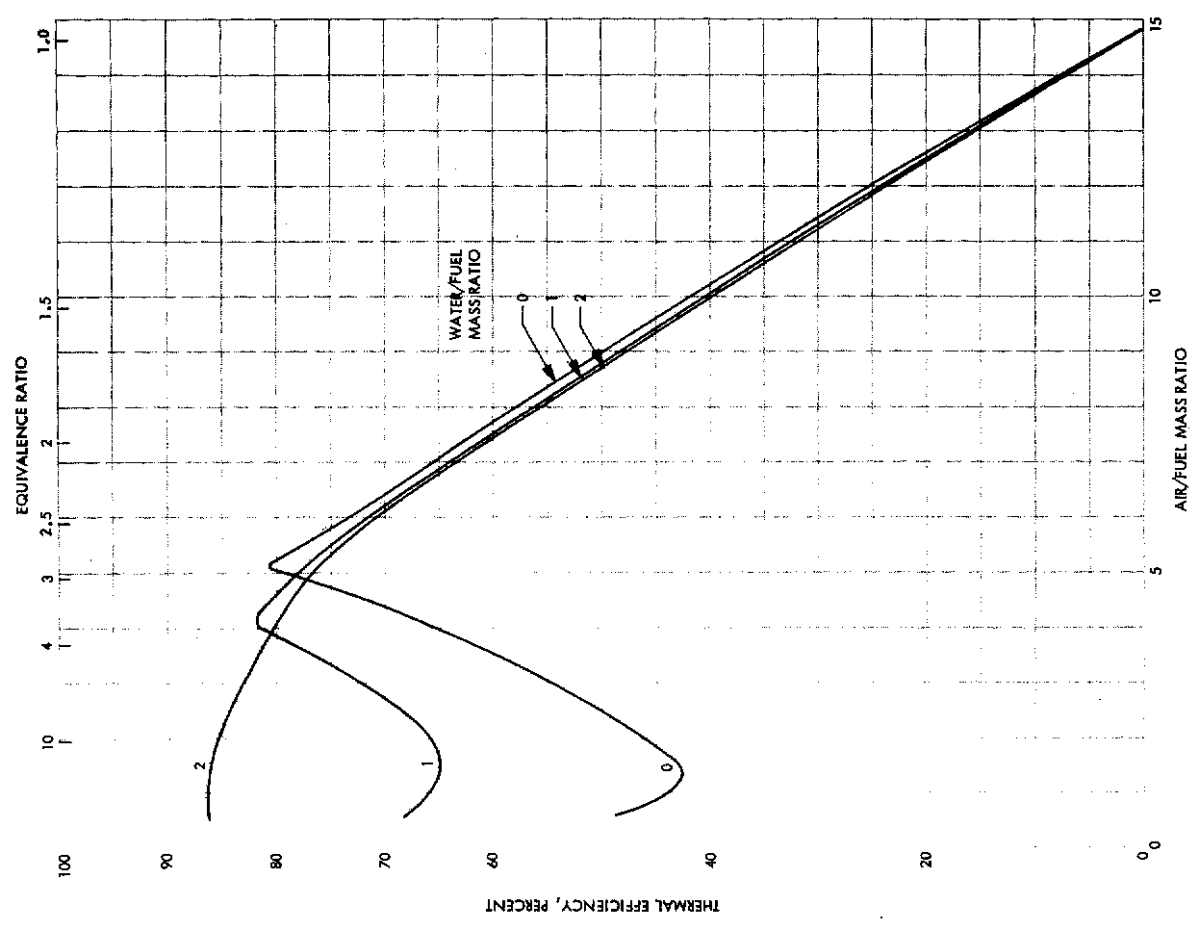
Fig. 13 shows how much of the total (system) fuel must be sent through the hydrogen generator in order to obtain certain values of the parameter "hydrogen/other fuel," as a function of the A/F to the generator. For instance, at an A/F of 5.15, to obtain a hydrogen/other fuel fraction of 0.10, 52% of the total fuel must pass through the generator, which leaves 48% to be fed directly to the engine.

As discussed earlier, the fraction of the total fuel that passes



THEORETICAL EQUILIBRIUM, ADIABATIC COMBUSTION
INDOLENE (CH_{1.92}) - WATER-AIR AT 80° F, 44 psia

Fig. 12 - Hydrogen contribution to heating value



THEORETICAL EQUILIBRIUM, ADIABATIC COMBUSTION
INDOLENE (CH_{1.92}) - WATER-AIR AT 80° F, 44 psia

Fig. 11 - Generator thermal efficiency

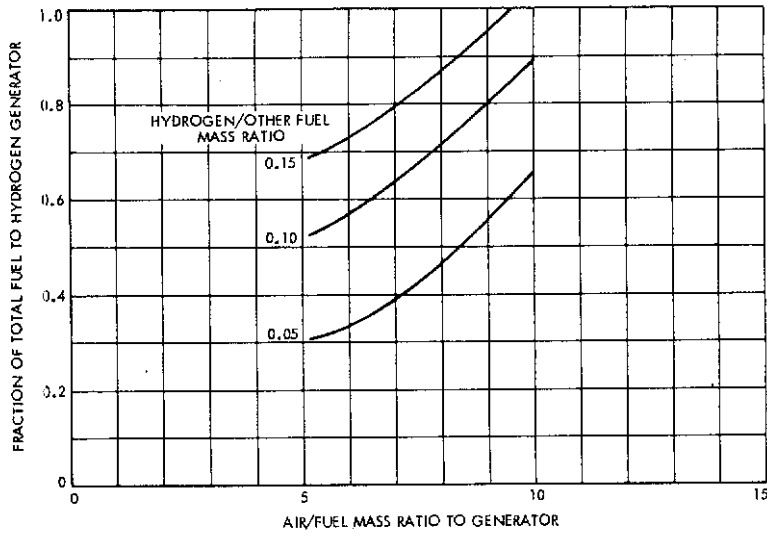


Fig. 13 - Fraction of total fuel to hydrogen generator

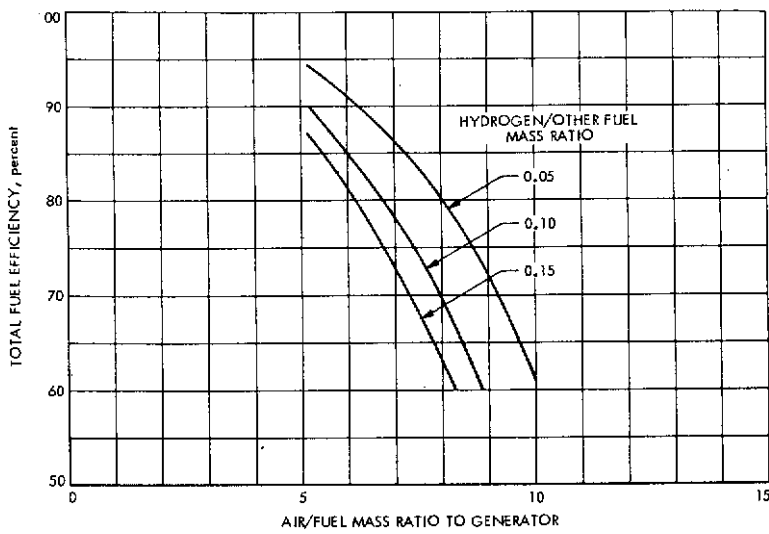


Fig. 14 - Total fuel efficiency

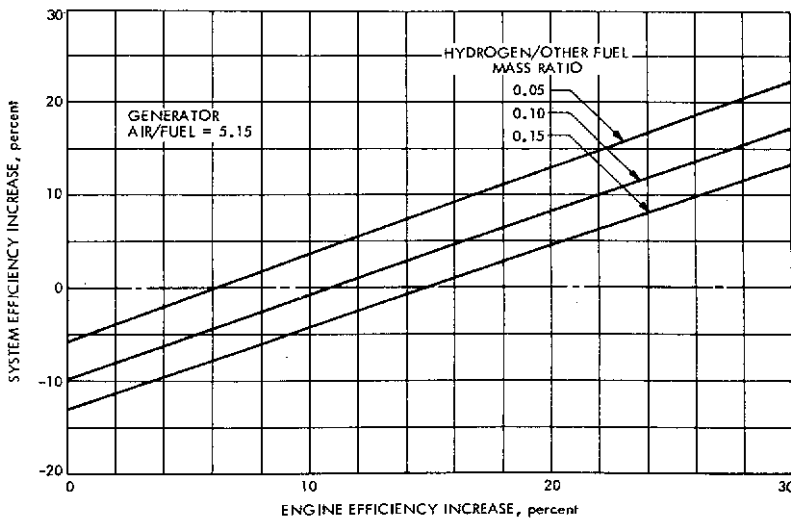


Fig. 15 - Calculated system efficiency increase

through the hydrogen generator represents an energy loss relative to the fuel that goes directly to the engine. By weighting the generator fuel with the generator thermal efficiency and the engine fuel with 100%, the overall total fuel efficiency can be obtained. This total fuel efficiency is plotted in Fig. 14, again versus the generator A/F, at several values of hydrogen/other fuel. Using a previous example of a generator A/F of 5.15 at a hydrogen/other fuel ratio of 0.10, the total fuel efficiency will be 90%.

This decrease from 100% in fuel efficiency without hydrogen to 90% with 10% hydrogen must be made up by an increase in IC engine efficiency in order to achieve overall increases in system efficiency when using hydrogen. This is indeed the case in practice. By multiplying the total fuel efficiency from Fig. 14 by selected new engine efficiencies, the overall system efficiency can be obtained. Fig. 15 shows this increase in system efficiency as a function of the increase in IC engine efficiency for various values of hydrogen/other fuels, at a fixed value of 5.15 for the A/F to the generator. For instance, for a hydrogen/other fuel ratio of 0.10, an engine efficiency increase of 22% is required to obtain a system efficiency increase of 10%. Lowering the hydrogen consumption to 5% for the same engine efficiency results in a system efficiency increase of 15%.

These increases in efficiency refer to a baseline engine operation without hydrogen. By adding hydrogen, leaner operation is possible with associated increases in engine efficiency. It should be emphasized that Fig. 15 is solely based on heat balances and equilibrium yield calculations for the hydrogen generator. The actual engine efficiency increases and the actual hydrogen/other fuel ratios that are required to obtain them vary considerably from engine to engine, as well as with various engine operating parameters. These factors are discussed in Ref. 2. Experimental work on dynamometer tests with a combined hydrogen generator/IC engine system are currently in progress, and the results will be reported in the near future.

CONCLUSIONS

The practical implementation of operating an IC engine on hydrogen-enriched gasoline depends on the availability of an onboard hydrogen generator. A theoretical analysis of the partial oxidation approach to hydrogen generation shows that satisfactory yields of hydrogen can be obtained in this manner from gasoline and air. Experimental work with a catalytic reactor has verified the equilibrium prediction. A 6 in diameter \times 10 in long catalytic generator has been developed that can deliver a clean hydrogen-rich gas under close to theoretically predicted conditions.

A noncatalytic thermal hydrogen generator has also been developed. It has to be operated with high air preheat tem-

peratures of the order of 1200°F or higher in order to obtain hydrogen yields of the order of 80% of the theoretical maximum value. Soot formation still tends to be a problem with the thermal generator, and further work is continuing to eliminate soot production.

Overall technical feasibility of onboard hydrogen generation from gasoline and air by the partial oxidation approach has been demonstrated.

Initial work with leaded gasoline has shown promise that catalyst poisoning may not be a problem.

The effect of the generator operating variables on the thermal efficiency has been calculated. Optimum performance occurs at the lowest possible A/F just short of the soot formation value. At this point a generator thermal efficiency of 80% has been demonstrated.

The effect of generator thermal efficiency on system fuel economy has been calculated. It is a strong function of the hydrogen-to-fuel ratio required in the IC engine. Overall, increases in engine efficiency are more dominant than the energy loss incurred in generating hydrogen, resulting in improved fuel economy for the system as a whole.

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