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FUSION AS A SOURCE OF SYNTHETIC FUELS*†

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ABSTRACT

In the near-term, coal derived synthetic fuels will be used; but in the long-term, resource depletion and environmental effects will mandate synthetic fuels from inexhaustible sources--fission, fusion, and solar.

Of the three sources, fusion appears uniquely suited for the efficient production of hydrogen-based fuels, due to its ability to directly generate very high process temperatures (up to ∿2000°C) for water splitting reactions.

Fusion-based water splitting reactions include high temperature electrolysis (HTE) of steam, thermochemical cycles, hybrid electrochemical/thermochemical, and direct thermal decomposition. HTE appears to be the simplest and most efficient process with efficiencies of 50 to 70% (fusion to hydrogen chemical energy), depending on process conditions.

Low cost fusion hydrogen would profoundly affect energy use patterns. It could be transported by pipelines and used for industry, space heat, etc, directly as a fuel or blended with natural gas. It could also be used for air and ground transport as a liquid or in the form of metal hydrides.

Hydrogen is a feedstock for many chemical (e.g., ammonia) and petrochemical applications and can be used to make carbonaceous portable fuels from non-fossil carbon (atmospheric CO_2 or limestone) or fossil carbon (coal).

INTRODUCTION

Most of the energy used by modern industrial nations is consumed as portable liquid and gaseous fuels. In the United States (U.S.), for example, final demand sectors use 45 Q/year [1 Q = 10^{15} BTU] of liquid and gaseous fuels, 6.6 Q/year of electricity, and 14 Q/year of solid fuels (coal). Some additional 7.2 Q/year of liquid and gaseous fuels generate part of the electricity required.

This pattern has evolved because of the convenience, versatility, and until now, low cost of liquid and gaseous fuels. Some sectors

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cannot use electricity or solid fuels (e.g., the auto and air transport), while others prefer liquid or gaseous fuels because of cost, convenience, and environmental advantages (e.g., the space heat, industrial process heat, and petrochemical).

However, the rapid depletion of conventional oil and gas deposits which now provide liquid and gaseous fuels has resulted in steeply escalating prices, and it is likely that they will be gone in a few decades.

What are the alternatives to fossil liquid and gaseous fuels? First, demands can be reached by conservation; second, other energy supplies (e.g., electricity, coal, solar) can be directly substituted; and finally, synthetic liquid and gaseous fuels can be produced, either from more plentiful fossil resources (e.g., coal, oil shale, tar sands) or from the inexhaustible energy sources (IES)--fission, fusion, and solar.

Conservation will undoubtedly be important, but its long run effect will be limited. Technical and economic bounds to reductions in end-use demands and increasing population, along with the desire for a higher standard of living, will force the development of alternate energy supplies to meet demands.

Substitution will also be important, but there will be limits to the degree other energy forms can replace liquid and gaseous fuels. The auto transport sector, for example, is likely to continue using portable fluid fuels unless there is a breakthrough in electric vehicles.

It thus appears likely that liquid and gaseous fuels will continue to play a major role in the U.S. energy system and that these fuels will have to be synthetically produced as natural sources are depleted. EIA projections, for example, indicate that liquid and gaseous synthetic fuels will play a major role after 2000 AD and will supply well over 50% of our needs by 2030 AD.

However, use of fossil resources for synfuels may cause severe environmental problems, including changes in world climate due to CO_2 buildup in the atmosphere [1]. Use of the Inexhaustible Energy Sources (IES's) for synthetic fuel production is very desirable if they are technically and economically feasible.

Synthetic fuels produced by IES's would be based on hydrogen derived from water splitting. Hydrogen, itself, is an attractive fuel; and the hydrogen economy has been extensively studied [2,3,4]. Hydrogen can be transported by pipeline and used as a gaseous fuel in the residential, commercial, and industrial demand sectors. Liquid hydrogen has been proposed as a fuel for future air transport [5]. Hydrogen gas absorbed in solid metal hydrides has been tested for ground transport applications (automobiles, trucks, and buses) [6].

If hydrogen from an IES is combined with carbon from sources such as coal, biomass, or CO_2, a variety of carbonaceous fuels (gasoline, heating oil, jet fuel, methane, methanol, etc.) can be formed [7]. The problems of atmospheric CO_2 buildup remain if fossil carbon sources are used, although the CO_2 addition rate would be 2 to 3 times lower than would be the case if coal were the sole source for synthetic fuels. With non-fossil sources (biomass, atmospheric CO_2), the CO_2 concentration in the atmosphere would not increase and carbonaceous synfuels could be used indefinitely.

The IES's--fission, fusion, and solar--probably will have high unit capital costs. Low hydrogen production costs can only be achieved if the overall efficiency for conversion of thermal energy to hydrogen chemical energy is high.

The unique nature of fusion energy potentially allows very high hydrogen production efficiency. Possible production processes are examined later and the most promising, high-temperature electrolysis of steam, is described.

The schedule for development of fusion is long enough that fusion synfuel technologies can probably be developed well before the first commercial reactors come on-line. Thus, the first generation of fusion reactors could produce fuels.

HYDROGEN PRODUCTION PROCESSES USING FUSION ENERGY

The DT fuel cycle is favored for the first generation of fusion reactors since advanced fusion fuels, like DD or DHe^3, require much higher plasma temperatures and densities for useful power outputs. Each DT fusion releases 17.6 MeV--14.1 MeV as fast neutron energy and 3.5 MeV as alpha particle energy.

There are three types of processes for hydrogen production using fusion energy and water as feedstock:

1. Radiolytic - the energetic fusion products (neutrons, alpha particles, and gammas from nuclear reactions in the blanket) radiolytically decompose a process fluid to produce hydrogen.
2. Thermochemical - fusion product energy is converted to high-temperature heat in the blanket which decomposes a process fluid (or fluids) in a process (single- or multi-step) to produce hydrogen.
2. Electrochemical - high-temperature heat from the blanket is converted to electricity by a thermal power cycle. The electricity (plus heat) then generates hydrogen by the electrolysis of water.

Present knowledge about radiolysis indicates that fusion synfuel processes based on radiolytic reactions will have low efficiency. The best candidate, radiolysis of CO_2 gas, followed by the shift reaction to hydrogen has a maximum overall efficiency for fusion energy to hydrogen chemical energy of about 9%.

The efficiencies of thermochemical processes, as well as the efficiency of conversion of heat to electricity for electrochemical processes, generally increase with increasing temperature. Fusion offers the potential for very high-process temperatures, leading to high efficiency for hydrogen production.

The fusion alpha particle energy (3.5 MeV) appears at relatively low temperatures, as a heat flux on the first wall surrounding the plasma. Structural strength limits the coolant temperature for the first wall to ∿500°C--this energy is best used for electrical power generation.

In contrast, 14 MeV neutrons have a long range and deposit energy deep inside reactor blankets. This unique feature can generate very high temperatures for high-efficiency hydrogen production processes. The blanket interior can operate at much higher temperatures than the first wall if it is thermally insulated from the interior and has a separate coolant circuit.

In such "two-temperature zone" blankets [8], ∿60% of the total fusion energy appears as high-grade heat in the blanket interior.

Heat leakage from the hot interior is minor. Fusion thus has the highest temperature capability of all the inexhaustible energy sources. Containment of fission products limits temperatures in fission reactors; with solar energy impractically high concentration factors are required.

In summarizing potential hydrogen production processes using fusion energy, three temperature ranges are defined. For ultra-high temperature energy (Mode I, >2000°C), thermal decomposition yields hydrogen (e.g., the direct decomposition of steam to hydrogen or CO_2 to CO, followed by a shift reaction to hydrogen). Mode I energy can also generate electricity with an advanced power cycle (e.g., MHD) at ∿60% efficiency, compared to the ∿35 to 40% for conventional cycles. Such a power cycle could be used with electrolysis to efficiently produce hydrogen.

Mode II high-temperature energy ($\sim 500°C<T<2000°C$) can produce hydrogen by multi-step thermochemical cycles, can generate electric power at high efficiency, and can supply thermal input to a high-temperature electrolysis process. In the first case, a series of chemical reaction steps is driven by high-temperature heat inputs to split water into hydrogen and oxygen—with reaction chemicals being recycled. For the second case, an attractive option is the closed Brayton gas turbine cycle. In the third case, high-temperature electrolysis (HTE) involves the electrolysis of steam at high temperatures using ceramic electrodes/electrolytes. In the HTE process, heat substitutes for electricity, resulting in efficient hydrogen production. Mode III energy, at temperatures of ∿500°C or below, is limited to electrical generation in conventional cycles. Fusion synfuel blankets would minimize energy in this mode.

Various hydrogen production processes have been examined by investigators. Although definitive assessments cannot be made yet, preliminary conclusions can be draw. Thermal decomposition (Mode I) is attractively simple, but there is yet no way to cool the products fast emough to prevent recombination. Also, blanket materials suitable for very high temperatures have not yet been demonstrated.

Advanced power cycles such as MHD, high-temperature gas, steam turbines, the wave energy exchanger, and the potassium topping cycle have been proposed for fusion--with projected efficiencies of ∿50 to 60% (fusion heat to electricity). Most approaches would only use the high-temperature fusion heat. Lower temperature heat (Mode III) from the first wall would be used in a separate, lower efficiency power cycle, lowering average cycle efficiency. For Rankine cycles, however, this can be effectively used to evaporate the working fluid in the cycle.

Using advanced low-temperature electrolysis, i.e., solid polymer electrolytes (SPE), electrical efficiencies of 50 to 60% yield hydrogen efficiencies (fusion energy to hydrogen chemical energy) of 50 to 55%.

Many thermochemical processes have been studied in the last ten years, with no consensus on the most promising approach. Cycle irreversibilities appear to result in overall efficiencies not much greater than for low-temperature electrolysis with a conventional power cycle. Higher temperatures from fusion reactors may increase thermochemical process efficiency by reducing the number of irreversible steps. Even if efficient, however, process streams are corrosive and require complex separations. Losses of expensive process materials (e.g., iodine, bromine, cesium, or bismuth) could make the system uneconomic.

The remaining process, HTE, appears to have the highest potential efficiency for hydrogen production--in the range of 50 to 70%. HTE cells have operated satisfactorily for thousands of hours at ∿1000°C. Engineering development of large systems would be necessary, but no fundamental barriers are foreseen. Experiments with blanket materials for an HTE/fusion process are encouraging.

HYDROGEN PRODUCTION BY HIGH-TEMPERATURE ELECTROLYSIS

The electrochemical decomposition of water into hydrogen and oxygen requires both heat and electricity. In power cycles, efficiency is limited by the Carnot relationship and irreversibilities. In steam power cycles, electrical efficiency is ∿40%. Since heat input for water decomposition is used at essentially 100% efficiency, there is great advantage to increasing the ratio of heat input to electrical input as much as possible.

The energy (enthalpy) to decompose water is composed of electrical and thermal inputs. As temperature increases, reaction enthalpy remains constant, but electrical energy input (ΔG) decreases and thermal energy input ($T\Delta S$) increases. The increasing thermal input with temperature results in a higher process efficiency at projected conditions -- approximately one-half of the input energy is thermal and one-half is electric.

Conventional electrolysis of water is carried out at low temperatures with liquid water as the electrolyte. In high-temperature electrolysis, steam is electrolyzed using a solid ceramic electrolyte. The electrodes can be high-temperature metallic or ceramic materials. The heat input absorbed by the HTE cells comes from the sensible heat of the process streams. Typically, they cool by ∿100 to 200°C during passage through the electrolyzer.

In HTE-fusion plants, steam would be heated in the interior of a two-temperature zone fusion blanket and transported to the electrolyzers in ceramic-lined ducts. The electrical energy input would be generated by a power cycle operating on the rest of the heat from the fusion blanket.

Figure 1 illustrates a "two-temperature zone" blanket module [8, 9] that supplies high-temperature process steam to the electrolyzers. The low-temperature shell has a separate coolant circuit and is insulated from the hot interior. Neutron and gamma energy deposited in the interior ceramic (e.g., ZrO_2 or Al_2O_3) heats the high-temperature steam flowing through it.

The HTE cell is based on the Westinghouse fuel cell, which involves a thin layer electrochemical cell supported on a thick ceramic porous base [10]. This significantly reduces electrolyte thickness. If the electrolyte is self-supporting, electrolyte thickness is large and performance poor. The Westinghouse fuel cell is shown in Figure 2. Since the electrolyzer is a fuel cell in reverse, the same arrangement can be used for HTE.

The work in fuel cells has shown that high-temperature-solid oxide electrochemical cells can be operated at 1000°C for very long periods. The major problem has been the connection between cells. However, mixed oxides have been recently developed with all the required

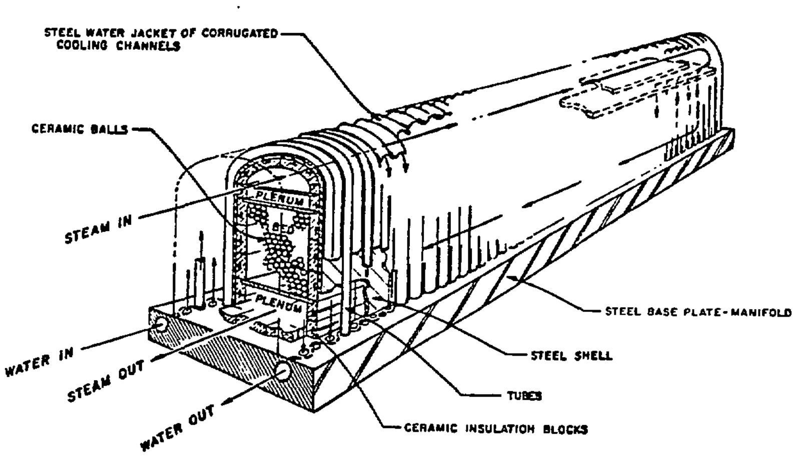

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Figure 1 Two-temperature zone blanket concept for high-temperature coolant processes.

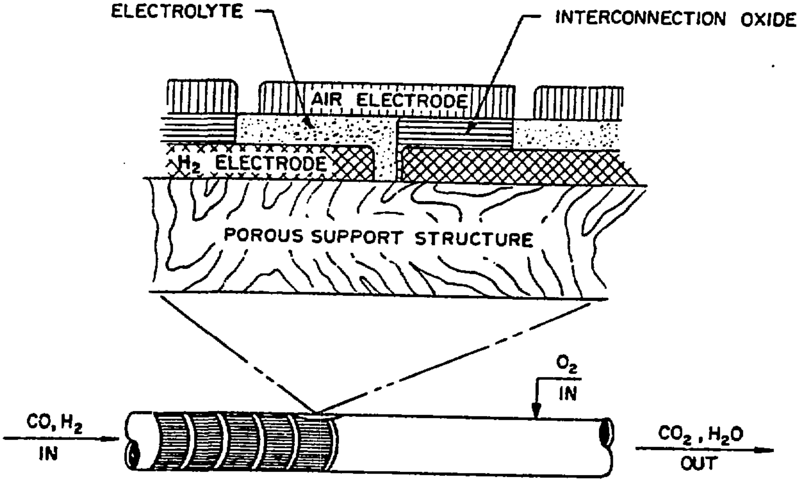

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Figure 2 HTE cell for high-temperature electrolysis (Westinghouse Design).

properties for the interconnectors. Tests of materials at Brookhaven National Laboratory (BNL) indicate that temperatures of 1400°C should be achievable.

Figure 3 shows the projected HTE process efficiency (fusion energy to hydrogen chemical energy) as a function of electrolysis temperature for two values of power cycle efficiency: 40%, corresponding to conventional power cycles and 60%, corresponding to advanced power cycles using high-temperature coolant from the fusion blanket. Efficiencies can be based on either the lower heating value for hydrogen (LHV--the H_2O combustion product is not condensed) or the higher heating value (HHV--the H_2O combustion product is condensed). Heating values for fuels are usually quoted in terms of the HHV.

HTE is considerably more efficient than conventional low-temperature electrolysis (LTE). Quite high efficiencies can be achieved at temperatures where existing materials appear adequate. For example, operation at 1500°C (1800°K) would give an overall efficiency of 52% with a standard power cycle and 70% with an advanced power cycle.

USES OF FUSION GENERATED HYDROGEN

Figure 4 indicates the potential major uses for fusion hydrogen. It would be used directly as fuel, as a raw material for chemical synthesis, and in combination with carbon could supply hydrocarbon fuels. The oxygen by-product will undoubtedly have many uses, some of which are shown.

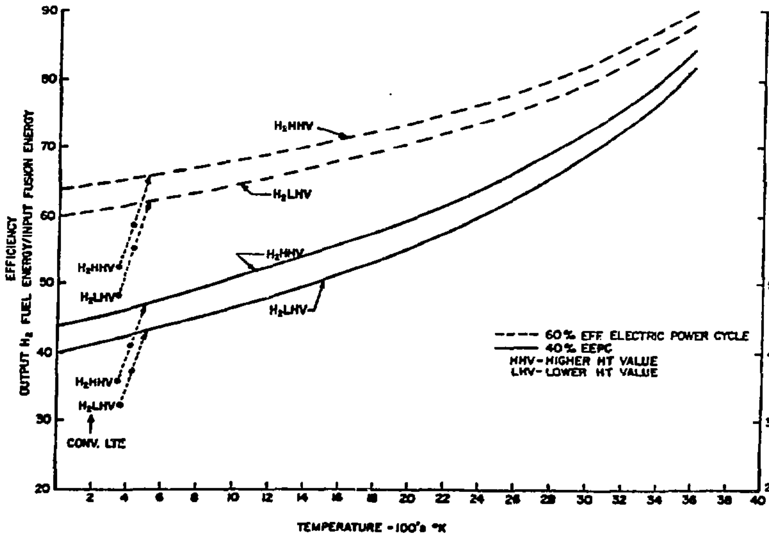

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Figure 3 Overall efficiency (fusion to hydrogen chemical energy) as a function of HTE temperature.

Approximately 250 fusion reactors (5000 MW(th) capacity) could produce all of the carbonaceous portable fuels now consumed by the U.S. This would reduce the needed coal production by 1200 million tons/year, compared with coal-only synfuel processes. In studies of fusion electric plants, the cost of the plant is in the range of \$400-800 kW(th). Fusion synfuel plants should have comparable costs. Figure 5 shows projected costs for synthetic fuels as a function of coal cost, assuming a fusion-hydrogen plant cost of \$500/kW(th), a fusion-to-hydrogen efficiency of 60%, and 15% fixed charges on capital investment. Costs for conversion of fusion hydrogen with coal-to-SNG or synfuel gasoline are also included. Coal-only synthetic fuel costs are taken from other studies. Projected O & M costs are included.

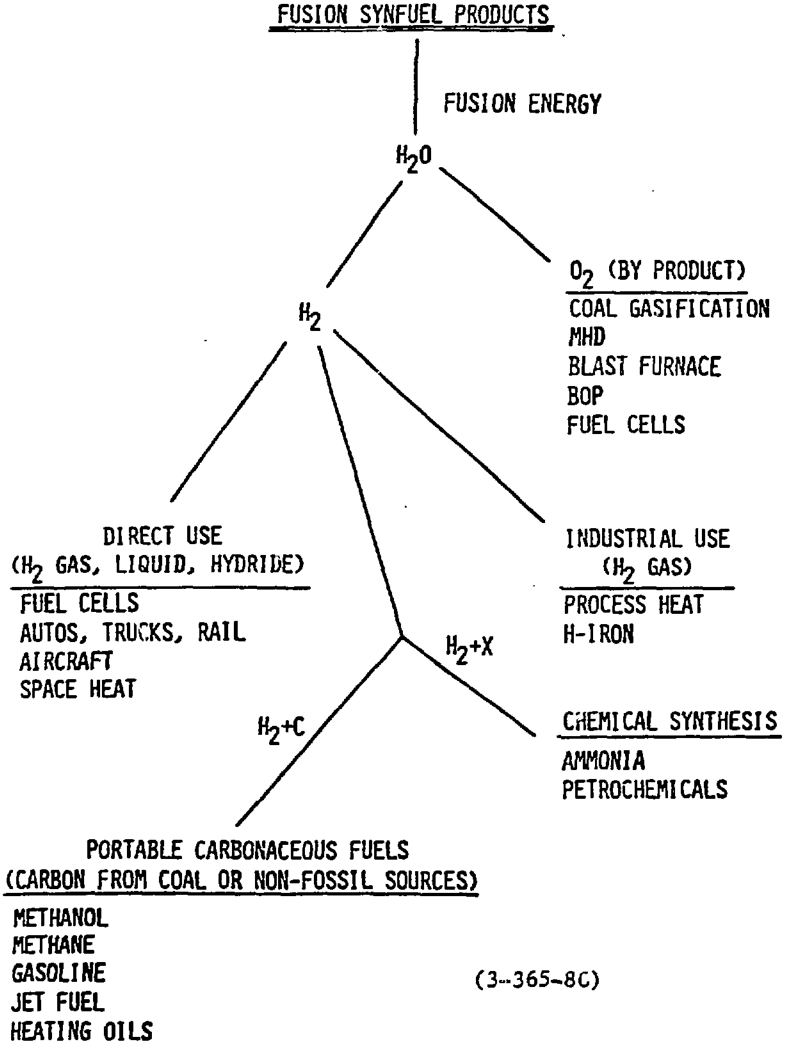

Figure 4 Fuels and chemical products from chemical energy.

The projected cost of fusion hydrogen is ∿5/GJ [1 GJ = 0.95 million BTU] and is independent of coal cost. The cost of synfuels from fusion/coal plants will depend on coal cost, since coal is a raw material. However, fusion/coal synfuel cost will be much less sensitive to coal cost than coal-only synfuels, since the former uses much less coal. Fusion/coal synfuels become cheaper than coal-only synfuels at a coal cost of \$60/ton for SNG production and \$35/ton for liquid hydrocarbons. Present coal costs for long-term contracts are on the order of \$30/ton. The much greater demand likely for coal and the depletion of low cost deposits will drive up coal costs. Fusion synfuels should thus be economically attractive when the first generation of fusion reactors come on-line, at about 2000 AD.

SUMMARY AND CONCLUSIONS

Portable liquids and gaseous fuels presently supply the major part of the U.S. energy needs and are likely to continue in this role. Natural oil and gas will be largely gone within the next few decades and will have to be supplanted by synthetic fuels. Fusion is a promising source for synthetic fuels. The unique ability of fusion energy to generate very high-process temperatures should result in efficient generation of hydrogen by water decomposition. HTE of steam appears very promising. The overall efficiency, fusion-to-hydrogen chemical energy, is projected to be in the range of 50-70%, depending on the process conditions and type of power cycle. Hydrogen can be directly used as a fuel or combined with carbon to produce portable liquid or gaseous carbonaceous fuels. This carbon could come from a variety of sources, including coal, biomass, and atmospheric CO_2.

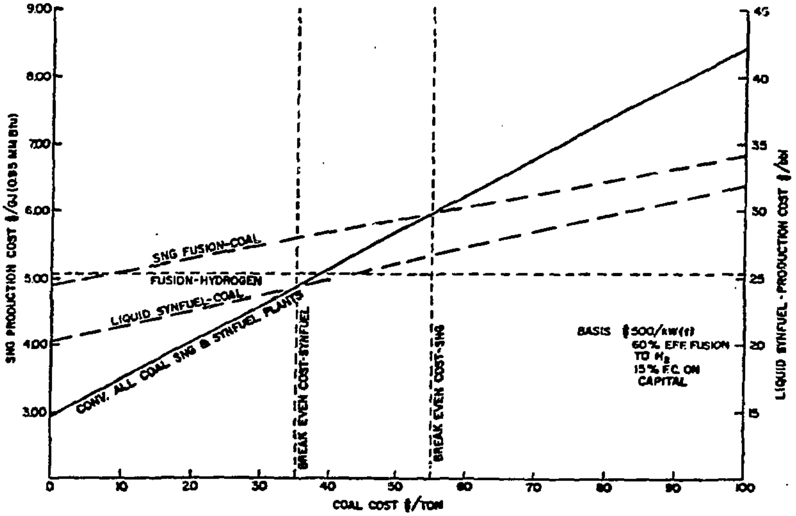

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Figure 5 Projected costs for synthetic fuels as a function of coal cost.

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