A Review of the Feasibility and Constraints of Hydrogen-Powered Flight

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I. Abstract

The use of hydrogen either in its liquid form or as a fuel cell has been of great interest to engineers in the aviation industry. The implementation of hydrogen in aircraft requires possible major infrastructure changes, such as the synthesis of hydrogen being improved and scaled up. This paper goes over multiple options of hydrogen synthesis, their production methods, and their benefits in that form. Hydrogen embrittlement is also mentioned as a possible issue for the storage, transport, and usage of hydrogen in aviation, and the potential flight range of hydrogen aircraft is explored in more detail. The theoretical flight ranges calculated for a mid-sized hydrogen aircraft were most possible around the 100 mile range, a flight from LAX to SAN being 110 miles. While hydrogen is a promising solution with its high energy density and reduced effect on the environment, there will need to be improvements in the efficiency of production and usage, as well as further research and testing.

II. Introduction

The aviation industry has been researching and testing different ways to reduce the effects of flying on the environment, and hydrogen has been one of the most promising candidates. Hydrogen, when combusted, releases only water vapor while kerosene creates carbon dioxide [1]. Not only that, liquid hydrogen has slightly more than three times the energy density per kilogram than kerosene [2] [3]. With a fuel source three times more powerful that also reduces pollution, it seems like a direct replacement if not improvement from kerosene. However, even with these massive benefits, there are some major and minor issues that need to be addressed before hydrogen can be effectively produced and used for aviation.

III. Storage and Production

1. Storage

Hydrogen is stored in either physical or material-based forms which then split off into other ways of storage. Physical based storage can store it as a compressed gas, compressed at a low

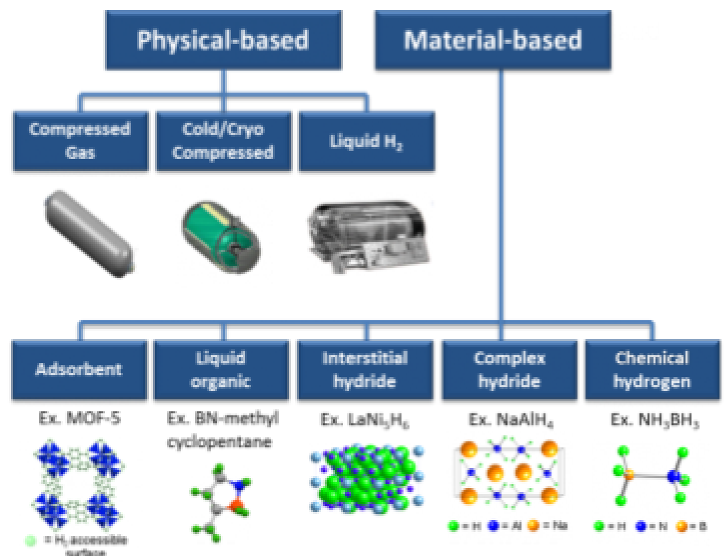

Fig. 1
Examples of possible hydrogen storage paths [4]

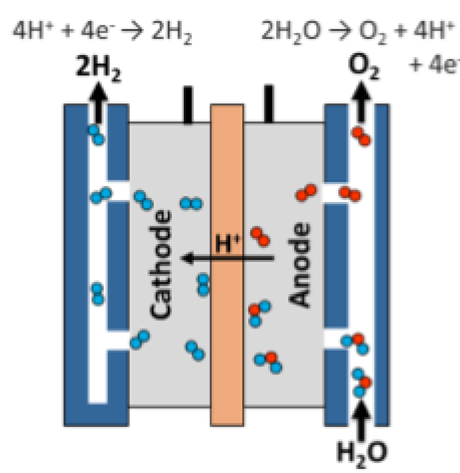

Fig. 2
Electrolysis diagram showing the movement of hydrogen and oxygen [6]

temperature, and as a liquid. Material based storage can store hydrogen as an adsorbent (MOF-5), a liquid organic (BN-methyl cyclopentane), interstitial hydride ($LaNi_5H_6$), complex hydride ($NaAlH_4$), or in its chemical form (NH_3BH_3) as shown in Fig. 1. These forms of storage still require storage in high-pressure tanks as a gas, or at a cryogenic temperature. This makes it difficult to store easily [4].

2. Production

There are a multitude of ways in which hydrogen can be produced, including electrolysis, water splitting, natural gas reforming, and photobiological production [5].The hydrogen produced here would be produced off-site in large amounts, then transported to the required location in the storage formats shown above. At the moment, most hydrogen is produced from non-renewable natural gas [16].

Electrolysis is one of the methods used to produce hydrogen, and rather simple in concept. Electrolysis uses electricity to split water into its hydrogen and oxygen components in an electrolyzer. [Fig. 2] Electrolysis is being considered as a possible source of hydrogen production in the future because of its potential to reach zero greenhouse gas emissions. Renewable energy also has a synergy with electrolysis, for example pairing wind farms with both electricity and hydrogen production. The current power grid is not optimal for electrolysis, because of the less efficient electricity generation process powered by fossil fuels [6]. These electrolyzers are easily scalable from small science class experiments to large scale hydrogen production facilities. There are two main types of electrolyzers, using different materials in the process.

Alkaline electrolyzers transport hydroxide ions through the electrolyte from the cathode to anode, generating hydrogen near the cathode [6]. This is a relatively simple method of electrolysis, also being more cost effective and easier to run. The second type of electrolyzer is solid oxide electrolyzers. These use ceramics as the electrolyte traditionally used in alkaline electrolyzers, utilizing the ceramic’s ability to conduct negatively charged oxygen ions at higher temperatures. Solid oxide electrolyzers require high temperatures to operate (around 700 to 800 degrees Celsius), and at this temperature steam at the cathode combines with the electrons from an external circuit to form hydrogen gas and negatively charged oxygen ions. The ceramic allows the oxygen ions to pass through and react with the anode and create oxygen and electrons for the external circuit referenced [6].

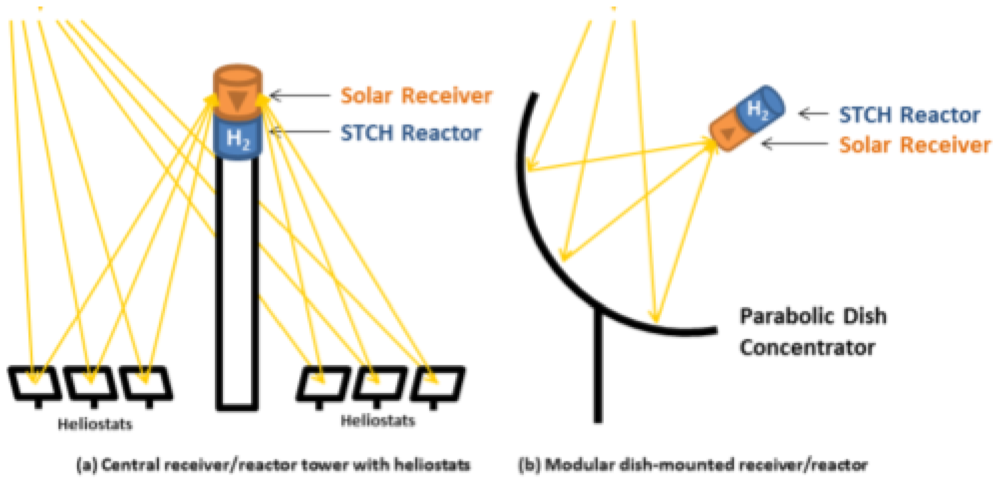

Fig. 3

Two forms of thermochemical water splitting [7]

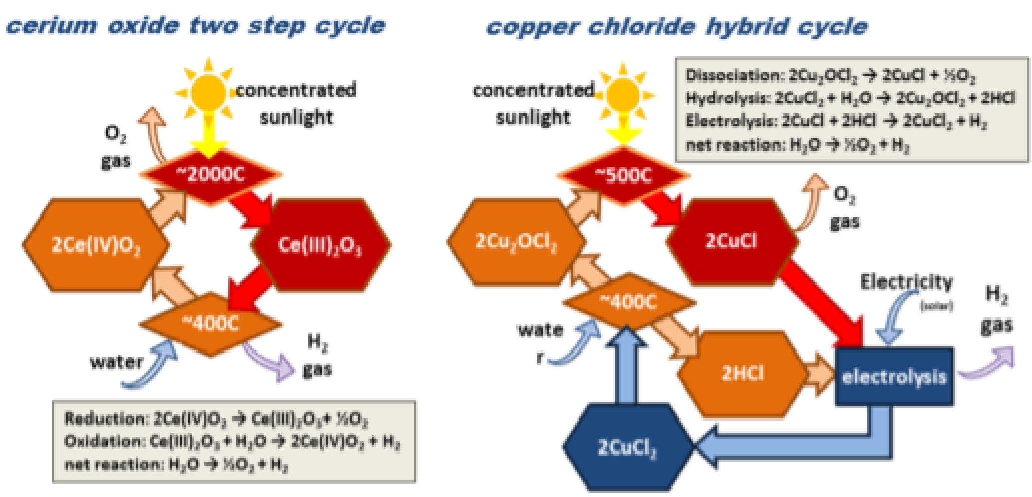

Fig. 4

Inputs and outputs of the water splitting cycle in more detail [7]

Steam-methane reforming reaction

$CH_4 + H_2O$ (+ heat) $\rightarrow CO + 3H_2$

Water-gas shift reaction

$CO + H_2O \rightarrow CO_2 + H_2$ (+ small amount of heat)

Fig. 5

hemical formulas of reactions explained in the main text [9]

Thermochemical water splitting is the process of using high temperatures and chemical reactions to create oxygen and hydrogen from water. This process is a potential long-term source of hydrogen, with potentially little to no greenhouse gas emissions. The high temperatures required to separate the elements is provided by either heat from nuclear reactions or solar power.(Fig. 3)

The heat used for the thermochemical process needs temperatures from 500 to 2000 degrees Celsius to start the chemical reactions to produce the hydrogen [7]. Chemicals used in the process vary from the types of cycle utilized, such as the Sulfur-iodine(S-I) cycle or calcium/bromine/mercury [8]. The benefit of this system is that the chemicals required for the cycle can be reused, so the total system only consumes water and heat. This system also has direct (two-step cerium oxide thermal cycle) and hybrid cycles(copper chloride cycle). The hybrid cycles are more complicated but require relatively lower operating temperatures, while the direct cycles are simpler but require relatively higher operating temperatures [7](Fig. 4).

Natural gas reforming is an advanced method of producing hydrogen that has been tested and used for a substantial period of time. In fact, 95% of the hydrogen produced in the United States is made by natural gas reforming utilizing the existing natural gas pipeline infrastructure [8]. Natural gas reforming is primarily used for hydrogen production today because of its near term nature, generating sufficient hydrogen amounts with a minor impact on the environment while cleaner, long term methods are being refined and tested.

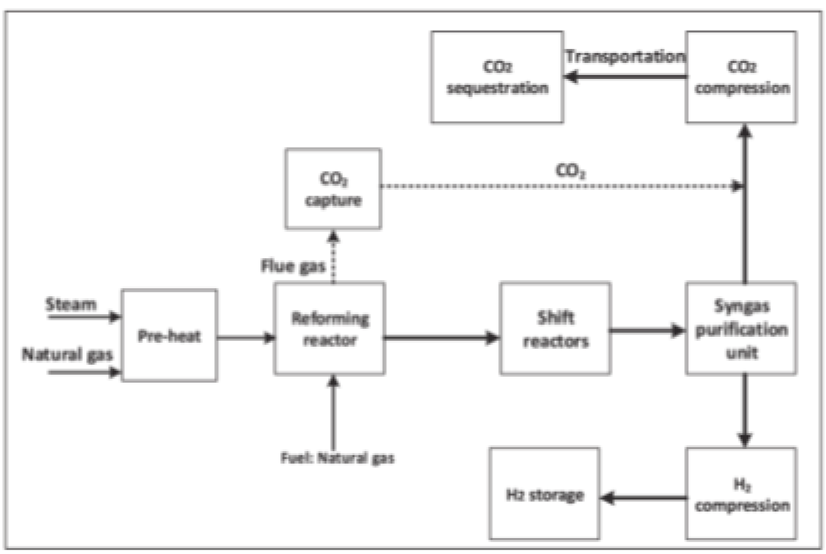

Fig. 6
Flowchart of the natural gas reforming process [10]

Most of the hydrogen produced in the United States is made by steam-methane reforming, in which 700 to 1000 degrees Celsius steam is used to produce hydrogen from a methane source such as natural gas in a few steps. (Other fuels such as ethanol, propane, or gasoline can be substituted for natural gas) The steam reacts with the methane under 3-25 bar pressure and with sufficient heat when reacting with a catalyst, creating hydrogen, carbon monoxide, and carbon dioxide through an endothermic reaction following the flowchart pictured in Fig. 6. In the next stage, called the “water-gas shift reaction,” ,following the equation shown in Fig. 5, the carbon monoxide and steam are reacted with a catalyst to produce carbon dioxide and more hydrogen. Lastly the “pressure-swing adsorption” step causes the carbon monoxide and other impurities to separate from the mostly pure hydrogen gas stream [8].

Another less effective form of this process is partial oxidation. In partial oxidation, the methane and other hydrocarbons in the natural gas source reacts to the insufficient oxygen needed to completely oxidize the hydrocarbons into carbon dioxide and water. With less of the required oxygen, the reaction produces mainly hydrogen, carbon monoxide(+ nitrogen if the air is not pure oxygen), some carbon dioxide, and more hydrogen. In comparison to the original reaction, partial oxidation is exothermic, faster, requires a smaller reactor vessel, and produces less hydrogen per unit of input fuel.

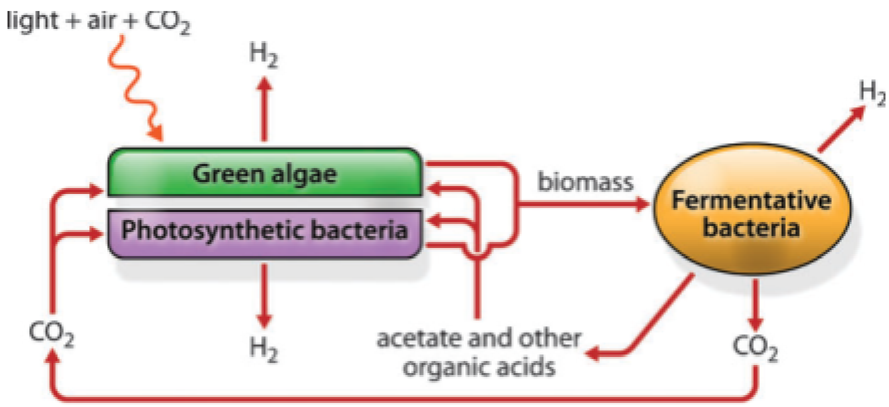

Fig. 7
Photobiological process in detail [12]

Photobiological hydrogen production is a form of hydrogen production that utilizes sunlight and microorganisms to turn water into hydrogen as pictured in Fig. 7. This technology currently struggles with low hydrogen production rates and other factors, but it has a high potential in long term hydrogen production approaching net zero carbon emissions. Photobiological systems are also extremely cost effective, because the algae and bacteria can be grown in water unfit for other uses and possibly wastewater [10]. In photolytic biological systems, the microorganisms (green microalgae/ cyanobacteria) use sunlight to split the water into hydrogen and oxygen ions. The hydrogen ions created can then be combined and released as hydrogen gas. Other issues with the hydrogen production is that this process requires oxygen which disrupts the hydrogen production reaction and mixes with the hydrogen gas. Other photosynthetic microbes use sunlight to break down organic matter other than water to generate hydrogen in a method known as photofermentative hydrogen production. This process also tends to have a very low hydrogen production rate, also including a low solar to hydrogen efficiency. Until a way to improve the production rate and efficiency of these systems are discovered by researchers, they will remain in the potential future for now. [10]

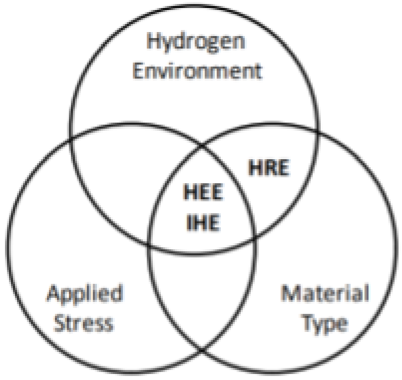

Figure 1
Classification of HEE, IHE and HRE type based hydrogen, stress, and material factors

Fig. 8 [13]

3. Hydrogen Embrittlement

In a paper from the NASA Johnson Space Center, hydrogen embrittlement is analyzed along with its effects on different metals, ways to reduce it, and more. A simplified definition of hydrogen embrittlement is the reduction in strength of certain materials when exposed to certain levels of hydrogen and stressors. The paper classifies hydrogen embrittlement into three categories sorted in Fig. 8: hydrogen environmental embrittlement (HEE), internal hydrogen embrittlement (IHE), and hydrogen reaction embrittlement (HRE).When the hydrogen is stored in tanks and moved through fuel lines of the engine or other parts on the aircraft, it will most likely undergo environmental embrittlement after an extended period of usage and stress. In hydrogen environmental embrittlement, certain mechanical properties can degrade when the material is under an applied stress and is exposed to a gaseous hydrogen environment. When this occurs, cracks can form in notches or defects in the material [22].

Hydrogen embrittlement could be an issue for the storing and usage of hydrogen, although the risk is low. Because hydrogen and applied stresses can cause small cracks in the material, the tanks and lines would have to be inspected and possibly replaced eventually. The low risk of this being an issue is because the effects of hydrogen embrittlement in most materials exposed to relatively low hydrogen pressures is negligible, with most recorded failures happening when materials were under high stress and extreme hydrogen pressure/temperature [22].

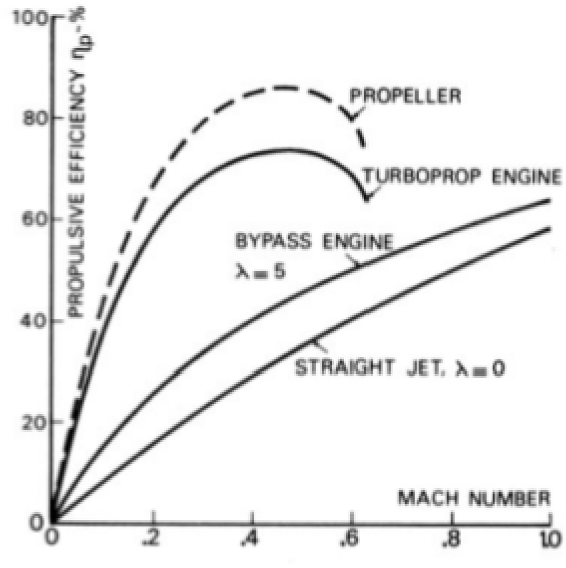

Fig. 4-18. Propulsive efficiency of sub-sonic turbo-engines

Fig. 9

Figure of turboprop efficiency compared to other types of engines [17]

IV. Flight Distance

1. Commercial Hydrogen Aircraft Pioneers

The distance a plane can fly using kerosene is, on average, further than planes that run on hydrogen. At the moment, most planes that run on hydrogen or plan to use fuel cells to power propellers on the aircraft to be able to fly efficiently. For example, some of the top hydrogen aircraft pioneers include Airbus's ZEROe projects, ZeroAvia, and Universal Hydrogen. (Their plans for the future, test flights, details, and results are all available online on their respective websites.) Airbus's concept aircraft use turbofan engines and turboprop engines [11], Zero Avia uses a Dornier 228 (turboprop) with their prototype hydrogen engines [12], and Universal Hydrogen uses the De Havilland Canada Dash-8 (Turboprop) with their hydrogen fuel cell powertrain. [13]. The benefit of fuel cells and turboprop aircraft is the ease of use, storage, and efficiency. Turboprop engines are usually superior in efficiency at lower altitude and airspeed, using less fuel for a larger flight distance, as shown in the graph in Fig 9. For this reason, hydrogen fuel cells can be used to power the engines or with special liquid hydrogen engines. This helps to stretch out the experimental flight range and make it more viable for use during the testing phases.

2. Flight Distance

To predict the possible range of hydrogen aircraft, the equation** used in this paper was derived from equations and unit conversions such as energy = power * time.

Boeing 737 (2586 miles* from SFO to JFK)

- Flight velocity of a Boeing 737 ≈ **262.395 m/s**
  - Flight velocity is needed to calculate the travel time and output energy [14]

- Thrust force of two Pratt & Whitney JT8D-1 engines ≈ **128.998 kN**
  - Thrust force is used to calculate the output energy [15]
- Output energy = Velocity * Ft (thrust force) = **33.849 MW**
  - Output energy needed to calculate the input energy needed
- Travel time = flight distance/flight velocity ≈ **15,860.683 sec**
  - Travel time needed to calculate input energy
- Energy (input) = power (w) * time (s) = **536,861.022 MJ**
  - Input energy needed to maintain stable flight (lift=weight, thrust=drag)
  - Power is converted from MW to w (1MW = 1e6 W)
- Liters of hydrogen needed: 536861.022 MJ / 10.1 MJ/L = **53,154.557 L**
  - MJ found in previous calculation divided by the energy density per liter of liquid hydrogen [2]
- Liters to cubic inches = **3,243,691 cubic inches**
  - Unit conversion to calculate cabin space needed (1L = 61.0237 in^3)

*The flight distance was found using multiple flight distance calculators [16-19]
**Calculation results applied in Fig. 10 and Fig. 11 found on the next pages
Fig. 12 is a flowchart that documents the data needed for the calculations, and the steps to obtain the final result of cubic inches of fuel needed. Fig. 10-12 were created by me to visualize the amount of space available on the plane for fuel, using public images from Google for plane size.

In Fig. 10, the image in the top right shows a cross sectional view of a Boeing 737, and assuming the cabin could require a center aisle for maintenance, the shape was traced and the scale of the image was found (1cm to 13.4 in). The irregular shape was cut into two triangles and a rectangle, the areas of which were combined and multiplied by two to find the total area in centimeters first. Then that square centimeter area was converted to inches squared. The goal volume was calculated using the fuel equation used previously. Dividing the goal volume by the area would find the length of storage needed, and in Fig. 10, the needed length of the storage area is much larger than the space available even on the entire plane.

In Fig. 12, the area is completely filled because the smaller size would likely make it easier to maintain from the outside, relative to a much larger commercial passenger plane. The same cross section was reused, using given measurements instead of the ones on the image. The red lines placed over the plane are the same length as the key noted in black and white on the right side of the plane image. As shown, 32 meters would be far too long to store on the plane, even with the entire passenger area filled with fuel.

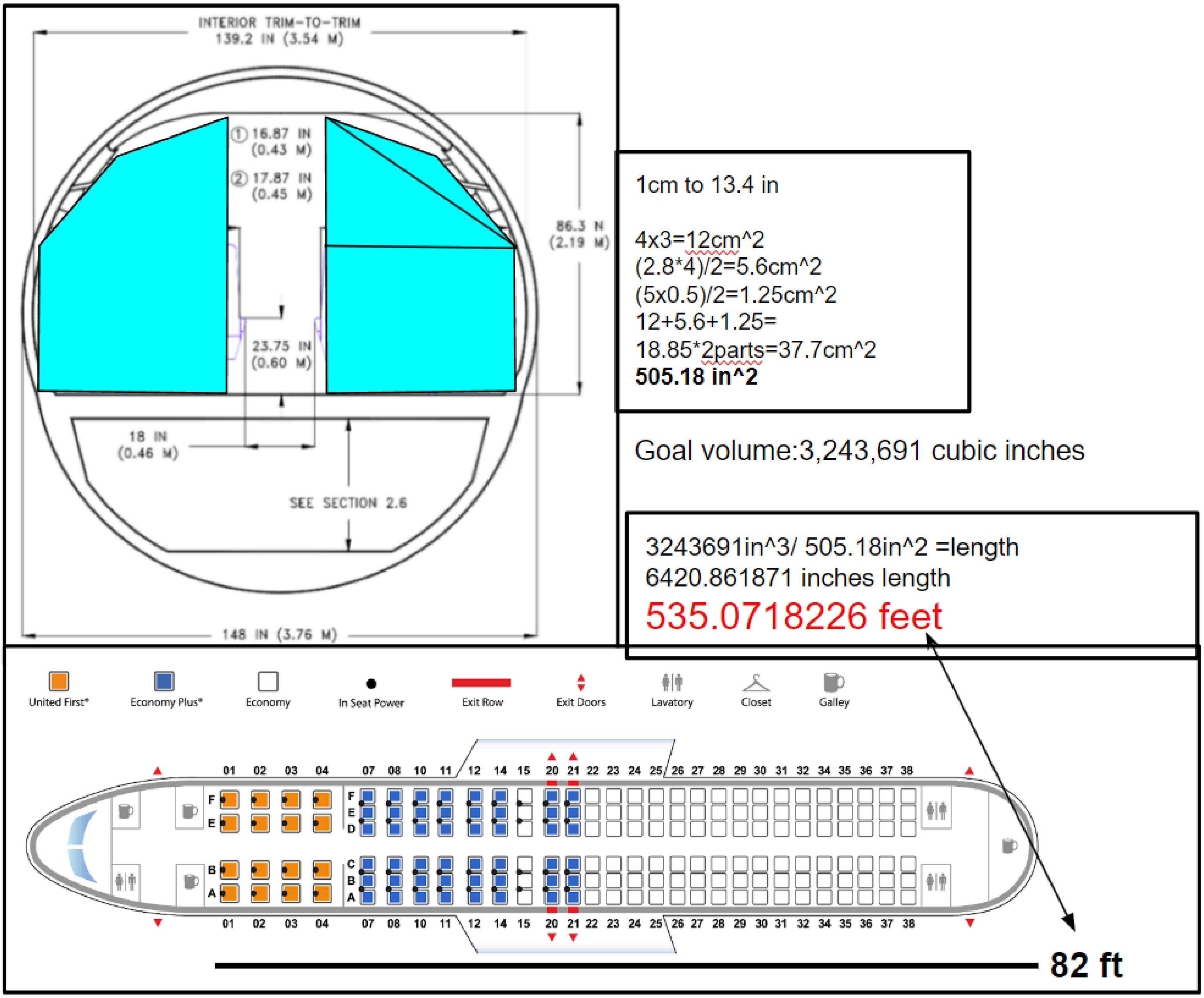

Fig. 10
Boeing calculations for flight distance

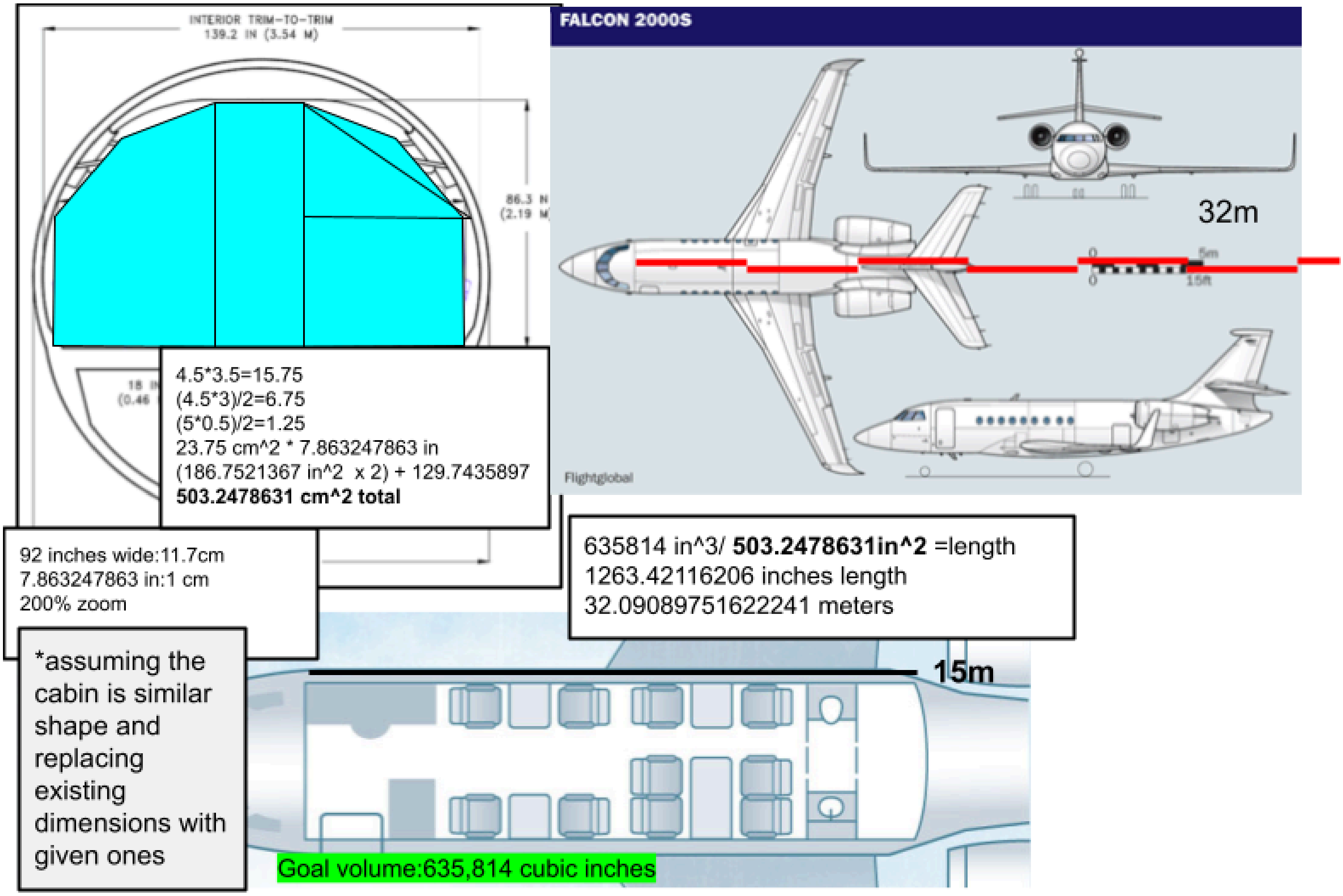

Fig. 11
Dassault Falcon 2000 calculations for flight distance

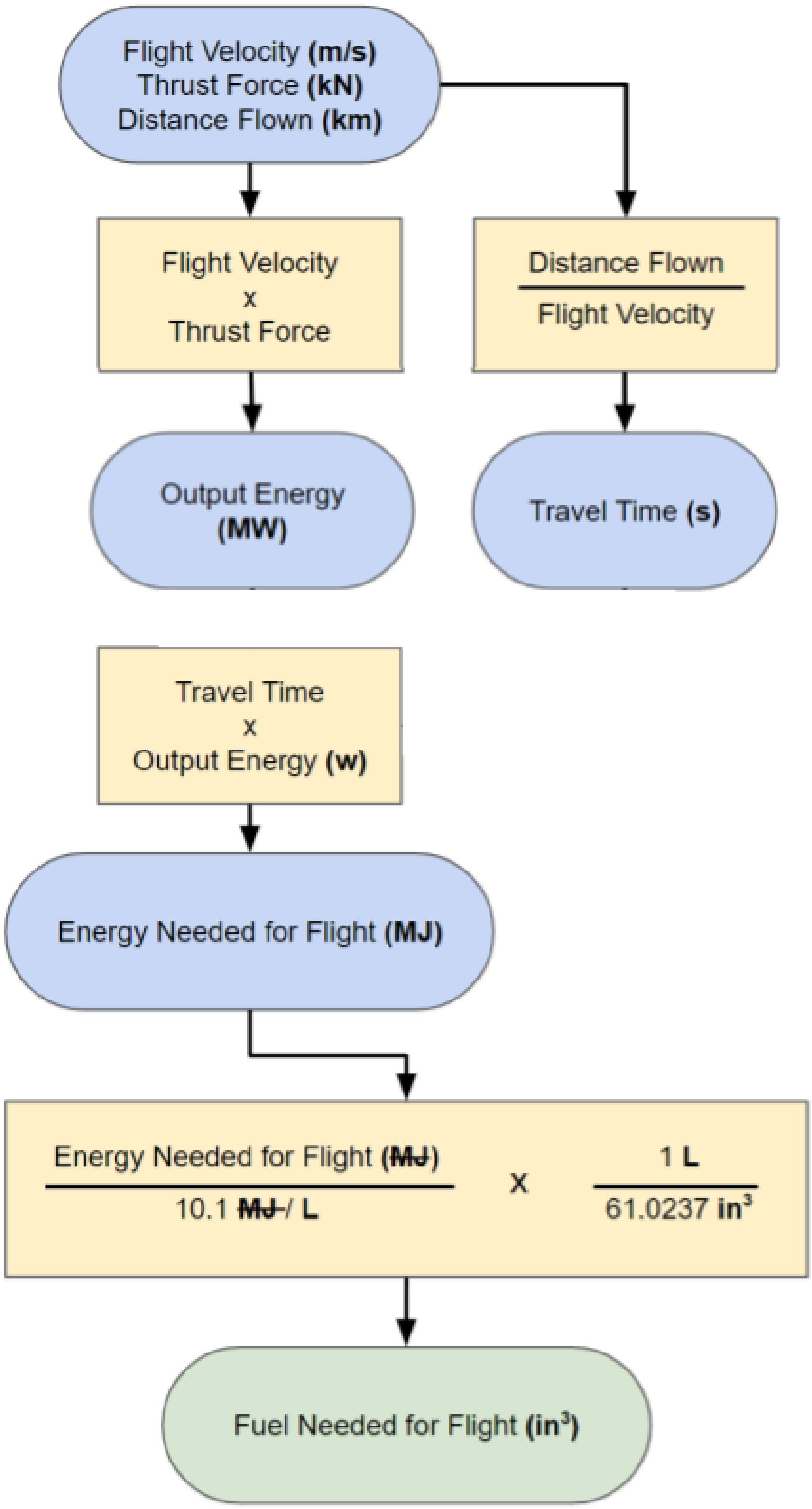

Fig. 12
Calculation Flowchart

Below is a chart of other distance calculations using the same formulas.

	Distance (mi) and Airports	Volume Required (cubic inches)	Storage length (ft):cabin space available (ft)	Successful (Storage length fits within cabin space)
Boeing 737	2586 SFO to JFK	3,243,691	535:82	No
Boeing 737	1050 SAN to SEA	1,317,043	217:82	No
Dassault Falcon 2000*	1050 SAN to SEA	635,814	105:49	No
Dassault Falcon 2000*	305 SAN to PHX	184,689	31:49	Yes
Dassault Falcon 2000*	110 SAN to LAX	66,609	11:49	Yes

*Dassault Falcon 2000 data
-velocity [20]
-engine specs [21]

The most prominent issue in using liquid hydrogen as a fuel source to power the engines of a large or medium size plane is fitting the fuel into the plane. While hydrogen does have a higher energy density, it takes up a large amount of volume as well. For example, long and short flights on the Boeing 737 would not work because the amount of fuel needed simply wouldn't fit. Even filling in the center pathway would not make up for the amount of fuel needed while still carrying passengers. The Dassault Falcon calculations best supported that the most optimal flights are short to medium range hops, from state to state or other applications. The best option for the Dassault Falcon 2000 was from San Diego to Las Vegas, with the liquid hydrogen fitting nicely in the back quarter of the plane leaving room for passengers. It should be noted however, that the efficiency in the equation was 100% with no loss from friction, air resistance, or other factors. These factors are most likely why companies like Universal Hydrogen have chosen to use turboprops with fuel cells supplying electricity instead of liquid hydrogen, in combination with the fact that liquid hydrogen is much more difficult to store.

3. Final Thoughts

Hydrogen aircraft will likely become a groundbreaking innovation prevalent in the industry in the future, but there still are a few problems to be addressed and parts in the chain to be scaled in order to be effective. Despite these hiccups, the massive reduction of carbon emissions from the sustainable methods of producing hydrogen have positive implications for the environment and the long term costs of aviation. The storage of hydrogen can be applied in multiple ways such as in the form of a gas, material based storage, and fuel storage, which could be afflicted with hydrogen embrittlement if neglected. To produce the hydrogen needed for large scale usage of hydrogen aircraft, electrolysis, water splitting, natural gas reforming, and photobiological production would be used in larger scales. Mainly, steam methane reforming already produces the majority of hydrogen in the United States using existing natural gas infrastructure, giving it an advantage over other production formats in its ability to scale up for higher demand for hydrogen. Electrolysis is another promising option, because of its synergy with renewable energy to potentially produce zero greenhouse gas emissions, while possessing similar scalability.

As for flight distance, hydrogen aircraft will likely have difficulty flying long distance flights. The calculations performed in this paper make multiple assumptions such as a lack of air resistance, perfectly consistent thrust from start to finish, and much more. While they may not be the most accurate estimates, they still provide the general picture of the difficulties of using hydrogen for long range flights. The effective range of hydrogen aircraft of medium size (such as a modified Dassault Falcon 2000) would be best used for short range hops between large cities and across state borders, possibly reducing larger air travel fees, carbon emissions, and air/road congestion. This short flight distance is due to the fact that hydrogen has a high energy density but still requires a larger volume of fuel to fly the same distance as a kerosene powered plane. At the current level of technology and scaling, hydrogen aircraft have difficulty keeping up with the flight distance and carrying capacity of standard aircraft. However, with time this technology can develop into a revolutionary alternative to traditional aircraft that can provide more efficient, cleaner flights.

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