# Fusion-Electric Propulsion for Hypersonic Flight

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## Abstract

Recent studies by R.W. Bussard have shown that charged nuclei of certain light element isotopes can be electrostatically compressed to sufficient density for nuclear fusions to occur. And the resulting fusion reactions involving such nuclei emit no neutrons and induce no radioactivity at all. Such "clean" fusion reactions can develop 4 to 8 times more engine thrust per fuel flow rate than chemical reactions with attractive engine thrust-to-weight ratios - ratios in the 3 to 6 g range. This paper shows that such propulsion could enable a 2- to 5-fold improvement in the payload delivery efficiency of earth-to-orbit aerospace planes and the accomplishment of environmentally favorable hypersonic flight.

## Introduction

The next breakthrough in manned space transportation may be accomplished by aircraft-like vehicles that can take off from runways, reach orbit, and return from space with a single fully reusable propulsive stage. Moreover, jet airliners derived from such hypersonic vehicles may enable extremely swift travel between the major cities of Earth. But adequate propulsive power for such flight is difficult to achieve with chemical combustion, and the exhaust products of chemical combustion pollute the atmosphere to some degree.

In this respect, recent studies by Bussard show that inertial electrostatic confinement of light element isotopes, such as hydrogen nuclei and boron-11, could enable "clean", powerful fusion reactions that emit no neutrons and cause no radioactivity and that develop 4 to 8 times more thrust per fuel flow rate than chemical reactions with significant ratios of engine thrust-to-weight. Furthermore, the hot electric discharge from such fusion produces significant ozone during high altitude flight, thereby enriching the upper atmosphere with ozone production in the vehicle wake. Thus, this paper explores use of such environmentally-favorable fusion propulsion for cost-effective hypersonic flight.

## Background

The use of inertial-electrostatic confinement (IEC) of fusion f-els was first proposed by Elmore[1] et al and by studies by Hirsch[2] showed that high fusion reaction rates could be achieved by compressing ions with grid potentials in a spherically concentric device. However, the amounts of fusion were severely limited by drive power losses due to collisions between particles and grids.

These limitations were overcome by Bussard[3,4,5] with a novel magnetic electrostatic means for trapping of energetic electrons to produce a stable negative potential well for ion confinement and with a unique concept for stable electrostatic wave group-trapping that enhanced ion compression in the central core.

These two new ideas formed the basis for revived IEC fusion research, with the Defense Research Advanced Projects Agency (DARPA) giving initial support[6] between 1984 and 1987. An analytical and a small-scale experimental effort was funded by the Strategic Defense Initiative Office through the Defense Nuclear Agency[7] and it showed the general feasibility of Bussard's concepts. A major program for further research and development was then supported by the DARPA in 1989-1992. Current research is supported by the US Navy, the Electric Power Research Institute, and the Basic Energy Sciences Division of the Department of Energy through the Los Alamos National Laboratory.

## Direct Conversion of Fusion Energy

There are certain fusion fuels that do not yield any neutrons at all during their reactions. These fuels include hydrogen nuclei (p) and boron-11, (p) and lithium-6, deuterium (D) and helium-3, and helium-3 ions alone. Book[8] shows that these particular reactions proceed as:

$p + {}^{11}B \longrightarrow 3\ {}^{4}He + 8.7\ MeV$

$p + {}^{6}Li \longrightarrow {}^{4}He + {}^{3}He + 4.0\ MeV$

${}^{3}He + {}^{6}Li \longrightarrow {}^{4}He + p + 16.9\ MeV$

$D + {}^{3}He \longrightarrow {}^{4}He + p + 18.3\ MeV$

${}^{3}He + {}^{3}He \longrightarrow {}^{4}He + 2p + 12.9\ MeV$

The charged particle energy emitted by these fusion reactions can be converted directly into electric power if the charged particles expand against an electric field.

Here, charged particles escaping radially from the center of a fusion reaction sphere can induce current flow in spherical shell grid structures to control voltage gradients of opposing potentials surrounding a power generating fusion core and the general feasibility of such direct conversion of fusion energy to electric power has been proven by experimental research studies by Moir and Barr[9,10].

Output power caused by the emission of charged particles from the fusion reaction will appear as modest currents (kiloamps) at relatively high voltages (typically at 0.5-2 MeV). Such current and voltage requires little power conditioning to drive relativistic electron beams for propellant heating, as well as for powering the fusion device, itself.

## Beam Heating and Engine Design

Energy carried by electron beams can be deposited directly into rotationally confined high-pressure plasmas, on the axis of a thrust chamber, producing very high temperatures. Resulting thermal radiation is absorbed by a radially inflowing fluid/gas, which then flows longitudinally into a magnetically-insulated converging-diverging nozzle to, produce thrust.

Gerwin[11] has shown that use of axial magnetic fields in such beam heated devices can reduce gas/wall heat transfer by as much as two orders of magnitude compared to conventional convective processes. This would enable the net effective specific impulse from hydrogen heating to reach levels of 2500 to 5500 sec (corresponding to temperatures of 20,000 to 80,000 K) without intractable difficulties in cooling combustor and nozzle walls. And maximum specific impulse will occur at pressures that enhance recombination of dissociated and ionized species in the nozzle flow.

Studies of electron beam interactions with dense plasmas by Thode and Sudan[12] and by Davidson[13], and experiments by Thode[14] show that beam energy can be absorbed effectively in thrust chambers of 0.5 meter length and coupled stably into the propellant flow. Only modest magnetic fields (typically 0.2-1.0 Tesla) are needed to inhibit heat transfer to walls downstream of the heating region and to stabilize propagating electron beams. Magnet coils for these fields can be located outside the chamber/nozzle structure and cooled cryogenically by hydrogen propellant before it is warmed further by other regenerative heat loads.

Figure 1, shows a typical integration of fusion-electric, electron beam, and thruster components into a fusion electric rocket engine for earth-to-orbit flight.

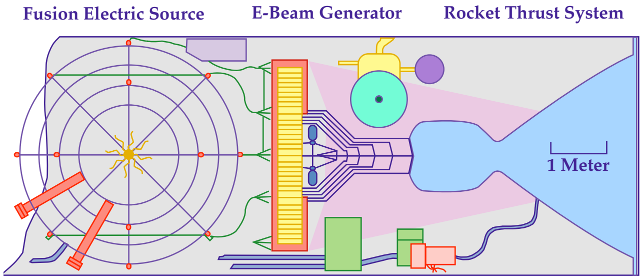


Figure 1 — Typical integration of Subsystems for Fusion-Electric Rocket

## Fusion-Electric Vehicle Performance

Bussard[15] has derived algorithms for calculating the component weights of fusion electric rocket propulsion systems defining them as a function of engine power, specific impulse, and engine thrust-to-mass. Engine weight and performance information[5] shows that engine thrust-to-mass ratios from 2 to 6 g can be associated with specific impulses from 4000 to 1500 seconds for power levels in the 2 to 6 GW range.

Such fusion engine thrust-to-mass ratios are. enormous compared to those of fusion propulsion systems of the past, because no neutron shielding is needed and because Bussard's inertial electrostatic scheme achieves fusion with much more modest confinement energy and mass.

Bussard[15] also made preliminary estimates of the configuration, size, weight and performance of an aerospace plane powered by fusion-electric rocket propulsion for single-stage-to-orbit (SSTO) flight. Such an SSTO vehicle, which also embodied chemical air-breathing propulsion from takeoff to Mach 2.5, weighed about 115 metric tons at takeoff and reached orbit with a hydrogen propellant consumption that was only about 38 percent of its takeoff mass. And although an independent assessment by Andrews of Boeing indicated that a somewhat greater propellant fraction (about 48 percent of takeoff mass) would be required, even this larger propellant fraction would enable very cost-effective earth-to-orbit flight.

## Chemical Air-Breathing and Fusion-Electric Flight

Figure 2 compares estimates of specific impulse (thrust per fuel flow rate) for chemical air-breathing and for fusion-electric propulsion art. Chemical air-breathing specific impulse characteristics are taken from by Maurice[16] et al, while fusion-electric propulsion characteristics are taken from Bussard[15]. These engine characteristics include internal flow losses and engine nozzle losses associated with atmospheric flight. However, they do not include losses due to gravity and vehicle drag.

It is seen that chemical air-breathing propulsion can provide extraordinary values of specific impulse at lower flight altitude and flight speed, while fusion-electric propulsion provides superior performance at higher altitude and for flight speeds greater than about Mach 10. It follows that air-breathing propulsion could be very attractive during the atmospheric phase of earth-to-orbit flight - up to flight speeds as high as Mach 10. Thus, as Bussard's initial study did, this investigation will consider both chemical air-breathing propulsion and fusion-electric propulsion for future flight.

## Underside Engine Exhaust for Fusion-Electric Flight

This investigation locates the fusion electric engine exhaust (its electron beams) under the vehicle, directly behind the air-breathing engine, as shown in Figure 3. This permits the fusion-electric engine to operate in conjunction with the chemical air-breathing engine, if desired, during the initial portion of flight.

Although such an underside exhaust location may require more engine packaging volume than an aft end location, it enables the fusion-electric engine to heat air flow (in addition to propellant) for additional thrust. Furthermore, the underside contour of the ship, which effectively expands engine exhaust flow for chemical air-breathing flight, should effectively expand engine exhaust flow for fusion-electric flight as well.

Vehicle drag would, of course, be minimized if the air-breathing engine would be retracted against the vehicle when air-breathing flight is complete. Although such retraction is not mandatory, it would probably improve airflow quality in the region to be heated by the electron beams. And air flow heating by electron beams should, at very high speed, be enhanced by confinement of the airflow within a narrow region between the vehicle under-surface and its bow shock.

## Vehicle Synthesis and Analysis

Vehicle synthesis and trajectory analyses have been performed for earth-to-orbit flight, assuming the fusion-electric propulsion characteristics derived by Bussard[5] and an underside location for the engine exhaust. Vehicle drag estimates were somewhat greater than that of Ref. 5, thereby resulting in somewhat more engine fuel consumption and dry mass.

A 15 percent engine propellant and dry mass margin was also supplied in order to obtain a degree of conservatism, and no fusion-electric specific impulse improvements due to the more favorable underside exhaust location were assumed.

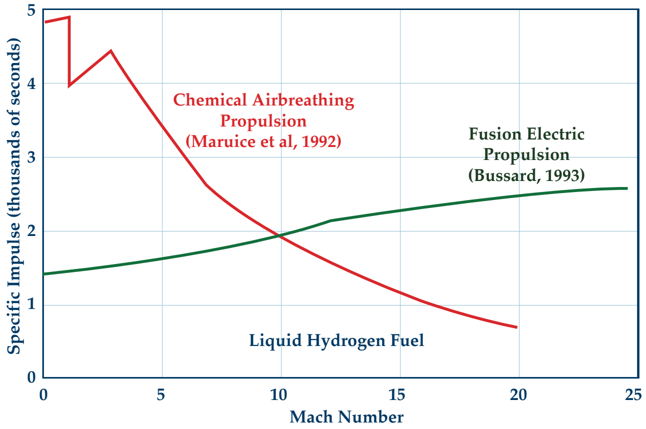


Figure 2 — Specific Impulse Variation for Chemical and Fusion Propulsion

As might be expected, increases in weight margins and drag resulted in vehicle payload delivery efficiencies that were somewhat less than Bussard's preliminary estimates[15]. However, they remained very significant and much greater than those achievable with chemical propulsion art.

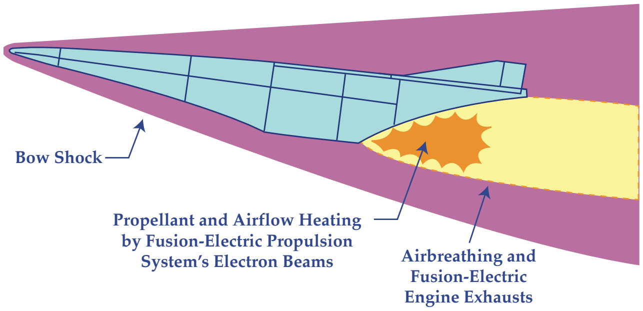


Figure 3 — Underside Locations for Chemical and Fusion Engine Exhausts

## Influence of Air-Breathing Propulsion Art

A major objective of this investigation was to determine the approximate amount of chemical air-breathing propulsion to be used during the atmospheric phase of flight. In this respect, Table 1 shows the influence of air-breathing propulsion on the effective specific impulse achieved during ascent to orbit and on the propulsive portion of a vehicle's takeoff weight. Here, extending air-breathing propulsion to higher speed increases specific impulse. But, drag and gravity losses also increase due to extended flight within the atmosphere and longer time to reach orbital altitude and speed. The propulsive fraction of a vehicle's takeoff mass (the fraction of its weight that is propellant and engine mass) is seen to be the least if effective air-breathing can be maintained until about Mach 10 is reached. Air-breathing to higher speed increased air-breathing engine and structural weight but it did not reduce propellant consumption. Thus, payload weight fraction would be decreased because of increasing the propulsive and air frame fraction of a vehicle's takeoff mass.

Table 2 shows the effect of air breathing on fusion-electric aerospace plane weight. It is seen that propellant, propulsion and airframe weights reach minimal values if effective air-breathing propulsion can be maintained from takeoff to about Mach 6.0 speed. And such air-breathing capability is almost (if not already) within our technical grasp today.

It is also seen that extension of air-breathing to about Mach 12 results in about the same vehicle takeoff mass, with slight reduction in propellant consumption being compensated by slight increase in structural weight. And although air-breathing to much higher speed than Mach 12 may be useful for aerospace planes that use chemical propulsion alone, it would be counterproductive when fusion-electric propulsion can be used. Here, chemical air-breathing propulsion would provide less specific impulse than fusion-electric propulsion beyond Mach 12. Thus, extending air-breathing propulsion beyond Mach 12 would increase the air-breathing engine and airframe weight of fusion-electric aerospace planes while not increasing specific impulse at all.

## Aerospace Plane Comparisons

Aerospace planes powered by chemical rocket systems and by chemical air-breathing and rocket systems have been described by authors such as Andrews[17] and Maurice[16]. Figure 4 shows weights for these aerospace planes and compares them with the weights that would be achievable with fusion-electric propulsion art.

It is seen that the takeoff weights of all-rocket aerospace planes powered by fusion-electric propulsion could be only about one-fifth those of chemical rocket planes, and that fusion-electric propulsion would enable omission of the large heavy "trolly"[17] needed for takeoff by chemical rocket planes. Even lighter fusion-electric aerospace planes are seen to be possible if chemical air-breathing propulsion that is within our grasp today is used during the initial phase of flight. And it is seen that the weight of such planes would be less than half that achievable with, even, the extraordinary chemical air-breathing propulsion advancements that have been assumed in reference 16.

## Table 1 — Effect of Air-Breathing on Characteristics of Fusion-Powered Aerospace Plane

| Maximum Air-breathing Speed | Effective Specific Impulse | Ascent Drag and Gravity Losses | Propellant Faction of Gross Weight | Engine Fraction of Gross Weight | Propulsion Fraction of Gross Weight |
|---|---|---|---|---|---|
| Mach 0.0 (All Rocket) | 1,900 sec | 2.37 km/sec | 0.423 | 0.241 | 0.664 |
| Mach 2.5 | 2,100 sec | 2.65 km/sec | 0.4 | 0.235 | 0.635 |
| Mach 6.0 | 2,500 sec | 3.00 km/sec | 0.375 | 0.215 | 0.59 |
| Mach 12.0 | 2,740 sec | 3.67 km/sec | 0.352 | 0.219 | 0.571 |
| Mach 20.0 | 2,740 sec | 5.29 km/sec | 0.388 | 0.277 | 0.665 |

## Table 2 — Effect of Air-Breathing on Weights of Fusion-Powered Aerospace Plane in Metric Tons

| Maximum Air-breathing Speed | Consumable (Propellant Weight) | Inert Propulsion Weight | Airframe & Tankage Weight | Systems & Payload Weight | Takeoff Gross Weight |
|---|---|---|---|---|---|
| Mach 0.0 (All Rocket) | 51.7 | 29.4 | 28.8 | 11.8 | 122.2 |
| Mach 2.5 | 40.8 | 24 | 25.3 | 11.8 | 102 |
| Mach 6.0 | 31.9 | 18.3 | 22.9 | 11.8 | 85 |
| Mach 12.0 | 29.9 | 18.7 | 25.3 | 11.8 | 85.6 |
| Mach 20.0 | 54.9 | 39 | 35 | 11.8 | 140.7 |

Table 3 compares the component weights of chemical and fusion powered aerospace plane with the same takeoff weight. It is seen that embodiment of fusion-electric propulsion can enable about a 4-fold increase in the payload carried by an aerospace plane of given takeoff weight.

## Table 3 — Effect of Propulsion on Aerospace Plane Weight in Metric Tons

| Vehicle System | Chemical Propulsion (Airbreathing to Mach 20) | Fusion Propulsion (Airbreathing to Mach 6.0) |
|---|---|---|
| Airframe/Tanks | 31.8 | 45.7 |
| Thermal Protection | 6.2 | 8.4 |
| Landing Gear | 5 | 5 |
| Chemical Propulsion | 43.1 | 17.8 |
| Fusion Propulsion | 0 | 27.1 |
| Systems | 6.7 | 6.7 |
| Crew | 0.6 | 0.6 |
| Payload | 4.5 | 17.9 |
| Liquid Hydrogen | 71.7 | 77.8 |
| Liquid Oxygen | 37.3 | 0 |
| Takeoff Weight | 206.9 | 206.9 |

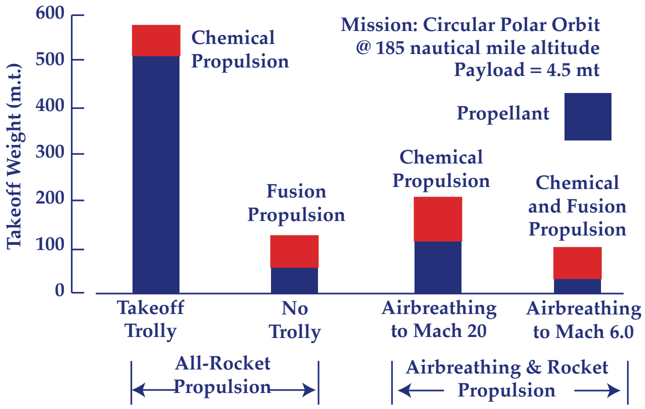
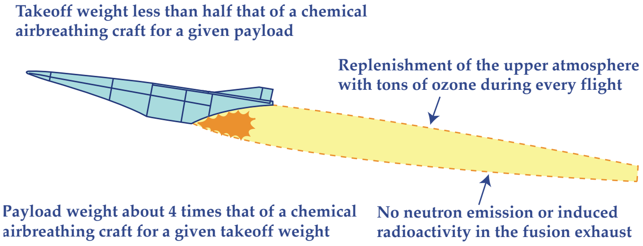


Figure 4 — Effect of Propulsion on Aerospace Plane Weight

## Fusion Electric Benefits for Hypersonic Flight

Very preliminary estimates were made of the effect of fusion-electric propulsion on the weights of a hypersonic airliner fueled by liquified methane and capable of carrying 300 passengers 6,500 nautical miles at Mach 4.0 speed. These estimates indicated that the takeoff weights of hypersonic airliners powered by chemical air-breathing and fusion electric propulsion would be less than half that achievable with chemical air-breathing propulsion alone. It was found that airliner takeoff mass could be reduced from about 410 to 190 metric tons if fusion electric propulsion was used during the long cruise portion of its powered flight.

It was also found that the fusion electron beam discharge into propellant and airflow would produce significant amounts of ozone in the upper atmosphere during Mach 4.0 cruise. Here, the high power electron beams create massive dissociation and ionization within propellant and air, and the resulting dissociated species participate in reactions that form ozone in the vehicle wake. Moreover, Bussard estimates that ozone production rates could enrich the upper atmosphere with an ozone mass that is somewhat comparable to that of the vehicle at the beginning of its flight.



## Conclusions

"Clean" environmentally favorable fusion-electric propulsion technology similar to what has been described would revolutionize air flight and space flight if it were combined with technologies, such as air-breathing propulsion and reusable structures that are emerging for hypersonic flight.

## Publication History

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