S.S.T.O. & T.S.T.O. LOX COLLECTION SYSTEM PERFORMANCES : INFLUENCE OF LOX PLANT ARCHITECTURE

Ir. Patrick HENDRICK
Royal Military Academy
Applied Mechanics Dept
Ave de la Renaissance 30
1000 Brussels - BELGIUM

Abstract

In-flight oxygen collection is a mean to improve considerably the performances of hypersonic S.S.T.O. (Single-Stage-To-Orbit) and T.S.T.O. (Two-Stages-To-Orbit) reusable vehicles. In a S.S.T.O., it permits to reduce much both gross take-off weight & dry weight and to transition from ramjet to rocket at a much lower Mach number, say about 6.5 instead of 15. Thus, programmatic development risks are all the more reduced because oxygen collection can be easily tested on the ground or in flight at a reasonable Mach number, say 2.5 or 3. This rather low transition Mach number reduces considerably the thermal heating too and the development costs of the airbreathing propulsion system.

The S.S.T.O. presented here is a VTOHL vehicle with a propulsion sequence rocket/ramjet/rocket with a rather low maximum airbreathing Mach number of 6.6. Collection takes place mainly in cruise at Mach 2.5 at constant altitude in ramjet mode.

The efficiency of the collection concept depends dramatically upon collection ratio Γ, i.e. the ratio of the collected Liquid Enriched Air (LEA) mass flow rate to the hydrogen mass flow rate. The influence upon Γ of air supercharging (or of the ascent trajectory), hydrogen recirculation in the tank filled with biphasic slush hydrogen, hydrogen expander and para→ortho hydrogen catalytic conversion is numerically analyzed and a LOX plant architecture is proposed. It is seen that the gain derived from para-ortho conversion and to a lesser degree recirculation is significant but that a supercharger (or a high pressure in the condenser) is not always very effective and could be in some cases negative. It is also noticed that the use of an expander is a big matter of discussion except perhaps if driving power is required. During cruise at Mach 2.5, at an altitude of 13 km, a dynamic pressure of 75 kPa and a collection plant with an efficiency equal to 80 %, Γ can reach 6.6 without expander.

It will be shown that, with Γ above 3 during cruise at Mach 2.5, an interesting gain can already be obtained at system level. With Γ above 6 the vehicle would be dramatically improved if the collection plant was very light but it is shown here that a reasonable value of Γ (3) can be sufficient.

Another very important element of the plant is the separation device. A low oxygen purity of the LEA penalises specific impulse in rocket mode and a relatively high separation efficiency has to be reached to first attain the condenser heat balance and secondly improve Γ. A rotary distillation air separator is used here but an innovative separation technology (which needs a rather low air pressure (6 to 8 bars) ahead) is also proposed.

Last but not least, the use of the gaseous depleted air (GDA) is discussed. Consequences of the choice of injecting GDA in the combustion chamber of the hydrogen fueled ramjet are analyzed.

Some sensitivity analysis results for S.S.T.O.'s & T.S.T.O's are given in the paper, showing for example the impact of the collection Mach number range upon take-off gross weight or stoutness (Küchemann's parameter).

Potentially in-flight LOX collection offers very promising possibilities, in particular elimination of the marginality and the lack of operational flexibility of the all-rocket reusable S.S.T.O. like the new X-33 project. But the success of this option is contingent upon the development of an efficient collection plant and its demonstration.

List of symbols and acronyms

A	Altitude
C_{OX}	LEA purity
ER	Equivalence Ratio
Γ	Collection ratio
GDA	Gaseous Depleted Air
GW	Gross Weight
ISP	Specific Impulse
LACE	Liquid Air Cycle Engine
LEA	Liquid Enriched Air
LH_2	Liquid Hydrogen
LOX	Liquid OXygen
LRE	Liquid Rocket Engine
M	Mach number

η_{sep}	Oxygen recovery factor
Π_c	Supercharger pressure ratio
Π_s	Air separator pressure ratio
Φ	Flow ratio
Q	Dynamic pressure
RD	Rotary Distillation Air Separator
Spm	LEA collected flow
S.S.T.O.	Single Stage To Orbit
T.S.T.O.	Two Stages To Orbit
VTOHL	Vertical Take-Off & Horizontal Landing

1. Introduction

In-flight oxygen collection (or ACES, for *Air Collection and Enrichment System*) vehicle proposals have been discussed since the early 1960's by R. Nau and others, and have been the subject of renewed interest since the late 1980's, particularly in the USAF. Indeed, atmospheric oxygen collection may be considered as the base of self-sufficient earth-to-orbit vehicle concepts (1, 2, 3) or as a way to improve some known concepts (4).

For the space vehicle concepts under consideration since the mid 1980's which are using a combined airbreathing-rocket propulsion, the power on the main part of the acceleration flight, in sense of kinetic energy increase, is provided by LH_2-LOX rocket engines. Therefore, oxygen fraction is significant (from 16% of the vehicle GW for a T.S.T.O. like Sänger up to 55% for a S.S.T.O. like HOTOL). For pure rocket vehicles, this fraction is even larger as they are powered by liquid rocket engines only (for a S.S.T.O. rocket of Delta Clipper type, oxygen fraction could be 75%).

With the ACES concept, the vehicle takes off with a small part of the required LOX quantity (like here) or no LOX at all (3) and therefore ACES allows, at given vehicle GW, to increase largely the payload fraction or, for a given payload and mission, to reduce significantly the GW. It allows also more flexibility in launch operations and an increase of the launch window.

Currently, the problem is in the definition of the concept of a LOX collecting vehicle, in the choice of an efficient thermodynamic cycle for the collection plant and in the development of the key technologies.

This paper discuss the problem of the choice of an adequate thermodynamic collection cycle as well as its performances and the problem of the design of some of its elements. The **integration** of all the components into one cycle and **into the vehicle and its propulsion system** is a dominant factor in this design.

2. S.S.T.O. vehicle concept and integration of collection plant

2.0. *Preliminary notice*

In LOX collection concepts, atmospheric air is deeply cooled, partly condensed and then separated into 2 flows: one of air enriched in oxygen called LEA (Liquid Enriched Air) and another one of air enriched in nitrogen called GDA (Gaseous Depleted Air).

2.1. *Vehicle concept description*

The reusable S.S.T.O. studied here is a VTOHL vehicle with a payload of 8 tons and 50% slush hydrogen fuel stored in the tanks at 13.8 K. The orbit height is 200 km and its inclination 98°. The launch base could be in Europe (latitude = 43.5° North) with still a large daily launch window (a few hours).

The propulsion sequence is rocket/ramjet/rocket (see also Ref. 1). The first transition (rocket to ramjet) occurs at Mach 1.9 and 9 km, and the maximum airbreathing Mach number is equal to 6.6 at 27 km, where the transition from ramjet to the final rocket mode takes place. As one can see, *this concept does not need any development of a scramjet engine.*

The in-flight LOX **collection** phase takes place **during the ramjet mode**, mainly in cruise at Mach 2.5 and an altitude of 13 km (then danger of precooler icing is highly reduced), with a dynamic pressure of 75 kPa. Indeed, LOX collection must take place during a phase with a high ISP (3000 s or more) otherwise collection could become a penalty. The collected LEA is sent to the LOX tanks for later use in the final rocket mode (from Mach 6.6 to 25).

The vehicle has a blended body-wing configuration. At the end of collection in cruise at Mach 2.5, its lift-to-drag ratio is approximately 4-4.5. The planform loading at take-off is 400 kg/m^2.

As the necessary heat exchangers (and air separator) are already on board, a partial LACE cycle could be used during the low speed rocket phase (at the cost of greater system complexity). This would increase the specific impulse during this phase, reduce the LOX consumption and therefore provide a lower take-off Gross Weight (GW) but that will not be assessed in this study.

2.2. *Need for integration*

LOX collection induces also penalties: a heavy collection plant, a high hydrogen fraction at take-off that leads to a large vehicle volume and an increase of the vehicle drag (or a decrease of the engine thrust) during collection due to the air stopped in the engine(5). Besides, the increase of the vehicle mass during collection requires a higher thrust potential at take-off than the one needed for the actual TOGW.

The benefits could be increased and penalties reduced by optimal integration of the collection plant with the power plant as it will continuously be shown in this study.

3. Thermodynamic collection cycle - Collection plant architecture

3.1. *General arrangement of the plant*

Collection plant should certainly include the following elements: heat exchangers (with hydrogen and GDA as coolants), condenser (with LH_2) and air separator (6). A helium closed loop could be introduced mainly for safety reasons (buffer between air and hydrogen) but also with the intend to be used as a heat pump to improve collection plant performances (higher Γ_{max}). It could also include an air compressor, a GDA compressor and other cryogenic turbomachines, like the ones present in the helium closed loop. It could have its own air intake or a bifurcated inlet from the power plant intake, and a separated nozzle or a common one with the power plant.

A generic architecture without intermediate helium closed loop is proposed in figure 1. Some elements could be removed as the supercharger, the recirculation circuit and the expander, what would define the **basic cycle**. Some elements could also be incorporated into another one if it is possible, because the collection plant has to be as simple as possible and the number of turbomachines kept small in all cases and especially here with fluids like hydrogen and helium with very low densities.

The four main elements of a collection plant are the precooler, the supercharger (air compressor), the condenser and the separator. The precooler is split in 2 parts : one before the supercharger and another one after it, each time with 2 heat exchangers, one with hydrogen as coolant and one with GDA as coolant. From the outlet of the air separator, the LEA enriched in oxygen flows into the LOX tanks and the GDA enriched in nitrogen flows under saturated conditions to be first used in the collection plant as a second coolant with the hydrogen from the tanks and further expelled from the vehicle as usefully as possible for the vehicle ISP.

For the vehicle and the collection plant, the most critical subsystems are certainly the air separator and the heat exchangers. On the one hand, the separator is the last element in the air treatment chain and as such, its separation performances will play a major role in the sizing of other elements and mainly the air precooler. The oxygen purity of the LEA delivered by the separator plays also a major role at a system level because a low purity penalises specific impulse in rocket mode (about -1.6s/% of impurity). It is the governing technology of the ACES concept (7). A review of the main principles of air separation and performances of main separation devices is presented in Ref. 8. On the other hand, heat exchangers and especially the precooler are the main contributors to the mass and volume of the collection plant. Therefore their number has to be kept as small as possible as well as their specific weight and volume. The cryogenic turbomachines which are necessary inside the collection plant play also an important role in the mass budget of the vehicle but, above all, they are crucial for the integration of the collection plant into the vehicle propulsion system.

3.2. *Use of depleted air*

One of the main aspects of collection plant integration is the manner to use GDA coming out of the air separator. Fraction of the air incoming for separation can be as high as 30-40% of total airflow through the inlet and at least 80% of this airflow will be GDA. Thus the GDA flow in this S.S.T.O. could reach more than 450 kg/s. Therefore proper depleted air exhausting should be designed. Different manners exist :

3.2.1. Discharge GDA just after the precooler with a temperature of about $0.6T_{air}$ and a pressure depending on the performance of compressors and pressure loss in heat exchangers. If collection plant is working simultaneously with a ramjet, combined ISP is far below that of a pure ramjet.

3.2.2. Discharge GDA after combustion with a small amount of hydrogen. Stoichiometric ratio which is higher compared to pure air/hydrogen mixture is optimal in terms of combined ISP of the system. Indeed, at an oxygen recovery factor of 80%, stoichiometric ratio of GDA and hydrogen is about 140 compared to pure air/hydrogen ratio of 34.3. With such an integration, combined ISP is comparable with the one of a pure ramjet. The energy of the burned GDA could be used for driving the collection plant turbomachinery after expansion in a turbine.

3.2.3. Send depleted air in the ramjet combustor as illustrated by figure 2. At low speed, i.e. Mach 2.0-3.5, combined ISP will exceed that of a pure ramjet. This solution is optimal in terms of vehicle efficiency but seems more complicated because of the necessary mixing of GDA with the main airstream in the ramjet burner.

In this study, GDA coming out of the precooler is injected into the ramjet combustion chamber during the whole cruise flight and a little bit beyond, till the "dumping" Mach number M_{cd}. That improves the ramjet ISP (1). Above M_{cd} , GDA is expelled from a separate nozzle: at these higher Mach numbers the ramjet combustor pressure becomes too high to reinject without a good GDA compressor (see par. 5.5).

As well as the partial LACE rocket that could be used during the low speed rocket phase, use of depleted air into the ramjet chamber is a good example of a *synergistically integrated* powerplant (cf. the many examples of Ref. 9).

3.3.*Important parameters of the collection process*

Collection plant performances are characterized by 3 main parameters :

Collection ratio Γ: LEA flow actually collected/total hydrogen flow

Oxygen recovery factor η_{sep}: kg O_2 in LEA/kg O_2 in air

Oxygen purity C_{ox}: kg O_2 in LEA/kg LEA.

At vehicle level, GDA pressure at the exit of the precooler is also very important. It will determine the possible further use of this flow. Actually, it is mainly the pressure ratio through the air separator π_s which influences the exit GDA pressure and also the choice of the pressure ratio through the supercharger π_c or of the ascent trajectory.

In this study, the collection plant air intake is a bifurcated inlet from the power plant intake and that introduces another very important parameter of the plant and of the vehicle: the collection flow ratio Φ. Φ is the ratio between the air flow through the collection plant and the total air flow at the entrance of the vehicle air intake.

3.4.*Collection plant mass and volume assumptions*

The mass and volume parameters are especially important in a S.S.T.O. and among them, those of the collection plant. In fact, specific mass and volume of the collection plant (separator included) increase with higher Γ 's and lower recovery factors as shown in table 1. On these weights as on all others in the vehicle study, a weight margin of 15% is always considered as usually required on space projects and also to cover uncertainties on aerodynamics or engine performances. Components are sized for the cruise phase (Mach 2.5) during which most of the LEA is collected.

Collection ratio Γ	3.4	6.0
Oxygen recovery	65 %	65 %
Collection plant specific mass	85 kg/kg LEA/s	150 kg/kg LEA/s
Collection plant specific volume	0.7 m^3/kg LEA/s	1 m^3/kg LEA/s

Table -1- Collection plant parameters

The air separator considered here is a structured packing rotary distillation air separator with the following characteristics :

LEA purity C_{ox}	94%
Oxygen recovery η_{sep}	65%
Pressure ratio π_s	4
Specific mass (AlLi)	3.1 kg/kg air/s
Specific volume	0.03 m^3/kg air/s

Table -2- 1990's RD predicted performances

This separator is heavier and more voluminous (not so much) than a double stage vortex tube air separator but shows high tested performances. One of the main problems added by air separation is certainly the large pressure ratio π_s present with vortex tubes and RD. That could be avoided (except the friction pressure losses) with a new air separation concept based on the strong paramagnetic character of oxygen and diamagnetism of nitrogen and argon. With a superconducting magnet (at 20T), it could be possible to separate oxygen from nitrogen and argon and obtain a very pure LEA.

4.Cycle performances in cruise

4.0.*Preliminary notice*

Collection could take place at a constant Mach number and constant altitude (cruise flight) or during acceleration with a variable altitude. In this study, the plant design is optimised for cruise when the ramjet operates fuel lean with an ER of about 0.6. The cruise conditions are Mach 2.5 at about 13 km altitude (Q=75 kPa). The influence of the collection Mach range upon vehicle performances is presented in par. 5.

4.1.*Performances in cruise conditions*

Cycle selection is driven by the constraint to keep, in all exchangers, wall temperature difference at least equal to that at the condenser pinch (ΔT= 10 K). It is not an easy task and it could result in large temperature differences at the precooler inlet on hydrogen and GDA sides.

Table 3 shows collection plant performances for a module with a total (ramjet flow included) static air flow of 300 kg/s. It is shown that the maximum collection ratio during cruise with the **basic cycle** is 2.5.

Option	Γmax	Φ
Basic cycle	2.5	30 %
+ Expander	3.3	30 %
+ Supercharger	5.1	34 %
+ Sup & Rec	5.5	36 %
+ Sup & Con	6.3	39 %
+ Sup & Rec & Con	6.6	41 %

Table -3- Collection plant performances at Mach 2.5

Ameliorations of the basic cycle are possible by adding a hydrogen expander, an air supercharger, hydrogen catalytic conversion or hydrogen recirculation.

4.1.1.Hydrogen expander

Γ_{max} can be improved by adding a hydrogen expander : work extraction from hydrogen lowers its temperature and improves its cooling capacity. Expansion must take place near the pinch (condenser) for maximum effectiveness and the work expanded by H_2 must be usefully used, for example to drive the hydrogen pump. Figure 3 shows the evolution of hydrogen temperature as a function of its enthalpy per kg of air in the presence of an expander. Table 3 shows Γ_{max} with an expander in the condenser. The improvement is significant but it will be shown hereafter that this solution is not compatible with other potential gains.

4.1.2.Air supercharger

By adding an air supercharger upstream of the condenser, Γ_{max} can be largely improved. Indeed a higher air pressure in the condenser has 2 most beneficial influences: it decreases much the heat of air liquefaction and allows a higher hydrogen temperature, thus more cooling capacity at constant ΔT_{pinch}. The penalties are a heavier condenser and an additional air compressor.

With a supercharger, the pinch point location must be reconsidered: the temperature difference between air and LH_2 will be lower at the supercharger inlet than at the condenser inlet (when compression takes place near the dew point, what is favourable for the compression work) as illustrated by figure 4. With an air compression, air must be cooled twice between compressor outlet temperature and compressor inlet temperature. The heat exchanger will be more complicated and the LH_2 cooling capacity is not sufficient for collection ratio's higher than 3: the supercharger incorporated in such a way is not very effective and a more rising ascent trajectory with a higher dynamic pressure could give better results (see also par. 4.3).

These disadvantages may be resolved by a hydrogen expander in parallel with the air compressor or by a compression near the precooler inlet which necessitates a heavier supercharger and more power. An intermediate solution has been chosen here: the supercharger is placed in the middle of the precooler which is split in 2 parts and a hydrogen expander is added in parallel with the supercharger as shown in figure 1. Thus, with a supercharger in the collection plant, use of an expander in the condenser is not possible.

With this "intermediate" position of the supercharger (+ its expander), Γ_{max} can reach about 5 (table 3) with a supercharger inlet temperature of 115 K and a condenser air pressure of 1100 kPa (see par 4.2).

4.1.3.Hydrogen catalytic conversion

Hydrogen exists in two forms differing by their proton spins : para and ortho hydrogen. In the tanks, hydrogen consists almost entirely of para form (99.8%) but, at room temperature, the so-called normal hydrogen is a mixture of 75% of ortho and 25% of para forms in equilibrium. That is important to note because the conversion from para to ortho is an endothermic process which absorbs 396 kJ/kg. But this process is too slow to provide extra cooling capacity, thus hydrogen must be exposed to an effective catalyst with an adiabatic conversion path (10). In opposition to the commonly spread ideas, an extremely active nickel oxyde silica gel catalyst is not so heavy (Ref. 11 gives a conversion rate of 100 g H_2/h/g cat, what gives 0.9 ton of catalyst for a hydrogen flow of 25 kg/s) and could bring some advantages in a collection plant and for the vehicle if high collection ratio's are needed.

Figure 3 shows the evolution of hydrogen temperature as a function of its enthalpy per kg of air in the presence of catalytic conversion performed near pinch temperature (condenser outlet) for maximum effectiveness (around 100 K). Table 3 gives Γ_{max} with a supercharger and hydrogen conversion for a catalyst efficiency of 70%.

4.1.4.Hydrogen recirculation

Recirculation can extract extra cooling capacity from the total cooling capacity available in the fuel tanks filled with biphasic slush hydrogen. As extraction goes on, the solid content of the slush decreases in the heat sink. Recirculation, as shown on fig. 1, requires 2 LH_2 circuits but the same pump may be shared by both circuits (slush is **never** pumped, it melts in the tanks). Table 3 gives Γ_{max} with a supercharger and recirculation: a value of 5.5 can be obtained.

4.1.5.All improvements together

All above analyzed ameliorations are a priori compatible except the expander that should be in parallel with the supercharger instead of in the condenser. Table 3 gives Γ_{max} with a supercharger, catalytic conversion and recirculation combined in the same cycle.

4.2.*Influence of condenser air pressure*

The pressure in the condenser is very important because it influences many collection plant parameters: π_c, GDA pressure at precooler outlet (for a constant π_s), cooling capacity of GDA, Γ_{max}, maximum Mach number for in-flight collection, etc. A higher condenser pressure lowers the latent heat of vaporisation of air and will always increase Γ_{max} but at the expense of compression work and system mass.

At vehicle level, if GDA must be injected into the ramjet chamber at Mach 2.5, its injection pressure must be at least 270 kPa. With a π_s equal to 4 and taking into account the pressure drops through the precooler (2.5%), that means a condenser pressure of at least 1110 kPa. This objective will influence the design of the supercharger and the trajectory choice.

4.3. *Influence of the vehicle trajectory*

The trajectory has a major influence upon the design of the collection plant. At a cruise Mach number of 2.5 and a condenser pressure of 1110 kPa, its influence upon the supercharger compression ratio is shown in table 4.

Q_{cruise} (kPa)	A_{cruise} (km)	π_c
75	12.82	5.07
80	12.35	4.76
85	11.91	4.48

Table -4- Influence of trajectory upon π_c

For the turbomachinery, a high Q_{cruise} is interesting but, for sure, that will have a negative influence on GW & W_{dry}. That suggests there must be a trade-off for the choice of Q_{cruise}.

5. Vehicle performances with collection during cruise & acceleration

5.0. *Collection plant design conditions*

All the sizing calculations which follow are done with a LEA collected flow Spm in the plant which is constant and equal to 70 kg LEA/s. This value and the hydrogen flow fix Γ which has a maximum value equal to 3.4. This medium value can be obtained with a basic cycle which only includes a supercharger (without recirculation or catalytic conversion). Other characteristics are those given in par. 3.4. That results in a collection plant of about 7 tons.

This value of Spm is almost an optimal one at a system level. It is linked with Γ and actually cancels the need for high Γs (5, 6 or higher) as shown in Ref. 12. These high values of Γ can indeed be very interesting but only if the collection plant specific mass and volume are quite low.

5.1. *Difficulty of acceleration operations*

Collection plant operations could take place before cruise and continue during acceleration until Mach 4 or 5 $^{(3)}$. However, during acceleration and at higher Mach numbers, powers to be transfered through heat exchangers do very significantly change.

Collection plant component specifications for cruise must be strictly met but specifications for acceleration ought only be approximately met. Should it not be possible to satisfy them, at least approximately, or should the weight penalty be excessive, the LEA collection Mach range would need to be narrowed, which would degrade vehicle performances, resulting in an increase of GW and W_{dry}.

Therefore, the influence upon vehicle performances of collecting from a collection start Mach number M_{cs} till a collection end Mach number M_{ce} with a cruise phase at Mach 2.5 in-between must be studied in detail. The baseline for the collection Mach range is in this study: 2.0 to 4.0 with a cruise at 2.5.

5.2. *Influence of collection start Mach number*

We show in table 5 the influence of M_{cs} upon the GW, the collected mass of LEA and the dry mass, with the cruise Mach number during collection equal to 2.5, M_{ce} equal to 4 and M_{cd} equal to 3.

M_{cs}	GW	LEA_{col}	W_{dry}
2.0	***307.8***	***260.6***	***69.6***
2.2	308.0	260.9	69.7
2.4	308.3	261.2	69.8
2.5	308.8	261.4	69.9

Table -5- Influence of M_{cs} (masses in tons)

It is profitable to begin to collect as soon as possible because it shortens the cruise length but the influence of a higher M_{cs} is very small because the time needed, for example, from Mach 2 till 2.5 is very short (about 15-20 s). Moreover, in such a design calculation, an increase of M_{cs} leads to a slight decrease of the Küchemann's τ (total volume of vehicle/planform area at the power 1.5) what gives a compensation due to a smaller vehicle drag.

We can conclude that *collection could begin at Mach 2.5* without too large disadvantages in terms of vehicle mass and cost.

5.3. *Influence of collection end Mach number*

We show in table 6 the influence of M_{ce} upon the GW, the cruise duration and the dry mass, with the cruise Mach number during collection equal to 2.5, M_{cs} equal to 2 and M_{cd} equal to 3.

M_{ce}	GW (t)	Cruise (s)	W_{dry} (t)
3.0	314.9	3663	70.9
3.5	314.6	3654	70.8
3.75	313.5	3625	70.5
4.0	***307.8***	***3558***	***69.6***

Table -6- Influence of M_{ce}

A higher M_{ce} shortens the cruise length too, what results in a decrease of GW with an increase of M_{ce}. Moreover the vehicle is lighter during a slightly longer time, what is favourable for the fuel consumption. We can see that the influence of M_{ce} is much larger above Mach 3.75. That is due to the pure (without GDA injection) ramjet ISP which is constant till Mach 3.75 and then decreases linearly with the Mach number.

Actually, the influence of a lower M_{ce} is not so large (a 2.3 % increase in GW between M_{ce}=3 and 4). We can also conclude that *collection could stop at Mach 3.*

A collection **Mach range between 2.5 and 3.0, with a cruise at 2.5**, gives a **GW** of **316 tons**.

5.4.*Collection in cruise only*

When **collection** takes place **during cruise at Mach 2.5 only** (M_{cs} = M_{cruise} & M_{cd} = M_{ce} = M_{cruise}+ 0.1), the penalty becomes more severe: the **GW** is equal to **343.2 tons** and τ = 0.138. We have an increase of 12 % in GW in comparison with the baseline. But this very limited collection range would much ease plant development and lower its specific weight and volume, thereby actually decreasing the penalty. Moreover, the payload fraction is still equal to 2.3%.

To study the influence of M_{cruise} , we need to reassess the mass & volume of the collection plant. A higher M_{cruise} will need a heavier and larger precooler what negatively influences the vehicle. But it will also give a higher dynamic compression in the intake what lowers π_c. It means also that the ramjet burner pressure is higher what would result in a need for an additional GDA compressor which would be very heavy and power consuming.

5.5.*Influence of* M_{cd}

As already said, in this study, GDA is injected into the ramjet burner during the whole cruise flight and a little bit beyond, till the "dumping" Mach number M_{cd}, to improve the ramjet ISP (a gain of 25 % is possible). Above M_{cd} , GDA is expelled from a separate nozzle (no additional thrust from that is accounted here). We show in table 7 the influence of M_{cd} upon the ramjet burner pressure p_b (at M_{cd}), GW and τ, with the cruise Mach number during collection equal to 2.5, M_{cs} equal to 2 and M_{ce} equal to 4. We suppose that the GDA pressure is sufficient for an adequate injection in the ramjet burner.

M_{cd}	p_b (kPa)	GW	τ
2.5+	270	320.9	0.143
3.0	370	307.8	0.146
3.5	460	299.6	0.148

Table -7- Influence of M_{cd} (2.5+ means just after cruise)

It can be seen that the reinjected GDA has a large positive effect upon GW (decrease of 6.6 % with an increase of M_{cd} from 2.5+ to 3.5). Nevertheless, as already said, M_{cd} has to be kept low because the needed GDA injection pressure becomes higher and higher and an additional GDA compressor must be avoided. M_{cd} equal to 3.0 seems to be a maximum and it already brings a large decrease of GW (4.1%).

6. Choice of main collection plant components

The main components are the heat exchangers, the air separator and the necessary turbomachines. The first two have already been discussed here or by others (1, 2, 3, 6 & 10) but not turbomachinery.

6.1.*Supercharger*

A possible architecture would be a mixed turbofan with afterburner placed above the ramjet (in parallel). Mixing and afterburning would take place in the ramjet burner. By-pass flow would be send to the collection plant and the core flow would serve (with hydrogen fuel) for driving different turbomachines, among which the supercharger. In cruise conditions at Mach 2.5, a fan pressure ratio of 4.8 and a by-pass ratio (BPR) of 4.5 would be adequate.

In acceleration conditions or for the LACE which could be used at low speed, variable fan pressure ratios and BPR's could be needed. A solution for that could be a VCE (Variable Cycle Engine).

6.2.*Hydrogen feed pump*

The hydrogen feed pump must provide during the airbreathing phase a much variable fuel flow but a moderate output pressure (from 400 kPa at Mach 2 to 2000 kPa at Mach 4). A major requirement is the capability to vary fuel flow rate by 170% or more at beginning and end of cruise, when the ramjet ER needs to drop from 1 to about 0.6 before returning to 1. This pump could be driven by a H_2-O_2 gas generator for flexibility.

7. Application to T.S.T.O. vehicles

LOX collection can also be harnessed to improve performances of T.S.T.O.'s with the collection/separation equipment installed on the 1st stage and the LEA transferred to the rocket propelled 2nd stage. For a 5 tons payload, a low speed propulsion with ejector-ramjets and staging (2nd stage separation) at Mach 6.5 (Sänger-type T.S.T.O.), LOX collection decreases GW by 19% from 290 tons to 234 when 95% of the LOX required by the 2nd stage are collected: a very significant improvement. In this collection plant, LEA flow reaches 75 kg/s and Γ_{max} is smaller than 2.5.

The benefit of LOX collection could also be great with a lower staging Mach as shown by results presented in Ref. 12 where a staging at Mach 3 gives a 12% decrease of GW in comparison with a LOX carrying vehicle. Subsonic staging could also be possible as presented in Ref. 4 & 12.

8. Conclusions

a.LOX collection offers marked improvements in S.S.T.O. & T.S.T.O. vehicle performances and greatly enhanced mission-profile operability. Mainly, the use of scramjets is not anymore essential provided lightweight technology is available.

b.Γ higher than 6 can be reached with a supercharger, hydrogen catalytic conversion and hydrogen recirculation. But, at system level, such a high Γ is not necessary. Very good results are already obtained with 3-3.4.

c.**Collection could start at Mach 2.5 and stop at Mach 3 with an extended cruise phase at Mach 2.5.** That still gives a **payload fraction of 2.53 %** and avoids an extra GDA compressor.

d.Reinjection of GDA in the ramjet burner till Mach 3 offers a good solution at system level.

e.In the collection plant, a mixed turbofan with a ramjet-afterburner could play the role of the supercharger and delivers the needed driving power.

References

1.VANDENKERCKHOVE J. & BALEPIN V. & CZYSZ P. & MAITA M., "Assessment of SSTO performance with in-flight LOX collection", AIAA-95-6047, Chattanooga, 3-7 Apr 1995.

2.BALEPIN V., YOSHIDA M. & KAMIJO K., "Rocket Based Combined Cycles for Single Stage Rocket", SAE 941166, Dayton, 18-22 Apr 1994.

3.LEINGANG J., MAURICE L. & CARREIRO L., "Airbreathing Space Boosters using In-Flight Oxidizer Collection", AIAA-92-3499, Nashville, 6-8 July 1992.

4.CZYSZ P. & LITTLE J., "RBCC - A Propulsion System for the 21st century", AIAA-93-5096, Munich, 30 Nov-3 Dec 1993.

5.ARDEMA M. et al., "Near-optimal propulsion-system operation for an air-breathing launch vehicle", AIAA Journal of Spacecraft and Rockets, Vol. 32, No. 6, Nov-Dec 1995.

6.BALEPIN V., DULEPOV N., FOLOMEEV E., HARCHEVNIKOVA G., TJURIKOV E. & AVRAMENKO A., "Flight Liquid Oxygen Plant for Aerospace Plane : Thermodynamic and Integration Aspects", SAE 931452, Dayton, 20-23 Apr 1992.

7.ESCHER W., "Cryogenic Hydrogen-Induced Air-Liquefaction technologies", AGARD-CP-479, Madrid, 28 May-1 Jun 1990.

8.BALEPIN V., HENDRICK P., PELLOUX-GERVAIS P. & SACLIER F., "O_2/N_2 Separation Processes for LOX Collection with Airbreathing Propulsion Systems", AAAF Space Propulsion Conference, Paris, 22-24 May 1996.

9.ESCHER W., "The Synerjet Engine", PT-XX (to be published), SAE publication, 1996.

10.AHERN J., "Thermal Management of Air-Breathing Propulsion systems", AIAA-92-0514, Reno, 6-9 Jan 1992.

11.SINGLETON A. et al., "Rate model for para-ortho hydrogen reaction on a highly active catalyst", Air Products, Advances in Cryogenic Engineering, Vol. 14, 1967.

12.JOHNSON C., HENDRICK P. et al., "Propulsion Systems Using Deep Cooled Air, Liquefied Air or Oxygen Collection", AAAF Space Propulsion Conference, Paris, 22-24 May 1996.

Figures

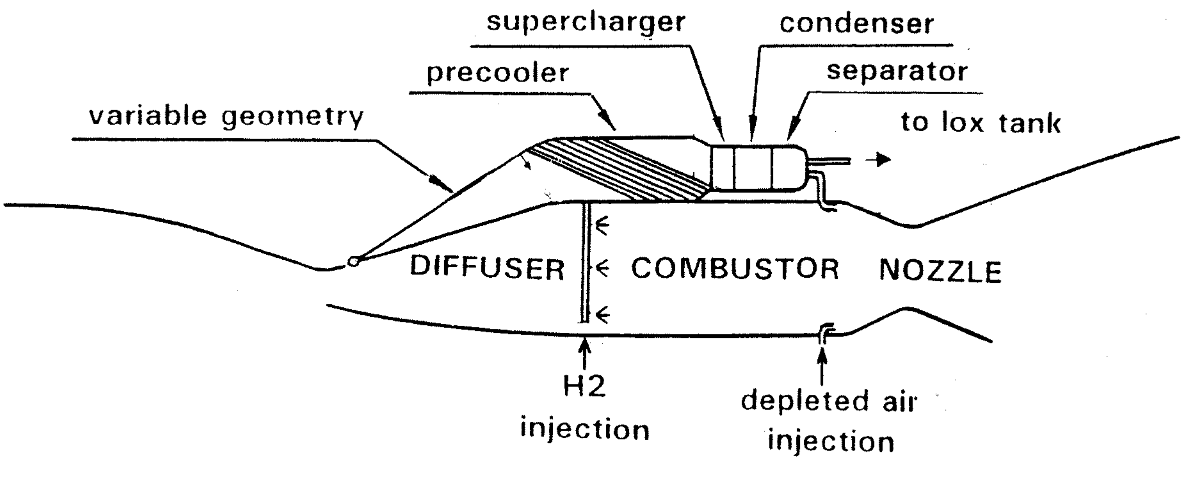

Figure 2 Ramjet-Collection Plant integration

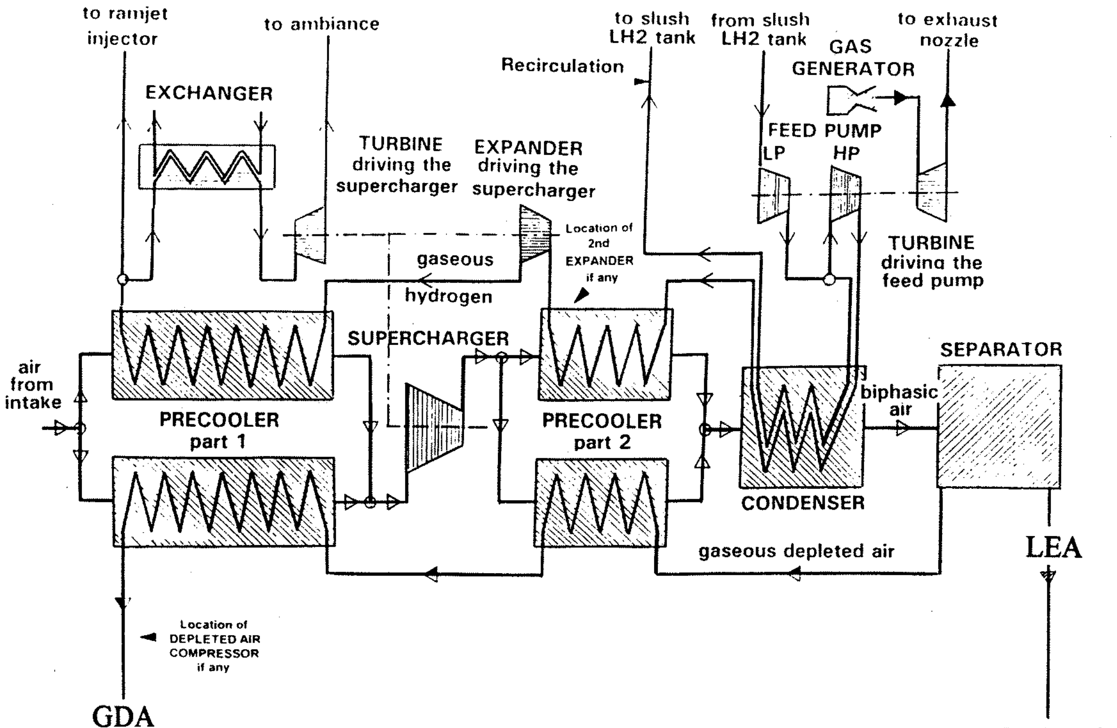

Figure 1 LOX Collection Plant

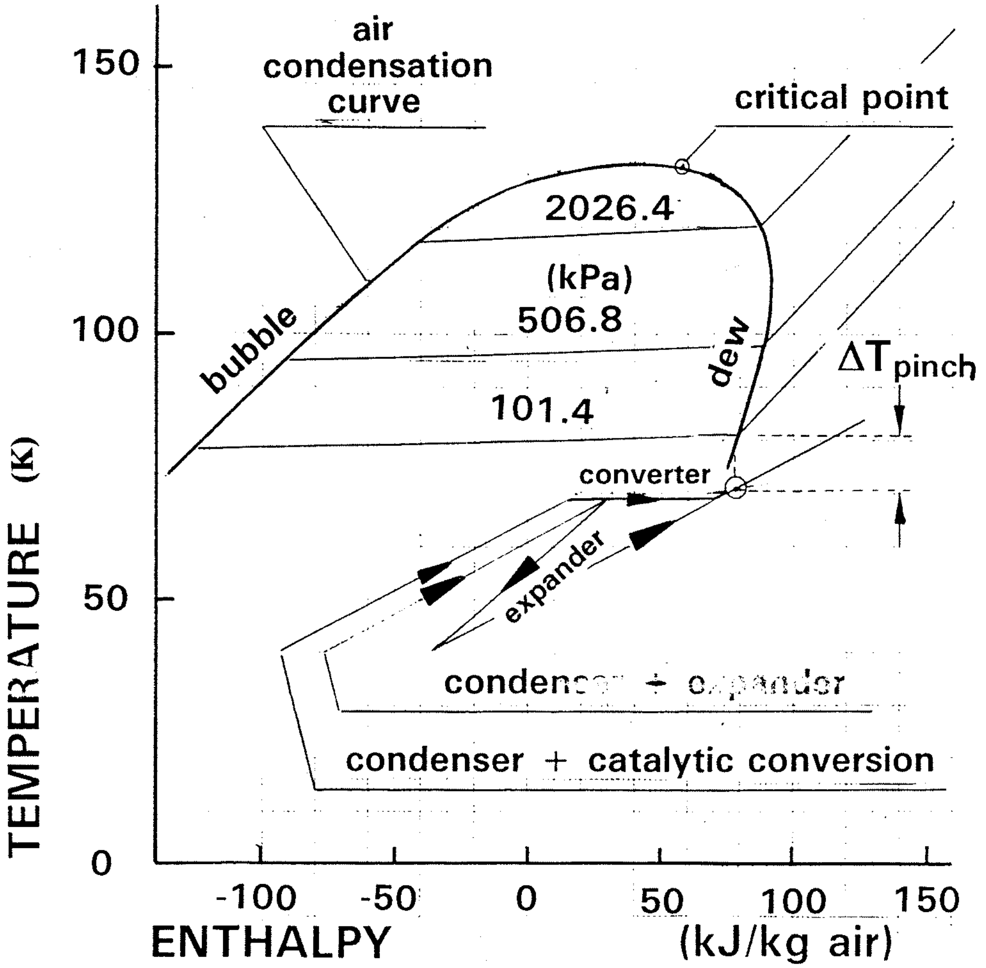

Figure 3

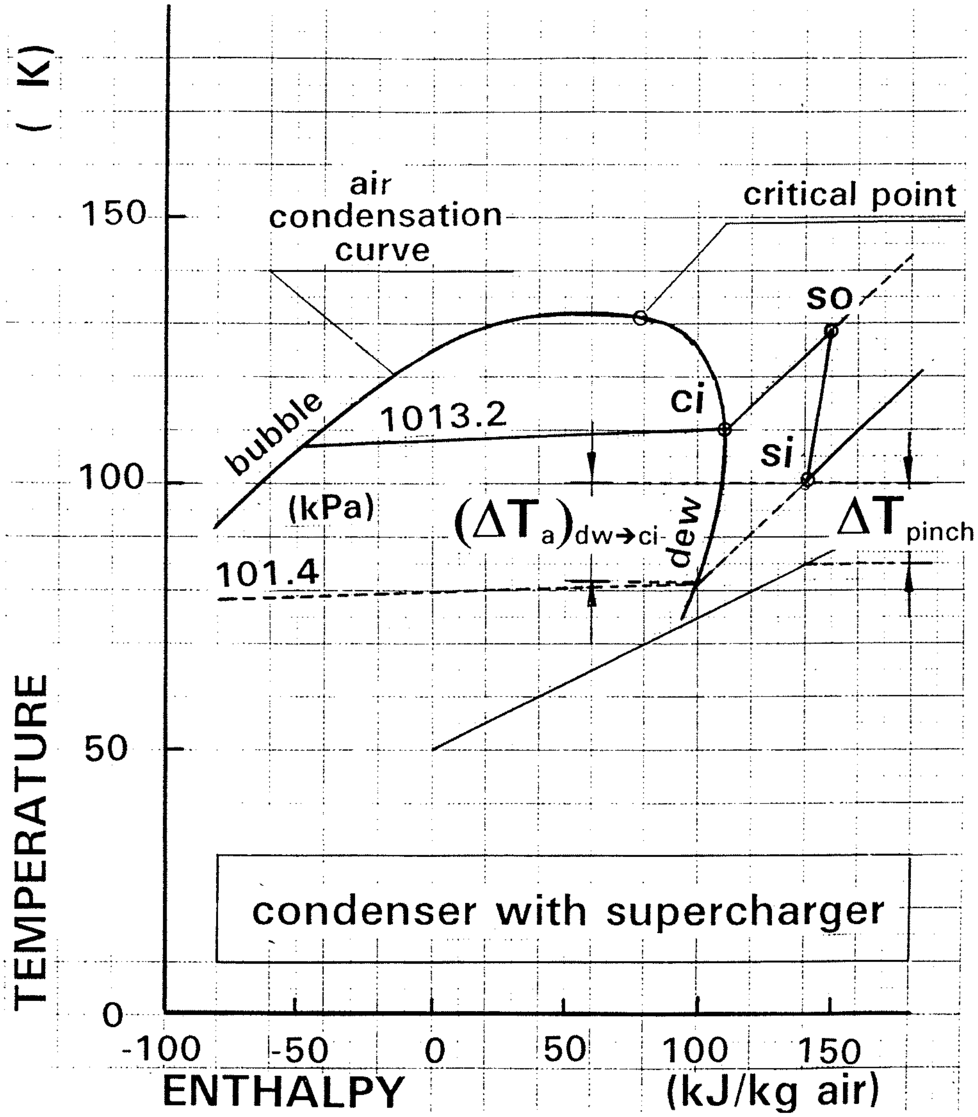
TEMPERATURE (K)
150
100
50
0
-100
-50
0
50
100
150
ENTHALPY
(kJ/kg air)
air
condensation
curve
critical point
so
ci
si
bubble
1013.2
(kPa)
101.4
dew
$(\Delta T_a)_{dw\rightarrow ci}$
ΔT_{pinch}
condenser with supercharger

Figure 4