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ASSESSMENT OF S.S.T.O. PERFORMANCE WITH IN-FLIGHT LOX COLLECTION

by

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Foreword

At the first International Workshop on Aerospace Planes & Hypersonic Technology, held in Tokyo in February 1994, the co-authors agreed to assess together the potential of an emerging technology, ***in-flight lox collection****, upon Single-Stage-To-Orbit reusable spaceplane performance. Within the available time, it has not been possible to resolve all issues and this paper reflects some differences of opinion in which cases the options are compared & discussed to identify the ways & means to improve performance.*

1 INTRODUCTION

1.1 Over the last decade much work has been devoted to the harnessing of airbreathing propulsion for reusable S.S.T.O. spaceplanes, to improve significantly the reliability, flexibility & economy of space transportation. The difficulties of the undertaking are formidable, however, and for all considered options (combined engines, LACE rockets or rockets & inserted ramjets with collection) new engines are needed. With combined engines, transatmospheric flight must be extended up to very high Mach numbers, much in excess of 10.

In-flight lox collection potentially offers the perspective to simplify much the propulsion at low speed and to limit transatmospheric flight well below Mach 10, perhaps down to 6, which would eliminate the need for a scramjet mode.

1.2 To derive full advantage of collection, most of the oxygen subsequently required in rocket mode outside the atmosphere must be collected in-flight, which requires a cruise.

The low speed acceleration is also provided by rocket engines up to about Mach 1.8 at which point a moderate dynamic pressure is achieved, the ramjets take over & lox collection starts soon afterwards, when precooler icing is not anymore a problem. Most of the collection is done during an extended cruise adjusted in length to obtain the desired collected fraction, say **99.5%**. It continues up to Mach 4 to 5 when air temperature at the precooler inlet becomes excessive (925 to 1330 °K).

The collection plant capacity is tailored to fuel flow during cruise: a lower capacity would extend cruise length too much & a higher would yield a too heavy plant. The plant design is optimised for the cruise, when the ramjet operates fuel lean with an equivalence ratio of about 0.6 and during acceleration, when they operate rich, the hydrogen flow is two to three times larger and exceeds that required by the limited plant capacity.

1.3 The same rocket engines can be used both at low speed till transition to ramjet mode and beyond transition airbreathing → rocket expected to take place between Mach 6 & 10, which avoids the development of new engines. Indeed the vehicle weight at transition airbreathing → rocket is typically 150% that at take-off and the rocket thrust required beyond is about 113% of the transition weight, which ensures a thrust-to-weight ratio of about 140% at take-off & nearly 200% in the critical transonic region. The high thrust even allows vertical take-off with a consequent undercarriage weight saving.

1.4 However, in pure rocket mode at low speed, the high propellant consumption incurred, typically 30% of gross take-off weight, would penalize much vehicle performance. It can, however, be much reduced, down to about 20%, by using the available collection plant capacity to operate the rockets in partial LACE mode as suggested in ref. 94-4. The penalty then becomes acceptable since the oxygen is afterwards replenished by collection at "air-breathing price".

1.5 Thanks to the extended cruise capability, long launch windows are available, in excess of 4 to 12 hours daily depending on base longitude, even for the sun-synchronous orbit & basing is not anymore constrained by geography.

1.6 Last but not least, lox collection can be thoroughly tested on the ground & demonstrated at low supersonic instead of hypersonic speeds.

2 MISSION REQUIREMENTS

The assumed mission requirements are listed in **table 1**:

REQUIREMENT	VALUE	UNIT
Orbit height	200	(km)
Orbit inclination	97.4	(deg)
ΔV_{om} for orbital manoeuvres	100	(m/s)
ΔV_{cs} for control & stabilisation	40	(m/s)
Daily launch window[i]	>4 to 12	(hr/d)
Crew	manned or unmanned	-
Payload weight	8	(t)
Base latitude	45	(deg N)
Weight margin	15	(%)

[i] depending on base longitude

Table 1

The sun-synchronous orbit is a most demanding mission for which a height of only 200 km is sufficient since it is more efficient for satellites to rise their altitude by means of their own propulsion. Without another manoeuver, the spaceplane may reach 285 km with the required ΔV_{om} = 100 m/s.

Significant increases in payload & orbital height are both possible at lower inclinations (about 10 t & 500 km at 30 deg)

When the S.S.T.O. is manned, only a crew of two with associated equipment & consumables for 10 days are accounted, extra astronauts being charged to payload weight.

3 ASSUMPTIONS

3.1 Spaceplane weight & volume

The weight & volume parameters used below are defined in ref. 95-1 for either manned or unmanned reusable S.S.T.O.'s and their values, assuming that moderately advanced technologies are harnessed, are given in **table 2** in which:

- structure index $(\mu_{str})_{\tau=0.1}$ is normalised for a Küchemann τ = 0.10: indeed the relative cross-section of the integral tanks & their moment of inertia available to carry bending loads both increase with τ (with increasing transition Mach or decreasing gross weight), which to a first approximation, improves μ_{str} as follows:

$$\mu_{str} = (\mu_{str})_{\tau=0.1} \times 1.25 \times 10^{-0.97 \times \tau}$$

- planform loading L_{to} is kept as a variable input which changes τ,
- variable system weight fraction f_{sys} accounts for vertical take-off which reduces undercarriage weight much or horizontal take-off &
- slush hydrogen is assumed.

CHARACTERISTICS	VALUE	UNIT
Structure index μ_{str} for $\tau = 0.10$[i]	19	kg/m^2
Fixed system weight C_{sys}[i] : unmanned	1750	kg
manned	4100	kg
Fixed system volume V_{fix} : unmanned	5.5	m^3
manned	39.0	m^3
Variable system weight fraction f_{sys}	10 or 18[ii]	%
Planform loading L_{to}	variable	kg/m^2
System volume fraction k_{Vs}	4.5	%
Void fraction k_{Vv}	15	%
Crew & consumable W_{crw}[i]: manned only	620	kg
Hydrogen condition	"slush"	n.a.
Configuration	blended wing-body	n.a.
Payload density ρ_{pay}	50	kg/m^3

[i] without weight margin

[ii] for vertical or horizontal take-off respectively

Table 2

3.2 Propulsion

A ramjet phase, which includes the cruise, is *inserted* between two rocket phases. Lox collection takes place during only part of the ramjet phase. The propulsion weight & volume assumptions are given in **table 3** in which:

- specific ramjet weight θ_{rjt} is the maximum thrust to weight ratio,
- specific rocket weight θ_{rkt} is the thrust to weight ratio,
- specific ramjet volume k_{Vrjt} is the volume to maximum thrust ratio &
- specific rocket volume k_{Vrkt} is the volume to thrust ratio.

CHARACTERISTIC	VALUE	UNIT
Ramjet specific weight θ_{rjt}[*]	32	kg/kg
Ramjet specific volume k_{Vrjt}	0.4	m^3/t
Rocket specific weight θ_{rkt}	72	kg/kg
Rocket specific volume k_{Vrkt}	0.05	m^3/t
I_{sp} of main rocket mode I_{s1} (vacuum)	450	s
I_{sp} of OMS rocket mode I_{s2} (vacuum)	440	s
Mixture ratio of main & OMS rockets MR	6.2	-
I_{sp} in ACS rockets I_{s3} (vacuum)	400	s
Mixture ratio of ACS rockets	5.5	-
Payload density ρ_{pay}	50	kg/m^3

[*] without weight margin

Table 3

For the first rocket phase, **partial LACE operation according to available plant capacity** improves the sea level I_{sp} from **335 up to 426 s** but decreases somewhat mixture ratio MR.

Figures 1.a & 1.b show ramjet specific impulse $\mathbf{I_{sp}}$ & specific thrust per unit span $\mathbf{F_{sp}}$ as functions of Mach $\mathbf{M_0}$ for four different pairs of dynamic pressure Q_0 & angle of attack α_0 and for stoichiometric operation. A data base provides ramjet & scramjet performances I_{sp} & F_{sp}.

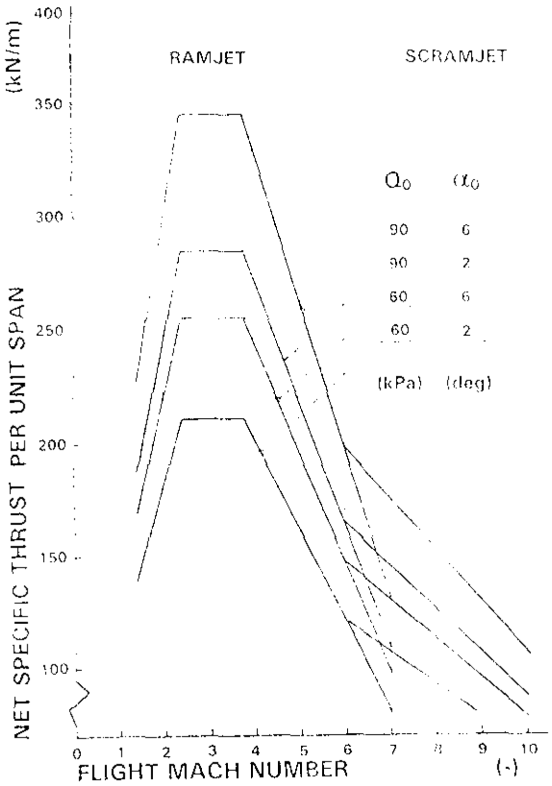


Figure 1a

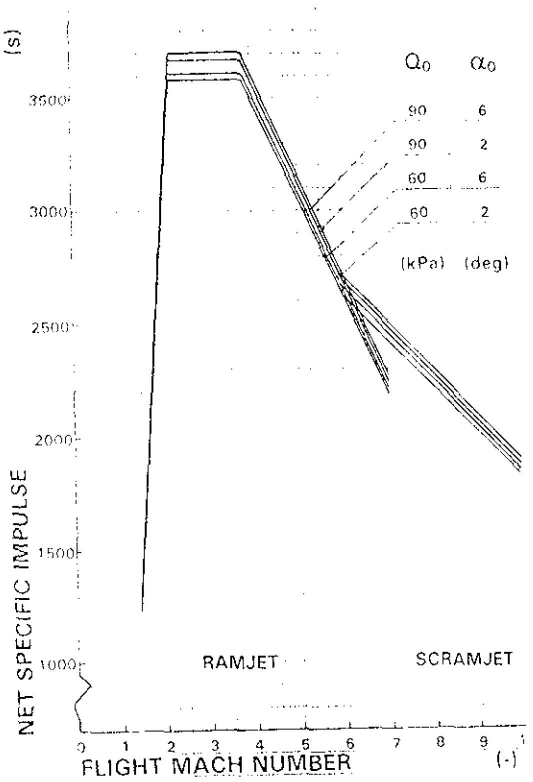


Figure 1b

During cruise the ramjet operates lean, $\varepsilon_{cruise} = 0.6$ for a well optimized *ramjet size, since thrust must be adjusted for constant speed.*

During acceleration, within the plateau which extends from Mach 2.2 to 3.8, the ramjets operate stoichiometric & outside the plateau fuel rich to compensate for the thrust lapses, with a linear variation in equivalence ratio to reach $\varepsilon_{accel} = 2$ at transition rocket → ramjet at Mach 1.8 & $\varepsilon_{accel} = 1.6$ at transition ramjet → scramjet (if any) at Mach 7.0.

The approximate dependence of specific impulse & specific thrust upon equivalence ratio is given by **table 4**.

Equivalence ratio ε	$F_{sp} / (F_{sp})_{\varepsilon=1}$	$I_{sp} / (I_{sp})_{\varepsilon=1}$
0.4	0.478	1.196
0.6	0.685	1.144
0.8	0.859	1.075
1.0	1.000	1.000
1.5	1.380	0.819
2.0	1.817	0.597

Table 4

Lox collection also influences ramjet & to a lesser degree rocket performance:

- for the ramjet, during collection, depleted air after separation is injected into the ramjet combustor which improves much specific impulse but lowers specific thrust as shown by **table 5** which provides I_{sp} & F_{sp} for a typical case (flow ratio Φ = 40%, separation efficiency η_{sep} = 85%, oxygen concentration in lea C_{ox} = 98%):

Mach number	$(F_{sp})_{with} / (F_{sp})_{without}$	$(I_{sp})_{with} / (I_{sp})_{without}$
2.5	0.842	1.280
3.5	0.850	1.292
4.5	0.855	1.299

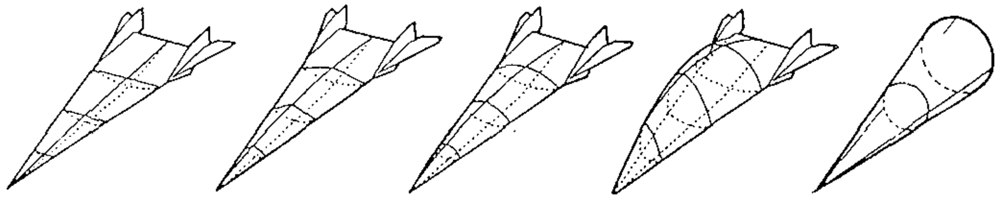
Table 5

- for the rocket a low oxygen purity i.e. a low oxygen concentration C_{OX} penalises specific impulse $(I_{sp})_{rkt}$. For mixture ratios near 6 the loss $(\Delta I_{sp})_{rkt}$ is 1.5 s per % C_{ox} below 100% (see ref.93-3).

3.3 Aerodynamics

The aerodynamic characteristics (i.e. coefficients C_{D0}, $C_{L\alpha}$ & C_{Di}) for the family of vehicles under considerations (always "**blended body & wing**" in this study) are derived from a "generic" data base which accounts for slenderness / stoutness through the influence of Küchemann's parameter τ on C_{D0}.

Parameter τ is the ratio of total vehicle volume to planform area at the power 1.5: it decreases with increasing gross weight when planform loading is kept & with decreasing planform loading when gross weight is kept. **Figure 2** *represents the shape of five "blended wing + body" vehicles differing by their* τ values.



	Minimum	Slender	Nominal	Stout	Circular Cone
τ	0.032	0.063	0.104	0.229	0.393
K_W	2.44	2.51	2.64	3.39	3.61
L/D	4.82	4.71	4.57	4.13	3.70

Figure 2

3.4 Trajectory

The ascent trajectory, schematised in horizontal projection by **figure 3**, is as follows:

- after vertical lift-off, rapid climb to an altitude of about 8 km to reach the selected Q_{cruise} before transition rocket → ramjet at Mach 1.8,
- acceleration & climb at constant Q_{cruise},
- cruise at constant M_{cruise} & Q_{cruise},
- turn whilst accelerating & climbing to align in the orbit plane,
- further acceleration & climb till transition Mach airbreathing → rocket is nearly reached,
- shortly before transition pull-up to increase the slope and minimise drag penalty during the subsequent rocket phase,
- transition airbreathing → rocket,
- further pull-up followed by a manoeuvre to inject the vehicle at rocket burn-out into the required transfer orbit at a specified altitude (to avoid excessive kinetic heating) & slope,
- ballistic flight in transfer orbit &
- circularisation at apogee.

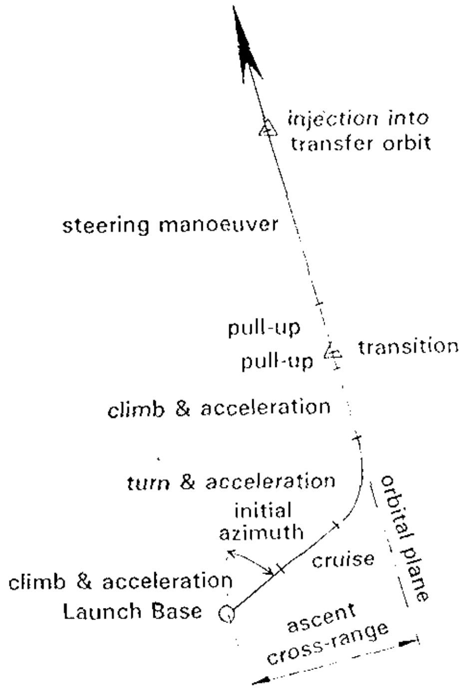


Figure 3

During the turn & subsequent acceleration the dynamic pressure is kept equal to Q_{cruise} till the required air pressure in the condenser is reached without supercharge after which Q_0 is progressively decreased to maintain that pressure, which also lowers the ramjet weight since this limits its internal pressure.

The choice of M_{cruise} is constrained by:

- dynamic pressure Q_{cruise} below 90 kPa for structural efficiency,
- cruise altitude either below 15 to 16 km or above 25 km to avoid environmental damage to the ozone layer &
- aerodynamic heating low during the extended cruise of about quarter- of-an-hour ($M_{cruise} < 4$)
- allow injection of depleted air into the ramjet combustor &
- complete the subsequent turn of about 90 deg at relatively low Mach to limit drag losses & to exit the high acceleration turn before initiating the pull-up prior to transition air-breathing → rocket.

4 LOX COLLECTION PLANT

4.1 Plant architecture

The lox collection plant is combined with the ramjet as shown by **figure 4** & its architecture is schematised by **figure 5**. It consists of:

- a **precooler**, downstream of the intake, which cools air flow fraction Φ through the plant down to a temperature somewhat above dew point, the coolants being hydrogen & gazeous depleted air after separation,
- a **supercharger** required to rise condenser pressure up to 600 kPa, for near optimum operation without a depleted air compressor at least during cruise,
- a **condenser** which liquefies part of the cooled air, the coolant being hydrogen,
- a **separator** which separates liquid enriched air (lea) from gaseous depleted air (gda),
- an **expander** fed by all the hydrogen plus a **turbine** fed by extra hydrogen dumped to ambience, both mounted on the same shaft, to drive the supercharger,
- an **exchanger** to heat the extra hydrogen upstream of the turbine,
- an hydrogen feed **pump** (LP & HP stages) &
- a **turbine** fed by **a gas generator** to drive the feed pump which needs to operate at widely variable powers.

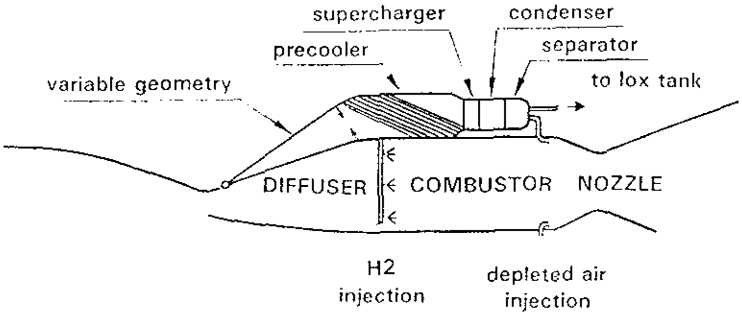


Figure 4

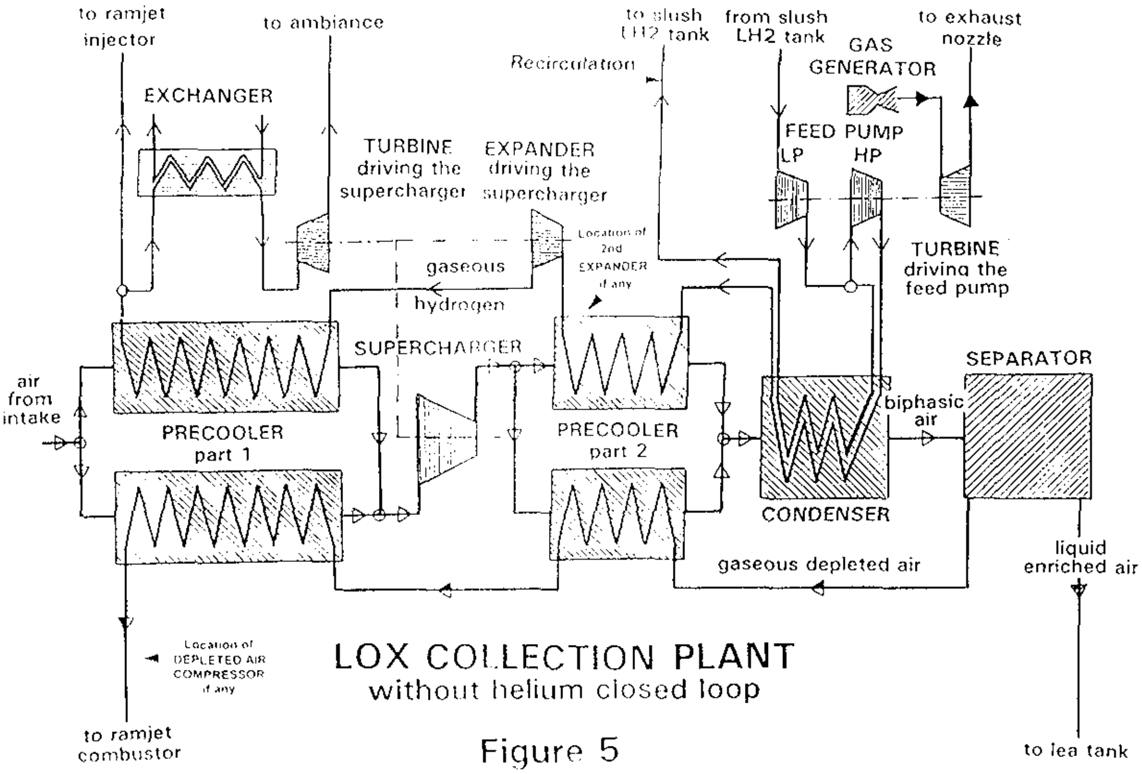
Table 6 summarises the architecture selected for the collection plant:

COMPRESSOR OR PUMP	TURBINE
supercharger	h2 expander[i] & turbine
h2 feed pump	h2-o2 gas turbine
h2 recirculation pump[ii]	h2-o2 gas turbine
liquid air pump	not applicable
enriched air pump	likely not needed
depleted air compressor	likely not needed
he compressor	he closed loop not assumed

[i] located between the two air-h2 exchangers in the precooler

[ii] on the same shaft than the h2 feed pump.

Table 6



LOX COLLECTION PLANT
without helium closed loop

Figure 5

4.2 Separator

The best known method of air separation is **fractional distillation** which requires rather large & heavy distillation columns which cannot be used in flight, for the low velocities of the liquid & vapour streams. It can, however, be dramatically improved with a rotary boilerplate (see ref. 92-6 or 95-4): at oxygen concentration C_{ox} = 90% & separation efficiency η_{sep} = 90%, a *specific separator weight of 25 kg/kg lea/s & a specific volume of* **0.98 m^3/kg lea/s** have been demonstrated.

A much lighter & compact approach is the use of **vortex tubes** in which the speed of sound is reached in the inlet nozzle. It has the following advantages:

- *much reduced size & weight of the tubes, made in light thin-walled plastics,*
- lack of moving parts &
- prospect of a low expansion ratio in the tube, about 2 (instead of 5 or more for distillation) which allows a low pressure in the condenser.

Specific separator weights of **5.0 to 7.5 kg/kg lea/s** & specific volume of **0.050 to 0.075 m^3/kg lea/s** are expected. In ref. 94-4 first experiments are described during which very high oxygen concentrations up to C_{ox} = **98.7%** have been obtained but with rather low separation efficiencies η_{sep} = **30 up to 42%**. The operation is stable & the results reproducible. Further development is planned, aiming at C_{ox} > 90% & η_{sep} = 45 to 55% with a single stage.

The use of two stage vortex tubes providing an oxygen concentration of 98% & a separation efficiency of 85% is assumed below.

4.3 Assumptions

The selected cruise Mach number $\mathbf{M_{cruise}} = \mathbf{2.5}$ is rather low since this improves collection ratio Γ_{cruise}, for the low fuel injection pressure in the ramjet & avoids a compressor to inject depleted air into the ramjet combustor. This is twice lower than $M_{cruise} = 5$ chosen in ref. 93-3 & 95-2. It is associated with a moderate dynamic pressure $\mathbf{Q_{cruise}} = \mathbf{80\ kPa}$ for structural efficiency. Slush hydrogen (50%) is used and its cooling capacity may be enhanced by **para → ortho conversion** prior to fuelling and by **recirculation** of part of the coolant to the tanks. The other important assumptions are provided by **table 7**.

Important assumptions	
separation efficiency (2 stages)	85%
oxygen concentration in enriched air	98%
temperature difference at pinch point	10°K
air pressure in the condenser	600 kPa
fuel injection pressure in ramjet	2 x $P_{combustor}$
air temperature at supercharger inlet	115 °K
efficiency of catalytic conversion	70 %
recirculation ratio	2.5
global plant efficiency	80%

Table 7

4.4 Cycle performance

Cycle selection is driven by the constraint to keep, in all exchangers, wall temperature differences at least equal to that at the condenser pinch. This is particularly difficult in the precooler, upstream of the supercharger, as illustrated by **figures 6a & 6b** which show the temperature & pressure evolutions through the plant. It is seen that this results in much higher ΔT's at the precooler air inlet (54 °K on the h2 side & as much as 356 °K on the gda side vs 10 °K at the pinch): *the cooling capacity is globally adequate but locally marginal.*

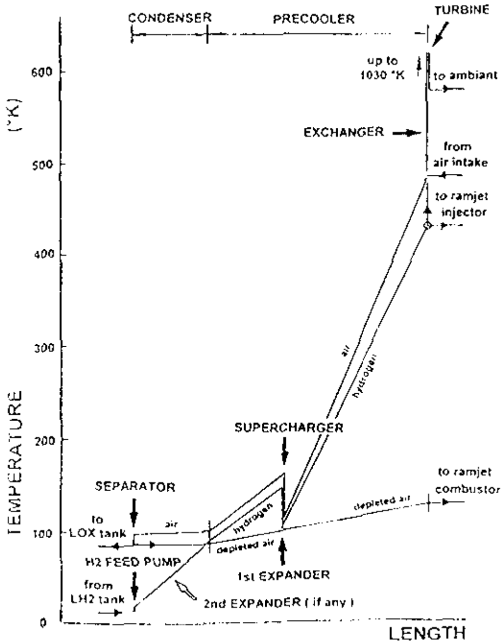


Figure 6.a

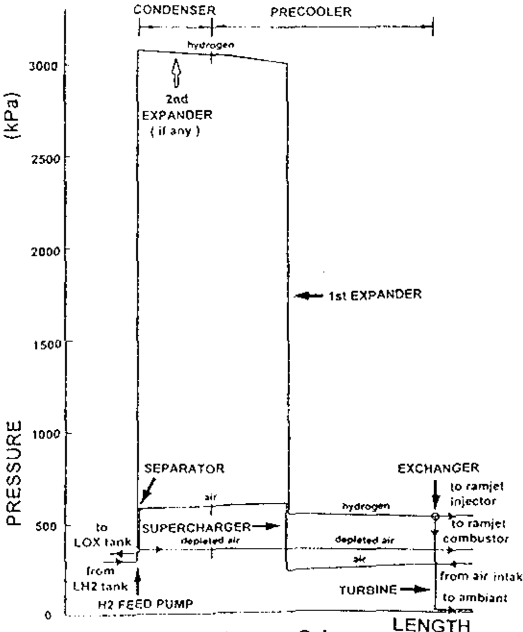


Figure 6.b

Table 8 provides collection ratio during cruise Γ_{cruise}, extra hydrogen fraction f_x, flow ratio Φ & collected lea flow F_c, for a module with a static air flow of 300 kg/s (incl.. the flow through the ramjet which uses the same intake). Four options are considered:

- **supercharger alone,**
- **supercharger + recirculation,**
- **supercharger + conversion &**
- **supercharger + recirculation + conversion.**

option	Γ_{cruise} (-)	f_x (%)	Φ (%)	F_c (kg lea/s)
Sup	5.140	6.19	33.899	17.79
Sup + Rec	5.462	6.71	35.505	18.63
Sup + Con*	6.320	8.14	39.573	20.76
Sup + Rec + Con	6.642	8.68	41.021	21.52

* Baseline

Table 8

It is seen that:

- the gain in Γ_{cruise} derived from conversion & to a lesser degree recirculation is significant (see also section 6.1 below) &
- extra hydrogen fraction f_x, flow ratio Φ & collected lea flow F_c increase with fuel cooling capacity.

Flow ratio Φ (i.e. fraction of the flow which goes through the collection plant) *must match available cooling capacity*: it is related as follows to *collection ratio* Γ, *equivalence ratio* ε, separation efficiency η_{sep} & oxygen *concentration in lea* C_{OX}:

$$\varepsilon = \frac{\Phi \times 0.2314 \times \eta_{sep}}{\Gamma \times \lambda \times (1 - \Phi \times \eta_{sep}) \times (1 + f_x) \times C_{ox}}$$

with $\lambda = 1 / 34.3$ *is the stoichiometric* ratio of h2 & air.

Figure 7 shows the variation of ε *versus* Γ, *for* $\eta_{sep} = 85\%$, $C_{ox} = 98\%$, $\Phi = 30$, 40 & 50% and $f_x = 0$, 5, 10 & 15%: *it is seen that, in a typical case with* $\Gamma_{cruise} = 6.3$, $\varepsilon_{cruise} = 0.6$ & $f_x = 10\%$, Φ *must be equal to about* **40%**. During acceleration the same value of Φ is kept *to minimise plant weight & avoid* intake geometry changes which yields $\Gamma_{accel} < 4$ at $\varepsilon_{accel} = 1.0$.

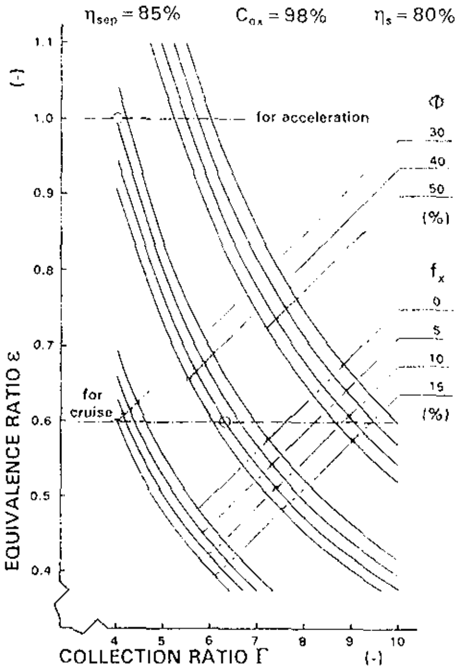


Figure 7

The supercharger & the hydrogen feed pump must be turbine driven. **Table 9** shows the required shaft powers, the total shaft power plus the powers exchanged in the precooler & the condenser. It is computed for the same intake providing a total air flow of 326.8 kg /s at M_{cruise} = 2.5 & Q_{cruise} = 80 kPa, of which Φ = 41.02% go through the collection plant for the last option.

PW_{sup}	6.535
$PW_{h2\ LP+HP\ pump}$	0.183
$PW_{h2\ rec\ pump}$	0.001
$PW_{ea\ pump}$	0.000
$PW_{da\ compressor}$	0.000
ΣPW_i	6.719
$PW_{precooler}$	60.635
$PW_{condenser}$	24.377

Table 9

It is seen that:

- the supercharger is by an order of magnitude the most power demanding element (97.3% of ΣPW_i), followed by the hydrogen feed pump. The power for the recirculation pump is minimal &
- the power exchanged in the precooler is 248.7% that in the condenser.

4.5 Specific weight & volume

A very preliminary estimate of specific plant weight w_{plant} & specific plant volume v_{plant} yields for M_{cruise} = 2.5:

- **w_{plant} = 50 kg/kg lea/s**
- **v_{plant} = 0.6 m^3/kg lea/s**

Higher & lower w_{plant} estimates are quoted, from **62.50 to 93.75 kg/kg lea/s** in ref 95-2 or even **120 kg/kg lea/s** in ref 93-3 for M_{cruise} = 5 down to **32.6 kg/kg lea/s** in ref. 93-5 for a subsonic cruise but details are unavailable & a difference in cruise Mach can make much difference.

The collection plant may be rather heavy: **1040 kg** for the plant module under consideration with a capacity of **20.8 kg lea/s**. For the time being *the above estimate is viewed as an objective,* which requires confirmation.

5 PERFORMANCE OF BASELINE VEHICLE

In a first instance vehicle performance is estimated for the mission of table 1, the assumptions of tables 2 to 3 & the 4 above discussed options (supercharger alone, supercharger + recirculation, supercharger + conversion & supercharger + recirculation + conversion) with collection starting at Mach **2.0** & ending at **4.5** (for which air temperature at the precooler inlet is still moderate, 1120 °K, air pressure in the condenser & ramjet internal pressure do not exceed much 600 kPa), with the extended cruise during which most of the lox is collected at **2.5**, for a planform loading of **380 kg/m^2** & for **99.5%** of the *lea needed beyond the 2nd transition actually collected. Conservatively* the transition airbreathing → rocket is at Mach **6.8** which ***does not require scramjets***.

Vertical take-off & horizontal landing are assumed.

Table 10 provides gross take-off weight GW, dry weigh W_{dry} & *Küchemann's* τ, *for the 4 options:*

Option	GW (t)	W_{dry} (t)	τ (-)
Sup	137.49	34.47	0.191
Sup + Rec	134.99	36.01	0.193
Sup + Con*	133.71	35.20	0.195
Sup + Rec + Con	133.20	37.27	0.196

* *Baseline*

Table 10

It is seen that performance does not vary much between options. With *respect to the supercharger alone, the addition of recirculation provides a small* gain and a somewhat larger improvement is derived from the addition of endothermic para → ortho hydrogen conversion: **2.7%** *in GW &* **2.1%** *in* W_{dry}.

On-board converters are considered feasible in ref. 92-1 but doubts exist concerning their weight. A most attractive possibility is to perform conversion on the ground just before take-off, around 100 °K, followed by rapid cooling to *slush temperature, provided that at* 13.8 °K *the exothermic reverse conversion* ortho → para is sufficiently slow to melt only part of the initial slush content in *the fuel tanks. Out of prudence, the time constant of the reverse reaction being* unknown to us, recirculation will not anymore be considered below, the baseline *option being supercharger (as required to get an air pressure of 600 kPa in the* condenser during cruise) + converter.

Table 11 gives the weight breakdown (incl. 15% margin) & **Table 12** gives other characteristics of the baseline vehicle.

Item	Weight (t)
structure	15.59
engine	6.85
collection plant	8.04
system	4.73
DRY WEIGHT	35.20
H2 at take-off	64.57
OX at take-off	25.95
PROPELLANT	90.52
PAYLOAD	8.00
GROSS TAKE-OFF WEIGHT	133.71

Table 11

Other characteristics	
propellant for in-orbit manoeuver	0.84 t
unused propellant	1.70 t
NET WEIGHT - DRY WEIGHT	2.64 t
COLLECTED LEA WEIGHT	137.49 t
COLLECTION RATE	0.14 t lea/s
WEIGHT AT TRANSITION	204.41 t
TOTAL VOLUME	1288 m^3
PROPELLANT VOLUME	900 m^3
PLANFORM SURFACE	352 m^2
WETTED SURFACE	1091 m^2
PLANFORM LOADING AT LANDING[i]	0.128 t/m^2
TOTAL ΔV IMPARTED	12 239 m/s

[i] includ. payload return

Table 12

It is seen, inter alia, that:

- collection plant accounts for **22.8%** of the dry weight,
- collected weight amouts to **102.8%** of the gross weight &
- collection time is **982 s** (about 17 m) for the low collection rate.

6 SENSITIVITY ANALYSIS

The influence of important vehicle characteristics is assessed below.

6.1 Influence of transition Mach number

Table 13 provides gross take-off weight GW, dry weight W_{dry} & Küchemann's τ, for 7 transition Mach numbers air-breathing → rocket.

$M_{transition}$ (-)	GW (t)	W_{dry} (t)	τ (-)
4.0	196.90	53.97	0.170
5.0	142.81	38.16	0.192
6.0	134.46	35.68	0.196
6.8*	133.71	35.20	0.195
8.0	128.23	33.64	0.197
9.0	128.37	33.38	0.196
10.0	139.24	35.99	0.189

* Baseline

Table 13

These results are represented on **figures 8a & 8b**. It is seen that:

- for $M_{transition} < 7$, for which scramjets are not required, both **GW & W_{dry} increase more & more rapidly with decreasing $M_{transition}$**: between 7 & 6 the penalty is rather small but below it becomes severe &
- for $M_{transition} > 7$, for which scramjets are required, both **GW & W_{dry} decrease with increasing $M_{transition}$, more & more slowly till an optimum is reached at about $M_{transition} = 8.5$ above which performance degrades rapidly.**

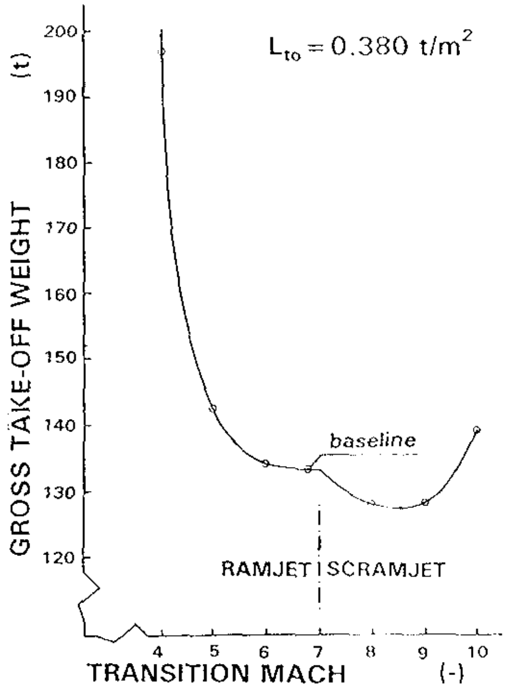


Figure 8.a

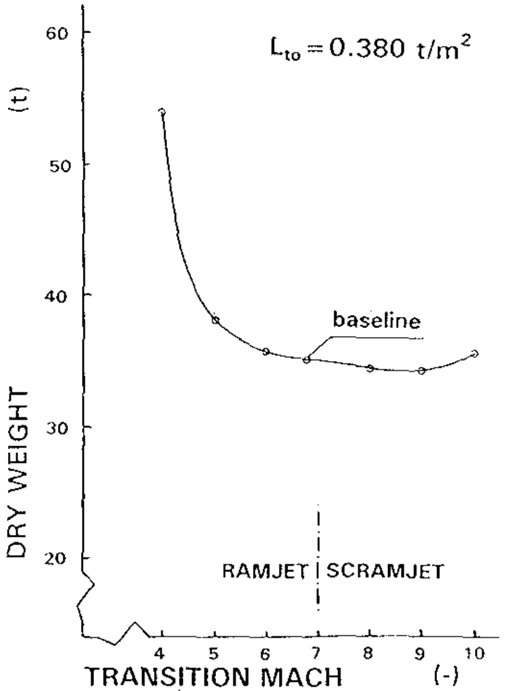


Figure 8.b

For $M_{transition}$ = 6 the penalty incurred is still rather moderate with respect to the optimum at 8.5: 10.5% in GW & 6.8% in W_{dry} and the practical advantages are important, namely an easier development without the need for scramjets, improved reliability, maintainability & reusability due to the lower heat loads but lox collection still possible up to Mach 4.5 or 5.0.

6.2 Influence of stoutness

Table 14 provides gross take-off weight GW, dry weight W_{dry} & Küchemann's τ, for 5 planform loadings L_{to} which determines stoutness.

L_{to} (-)	GW (t)	W_{dry} (t)	τ (-)
320	312.05	101.33	0.097
340	168.52	49.39	0.146
360	142.54	39.32	0.173
380*	133.71	35.20	0.195
400	128.65	33.57	0.216

* Baseline

Table 14

It is seen that both GW & W_{dry} decrease with increasing L_{to} i.e. τ. No optimum exists for the case under consideration for which the penalty in drag would match the improvement in structure index μ_{str} due to the higher stoutness (for L_{to} = 380 kg/m^2 & τ = 0.195, μ_{str} = 16.24 kg/m^2 instead of the normalized $(\mu_{str})_{\tau=0.1}$ = 19 kg/m^2).

Note: Cross-range at re-entry decreases with increasing Küchemann τ which may likely limit stoutness: indeed for τ = 0.10, 0.15 & 0.20 it is equal to 4440, 3219 & 2553 km respectively.

6.3 Influence of collection plant weight

Table 15 provides gross take-off weight GW, dry weight W_{dry} & Küchemann's τ, for 5 collection plant specific weights w_{plant}.

w_{plant} (kg/kg lea/s)	GW (t)	W_{dry} (t)	τ (-)
45	125.19	32.81	0.202
50	133.71	35.20	0.195
55	140.77	37.96	0.190
60	150.29	41.58	0.183
65	164.08	46.57	0.175

* Baseline

Table 15

It is seen that both GW & W_{dry} increase much with w_{plant}, whilst τ decreases at constant platform loading.

6.4 Influence of volumetric efficiency

Table 16 provides gross take-off weight GW, dry weight W_{dry}, Küchemann's τ & propellant volumetric efficiency η_{vol}, for 5 void fractions k_{Vv} (12% is very good & 30% unnecessarily comfortable) which determines volumetric efficiency.

k_{Vv} (%)	GW (t)	W_{dry} (t)	τ (-)	η_{vol} (%)
12	130.28	34.51	0.190	72.5
15*	133.71	35.20	0.195	69.8
18	135.98	36.09	0.202	66.8
24	144.11	38.84	0.214	60.9
30	154.96	44.09	0.226	55.2

* Baseline

Table 16

It is seen that both GW & W_{dry} increase rather rapidly with k_{Vv} whilst η_{vol} decreases much: for instance an increase in void fraction from **15%** to **24%** penalises GW by **7.8%**, W_{dry} by **10.3%** & η_{vol} by **12.7%**.

6.5 Influence of normalised structure index

Table 17 provides gross take-off weight GW, dry weight W_{dry} & Küchemann's τ, for 4 normalised structure indexes $(\mu_{str})_{\tau=0.1}$ (17 kg/m^2 is representative of harnessing advanced technologies & 23 kg/m^2 conservative ones) which is a major contributor to inert weight.

$(\mu_{str})_{\tau=0.1}$ (kg/m^2)	GW (t)	W_{dry} (t)	τ (-)
17	118.40	30.42	0.209
19*	133.71	35.20	0.195
21	154.50	43.13	0.181
23	201.96	60.54	0.158

* Baseline

Table 17

It is seen that GW & W_{dry} increase very rapidly with $(\mu_{str})_{\tau=0.1}$ whilst τ decreases: for instance an increase in $(\mu_{str})_{\tau=0.1}$ from **19** to **23 kg/m^2** penalises GW by **51.0%**, W_{dry} by **72.0%** & decreases τ by **19.0%**.

A low structure index is of utmost importance to achieve high performance: $(\mu_{str})_{\tau=0.1}$ as low as 16 kg/m^2 seems conceivable with advanced materials.

6.6 Influence of margin

Table 18 provides gross take-off weight GW, dry weight W_{dry} & Küchemann's τ, for 3 margins μ_a (5% is dangerously small & 25% unnecessarily comfortable).

μ_a (%)	GW (t)	W_{dry} (t)	τ (-)
5	100.94	24.72	0.228
15*	133.71	35.20	0.195
25	177.48	51.60	0.168

* Baseline

Table 18

It is seen that GW & W_{dry} increase rapidly with μ_a whilst τ decreases: for instance a decrease in μ_a from **15%** to 5% improves GW by **24.5%** & W_{dry} by 29.8% and increases τ by **16.7%**.

6.7 Influence of collection range

Table 19 provides gross take-off weight GW, dry weight W_{dry} & Küchemann's τ for 3 cases: the baseline with lox collection from Mach 2.0 to 4.5, a narrowed range from Mach 2.2 to 3.8 or with collection limited to cruise.

collection range (-)	GW (t)	W_{dry} (t)	τ (-)
$2.0 < M_0 < 4.5$*	133.71	35.20	0.195
$2.2 < M_0 < 3.8$	136.46	35.88	0.194
cruise at 2.5	158.54	41.54	0.182

* Baseline

Table 19

It is seen that limiting the lox collection range degrades performance: the penalty remains moderate for the narrowed collection range: **2.0%** in GW & **1.9%** in W_{dry} but becomes severe when collection is performed during the cruise only: : **18.6%** in GW & **18.0%** in W_{dry} *However, collection narrowed or limited to cruise is likely to ease plant development much & to lower its specific plant weight, thereby actually decreasing the penalty.*

6.8 Vertical versus horizontal take-off

Table 20 provides gross take-off weight GW, dry weight W_{dry} & Küchemann's τ, for vertical & horizontal take-off.

attitude	GW (t)	W_{dry} (t)	τ (-)
vertical*	133.71	35.20	0.195
horizontal	154.68	44.09	0.184

* *Baseline*

Table 20

It is seen that horizontal take-off degrades performance much for the *extra undercarriage weight needed to carry the full GW at take-off: the increase* in GW is 15.7% & in W_{dry} 25.3%.

6.9 Manned versions

Table 21 provides gross take-off weight GW, dry weight W_{dry}, Küchemann's τ & propellant volumetric efficiency η_{vol}, for an **unmanned vehicle**, a **piloted spaceplane** (as per tables 1 & 2) & an **automatic personnel carrier** for *8 astronauts + 6.8 t of cargo (extra cabin weight & volume, incl. life support* equipment, is accounted as ΔC_{syst} = 12 t & ΔV_{fix} = 120 m^3).

Type	GW (t)	W_{dry} (t)	τ (-)	η_{vol} (%)
Unmanned*	133.71	35.20	0.195	69.8
Piloted	172.76	48.85	0.175	68.2
Carrier	271.97	82.25	0.141	66.9

* Baseline

Table 21

It is seen that the performance price paid for a manned vehicle is major & depends much on the type of manned vehicle:

- **for the piloted vehicle it is already rather high:** 29.2% in GW & 38.8% in W_{dry} but
- **for the automatic personnel carrier it is major:** 103.4% in GW & 133.7% in W_{dry}.

7 DISCUSSION

7.1 The vehicle characteristics which have the highest potential to improve performance are:

- **use of an unmanned vehicle (highest sensitivity),**
- **a low structure index μ_{str},**
- **vertical take-off,**
- **harnessing of hydrogen catalytic conversion,**
- **a low void fraction k_{Vv} i.e. a high propellant volumetric efficiency &**
- **a low margin on inert weight μ_a.**

the other characteristics having only a rather small sensitivity. The first & the last characteristics are imposed mission / programme requirements.

Most above considered cases show rather good performances, some better than others, however. Therefore decisions should take into account practical considerations such as technical difficulties or costs rather than seek for optimal performance. A good example would be to select a transition air-breathing → rocket at Mach 6 only, as elaborated in section 6.1 above.

7.2 The combined effect of transition airbreathing → rocket Mach number & vehicle stoutness is more complex than suggested by the above linear sensitivity assessment illustrated by figures 7-a & 7-b. The curves L_{to} = constant are far from parallel & even cross each other but an optimum always exists, less pronounced when L_{to} rises.

7.3 Comparison between tables 8, 10 & 15 shows that performance is more sensitive to collection plant specific weight than to collection ratio Γ. Indeed an improvement by **22.7%** in collection ratio, derived from catalytic conversion, decreases GW by **2.1%** & W_{dry} **by 2.7%** but a **10%** improvement in plant specific weight decreases GW **by 6.4%** & W_{dry} by **6.8%**.

8 CONCLUSIONS

8.1 Potentially an S.S.T.O. with in-flight lox collection, propelled by rockets + inserted ramjets offers rather promising possibilities, in particular elimination of the extreme marginality & complete lack of operational flexibility which characterise the all-rocket reusable S.S.T.O.: indeed most above considered cases have payload fractions in excess of 5.5% whilst 2% is difficult to achieve for the latter. In addition, for the same mission, it typically improves gross take-off weight by 75% (which is spectacular) & but degrades dry weight by 14% with respect to its all-rocket counterpart, which results from the addition of the ramjet + the collection plant and from the vehicle being nearly 50% heavier at transition air-breathing → rocket than at take-off.

8.2 Other advantages of in-flight lox collection are:

- a rather low Mach at transition air-breathing → rocket, about 6, is possible, which would avoid the use of scramjets and lowers much the thermal loads on the structure & the ramjets,
- a rather low Mach number of about 2.5 is best for the cruise, which should much facilitate a representative in-flight demonstration &
- *a moderate air pressure in the condenser is best for collection, which should* ease development problems and improve both reliability & reusability.

8.3 *The success of in-flight lox collection, however, is contingent upon the development of an efficient, lightweight & compact collection plant & its demonstration.*

8.4 In-flight lox collection is not the only promising option: an other one is the LACE rocket which, except for the separator, relies upon the same basic technologies and would typically improve both gross take-off weight by 77%, & dry weight by 50% with respect to its all-rocket counterpart, which is equally spectacular.

8.5 The comparison between in-flight lox collection & LACE rocket requires a delicate trade-off between on the one hand a lower investment (i.e. amortization) in favour of the latter as the result of its lower dry weight and on the other of a much higher operational flexibility (i.e. likely lower running costs) in favour of the former, providing much longer launch windows & the possibility to use bases located almost everywhere in the world.

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