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New Upper Stage Propulsion Concept for Future Launchers

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ABSTRACT

A pressure-fed system is leading to a stage easy to operate, reliable, needing no costly solutions (Expander engine, Boost pumps)
On another hand, many R&D programs are going on all ceramic liquid engines, engines cooled by "effusion" (DLR), Transpiration (PTAH-SOCAR from MBDA), Film or Trim (Astrium, Snecma), so very light engine may be offered on the market in a close future

Operating to relatively low pressure the specific impulse is slightly lower than a conventional one with a turbomachine (expander type or other) and the structural index lightly less interesting: a concept with the LOX tank nested inside the fuel tank with a scrolling common bulkhead appears easily usable for LOX Methane stage due to the fact that the 2 propellants are liquids in the same range of temperature and may lead to an interesting mass saving
Even if such an upper stage may lead to a dramatic increase of the performance of a small launch vehicle such as Vega (replacement of Z9 and Avum), the aim of this presentation is mainly to show the interest of special tools to make the very first evaluation of the interest of a new solution
The Inner Arch developed for the Cnes DLA two softwares:

- One dedicated to solid propulsion projects :APSOL
- One dedicated to liquid propulsion projects ELIS

A third one, PERFOL, is used to optimize the trajectory and the propulsion parameters
The paper will describe the main software used for this study and illustrate the interest of the approach

Introduction

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On another hand, many R&D programs are going on all ceramic liquid engines, engines cooled by "effusion" (DLR), Transpiration (PTAH-SOCAR from MBDA), Film or Trim (Astrium, Snecma), so very light engine may be offered on the market in a close future

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A common bulkhead is the lighter solution for an upper stage, a scrolling bulkhead allow saving mass of the pressurization system:

- Only one pressurization system is needed
- One can use the lower molar mass gas Hydrogen as pressurant

A four ceramic engine is hooked on the aft dome of the tanks with a movable joint. They are gimballed along one axis, so to have a 3 directions control; in the case of a heated pressurization system an all ceramic heat exchanger is implemented at the divergent entrance

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The softwares

APSOL and ELIS

These two light softwares are written under excel; they made so to give trends:

- Comparing architecture option
- On the influence of operating parameters
- The effects of technological options

The advantage of Excel, in this case is, the possibility to directly look at the effect on the design changing a parameter

To be effective, they have to be calibrated on detailed projects

APSOL

It is dedicated to Solid Propulsion rockets

A first page regroup the main data and the main results needed for instance for the performance study (mass breakdown, Isv, As) and a scheme

One distinguish the design of a first or an upper stage (nozzle design)

The main inputs are: as parameters, the diameter, the propellant mass, the nozzle submergence ratio, the maximum operating pressure

As technology: the propellant, the grain type, the case type (metallic or composite) the throat insert material; to each technology choice corresponds a set of parameters

Pages are dedicated to:

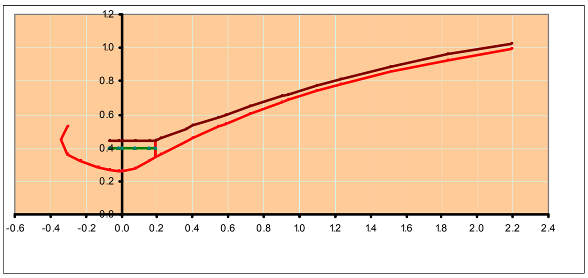
- The case

Example of results for a composite case

Solution composite		
e-v : épaisseur virole théorique	15.50	mm
e-f : épaisseur fonds	6.20	mm
Nb couches théoriques	24.70	
Nb couches pour virole	25.00	
Nb couches pour fonds	13.00	
	9.8819631	
e-v : épaisseur virole	15.69	mm
e-f : épaisseur fonds	8.16	mm
Masse Virole	1698.19	kg
Masse Fonds	493.42	kg
Masse Renforts divers	69.4	kg
Masse CPN composite	**2261.0**	**kg**

1. The grain
2. The TVC
3. The nozzle

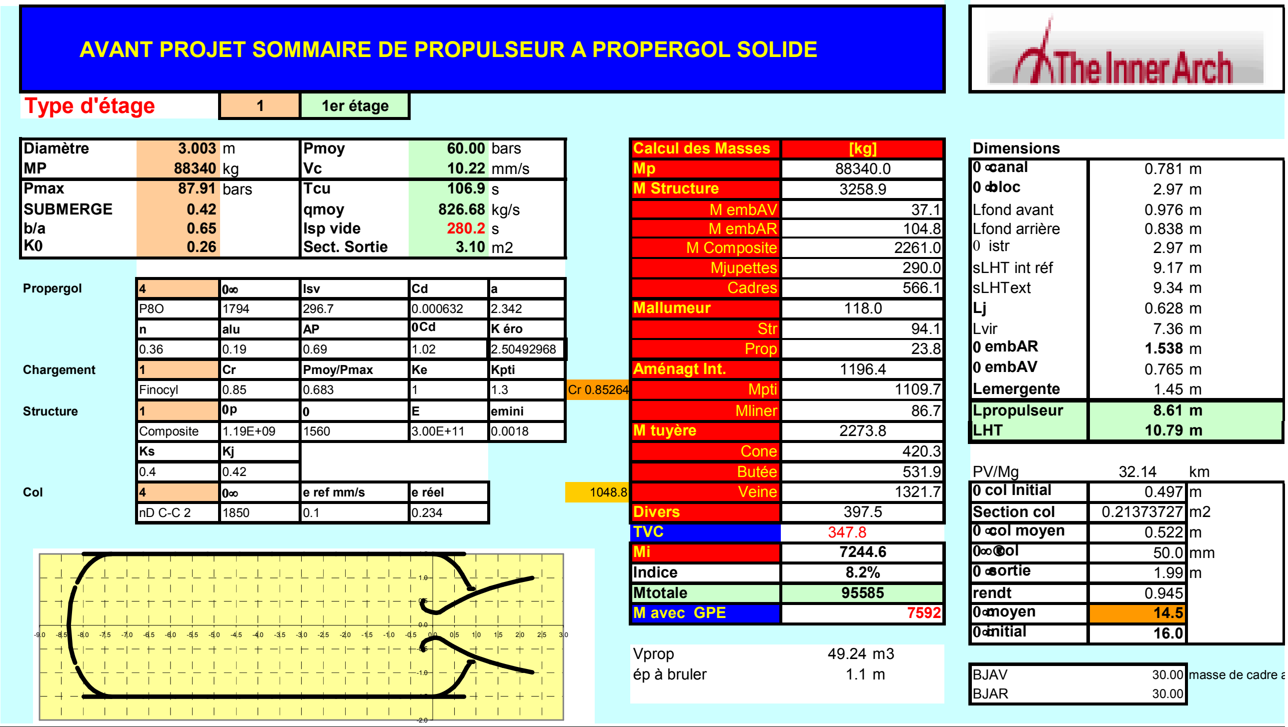
Example of a nozzle design: the thicknesses are estimated



Secondary data can be entered at the nozzle level such as the gimballing angle

The practical specific impulse is computed by the Landsbaum, Salinas and Geary method [1]

The code is able to design fixed nozzle or downstream pivot point flexseal SRMs



AVANT PROJET SOMMAIRE DE PROPULSEUR A PROPERGOL SOLIDE

The Inner Arch

Type d'étage	1	1er étage

Diamètre	3.003	m	Pmoy	60.00	bars
MP	88340	kg	Vc	10.22	mm/s
Pmax	87.91	bars	Tcu	106.9	s
SUBMERGE	0.42		qmoy	826.68	kg/s
b/a	0.65		Isp vide	280.2	s
K0	0.26		Sect. Sortie	3.10	m2

Propergol	4	0∞	Isv	Cd	a	
	P8O	1794	296.7	0.000632	2.342	
	n	alu	AP	0Cd	K éro	
	0.36	0.19	0.69	1.02	2.50492968	
Chargement	1	Cr	Pmoy/Pmax	Ke	Kpti	
	Finocyl	0.85	0.683	1	1.3	Cr 0.85264
Structure	1	0p	0	E	emini	
	Composite	1.19E+09	1560	3.00E+11	0.0018	
	Ks	Kj				
	0.4	0.42				
Col	4	0∞	e ref mm/s	e réel		1048.8
	nD C-C 2	1850	0.1	0.234		

Calcul des Masses	[kg]
Mp	88340.0
M Structure	3258.9
M embAV	37.1
M embAR	104.8
M Composite	2261.0
Mjupettes	290.0
Cadres	566.1
Mallumeur	118.0
Str	94.1
Prop	23.8
Aménagt Int.	1196.4
Mpti	1109.7
Mliner	86.7
M tuyère	2273.8
Cone	420.3
Butée	531.9
Veine	1321.7
Divers	397.5
TVC	347.8
Mi	7244.6
Indice	8.2%
Mtotale	95585
M avec GPE	7592

Vprop	49.24	m3
ép à bruler	1.1	m

Dimensions		
0 canal	0.781	m
0 bloc	2.97	m
Lfond avant	0.976	m
Lfond arrière	0.838	m
0 istr	2.97	m
sLHT int réf	9.17	m
sLHText	9.34	m
Lj	0.628	m
Lvir	7.36	m
0 embAR	1.538	m
0 embAV	0.765	m
Lemergente	1.45	m
Lpropulseur	8.61	m
LHT	10.79	m

PV/Mg	32.14	km
0 col Initial	0.497	m
Section col	0.21373727	m2
0 col moyen	0.522	m
0∞col	50.0	mm
0 sortie	1.99	m
rendt	0.945	
0 moyen	14.5	
0 initial	16.0	

BJAV	30.00	masse de cadre a
BJAR	30.00	

APSOL First page

ELIS

The main choices are:

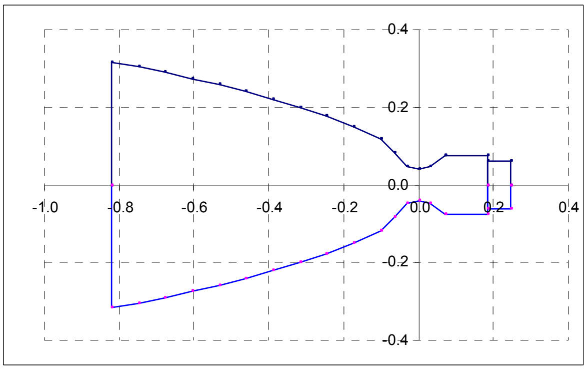
- ○ The propellant combination limited to 4 but new ones can be easily implemented
- ○ The tank architecture
- ○ Pressure-fed or turbomachine
- ○ Metallic or composite tanks
- ○ Different type of combustion chambers (regenerative, colombium, ceramic)
- ○ Self or helium pressurization with or without final blow-down (one distinguish a one shot design from and upper stage with a long intermediate ballistic phase and several location for the gas storage

The main inputs after the previous choices done are: the stage diameter, the propellant mass, the engine number and area ratio, the total thrust; the blow-down ratio if pressure fed the chamber pressure, for the mixture ratio there is the choice between a pre selected one or the one specially selected (to make for example an optimization of the mixture ratio)

A first page regroups the main data and the output: a mass breakdown, combustion time, Practical specific impulse Isp , total exit area of the nozzle and a scheme

Dedicated pages are implemented

- ○ Operating parameters
- ○ Pressurisation system
- ○ Fuel tank
- ○ Oxidiser tank
- ○ Engine
- ○ Tankage assembly and secondary structures



Example of nozzle drawing

PERFOL

This software optimises the trajectory and the flight sequence but with the following requirements:

- Robustness and easiness: anybody without any skill in performances computation ,may use it an obtain an accurate result, from different launch pad , for different missions: the input is simplified as much as possible
- Computation time short enough to be used in a MDO software/platform
- Microsoft environment
- Excel interface

The optimization problem is classically formulated with:

- A parametric optimization of the command and trajectory segmentation
- Parametric optimization with non linear constraints
- Reduce gradient method

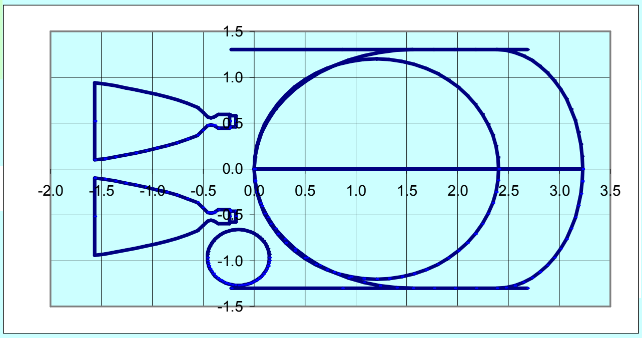
AVANT-PROJET SOMMAIRE DE PROPULSION LIQUIDE PRESSURISE

Détage (m)	2.60	Type d'étage	0	One Shot
	2	PRESSURISE	31	Configuration Réservoir: Integré sph
blow-down (critère Ps / Pa =			0.4	

LOX/CH4	2		Rm 1 ou 2	
Réservoir compo	1	composite	2	optimal
Chambre Céram	1	Céram	3.3	
Mer ut (kg)	10000	Pch(bar)P	20	bars
DrésOx (m)	2.40	Pch(bar)T	115	bars
Fi (kN)	70.00	Pr (bar)	26.0	bars
Rmoteur	3.50	Tc	597.5	s
Débit initial	19.8	Tc sans	504.9	
Débit O	15.4	As	0.556	m2
Débit F	4.4	Isv	360.3	s
Nbre chambres	4	Is sol	-761.1	s
As/At	120			

Oxy	Fuel	Isv th	L*(High)	Cstar	Rmétage	Dmr	Rmoteur
1140	424	384.8	0.71	1888	3.5	0	3.50
Code Ergols		Code Chambre		Code Configuration		Matériau Réservoir	
1	LOX/Kéro	1	Céram	10	Séparés	1	composite
2	LOX/CH4	2	Niobium	20	Fd commun	2	Alu
3	LOX/LH2	3	Régéné	31	Integré sph	3	Titane
4	NTO/MMH	4	Ablatif	32	Integré éllip	4	Inox
corriger b/a				40	Faux Fond Commun		
La tuyère décolle				50	Tandem		
				61	Fuel Torique		
				62	Oxydant Torique		
				63	Bi Tore		

Bilan masse (kg)		Dimensions (m)		
		LHT	3.97	
MP ut	10000.0	Lréservoirs	3.23	
Mp résiduel	100.0	Hmoteur	1.39	
Rés Gaz	16.7			
Hélium	26.6	Baie moteur(hors pressu)		
Moteurs	62.6	Moteurs	50.9	
Isol Réservoirs	31.6		0.0	moteur fixé
Réservoirs/Jupes	468.3	bati	5.1	sur fond
inerte pressu	112.3	prop system	6.6	
Divers étage	172.0	Total moteur	62.6	
Total inertes	815.1			
Décollage	10990.0			
inerte+inconso flu	958.4			
indice sec	0.082			
indice étage	0.096			
Mergol chargés	10116.7			



ELIS First page

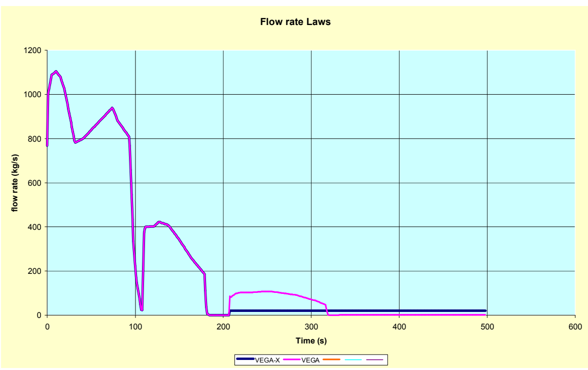
The originality is an analytical computation procedure, the initialization process, and a gradual approach in term of complexity of the solution, for the initialization and the analysis of the optimality of the result, expert systems are implemented

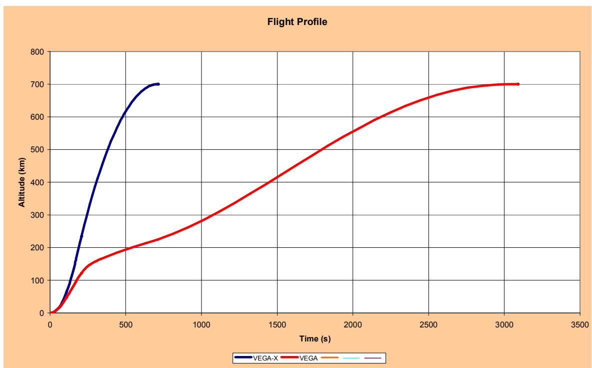
The thrust law can be a real one or tailored

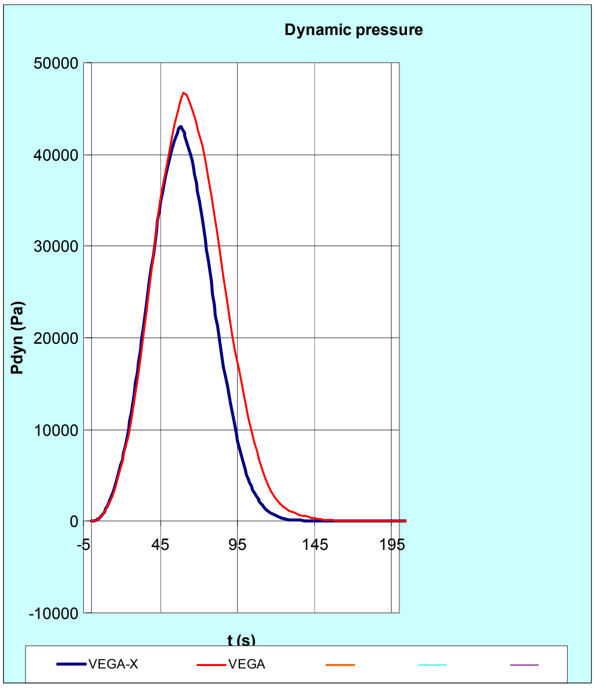
The out put is an **optimal trajectory and sequence** with:

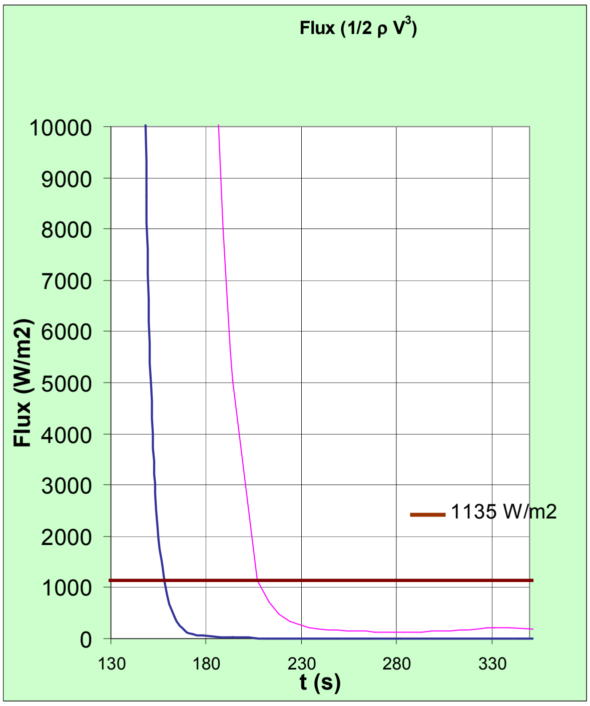
- A synthetic table of the result (see above)
- a listing with dimensioning events and parameters of the trajectory for mechanical dimensioning) and synthetic tables
- graphical display of the major parameters: some are shown hereunder, with the altitude versus range , the Pdyn, the shroud is jettisoned under flux constraints, the last one is the trajectory with the fall-out point of the stages

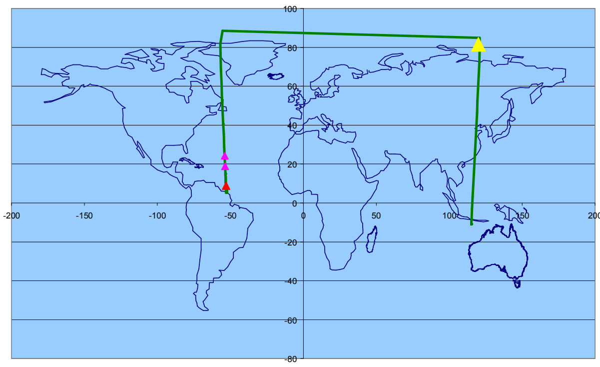
PERFOL: Interface











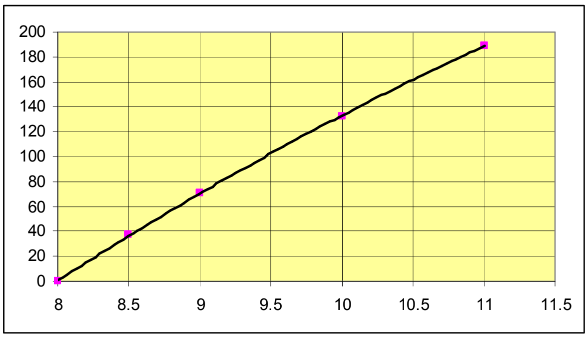
The project

The VEGA is a four stage (P80-Z23-Z9-AVUM) launch Vehicle with several diameters; the selected diameter for the stage will be the shroud diameter, 2.6m, and not the Z23, to have a shorter stage

The LOX-Methane stage that will replace the Z9 and AVUM will have an equipment bay of 300kg (GNC, RACS, Electrical harness, TLM, structure of the equipment bay)

A very important point will be **to go directly into orbit without any intermediate ballistic phase** during the LOX/Methane stage functioning; such a procedure allow to have a relatively high average temperature of the final gaseous dome and so a low requirement in the pressurant need

The first step was to select the propellant mass; so using ELIS a law of Dead Mass versus propellant mass was established and payload versus the upper stage propellant mass was directly established running PERFOL

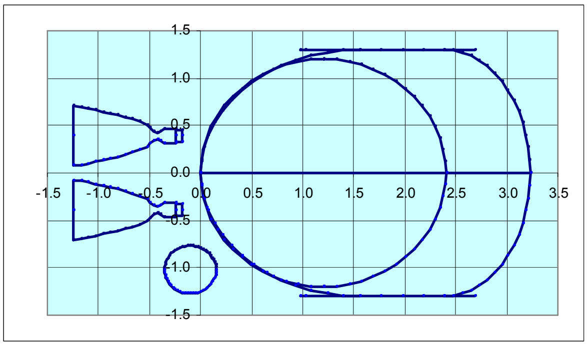


Resulting of the intrinsic LOX/CH4 performances, the interest would be to have an upper stage of a propellant mass over 11 tons (the optimum zone is in an upper range); nevertheless to select for the exercise a 10 tons mass to have a stage with a reasonable size,

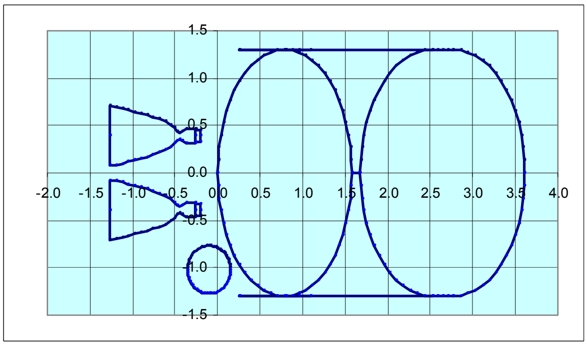
Technological choices

The architecture

The software allows direct and fast comparison between different stage architectures

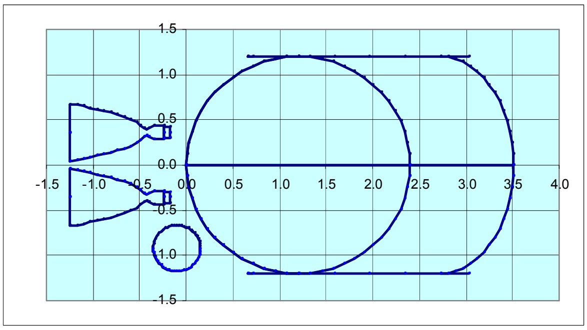


Selected configuration



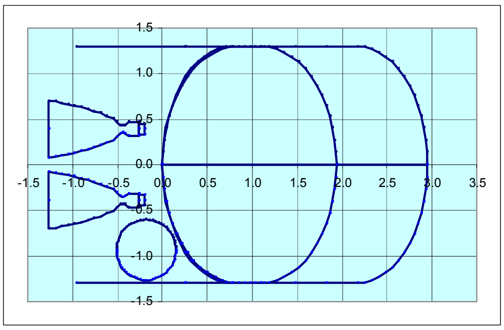
Separated Tanks

A classical separated tank configuration is longer and heavier



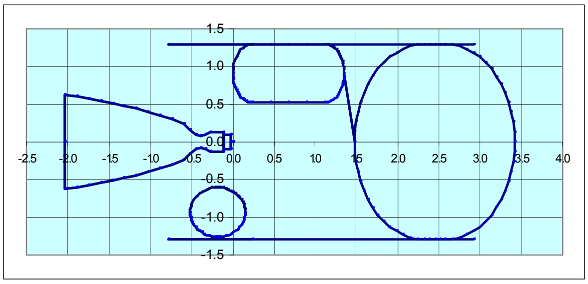
Same diameter

If the tanks have the same diameter, with a pure spherical oxygen tank the stage diameter will be lower than 2.60m and with a pure ellipsoidal, i twill be greater



Ellipsoidal Oxygen Tank

This one is shorter an lighter but does not allow easily a reversible bulkhead (cylindrical part)



Toroidal Tank

The above toroïdal configuration combines many drawbacks

So the first configuration was selected

The stage uses the couple LOX Methane, the special interest of this propellant is to exist in liquid state in the same range of temperature, so the stage may have a non insulated common bulkhead, the most interesting configuration for an upper stage

The bullhead is in fact an apex initiated metal diaphragm as used for positive expulsion devices. A combination of Pure Aluminum/2219 is chosen for its good compatibility with the LOX (reversible dome in aluminum the lower part is made of 2219) and for the knowledge on reversible dome(thickness between 1 and 2 mm);the metallic diaphragm is covered by a dome made with a relatively tight cloth , the pressurizing gas will be injected between this dome and the reversible diaphragm so that this dome will be in a slight overpressure with regards to the methane compartment ; the methane tank will keep its internal shape that solve the problem of propellant expulsion (classical lateral sump); moreover this cavity filled wit a cold gas will provide a natural insulation between the propellants . The gas pressurize first this internal cavity and then the methane dome

The major interest of this choice is to allow having only one pressurization system: the oxygen tank is pressurized by the methane tank by the reversible bulkhead. As the propellant in contact with the pressurant is methane, gaseous hydrogen may be selected such as to save some mass in comparison with helium (gas mass saving only, the mass of the bottle being roughly the same)

Tank material choice

The software allows a comparison between material; a configuration as proposed in [R2] with a metallic tank nested in a composite tank was chosen, the mass saving being interesting. Another major contributor is in fact the skirts mass, they are assumed to be made with a carbon/aluminum Honeycomb

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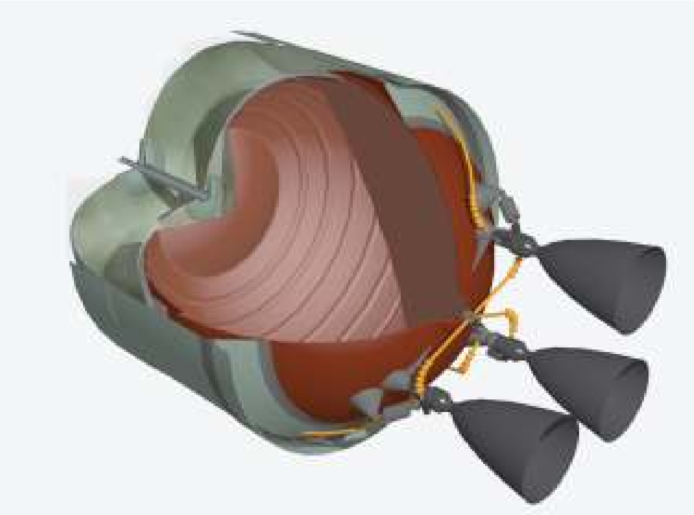
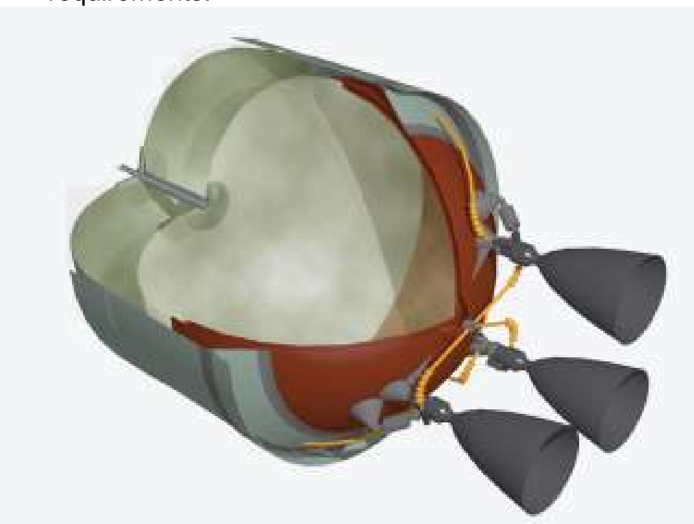


Stage: initial state

The thermal insulation is external (Klegecell), an expanded tight polyurethane foam (51 kg/m^3). The thickness will be 15 mm for LOx aft dome. The external part of the front methane bulkhead is insulated with additional MLI (Multi-Layer Insulation) to meet the equipment bay cooling requirements.

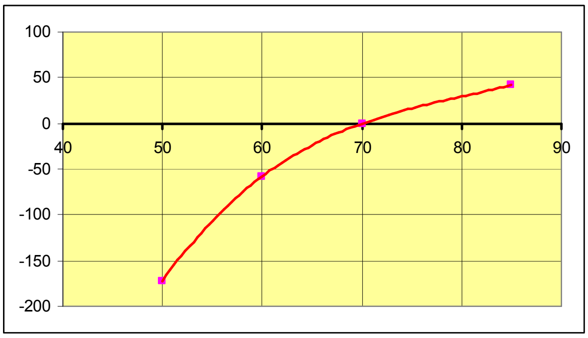


Stage: end of expulsion

The engine chambers (basic solution) are made of ceramic/ceramic.(Min. Thick.= 2mm,Density=2800 kg/m^3 ,Θmax =1800K)
They are directly hooked on the metallic dome (welded support with a simple articulation), each one of the 4 engines have one degree of freedom and are actuated by an electric actuator
The pressurization system will use gas stored in external bottles; the gas will be Hydrogen and the bottle made of wounded carbon-epoxy with a metallic liner, the numeric pressure regulator will regulator will maintain a constant pressure during the first part of the flight and will allow a blow-down phase; the final pressure have to be as low as allowed by a stable operation of the engine, as low it will be better will be the global performance

Determination of the optimal parameters

Choice of the thrust level
Lower is the thrust, lower are their mass, shorter they are for a given area ratio or greater the area ratio is for a given interstage length, higher is the thrust higher the cost is ;so the thrust have to be as low as possible without a significant loss of performances..



Payload mass increase versus engine thrust

Using PERFOL, the intrinsic Launch vehicle is becoming less sensitive over 70kN so we will select this value in a first approach

Choice of the blow down ratio
This parameter is simple to choose, lower the final pressure is, lower is the dead mass of the stage, a blow-down ratio of 0.4 seems compatible with a stable engine in all the operating domain
, the consequence will be about 300kg of mass saving in the case of Helium (external storage system with a Pc of 2Mpa

Choice of the combustion pressure
The optimal combustion pressure is 20 bars ,
Taking into account the size of the engine and the mass of the rear skirt

Mixture ratio optimization
The basic selected O/F is 3.5, the results show a very small interest to increase the combustion mixture ratio close to 4

Interest to select Hydrogen as pressurant
The interest result mainly from the lower molecular mass, the mass saving is around 10 kg
In fact for the mass of the pressurization system; the major parameter is the blow down ratio, the storage mass decreasing with it

Mass Break-Down
Even keeping the helium as pressurant, the stage will have a very good structural index and the engine a high level of specific impulse 360s for an area ratio of 120
This first result may justify the interest of a more detailed study to obtain a more realistic dimensioning, the result of which will allow improving the ELIS internal models

Mass Breakdown (kg)	
Useful propellant	10000.0
Residual propellant	100.0
Gaseous Residual	16.7
Helium	26.6
Engines	62.6
Tank Insulation	31.6
Tanks & Skirts	468.3
Pressurisation	112.3
Stage components	172.0
Dry mass	**815.1**
Lift-off mass	10990.0
Mission End	958.4
Dry index	0.082
Mission End index	0.096
Loaded propellant	10116.7

Global performances

The result using PERFOL confirm the potentiality of the replacement of the Z9 and AVUM by a single LOX Methane upper stage with a payload greater than 2 tons with both a lower maximum dynamic pressures: and at ½ stage separation.
Note: In the example shown hereunder, the performance was calculated with propulsion realistic laws; in a first project phase PERFOL allows to parameter the thrust law shape having so in few minutes an idea of the optimal one.

Conclusion

After a calibration phase on existing stages, the developed tools will open an efficient way to evaluate the interest a new solution and optimize its propulsion parameters; PERFOL is very robust and really easy to use, so every performance evaluation tasks can be directly done-even by an engineer without any skill in Flight mechanics- and without using anymore too much simple tools

REFERENCES:

[R1] Aerospace America-January 1999-The future of Earth-To-Orbit propulsion by Robert C.TRUAX
[R2] 0.94-Meter Cryogenic Demonstration Tank-MJ. Warner, DJ. Son, DM. Lester, Thiokol Propulsion-45th International SAMPE Symposium and Exhibition, 21-25 May 2000
[R2] Brevet Français FR2840384 Publié le 12/05/2003 Réservoir pour fluide sous pression comprenant deux compartiments et procédé de fabrication d'un tel réservoir
[R3] Brevet Français N° publication WO03074859 Publié le 9/12/2003 Moteur de fusée en matériau composite
[R4] AIAA-2001-3692 Innovative Upper Stage Propulsion Concepts for Future Launchers

VEGA-X

Mp	Mi	Tc	Type	Isp_mean	Q_mean	Q0/Q_mean	T_break	
88 534.	8 616.0	108.8	loi1	270.3	813.7	1.3	1.0	
24 033.	2 568.2	98.7	loi2	286.8	243.4	1.5	1.0	
10 000.	1 260.0	505.0	constant	360.0	19.8	1.0	1.0	
Initial Mass (ton)	Payload (kg)	PdynSep1-2 (kPa)	Flux max (Kw/m2)	Accel max (m/s2)	Pdyn max (kPa)	Z apogee (km)	Z perigee (km)	inclination (dg)
137.7	2 176.7	0.3	37.0	40.4	44.6	700.0	699.9	90.0

VEGA

Mp	Mi	Tc	Type	Isp_mean	Q_mean	Q0/Q_mean	T_break	
88 534.	8 616.0	108.8	loi1	269.8	813.7	1.3	1.0	
24 0330	2 568.2	98.7	loi2	286.8	243.4	1.5	1.0	
10 070.	1 424.7	124.5	loi3	294.5	80.9	1.1	1.0	
396.0	826.1	500.0	constant	315.5	0.8	1.0	1.0	
Initial Mass (ton)	Payload (kg)	PdynSep1-2 (kPa)	Flux max (Kw/m2)	Accel max (m/s2)	Pdyn max (kPa)	Z apogee (km)	Z perigee (km)	inclination (dg)
138.3	1 318.7	2.3	78.9	41.4	52.9	700.1	699.9	90.0