I.A.A Commission III

PARIS MEETINGS – MARCH 2010 MINUTES

Meeting Date(s)	:	**March 22nd** & 23rd, 2010	Page
Venue	:	March 22nd, ESA HQ PARIS, FRANCE	**1/11**

Participants:

1.	JOHN C MANKINS	AIMS	Chairman
2.	G. REIBALDI	ESA	Vice-Chairman
3.	CHRISTOPHE BONNAL	CNES	
4.	CALABRO MAX	APPLIED PHYSICS LAB	
5.	DAVID Y KUSNIERKIEWICZ	JOHNS HOPKINS UNIV/ INNER ARCH	
6.	SEISHIRO KIBE	JAXA	
7.	HANS E.W. HOFFMANN	ORBCOMM INC	
8.	WILLIAM SIEGFRIED	(RETIRED)	
9.	ERNST MESSERSCHMID	UNIV STUTTGART	
10.	OTTO KOODELKA	TU Graz(AUT)	
11.	ANDREWS RITTWEGER	EADS ASTRIUM	
12.	TETSUO YASAKA	GPS INSTITUTE	
13.	CHRISTIAN SALLABERGER	MDA	
14.	PETER SWAN	SO WEST ANALYTIC NETWORK	
15.	JUNICHIRO KAWAGUCHI	JAXA	
16.	ALAIN DUPAS	DUPAS & ASSOCIATES	
17.	S. RAMAKRISHNAN	ISRO	Secretary

PARIS MEETINGS – MARCH 2010 MINUTES

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Venue	:	March 22nd, ESA HQ PARIS, FRANCE	**2/11**

Objective : Progress Review preparatory to SAC Presentation

Agenda :

1) Review of actions from the previous minutes of meeting
2) Composition of Commission III
3) Study Group Status:

   SG3.1 Advanced Propulsion Prospective - Status/Way forward presentation by Max Calabro

   SG3.9 Private Human Access to Space - Status/Way forward presentation by C Bonnal

   SG3.10 Technologies to enable near term interstellar Precursor Mission - Presentation by C Bruno

   SG3.11 Solar Energy from Space - Draft by J Mankins

4) New Study Groups Status and way forward :
   - Space Elevators
   - Human Exploration

5) Symposia Status :
   - IAC2011
   - IAC2012

6) AOB
7) Summary of Commission III Meeting for Presentation at SAC

Minutes :

Subject Description	Action	Due Date
Chairman, Commission III welcomed the members and participants for the progress review meeting and outlined the agenda **1. Review of Actions from Oct,'09 meeting** Study Group report status with respect to SG 3.1, 3.9, 3.10 and 3.11 are to be discussed as part of agenda –3. **2. Composition of Commission III** The current composition of Commission III (2009-11) is given in Annexure-I. **3. Study Group Status :** **SG3.1 Advanced Propulsion Prospective** # The draft report from Mr. Max Calabro has been sent to members for comments. Mr. Christophe Bonnal and Mr. Roger Lenard have given feedback.		

Minutes :

Subject Description	Action	Due Date
# The revised draft document titled 'Chemical Propulsion from Earth to Orbit' was presented to the Commission by Mr. Max Calabro (Annexure-II). Following specific suggestions ere made: o The study report should bring out short term & long term perspective/recommendations. o The list of members of the Study Group to be included in the report.		
Preliminary Feedback on draft report to be sent to Mr. Max Calabro.	*C. Bonnal Hoffmann S.Ramakrishnan*	*May' 10*
Final document submission to Commission III for review	*Max Calabro*	*Aug' 10*
Commission III discussion for Peer review	*Comm III*	*IAC 10*
SG 3.9 <u>Private Human Access to Space</u> # Progress report & study report - contents presented by Mr. C Bonnal (Annexure-III) & (Annexure-IV)		

Minutes :

Subject Description	Action	Due Date
# Proposed 2nd IAA symposium on the topic in May 2011 # First Study Report on Private Human Access to Space to be limited to sub-orbital flights		
Draft report for Review by IAA Commission III Members & Proposal for Part-2 (Orbital flights) Study Plan	*C. Bonnal*	*Sept' 2010*
SG 3.10 <u>Technolgies for near term interstellar Missions</u> To be taken up in the Commission meeting on 23rd March FN, when Mr. Bruno is expected to attend. **SG 3.11 <u>Solar Energy from Space</u>** # Mr. John C Mankins presented the draft study report summary (Annexure-V)		
Final Draft report for review by Commission III members	*John C Mankins to S Ramakrishnan*	*April '10*

Minutes :

Subject Description	Action	Due Date
4. <u>New Study Groups Status</u> **4.1 <u>Space Elevators</u>** # Proposal for forming a study group on Space Elevators from Dr. P. Swan and the comments on the same from Mr. C. Bonnal & Mr. Roger Lenard were discussed.		
It was agreed that the proposal should be recast with 'Assessment of technological feasibility & challenges of Space Elevators' as the main theme.	*Dr. P.Swan*	*Action completed on 23.3.10*
A symposium on the subject may be organized with invited papers on every technological aspect from active supporters working in this area and also papers on key challenges as perceived by the skeptics of this concept.	*Dr. P. Swan*	
4.2 <u>Human Exploration</u> Study Group on Human Space Flight is under formation. Active work by this SG will commence later as this study will build upon the HSF Study		

Report to be released at IAA 50th Anniversary, Space Summit meet in Nov'10.		

I.A.A Commission III

Minutes :

Subject Description	Action	Due Date
5. Symposia Status IAC 2010 & IAC 2011 Symposia status was reviewed (Annexure-VII & Annexure-VIII) **6. Any Other Business** # The Commission was briefed about the IAA 50th Anniversary Space Agencies Summit proposed at Washington, USA on Nov 17th, 2011. The summit aims to bring out study reports on four key areas of interest for Space faring nations and also release a Policy statement paper on these four issues by Heads of Space Agencies. Several Commission III members are actively involved in the above Summit related tasks. # The Commission noted the new developments at NASA/USA, specifically the plan to assign the task of human transportation from Earth to LEO by Private Launchers.		

I.A.A Commission III

PARIS MEETINGS – MARCH 2010 MINUTES

Meeting Date(s)	:	**March 22nd** & 23rd, 2010	Page
Venue	:	March 22nd, ESA HQ PARIS, FRANCE	**8/11**

Minutes :

Subject Description	Action	Due Date
# The Commission will identify new study groups , will also address the issues of restructuring the approach to IAA Symposia and aligning of study groups with IAC sessions. 7. Status Report to SAC # To be reviewed in the meeting on 23rd March along with other left-out agenda.		

PARIS MEETINGS – MARCH 2010 MINUTES

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7.	E MESSERSCHMID	UNIV STUTTGART	
8.	ANDREWS RITTWEGOR	EADS ASTRIUM	
9.	PAIVI JUKOLA	-	
10.	JONJIRO ONODA	JAXA	
11.	WENDELL MENDELL	NASA	
12.	MARIA A PERINO	THALES ALENIA	
13.	CHRISTIAN SALLBERGER	MDA	
14.	WOBAYAKI KAYA	-	
15.	JUNICHIRO KAWAGUCHI	JAXA	
16.	KUNINORI UESUGI	-	
17.	SEISHIRO KIBE	JAXA	
18.	ALAIN DUPAS	DUPAS & ASSOCIATES	
19.	ION STROE	-	
20.	S. RAMAKRISHNAN	ISRO	Secretary

I.A.A Commission III

PARIS MEETINGS – MARCH 2010 MINUTES

Meeting Date(s)	:	March 22nd & **23rd, 2010**	Page
Venue	:	March 23rd, IAA OFFICE PARIS, FRANCE	**10/11**

Objective : Progress Review Continuation

Agenda :

1) Presentation on SG 3.10 status
2) Revised Study proposal on Space Elevators
3) Commission III report to SAC
4) AOB

Minutes :

Subject Description	Action	Due Date
1. SG 3.10 Technologies for Interstellar Precursor missions # Agenda was not discussed since Mr. C. Bruno could not attend the meeting due to flight delay. However the draft report is available and shall be distributed to the Commission III Members	**- S Ramakrishnan to distribute the Draft Study to the 11 Commission III Members** **- Com. III Members to provide comments and to decide on readiness for Peer review**	**15 April 2010** **03 July 2010**

Subject Description	Action	Due Date
2. **Study Proposal on Space Elevators** # The modified proposal for new Study Group on Space Elevators from Dr. Peter Swan was reviewed by the Commission. The Commission accepted the proposal in the new revised form (Annexure-IX) 3. **SAC Report** # The IAA Commission III Satus Report to SAC was presented and reviewed. (Annexure-X) 4. **AOB** # Members of IAA interested in taking up co-editor role for ACTA Astronautica publications may contact Mr. C. Bonnal.		

Composition of Commission III

March 2010

- John C. Mankins (USA), Chairman
- Giuseppe Reibaldi (It), Deputy Chairman
- S. Ramakrishnan (In), Secretary
- Christophe Bonnal (F), Member
- Hans E. W. Hoffmann (D), Member
- Wendell Mendell (USA), Member
- Claudio Bruno (It), Member
- Junjiro Onoda (J), Member
- Roger Lenard (USA), Member
- Christian Sallaberger (Ca), Member
- Tetsuo Yasaka (J), Past Chair

Annexure - i

Chemical propulsion from Earth to Orbit

W.G. 3.1 Working Document

Summary

1. Introduction /Mission
2. Propulsion technologies
   a. General
   b. Solid propulsion
   c. Liquid Propulsion
   d. Hybrid propulsion
3. Historical Survey/Highlights
   a. History of Solid Propulsion
   b. History of Liquid Propulsion
   c. History of Hybrid Propulsion
4. Existing Launchers Improvements and Development of New Families
5. Current Status and Roadmaps
   a. Solid propulsion
      i. Current Status/ General
      ii. Casing
      iii. Nozzles
      iv. Propellants
      v. Trends for next and future Launchers
   b. Liquid Propulsion
      i. Current Status/ General
      ii. Composite materials in liquid propulsion
      iii. Trends for next and future Launchers
   c. Hybrid propulsion
      i. Current Status/ General
      ii. Challenges in Hybrid Propulsion
6. General Conclusion
   a. Sensitivity Analysis
   b. Recommendations

REFERENCES/
Hybrids
Solids
Liquids

1. Introduction/missions

The earth to orbit history began in 1942 with the V2, the first industrial launch vehicle: its original sin was to be a military rocket. Since this time, this sin was never forgotten: all the technologies are of dual use and so cooperation between states is always difficult, even inside the European community where no common strategic forces exist: the cooperation is mainly limited to basis research and to technologies needed by the Ariane 5 programme and a budgetary rule is applied: the rule of the money return: each state doing works for the amount of money they gave

Currently the best mastered propulsion technologies are:

- Chemical propulsion able to produce high thrust with an Isv lower than 460 s

  Among chemical propulsion, use of LOX/LH2 associated with a closed loop engine (High pressure staged combustion for a first stage) is the best solution for the main propulsion from the performance standpoint; nevertheless its cost '(development and recurring), a high technological level difficult to master leave rooms for other kind of chemical propulsion such as Solid Propulsion, very economical, well fitted to produce a high thrust and so for boosters and small launchers and leave rooms for the other kind of liquid propulsion

- Electrical propulsion with an Isv greater than 1500s but with thrust in the range of some Newton

So a first consequence could be to use electric propulsion as soon as possible in a flight sequence by reaching first a stable orbit with a chemical propulsion launch vehicle; the final orbit –GEO, moon parking orbit or others – could be obtained by a low thrust trajectory (see figure1)

Such a scenario assumes that no limitations exist for feeding the electric upper stage with power, travelling time being a key issue for GEO missions. It is not the case today; there is some reluctance to use of nuclear generator in a close region of the earth: beamed energy could be an answer, waiting more sophisticated propellantless propulsion

So, chemical propulsion remain today the most efficient way to inject directly a payload on a GTO or even in GEO and potential major improvements exist.

Moreover for future travel into space, telecom applications, will demand to leave this orbit clean and to share the GEO, a first mandatory task could be to evacuate the satellites out of order; collision of large "debris" increasing considerably the number of "debris". Service, repair and upgrade large spacecrafts associated to the interest of space tugs going from a station on low earth orbit to a GEO platform or to a moon parking orbit and coming back to the station for its servicing (refilling mainly) would be to study

Science missions have ambitions to place large observatories at Lagrange points either as formation flying distributed apertures or locally assembled large structures[1]. Exploration looks to the days of a permanent human presence on the Moon and Mars and entrepreneurs to mass space tourism and eventually interplanetary trade.

2. Propulsion technologies

a. General

Current and projected space launch systems typically employ architectures that combine solid and liquid rockets to deliver payloads to orbit reliably and cost effectively. Therefore, for these mixed mode architectures, performance and reliability depends on both modes attributes. A mixed architecture results of a global optimisation of a launch vehicle: solids have a better structural index than liquids, are able to produce high thrust at low cost but have a lower specific impulse, hybrids are not mature; so, today solid propulsion is confined to the stages of small launch vehicles (except eventually the upper orbital stage) or to boost large liquid launch vehicles

Since chemical propulsion's primitive process is chemical energy deposition in propellant products, liquid or hybrid rockets' separation of reactants until post injection and solid rocket propellants' well mixed reactants at 0.1- 600microns length scales define these system's general characteristics, potentials, and challenges e.g. The set of "natural" liquid and hybrid propellant is much larger than solid propellants' (inter-ingredient compatibility is not required), the performance of solid rocket propellants is more dependent on innovative chemical syntheses and their large scale industrialization. In addition, the liquid rocket's visible mechanical complexities and a solid rocket's invisible propellant complexities have unique consequences i.e. Solid propellants' critical dependence on propellant formulation, adequate characterization, subsequent processing into loaded motors, and instant readiness.

Reliability

Since the reliability of mixed mode launcher architectures depend on the reliability of both modes, historical information circa July 31, 2008 were examined to reassess solid and liquid rocket reliability. For these data there were 416 failures and 4506 successes in worldwide orbital space launches since 1957. Although root causes for the 416 failures are difficult to determine (and categorize), launch failures since 1980 have been investigated, and data compilations show there were 140 failures and 2497 successes for worldwide space launches between January 1, 1980 and July 31, 2008.

A space launch failure can usually be attributed to problems associated with a functional subsystem, such as command and control, environmental protection, electrical, guidance-navigation and control, ground support equipment, propulsion, separation, structures, telemetry, thrust vectoring and attitude control, and tracking and flight safety. In some cases failure is ascribed to unknown causes, when subsystem failure information is not available. Propulsion subsystem problems are presented in Table 1. The 82 of the 140 worldwide launch failures in 1980–2008 were failures of the propulsion subsystem. The 18 of the 33 US failures and 41 of the 74 CIS/USSR failures in 1980–2008 were failures of the propulsion subsystem. The propulsion subsystem is the heaviest and largest subsystem of a launch vehicle, and its failure can be divided into failures in solid rockets (SR) and liquid rockets (LR). Out of the 82 propulsion failures in 1980–2008, 15 were SR and 67 were LR propulsion subsystems. There were 662 launches with SRs and 2462 launches with LRs. Therefore, the success rate is 97.73% for SR and 97.28% for LR propulsion subsystems. In Table 1, the sum of number of launches with SRs (662) and with LRs (2462) is greater than the total number of worldwide space launches 2637 in 1980–2008, because some hybrid launchers use both solid rocket motor (SRM) and LRE for the same launch. Clearly, success rates for SR and LR subsystems for the last 29 years (1980–2008) were essentially identical i.e. SR and LR subsystem reliabilities have effectively converged.

Table 1

Success rate of solid and liquid propulsion subsystems in space launches.

Country	Propulsion				Non-propulsion		Total	
	Solid		Liquid					
	Succ	Fail	Succ	Fail	Succ	Fail	Succ	Fail
USA	462	6	518	12	606	15	588	33
CIS/USSR	6	0	1557	41	1605	31	1563	73
Europe	101	0	173	9	182	1	173	10
China	0	2	95	3	100	3	95	8
Japan	54	2	37	2	58	1	54	5
India	19	1	15	0	20	5	19	6
Israel	5	1	0	0	6	1	5	2
Brazil	0	2	0	0	2	0	0	2
N. Korea	0	1	0	0	1	0	0	1
Total	647	15	2395	67	2580	57	2497	140
80-08 (%)	97.73		97.28		97.84		94.69	

Table 1 success rate of solid and liquid propulsion subsystems in space launches

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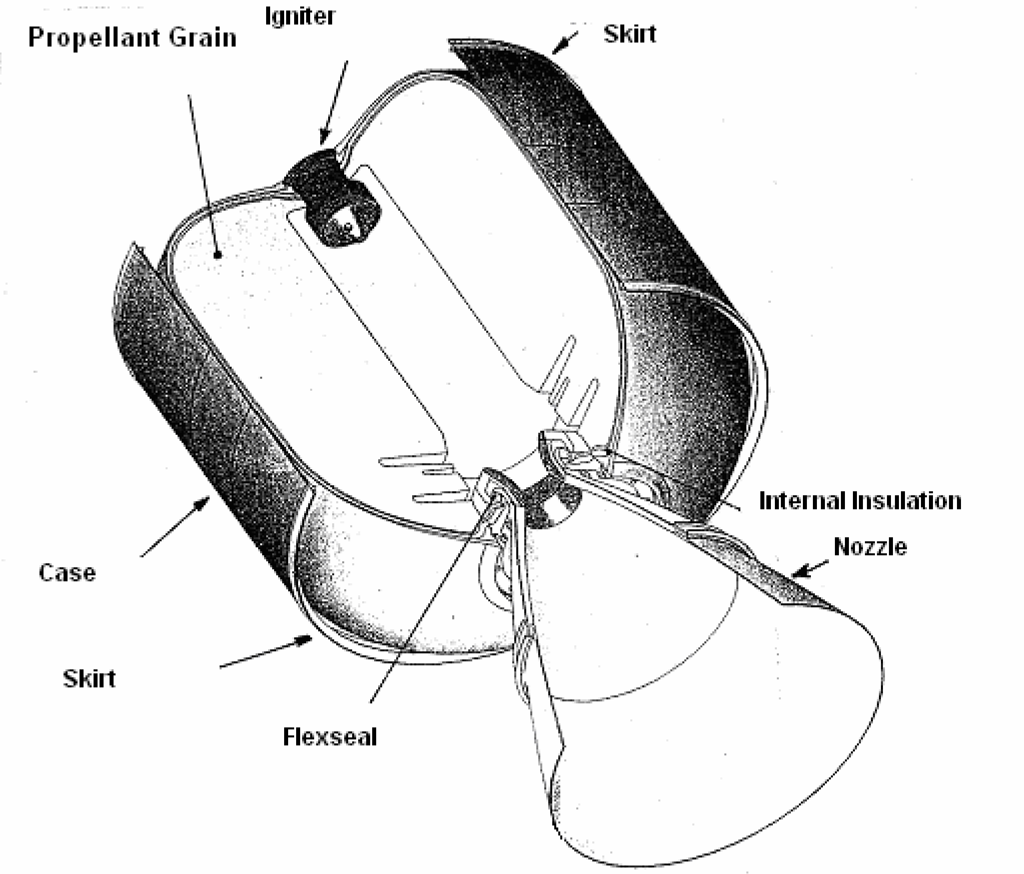
b. Solid propulsion

A structure or case· contain the propellant grain and is the combustion chamber (pressure up to120 bars max), this case is internally insulated so that the case stay at its initial temperature all along the combustion time (combustion temperature up to 3600k)

The hot gases are ejected through a movable nozzle (flexseal technology); the material of the nozzles are ablative; the combustion time is generally under 2 minutes·

Currently the propellant used for civilian applications are –quite exclusively- a combination of Hydroxyl Terminated Polybutadiene (currently HTPB or PBAN for the Shuttle Boosters), Ammonium Perchlorate (AP) and Aluminium

The interfaces with the launcher are insured by skirts (mechanical) and a raceway (electrical, command)



c. Liquid propulsion

Liquid propulsion definition is when liquid(s) stored in a tank produce hot gases by decomposition or combustion with a second liquid

- Monopropellant producing hot gases by thermal or catalytic decomposition
- Bi propellants: a liquid fuel+ a liquid oxidizer

Hydrazine monopropellant is mainly is used for ACS
Storable bi propellants -NTO/UDMH- is used on launch vehicles of the first generation still in use
Today the launch vehicles use or will use –except for boosters – mainly LO2/KEROSENE or LO2/LH2

LOX (7MPa)

	O/F	Tc	Cstar	d	Isv 40
		K	m/s		s
LH2	5.5	3411	2341	0.344	454.2
RP-1	2.7	3692	1788	1.028	358.2
Methane	3.5	3564	1833	0.833	368.8
UDMH	1.8	3624	1843	0.986	368.7

NTO (7MPa)

	O/F	Tc	Cstar	d	Isv 40
		K	m/s		s
RP-1	4.5	3466	1642	1.252	329.9
Methane	5.5	3343	1678	1.048	335.2
UDMH	2.8	3435	1710	1.177	339.4
MMH	2.2	3395	1741	1.193	341.0

For Launchers the choice of Thermodynamic cycles is critical:

1. Pressure-fed: main use upper stages, satellites , OTV

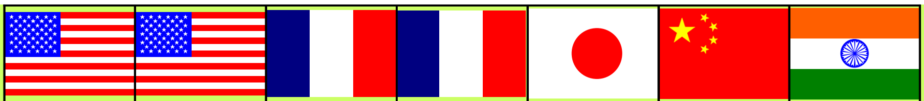
Advantages: Simple, reliable, low cost, and easily restartable (PMD under 0g: satellites, ATV)

Draw-back Performances, higher the pressure is heavier are the tanks

2. Turbopump cycles: main use booster stages

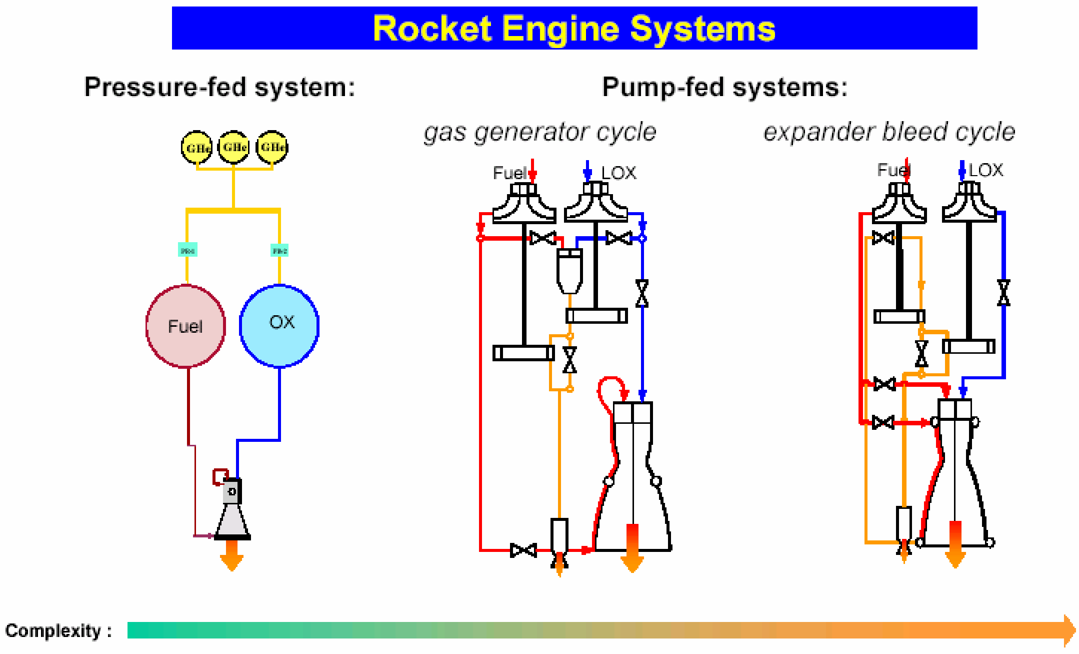
Many cycles exists ; among tem for

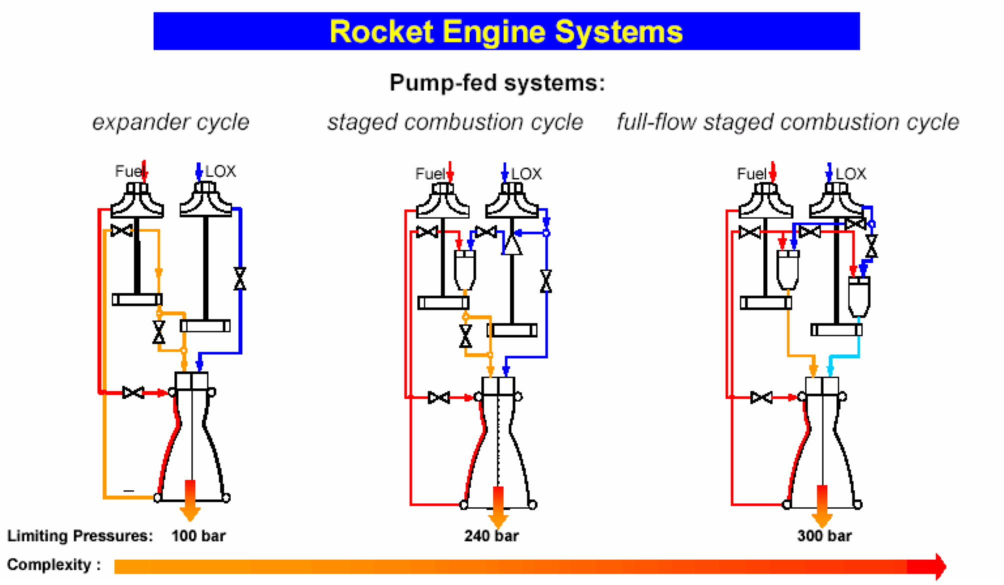
- First stages :
  Thrust, operating time, as/at result of an optimisation at system level taking into account engine constraints: search of maximum Isp along trajectory
  Interest for high combustion pressure staged combustion
- Upper stages : maximum Isv , minimum mass for a given length
  Interest for closed cycle with EEC



ENGINE VEHICLE	RL10A-4-1 CENTAUR	RL10B-2 CENTAUR	HM-7B ARIANE 4	VINCI ARIANE 5	LE-5A H-II	YF-75 LM-3A	KVD-7.5 GSLV
Thrust, (kN)	99	110	63	180	121	78	78
Thrust / Weight	59	39	41	32.5	51	?	27
Length, (m)	1,8/2,3	2,2	1,9	4,2	2,5	2,3	2,1
Specific impulse, (s)	451	465	444	464	452	440	460
Chamber pressure, (bar)	42	44	37	61	39	37	59
H2 Pump Dis. pres, (bar)	96,5	104	56	223	67	63	?
Area ratio	84:1	285:1	82:1	242.7:1	130:1	80:1	~ 200:1
Restartable	Yes	Yes		Yes	Yes	Yes	Yes
Cycle	Expander	Expander	Gas generator	Expander	Open expander	Gas generator	Staged combustion
1st flight (original/current)	1963/95		1979/84	2006	1986/94	1984/94	1997
Features	Extendable nozzle	Extendable nozzle		Extendable nozzle	5 % idle thrust		Built in Russia

Examples of upper stages engines





d. Hybrid propulsion

When one propellant is a solid and the other one is a liquid, a rocket motor is designated as hybrid architecture. Most of chemical rocket motors require at least two reacting media: a fuel and an oxidizer to burn and produce hot gases
The hybrid rocket may be classified into various types as shown on the following figure 1.
The standard hybrid arrangement consist of a pure fuel grain cast and cured in the combustion chamber (as a solid rocket motor) and of a liquid oxidizer stored into in a separate tank and injected under pressure in the combustion chamber (several configurations exists depending of the propellants and the application).
The solid state can also be obtained or freezing a fuel grain such as ethylene and n-pentane that has been tested at lab scale, or a gelled liquid fuel sustained by an internal matrix
The inverse hybrid uses a liquid fuel and an oxidizer grain; it works in the same way as the "standard" one.
Of all of the design concepts mentioned before, the standard hybrid rocket (scheme "a") has received the most attention: from its first introduction during the 30s by I. Andrussow with O.Lutz

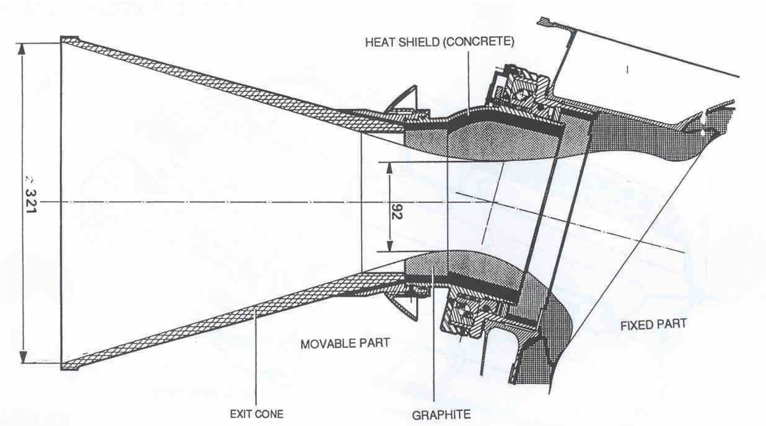
and W. Noeggerarth, tested a 10-kn hybrid using coal and gaseous nitrous oxide (work done for I.G.Farben)………… To its use to win the Xprize
The inverse hybrid, even if subject to some studies is not a solution: industrial manufacturing of an oxidizer solid grain is not easily feasible with the current techniques.

An historical survey shows aside of research works, propulsion used by students and for small satellites, some dead ends as the LOX/HTPB one for earth to orbit access were examined for its potential very low cost, however this combination highlights a series of technical problems without any performance advantage over the existing LOX/kerosene family.
Nevertheless if the combination of propellant is not only focused on the lower possible cost hybrids may represent a potential breakthrough, using advanced hybrids, for the earth to orbit (ETO) access.

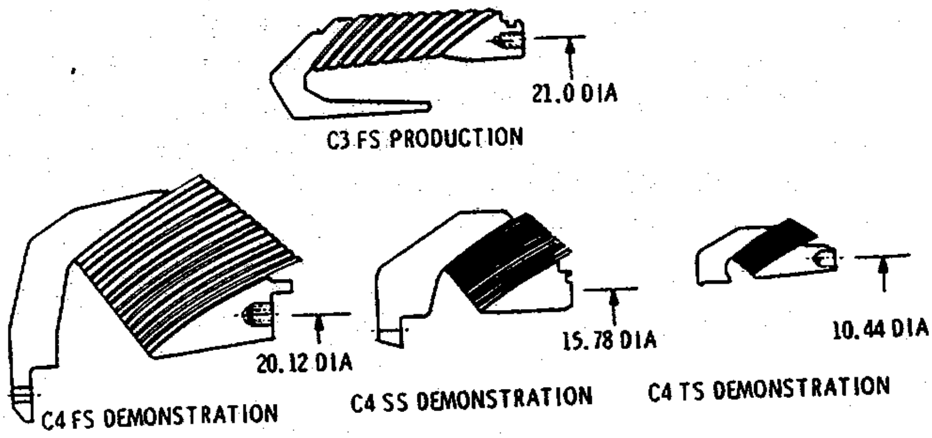
3. Historical survey/highlights

a. History of Solid Propulsion

The solid rocket propulsion is the oldest one. The use of black powder to propulse small incendiary rocket or fireworks was discovered by Chinese alchemists at the end of the first millennium, the first description of a weapon date of 1045 (“blazing arrow “); this knowledge migrate from china to India, then to Arabic countries and then to Europe , it was used many times(as examples use in Antioch by the Arabs in 1095, Joan of arc defends Orleans in 1428 using rockets). In 1660 Pascal explained and formulated the principle of rocket propulsion.
The 19th century is considered as the first “golden age” for solid rockets; in great britain under the leadership of William Congreve military rockets were improved using the technologies developed for fireworks; the rockets were used in all the battles till this era, but the major facts are that Nobel and Vielle established the basis to produce and use modern propellants instead of black powder.
Before the Second World War SRMs were based on extruded double base propellants and metallic case, so the calibre was limited and the grain shapes simple.
Today modern civilian solid motors are constituted of a filament wound case containing an aluminised HTPB composite propellant grain and a movable nozzle with a flexseal, their diameter don’t know real limitations; the USA were at the origin of this revolution with the california institute of technology.
The HERCULES Company (ATK now) developed the double base family with modern XDLB and NEPE propellants; for security and cost reasons these propellants are only used for military missiles even if their performances are slightly better than composite ones.
Aerojet, Thiokol and ARC developed a new type: composite propellant, it was discovered by John Parsons in 1942 (Asphalt/Potassium Perchlorate); all the three companies converged as binder to the use of a Polybutadiene (Carboxy or Hydroxylated) after having many propellants with other binders (PVC, Polyurethane, Polysulfures). The addition of aluminium to increase the performances was found by Arc during the 50s. As soon as 1962, large segmented boosters were produced (titan 3c).
Metallic case were progressively replaced for military applications by filament wound case, first using glass fiber, then kevlar and today carbon fibers; these last ones will allow cases being 2 or 3 times lighter than the best steel in the same conditions of pressure and internal volume. For civilian application, today only the Ariane 5 boosters use a metallic case.
For the nozzle , the need to control the stage leads first to use a configuration with four rotating nozzles, then for upper stages fluid injection; today only the flexseal technology is used for large boosters ; this technology was used for the first time in the USA on the Polaris a3 missile during the sixties.



EXAMPLE OF ROTATING MOVABLE NOZZLE USED ON DIAMANT'S SECOND STAGE



b. History of liquid propulsion

In 1898, a Russian schoolteacher, Konstantin Tsiolkovsky (1857-1935), proposed the idea of space exploration by rocket. In a report he published in 1903, Tsiolkovsky suggested the use of liquid propellants for rockets in order to achieve greater range.
Early in the 20th century, an American, Robert H. Goddard (1882-1945), conducted practical experiments in rocketry. While working on solid-propellant rockets, Goddard became convinced that a rocket could be propelled better by liquid fuel. No one had ever built a successful liquid-propellant rocket before. It was a much more difficult task than building solid-propellant rockets. Fuel and oxygen tanks, turbines, and combustion chambers would be needed. In spite of the difficulties, Goddard achieved the first successful flight with a liquid-propellant rocket on march 16, 1926. Fuelled by liquid oxygen and gasoline, the rocket flew for only two and a half seconds. Goddard's gasoline rocket was the forerunner of a whole new era in rocket flight.
The birth of the first industrial rocket occurs during the second World War: the German V2 with a LOX/alcohol engine (range 300km, thrust: 270kN)made its first flight in 1942, initially produced at 300 units per month initial, the rate was 900units per month in 1945

Nowadays, liquid propulsion relying on storable, LOX based or cryogenic propellants is a mature field and a core technology for most launchers in service.

LOX / hydrocarbons

LOX fed and turbopump fed engines were already tested before WW II. The first large thrust LOX / alcohol engine was flight tested on the A4 (V2) in 1942. The chamber pressure was still moderate and the development of large thrust engines was hampered by low frequency hydraulic instabilities or high frequency combustion instabilities in the case of storable and LOX-kerosene engines.

The regenerative cooling of a liquid propellant rocket engine was designed by the German scientist Eugen Saenger in the early 1930's. This discovery proved to be a vital asset for the development of all subsequent high-thrust rocket engines, beginning with that of Von Braun's A-4.
The alcohol was promptly replace by more energetic hydrocarbons from the kerosene family, storable fuels
The most known applications of LOX/kerosene are the first stage of the Saturn 5 launcher, the Soyuz

LOX/kerosene demonstrated the need of a deep knowledge on combustion instabilities, a big deal of work was first performed in Russia and the USA (Aerojet, Rocketdyne, Caltech) and after in Europe (Onera and SEP) and on other combinations . This contributed to the successful development of the propulsion of well known launchers, as Soyouz (RD 107 and RD 108), titan (LR 87), delta (RS 27), atlas, and Ariane 1 (Viking). These engines used the gas generator cycle.

Today, all the knowledge accumulated with LOX/kerosene is giving it a strong advantage over a cleaner and easier to use fuel: methane

LOX / Liquid Hydrogen

Tsiolkovski identified one century ago liquid hydrogen and liquid oxygen as the most promising propellant combination for rocket engines. The first drops of liquid hydrogen were obtained just a few years before in 1905. It took more than fifty years to see the first practical application of this combination to an upper stage (Centaur). In the mean time, large thrust engines, operating with storable propellants or with LOX hydrocarbons combinations, were already in use since the 50's.

In the 50's, nuclear thermal propulsion was extensively studied in the USA, consequently a better knowledge of hydrogen application for propulsion and of hydrogen based thermodynamic cycles became available. Combined with the development of liquid hydrogen fuelled turbojets, this favoured the start of cryogenic engines, first of all the rl10.
The early sixties showed the development of cryogenic engines in France (HM 4) and in Russia (RD 56 and RD 57).
In Japan, the first cryogenic engine (le-5) was developed in the 70's for upper stage application.

Storable propellants

Storable propellants were initially used during World War 2 on German rocket-plane and early air-launched missile propulsion systems that relied mostly on nitric acid/furalin.
This technology was later taken over by SEPR (France) and applied on their successful SEPR-844 engine that helped power the mirage 3 interceptors and became the world's only reusable rocket engine used on operational fighters.

In the United States, more powerful storable propellants were developed and used: Nitrogen Tetroxide, Aerozine 50, UDMH or MMH.
They led to the development of the titan family of missile propulsion and many spaceflight applications (satellites, space probes and manned vehicles). The titan i to iv was the workhorse launch vehicle for the air force for over 50 years, with lr87 first stage engine and lr91 second stage engine developed by Aerojet.
Storable propellant upper stage and spacecraft engines proved to be highly reliable and are still flown today. The Aerojet space shuttle OMS engine has successfully flown over 120 missions and the delta II upper stage (AJ10-118) engine has successfully flown over 200 flights.

In Europe, storable propellants were used on sounding rockets (Veronique and Vesta), on the Diamant launch-vehicle first stage engines Vexin (nitric acid/turpentine) and valois (NTO/UDMH). They were also implemented on the French-built second stage ("Coralie") of the Europa launch vehicle (pressure-fed stage).
In addition, SEPR initiated the development of a storable propulsion engine (NTO with a fuel consisting of 50% hydrazine and 50% UDMH) for the German-designed third stage ("Astris") of the European launch system "Europa".

The storable propellant technology has later on also been applied by EADS Astrium ST to the current Ariane 5 upper stage engine Aestus with NTO/MMH as propellant combination.

Another well known representative of the storable propellant family is the viking engine, developed by sep, which remains one of the most successfully produced rocket engines, with more than 1100 built (Ariane 1 to 4). Its uniqueness resides in its regulation system that relied on two regulators. First the main regulation which equalizes the chamber pressure to a reference value by "throttling" the flow to the gas generator, then a "balance regulation" that eliminates the influence of pumps efficiency or in-flight variations of pump inlet pressure on the mixture-ratio. Built under licence as the Vikas, it is still in use in India (PSLV and GSLV launchers).

Storable combinations are still widely used. Cleaner propellant combinations (e. G. Nitrous oxide – hydrocarbons) are tested at small scale to identify their potential.

Engine cycles

Subsequently to the early era of gas generator engines, the development of very high pressure engines was felt necessary for ascent stages and boosters: high pressure meant more compact engines with better average specific impulse resulting from both a much better seal level and in vacuum specific impulse.

Practically, this was only possible with a staged combustion engine. Incidentally, the staged combustion provides another advantage: as the turbine exhaust (either oxidiser rich or fuel rich) is gaseous, the main chamber combustion is consequently very stable (gas / liquid combustion).

Early staged combustion work was performed in Germany (MBB P111) and in Russia. Most Russian engines in use today are relying on this technology: RD 253 AND RD 275 (Proton) for UDMH/ NTO, RD 171, RD 180, RD 190 for LOX / kerosene (Zenith, Atlas 5, Angara).

In the late 60´s the Messerschmitt-Boelkow-Blohm gmbh (MBB) in Ottobrunn (Germany) developed an innovative technology which allowed the design of higher pressure combustion chambers. A copper inner wall with milled cooling channels was associated to a structural nickel jacket, the nickel shell being obtained by electro-deposition over the copper core. This break-through technology for high pressure combustion chambers was applied in the joint MBB / Rocketdyne LOX/lh2 project bord (1966 to 1968). Test results showed that adequate lh2 cooling could successfully be obtained at a nominal pressure of 210 bars (3,045 psia) and even at pressures as high as 286 bars (4,150 psia), the highest known pressure ever achieved for a LOX/LH2 rocket engine.

In Europe, this regenerative cooling technology was used for the HM7 on the third stage of the Ariane 1-4 launchers, and later for Vulcain and Vinci. The space shuttle main engine (SSME), developed by Rocketdyne, was the first staged combustion cryogenic engine used operationally that relied on this technology. The RD 0120 (CADB) and LE 7 (MHI) are the other representatives of this family of engines. In Europe, MBB and SEP studied a staged combustion cryogenic engine of 20 tons thrust for Europa 3 upper stage, using the same thrust chamber technology based on nickel electro-deposition, but this development was stopped. This project was also highly innovative with a single-shaft axially-mounted turbopump.

In Japan, this cooling technology was also applied to the open expander engine (LE-5B) in order to enhance the structural and operational margins, thus increasing engine reliability. LE-5B proved its robustness and reliability in actual flights of H-II and H-IIA.

The most recent commercial developments in large cryogenic engines were aimed at providing a high performance level at a reduced cost with an emphasis on robustness: RS 68 in USA, and Vulcain 2 in Europe as well as LE7A in Japan. Based on these criteria, the gas generator cycle was sometimes preferred to the closed cycle (RS68).

C. History of hybrid propulsion.

From its first introduction during the 30s by I. Andrussow with O.Lutz and W. Noeggerarth, tested a 10-kn hybrid using coal and gaseous nitrous oxide (work done for I.G.Farben)…………. To its use to win the Xprize

The early developments date back to the 1930s: the first recorded flight of a gird-09 on august 1933 was reported by Sergei Korolev and Mikhail Tikhonravov (180mm of diameter, 500n thrust, it reached an altitude of 1500m). The propellants were a gelled gasoline suspended on a metal mesh and self pressurized LOX.

In the mid 1940s the pacific rocket society tested LOX with wax/black carbon, rubber-based-fuel and also wood (douglas fir), the most successful and the last (?) Flight occurred in june 1951- xdf-23- using a rubber based fuel reaching an altitude of about 9km.
In the mid 1950s general electric, under the sponsorship of the army ordinance department, ran more than 300 tests on 90% hydrogen peroxide (catalytic decomposition) and polyethylene; the work demonstrate an easy throttling by means of a valve an a stable combustion but also a low burning rate that could not be varied significantly and practical problems to use hydrogen peroxide resulting of its inherent thermal instability.
In the same period, both the applied physics laboratory of the John Hopkins university, Thiokol and PSLV (CSD) experimented reverse hybrids with various oxidizers; this solution was quickly abandoned running into difficulties
In the mid-1960s, PSLV, sponsored by NASA, tested a FLOX (mixture 30/70 of liquid oxygen and liquid fluorine) associated with a solid made of PBAN loaded with Li and LiH. This combination is hypergolic. The motor was 1.07m of diameter with an eleven port wagon wheel grain; the specific impulse was about 380s for an area ratio of 40 (aviation week- 26 January 1970)

Between 1960 and 1980, the us developed target drones with 2 levels of thrust:
The sandpiper conceived by PSLV, using MON 25 and PMM/MG fuel (10%Mg), the first of the 6 flight occurred in January 1968,(combustion duration 300s, throttling ratio 8/1, horizontal flight up to 160km, launched from an aircraft)
The high altitude supersonic target (hast) using IRFNA fed by a turbopump and PMM/PB (20/80) fuel in a stacked cruciform grain (38 samples), thrust modulation was in a ratio of 10/1. While the sandpiper was expandable, the hast was recovered after flight; it used a CSD motor
The Firebolt target (with 40 samples) under development by Teledyne Ryan, manufactured by beach aircraft was a later version with a motor similar to the Hast. The Firebolt completed its evaluation period in 1984; however no production contract was ever given.

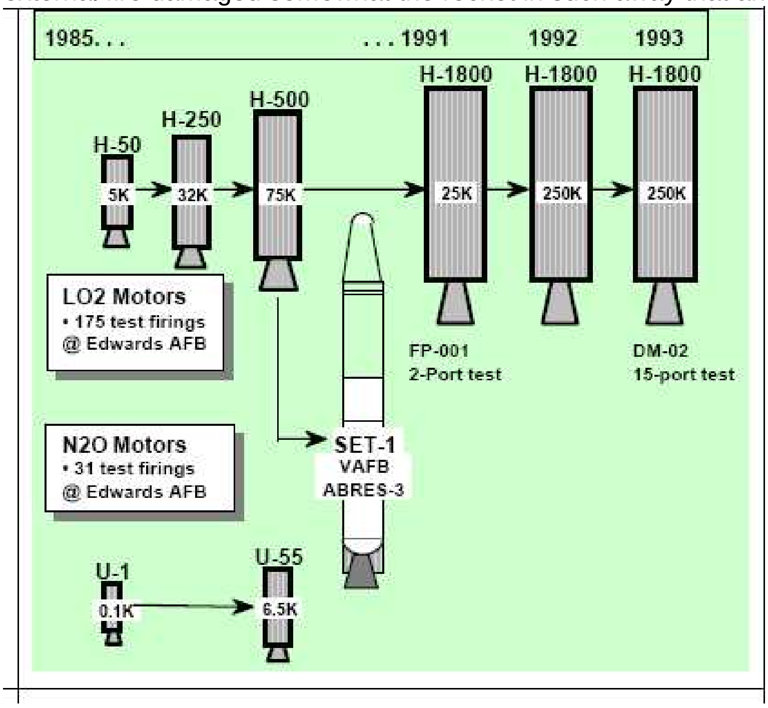
Table 1: performances capability for several fuel/oxidizer couples [1]

Performance of hybrid propellants				
Pc = 3.5 MPa and Pe = 0.1MPa (Sea level)				
Fuel	Oxidizer	Optimum O/F	Isp, s	c*, m/s
HTPB	LOX	1.9	280	1820
PMM(C5H8O2)	LOX	1.5	259	1661
HTPB	N20	7.1	247	1604
HTPB	N204	3.5	258	1663
HTPB	RFNA	4.3	247	1591
HTPB	FLOX(OF2)	3.3	314	2042
Li/LiH/HTPB	FLOX(OF2)	2.8	326	2118
PE	LOX	2.5	279	1791
PE	N20	8	247	1600
Paraffin	LOX	2.5	281	1804
Paraffin	N20	8	248	1606
Paraffin	N204	4	259	1667
HTPB/Al(40%)	LOX	1.1	274	1757
HTPB/Al(40%)	N20	3.5	252	1637
HTPB/Al(40%)	N204	1.7	261	1679
HTPB/Al(60%)	FLOX(OF2)	2.5	312	2006
Cellulose(C6H10O5)	GOX	1	247	1572
Carbon	Air	11.3	184	1224
Carbon	LOX	1.9	249	1599
Carbon	N2O	6.3	236	1522
Cryogenic hybrids				
Pentane(s)	LOX	2.7	279	1789
CH4(s)	LOX	3	291	1871
CH4(s)/Be(36%)	LOX	1.3	306	1918
NH3(s)/Be(36%)	LOX	0.47	307	1967
Reverse hybrids				
JP-4	AN	17	216	1418
JP-4	AP	9.1	235	1526
JP-4	NP	3.6	259	1669

Note: JP-4 is kerosene and nearly all of these combinations of the table have been tested at least at laboratory scale.

After 1995, there were 2 significant sounding rockets programs in the USA:
The Hyperion using N2O and HTPB (4 flights, the last in 1997),
Lockheed martin flew in 2002 a larger one using LOX/HTPB with an initial thrust of 267kn.

In Europe, Onera developed the lex sounding rocket with 8 successful flight between 1964 and 1967 - Mon 40/NMTD (metatoluene diamine/nylon) – reaching an altitude in excess of 100km and then with SEP (snecma today) and nord aviation ((Astrium Space Transportation today) a biggest version-the Spal 30- for a drone (no in-flight test). The formulations have shown a relatively high burning rate and the propulsion system a very good overall efficiency. In Sweden, Volvo in-flight tested (1965) 2 hr-3 sounding rockets (IRFNA and PB/aromatic amines), formulation very close to those of Onera [6].
More recently, NAMMO Raufoss conducted a static firing of their first full-scale hybrid motor, a part of the Norwegian sounding rocket (NSR). (30kn thrust, 200kg of LOX), this development is leaded with in cooperation with Lockheed Martin (LM) Michoud operations, New Orleans, USA.
The large scale hybrids were tested only in the USA. First PSLV with the HTM series motors in the 1960s under the US air force funding, tested a NTO and aluminized PB as the fuel (97cm in diameter; 180kn thrust)
The company Starstruck was created in 1981 to develop a large sounding rocket, the dolphin, using LOX/PB and weighting about 8 tons; after 6 ground tests, a flight was a failure (1984). The company was reorganized and named AMROC, AMROC was an entirely private funded company. During the period 1985-1993, 139 motors of different sizes were built and 240 firings were performed, mainly with LOX/HTPB, between 20 and 1100kn with a new flight failure in 1989, set-1.a stuck valve by frozen humidity prevented the reaching of the thrust and after shut-down an external fire damaged somewhat the rocket in such away that another launch became impossible.



AMROC test history [1]

In 1990-1993 AMROC mainly carried the design of Aquila, a small launch vehicle (900kg on a LEO); this development was based on the h-250k, a hybrid motor LOX/PB of 1000kn of thrust
The hybrid technology option project (Hytop) including AMROC, CSD and Martin Marietta took the relay (large motors tested in 1993 and 1994 with low frequency instabilities problems) to demonstrate the low cost development of hybrid propulsion; in 1995, AMROC lost its sponsors, the cost to solve the problems was too high and ceased its activities . AMROC was bought by the Spacedev society in 1998
Nevertheless a new program hybrid demonstration program (HPDP) with Thiokol replacing AMROC was initiated. Configurations are still based on LOX/HTPB, wagon wheels grain solutions. 4 tests of a 1.1 MN thrust motor were performed with a lot of combustion issues.

AMROC, even if it was not successful, have demonstrated the capacity of hybrid motors to be extinguished and reignited, the safety and the non explosive nature of hybrid.
“in summary, more than 15 years from the mid 1980s to the early 2000s were spent in development of large hybrids by three organizations, Starstruck, AMROC and the consortium mentioned above. All these programs were based on the LOX-HTPB propellants because of cost, good physical properties and performances. The major problem encountered by all these groups was combustion stability when scaled to larger sizes. [3]

Lockheed Martin HYSR project: a large-scale hybrid rocket was successfully launched from the NASA WFF on 18 December 2002 as a technology demonstration for hybrid propulsion and related subsystems. The HYSR program started in 1999. The overall goal of the program .was to develop a single-stage propulsion system capable of replacing existing two and three-stage sounding rockets, the hybrid rocket had a propellant combination of LOX and HTPB and produced approximately 60,000 lb of vacuum thrust. The three-year technology demonstration program was a collaborative effort between NASA and Lockheed Martin

Scaled composites: spaceship one: the Ansari Xprize was a contest with a 10 million reward for the first commercial company to get 3 people to 62 n miles high and repeat within 2 weeks composites built a two-stage airplane to win the prize with the second powered by a N2O/HTPB hybrid rocket with a 80s maximum burn. N2O was self pressurized
The in-flight use of a N2O/HTPB motor by Rutan on the spaceship one to win the x prize closed happily the US hybrid history (even if it experienced some combustion instabilities). The history will continue with a larger vehicle the spaceship 2

Figure 1 : space ship 2 overview credit: virgin galactic

4. Existing Launchers Improvements and Development of New Families

Today are planned a certain numbers of improvements of existing launchers and the development of new families: all are using state of the art technologies (with the help of international cooperation in some cases) Moreover, if possible t, using existing stages as they are or extended, and every time trying to create a family with a limited number of stages ; this way is sometimes called “the Building Block Launcher” solution Interest in a building block launcher (BBL) is easy to understand e.g. limited development time and low risk and costs. However, this interest is conditioned by launcher suitability for a required mission.

Ariane 5 improvements

The three stages A5 launch vehicle uses as first stage two large Solid Rocket Boosters operating in parallel with the LOX/LH2 central core. The two large boosters have a metallic case resulting of a design made during the seventies.

A5 mid-evolution (ME) could be operational at the end of the next decade (2018) if the decision to develop is decided favourably by 12/2011.

Since this solution will fully optimize Ariane 5's staging for the upper stage with a new cryogenic upper stage using the VINCI , an expender engine today underdevelopment . Improved performance would then require modification of Ariane's lower stage and studies have created interest for these improvements. The “P80”, Vega's current first stage, was initially a solid rocket booster demonstrator focused on monolithic composite case, electrical actuators, low couple nozzle, etc. Therefore, P80 was a demonstrator of a possible MPS evolution e.g. MPS2—successfully static tested in 2006 and 2007 in French Guyana.

There are multiple MPS2 projects and they offer a wide range of evolutions. Relative to performance, the composite case alone offers a mass reduction that exceeds 40%.

The performance of SR boosters, even when the basic design is fixed, can be enhanced by processing improvements that include continuous propellant mixing, reduced pyrotechnic mass, application of “classical” industrial means, and detailed simulations that optimize their impacts. Therefore, these aspects will be considered.

Vega launcher improvements

Vega is three SRMs stages with a liquid upper stage (AVUM) Vega's expected maiden flight date is 2010. However, since its actual performance near 1.5 t is low, different evolutions are under study to improve performance. Among these evolutions, one would increase the P80 first stage (88 t of propellant) to the P100's 100 t of propellant at constant diameter or extend the Z23 solid rocket motor (24 t of propellant) to the Z40 (40 t of propellant) by a diameter change from 1.9 to 2.6 m.

H-II improvements

Among Japan launch vehicles, the H-IIA has been supporting satellite launch missions as a major large-scale launch vehicle with superb reliability.

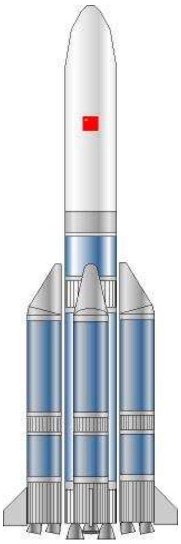
The H-IIB launch vehicle is an upgraded version of the current H-IIA's launch capacity and is expected to enable future missions that include cargo transport to the International Space Station (ISS) and to the Moon.

The H-IIB launch vehicle has two major functions. One is to launch the H-II Transfer Vehicle (HTV) to the ISS. The HTV will carry necessary daily commodities for the crew astronauts and experimental devices, samples, spare parts, and other necessary research items for the ISS. The other major function is to respond to broader launch needs through adroit utilization of H-IIA and H-IIB launch vehicles in concert. Moreover, H-IIB's larger launch capacity enables simultaneous launches of multiple satellites per mission thereby significantly reducing satellite launch costs. These advances will enhance the Japanese space industry's vitality (Fig. 1).

The H-IIB launch vehicle is a two-stage rocket that employs two liquid rocket engines (LE-7A) in the first-stage (one for the H-IIA) and four strap-on solid rocket boosters (SRBA) grained with hydroxyl terminated

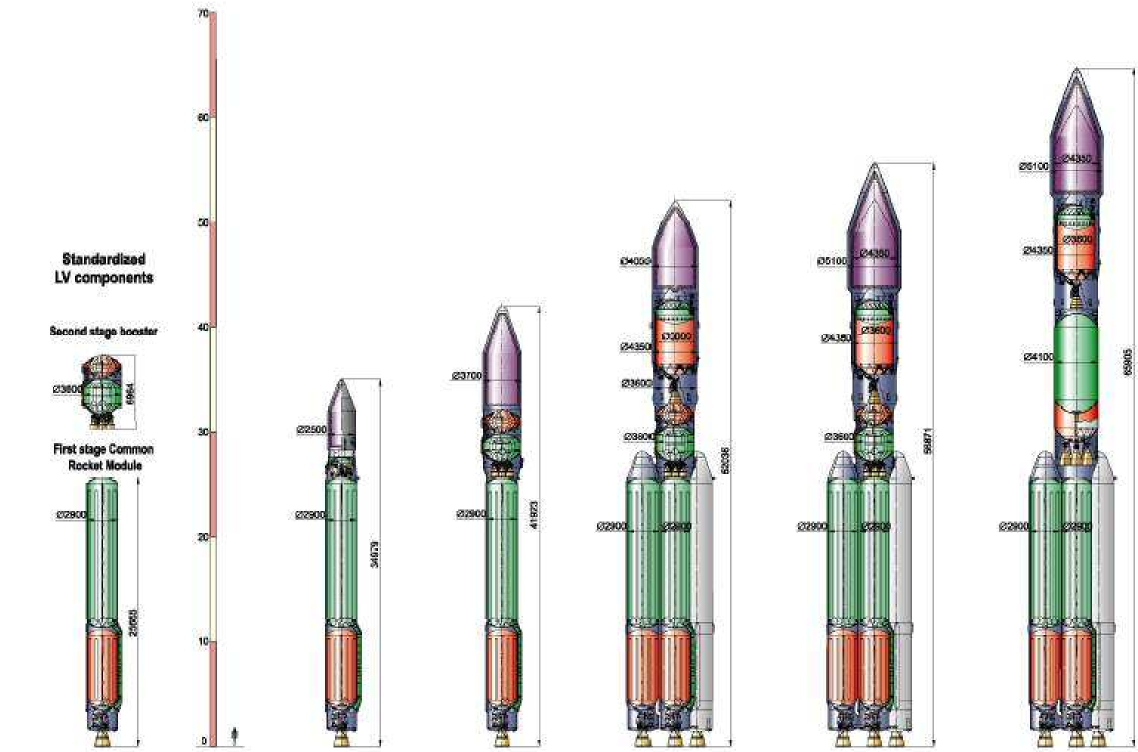
polybutadiene (HTPB) propellant (the standard H-IIA has two SRB-A strap-ons). In addition, the H-IIB's first-stage body has been expanded to a diameter of 5.2m (4m for the H-II). It also extends the first stage's total length by 1m from the H-IIA's. As a result of these enhancements, the H-IIB loads 1.7 times more propellant than the standard H-IIA.
The H-IIA, H-IIB development strategy of clustering engines of demonstrated reliability reduces development time and cost without performance penalties.
H-IIB development began FY2003 and the first launch occurred FY2009.

New Generation of Chinese launch vehicles



The current Chinese technology used on the Long March family is mainly based on not green propellant and with relatively low performances NTO/UDMH .So, R&D is made in the aim to develop Launchers able to deliver 20tons on LEO and 10 tons on GTO
This new generation will use for the lower stages two " clean "engines under development : one 1200 kN of thrust LOX/Kerosene (Sage combustio), one 500kN LOX/LH2
Using the « BBL » logic, Two families will be created , using three basic modules of respective diameters 5m, 3.35m and 2.25m.
This chosen way illustrate a dilemma for the choice between LOX/KEROSENE or LOX/METHANE when developing a new technology: even if LOX/Methane appears as a very promising technology both for the performance than for the easiness of the development, LOX/KEROSENE was widely used as well in the USA and in the former URSS and so a great amount of knowledge is available.

New Generation of Russian ANGARA



The new ANGARA family will replace toxic hypergolic propellants with less hazardous, less polluting staged combustion kerosene and liquid oxygen (LOX) propulsion.
Angara's first stage will be built around basic "Universal Rocket Module" (URM) building blocks, with each block powered by a single-chamber 196 tonne thrust RD-191 LOX/kerosene engine.

RD-191 is derived from the four-chamber Energomash RD-171 engine that powers the Zenit launcher.
The smallest Angara variants (Angara 1.1 and Angara 1.2) will use one URM. The most powerful variant, Angara 5, will use a cluster of five URMs, A medium Angara 3 launcher using three URMs. . A 30 tonne thrust LOX/kerosene RD-0124 engine will power the second stage of all but the smallest Angara version. This staged-combustion engine has already been developed to power the upgraded Soyuz-2 third stage. Briz-KM, developed for use on Rokot, will serve as the Angara 1.1 second stage and as the third stage for Angara 1.2. The Briz-M stage previously developed to fly atop Proton-M boosters will serve as the upper stage for the Angara 3 and 5 vehicles. .
Future plans call for development of liquid hydrogen fueled "KVRB" upper stage for Angara 5. This stage would be powered by a single 10.5 tonne thrust KVD1M3 engine with a 461 sec specific impulse.
Payload capabilities will extend from 2 metric tons (tonnes) to a 200 km x 63 deg low earth orbit (LEO) for Angara 1.1 to 24.5 tonnes for Angara 5 when launched from Plesetsk. Angara 5 will be able to boost 5.4 tonnes to geosynchronous transfer orbit (GTO) from Plesetsk with a Briz M upper stage. Use of the KVRB stage would improve GTO performance to 6.6 tonnes.

ARES I and ARES 5 in USA

A perfect example of a BBL approach is the Ares I and Ares 5 launch vehicle in the USA. For the next launchers for the Constellation program, it was decided to use existing propulsive technologies, and in this frame the RSRM is the basis for the Ares 1 first stage, and the Ares 5 boosters (coupled with a five (or six) RS68 large cryogenic stage).
Compared to existing RSRM, several motor design modifications are required to meet Ares 1 requirements and in particular: ballistic performance, operability improvements, enhanced reliability, regulatory compliance, and replacement of obsolete materials and processes:

- design features in the motor,
- propellant grain (one additional segment, grain shape and propellant burn rate evolution to meet thrust and pressure laws requirements, . . .),
- nozzle throat and exit cone designs modifications,
- and replacement of materials used in the manufacture of the internal insulation, the case bond liner, and the O-rings used to seal the joints between motor segment (use of asbestos free material, new lower-temperature materials in the O-rings, . . .).

To validate them, the new materials and processes will be first applied on subscale specimen or RSRM for ground tests. Then four DM tests are planed for the design validation (Fig. 2).

Fig. 2. Ares launch vehicles.

Prospective Studies in Europe
In Europe the BBL approach has been studied for two main reasons: elaboration of a complementary launcher (for Ariane 5) and replacement of Ariane 5 to better fit a different market (definition of a single payload launcher for GTO, called 1/2 Ariane 5).
Five (5) stages developed for Ariane 5 are available:
• EAP boosters (240 t of solid propellant, metallic casing),
• Core stage EPC (170 t of cryo-propellant) with Vulcain 2 engine (135t thrust),
• Storable upper stage EPS (10 t of NTO/MMH propellant) with Aestus engine (3 t),
• Cryogenic upper stage ESCA (14 t of cryo-propellant) with HM7 (7 t of thrust) engine derived from Ariane 4, and
• Vinci demonstrator fit for a future high performance upper stage (18 t of thrust).
In addition, Vega's development brings additional stages:
• The P80, partially an EAP demonstrator for advanced boosters, and the first stage of Vega (88 t of solid propellant, filament wound (FW) casing).
• The Zefiro 23 and Zefiro 9 (24 and 10 t of solid propellant).

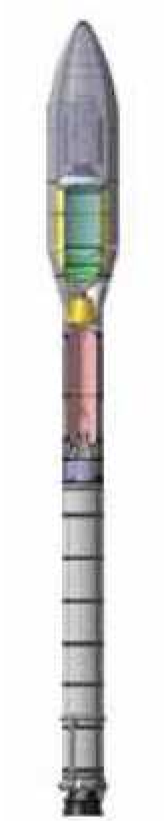


Figure 4 BBL - Solid version (Astrium ST)

In the BBL approach, several solutions have been compared: small Ariane 5 with replacement of the EAP by P80,2-stage configuration with double Vulcain, etc. The simpler, more cost effective solution has always been the “Solid BBL”, three stages, composed with an EAP (P240) as first stage, a P80 as second stage, and an upper cryogenic stage (Fig. 3).

In studies paralleling the above, designs to reach 5 t without supplementary booster(s) and 8 t (for max commercial payload) by adding SRBs have been examined. Numerous practical solutions exist e.g.
• Re-use existing projects to increase the performance of the building blocks P240 and P80.
• Add small boosters to the first stage.
• Derive the building blocks and optimize them for the BBL, even if A5 compatibility is lost (if it is a replacement launcher there is no need to maintain compatibility)
(Fig. 4).

Future heavy launchers
Different concepts are considered: liquid stages, reuse of four A5 SRM . . . In each configuration, solid rocket boosters may be employed. An original design is composed of a big SR first stage. Simulations have always shown this configuration presents a recurring cost increase when compared with hydrogen or methane configurations. Therefore, the goal here is to reduce development costs (prohibitive for a huge monolithic stage) by exploiting either innovative technologies and production processes or an intermediate building block configuration (reuse existing production facilities and slowly modify and optimize building blocks to reach requirements
by either retaining a three stage configuration or introducing a two stage using multiple segment boosters). A 3-segment filament wound booster with 435 t of propellant would be equivalent in performance to an optimized 370 t monolithic booster.

Small launch vehicle (Japan)
Scientific missions using small satellites are being proposed for the next several years. Their functions include space observation, Earth monitoring, and lunar and planetary exploration. Moreover, applications that reinforce technical foundations by demonstrating components, spacecraft, design for flight capabilities, etc. are of interest. These missions require a variety of orbits: low-Earth, polar, highly elliptical, and transfer for lunar and planetary missions. Therefore, a versatile launcher with these capabilities is desirable and an all solid system's mission capabilities simplicity, readiness, and cost effectiveness recommend it over liquid and mixed mode systems. Consequently, a new solid rocket launch vehicle designed to realize various missions with frequent, timely, short lead-time launches at low-cost is being considered in Japan. An important aspect of this vehicle's development is to maintain and improve solid rocket and related technologies.

Japanese system technology has been fostered through solid rocket developments from the 1955 pencil rocket to the present M-V launch vehicle. Moreover, this system technology covers the vehicles' entire life-cycle e.g. design, manufacture, integration, assembly, and launch operations. This *total* system viewpoint is necessary to achieve cost-effective, highly reliable, and optimally performing solid rocket system technologies of the future. Moreover, this approach strengthens the solid propulsion community's fundamental technology bases as well as develops solid rocket motors for sub-booster, first stages, upper stages, niche application, etc. and all solid vehicles for many applications

Currently, the new all solid launch vehicle has three stages and can launch a satellite weighing 1.2 t into LEO and 0.6 t into the transfer orbit to SSO. The first stage of the rocket is the SRB-A employed as sub-booster of Japan's flagship launch vehicle H-IIA. Although the SRB-A's thrust is low for this new first-stage application, it is extremely cost efficient.

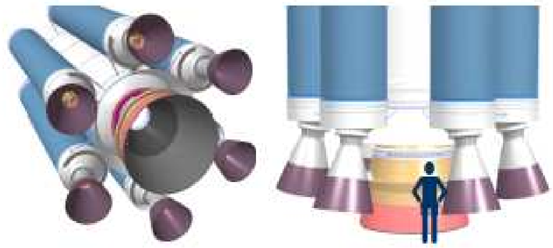


Figure 5 BBL with 6 strap on boosters (P30) (Snecma)

In contrast, the launch vehicle's upper stage motors are new designs based on the M-V's upper-stage-motors.

To achieve high-performance and low-cost simultaneously, each stage's size and performance is optimized to maximize the orbiting satellite's mass. Fig. 6 presents an artist's image of the new all solid launcher: it is about 24m high, 2.5m diameter, and weighs about 91 t.

Figure 6 Japan Small launch vehicle

From viewpoints of responsiveness and operability, manufacturing and preparation time should be minimized within adequacy constraints. Ideas to realize this include improving launch operation efficiency for rocket assembly and checkups with compact ground inspection and test facilities.

The key to this concept is avionics as well as a newly designed rocket structure that enables easy rocket operations.

For the new rocket, networked avionics and a more “intelligent” rocket will enable autonomous checkups prior to launch. In future extensions with avionics of enhanced “intelligence,” it is expected that launch control can be drastically simplified.

Currently, micro-satellites that weigh less than 100 kg are launched as piggy-back payloads. In this approach opportunities and launch windows are strictly limited because their launch priority is very low. Therefore, it is currently difficult to place micro-satellites in their ideal orbits. Consequently, availability of a small, low-cost solid launch vehicle to launch micro-satellites is desirable. Moreover, air launching or sea based launching enhances orbit flexibility and responsiveness.

Furthermore, the simplicity of ground equipment required for launch operation identifies a solid rocket system as an excellent candidate.

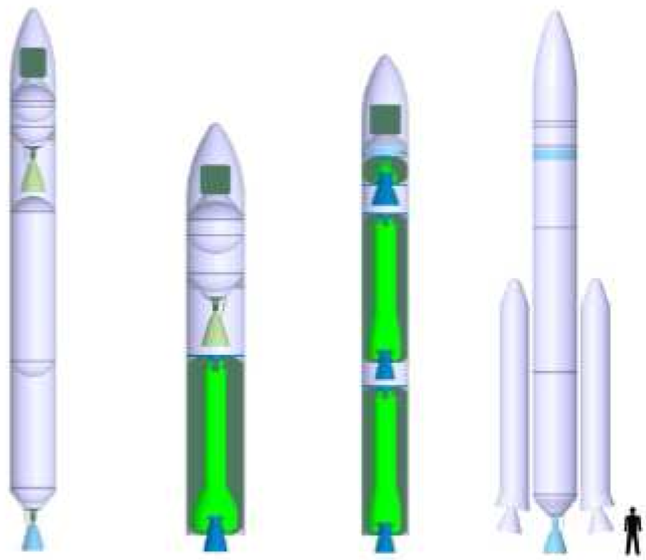


Figure 7 Comparison of micro launchers

Airborne micro-launchers

Analyses of classical micro-launchers' inadequacies found three key reasons: program organization, scale effects, and ground installations (including launch pad). Therefore, airborne

Figure 8 MLA Trimaran (Snecma & Dassault Aviation)

launchers with reduced ground dependencies have additional performance potentials e.g. • Significant initial velocity (≈ 150–200 m/s for most cases; with supersonic aircraft 300–800 m/s).

• Reduced gravity losses when altitude of separation from aircraft is large.

• Improved nozzle performance because atmospheric pressure at separation from aircraft>1 bar enabling increased nozzle expansion ratio.

• Reduced losses from safety concerns i.e. flight launch over uncritical areas, etc.

• Reduced ground environment impacts.

. Landers, Jettison motors

For exploration missions (Mars or Moon insertion; soft landing; ascent vehicle) liquid propulsion seems to be more suitable due to versatility and adaptability. However solid propulsion may be used, with a combination with attitude control system (ACS) if needed. The main advantage for this technology is simplicity, superb storability, energy density and high thrust capability. Thrust magnitude control, limitation of scatterings, etc. would enhance its potentials.

NASA's Vision for Space Exploration has multiple solid propulsion elements that are currently in production. Aerojet has completed two successful hot fire demonstrations of the full scale Orion Jettison Motor that is being designed to separate the spacecraft's launch abort system from the crew module during launch. These demonstration tests serve as pathfinders for the delivery of the rocket motor that will be used for the first full-scale test of the launch abort system at the US Army's White Sands Missile Range in New Mexico (Fig. 7).

In addition to the work being performed on the Orion Launch Abort System and ARES I and V launch vehicle, the NASA Constellation program has multiple opportunities for solid rocket motor developments within the next several years.

5. Current status and roadmap

a. Solid propulsion:

i. General

Current status

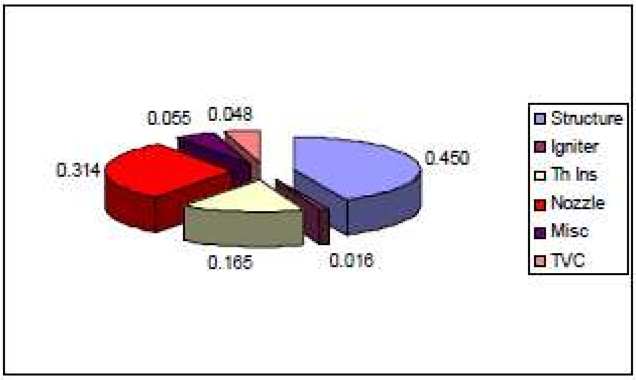
Most existing and “in development” launchers employ SRM (Table 2). Moreover, their solid rockets' technologies are effectively identical and improvements have conformed to Roadmap2000 [1].

Table 2
SRM boosted launch vehicles in the world.

Status	Country/launchers
Existing or ongoing development	USA: STS, Delta IV, Atlas V, Delta II, Taurus, Minotaur I, Pegasus XL Europe: Ariane 5, Vega Japan: H-IIA, H-IIB Others: Start-1, CZ-2C/SD, KT-1, GSLV, PSLV, Shavit-2, Shavit-1, VLS-1, TPD-1
Next launchers mid-term (2020)	USA: Ares I, Ares V, Minotaur IV Japan: small launcher Others: GSLV-MkIII

Launch vehicle sensitivity analysis- *Composite material strength*

The Tsiokolvsky equation $\Delta V = g0Isv\ \ln(Mi/Mf)$ reveals launch vehicle velocity increment ΔV depends on a stage's dead mass *Mi* and its propellant's delivered specific impulse *Isv*. Therefore, since advanced solid rocket motor technologies have converged on filament wound cases, movable(flex-seal) nozzle(s), and HTPB propellants, their domain of application is limited to small launch vehicles, strap-on boosters, and niches. For these applications their structural index and their ability to deliver high thrust at low total cost provide a decisive advantage relative to classical liquid rockets. Composite filament cases, successfully employed in applications for more than 40 years, have created a small revolution in SRM design e.g. the case's performance criterion pressure x internal volume/solid propellant case mass for a composite case is 5 times a metallic one's. Consequently, since this enables increased operational pressure, *Mi* (case mass) reduction is synergistically combined with increased *Isv* per the Tsiokolvsky equation above. An EADS (Astrium today) [3] study, whose results are tabulated below (Table 3), reveals the performance increase associated with composite cases.
With these tabular values, the Ariane 5 ECB version's performance gain is □30%. Consequently, new launch vehicles should naturally migrate toward high strength composite cases.



The Fig. 8 presents a typical mass breakdown for a SRM (90 t class) with a filament (carbon of medium performances) wound case. Therefore, three major potentials exist that can significantly reduce inert mass *Mi*: (i) market availability of higher strength fibers i.e. carbon reinforced nanotubes, (ii) availability of lower density insulations, and (iii) minimizing internal thermal protection demands via improved processing, grain regression simulation, and optimization.
For example, the Vega Launcher with fiber strength increased by a factor of 3 would save 1600 kg on the first stage, 400 on the second, and 320 on the third for a 23% *increase of payload mass*.

b. CASING:

In a solid rocket motor, the casing is devoted not only to contain the pressure of the combustion chamber but also to carry the general loads delivered by the motor to t the launcher. For this latter function, in addition to static loads, additional constraints often come from the dynamic behavior of the launcher itself where the case stiffness is most of time an important parameter.
A segmented case is mandatory when the propellant grain is too large to be cast in one shot (monolithic propellant grain). At the time being, 100 to 150 metric tons grains are commonly cast,

meaning internal volumes in the range of 100 m^3. It would be possible to manufacture larger cases if necessary, but this choice is most of time resulting from constraints on the casting process.
The main drawbacks of segmentation are the mass and cost penalties coming from the inter-segment joining:
- when the case material is metallic, these penalties are limited but not negligible due to the extra thicknesses and working hours coming from the mounting flanges. Clevis/tang or simple bolted flange assembly designs are commonly used.
- when the case material is composite, these penalties are high due to the need of an intermediate metallic frame between the composite cylindrical part and the joining interface. So, the effective joining is performed on the metallic frame[i] .

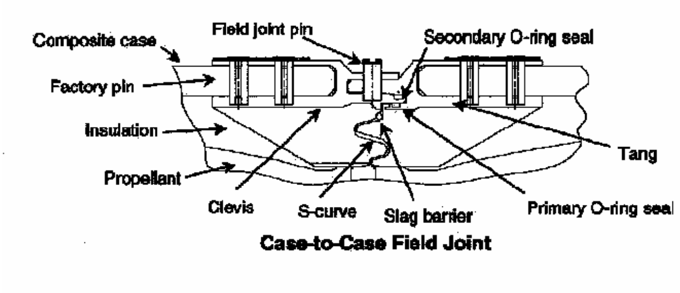


Figure 2 view of SRMU inter-segment joining principle

From designer standpoint, solid rocket motor cases can be made either from metallic or composite material. Nevertheless metals are less and less used for the pressure vessel function, being replaced in modern SRM by the lighter composites. No expected breakthrough in specific rupture strength of metallic materials could reverse this trend. The main advantage of metallic cases is their reusability (overthicknesses have to be introduced in the design and so production/recovery/refurbishment costs have to be cost effective versus an expandable version).

As illustrated by three examples on following launchers - delta 2, titan and h2 – the metallic cases of solid rocket motors have been turned to composite since the 90's. This trend was confirmed also for the commercial eelv atlas 5 and delta 4 whose architecture are based on cluster of large strap-on boosters (overall mass in the range of 30 to 40 tons of propellant) designed with composite case. In Europe, the p80 fw demonstrator has been developed with the objective to prepare a new generation of large solid rocket motors with composite case. Also, in Japan the muv second stage (m23) has recently evolved from a steel case to a carbon case. Even for the shuttle system an upgrade version with filament wound motor was under development in the mid 80's before the challenger accident: two motors were successfully fired at test bench. Nowadays, for ares 1 the risk limitation benefiting from the 'heritage' principle stimulates to stay using a 5 segment rSRM motor, keeping unchanged the metallic case. Nevertheless, for the ares 5, an alternate design with composite case is officially retained by NASA as growth potential.

Composite versus metallic: cost & process

From cost and process standpoint, the situation of metallic hardware seems on an asymptotic evolution while composite costs may still be reduced. The overall performance-to-price ratio of the carbon fibers is still increasing. Efficient carbon fibers are right now available at competitive prices and future decreases are predicted. From manufacturing process, the filament winding techniques are now mature and several new processes could bring cost reduction such as, for example, infusion of dry preform or thermoplastics prepreg.
For the two design options, there is no real limitation in term of sizes, neither diameter nor length. In the 60's, a 260 in steel case has been successfully manufactured by Aerojet; nowadays large dimensions are not a practical limitation for composite materials as illustrated by the recent development of very large airplane structures (e.g.: boeing 787 full barrel airframe).
Non destructive control techniques are now mature to detect defects in both metallic and composite cases.

Composite versus metallic: design & performance

A comprehensive analysis of the optimization has been carried in roadmap2000Erreur ! Signet non défini.. For composite cases, carbon fibers for a monolithic fw booster lead to a pv/mg performance factor (pressure x volu compared with 30 km for Kevlar and 20 k :arbon structures lead to large gains in str el.

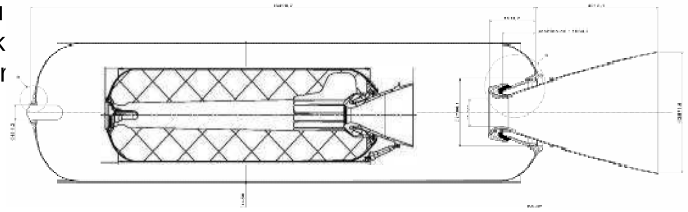


Figure 3 Comparison views of the P80 motor and P425 Project

From pure material perspective, fw carbon/epoxy material exhibits huge advantage of over steel, but it is necessary to take into account important mass penalties such as joining zone with metallic interfaces (igniter, nozzle, launcher attachments…) or specific stiffness requirements (propellant Bonding, limitation in axial motor elongation or bending…). For large SRM, compared to high strength steel technology, the resulting case overall mass is more or less divided by two with fw carbon/epoxy technology. For an upper stage, this advantage is very important but even for lower stage this can lead to a significant improvement on the payload capability.

The internal and external interfaces are easily manageable with metallic cases. For composite design, polar boss to roving joining and skirts to roving joining, even if they remain always difficult points, .are now mastered technologies.
Currently, with high strength carbon fibers, withstanding the pressure is not the design key driver and thus it cannot be practically foreseen large additional gain with stronger fibers. Current case design is more and more constrained by stiffness requirements and/or thrust transmission through the skirts: further mass reductions will therefore be very limited.
The increased specific strength capability of composite motor casing leads to higher optimum pressure than with metallic casing. Typically the optimum pressure for metallic case is in the range of 6-7 MPa. With FW carbon fiber composite, this optimum value is increased up to 8-9 MPa for segmented case and 9-10 MPa for monolithic case.

Case design	Range of Pressure	International SRM examples
Metallic	60 to 70 bar	RSRM, MPS,
Segmented composite	80 to 90 bar	SRMU
Monolithic composite	90 to 110 bar	Castor 120, SRB-a, P80

Table 3- optimum pressure versus case design parameter

For a stage operating at ground level with a limited diameter of the exit cone, increasing the combustion pressure is the only way to increase significantly the specific impulse: this is of paramount importance for the overall launcher performance. For the Ariane v mps, with the same outlet cross-section of 3 m, a 3 MPa pressure increase would lead to an Isp gain of about 10 s, thus to a payload gain of nearly 10%.

The increase of the maximum pressure leads to increase the mass of the case; which is more sensible when the booster has several segments. In a filament-wound structure, the extra-weight of a full-diameter inter-segment connection is very penalizing and it is necessary to minimize the number of connections in order to draw the best advantage from the reduction in mass due to fw carbon structures. The optimum combustion pressure will result from a thorough analysis taking into account the technology and the practical constraints of the booster (it will be necessarily lower than in a monolithic booster: for Castor 120 it is 10MPa and 8 MPa for TITAN IVB).

General trends & potential breakthrough

The main trend seems to be to design light cases with composite materials and to open the possibility of monolithic motor design with very large dimensions, as illustrated by the p80 recent development. For example a preliminary project of a 425 tons monolithic motor was performed in France underlining that no show-stoppers were existing for the case itself[ii] (see ref. Case 3 and fig. Case2). The following table gives some comparison on such a case sizes versus p80 case showing that the extrapolation is not so huge.

Motor	P80 case	P425 project	Size factor
Case diameter	3 m	4.5 m	1.5
Case length	9 m	18 m	2.0

If for casting constraints segmentation is still mandatory, one of the big potential improvements that could appear within some years is a full composite inter-segment joining without any metallic parts. As an example we can underline the potential of in-situ wrapping of thermoplastic composite tape to build up such a joining. Of course the joining would not be dismountable but there is no real need of this function.

New fibers incorporating nanocarbon fibers begins to appears on the market, if the production and winding of these fibers are mastered, a new breakthrough will appears resulting of their very high ultimate strength; nevertheless to take the full benefit of these fibers will need to be able to increase the MEOP keeping the same range of combustion time, so improvements of throat material (ablation behaviour) and development of lower burning rate/lower erosive propellant could be useful

	Aluminum	**Carbon Fibers**	**Carbon Nanotubes**
Density	**2.7**	**1.8**	**1.4**
Young Modulus (Gpa) (axial stifness)	**70**	**200 – 800**	**1000 - 1500**
Poisson Modulus (Gpa) (transverse stifness)	**26**	**100 – 300**	**Very low**
Ultimate Stress (Gpa) (traction)		**2 - 7**	**10 – 50**
Ultimate Strain (%)		**0.4 – 2**	**20**

NOZZLES

This section treats a solid rocket motor nozzle's main functions: converting the combustion chamber's chemical energy deposition into thrust and adroitly vectoring this thrust for vehicle guidance and control. Since the nozzle's function is to convert hot, high pressure products of the propellants' chemical reactions to directional thrust by acceleration the products through a converging-throat-diverging geometry, the nozzle's internal surfaces are subjected to a very harsh environment: hot gases and liquid/solid phase alumina. At this time there is no material that can withstand this environment throughout the motor burn without erosion/ablation and surface recession. Since convective heating typically reaches a relative maximum at the throat, heat resistant materials e.g. Carbon-carbon composite (c/c) thermo-structures, graphite, and graphite phenolic composite materials – are employed. For the exit cone's diverging geometry, where heating is reduced, ablative materials e.g. Carbon fiber reinforced plastic (CFRP) or silica fiber reinforced plastic are employed.

Thermo-structural composite materials

3d needled or braided and 4d reinforcement are available for carbon/carbon throat elements and its "nose" when required by the nozzle design and its aero-thermal flow field. Fig v presents a nozzle entrance/throat with c/c nose and throat. C/c material densities ranging from 1.65 to 1.9gm/cc (resistance to ablation and cost increase with density) can be selected. In the future, very high temperature metallic or ceramic coatings and carbon nano-tube reinforcement (or fillers) will be investigated.

Figure 4 view of c/c nose and throat parts (SPS)

Because recession rate differs for c/c and CFRP materials, wetted surface discontinuities (steps) can form at material interfaces during motor operation. The backward step that forms after the c/c throat disturbs the subsequent flowfield and can lead to a downstream surface groove and ultimately failure (these phenomena are particularly significant in high-pressure motors). Therefore, skillful contour design and material selection are necessary. Computational fluid dynamic (cfd) calculations fully coupled to models of the materials it is constructed from are employed to optimize contour and materials to minimize deleterious effects while maximizing thrust.

For a solid motor of short duration, a ceramic matrix composite (CMC) nozzle can be a candidate. CMC nozzle are manufactured from carbon and carbon-silicon fibers with a carbon-silicon matrix: a heat resistant structural material with low thermal conductivity.

Figure 5 view of a CMC combustion chamber and exit cone (ihi aerospace)

carbon/carbon structures present an alternative and fig. 13 presents a c/c exit cone. The ius orbus 21 and the mage (illustrated) motors were successful applications of this technology.

With current technology large c/c exit cones are readily manufactured, reliable, and cost competitive with classical phenolic based designs when integrated for additional performance. Indeed, deployable designs can be implemented to minimize overall motor length prior to operation. Figure 14 presents c/c extensions for solid rocket motors. The nozzle extension on the left is fixed and the nozzle extension on the right is extendable (two cones) and illustrated fully extended during a hot firing test at altitude.

Figure 6 MAGE Apogee boost motor with C-C throat and C-C nozzle extension (SPS)

Thermo-ablative composite materials

The ideal ablative material retains its shape with minimal recession post charring and sufficient thermally protections. A future material candidate is 3D-CFRP. In 3D-CFRP, carbon fibers also cross the cloth laminations to reinforce the transverse direction and enable strong, hard char formation.

Figure 11 View of C/C nose and throat parts (SPS)

Carbon Phenolic insulators are typically manufactured by automated wrapping of (ex-rayon) carbon/Phenolic Prepreg tape and can be classified as CFRP. Although this material performs in highly erosive environments, it generally requires mechanical support to withstand mechanical loads. Post firing tests of these materials often reveal large cracks resulting from cool down thermal contraction that, unfortunately, have complicated hardware design and material models. Moreover, after charring, the char’s inter-laminar strength is very low. Therefore, ply separation and pocketing can complicate applications. Therefore, successful applications require “deep knowledge” of material processing techniques and sensitivities and design technology. Clearly, part designs must adequately account for all these behaviours to be successful.

Figure 12 View of a CMC combustion chamber and exit cone (IHI Aerospace)

The new generation of 3d reinforcement provides more homogeneous material, improved mechanical properties (particularly in the inter-ply direction) for both and charred material states. This capability eliminates numerous issues related to delamination and designs for large self-standing parts without metallic supports. Moreover, 3D reinforcement enables low cost ex-pan carbon fiber material replacements of high cost ex-rayon materials. RTM process are also accessible for Phenolic resin injection avoiding cost and technical issues related to traditional Prepreg tapes. Fig. 12 illustrates a 3D CFRP part.

Thrust vectoring

When thrust vectoring is necessary, the “universal” solution is currently flex-seal and external actuators. However, alternatives e.g. Socket-ball, tech-roll joints or liquid injection in the exit cone – are employed in special applications.

Flex-seal

The flex-seal concept is based on a sequential stack of elastomeric pad and structural shims that conform to a spherical shape. This design allows ready omni-axis nozzle vectoring of ~5° - 6°. However, special applications can be desi gned to achieve omni-axis vectoring of 15 to 20°.


Figure 15 View of the P80 flex-seal insulator (SPS)

Within the flex-seal concept two improvements are increasingly employed for space applications:
- self protection of the flex-seal to avoid complex thermal protection systems. This is accomplished by increasing shim thickness. Although this technology was originally developed for defense applications that required very compact designs, it is now sufficiently mature for low risk use in large space program applications
- low torque, low power flex-seals employ synthetic rubbers (rather than natural rubber) to easily achieve 50% torque and TVC power level reductions. In the future 'near zero torque' designs should further decrease TVC power requirements to very low levels

Actuators

The evolution of low torque TVC is important for stage level applications because it reduces power necessary for a required steering angle or angular velocity thereby enabling electro-mechanical actuators (EMA). EMA’s eliminate hydraulic power issues: cleaning, leakage, and pressurization phase lags. Moreover, EMA’s sourced by lithium-ion battery power packs contribute to SRM “instant readiness.” Furthermore, future evolutions of ‘near zero torque' flex-seal designs should decrease TVC power requirements to levels compatible with super-capacitor energy sources further reducing TVC system cost.

PROPELLANTS

Solid propellants for space application are typically based on Polybutadiene binder, ammonium perchlorate (ap) oxidizer, and aluminium (al) as fuel. This choice result of a good compromise cost, safety, performances. Space propellants have to be in class1.3 (no risks of detonation) ap is a powerful oxidiser, aluminium a powerful fuel both produced at a low cost

The national aeronautics and space administration (NASA) is developing new launch system: the ARES I crew launch vehicle (CLV) and the ARES v cargo launch vehicle (calv) – to replace the Space Shuttle and return to the moon. ARES I's first stage is a five-segment solid rocket motor that will utilize space shuttle booster technologies. Moreover, the AREs V launcher will be boosted by two 5-segment solid rocket motors (propellant similar to ARES I's first stage). The European small launcher Vega (in development) has three solid rocket motor stages and a bi-liquid upper stage. These developments follow roadmap2000's predictions.

This overview of applications shows that for the next decades the SRM for launchers will use current propellants possibly with adjustments to meet the needs

General trends in solid propellants evolution

Research and development of new solid propellants are performed for military applications in order to improve responses to the stimuli of IM-tests (insensitive munitions) and to increase performance. For space application, development efforts focus increasing performance without increasing to much the cost. Other characteristics such as mechanical and ballistic properties and safety characteristics must be maintained or improved.
The performance improvement can be search through a better theoretical specific impulse or a higher density or a lower two phase flow losses or a lower erosive power or a combination of these factors
All studies and measurements performed during the recent decades have demonstrated that the environmental impact of launchers is very small and rather negligible compared to other anthropogenic sources.[1] however, the propellant-manufacturers are assessing technologies that can reduce adverse environmental effects.

In the USA, the integrated high-payoff rocket propulsion technology (IHPRPT) program was initiated in 1996 to improve rocket propulsion systems.[2] for solid propellant motors the goal is to improve the overall performance by 8%.[2] in roadmap2000, the recommendation is to progress step by step to qualify new technologies with a series of relevant demonstration motors.[3] the European perspective was described in 2004. Among the key solid propellants technologies that have been mentioned are as continuous casting process, high-energy propellants and green propellants.[4]

Energetic compounds

As noted in the previous section, a solid propellant normally is comprised of an oxidizer, a fuel and a polymeric binder. Each of these three components individually has been the subject of considerable research in recent years. There has been a veritable explosion of new compounds available to the formulator. Each has unique characteristics, advantages and disadvantages and the evolution of solid propulsion may well be driven by the development of these new molecules.
Of course, a significant proportion of solid propellants are formulated with a polybutadiene binder especially based on total pounds of propellants manufactured around the world. It is plasticized using one or more of a small number of inert, commercial plasticizers. A co-polymer consisting of polyethylene oxide and polytetrahydrofuran (HTPE) has been developed in the usa by ATK in order to satisfy the need of military applications concerning im-test behaviour. A low-energy plasticizer is combined with it. Other polymers such as polyethyleneglycol (peg), polycaprolactone (PCP) and polyglycidyl adipate (PGA) are used for incorporating higher percentages of high-energy plasticizers. Energetic polymers have been developed or are currently being studied. Glycidyl azide polymer (GAP) has gained comparatively wide acceptance. Gap is used in commercial applications such as gas generators.[5] it is produced in USA (3M) and in France (Eurenco). Other polymers, polyglycidyl nitrate (polyglyn), poly(3-azidométhyl-3-methyLOXetane) (PAMMO),

poly(3,3-bisazidomethyLOXetane) (PBAMO) and poly(3-nitratomethyl-3-methyl-oxetane) (PNMMO) are currently being studied. Generally, they are plasticised with energetic products.[5, 6] the polymer, poly(methylvinyltetrazole) (PMVT), is quoted as being under development in Russia.[7]
The energetic fillers involved in propellant formulation, which are described in the open literature, are mainly AP, RDX, HMX, HNIW, ADN, and HNF. Ammonium Perchlorate (AP, NH_4CLO_4) is used in the largest number of propellants manufactured across the world and will be used in propellants for new SRM developments. AP was chosen because it shows a low sensitivity, good thermal stability and a high density and it has a good oxygen balance and enthalpy of formation that lead to outstanding delivered energy. It is a chlorine containing product. HCl is generated and its comparatively high molecular weight has a negative impact on performance. Chlorine species in the effluents may induce local environmental impacts. RDX, HMX and HNIW lead to increased performances. HNIW is of particular interest in energy terms because of its high density and likewise HNF and ADN because of their excellent compromise between enthalpy of formation and oxygen balance. An examination of oxygen balance values shows that RDX, HMX and HNIW are monopropellants or slightly oxidized. By contrast, HNF and ADN are oxidizers in the true sense of the term and are often called chlorine-free oxidizers. All these products sensitize propellants to shock sensitivity in the gap test when they are used at any level above 15-20 percent.
As fuel to replace aluminium, aluminium hydride is studied both in USA and is used in Russia .

Future trends for solid propellants

The pacing item in the development of a new propellant can be considered largely to be the maturity including availability of the relevant new raw materials.

Short term

Only raw materials that are well known, at least at laboratory scale, may be considered for short-term applications.
Replacement of part of the ap with an energetic material could be the first step of development of new materials. This could allow the ballistic properties and sensitivity characteristics to be preserved while increasing the specific impulse. As has been indicated above, cost is a very important parameter. A study of the comparative cost of raw materials, conducted in roadmap 2000 concluded that the costs of AP and RDX are low, the cost of HMX, ADN and HNF are moderately high, and that of HNIW is high. Taking into account the level of maturity, RDX is a good candidate. This is the solution developed by ATK in 2000 under IHPRPT program. A demonstrator booster was successfully static tested.[8] the specific impulse was increased and the oxidizer-to-fuel ratio was lowered. The latter induces less erosive effect on carbon-based material in the nozzle. CSD / SEP (now SPS) experiments on motor using a 90% total solids aluminized propellant had shown 40% decrease of the nozzle erosion with a composition containing 12% HMX in comparison with formulation without HMX.[9] the replacement of a small part of the AP by RDX or HMX leaves the mechanical and ballistic properties largely unchanged with only a small reduction in the burning rate. Safety characteristics are similar. Obviously, the replacement of part of the AP by another filler leads to a reduction in the amount of hydrochloric acid produced.

Classically, solid rocket motor grains for defense and space applications are made by a batch cast process. During the period 1985 – 1995 efforts were made in USA to develop a continuous process for the production of composite propellants. R&D studies were started at SNPE in the mid-80s in order to develop this continuous process for composite propellant manufacturing.[10] recently, SNPE has proposed to establish a continuous mixing facility for manufacturing the large Ariane 5 segments to have and more consistent and controllable formulation than possible with a batch process.[11]

Mid term

For mid-term applications, chlorine-free oxidizers are intriguing candidates. Two products are the leading entrants in this class of compounds, ADN and HNF. Hydrazinium Nitroformate (HNF – $CH_5O_6N_5$) is produced by APP (Aerospace Production Products) in the Netherlands. The product is

friction-sensitive and its impact sensitivity is intermediate between that of ADN and that of HNIW. The crude product has a needle-like shape and morphology alteration through crystallization or other processing is required prior to formulating. Crystallization studies have improved particle morphology, but the particles are not yet quite round and there remain progress to be made. HNF shows a lower thermal stability than those of the other products. Progress at the raw material level and specially improvement of the thermal stability,is still needed before considering this product as a candidate for a propellant development.
Ammonium Dinitramide (ADN – $NH_4N(NO_2)_2$) was first manufactured in the USSR during the 1970s. ADN exhibits similar sensitivity as RDX. ADN-based propellants were used in the former USSR for propulsion of strategic missiles but the details have not been published.[5] most of the results available in the open literature mention studies conducted by defence agencies on non-aluminized propellants for tactical missiles. The specific impulse of aluminized propellants increases with the rate of ADN replacing the AP. The density decreases leading to a net of little gain in a density-impulse calculation.
High energy propellants based on nitrate ester plasticized poly ether binders and with a high content of Nitramine show an increase of specific impulse near 10s compared to conventional formulations. They have been designed for defence applications and are sensitive to shock sensitivity and typically receive a 1.1 hazard classification rating.
The replacement of Aluminium by Aluminium Hydride main provide interesting increase of specific impulse; the major problem is to find an economic process to manufacture a stable product

Far term

The search for new molecules continues with the same objectives as before which are to increase enthalpy of formation and density without overly increasing hazards or decreasing stability. An approach, being widely investigated at the time of the writing of this article, is to increase the enthalpy of formation by building nitrogen-rich molecules and incorporating cyclic and cage structures. The density typically increases in parallel to these parameters. This approach has led in the past to the development of HNIW. The newer molecules of interest may be, for example, furazanes, furoxanes, tetrazines, tetrazoles etc. This trend sees its upslope with the “high energy density materials” or HEDM. They include molecules from those that have been known for many years and are quite stable to more exotic, metastable molecules. Their decomposition leads to the formation of lighter molecular weight gas products at very high temperature. The poly-nitrogen compounds are good potential candidates because of the high energy in the molecular nitrogen triple bond and weak energies of the double and single bond. Some of the more exotic candidates are still theoretical having not been synthesized anywhere. In these cases, am estimated density and enthalpy of formation are calculated. Some of the calculated values are far greater than for the molecules mentioned before. These high values of enthalpies of formation would lead to very high specific impulses. For example, octaazacubane (n_8) with a predicted enthalpy of formation value of 2200 kj/mole corresponds to a specific impulse of 529s.[13] the most immediate approach is to envisage these molecules as comparatively low percentage doping agents. For example, a composition with 10 HTPB/30 AP / 60 n_8 shows a predicted specific impulse (standard conditions) of 353s and a volumetric specific impulse of 704 s.g.cm^{-3}. The predicted combustion temperature is near 5000k. Significant efforts will need to be devoted to this synthesis. On that path, successes are reported for salts of N_5^+.[14] the use of such products will certainly require new materials for thermal protection such as insulation and liner and especially in the nozzle. This concept illustrates the great potential in term of performance for these exotic candidate materials and they offer a long term breakthrough in performance for solid propellants.

Composition				Energetic performance			
HTPB	AP	N_8	Al	ρ gcm^{-3}	Tc K	Isv* s	Isρ $sgcm^{-3}$
12	68	0	20	1.804	3578	317.9	573.5
12	54	20	14	1.866	3945	355.8	663.9
10	42	40	8	1.977	4207	391.3	773.6
10	30	60	0	2.041	4933	430.6	878.9

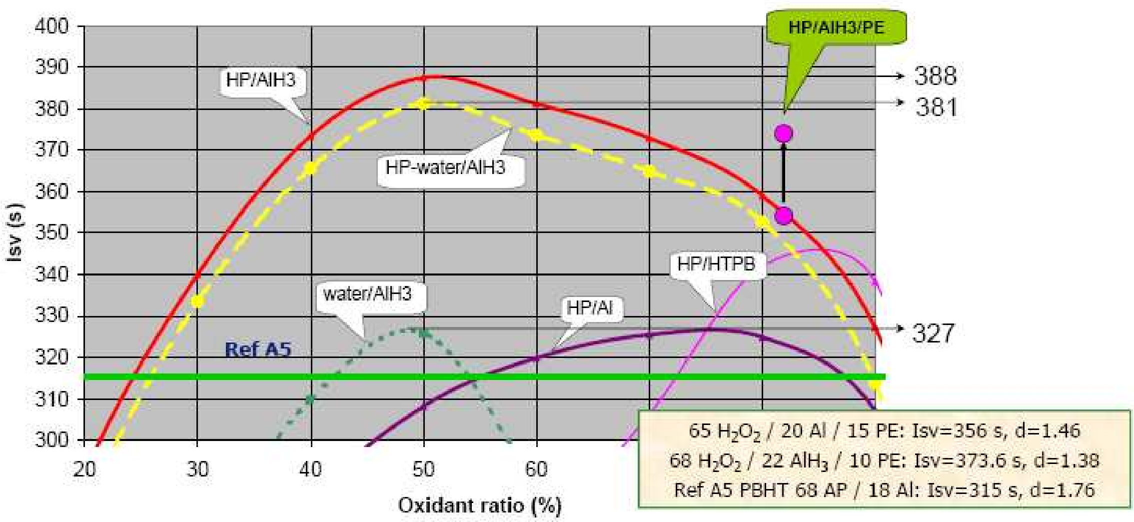
* P=7MPa, vacuum, ε=40

Example of propellant with HEDM [**Pérut and Jacob, 2007]**

The interest of a new way of research: cold propellants

In a far term approach only HEDM will allow to obtain a better specific impulse than liquids (and except H2/O2) , all the other intermediate solutions would allow only a limited performance increase (10 to 20s) with in counterpart problems or of cost or of safety

Basically, a solid composite propellant is a mixture of a metallic fuel, an oxidiser, and a binder (whose role is also to produce hot gases) it exists under its self ignition temperature (around 300℃ for the current HTPB propellants).
Taking the benefit of the industry of the cold, some very powerful combination may exist: for example us and German work (pr lo) demonstrated that a solid mixture of oxygen and hydrogen is burning as any other solid. Without selecting a such extreme solution that need a very important level of freezing, others one exists compliant with the industrial cold industry in the temperature range -20℃ 0℃+ . The "solid" propellant could b e a cold gelled formulation. Remaining in this range of temperature allows the use of the classical hardware of solid propulsion with minor adaptations (i.e. Composite cases, flexseal)



The above chart shows that-without waiting molecules that doesn't exist yet- with cheap products as HTP water and aluminium it is possible to compete in terms of Isv with the couple LOX/Kerosene with "solids" existing in the range of temperature of 0 -30℃
In The USA, the Alice project flown sounding rockets based on water and nano aluminium mixtures


BATES grain

Firing test

SNPE courtesy

A French Patent 2 929 942 registered with the number 08 52423 was taken in 2008; A first technological validation programme was funded by CNES concluded by a firing test (Bates scale see pictures)

<u>Reliability</u>

Solid rocket motor (SRM) quality assurance is based on detailed examinations of specific units with non-destructive inspection (NDI) technologies (x-ray and ultrasound), quality assurance motor tests, and total quality control of motor processing. Therefore, because all motors cannot be inspected individually without prohibitive cost and propellant production/processing aspects of motor manufacture have not been amendable to local inspection with small spatial and temporal scales overall process control has been employed. Therefore, the final product's quality is guaranteed by process and trend control, that is, the quality is indirectly guaranteed with the complement of direct product inspections.

The validity of the SRM development is usually authorized through the qualification-model (QM) static-firing tests. Sometimes problems may be discovered still in this phase of the development if there is some overlook in the previous development activities, and such findings are reflected in the reconsideration of the design and manufacture. It may be more fortunate that such a failure comes out in QM tests than nothing of all problems come out. The problem seeds lurk in the place not to be noticed easily. After several times of the flights, it sometimes appears as a major failure of the mission in some case. The lesson fee in the case becomes very high. Learning from the failure is useful, but sometimes, the failure influences the fate of the project, too. There is not a shortcut to the improvement of the reliability. It is important to know where the seeds of potential failures lurk and to take measures to avoid them beforehand. For this purpose, it is necessary to well understand, during the development of SRM, all the physical phenomena happening in the process of manufacture and operation. With this meaning, there will be a great and growing demand for the further development of the numerical simulation technology in future.

The research of the numerical simulation of SRM has covered a variety of aspects, such as,

- The SRM internal ballistics evaluation by the burn-back simulation [(1; 2)], also with the casting process effect [(3; 4)];
- The modeling and simulation of the random packing [(5)] and of the combustion of the heterogeneous solid propellants [(6; 7; 8; 9; 10)] containing fine/ultrafine aluminum fuel [(13; 14)];
- The multi-dispersed multi-phase flow simulation including aluminum/alumina droplets [(11; 15; 16)], the model of aluminum agglomeration [(11; 12; 17; 18)], and the simulation of slag mass accumulation of condensed phase [(19)];
- The simulation of the vortex-shedding [(20)] and the thrust oscillation [(21)] with the view point of the adaptive control [(22)], of the effect of burning aluminum droplets [(23)], of the nozzle cavity

effect [24], of the wall and the inhibitor effect [25; 26], and of the large solid rocket boosters [27; 28; 29; 30; 31];

- The simulation of the internal flow with respect to the nozzle ablation [32; 33; 34] and to the roll-torque generation [35],;
- The simulation of combustion stability [36];
- The assessment of the acoustic, the vibration, and the shock environments of the SRM firing [37], the assessment of the attenuation of the radio frequency signal due to the SRM plume [38; 39], and so on.

In order to improve the reliability of the SRM, it is important to establish the accuracy of the numerical simulation with the progress of the model refinement of each physical phenomenon by the check with the real firing results. One of the good examples of such establishment is the research on the thrust oscillation problem observed during the second half of the burning period of p230 motor, the booster of Ariane-5, and the numerical simulation has been applied to clarify the role of the vortex shedding from the obstructs like the inhibitors, from the propellant grain edge, and from the combustion surface, on the acoustic pressure growth [20; 23; 24; 27; 29; 30].

Although propellant characterization and internal ballistics are based on homogenized propellant, heterogeneous propellants and their innately stochastic, poly-disperse chemically discrete morphology dominate applications and its superior energetic, ballistic tailoring, etc. Advantages continues its dominance. Therefore, theory's smooth burning surface topography, deterministic, and spatially uniform injection boundary conditions (irrotational for isobaric flow in quiescent environments) are robust for neither flowfield nor condensed phase because heterogeneity information has been purged (without justification) to achieve tractability (see price's seminal criticism). Moreover, Massa, Jackson, And Buckmaster prove heterogeneity information removed from boundary conditions must be appropriately restored to the governing equations *if results are to be robust for the heterogeneous propellant*. Therefore, internal ballistics technologies based on homogenized propellants cannot be robust for heterogeneous propellant grained applications and preclude "deep understanding" of application processes.

George and Davidson's demonstration that asymptotic turbulent flows are sensitive to their source's space, time characteristics (large eddy structures appear to propagate this information through the flowfield) implies fig. 16's phenomena can alter its deflagration sourced flowfield's large eddy and turbulence structures. This flowfield sensitivity to heterogeneity is supported by the empirical minimization of rs maverick's omni-present pressure oscillation for iso-burning rate, -composition, and -grain/motor geometry constraints by adroit heterogeneity change.

Glick and Hessler[iii] prove acoustic stability theory is not robust for heterogeneous propellants.

Figure 7 full-field instantaneous temperature contours for ap/HTPB propellant (left) and slices from the surface out to 1.5 mm (right) show jet-like structures persist far downstream of the combustion zone (courtesty dr t.l. jackson, csar/uiuc)

The above implies detailed flow field simulations with homogenized propellant boundary conditions and without appropriate heterogeneity related information restoration to equations governing flow field and condensed phase cannot be robust for heterogeneous propellant grained solid propellant applications.

Another example is the lessons learned from the failure of the nozzle-liner due to the localized ablation (erosion) of the solid rocket booster (SRB-a) of the Japanese H-IIA launch vehicle [40]. Of course, in this case, the proper material selection for the ablative parts is essential on one hand, the appropriate design of the contour of the nozzle is very important. The numerical simulation of the three-dimensional internal flow was greatly utilized in the return-to-flight activities of SRB-A.

An example of the current and the future interests is the roll-torque generation due to the SRM operation. It is a problem known from the old days [41; 42], but the evaluation of the roll torque due to the firing is not a simple task [35]. For the situation when a booster is used as the first-stage motor, like ares-1 of usa and like the Japanese next solid rocket, and for the situation like European vega lv as the new launch system made of new SRMs, the evaluation of the amount of the torque in the design phase will be strongly required.
The physical phenomena occurring in SRM are based on various disciplines, so the research on the multi-disciplinary numerical simulation has proceeded and becomes another significant trend of the numerical simulation of SRM [28; 43; 44; 45; 46]. In order to integrate the simulations of different disciplines concerning SRM, the technical development of the computer science which makes it possible to treat simultaneously the distributed scales of both the time and the space about each phenomenon. The future improvement on this technology is expected.

One can consider a possible example of the future multi-disciplinary simulation as follows. Firstly, the simulation of the propellant slurry cast into the motor chamber is coupled with the random packing simulation. By realizing this coupling, one can analyze the difference of the local packing characteristic due to the local slurry flow parameters such as the stress and the velocity. Moreover, one can evaluate the pressure response characteristics and the steady burning rate at the local position by the three-dimensional heterogeneous combustion including the aluminum aggregation and the agglomeration effects. Such information can constitute the non-steady burning-surface boundary conditions for the simulation of the multi-dispersed, multi-phase flow consisting of the burning aluminum/alumina droplets and the combustion gas inside motor chamber. The flow simulation can analyze also the acoustic, vortical, and combustive perturbation behaviors. This cfd simulation, moreover, if coupled with the thermo visco-elastic analysis of the propellant grain, with the ablation simulation of the throat and the nozzle liners, and with the local regression analysis of the propellant grain, will make it possible to evaluate the more realistic characteristics of the ignition process, the erosive and unsteady burning, the thrust oscillation, the roll-torque generation, and the total internal ballistics of SRM.
These progresses in the numerical simulation technology will boost the improvement of the reliability of the SRM.

SRM AND LAUNCH VEHICLE RELIABILITY ENHANCEMENT

Available launch-failure data reveal that failure can have its root in any phase of launch vehicle development—difficulties have been noted in inadequate designs and component tests; in improper handling in manufacturing and repair processes; and in insufficient pre-launch checkouts. Design deficiency has been found to be the primary root cause of the sr failures in space launches and is the main failure root cause for all new vehicles using SRS. Failures caused by process error or poor workmanship are usually associated with matured vehicles. Many past failures could have been prevented and the reliability of SRM and its associated launch vehicle systems can be enhanced, if the following rigorous mission assurance measures had been taken.

• review and implement all lessons learned from past failure studies to avoid failure recurrences.
• incorporate the preventive measures learned from the past failures into all aspects of system development—design, fabrication, testing, and operations.
• apply current analysis techniques in the design phase of a new solid-propellant vehicle to ensure fast, accurate, and low-cost modeling of precise configurations with positive margins prior to hardware fabrication to reduce risk.
• practice stringent control of raw materials, components, and semi-finished products in the fabrication phase of a motor.
• cast propellant in a vacuum, if possible, to reduce the number and size of internal voids.
• design nozzle and case with sufficient thermal and structural margins to allow for material, manufacturing and processing deviations.
• apply advanced electron beam welding, automation, and robotics for quality component manufacturing.
• perform detection of defects in solid propellant and in bond-lines between propellant and insulation and between nozzle insulators and supporting structures before motor assembly.

• pay attention to component design details and use only fully-qualified and defect-free components in the manufacturing phase
• minimize hardware reworks and tailor inspection testing for specific reworks.
• validate the design by subjecting components to severe thermal and pressure load for tolerance to fabrication and operating environment variances in the testing phase.
• conduct adequate solid motor performance qualification by testing srs under conditions that simulate an actual launch (test as you fly).
• implement multistring/redundant avionics, electrical, and ordnance components in the launch vehicle fault tolerance.
• design launch vehicle for low cost in manufacturing, operations, materials, and processes rather than for maximum performance or minimum weight.
• reduce pyro-shock levels in the launch vehicle whenever possible
• analyze the results of testing during the development and qualification phases and take measures to improve product reliability.
• perform complete electrical and pneumatic connection tests for each stage and between the stages before vehicle assembly.
• perform adequate system engineering and integration and simplify pre-launch procedures and launch processes to reduce contamination and damage in handling and processing.
• conduct adequate system performance and flight simulation tests.
• test components, software, and system-level electrical elements under conditions that simulate an actual launch.
• confirm the separation mechanism function with a full-size dummy booster.
• limit space launch operation to the design environment and flight experience.
• improve launch-management training and avoid high-risk, schedule-driven launch decisions.

Trend for next and future launchers

Solid propulsion offers reliable, low cost, high thrust propulsion for booster applications to all launchers, upper stages of small launchers, and niche application.

The main conclusions of roadmap2000 are still valid.

Significant improvements in reliability and cost are projected through intense numerical simulation and new processes. It will enable the training of next generation SRM engineers if sufficient development programs are decided.

The main performance increment will come from advanced propellants.

fig 17 is a plot of the evolution of the energy mastered along the humanity. It took millenniums to go from stone, bow and arrow to chemical energy. It took centuries to go from black powders to composite propellants. It took decades to go from RDX to cl20. Each breakthrough or innovation offers a jump in performance, becomes the state-of-art, and is little improved until the next innovation supplants it. On the contrary, the life-time of on innovation shortens and shortens. In the field of energetic materials, solid propulsion is still having long cycles of use of existing technologies, whether because the cost constraints on space launchers developments condemns to building block initiative, or because existing technology stay the best. Solid propellants used for space applications are today stuck to composite propellants, which represent the best compromise in performance, sensitivity and cost. The growing of knowledge and the acceleration of computing initiative in the field of chemistry could lead in the mid-term to the discovery of new ingredients that will supplant actual ones.

Appearance of detailed histories for solid propellant[iv], us[v] and Russian[vi] solid propulsion systems' developments and an assessment of advanced space propulsion[vii] had minor impacts on roadmap2000 because it had largely anticipated them. In contrast, completion of the computer simulation of advanced rockets (CSAR) program[viii] at the university of Illinois at Urbana Champaign (part of the us department of energy's strategic computing initiative), discovery of unacceptable vibrations in NASA's ARES 1 flight vehicle driven by the booster's omni-present booster pressure oscillations[ix,x,xi], and increasing shortages of skilled and experienced personnel[xii] and solid rocket developments[10], introduced challenges absent in roadmap2000:

a. Design for static test (and static tests as "proof" tests) is not robust for flight[x,xi] e.g. Mars pathfinder lander's retro motors static test stable, simulated flight test unstable behaviour, titan iii[xiii], and potentially Ares I[ix],
b. Propellant characterizations and internal ballistic predictions based on homogenized propellant are inadequate for heterogeneous propellants' innately stochastic, poly-disperse, chemically discrete morphology[xiv,xv,xvi,xvii],
c. Routine motor testing inadequacies[15, xviii],
d. Shortages of skilled and *experienced* personnel, and
e. Shortages of new solid rocket motor development programs.

Although (a-c) are long standing deficiencies, (d,e) are more recent. Moreover, (d) and (e) are coupled and ameliorate (a-c). During solid propulsions' period of rapid technical development skilled and experienced personnel and empirical information from numerous motor development programs, that typically challenged the state of the art, transcended (a-c) and theory limitations, and mentored hands on transformation of merely formally trained personnel into skilled and experienced personnel through "hands on" involvement with real motor development challenges. Therefore, a current shortage of skilled and experienced personnel mentors and new motor developments' "hands on" challenges, and inhibits transformations. Consequently, continuation of this situation threatens future capability, and stuck all SRM technologies to the level reached today, whereas all the conditions could be met for a rapid improvement in propulsion technologies, at the rhythm observed in automotive safety.

c. Liquid propulsion:

i. Current status

The design of a propulsive system involves a compromise between potentially conflicting objectives: reliability, performance, low recurring cost and low development cost.

Following a focus on performance and the development of technologies which brought engine performances very close to their theoretical specific impulse limit, current developments have placed more emphasis on:

- Reliability (reduced failure occurrence)
- Cost reduction (both direct – simpler manufacturing processes and reduced parts number – as well as indirect: simplified operation and reduced system complexity) [dam01], [vdk01].
- Improved endurance and life increase (with indirect benefit on reliability).

The requirement for reliability is becoming increasingly the prime requirement due to:
- The high cost of payloads (especially the scientific and institutional ones) ;
- The visibility of a launch failure and the resulting deterioration of the climate of confidence among the actors of the space industry: payload customers, insurers, public authorities.

The relative weight of performance and cost parameters may vary from a project to another:
- The performance requirement may be essential for upper stage : every additional second of specific impulse results in a significant payload increase;
- The recurring cost parameter is dominant for (expendable) booster engines ;
- The development cost constraint can be very important for a dedicated scientific mission.

Figure 8 Time evolution of Energy

Lessons learnt from recent developments have shown that the hierarchy of these design requirements should be clearly expressed at the beginning of a project and maintained along the duration of the project, avoiding shifts from a priority to another.

An increasingly visible trend is the importance of international cooperation [leu01], [sac01], and [tak01].
Numerous projects involve cooperation between companies belonging to multiple countries.
The development of Ariane is one of the earliest examples of international cooperation, mostly in the frame of Europe.

Rd 180 engine implementation on atlas 5 is another well known example of this trend.

International cooperation requires solving the following difficulties:

- Exchange of large amount of data in compatible formats, especially for cad models ;
- Compatibility between different technical standards or norms ;
- Barriers arising from international trade regulations when dealing with sensitive technologies.

Improvements in design (especially with simulation tools) and manufacturing methods which have transformed the automotive and aircraft industries in the late 90's and early 2000's have equally transformed the field of space propulsion.
Numerical simulations and computer aided design have contributed to significantly shorten development duration by eliminating the trial and error process, which led to long developments in the past.
Recent demonstration engines such as the Vinci, Ariane 5 upper stage engine, have reached reliable steady state operation in a much smaller number of tests than would have been required in the 70's or 80's.

Additionally, increased focus on productivity, reproducibility and environmental concerns has also modified working methods in the space industry as much as in any other industrial sector.

Just as numerical simulation has transformed the development of propulsive systems, miniaturization and new instrumentation technologies have transformed the field of component and engine testing.
The last ten years have seen the emergence of new type of instrumentation, which helps test engineers in extracting as much information as possible from the test:

- Flush pressure gauge with high bandwidth have helped characterizing fluid excitations of structures which are the source of numerous high cycle fatigue failures in rocket engines,
- Laser, optical and magnetic instrumentation have contributed to the knowledge of turbine blade variations,
- Thermal instrumentation and infrared camera have led to a more accurate evaluation of heat fluxes,
- Etc…

Capitalizing on these new instrumentation technologies, design and test engineers have access to an immediate understanding of the behaviour, reduce the number of tests, and avoid unnecessary design loops induced by wrong corrective actions due to incomplete or faulty interpretation of the physics.

Furthermore, miniaturization, new instrumentation techniques and availability of computing power will boost the use of regulation and health monitoring technologies, thus significantly contributing to performance and reliability of propulsive systems.

An extensive use of "smart" system and health monitoring technique which will be able to provide the status of propulsive system with increased accuracy and correct its deviations is likely to be seen in the coming years.

ii. Composite materials in liquid propulsion

Composites tanks are currently the reference solution for pressurisation tanks
Composites materials may be also used or for propellant tanks applications or for engines
For tanks applications, one may distinguish pressure-fed systems where the thicknesses are rather high: the competition with metallic tanks is favourable to composites and the technology can be similar to those used for solids: the particular problems to solve are linked to material compatibility with oxidisers, leakage, and behaviour to cryogenic temperature. Development and researches are performed in different countries
For large tanks of expandable turbopump-fed stages, the competition is much more difficult: the current metallic solutions lead to very low thicknesses , to be competitive very specific and costly solutions would have to be developed : nevertheless with new composite materials incorporating carbon nanotubes it could be a breakthrough solutions for reusable liquid systems (tanks and secondary structures)

For engine applications, one domain of research is to realise entirely or not an engine with hot composite: the cooling system being radiative (small engines) or radiative and dump-cooling/effusion/transpiration for intermediate engine or even regenerative cooling for high thrust engine chamber: small engines and divergent parts see today promising applications, large chambers applications for cryogenic engine is questionable due to the very severe thermal conditions

iii. **Trend for next and future launchers**

The requirement of the commercial satellite market, which dictates a regular increase in satellite mass and a stronger than ever demand for reliability, will probably lead to a family of new or improved engines with more design margins, simpler to use and to produce.

The regular rate of mass increase for telecommunication satellites over the past few years can be explained by the restriction of use of geo-stationary positions which induce telecommunication operators to concentrate as much transmitting capability as possible in one single spot.

Additionally, a common goal of all existing commercial launch suppliers is to possess an array of launch vehicles which enable them to provide a wide variety of launch services. This is obtained by simultaneously operating a fleet of heavy, medium and small launch vehicles as much as by increasing the flexibility of existing launchers, very often through the development of new upper stages offering new features or additional performance such as a restart capability or an increased propellant load.

In order to maintain the quality of their launch service, launch suppliers need to rely on a dedicated and skilled work force which should be ready to deal with any anomaly or solve any production mishap that may endanger their reliability record. Maintaining a research and development effort, starting new developments may help in keeping motivated teams of engineers and technicians which are as much essential in serving today's need as in preparing the future.

At least in Europe, next launchers are foreseen to be improved versions of existing and expendable ones. Improving the upper stage capability is a very efficient way to increase the overall launcher performance (payload), hence the interest of new cryogenic upper stage engines like Vinci [las01], [all01], MB XX [sac01], rd0146 [rem01].

The next launcher generation (2020-2025) is less clearly identified. A programme dedicated to the preparation of future launcher, the future launchers preparatory programme (FLPP), began in Europe in February 2004 and aims at having a next generation launcher (NGL) operational around 2020. The FLPP is focused on developing concepts for various launch vehicle systems together with the technology needed to realize them.

The debate is still open concerning the choice of upper stage propellants: cryogenic, LOX – methane or storable.
In Europe, this trade-off is focused on small and medium launchers, while in Japan all types of launchers are considered.
The interest in using hydrocarbons, especially methane, for rocket propulsion is driven mainly by the high fuel density, high boiling point, reduced handling constraints, and reduced need for safety precautions relative to hydrogen.

The emergence of very cheap launchers using simplified main engines while still offering an attractive Isp (e. g. Falcon 1), could introduce a rupture in the launch industry, especially for small payloads, if the concept proves to be successful.

In the USA, manned space transportation came back to the forefront with the development of ares i and ARES v. In 2006 NASA made significant progress on ARES I and ARES V system development, selecting Boeing to build the upper stage of ARES I and Pratt & Whitney Rocketdyne for design, development and testing of the j-2x engine that will power the upper stages of ARES I and v. For the booster of ARES V it is planned to use a version of the rs-68 engine cryogenic engine currently used on the delta iv launch vehicle.

Propulsion is also being developed to support the in-space portion of the exploration architecture. Aerojet is developing a pressure-fed engine for the new human transport Orion service module. This engine is based upon the space shuttle orbital manoeuvring engine, which uses storable propellants. The plan is to also use this Orion service module engine to perform the ascent function using storable propellants, although methane / LOX options are also being considered.

For the descent stage of the lunar exploration architecture NASA has identified pump-fed hydrogen performance levels as being needed. Readiness for this application is being pursued along two fronts. First Pratt & Whitney Rocketdyne is supporting deep throttling demonstrations in the cece program (giu01). Northrop Grumman is also pursuing deep throttling technology for LOX / hydrogen propulsion based upon the pintle injector technology approach.

Meanwhile space exploration can also rely on robots and automated vehicles.
Europe is focused on automatic planetary exploration. Ascent and landing of heavy robotic payloads will also require the development of new engines.

Space tourism is an emerging field in which most work is currently devoted to suborbital flights. Virgin galactic Spaceship 2, the Rocketplane XP and the ongoing EADS Astrium project are the most well known illustrations of this activity.
Space tourism could also be seen as a way to mature very cheap and reliable propulsion techniques having the potential to drastically reduce the launch cost.

New concepts, like low thrust cryogenic propulsion, may enable to extend the domain of cryogenic propulsion to lower propellant masses and smaller launchers (orbital stage or upper stage of micro launchers with payload below 300 kg) [car01], [fio01], [val02].

Fully reusable launchers will probably not be developed in a foreseeable future, but the introduction of reusable boosters (like lfbb: liquid fly back boosters) could come earlier as a forerunner of full re-usability.

Cleaner propellant combinations relative to usual storable propellants (MMH, UDMH, nto), commonly designated as “green propellants” could come to fruition, provided early demonstration at low thrust level are satisfactory [gra01], [jud01], [val01], [bom01].

Areas of future improvements

In the mid and long term, areas of future improvements will probably represent a continuation of the objectives which are already observed in the selection of propulsive solutions for ares 1 and v in the us or in ESA future launcher preparatory program in Europe. These main areas of consolidation and improvement are:

- Reliability
- Cost reduction which should not be obtained at the expense of reliability
- Availability
- Reduction of development duration
- Increase of performance considered in term of thrust and specific impulse and also in term of life duration.

Reliability will remain the number one design criterion in the future. But there will be an increased awareness that achieving the best possible compromise between various objectives as early as possible is essential.
New design tools may help in this task: parametric design methods, sensitivity analysis, probabilistic methods (e.g. for structures).

In the field of car engines and turbojets, while the basic technologies have apparently remain the same over the last 50 years, the reliability and life duration made tremendous progress thanks to use of new material, digital control and regulation. The same evolution could be expected for rocket engines.

New material processes such as metal deposition and new welding technologies will probably allow higher operating temperatures or facilitate the production of complex hydraulic shapes.

The goal of increasing engine life duration - which will be essential in the long term for re-usable vehicles - also contributes to increase the reliability level when applied to expandable vehicles.

For commercial launch vehicles, the reduction of launch cost expressed in term of $ per kilogram or lb of payload will remain essential.
For large expandable launch system and infrastructures, this goal can be obtained through a continuous increase in performance, for instance in order to keep the dual launch capability for Ariane, or by an increased focus on design simplicity.
For instance, in the case of Ariane or h2, every second of main engine specific impulse brings around 100kg of additional payload.

Meanwhile, it can be expected that private entrepreneurs will continue to focus on organizational flexibility as well as design simplicity in order to profitably operate small or medium launch systems such as today's falcon.

Green propellants could contribute to the cost reduction by lowering the direct cost of propellants and reducing the propellant handling cost.

In the long term, the launch cost reduction could be obtained by using partially reusable launchers (FLBB) or totally re-usable system.
This future step will probably require a technological rupture in the field of aerospace material with respect to strength to density ratio as well as fatigue and creep capability.
It is difficult to predict when this transition could occur.

<u>Roadmap</u>

In this paragraph a distinction is made between a short and mid term future for which a predictable continuation of current programs can be expected and a long term future full of unforeseeable technological ruptures and open to unbridle imagination.

Short and Mid Term

USA

The space exploration program objectives were clearly defined over the 2006 – 2007 period and the program is now well on track.
Its main objectives are:
To safely fly the shuttle until 2010,
To develop and fly the crew exploration vehicle before 2014,
To return to the moon no latter than 2020.

The propulsion options which were retained to fulfil these objectives are:
The J2X, a 1300 kN cryogenic engine based on the Saturn era j2 engine and the powerpack of the more recent x-33 aerospike demonstration,
An upgraded version of the RS68,
Development of the pressure-fed storable engine for the Orion crew vehicle service module, based on the shuttle orbital manoeuvre engine.

In July 2007, NASA announced that the common extensible cryogenic engine demonstrator (cece) based on Pratt & Whitney Rocketdyne rl10 engine was under development to support future space vehicles, with specific focus for the deep throttling lunar lander stage.
In the Apollo lunar module, the lunar descent engine from TRW was capable of throttling from 10,125 lb down to 1250 lb. It was a pressure fed storable system that has limited performance for the new NASA lunar missions.

The CECE will serve the same purpose. In its demonstrator configuration, it is a 13800 lb engine fuelled by higher performance liquid oxygen and hydrogen. Its main requirements include the capability to be throttled down to about 10% of maximum thrust.

NASA's propulsion and cryogenic advanced development (pcad) program is investigating the use of liquid oxygen and liquid methane technologies applicable for lunar ascent. Aerojet is currently developing a 5500 lbf pressure-fed LOX/liquid methane high performance engine that will be tested in 2009. Aerojet also just completed the successful development and testing of a 100 lbf LOX/liquid methane reaction control engine for similar applications.

At the same time, the consolidation of the existing space launch infrastructure was completed in 2006 with the creation of the united launch alliance which combines the delta launch system (delta ii and iv) and the rival atlas v system.
Booster propulsion for these US air force systems include the RS68 engine produced by pwr for the delta vehicle and the rd-180 kerosene booster engine produced by NPO-Energomash in Russia, but supplied for the atlas vehicle through a joint venture with PWR. For the upper stage, both launchers use models of the rl10 hydrogen/oxygen engine. Significant activities to improve these propulsion systems are currently limited to a performance improvement for the rs-68 designated rs-68a.

Aerojet is providing the kerosene-fuelled AJ26, a highly modified version of the Russian nk-33 LOX-rich staged combustion engine, as main propulsion for the first stage of the orbital sciences Taurus ii launch vehicle, scheduled for first flight in 2010.

Farther term technology readiness for the next generation of air force systems is being pursued under the IHPRPT (integrated high payoff rocket propulsion technology) program. During phase i of IHPRPT PWR and Aerojet successfully completed demonstration of new hydrogen/oxygen propulsion in a full-flow staged combustion cycle. The recently initiated IHPRPT phase II activity is focused on the kerosene/oxygen oxygen-rich staged combustion cycle and is being performed by Aerojet.

Meanwhile developments of new engines for space application and spacecraft control were on going. In 2007, a major accomplishment by Aerojet was the successful hot-fire testing of an mr-80 series monopropellant hydrazine engine. This is a mars lander derived engine tested as a proof of concept for an Ares roll control engine.
Orbital technologies (Orbitec) continue its development of the forward-1 reusable 7500 lbf LOX-liquid propane vortex engine. Forward-1 is a pump fed engine system that uses a regenerative-cooled nozzle and vortex cooling in the chamber.

Europe

ESA and the national space agencies (DLR, CNES, ASI)

The short term main goal of ESA and the national space agencies is the consolidation and improvement of Ariane 5 and the completion of the development of Vega.

In parallel these agencies are actively promoting and managing research and demonstration programs aimed at initiating new technologies and upgrading the technology readiness level of emerging ones. The previously mentioned future launcher preparatory program (FLPP) led by the European space agency (ESA) is one the most significant of these programs. The FLPP is proceeding to mature technologies for upper stages engines as well as high thrust engines.

As part of ESA FLPP, an expander engine demonstration based on the Vinci engine is on going. In 2008 the cryogenic propellant Vinci engine tests continued with a goal of providing further information on the engine operation capability. The Vinci is an expander cycle upper stage engine with an increased performance and multiple firing specification, which is typical of what is currently required to enlarge the scope of missions and increase the capability of heavy expandable satellite launchers. Its overall system design is under responsibility of snecma (France) under ESA contract. It is a key element of European future launcher evolution.

In parallel ESA and industry are preparing demonstrations activities for high thrust engines to be started by the end of 2008 in order to meet the propulsion requirements of post 2020 launchers.

The Vulcain x is also one of the lead European demonstration programmes in the field of liquid propulsion. It is using the Vulcain 2, Ariane 5 main stage engine, as a platform for implementing new technologies in various field of liquid propulsion.
The Vulcain x program aims at demonstrating new technologies and sub-systems architecture for introduction in future developments: a fuel turbo pump with fluid bearings, a gas generator with tri-coaxial injection elements, a sandwich technology nozzle and high band-width regulation valves.
The Vulcain x program has been initiated by the French national agency (CNES) and has been extended at a European level.

As part of the Vulcain x program, vac of Sweden has developed a nozzle relying on the sandwich technology and advanced welding and metal deposition processes.

In addition to European programs involving industrial partners of several countries, each national agency is often pursuing specific goals, which are related to historic field of expertise or specific national needs.

The CNES launchers roadmap covers the whole range of payloads from 30 kg in leo to more than 12 tons in GTO. All these developments are foreseen to be implemented in a European frame.

CNES is promoting research on “green” and low cost upper stage propulsive system for nano / micro launch vehicles.

Germany is focusing on combustion with on-going works on LOX / lh2 combustion, LOX / methane combustion and staged combustion.
The German aerospace agency is investigating various aspects of methane-oxygen combustion, such as propellant injection, atomisation, ignition, high-pressure combustion, combustion instabilities, and performance of methane for regenerative cooling.
Italy is also promoting activities related to LOX-hydrocarbon engines.

Japan

Production and management of the Japanese key rocket of h-iia, the first flight of which successfully occurred in 2001, was shifted from the Japanese space agency (Jaxa) to MHI on april 2007 when entering into the commercial launch market. Jaxa along with MHI and other industrial partners has been continuously improving the reliability of le-5b and le-7a engines to support h-iia launch service.
New design techniques such as probabilistic design approach (PDA) and sensitivity analysis were demonstrated with advanced computer-aided engineering (CAE) technology as a pilot program for future engine development.
Jaxa and MHI are still focusing on technology development to improve engine reliability, which is the basis of the commercial launch service and will be also a major key driver for future manned vehicles, which will be part of Japanese space activities in the 21st century. [kob01].

The choice of the open expander cycle which is more tolerant to system failure, also contributes to improve reliability. For instance, the LE-5B engine can start up to full power in spite of unexpected interface conditions such as low inlet LH2 pressure and poor chill conditions.
With a focus on system simplicity, robustness and tolerance to failure, Jaxa is applying this highly reliable, flight-proven open expander cycle technology to next generation 100 ton-class engine as designated “le-x” for upgraded H-IIA family and next generation launcher in 21st century. [ats01], [neg01]

Jaxa leads fundamental technology developments such as advanced inducer, combustion injector with the latest high speed visualization technology.

Jaxa's engineering digital innovation (JEDI) centre is developing the advanced computer simulation technology to support these fundamental programs.

As part of a "propulsion for exploration" program, Jaxa is also developing large range throttling LOX/lh2 engine for vertical assent / vertical landing reusable vehicle.

IHI aerospace (ia) is developing a LOX / methane engine under Jaxa contract. Currently, the engine has gas generator and turbopump and will be applied for 2nd stage of GX rocket. [yam01]

China and India

China is expanding the family of long march launchers adding increased capability and flexibility to this launch system. China is also actively engaged in a national space exploration program the recent highlights of which were a manned flight around the earth and the circumlunar flight of a scientific probe.
China develops new engine for the long march 5 (LM5) heavy lift launcher. Development has been started for a 1200 kN LOX / kerosene booster and 500 kN LOX/LH2 upper stage engine. Long march 5 will be in the class of Ariane 5 and delta 4 and operation is expected for 2014.

India is developing and upgrading the GSLV and PSLV launchers.
As part of this effort, india is developing a new 200 kn thrust gas generator upper stage cryogenic engine [sur01].

Long Term

When looking at the evolution of liquid propulsion over a century, one can observe that it relies on a few permanent simple concepts which have been implemented in a more and more efficient way using the available technical knowledge at the time when successive generations of engines were designed.

These concepts are the following:
Liquids are one of the most efficient way to store chemical energy in a dense form ;
Thrust and exhaust velocity are generated by the expansion of light molar mass gases; the higher expansion (high chamber pressure, high nozzle expansion ratio), the higher the thrust;
Liquids should be stored at the lowest possible pressure and a system to increase their pressure may be required.

This last point is linked to another question: the use of densified cryogenic propellants. This technique has been proposed since several years but not applied up to now, except on Energia / Bouran. The application may be interesting in the future, especially for in-orbit propulsion (tank pressure below atmospheric pressure).

The available knowledge obviously relies on state-of-the-art fluid mechanics, material and strength of material science, electrical engineering for auxiliary power and control.
Using this concept / knowledge approach and trying to project one self into a long term future, the questions to be asked are the following:
Will the basic concept change?
Will the available technical knowledge offer new solutions to implement these concepts?
A short sample of the questions arising from these general considerations can be expressed as follows:
Could new energetic chemical combination further improve the energy versus density ratio of today's known propellants? Energetic propellants are already investigated relying on software which can help engineering new molecules and predict their properties.
Shall we see a wider application of the pulse detonation engine?
Will smart material with a capability of providing their deterioration status and heal their damage be used?

Besides technical aspects, as much as today, the evolution of liquid propulsion will remain driven by the “customers” needs (commercial, institutional or tourist).
The planetary exploration (automatic or manned) may be the main driver of liquid propulsion in the future.
The use of cryogenic propulsion for interplanetary mission will probably require active refrigeration, i. E. Zero boil off (zbo).
At least for LOX, in situ propellant production could drastically reduce the expenditure of recurring mission.

Another possible evolution – beyond the space tourism - is the suborbital passengers transport – i.e. The extension of liquid propulsion from launchers to hypersonic, airline-like transportation. The vehicle may use a two-stages concept, with airbreathing propulsion on the first stage and LOX – LH2 engines on second stage. [sip01].
The considerable increase in the production rate and the requirements of reusability will have a deep impact on the launcher business.
On a more modest scale, the increase of launch rate for commercial missions will be the decisive factor to shift from expendable to partially reusable launchers.

For both expendable and reusable launchers, the simplification of launch procedure will be a decisive cost reduction enabler. To this end, a significant part of the ground support equipment and its software has to be transferred on the launcher, possibly using the resources of health monitoring system.

d. Hybrid propulsion:

i. Current Status

Even if Hybrid Propulsion is not operationally used today , except on the Spaceship One and on the Spaceship two, this type of propulsion may offer a potential breakthrough for the Earth to orbit propulsion

Resulting of its characteristics (i.e. separately stored fuel and oxidizer), hybrid propulsion systems may offer important advantages over their liquid and solid competitors.

The following advantages for the classical hybrids are commonly recognized in the propulsion community and will be discussed:

- Higher performances than liquid and solid rockets.
- A very safe fabrication, storage and testing.
- A better operability for a lower cost
- A minimal environmental impact.
- A much lower propulsion system cost
- A high reliability (half the pumps and plumbing of a liquid propulsion system; a insensitive solid-propellant grain, tolerant to cracks).
- Stop-start-restart capabilities
- A controllable thrust shaping on demand

A R& D programme (Orphee) is undergoing in Europe , and different countries are flying sounding rockets

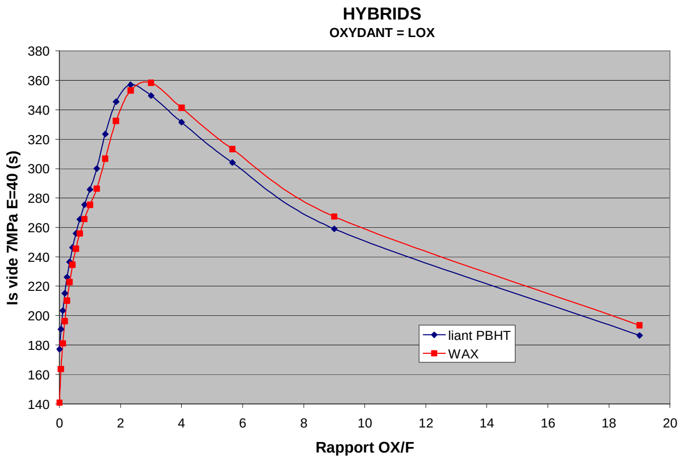
Propellant		Mixture ratio	Equivalent density (kg/m3)	Isv th (Pc 7MPa, Σ=40)
Solid (HTPB)		68/18/14	1750	315
Hybrid(LOX HTPB)		72/28	1060	354
Liquid Bi prop	NTO/MMH	2.37	1200	341
	H2O2/RP1	7.0	1320	314
	LOX/RP1	2.77	1030	358
	LOX/CH4	3.45	830	369
	LOX/LH2	4.8	320	455

Theoretical isv: comparison between current propellant and LOX/HTPB[8]

ii. *Challenges in hybrid propulsion*

Hybrid propulsion could clearly presenting an interest .so, the question is: why it was never fully developed for large boosters for an earth to orbit use

Versus liquid propulsion, the specific impulses of classical hybrids are not better. Develop and create a new propulsion family is costly in terms of financial and human investments; the propulsion industry is sharply divided with their experience in liquid or solids this technology don't took any benefits of military involvements: solid propellant propulsion is currently quite the only technology used (even for very special systems, battleships generally forbid the use of liquid propellants)



More important are the technical problems:

- The regression rate is really too low, it results a complex design of the solid part with a multi port grain, a combustion difficultly mastered (the regression rate depends on many parameters) and so a great amount of residuals may handicap hybrids.
- The challenge is to find a new fuel with a regression rate higher in a ratio of a minimum 5 versus these of LOX/HTPB to allow a single port grain as on solid
- The specific impulse level have to be better than the liquids (except LOX/LH2), giving to this kind of propulsion a definitive advantage both on solids and liquids whatever the application could be
- Nevertheless the objective to obtain the same level of the LOX/methane or to be a little better in term of Isv could be an interesting objective if a target of very low cost can be reached without any technical problem

New energetic hybrids

So, what could be an improved hybrid?

The choice of the oxidizer, for every body, seems obvious, the more energetic high density, non toxic, cheap to produce with a capacity of self pressurization and eventually nozzle cooling is the liquid oxygen.

For application or mission asking a long term storage into space or an easier handling; Hydrogen Peroxide and Nitrogen Tetroxide with addition of NO (MON) are the best candidates

The major problem is to select a new fuel with the two major objectives:

- Increase significantly the regression rate,
- An higher specific impulse,
- Or both,

without losing any specific advantages of hybrids. So, the solid grain has to be constituted of combination of a basic polymer , a fuel (no oxidizer at all).and an additive (metal or hydride) the formulation used on the LEX could be taken as reference(Nylon/Metatoluene Diamine with a regression rate between 3.5 and 5 mm/s)

Note: when reading the literature, many tests have been made at low pressure, so some laboratory results may be not relevant. In a modern motor the combustion pressure will be in the range 6 to 10 MPa for the point of view of regression rate

The choice of the basic polymer or fuel

For many years HTPB was a likely candidate for hybrid motors for ETO applications: the overall reaction with oxygen is taken as:

C_4H_6 + 11/2 $O_2 \rightarrow 3\ H_2O_2$ +4 CO_2 + 6.8 kcal/g [Lengellé]

HTPB has a high endothermic heat of ablation, the pyrolised fuel vapor is transported to the flame zone by convection and diffusion, where it mixes with the oxidizer and burns, but the fuel flux due to the pyrolisis block some of the heat transfer to the surface which is the cause of a low regression rate [Chiaverini]

Moreover, if looking the way to incorporate additives, some hydrides may react with the isocyanates (USP 2003/0164215, September 4, 2003) used for HTPB manufacturing even if the problem is yet solved

So other binders have to be considered:

An energetic binder as the GAP is. GAP has a low heat of ablation (70cal/g versus 800 for PE and HTPB), the regression model is different, GAP possess an autonomous burning rate and so the regression rate may reach 15mm/s instead of 1 mm/s and may be envisaged as ballistic additive taking care to keep the self extinction capacity of the solid

Dicyclopentadiene (DCPD) polymer was subject of studies because it has the useful attributes of being hydrophobic and capable of encapsulating reactive fuels such as $LIALH_4$ (LAH) [Heister]

Wax used in hybrids is a mixture of n-alkanes (non polymeric saturated hydrocarbons) and as DCPD or pe doesn't contain oxygen, it is well capable to encapsulate reactive loading, with a better ratio carbon/ hydrogen. Its performance associated to LOX is better than DCPD and equivalent to HTPB, so wax could be an ideal candidate to replace HTPB. The major advantage on HTPB is to have a basic regression rate (without any additives) greater in a ratio 2.5-3.5]

The choice will not be done not on a criterion of high Isv but on criteria of safety, combustion properties and compatibility with solid reactive fuels or additives

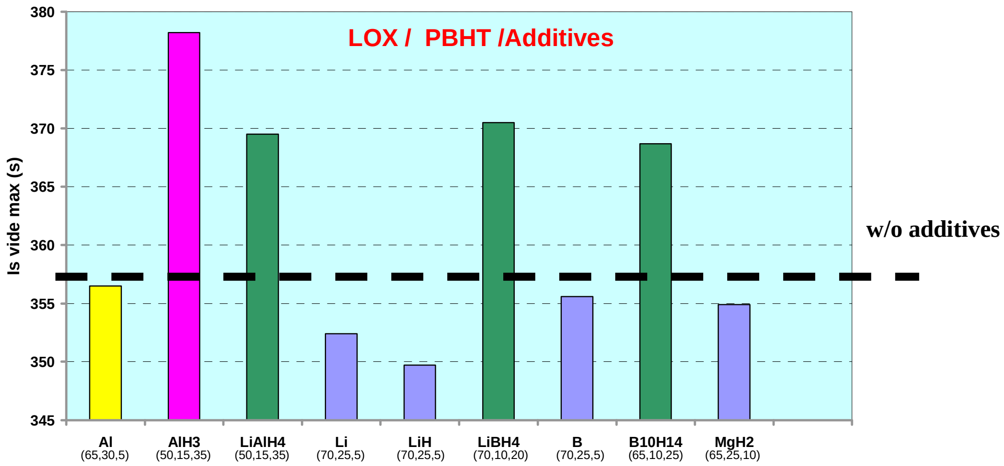
The choice of an additive/reactive fuel

The effect of additives on the performance

From the stand point of performances, the following table shows the interest of some additive often studied at small scale levels .this table shows that if aluminum is studied, it is not for its effects on the specific impulse that is lower than a pure LOX/HTPB combination, boron and magnesium hydride are also not better, LI and LIH are giving a lower performance

Alane (ALH_3), LAH ($LIALH_4$), $LIBH_4$, $B_{10}H_{14}$ and magnesium Borohydride are good candidates

The effect on the global density is also always positive these additive being denser than the binder (HTPB or wax or others**)**



SNPE computations (reference LOX/HTPB 357s, LOX/wax 359 s)

The effect of additives on combustion and regression rate

Preliminary note: most of the studies have been made with polymeric binders and often at low pressure, the effect of pressure is generally not mentioned

The basic reference document on the subject is Risha in [1] pages 414-456

Conventional ballistic catalysts

The increase of burning rates through addition of catalysts (CUC_{L2}, $K_2CR_2O_7$, Ferrocene) is the range 5 -25%.

Aluminum

In the 1960s, the U.S. air force made a significant effort to develop hybrid rocket, as a viable alternative to liquid and solid rocket propulsion systems [14] [28] and tested aluminized fuels

The sizes of the particles traditionally used in the early development of hybrid rockets were usually on the order of micrometers, with the smallest being 2-5 □m. The greater energy release from the oxidation of the metal particles substantially increased the regression rate compared to nonmetallized solid fuels. With this apparent benefit in mind and recent advances in nanotechnology, nanosized particles possess the ability to release the energy in a shorter time and closer distance from the regressing fuel surface. There are many others direct advantages for incorporating nanosized particles into solid fuels and fuel-rich propellants

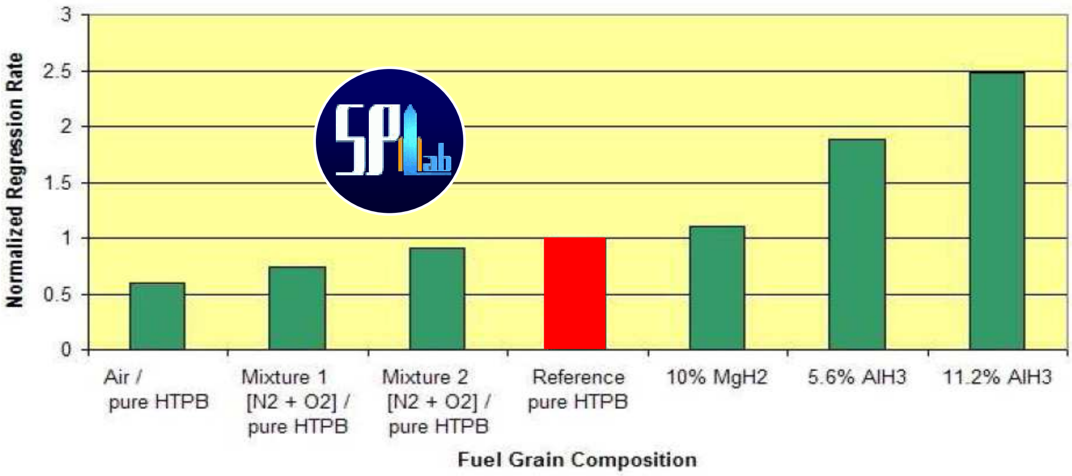
Nevertheless, the major conclusion is that aluminum is not the good solution to increased dramatically the burning rate that remains at the level of 1 mm/s with oxygen associated with HTPB (62% burning rate increase [chiaverini]or with any polymeric binder

There are few results with waxes where the basic burning rate is greater in a ratio 2.5-3.5[Chiaverini [1]] “regression rate appear promising for an operational use” (Evans)

Hydrides

One major advantage of hydrides is the fast deshydrogenation under a thermal flux , then the hydrogen will burn with the oxidizer and the binder gazes in the primary flame zone ,” the

deshydrogenation of α-alane takes place on a time scale of at most 100 microseconds" (9-IWCplerici ,Glumac &Krier). So, it will lead to a good combustion and a high regression rate
The work of the Politechnico di Milano confirms this trend



The above figure shows the very important effect of addition of hydrides on the burning rate , addition of 11.2% of Alane to the fuel (5% of the global amount of propellant) increase the regression rate by a ratio of 2.5 , the optimum amount is 70% of the fuel (35% of the propellant)
<u>European hardware state of the arts</u>
The hardware needed to realize a hybrid booster in perfectly in the state of the arts of the European industry:
The technologies of liquid part: depend of the stage size and of the selected oxidizer, the practical possibilities of choice for the oxidizer are very limited:
The family of nitric acid and MON used at the beginning of the development for sounding rockets and now generally discarded for safety reasons
The LOX is the most powerful cryogenic oxidizer excepted fluorine whose mixtures and compounds are too dangerous to use
The hydrogen peroxide may be useful for missions requiring long term storage in space
N2O nitrous oxide, storable, non toxic, relatively friendly to use and so preferred for the space ship one
So, the technologies for the liquid storage are coming from the shelf
Small and most large scale hybrids have been tested with pressure-fed systems (Lex, Volvo, Namo, Firebolt, Space Ship One) with metallic tank or for the spaceship one a composite tank
Larger stages may need to be powered by pump fed system; only in the us were developed such a system:, AMROC, allied system aerospace, and NASA SSC
In terms of hardware, the metallic tank solutions are the same than used in Europe on the Ariane program, in case of a pressure fed large composites tanks can be realized by several companies (with metallic liner). The Ariane 5 industrial partners have all the know how to realize the liquid storage (pressurization system, tank, turbopump if any, injection valve)
For the solid storage/combustion chamber a composite tank is generally to use as for modern large solid stages (use of a metallic case is interesting for only the very small diameter rockets)
As for the liquid part, among the potential players, the Ariane industrials in charge of the P250 have the technologies needed for a development

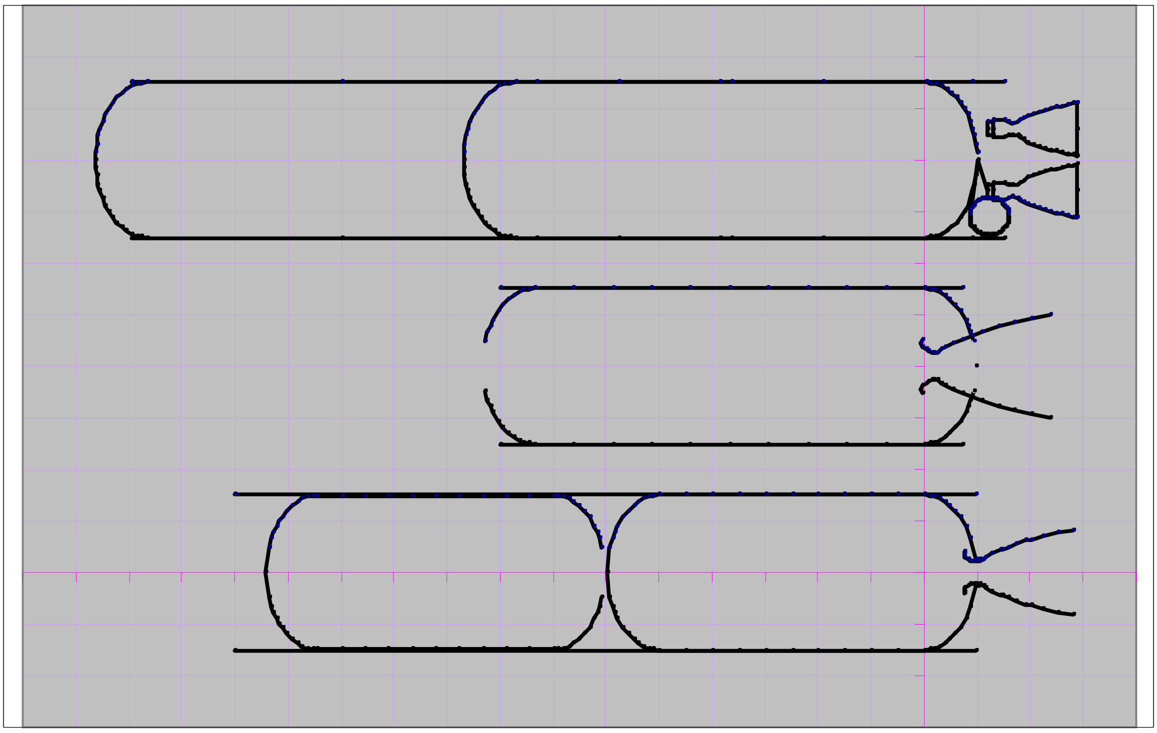
Conclusion on Hybrids

The particularity of hybrid propulsion is to use the state of the arts of both liquid and solids; the only show stopper is the propellant itself
The past work focused on LOX/HTPB or PE (selected for their low cost) appears to be a dead-end (combustion problems and global low performances resulting of a high level of residuals)
The solution that appears through the past experience is the addition of hydrides to a binder (HTPB, GAP or other) or to a binder and a homogeneous fuel or a mixture of both, with or without

others additives; within these solutions some will not present any manufacturing problem and some may have a low cost.
Nevertheless following phases studies have to demonstrate the compatibility of the potential regression rate range with a high performance global design of a stage and the manufacturing at a reasonable cost of a hydride giving a high level of performances

6. General Conclusion

a. Sensitivity Analysis

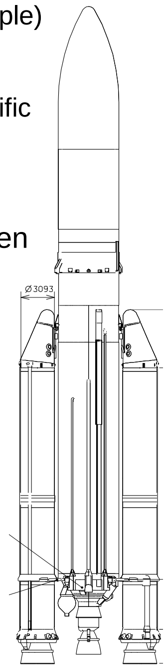


Comparison LOX/Methane/SRM/ Hybrid Stages (90t of propellant)

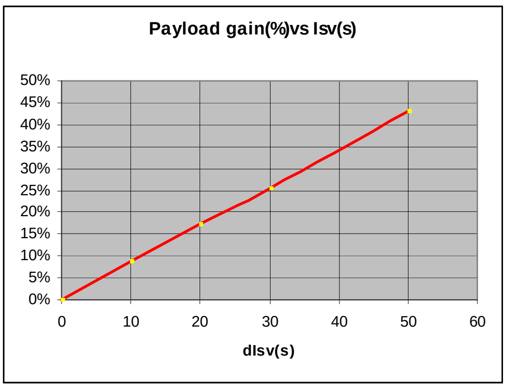
A common sensitivity analysis is difficult to operate; the above scheme shows a comparison between a classical storable liquid, a SRM and a modern Hybrid

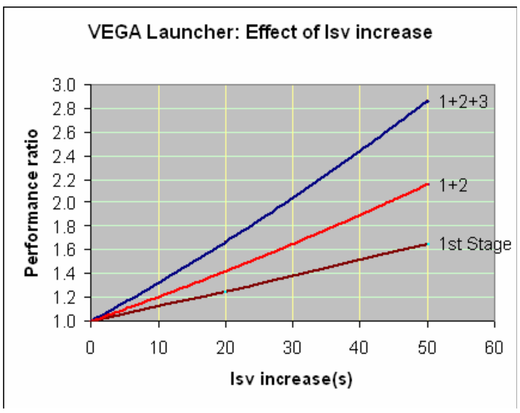
From a performance standpoint a classical storable liquid (Ariane 4 technology for example) is not better than a conventional solid and much more expensive when used on a small launcher

For new solid propellants Two Performances Drivers have to be considered: Specific impulse and density



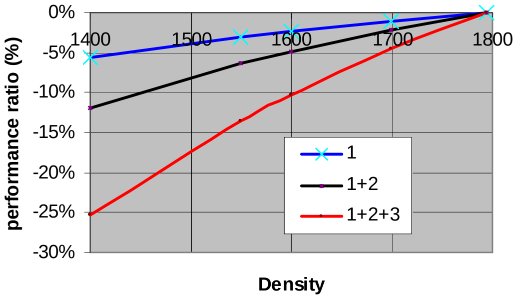
Nevertheless their intrinsic influences are not of the same importance when analyzed doing a comparative design of stages with propulsion models and then the use of a trajectory code

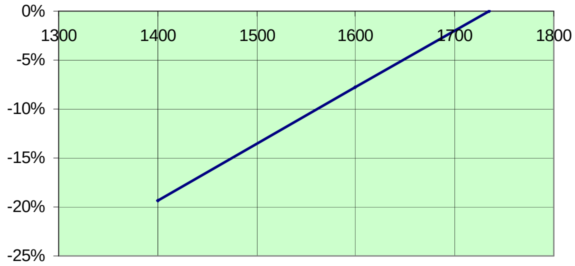




Payload gain: Ariane 5 and VEGA

The first graph show the influence of an Isv increase of the propellant of the Ariane booster (ECA version), the second one of an Isv increase of the propellant of the Vega Launcher





Effect of density: VEGA and Ariane 5

The effect of the density is evaluated running a SRM model to estimate the dead mass increase. The density effect is less important: the specific impulse increase is a major driver

b. Recommendations

If no strong action are taken, Chemical propulsion will follow the liquid and solid roadmaps described here above leading to continuous improvement of the current technologies and small R&D programmes on new technologies

Nevertheless, resulting of the dramatic influence of the Specific Impulse on the performance of a launcher a potential breakthrough exists

Lox-LH_2 for upper stages and even for lower stages is very interesting in future launcher for the high specific impulse it may provide associated to closed cycle engines , the only draw-backs for this technology is its cost and the difficulty to master for new countries willing to have access to space

Lox Kerosene will be also a basic technology taking into account the Russian knowledge of closed cycle engines even if Lox Methane is slightly better in terms of global performances ; development a new technology is always costly

So even if Lox LH_2 has probably no competitor for use on upper stages, very effective cost effective solutions may exists in a mid term perspective and have to be explored

- New conventional solids may lead to propellants without hydrochloric acid and a potential increase of specific impulse of 30 seconds over classical solids
- New Hybrids with a potential increase of specific impulse of 60 seconds over classical solids and 20s over Lox Kerosene
- A more difficult solution is the Cold Solid Propellant (CSP) equivalent in terms of Isv to new Hybrids

All these solutions that combine high thrust to high Isv may lead to a revolution in the launcher architecture and except for the propellant itself may use technologies from the shelf

The following table illustrates example of potential solutions

Current Propellants and Potential mid-term challengers

	Propellant	Composition	Isp Σ=40	Density
LIQUIDS	NTO/MMH	68.8/31.2 (2.37)	340.8	1.192
	LOX/RP1	72.9/27.1 (2.7)	358.2	1.028
	LOX/Methane	77.7/22.3 (3.5)	368.8	0.833
	LOX/LH2	84.6/15.4 (5.5)	454.2	0.344
SOLIDS	AP/AL/HTPB	68/18/14	315.0	1.750
	ADN/GAP/Al	55/25/20	330.6	1.748
	ADN/GAP/AlH3	52/23/25	345.6	1.561
	AP/HTPB/AlH3	63.2/13.2/23.6	330.8	1.513
	AP/HTPB/Al	68/12/18	315.6	1.767
	GAP/ADN	25/75	306.6	1.632
CSP	*HTTP/AL/PE*	65/20/15	356.0	1.460
	HTTP/ALH3/PE	68/22/10	373.6	1.380
HYBRIDS	LOX/HTPB	72/28	354.0	1.060
	LOX/GAP/ALANE	40/10/50	371.9	1.291
	LOX/HTPB/ALANE	50/15/35	377.8	1.167

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IAA Commission III meeting

Annexure - III

Paris, March 22nd, 2010
Christophe Bonnal

Progress report on

IAA Study Group 3.9 "Private Human Access to Space"

Proposer(s): H. Rauck – G. Brachet **Chair:** Ch. Bonnal
Primary IAA Commission Preference: Commission 3
Secondary IAA Commission Interests: Commission 5

Overall Goal:
Identify and quantify the key topics associated to Manned Private Access to Space for both Orbital and Sub-orbital missions.

Key words:

- Technical aspects
- Legal and regulatory aspects, safety aspects
- Financial aspects, market analyses, associated business plans
- Motivations of potential customers
- Physiological and Psychological requirements, ergonomic constraints

Expected outcome of the study:
IAA Position Paper giving the keys to the topic and potentially including recommendations. Subdivision of the study into key chapters, with one "book captain" per chapter ; 7 or 8 members per chapter covering a wide range of origins (countries, agencies, industrials, searchers, operators…)

Time line:

Initially: 3 years following the initial proposal (March 2007)

Revised timeline:

- 1st IAA symposium on Private Human Access to Space (Arcachon)
  ⇨ 28-30 May 2008
  Publication of the full CD with all the papers, most of the presentations, pictures, … Distribution to all participants
  ⇨ End of September 2008

Report during IAC Glasgow ⇨ October 2008

- Publication in Acta Astronautica of the 15-20 best papers out of the 68 presented in Arcachon
  Process undergoing: 15 papers pre-selected
  - 4 rejected
  - 2 withdrawn after review
  - 14 finalized ⇨ Finished under printing Vol 66, 11-12

- SG: Formal invitation of members of the SG

Additional members are welcome, but may lead to problems of coherence and homogeneity (lack of efficiency; depends on the definition of a Working Group !)
⇨ Daejeon, October 2009
Extended table of contents ⇨ IPC, Paris March 2010
Draft for Peer Review within IAA ⇨ Praha, September 2010
Final publication ⇨ IPC, March 2011.

- 2nd IAA symposium on Private Human Access to Space
  Numerous demands for a new edition of the symposium
  Arcachon with Avantage Aquitaine again (very positive feedback last time)
  Proposed slots: 2-4 may 2011 or 30, 31 May, 1st June 2011
  ⇨ Urgent decision
  ⇨ Need to identify potential conflicts

- Associated proposal to delay the preparation of the Position Paper. Already discussed with IAA SG
  ⇨ No urgency
  ⇨ Numerous open points to date

IAA Position Paper on Private Human Access to Space **Annexure - IV**
Volume 1: Sub-orbital

Table of contents, sub-chapters, length and chapter responsibles:

1. Introduction (4 pages, Bonnal)
   a. Context, history,
   - Introduction: first private human access to orbit, Jake Garn (1985), Christa McAuliffe (1986), Toyohiro Akiyama (1990); Dennis Tito (2001), Mark Shuttleworth (2002), Anousheh Ansari (2006)…Guy Laliberté (2009)…Epiphenomenon, availability of Soyuz, questionable future → Orbital private access to space out of scope of the PP
   - Introduction: history of commercial space operations, Conestoga (1982), early proposals by Kaiser, Roton, Kistler projects
   - Definition of “private”: commercial service or ticket paid by non-space-related entity
   - Two domains of access to space: sub-orbital and orbital; short definition, conventional limit of space
   - History: Tsien Hsue-Shen 1949, Ansari X-Prize, flights of Space-Ship 1, 4 October 2004
   - First commercial service = Mir Corp

   b. General overview,
   - General principle: typical trajectories
   - Difference in energy
   - Dedicated vehicles; current examples

   c. IAA action description
   - Objective position concerning credibility of future development
   - List of questions with some answers
   - Identification of key open points

2. Societal motivations (6 pages, Peeters – Eymar)
   a. New transportation culture, Space age
   - Sensations of astronauts :
     - o Weightlessness: 0 g during 3 to 4 minutes, floating in the cabin
     - o Visions of earth: round, blue, fragile; role of witness for environment
     - o Visions of sky: dark, starry even during day
   - Culture of difference:
     - o Fun, new experience: no need for any risk
     - o Adrenalin shot: similar to bungee-jump: the riskier the better
     - o Right-stuff syndrome: the harder the better
     - o Social differenciation with neighbours: astronaut wings, money is the difference

   b. Effects on society

   c. Outreach
   - Impact on youngsters : dream is alive, Space adventure

d. Communication strategy
- Difference between Tourist and Private passenger
- Image of the private space flight
- Student Aerospace Challenge from ACE as an example
    - 10 WPs
    - 82 students from 15 teams
- Planete Sciences as an example
    - Be a rocket scientist
    - Progressive approach to space

3. Market analysis (6 pages, Salt – Eymar):

a. Comparison with other domains:
- Luxury tourism, cruises, week-ends:
    - Attraction towards VIP
    - New culture: bridal, fashion
- Game, luna-parks
- Company rewards
- Similar to first flights in aeroclub

b. Current analyses and forecast
    - Abitzch 1994
    - Futron – Zogby
        - Assessment of sub-orbital market
        - Survey as a function of mission costs
        - Identification of the motivations
- Question of robustness of market analyses

c. Space tourism companies
- VG
    - Description
    - Status of the orders
- Space Adventures

d. Key elements of business plan
- Initial investment:
    - Typology: who are the investors
    - Current status of the worldwide situation
- ROI, amortization duration

e. Consequences of sub-orbital private access growth on space/aeronautics domains
- Potential mutual benefits between private access to space, public space, aeronautics
- Identification of the role of the various actors and potential change wrt current industrial order
- Phased approach to public access to space
- Quest for new markets, workloads
- Attraction of new talents, training of new managers
- Experimentation of unusual program behavior, Skunk-Works type
- Company image

4. Medical, Physiological and Ergonomics (7 pages, Gerzer – Antuñano) :
    a. Risk factors for the crew and passengers
    - Physiological constraints: identification of acceptable requirements
        - Maximal g load x time
        - Level of vibrations, noise
        - 0 g effects
        - Radiations
    - Psychological constraints:
        - Stress vs age
        - Confinement
        - Promiscuity with other passengers

    b. Medical selection, dedicated ground infrastructures
    - Selection criteria
        - FAA rules
            - Acceleration / Deceleration
            - Decrease of barometric pressure
            - Microgravity
            - Radiation
        - Practical medical screening
            - Medical history questionnaire
            - Company physician reviews the questionnaire
            - Potential physical examination and medical laboratory testing
        - Identification of counter indications
            - Cardiovascular pathologies
            - Cerebrovascular diseases
            - Chronic dizziness
            - Muscoloskeletal disorders
            - Ophtalmologic disorders
            - Strong myopa leading to retinal detachment…
            - Behavioral issues
        - Minimum age for participants; potential rejection of pregnant women or terminal medical conditions people; problems of ethics
        - Typical medical screening:
            - Identification of a set of No-go criteria
            - Extended cardio-vascular stress tests
            - Carotid thickness
            - Tilt table
    - Training facilities
        - Some medical conditions may be cleared through simulated spaceflight environments, 0 g airplanes, high performance airplane, hypobaric chamber, human centrifuge
        - Typical training tests
            - Parabolic flight
            - Centrifugation
    - Very limited medical experience and knowledge on individuals with significant medical problems
        - Up to now, healthy career astronauts
        - Most of medical and physiological data collected on normal and healthy individuals

  - Individual medical data from professional astronauts not available
  - Open sharing of G. Olsen medical file
- Identification of the inflight medical events among US astronauts
  - Astronauts fatalities

c. Medical risks
- Space motion sickness
- Undisclosed use of medications
- Disruptive behaviour

d. Habitability requirements, flight suits
- Ergonomics
  - Constraints; requirements for space suits
  - Examples, Black Diamond
  - Comparison with other domains: diving, roller coaster, …
- 0 g environment constraints

e. Applicable and similar experiences
- 0 g plane

5. Legal, Insurance and Regulatory aspects (11 pages, Couston – Masson-Zwaan):

a. General legal frame
- Definitions
  - Definition of Space:
    - History: X-15 flights with associated astronauts wings
    - Von Karman definition
    - Current definition
  - Definition of an astronaut:
    - No legally binding definition
  - Definition of a space object
  - Definition of Launching State
- Liability
  - Of passenger
  - Third party
    - Tour operator liability
- Current techniques used in comparable context
  - 0 g aircraft
  - Conventional launcher + capsule
- Context:
  - Role of EASA:
    - Creation of a space department
    - Rules of conformity control of the vehicle at European level
    - Short term: simplification of procedures
  - ITAR, export rules
- US Commercial Spacelaunch Amendments Act of 2004
  - Establishes experimental permit, notion of paying customer, no limit on the number of experimental flights, requires passenger to be fully informed of potential risks, including the fact that there are some unknown risks, participation on spaceflight may result in death
  - Sole authority over licensing of suborbital vehicles
  - Allows informed consent of the customer to accept the risks of spaceflight

b. Risks and Insurances
- Potential effects of a catastrophic failure
- Identification of the risks and insurance markets involved:
    - Ground
    - Flight
    - Tourist
    - Manufacturers/service providers
    - Travel agency/tour operator
    - Financial

c. Regime and Users status

d. Specific national regimes
- US
- Europe, France

6. Technical aspects (12 pages, Calabro – Bultel – Bernard-Lépine):

a. Potential solutions, variants at system level: key elements
- Number of stages
- Shape
- Number of passengers
- From ground or airborne
- Type of trajectory
- Number of propulsive systems: air-breathing in addition to rocket ?
- Level of reusability vs mass production

b. Sub-system level: key elements
- Type of rocket propulsion:
    - solid, liquid, hybrid: pro and cons
    - environmental constraints, toxicity, carbon signature, NOX, Reach
- Return strategy: wings, retro-rockets, parachute, ballute, flexible structure

c. Availability of technologies:
- Innovative concepts
- TRL, roadmaps for technologies

d. Growth potential: P2P, hypersonic passenger travels
- Long duration 0 g flights to increase domain of 0 g planes
- Scientific applications:
    - Examples of NOAA contract with VG
    - Secondary use of carrying plane for Two Stages concepts: traffic monitoring, cargo transport, small orbital system; examples of VG and Rocketplane proposals
- Production activities: large volume and high mass compared to sounding rockets, highly repeatable
- Global monitoring of Earth zones
    - Immediate screening after disaster
    - Repetitive survey of a given zone: agriculture, flooding, pollution, development

  - o Homeland security: monitoring of borders
- Point to Point access
  - o Principles and associated figures: long distance express flights
  - o Current limits, acceleration, thermal constraints
  - o Some examples: Fast 20XX, V-Prize initiative
- Further evolutions
  - o Orbital missions
  - o Trip around the Moon

e. Current examples, short descriptions based on publicly available info (web sites)
- Virgin Galactic Space-Ship 2
- Rocketplane
- Astrium Space Plane
- X-Cor
- New-Sheperd – Goddard
- Masten Space System
- DaVinci – Dreamspace
- Armadillo
- Benson SpaceDev Dreamchaser
- Inter-orbital Systems Neptune
- Starchaser Thunderstar
- VSH

7. Ground Infrastructures (8 pages, Droneau – Webber) :

a. Space tourism and Grand public
- Main functions of a spaceport
  - o Training
  - o Lodging for tourist and relatives
  - o Side activities: space related theme park
- Showcase for operator
  - o High level of lodging

b. Spaceports : selection criteria
- Safety:
  - o Safety of ground operations,forbidden perimeter
  - o Risks of casualty on ground associated to flight: flight corridor safety
- Accessibility vs desertness
- Interest of the overflown zone
- Constraints associated to air-traffic
- Meteorological constraints

c. Current examples
- Spaceport in Sweden
- Spaceport America New Mexico
- Oklahoma Spaceport
- Numerous other proposals in the US: description and status
- Ideas of Montpellier spaceport
- Examples of the Mars Simulation Facilities; applicability to Private Human Access to Space

8. Reliability, Safety, Risk (4 pages, Romero – Bonnal):
    a. Reliability requirements
    - Preliminary Hazard Analysis:
        - o Identification of critical phases and sub-systems
        - o FMECA
    - FO/FS requirements
    - Abort cases:
        - o Engine-off capability
        - o Tolerance to failure, failure divergence time, containement after failure
        - o Return strategy

    b. Safety requirements
    - Quantitative requirements
    - Comparison with current state of the art
    - Identification of the domains of improvement
    - Should we talk of the SS2 tank explosion? What do we know about it?

    c. Flight constraints
    - Feasibility of "floating" passengers, return to seats, potential consequences

9. Conclusions (4 pages, Bonnal):
    a. Key hurdles to overcome

    b. Recommendations, role of Agencies
    - No use of public money if no « general interest » objective
    - Potential customers of services or vehicles
    - Role for certification, regalia role associated to national laws
        - o Definition of applicable technical requirements, safety factors, required tests: state of the art development
        - o Role in the development process, technical reviews,
        - o Qualification, certification, licensing
    - Synergies with conventional space activities
        - o Innovative propulsion
        - o Reusability: applicability to future RLVs,
            - ▪ Reusable propulsion
            - ▪ Health Monitoring, FDIR
        - o Aerodynamics, transsonics, reentry
        - o Human factors
    - Synergies with military activities, from reconnaissance to strike; parallel with modern UAVs
    - Support of competitiveness of industry; country image
    - X-Prize cup, extension of the domain
    - Open-mind attitude
        - o Potentially important domain in future
        - o Comparison to beginning of aviation

Grand total : 62 pages (for comparison : Space Debris = 64 pages)

Solar Energy from Space: the First International Assessment of Opportunities, Issues and Potential Pathways Forward

STATUS REPORT

International Academy of Astronautics - IAA Commission 3

John C. Mankins, Chair
Nobuyuki Kaya, Co-Chair

22 March 2010

Annexure - V

AGENDA

- Introduction
- Overview of the IAA Solar Energy from Space SG
- Status Review for the SG
- Working Discussion
- Conclusion

INTRODUCTION (cont.)

- A new study group addressing solar energy from space has been started
- Title of Study:
  - Solar Energy from Space: the First International Assessment of Opportunities, Issues and Potential Pathways Forward
- Chairs of the Study:
  - J. Mankins
  - N. Kaya
- Members:
  - See later page

GOALS

- Primary Goals…
  - Determine what role solar energy from space might play in meeting the rapidly growing need for abundant and sustainable energy during the coming decades,
  - Assess the technological readiness and risks associated with the SSPS concept, and (if appropriate)
  - Frame a notional international roadmap that might lead the realization of this visionary concept.
- *In addition…*
  - Identify and evaluate opportunities for synergies (if any) between the prospective benefits of SSP technology and systems for space missions and SSPS for terrestrial markets.
  - Identify the opportunities to introduced extraterrestrial materials into an SSPS industry and assess potential connections between international lunar exploration programs now being undertaken and SSPS.

DETAILED OBJECTIVES (1)

- Identification of relevant markets and applications for new energy sources—including both ultimate applications in terrestrial markets, as well as interim applications in space programs.
- Identification and evaluation of the technical options that may exist for solar energy from space to contribute to meeting global energy needs.
- Identification and evaluation of the technical options that may exist for space solar power to contribute to ambitious government and commercial space mission concepts and markets
- Identification and evaluation of options for the utilization of extraterrestrial resources, in particular lunar resources in future space solar power systems
- Preliminary determination of appropriate SSPS architecture level figures-of-merit, and values of these that must be achieved in order for solar energy from space is to become economically viable for a range of terrestrial market opportunities and space applications.

DETAILED OBJECTIVES (2)

- Preliminary identification of other issues and policy questions that would require resolution for SSPS to become a reality (e.g., spectrum allocation).
- Assessment of the technical feasibility, technological maturity and degree of difficulty in the above space solar power options.
- Formulation of a strategic approach to realizing the potential of energy from space—and one or more technical / programmatic roadmaps implementing this strategy.
- Development of a summary report, documenting the results of the study and articulating the prospects for Energy from Space to make a substantial contribution to satisfying future global needs.

- These initial intermediate goals will be updated during the course of the study.

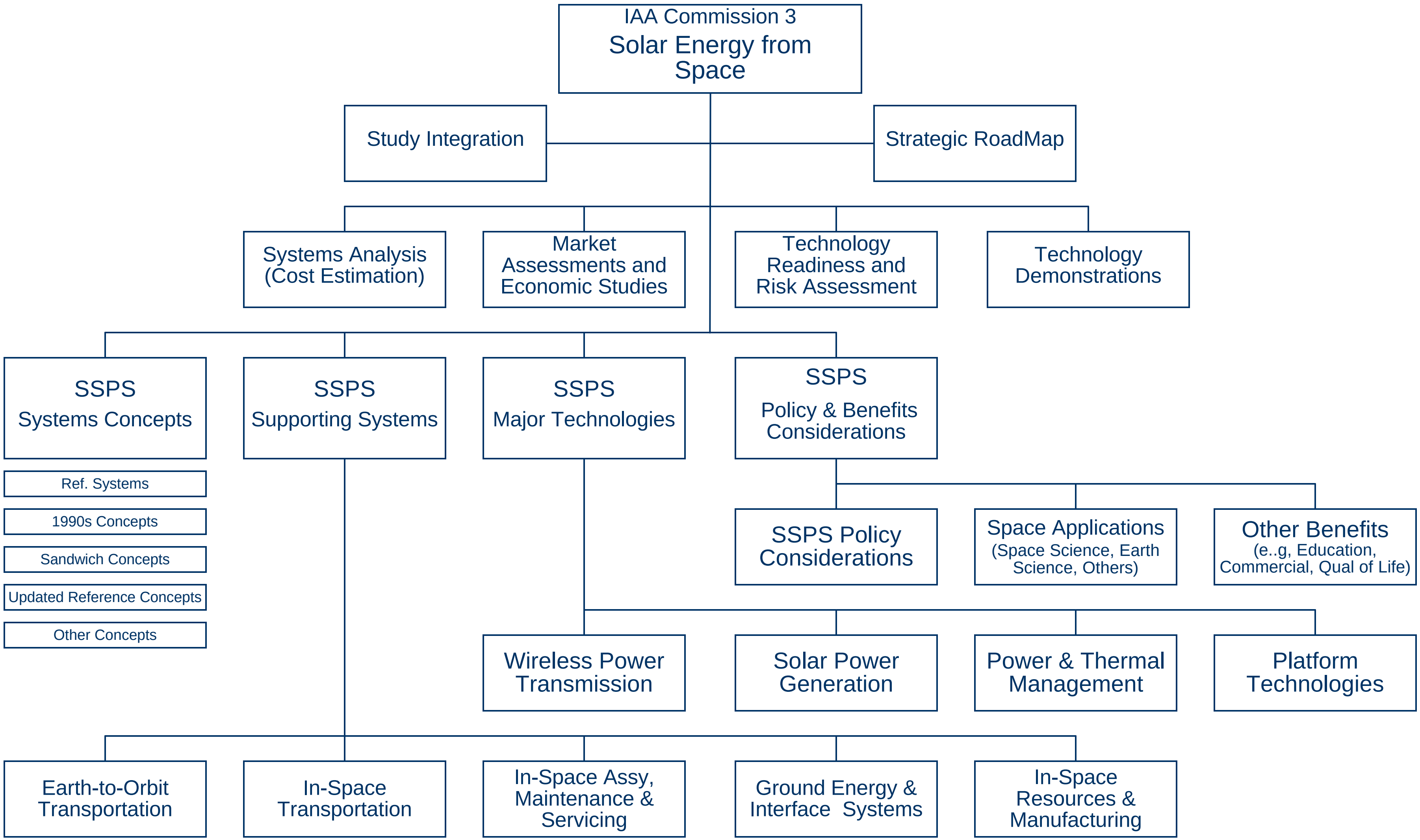
STATUS

- The new IAA Solar Energy from Space Study Group has been formed
  - Various additional members have agreed to participate since the the study was initiated by the IAA in March 2008
- A web-based group has been formed and many of the study group members have been registered
- Three working meetings were implemented in 2008
  - Japan - at or near the ISTS Conference at Hamamatsu in June 2008 (not a formal IAA workshop…)
  - US - at or near the AIAA / IECEC Conference in Cleveland, Ohio USA in July 2008 (not a formal IAA workshop)
  - A meeting of the overall study group at the Glasgow Congress in September 2008

STATUS (2)

- Participated in a Meeting held at the 2008 USRI Conference in Chicago, IL USA (August 2008)
  - "Robust" technical discussion on this subject
  - Invited identification of Study Group Members
- Work Breakdown Structure for the study group has been composed, and draft final report outline developed…
- Joint Session with the IAF organized for the 2008 IAC Congress in Glasgow
  - Discussion of the organization of report and working groups was started at the Glasgow meeting
- Joint Session with the IAF organized for the 2009 IAC Congress in Daejeon, ROK
  - Preliminary discussion held with 2009 LOC/IAF Co-Chair for Korea IAC (Energy is a focus area for this IAC/LOC)

IAA Study: Solar Energy from Space
WBS



IAA Study Group Membership as of 22 March 2010

- John C. Mankins, Chair
- Prof. Nobuyuki Kaya, Co-Chair
- Joe T. Howell (US)
- Henry Brandhorst, Ph.D.
- A.C. Charania (SEI)
- Raghavan Gopalaswami (India)
- Jerry Grey (AIAA)
- Koichi Ijichi (USEF)
- Neville I. Marzwell, Ph.D.
- Frank Little (TAMU)
- Shoichiro Mihara (USEF)
- Susumu Sasaki, Ph.D. (JAXA)
- Prof. Dr. Kai-Uwe Schrogl (IAA Commission V)
- Leopold Summerer (ESA)
- Peter Swan (IAA Commission VI)
- Didier Vassaux (CNES)
- Janet Verrill (Space Power Assoc.)
- Robert Wegeng (US/PNNL)

Next Steps

- Complete Study Group Final Report during the next month or so
- Submit the Report to IAA Commission III to begin the process of Peer Review
- Following Peer Review, pursue Report Publication...

IAC 2010 Symposia Status **Annexure - VII**

	IAC 2010 IAA Symposia		
ref	**Symposium Title** / Session Title	**Coordinator (Symp.)** /Chairman (session)	**Status 11/03**
A.5.	**Human Exploration of the Moon and Mars Symposium**	**W. Mendell, C. Sallaberger**	
	A.5.1 Strategies to establish Lunar infrastructure	M-E Perino, W Mendell, *B Foing (R)*	16 abstracts submitted
	A.5.2 Long-term scenarios for Lunar presence	U.Apel, W.H. Siegfried, *N Ghafoor (R)*	2 abstracts submitted
	A.5.3 Human and Robotic partnerships to realize space exploration goals	C Sallenberger, A.r. Gross, *R. Willnecker, M Bottacini (Rs)*	11 abstracts submitted
	A.5.4 Going beyond the Earth-Moon system: Human missions to Mars, Liberation points ,and NEO's	G. Gargir, E. Messer-schmid, *G.Schwehm (R)*	19 abstracts submitted

C.3.1	**Space Power Symposium**	**J. C. Mankins**	
	Joint Session with IAA Commission 3 (Space Technology & System Development) on "Solar Energy From Space"	N. Kaya, J. Mankins, *J.T. Howell , L. Summerer (Rs)*	8 abstracts submitted

D.3	**Symposium on Stepping Stones to the Future: Strategies, Architectures, Concepts and Technologies**	**J. C. Mankins, A.Pradier**	
	D.3.1: Strategies, Architectures to Establish a "Stepping Stone" Approach to our Future in Space	J.C.Mankins, W. Prisniakov, *W. H. Siegfried(R)*	14 abstracts submitted
	D.3.2: Novel Concepts and Technologies for the Exploration and Utilization of Space	J T. Howell, H Yamawaka, *M.A. Perino, N.Suzuki, (Rs)*	16 abstracts submitted
	D.3.3 Infrastructures and Systems to Enable Ambitious Future Exploration and Utilization of Space	W. H. Siegfried, S Hovland, *S Hovland, G. Woodcock (Rs)*	5 abstracts submitted
	D.3.4 / E.5.4 Joint session on Space Technology and System Management Practices and tools part 1	P.A. Swan, P. Jukola, C. *Moore (R)*	9 abstracts submitted
	D3.5/ E5.5 Joint session on Space Technology and System Management Practices and tools part 2	J.C.Mankins, P.A. Swan, *C. Moore, P. Jukola (Rs)*	1 abstract submitted

D4	**Symposium on Far Futures (Visions and Strategies for Far Futures)**	**Hans E.W. Hoffmann, G.Reibaldi**	
	D.4.1 Human exploration beyond Mars	A. Dupas, P. Jukola, *O. de Weck (R)*	2 abstracts submitted
	D.4.2 Interstellar Precursor Missions	R. X. Lenard, C. Bruno, *D. Andrews (R)*	7 abstracts submitted
	D.4.3Access to space in the Far Future	H. Rauck, A. Pradier, *P. Jukola (R)*	1 abstracts submitted
	D4.4: Space Elevator and Tethers	P. A. Swan, R. E. Penny, *D. Raitt (R)*	16 abstracts submitted

IAC 2011 Symposia Status **Annexure-VIII**

	IAC 2011 IAA Symposia		
ref	**Symposium Title** / Session Title	**Coordinator (Symp.)** /Chairman (session)	**Status**
A.5.	**Human Exploration of the Moon and Mars Symposium**	**W. Mendell, C. Sallaberger**	
	A.5.1 Strategies to establish Lunar infrastructure	M-E Perino, W Mendell, *B Foing (R)*	
	A.5.2 Long-term scenarios for Lunar presence	U.Apel, W.H. Siegfried, *N Ghafoor (R)*	
	A.5.3 Human and Robotic partnerships to realize space exploration goals	C Sallenberger, A.r. Gross, *R. Willnecker, M Bottacini (Rs)*	
	A.5.4 Going beyond the Earth-Moon system: Human missions to Mars, Liberation points ,and NEO's	G. Gargir, E. Messer-schmid, *G.Schwehm (R)*	
C.3.1			
	Space Power Symposium	**J. C. Mankins**	
	Joint Session with IAA Commission 3 (Space Technology & System Development) on "Solar Energy From Space"	N. Kaya, J. Mankins, *J.T. Howell , L. Summerer (Rs)*	
D.3			
	Symposium on Stepping Stones to the Future: Strategies, Architectures, Concepts and Technologies	**J. C. Mankins, A.Pradier**	
	D.3.1: Strategies, Architectures to Establish a "Stepping Stone" Approach to our Future in Space	J.C.Mankins, W. Prisniakov, *W. H. Siegfried(R)*	
	D.3.2: Novel Concepts and Technologies for the Exploration and Utilization of Space	J T. Howell, H Yamawaka, *M.A. Perino, N.Suzuki, (Rs)*	
	D.3.3 Infrastructures and Systems to Enable Ambitious Future Exploration and Utilization of Space	W. H. Siegfried, S Hovland, *S Hovland, G. Woodcock(Rs)*	
	D.3.4 / E.5.4 Joint session on Space Technology and System Management Practices and tools part 1	P.A. Swan, P. Jukola, C. *Moore (R)*	
	D3.5/ E5.5 Joint session on Space Technology and System Management Practices and tools part 2	J.C.Mankins, P.A. Swan, *C. Moore, P. Jukola (Rs)*	
D4			
	Symposium on Far Futures (Visions and Strategies for Far Futures)	**Hans E.W. Hoffmann, G.Reibaldi**	
	D.4.1 Human exploration beyond Mars	A. Dupas, P. Jukola, *O. de Weck (R)*	
	D.4.2 Interstellar Precursor Missions	R. X. Lenard, C. Bruno, *D. Andrews (R)*	
	D.4.3Access to space in the Far Future	H. Rauck, A. Pradier, *P. Jukola (R)*	
	D4.4: Space Elevator and Tethers	P. A. Swan, R. E. Penny, *D. Raitt (R)*	

\\\\\\\ ***Annexure - IX***

Proposal for Forming an IAA Study Group

Title of Study: Assessment of the Technological Feasibility and Challenges of the Space Elevator Concept

Proposer(s): Peter Swan, Ph.D. & David Raitt, Ph.D.

Primary IAA Commission Preference: Commission III

Members of Study Team

Chairs: Peter Swan & David Raitt

Secretary: Cathy Swan

Members: (accepted) Robert Penny, Lubos Perek, Tetsuo Yasaka, Radu Rugescu, Richard J. Tremayne-Smith, Ted Semon, Bryan Laubscher, Michael Laine, Ben Shelef
(Invited) Wiley Larson
(invited) other members of Commission III

Short Description of Scope of Study

Overall Goal:

(1) Assessment of the Technologies
- **Ribbon Material**
- **Dynamics of Ribbon**
- **Base Station Infrastructure**
- **Ribbon Rider Motor / Wheels**
- **Power to Ribbon Rider (Lasers vs. sun)**
- **Ribbon Rider Platform**

(2) Systems Design Issues
- **Space Debris**
- **Deployment**
- **Environmental Elements**

(3) Description of Space Elevator Implementation – Dynamics and Control of Long Ribbon, Build-up of

1-meter wide Ribbon, Power Approach, Payload Carrying Capacity, Anchor Design

Intermediate Goals: (1) Conduct sessions at IAC's (South Africa, Naples) with purpose of presenting technological aspects of the Space Elevator. [direct questions from study group]

(2) Conduct a min-symposium co-sponsored by the Academy and the International Space Elevator Consortium presenting the results of this study. [could be session at IAF at Naples]

Methodology: The initial step is to sponsor sessions inside the IAA D.4.4 Symposium (Symposium on the Far Future: Space Elevators & Tethers). A parallel step is to create a study group, establish goals, objectives and timelines for a Space Elevator cosmic study. Conduct a min-symposium to present the results of the study. The last step would be to produce a report for the Academy that discussed the feasibility of a Space Elevator and identify the potential benefits to humanity.

Time Line: 1st Meeting Oct 10 in Prague – to establish study group and schedule [of course much will be started thru email and telephone calls starting when the study is approved.]

March 11 in Paris – to discuss progress, identify action items, finalize South Africa and Naples papers to support study group

3rd Meeting: Oct 11 in South Africa – to discuss presentation during IAF and finalize some portions of the report.

4th Meeting: Mar 12 in Paris – summarize conclusions and recommendations in the report and draft final aspects of Academy product.

5th Meeting: Oct 12 in Naples – produce the Academy report for commission review and have a session focused on the report in co-sponsorship of the International Space Elevator Consortium

6th Meeting: Paris 2013– produce the Academy report- for peer review

Final Product :

Academy Publication entitled: Assessment of the Technological Feasibility and Challenges of the Space Elevator Concept

Target Community and Expected Effects: Those organizations wishing to have inexpensive access to space: Mars/Moon program, Life in space believers, geosynchronous satellite owners (communications, solar power satellites, etc.), planetary defense organizations, commercial satellite builders, space tourism companies, and governments.

Support Needed: Minimal at the present time: Title a session in Prague, South Africa and Naples: Vision of the Far Future – Space Elevators and Space Tethers – the last two structured to support study group.

Potential Sponsors: space agencies, Mars/Moon programs, planetary defense organizations, commercial space organizations, future human habitats and world governments.

To be returned to the IAA Secretary General Paris by fax: 33 1 47 23 82 16 or \by email: sgeneral@iaamail.org

Date: 22 March 2010 **Signature: signed Peter Swan**

No Signature required if document authenticated.

Initial Phase

Application received: Created study group – March 2010
Chairing Session in Prague on Space Elevators and Space Tethers focused toward the cosmic step.

Commission Approved:

SAC Approved:

Web Site Section opened:

Members Appointed:

Final Phase

Peer Review by Commission Completed:

Recommended by the Commission:

Instructions and application form: see: "Scientific Activity" section at http://iaaweb.org/content/view/256/393/

Final Report Received:

SAC Approved:

BOT Accepted:

Publisher Selected:

Study Published:

IAA Commission III
STATUS REPORT TO THE SAC

Paris; 23 March 2010 Annexure - X

Composition of Commission III
March 2010

- John C. Mankins (USA), Chairman
- Giuseppe Reibaldi (It), Deputy Chairman
- S. Ramakrishnan (In), Secretary
- Christophe Bonnal (F), Member
- Hans E. W. Hoffmann (D), Member
- Wendell Mendell (USA), Member
- Claudio Bruno (It), Member
- Junjiro Onoda (J), Member
- Roger Lenard (USA), Member
- Christian Sallaberger (Ca), Member
- Tetsuo Yasaka (J), Past Chair

Study Groups Status

Study Group No	Studies in Progress Commission 3	Chair	*Studies with Problems*	Proposal received	Commission Approved	SAC Approved	Members appointed	First Draft Available	Final Draft vailable	Commission Reviewed	Final Report Available	SAC Approved	BOT Approved	Study Published	Status	Timeline
3.1	Advanced Propulsion Prospective	Calabro													First part available	2010
3.2	Nuclear Propulsion	Bruno													Publication on IAA Website	2008
3.5	Dealing with Earth-threatening Asteroids and Comets	Bekey													Published	2008
3.6	Strategies & Concepts for Future Space Exploration & Development	Mankins, Vallerani													Pending Submission to Acta	
3.8	Space Elevator Feasibility and Impact	Swan / Raitt	**Cancelled**													
3.9	Private Human Access to Space	Bonnal													Rescheduled	2011
3.10	Technologies to enable near term Interstellar Precursor Mission	Bruno / Matloff													Normal	2010
3.11	Solar energy from space: the first international assessment of opportunities, issues and potential pathways forward	Mankins / Kaya													Normal	2010

* Note: SG C 3.9 is being restructured into 2 parts; see below…

Study Group Status (1)

- C3.1 / Advanced Propulsion Perspective
  - Reviewed the status of the Study Group
  - Distributed rough draft of the final report for internal review by selected C3 members
  - Revised SG plan to completion: goal will be to get to readiness for peer review before the IAC @ Prague (Sept 2010)

- C3.9 / Private Human Access to Space
  - Reviewed the status of the study group
  - Proposition for a second workshop in Spring 2011; concept of delaying the completion of the Position Paper…
  - Decision to sub-divide the Study into Part 1 (Sub-orbital), and Part 2 (orbital); Study Plan has been updated accordingly, and is under review by Commission III members…

Study Group Status (2)

- C3.10 / Technologies to Enable Near-Term Interstellar Precursors
  - General status reported as good; draft report delivered to Commission III for internal review
  - Discussion by C. Bruno unavailable due to delayed flights
- C3.11 / Solar Energy from Space
  - Reviewed the status of the study group
  - Reviewed the draft study group report (version 1); currently undergoing internal review by the SG
  - Extended Working Discussion; See Charts from J. Mankins
  - Final Report Draft for C-3 review due in ~ 1 month
- C3.12 / Human Space Flight
  - Approved by the Commission III
  - Team in formation
  - Will build upon foundation of 2010 50th Anniversary HSF SG

Potential New / Restructured Study Groups

- C3.XX / Space Elevator Technological Feasibility
  - Working Discussion in progress; updated plan prepared
  - Key need to do an assessment of the Technological Feasibility of the Space Elevator
  - SG proposal approved by the Commission III on 23 March 2010; will be forwarded to Academy following IPC

- Potential Future Studies to be considered in Prague

Symposia Status

- 2010 / Prague
  - Generally, all sessions and symposia will be satisfactory/good
  - There are some issues resulting low paper count in some sessions
  - Specific adjustments will be worked during the IPC discussions
- 2011 / South Africa
  - Previously announced plans for restructuring the IAA Commission III Sessions based on Study Groups is proceeding
  - Generally, planned sessions and symposia in Call or Papers are satisfactory, with adjustments continuing
  - Some near term adjustments in the details of the sessions are needed (including identified some changes Chairs, Co-chairs and Reporteurs)
- 2012+
  - Will be completing several study groups in the coming 12 months and laying out new studies of importance to the Academy and the space community
  - Will examine upcoming "course changes" for future Symposia on this basis

IAC 2010 Symposia Status

	IAC 2010 IAA Symposia		
ref	**Symposium Title** / Session Title	**Coordinator (Symp.)** /Chairman (session)	**Status 11/03**
A.5.	**Human Exploration of the Moon and Mars Symposium**	**W. Mendell, C. Sallaberger**	
	A.5.1 Strategies to establish Lunar infrastructure	M-E Perino, W Mendell, *B Foing (R)*	16 abstracts submitted
	A.5.2 Long-term scenarios for Lunar presence	U.Apel, W.H. Siegfried, *N Ghafoor (R)*	2 abstracts submitted
	A.5.3 Human and Robotic partnerships to realize space exploration goals	C Sallenberger, A.r. Gross, *R. Willnecker, M Bottacini (Rs)*	11 abstracts submitted
	A.5.4 Going beyond the Earth-Moon system: Human missions to Mars, Liberation points ,and NEO's	G. Gargir, E. Messer-schmid, *G.Schwehm (R)*	19 abstracts submitted

C.3.1	**Space Power Symposium**	**J. C. Mankins**	
	Joint Session with IAA Commission 3 (Space Technology & System Development) on "Solar Energy From Space"	N. Kaya, J. Mankins, *J.T. Howell , L. Summerer (Rs)*	8 abstracts submitted

D.3	**Symposium on Stepping Stones to the Future: Strategies, Architectures, Concepts and Technologies**	**J. C. Mankins, A.Pradier**	
	D.3.1: Strategies, Architectures to Establish a "Stepping Stone" Approach to our Future in Space	J.C.Mankins, W. Prisniakov, *W. H. Siegfried(R)*	14 abstracts submitted
	D.3.2: Novel Concepts and Technologies for the Exploration and Utilization of Space	J T. Howell, H Yamawaka, *M.A. Perino, N.Suzuki, (Rs)*	16 abstracts submitted
	D.3.3 Infrastructures and Systems to Enable Ambitious Future Exploration and Utilization of Space	W. H. Siegfried, S Hovland, *S Hovland, G. Woodcock (Rs)*	5 abstracts submitted
	D.3.4 / E.5.4 Joint session on Space Technology and System Management Practices and tools part 1	P.A. Swan, P. Jukola, C. *Moore (R)*	9 abstracts submitted
	D3.5/ E5.5 Joint session on Space Technology and System Management Practices and tools part 2	J.C.Mankins, P.A. Swan, *C. Moore, P. Jukola (Rs)*	1 abstract submitted

D4	**Symposium on Far Futures (Visions and Strategies for Far Futures)**	**Hans E.W. Hoffmann, G.Reibaldi**	
	D.4.1 Human exploration beyond Mars	A. Dupas, P. Jukola, *O. de Weck (R)*	2 abstracts submitted
	D.4.2 Interstellar Precursor Missions	R. X. Lenard, C. Bruno, *D. Andrews (R)*	7 abstracts submitted
	D.4.3Access to space in the Far Future	H. Rauck, A. Pradier, *P. Jukola (R)*	1 abstracts submitted
	D4.4: Space Elevator and Tethers	P. A. Swan, R. E. Penny, *D. Raitt (R)*	16 abstracts submitted

IAC 2011 Symposia Status

ref	IAC 2011 IAA Symposia		
ref	**Symposium Title** / Session Title	**Coordinator (Symp.)** /Chairman (session)	**Status**
A.5.	**Human Exploration of the Moon and Mars Symposium**	**W. Mendell, C. Sallaberger**	
	A.5.1 Strategies to establish Lunar infrastructure	M-E Perino, W Mendell, *B Foing (R)*	
	A.5.2 Long-term scenarios for Lunar presence	U.Apel, W.H. Siegfried, *N Ghafoor (R)*	
	A.5.3 Human and Robotic partnerships to realize space exploration goals	C Sallenberger, A.r. Gross, *R. Willnecker, M Bottacini (Rs)*	
	A.5.4 Going beyond the Earth-Moon system: Human missions to Mars, Liberation points ,and NEO's	G. Gargir, E. Messer-schmid, *G.Schwehm (R)*	

C.3.1			
	Space Power Symposium	**J. C. Mankins**	
	Joint Session with IAA Commission 3 (Space Technology & System Development) on "Solar Energy From Space"	N. Kaya, J. Mankins, *J.T. Howell , L. Summerer (Rs)*	

D.3			
	Symposium on Stepping Stones to the Future: Strategies, Architectures, Concepts and Technologies	**J. C. Mankins, A.Pradier**	
	D.3.1: Strategies, Architectures to Establish a "Stepping Stone" Approach to our Future in Space	J.C.Mankins, W. Prisniakov, *W. H. Siegfried(R)*	
	D.3.2: Novel Concepts and Technologies for the Exploration and Utilization of Space	J T. Howell, H Yamawaka, *M.A. Perino, N.Suzuki, (Rs)*	
	D.3.3 Infrastructures and Systems to Enable Ambitious Future Exploration and Utilization of Space	W. H. Siegfried, S Hovland, *S Hovland, G. Woodcock(Rs)*	
	D.3.4 / E.5.4 Joint session on Space Technology and System Management Practices and tools part 1	P.A. Swan, P. Jukola, C. *Moore (R)*	
	D3.5/ E5.5 Joint session on Space Technology and System Management Practices and tools part 2	J.C.Mankins, P.A. Swan, *C. Moore, P. Jukola (Rs)*	

D4			
	Symposium on Far Futures (Visions and Strategies for Far Futures)	**Hans E.W. Hoffmann, G.Reibaldi**	
	D.4.1 Human exploration beyond Mars	A. Dupas, P. Jukola, *O. de Weck (R)*	
	D.4.2 Interstellar Precursor Missions	R. X. Lenard, C. Bruno, *D. Andrews (R)*	
	D.4.3Access to space in the Far Future	H. Rauck, A. Pradier, *P. Jukola (R)*	
	D4.4: Space Elevator and Tethers	P. A. Swan, R. E. Penny, *D. Raitt (R)*	

Future IAA Study Groups

- Commission III is planning to identify several new study groups during the coming year – addressing topics of importance for the future space global space activities–Also, Commission III plans to more closely align Study Groups and IAC Sessions
- A general restructuring of the approach to Symposia and Sessions will follow (planning to target the IAC following Prague); three types of Symposia / Sessions are envisioned…
  - Sessions addressing topics of interest that will likely result in study groups in the near term
  - Sessions that support new / ongoing Study Groups
  - Sessions that report on results of recently concluded Studies, and recent relevant developments
- Commission III plans to work closely with other IAA Commissions, and with relevant IAF Technical Committees in re-structuring its current IAC Sessions
- In addition, all new Study Groups will be invited to organize events external to the annual IAC
- Commission III is seeking assistance in how best to involve younger professionals in IAA activities

Special Topics & Issues

- There is a need for more definition of "what happens next" after the completion of an IAA Study Group: How can we increase the Impact of IAA Studies?
  - Publication of Report(s) is only the start...
  - Distribution to Whom?
  - Protocol for Communication of Results (e.g., Dedicated Session at Next IAC? Other?)
  - Assessment / Follow-up on Results following Completion & Distribution
  - Especially with regard to Findings / Recommendations from a SG
- Need to resolve rules for refreshing the IAA Commission membership
- Special Topic No 1: please confirm no conflicts on 30-31 May and 1 June 2011 for second symposium on private Human Access to space
- Special Topic No 2: C-3 has a General interest in future involvement in identifying future Plenary Session topics. How can we participate? (Example: in S.A. a highlight lecture on the SSP SG results…)