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A PERSPECTIVE ON THE USE OF STORABLE PROPELLANTS FOR FUTURE SPACE VEHICLE PROPULSION

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ABSTRACT

Propulsion system configurations for future NASA and DOD space initiatives are driven by the continually emerging new mission requirements. These initiatives cover an extremely wide range of mission scenarios, from unmanned planetary programs, to manned lunar and planetary programs, to Earth-oriented ("Mission to Planet Earth") programs, and they are in addition to existing and future requirements for near-Earth missions such as to geosynchronous earth orbit (GEO). Increasing space transportation costs, and anticipated high costs associated with space-basing of future vehicles, necessitate consideration of cost-effective and easily maintainable configurations which maximize the use of existing technologies and assets, and use budgetary resources effectively. System design considerations associated with the use of storable propellants to fill these needs are presented. Comparisons in areas such as complexity, performance, flexibility, maintainability, and technology status are made for earth and space storable propellants, cluding nitrogen tetroxide/monomethylhydrazine and LOX/monomethylhydrazine.

INTRODUCTION

As the nation approaches the next century, some very harsh realities must be faced, and some equally important decisions will be made. The economic and programmatic realities of space flight, and of space vehicle development and operation, have been forced home. We have learned that space systems are expensive and complex, require a long time to develop, and are allowed very little margin for error.

In spite of these realities, however, we know that doing business in space in the future is going to require significant advances in orbital capability over what is currently available. We also know that the systems of the late 1990's and early 2000's should be planned now. Delays in making decisions regarding the configurations of future space vehicles will result in a serial impact to future availability. This balancing of the need to do so much better, against the need to get moving in systems development, is a key element in the definition of future system configurations.

No aspect of space vehicle configuration is more important than propulsion. Propulsion can make up more than 90 percent of total vehicle weight. It determines vehicle size, weight, operational flexibility, delivery capability, reliability, and maintainability. It can also significantly determine vehicle development and operating cost. Increasing space transportation costs, and anticipated costs associated with space-basing of future vehicles, necessitate consideration of cost-effective and easily maintainable propulsion systems which maximize the use of existing technologies and assets, use budgetary resources effectively, and provide a safe, reliable, and near-term delivery capability. These factors are key to the economical and practical commercial development of space.

System designs based on the use of storable propellants can not only fill these needs, they can also provide the "stepping stones" for the development of many of the technologies required for other chemical propulsion systems, such as cryogenic propellants, as well as provide a delivery capability which compliments cryogenic based vehicles in the ultimate inventory of STV's (Space Transfer Vehicles).

Storable propellant propulsion systems have many attributes uniquely associated with the characteristics of the propellants themselves. They also represent the bulk of our experience in orbital space systems development - a data base of success which cannot be over-looked in our plans for the future.

This paper discusses many of the pertinent aspects of storable propellants which warrant their consideration for future space vehicles.

A HISTORICAL PERSPECTIVE

From the advent of our space program, storable propellant propulsion systems have played a major and vital role. They have been used as the work horse systems for military and commercial satellites, planetary spacecraft, and as the primary transportation mode for manned space travel. Examples of these systems are shown in Tables I and II. Historically, these systems have proven to be highly reliable and safe concepts with consistent performance.

Table I. Manned Earth Storable Propellant Spacecraft

SPACECRAFT	PROPULSION SYSTEM	PROPELLANTS	VACUUM THRUST (N)
GEMINI	ATTITUDE CONTROL	NTO / A-50	100
GEMINI	RE-ENTRY CONTROL	NTO / MMH	100
GEMINI	MANEUVERING	NTO / MMH	420
GEMINI / AGENA	TARGET VEHICLE	IRFNA / UDMH	71,200
APOLLO CM	RCS	NTO / MMH	415
APOLLO SM	SPS	NTO / A-50	91,220
APOLLO SM	RCS	NTO / MMH	445
APOLLO LMD	DPS	NTO / A-50	4,670 - 43,830
APOLLO LMA	APS	NTO / A-50	15,570
APOLLO LMA	RCS	NTO / A-50	445
SHUTTLE ORBITER	OMS	NTO / MMH	26,700
SHUTTLE ORBITER	RCS PRIMARY	NTO / MMH	3,870
SHUTTLE ORBITER	RCS VERNIER	NTO / MMH	110

Table II. Unmanned Earth Storable Propellant Spacecraft

SPACECRAFT	PROPULSION SYSTEM	PROPELLANTS	VACUUM THRUST (N)
TITAN III	TRANSTAGE	NTO / A-50	36,260
TITAN II 624A	TRANSTAGE RCS	NTO / A-50	110 & 200
DELTA	SECOND STAGE	NTO / A-50	44,050
ARABSAT, L-SAT	ATTITUDE CONTROL	NTO / MMH	20
INTELSAT	ATTITUDE CONTROL	NTO / MMH	4
AGENA	ATTITUDE CONTROL	IRFNA / UDMH	400
GALILEO	PROPULSION MODULE	NTO / MMH	400
OMV	PROPULSION MODULE	NTO / MMH	2,310
SYNCOM	APOGEE KICK SYSTEM	NTO / MMH	890

The selection of earth storable propellants for our primary space systems was based on their unique physical and thermodynamic characteristics of providing hypergolic ignition and remaining in a liquidous state at atmospheric conditions. These properties allowed a spacecraft to be designed with a propulsion system that possessed instant on-demand start and shutdown capability, well understood performance and operating characteristics, indefinite on-orbit stay time with a minimum active thermal control system, a compact design, and high projected reliability.

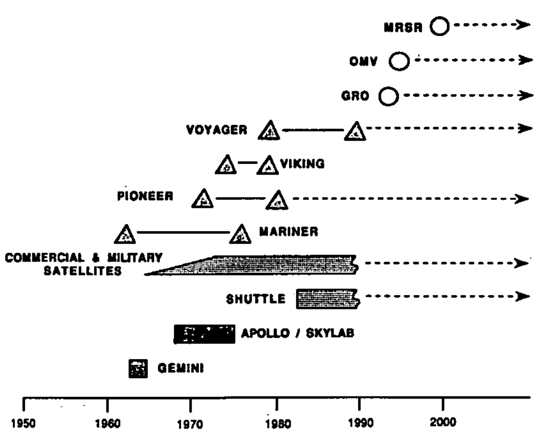


FIGURE 1. STORABLE PROPELLANT EXPANDING SPACE FLIGHT EXPERIENCE BASE

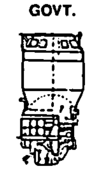
Over the past three decades our space operational experience base with storable propulsion systems has been ever expanding, as illustrated in Fig. 1. This knowledge base includes understanding how to design systems for continuous operation in space for many years, as experienced in commercial and military satellites and the planetary probes, plus how to achieve highly reliable and predictable performing systems, as required in the Gemini, Apollo, and Space Shuttle manned programs. In addition, we have learned how to design and operate maintainable and reusable propulsion systems, as demonstrated in the Shuttle program. As a result of this experience we have developed an engineering knowledge base that has a sound and proven background. The end result is the very high potential of achieving targeted system development, operational cost, and schedule with minimum risk.

These benefits cannot be overestimated. The budgetary issues which are currently of concern for the development of future systems, such as Space Station Freedom, are going to be with us well into the next decade and beyond. We must be able to confidently project well-founded development costs, as well attempt to utilize technologies which minimize these costs. The tremendous costs of developing the technologies required for higher performance propulsion, such as that projected for cryogenic-based systems, must be considered in planning future systems.

CURRENT UPPER STAGE CAPABILITY

Many of the systems which make up the historical data base of storable propulsion are still operational. What does not appear in such a list is a general purpose upper stage for placing payloads into GEO or on planetary trajectories, and yet, such a vehicle is a key element of many of the space infrastructure studies conducted in recent years.

Current upper stage delivery capabilities from the Space Shuttle and from ELV's (Expendable Launch Vehicle) have been significantly driven by the Challenger accident and the termination of the Shuttle-based Centaur. The results have been reduced access to space, limited delivery capability from the STS, and an increased demand for ELV's. Figure 2 illustrates that the only operational Shuttle compatible stages are solid-fueled and provide relatively low delivery capability. The Titan/Centaur can accommodate heavier payloads, but it is unlikely that its launch rate capacity will be sufficient to meet projected demands. Another key fact influencing delivery capability is that constraints on stage volume are not unique to Shuttle, in that the largest available payload canister on the Titan IV is equivalent in diameter to the Orbiter's fifteen foot diameter payload bay. Thus, upper stage volume constraints are going to be with us for some time to come.

CHARACTERISTIC	PAM-D	IUS-2	TOS	CENTAUR G'
• STAGE:				
MANUFACTURER (1)	MDAC	BAC	MMC	GDC
LENGTH (m)	2.4	5.0	3.3	8.9
DIAMETER (m)	1.3	2.9	2.3	4.3
GROSS WT (kg)	2,184	14,759	10,886	23,843
PROP. WT (kg)	2,014	9,708/2,749	9,752	20,412
• ENGINE:				
MANUFACTURER (1)	THIOKOL	UTC	UTC	P&WA
PROPELLANT	SOLID	SOLID/SOLID	SOLID	LO2/LH2
THRUST (kN)	66.3	200.2/81.2	195.8	146.8
SPEC IMP (N-s/kg)	2795	2864/2942	2893	4374
• LAUNCH VEHICLE	STS	STS/TITAN	STS	TITAN
• DELIVERY CAP.:				
GTO (kg) (2)	1,247	4,536	6,078	
GEO (kg)	—	2,309 (3)/1,855	—	4,536
• DEVELOPMENT:				
STATUS	OPER.	OPER.	OPER.	DEV.
SPONSOR	COMER.	GOVT.	COMER.	GOVT.
• ILLUSTRATION				

NOTES:
(1) MDAC = McDonnell Douglas Astronautics Company; BAC = Boeing Aerospace Company; MMC = Martin Marietta Corp.; GDC = General Dynamics Corp.; UTC = United Technologies Corp.; RD = Rocketdyne Division, Rockwell International Corp.; P&WA = Pratt and Whitney Aircraft.
(2) Includes final apogee propulsion system weight
(3) STS Lift = 22,680 kg (50,000 LBM)

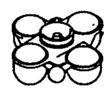
Figure 2. Existing Upper Stages

Some recently studied stage concepts are shown in Fig. 3, including two GEO deliver stages - the TOS/AMS (Transfer Orbit Stage/Apogee and Maneuver Stage) and the ASPS (Adaptable Space Propulsion System). Except for the ASPS, these are all commercial undertakings not sponsored by the government.

Several conclusions can be drawn from this view of upper stages. First, the largest current operational GEO delivery capacity from either the STS or the Titan is approximately 2,270 kilograms (5,000 pounds). This places severe constraints on planned future spacecraft requiring a delivery stage. Second, a large performance gap exists between the IUS and the only system in development, the Titan/Centaur G'. Reliance upon this compliment of stages for future needs will severely limit satellite design options. Third, there is an abundance of interest in storable propellant systems as a means of filling this gap. They offer excellent performance capability, and several system and operational advantages.

FUTURE PAYLOAD DELIVERY REQUIREMENTS

The limited delivery capability currently available can be contrasted with what is projected as delivery requirements into the next century. It should be kept in mind that the next century is not that far away. Considering the typical

CHARACTERISTIC	SCOTS	TOS/AMS	LPM	HPPM	ASPS
• STAGE:					
MANUFACTURER (1)	RCA	MMC	ATC	ATC	(2)
LENGTH (m)	2.8	5.2	1.5	1.5	4.6 - 5.8
DIAMETER (m)	1.8	3.4	4.1	3.8	4.3
GROSS WT (kg)	4,345	16,025	6,518	5,970	19,050
PROP. WT (kg)	3,826	9,749/3,236	5,997	5,219	17,240
• ENGINE:					
MANUFACTURER (1)	THIOKOL	UTC	ATC	ATC	(3)
PROPELLANT	SOLID	SOLID/NTO-MMH	NTO/MMH	NTO/MMH	NTO/MMH
THRUST (kN)	155.7	155.7/11.8	16.7	16.7	16.7 - 44.5
SPEC IMP (N-s/kg)	2952	2893/3089	3217	3217	3315 - 3354
• LAUNCH VEHICLE	STS	STS	STS	STS	STS/TITAN
• DELIVERY CAP.:					
GTO (kg) (2)	2,495	8,845 (5)	4,400	2,931	13,650
GEO (kg)	-----	2,948	1,542	1,355	(6)
• DEVELOPMENT:					
STATUS	CONCEPT	CONCEPT	CONCEPT	CONCEPT	CONCEPT
SPONSOR	COMER.	COMER.	COMER.	COMER.	GOVT.
• ILLUSTRATION					Note (6)

NOTES:
(1) RCA = Radio Corporation of America; MMC = Martin Marietta Corp.; ATC = Aerojet Techsystems Co.; GDC = General Dynamics Corp.; MDAC = McDonnell Douglas Astronautics Company; UTC = Untied Technologies Corp.;
(2) GDC, Lockheed, MDAC, TRW
(3) Aerojet, Bell, Rocketdyne
(4) Includes final apogee propulsion system weight
(5) Stage, Propellant, Payload, and ASE limited to an STS lift capability of 29,500 kg (65,000 LBM)
(6) See Figure 8

Figure 3. Upper Stage Concepts

budgetary, procurement, and development durations, the earliest that new systems could be available is the mid to late 1990's.

The two basic regimes of spacecraft activity for which future space vehicles must be designed are earth orbiting and planetary. Earth orbiting requirements involve the placement of communication and earth observation satellites, and military spacecraft, while planetary requirements are exclusively scientific in nature. The intentional phase-out of ELV's prior to the Challenger accident has had a significant influence on planning of future spacecraft. Most of the spacecraft on the docks or being built were designed for delivery by Shuttle-based stages, including the Centaur. The uncertainty in the development of higher performing Shuttle-based stages has also limited the options available to the designers of future spacecraft.

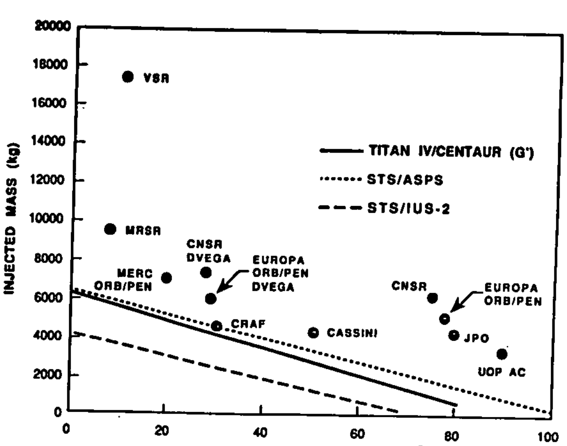


Figure 4. Planetary Mission Capture vs. Stage Capability

On the other hand, the recent trend has been to plan larger, more costly spacecraft for future missions. For GEO missions, crowding of the geosynchro nous arc may require co-locating capabilities into single GEO satellites. For planetary missions, much higher injection energies will be required compared to earlier craft, such as the Mariners. The energy requirements of many of these future missions is shown in Fig. 4. Mars and Jupiter mission plans call for combining orbiters with surface probes, and the Mars and Comet Nucleus Sample Return missions involve carrying the extra mass associated with the return vehicles. Added to these is the fact that planetary missions are extremely sensitive to propulsive performance. Figure 4 shows that most missions fall outside of the capability of even the Titan/Centaur. The lack of available high performance stages has resulted in the use of gravity assisted trajectories which increase mission risk and tend to narrow the available launch windows. Added to these issues for planetary missions is that their high cost and high public profile makes the reliability of the transportation vehicle extremely important.

Military spacecraft pose a different set of issues due to their national defense requirements. These issues include spacecraft placement accuracy, minimizing the number of lost spacecraft to avoid lost observance coverage, quick launch call-up, simplified launch vehicle interfaces and minimized on-orbit venting to insure secrecy, dual launch system compatibility for assured access to space, on-demand restart capability for collision avoidance, etc. These are all significant factors for the designers of military spacecraft which can be influenced by the availability and selection of a delivery vehicle.

Military spacecraft are also growing in size and mass. The Defense Support Program (DSP) involves craft weighing between 2,270 and 3,170 kilograms (5,000 and 7,000 pounds). MILSTAR and the Boost Surveillance and Tracking System (BSTS) involve craft weighing as much as 4,540 kilograms (10,000 pounds). Options for delivery of up to 6,800 kilograms (15,000 pounds) to GEO have recently been studied by the Air Force. Future delivery systems for military spacecraft must also provide a level of responsiveness and availability which would be difficult for cryogenic systems to achieve with current technology.

Even with all of the uncertainty surrounding delivery capability, the need appears to still be there. Figures 5 and 6 illustrate GEO traffic demand estimates established in 1981 and more recently, respectively. Two conclusions can be drawn from these figures. First, the significant increase in the number of spacecraft below 2,270 kilograms (5,000 pounds), along with a decrease in number of spacecraft between 2,270 and 6,800 kilograms (5,000 and 15,000 pounds), could reflect a realization by spacecraft designers that there will be limited capability to deliver the heavier payloads. Second, the large number of payloads still remaining in the 2,270 to 5,440 kilogram (5,000 to 12,000 pound) range would likely overwhelm the availability and launch frequency of the Titan/Centaur.

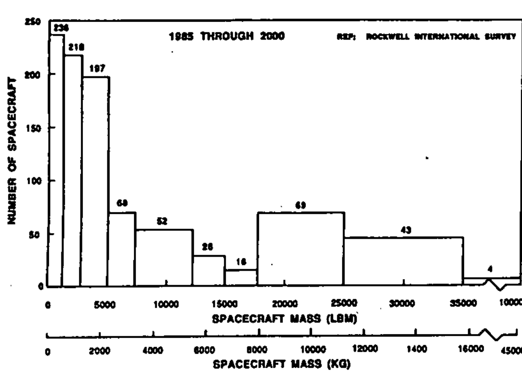


Figure 5. GEO Traffic Demand vs. Spacecraft Mass - 1981

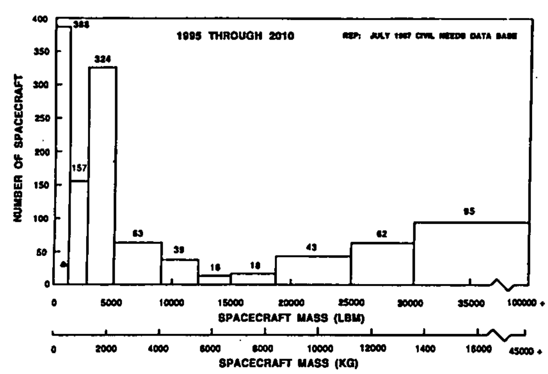


Figure 6. GEO Traffic Demand vs. Spacecraft Mass - Recent

The unfortunate outgrowth of this conflict between future spacecraft desirable features and expected delivery capability is that the designers of mid-to-late 1990's spacecraft will use the limited upper stage capabilities of the late 1980's as a design basis. This will reduce mission benefits, add mission risk, and increase cost due to efforts to reduce spacecraft weight and size. Low risk, highly reliable, and low cost delivery stages based upon storable propellants can be available by the mid 1990 time frame.

STORABLE PROPULSION SYSTEMS CHARACTERISTICS

Future requirements for upper stages and space transfer vehicles will center around re-usability, large payload delivery capability, space basing, and man-rating. These in turn will require high propulsion system performance, mass fraction, flexibility, storability, responsiveness, and reliability. The various chemical propulsion propellant combinations historically used offer varying degrees of the attributes required to meet these requirements. Table III provides a comparison of the system-related characteristics of solid, cryogenic, earth storable (i.e., NTO/MMH), and space storable (e.g., LOX/MMH) propellant combinations. This table illustrates that storable propellants offer many advantages over solid and cryogenic propellants.

Table III. Comparison of Chemical Propulsion System Characteristics

CHARACTERISTIC	SOLID	CRYO	STORABLES* EARTH	STORABLES* SPACE
• PERFORMANCE	POOR	EXCELLENT	GOOD	VERY GOOD
• SPACE STORABILITY	EXCELLENT	POOR	EXCELLENT	GOOD
• STAGE LENGTH	GOOD	POOR	GOOD	GOOD
• PROPELLANT DENSITY	VERY GOOD	POOR	VERY GOOD	VERY GOOD
• SYSTEM MASS FRACTION	VERY GOOD	POOR	GOOD	GOOD
• DUTY CYCLE FLEXIBILITY	POOR	GOOD	EXCELLENT	VERY GOOD
• ON-ORBIT DEMAND START	YES	NO	YES	NO
• ON-ORBIT RESTART	NO	YES	YES	YES
• OPERATIONS COMPLEXITY	LOW	HIGH	LOW	MODERATE
• SYSTEM COMPLEXITY	LOW	HIGH	LOW	MODERATE
• ON-ORBIT VENTING REQ'T	NO	YES	NO	YES
• TOXICITY/CORROSIVITY	HIGH/HIGH	LOW/LOW	HIGH/HIGH	HIGH/LOW

* EARTH STORABLE: REMAIN LIQUIDOUS AT ATMOSPHERIC CONDITIONS
SPACE STORABLE: ARBITRARILY, NORMAL BOILING POINT > -300 °F

Table IV. Liquid Propellant Performance Comparison

	PROPELLANT COMBINATION	OPTIMUM O/F	ISP* (N-s/kg)	BULK DENSITY (kg/m³)	DENSITY IMPULSE (N-s/m³)
EARTH STORABLE	NTO / HYDRAZINE	1.42	3600	1220.5	4,393,800
	NTO / MMH	2.00	3540	1185.3	4,194,900
SPACE STORABLE	LOX / MMH	1.65	3933	1042.8	4,101,120
	LOX / RP-1	2.75	3815	1017.1	3,879,860
	LOX / ETHANOL	1.75	3658	988.3	3,614,100
	LOX / PROPANE	2.80	3835	911.4	3,497,520
	LOX / AMMONIA	1.40	3619	893.8	3,235,390
	LOX / METHANE	3.45	3923	706.4	2,769,640
CRYO	F_2 / HYDROGEN	9.74	4927	520.8	2,565,000
	LOX / HYDROGEN	5.75	4737	352.4	1,661,350

* MAXIMUM THEORETICAL VACUUM SPECIFIC IMPULSE AT PC = 241 N/cm² (350 PSIA) AND NOZZLE EXPANSION RATIO = 350:1

Storable propellants allow unlimited orbital stay times and extreme mission flexibility. Their excellent bulk density results in highly volume efficient stage designs, which, for the constrained diameter associated with the Shuttle Orbiter and the Titan IV, results in very short stage lengths. They require minimal thermal control systems, which makes for more reliable and responsive system designs. Although storable propellants cannot achieve the specific impulse of cryogenic propellants, when bulk density is considered, they are far superior with respect to overall system performance. This fact is enumerated in Table IV. On the average, earth and space storable propellant combinations provide more than double the density-impulse than the purely cryogenic LOX/LH2 combination. For volume constrained launch vehicles, density-impulse is of extreme importance.

These characteristics of storable propellants have some very practical pay-offs. The short stage length allows longer payloads and payload mixing for orbiter-transported systems. Low stage volume reduces the size and weight of an aero-brake for re-usability. Commonality of propellant with stage attitude control systems results in efficient overall system design with fewer components. There is no need for vacuum jacketed lines and complex refrigeration systems. Earth storable propellants require no pre-start chill-down or continuous tank venting. Prelaunch servicing can be performed remotely from the launch pad, and monitoring and control during launch is significantly simpler.

That the described characteristics of storable propellants actually can have an impact on stage designs is illustrated in Fig. 7, which relates stage performance sensitivities for a Shuttle deployed system. For a given propellant volume, storables can provide twice the total impulse of a cryogenic stage. This manifests itself in much shorter stage lengths required for a storable system to deliver a given payload mass to GEO, as shown by the right graph in Fig. 7.

A third basis from which to compare propellants is for a given total stage/payload weight. The bottom graph in Fig. 7 shows that for a total system weight of 24,950 kilograms (55,000 pounds), a LOX/LH2 system can deliver a greater mass to GEO as an expendable stage, but as a reusable geosynchronous transfer stage, the difference in performance between a cryogenic and a storable system is relatively small. This is due to the fact that stage mass fraction is a more important parameter for the reusable GTO missions. Storable stage mass fractions can be as much as 10 percent higher than that of cryogenic stages.

Designers of future space transfer vehicles must determine if these types of system-related benefits are secondary in importance to specific impulse. The lower payload delivery capability of storable systems may very well be out-weighed by their significant design, operational, reliability and cost advantages.

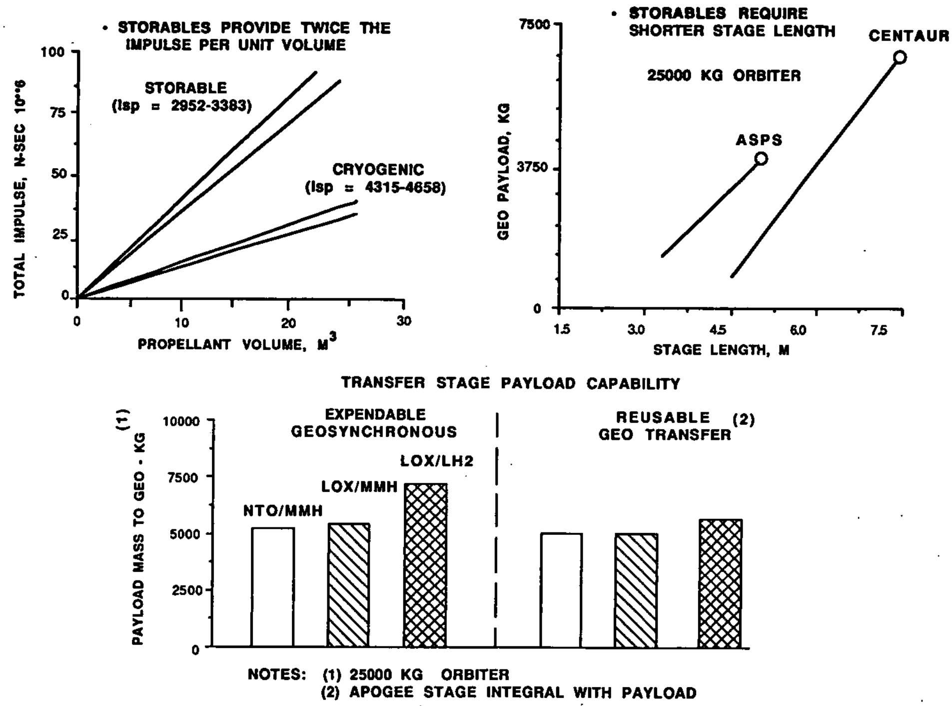


Figure 7. Liquid Propellant Performance Summary

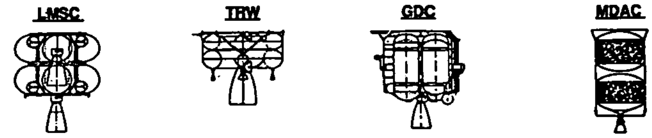
THE ADAPTABLE SPACE PROPULSION SYSTEM (ASPS)

The decision by NASA to terminate the Shuttle/Centaur program was due, in large part, to many of the draw-backs associated with cryogenic propellants. As a result, the capability to deliver payloads exceeding IUS capability from the Shuttle was lost. The concept of the ASPS was pursued by the Air Force with the objective of regaining a dual delivery capability for 10,000 pound class payloads from either the STS or the Titan IV. The resulting stage designs are briefly discussed here to demonstrate the capability of storable propellant systems to achieve significant performance capability with existing technology, while being compatible with a relatively stringent set of Shuttle integration requirements.

Figure 8 summarizes the major features of the four concepts proposed for the ASPS by TRW, Lockheed (LMSC), General Dynamics (GDC), and McDonnell Douglas (MDAC). All are single stage vehicles, except for LMSC's. The most conventional concept is GDC'c four parallel tank design, with the capability of burying the main engine powerhead between the tanks to further shorten stage length. GDC selected a high thrust version of the Air Force XLR-132 pump-fed storable engine in order to minimize trajectory gravity loses associated with the lower thrust version of that engine.

MDAC's tandem, or in-line, tank concept is relatively length inefficient, but offers the advantage of a high mass fraction. The major difference from the other concepts is MDAC's use of the low thrust XLR-132 engine. Even though the low engine thrust imposes both Shuttle and Titan GEO performance penalties, this concept could be very cost-effective due to its use of MDAC Delta tank tooling.

The most unique concept is TRW's in-line toroidal tankage design. It is attractive due to its very good GEO delivery performance, and the length efficiency that comes from burying the engine into the stage. TRW chose the relatively long Uprated Shuttle Orbital Maneuvering System Engine (UOME) because of its low technology risk compared to the XLR-132. It was feelt that development of a toroidal tank would be less risky than development of a new high performance engine such as the XLR-132.

	LMSC	TRW	GDC	MDAC
ILLUSTRATION				
NO. OF STAGES	2	1	1	1
TANKAGE	8 SPHERICAL	2 TOROIDAL	4 CYLINDRICAL	2 CYLINDRICAL
STAGE LENGTH (m)	5.1	4.6	4.9	5.9
IN-BAY ASE	CRADLE	INTEGRAL	INTEGRAL	CRADLE
ENGINE	NEW AGENA	U/R OME	XLR-132+	XLR-132+
ATT. CONTROL	SEPARATE BI-PROP	INTEGRAL BI-PROP	SEPARATE MONO-PROP	SEPARATE MONO-PROP
DEPLOYMENT	PDS	SPDS	SPDS	SPDS
STAGE DRY WT. (kg)	2,076	1,600	1,679	1,126
USABLE PROP. (kg)	16,700	17,500	17,050	16,450
MASS FRACTION (1)	0.899/0.857	0.908	0.901	0.929
ASE WEIGHT (kg)	1,070	870	1,300	2,520
ENGINE THRUST (N)	33,000	26,700	33,400	16,700
ENGINE ISP (N-s/kg)	3373	3344	3366	3334
PAYLOAD TO GEO (kg)				
STS	4,780	4,850	4,720	4,760
TITAN	4,480	3,320	3,530	3,610

(1) $\text{MASS FRACTION} = \dfrac{\text{USABLE PROPELLANT}}{\text{USABLE PROP + STAGE WEIGHT AT BURN-OUT}}$

Figure 8. ASPS Concepts Comparison

The key results to come out of the ASPS studies are summarized below.

1. Storable ASPS concepts using established technology and innovative design can be developed to provide the goal of economically delivering 4,540 kilogram (10,000 pound) payloads in GEO using the STS as a launch system.

2. No major STS safety or integration issues were identified, and the system could perform within existing STS delivery capabilities. Ground processing requirements were found to be within current KSC capabilities.

3. A storable propellant based ASPS can make extensive use of currently developed hardware and hardware already under development.

4. The ASPS is readily compatible with both the STS and the Titan IV, and is easily adaptable to advanced heavy lift launch systems such as the Advanced Launch System (ALS) and the Shuttle-C.

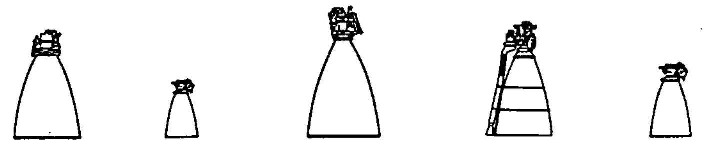
5. The key development item for a new propulsion system such as the ASPS - the engine - has several candidates available, including modifications of proven designs.

These results emphasize the fact that the technologies required for storable propulsion are extensive and well in-hand. The next discussion focuses on the current status in high performance earth storable propellant engines.

STATUS OF HIGH PERFORMANCE EARTH STORABLE ENGINES

Figure 9 summarizes the characteristics of the five prime candidate engines considered for the ASPS. These engines represent the state-of-the-art in earth storable propellant engines. The key technology advancement which these engines take advantage of is the development of small, high speed turbopumps to increase operating chamber pressure. This allows the use of smaller, lighter weight combustion chambers than possible with pressure-fed engines.

Of the engines shown in Fig. 9, three - Transtar, UOME, and the 16,700 N (3,750 lbf) XLR-132 - have had extensive sub-assembly and engine level testing. These engines represent a range of characteristics which will allow designers of future stages the leeway to trade several system features and capabilities. These

	TRANSTAR	XLR-132	UOME	NEW AGENA	XLR-132+
ILLUSTRATION					
THRUST (N)	16,700	16,700	26,700	33,000	33,400
CHAMBER PRESS (N/cm2)	241	1,033	241	496	1,033
COOLANT	MMH	NTO	MMH	NTO+SO *	NTO
PUMP SPEED (RPM)	50,000	60,000	40,000	25,000	60,000
CYCLE LIFE	20	20	500	?	20
SPEC IMP (N-s/kg)	3295	3334	3334	3334	3354
EXPANSION RATIO	400:1	400:1	400:1	400:1	400:1
MIXTURE RATIO	1.80	2.00	1.95	2.02	2.00
WEIGHT (kg)	77	60	132	80	87
LENGTH (m)	2.3	1.3	3.2	2.4	1.6
STATUS	IN DEV	TECH DEMO	PRE-DEV	CONCEPT	CONCEPT

* SILICONE OIL ADDED TO FUEL TO REDUCE HOT GAS WALL HEAT FLUX

Figure 9. Earth Storable Candidate Engines for Advanced Vehicles

include high vs. low chamber pressure, fuel vs. oxidizer cooling, restart capability, cycle and firing life capability, and reliability. Based upon the degree of development testing already accomplished on these engines, there is high confidence in the estimates of three to four years for engine full scale development.

CONCLUDING REMARKS

With the successful return to flight of the Space Shuttle, there has been renewed attention to our capability to deliver large payloads to beyond low earth orbit (LEO). The basic launch vehicles are either in place, with the Shuttle and the Titan, or are in the advanced planning stage, with the ALS and Shuttle-C. However, we are sorely lacking in vehicles to carry on from LEO. Our best efforts at advanced planning for a future upper stage are represented by the cryogenic Orbital Transfer Vehicle (OTV), which represents a complex, costly, and technologically challenging venture.

Future upper stages and space transfer vehicles designed around storable propellants offer a realistic alternative. The implementation of storable systems is not dependent on significant achievements in performance, storage, and transfer technology. Storable systems provide a low risk, high reliability basis for many space transportation vehicle scenarios. High energy mission requirements can be met years sooner, and at a lower cost, than possible with cryogenic systems.

Because of the projected delivery requirements, the ultimate infrastructure must include the high energy capability of cryogenic systems. The development of storable systems is not, however, a dead-ended path. The unique capabilities of the storable systems would compliment those of the cryogenic systems. Many of the key developments required for near term storable vehicles are directly applicable to future cryogenic vehicles, such as lightweight structural materials and overwrapped tankage, adaptive guidance and control, advanced information processing, health monitoring and redundancy management, meteoroid protection, space maintainability, and automation.

The development of a storable propellant upper stage would be consistent with the objectives of the NASA goal for a delivery capability which:

1. Meets early civil space leadership initiative mission requirements;

2. Matches planned launch vehicle capability, availability, and constraints;

3. Is compatible with space station plans; and

4. Has the capability to grow and/or evolve.

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LIST OF ACRONYMS

A-50	Aerozine 50	LPM	Liquid Propulsion Module
ALS	Advanced Launch System	MMH	Monomethylhydrazine
AMS	Apogee and Maneuver Stage	MRSR	Mars Rover Sample Return
APS	Ascent Propulsion System	NTO	Nitrogen Tetroxide
ASPS	Adaptable Space Propulsion System	OMS	Orbital Maneuvering System
BSTS	Boost Surveillance and Tracking System	OMV	Orbital Maneuvering Vehicle
CM	Command Module	OTV	Orbit Transfer Vehicle
CNSR	Comet Nucleus Sample Return	O/F	Oxidizer/Fuel Mixture Ratio
DPS	Descent Propulsion System	PAM	Payload Assist Module
DSP	Defense Support Program	PC	Chamber Pressure
ELV	Expendable Launch Vehicle	RCS	Reaction Control System
GEO	Geosynchrnous Earth Orbit	RP-1	Rocket Propellant - 1 (Kerosene)
GRO	Gamma Ray Observatory	SCOTS	Shuttle Compatible Orbit Transfer Subsystem
HPPM	High Performance Propulsion Module	SM	Service Module
IRFNA	Inhibited Red Fuming Nitric Acid	SPS	Service Propulsion System
ISP	Specific Impulse	STS	Space Transportation System
IUS	Inertial Upper Stage	STV	Space Transfer Vehicle
LEO	Low Earth Orbit	TOS	Transfer Orbit Stage
LH2	Liquid Hydrogen	UDMH	Unsymmetrical Dimethyl-hydrazine
LMA	Lunar Module Ascent		
LMD	Lunar Module Descent		
LOX	Liquid Oxygen		

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